Joseph Magill

Jean Galy

Radioactivity · Radionuclides · Radiation

Joseph Magill
Jean Galy

Radioactivity Radionuclides Radiation

Including the Universal Nuclide Chart on CD-ROM

With 130 Figures, 57 in Colour, 43 Tables, a CD-ROM
and with the Fold-out of the Karlsruhe Chart of the Nuclides

Springer

Joseph Magill
Jean Galy

European Commission
Joint Research Centre
Institute for Transuranium Elements
P. O. Box 2340
76125 Karlsruhe, Germany
magill@itu.fzk.de · jean.galy@itu.fzk.de
www.nuclides.net

Library of Congress Control Number: 2004111115

ISBN 3-540-21116-0 Springer Berlin Heidelberg New York

Cover image: The illustration shows a 10 year-old curium oxide (^{244}Cm half-life 18.1 y) sample. The dendritic surface features are the result of transmutation by natural radioactive decay in about 55–60% of the atoms. More details are given in Chapter 5.

Springer is a part of Springer Science+Business Media
springeronline.com

Printed in Germany

Cover design: Erich Kirchner, Heidelberg
Typesetting: Typeset in Word by the authors and edited by PublicationService Gisela Koch, Wiesenbach, using a modified Springer LaTeX macro-package.

Printed on acid-free paper 57/3141/Ko – 5 4 3 2 1 0

Contents

RADIOACTIVITY

1. Origins and Discovery

The Greek Elements and the Indivisible Atom

Around 2500 years ago, most people believed in a world ruled by gods with supernatural powers. All the more surprising then to realise that there was a group of Greek thinkers seeking a rational explanation of the observable world in terms of natural causes and effects. This "natural" philosophy, although different from the scientific enquiry we know today, was based on reason and contained the principal ingredients of the scientific approach [1] i.e.

- The identification of the universal and essential
- The belief that nature can be explained in terms of simple "elements" and their interactions

The first school of rational thought is believed to be the Milesian school based in Miletus in Ionia in the 6th and 5th centuries B. C. At this time Miletus was the most important city on the Aegean Sea. It was in this early school that Thales, Anaximenes, and Anaximander were searching for rational and natural causes in terms of a "primary reality" or "primordial substance". These early philosophers differed, however, in the choice of what the substance should be. Thales believed water was primordial, Anaximenes chose air, and Anaximander *apeiron* – an indefinite substance. They each had their own views on how the simple elements could transform to give rise to the diversity of natural objects. Thales believed in an unknown process. Anaximenes proposed a process of rarefaction and condensation, and Anaximander a growth or push as the driving force.

Since none of these single element theories were entirely satisfactory, more sophisticated approaches with two-elements theories (Xenophanes and Parmenides), four-element (Empedocles of Agrigentum), or indeed infinite-element (Anaxagoras of Clazomenae) were proposed.

The contribution made by Empedocles is particularly noteworthy. In addition to postulating that there are four primordial substances, he postulated that these primary substances are made of small, homogeneous, changeless, indivisible particles and that all material bodies are formed by particles of one substance penetrating into particles of another. Clearly, one can identify the basic elements of modern atomic theory in these ideas which were to survive for more than two thousand years until the developments of modern chemistry to be established by Priestley, Lavoisier, and Cavendish in the eighteenth century.

Table 1.1. Primordial substances of the early Greeks – Promoters of single and multiple element theories

Element(s)	Promotor	Period
Water	Thales (founder of the Milesian school)	7th B.C.
Apeiron (an invisible, infinite substance)	Anaximander (pupil and successor of Thales)	7th B.C.
Air	Anaximenes (successor to Anaximander)	6th B.C.
Fire	Heraclitus of Ephesus	6th B.C.
Earth + Water	Xenophanes of Colophon (founder of the Eleatic School)	6th B.C.
Fire + Earth	Parmenides (prominent member of the Eleatic school)	6th B.C.
Water + Air + Fire + Earth	Empedocles of Agrigentum	5th B.C.
Infinite number of elements	Anaxagoras of Clazomenae	5th B.C.
Geometrical triangles	Plato	4th B.C.
Warm, cold, dry, moist	Aristotle	3rd B.C.

Pythagoras

In stark contrast to the Milesian school, Pythagoras held that the basis of reality is to be found in numbers rather than in fire, earth, water or air. For the Pythagoreans, number is the primordial element. In addition, these numbers were closely related to the simple geometric objects i.e. point: 1, line: 2, plane: 3, volume: 4. Since everything has a shape, all objects can be broken down into geometric shapes and hence to numbers. The Pythagoreans did not reject the elements of fire, water, earth, air and the ether. They regarded these as perceptible elements, constructed from geometric objects, i.e. the earth is a cube, fire is tetrahedron, air is octahedron, water icosahedron and the ether is duodecahedron.

The Atomist of Antiquity

The theory of atomism, where atoms are postulated as the "elements", follows the philosophies of the Milesian school and the Pythagoreans. The leading proponent, Leucippus, was contempory with the Eleatic school and Empedocles. Atomism was an attempt to address the problem of coming into being and of change. Fundamental to atomism is the idea of two basic elements: corpuscles and void. In particular, the idea of void being primordial was central to the atomists.

The atoms are compact and full and are in constant motion. The atoms of Leucippus and Democritus differed from each other by their size and shape. Fire, water, air and earth, are organisations of certain atoms. The theory of atomism reached its pinnacle one century later with the work of Epicurus who introduced the notion of weight in addition to size and shape and the idea that in void, all atoms moved with the same speed.

Plato

Although Plato's philosophy was based on Empedocles's theory of the four primordial substances – fire, earth, air, and water – he did invoke some of the ideas of Pythagoras through the attribution of geometric shape to each of the elements i.e. the introduction of geometric atoms. The attribution of the elements with polyhedra was as follows: fire (tetrahedron), earth (cube), air (octahedron) and water (icosahedron – 20 faces). These geometrical objects could all be constructed from Plato's polyhedra atoms based on two types of primordial triangles. Of particular interest in Plato's theory is the fact that through dissociation and recombination of these primary triangles to form new objects, the idea of transmutation of elements arises naturally.

Aristotle

In contrast to Plato, Aristotle did not believe in atomism. Instead of primordial elements, he introduced the idea of primordial qualities of warm, cold, dry, moist. The four primordial substances derive from these qualities i.e.

warm + dry = fire
warm + moist = air
cold + dry = earth
cold + moist = water

By interchanging qualities, transmutation of elements again arose naturally. By interchanging, for example, dry with moist, the element fire could be transmuted into air. Chemical reactions were seen as combinations and separations of elements.

Modern Atomism

These ideas of the Greeks were to persist for more than two thousand years until the introduction of scientific atomism which can be traced to the 18th Century. Through the work of Lavoisier, Cavendish and Priestly, it was shown that the idea of four elements was incorrect through the demonstration that water and air are compounds. The discovery by Proust of the laws governing the combinations of chemical elements and by Dalton of the law of simple multiple proportions cemented these ideas further. In particular, it was the work of Dalton which forms the basis of modern-day quantitative theory of matter. Whereas Dalton maintained that atoms are indivisible and indestructible, he advanced our ideas through postulating:

- All atoms of a elements are similar and have the same weight
- Atoms of different elements have different weights

- The basic building blocks (molecules) of compound bodies are formed by the union of different atoms in definite proportions
- During chemical reactions, no creation or destruction of matter can occur

The most important of these ideas, however, was that constituent atoms of an element all have the same weight. Already in Dalton's time, 36 elements had been identified. By the time Mendeleev proposed his periodic table in 1869, this number had risen to 63.

Twentieth Century Science and the Multi-Corpuscular Atom

By the end of the nineteenth century, the atomic theory with its origins dating back over two thousand years to the Greeks Leucippus and Democritus, had become universally accepted. Chemists were filling in the details of the periodic table and physicist were occupied with the kinetic theory of gases (Clausius, Maxwell, Boltzmann), Brownian motion (Einstein), and the determination of Avogadro's number and the "counting" of atoms [1].

This general acceptance of the atom as the fundamental constituents of matter, however, was to prove short-lived. Although the atom was to remain as the basic building block of the chemical elements, evidence was starting to emerge that these "atoms" did have an internal structure consisting of smaller components and could no longer be regarded as being "indivisible" or fundamental.

At the end of the nineteenth and start of the twentieth centuries a series of spectacular discoveries were made which would lead to a new era in science. The Nobel prize was first awarded in 1901 for outstanding contributions in scientific progress.

The hypothesis of the indivisibility of the atom came to an end with the discovery of the electron by J. J. Thomson in 1897. In his work on electrical discharges in gases, he showed that "cathode rays" observed in his experiments, were particles with a negative electrical charge and that "electricity" had a granular structure. These particles or "corpuscles" as referred to by Thomson were later given the name "electron" by Stoney. Of great importance is also the fact that Thomson showed that the properties of these electrons were independent of the gas undergoing electrical discharge and that these electrons were a fundamental constituent of all atoms.

"Since electrons can be extracted from all chemical elements, one must conclude that they are a part of the constitution of all atoms." (J. J. Thomson, 1914)

Independent evidence of the electron as a sub-atomic particle was provided by the realisation that the β particles spontaneously emitted in the newly discovered phenomena of radioactivity, were high energy electrons (see following section). The idea of electrons being a fundamental constituent of all atoms, however, raised further problems. Primary among these were the number of electrons contained in a particular atom and how to explain the electrical neutrality of atoms. Later studies indicated that the number of electrons was roughly equal to half the atomic weight. Another question was related to the role of the electron in the structure of the atom.

In the following sections the discovery of radioactivity and the role of the electron in the structure of the atom are described in more detail.

Discovery of Radioactivity

In November 1895 Wilhelm Conrad Röntgen discovered X-rays. In a meeting of the French Academy of Science, the following January in Paris, Henri Becquerel heard Poincaré report the recent discovery. The X-rays discovered by Röntgen were the result of fluorescence produced by cathode rays in a cathode ray tube. Becquerel wondered if luminescence was a precondition for the observation of X-rays – he had already studied phosphorescence of uranium compounds.

Fig. 1.1. Henri Becquerel and family in their library. © R. Oldenbourg Verlag

Fig. 1.2. Pierre and Marie Curie, about 1898. © R. Oldenbourg Verlag

In one of his early attempts, Becquerel exposed uranium-containing minerals to sunlight to cause the material to glow (phosphorescence). The sample was placed on top of a photographic plate wrapped in black paper. Following development of the plate he could observe if radiation had penetrated the paper. This was indeed the case. By placing various objects (coins etc.) between the mineral and the photographic plate, he could reproduce the shapes of the objects.

From his detailed records, it is known that Becquerel decided to develop plates that had been in his drawer together with the uranium mineral. These had not been exposed to sunlight. Remarkably, the plates had been "fogged" by the uranium without activation by sunlight. The uranium was emitting rays by itself. Becquerel had discovered radioactivity.

Shortly after this event, Pierre and Marie Curie showed that thorium also acted like uranium. In an effort to try to isolate the source of the rays, they discovered the elements polonium and radium. Rutherford started working with these newly discovered uranium rays believing that they were similar to the X-rays discovered by Röntgen. In 1899, he discovered that these "rays" could be bent by a magnetic field and that there were two types of rays: alpha and beta. Today we know that the

alpha particle is a nucleus of helium and the beta particle is an electron. In later experiments, Rutherford would use these alpha particles to probe the structure of atoms.

Structure of the Atom: Kelvin-Thomson "Plum Pudding" Atom

The discovery of radioactivity, and the discovery of the electron [2], were the starting points for theories of atomic structure. One of the problems associated with the discovery of the electron as a fundamental constituent of matter, was how to explain the electrical neutrality of the atom.

A first step in this direction was taken by Lord Kelvin (Sir William Thomson) and J. J. Thomson who proposed almost simultaneously one of the first models of the structure of the atom. In order to enforce electrical neutrality, Kelvin proposed a configuration, in 1902, in which the negative charges of the electrons and the positive charges cancelled out. He considered the atom to consist of a sphere in which the mass and charge are distributed uniformly with electrons embedded like plums in a pudding. In this model, electromagnetic radiation would be emitted if external forces caused the electrons in the atom to vibrate. In 1903–1904, J. J. Thomson proposed a modification of this in which the electrons moved at high speed in concentric circles in a sphere of continuous positive charge.

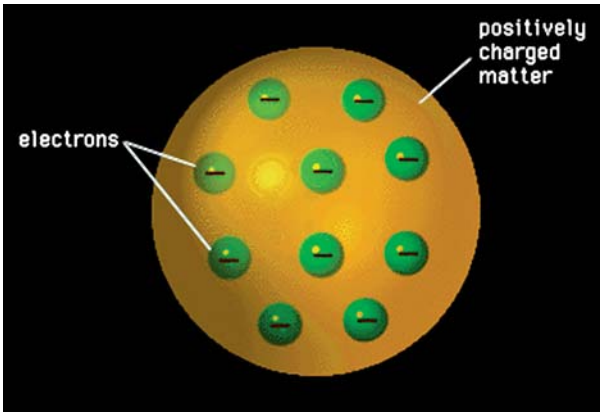


Fig. 1.3. Kelvin-Thomson "plum pudding" model of the atom [3]

Rutherford's Planetary Model of the Atom

In 1911 [4], Rutherford postulated that, in contrast to the "plum pudding" model, the positive charge of the atom was concentrated in a central "nucleus" much smaller than the atom which contained most of the atom's mass, with the negative electrons orbiting around the nucleus similar to the way planets move around the sun. Each atom with its specific number of electrons, must contain an equal and opposite number of positive charges to ensure electrical neutrality. Since the electron is the fundamental unit of negative charge, Rutherford postulated that the unit of positive charge in the nucleus is the "proton".

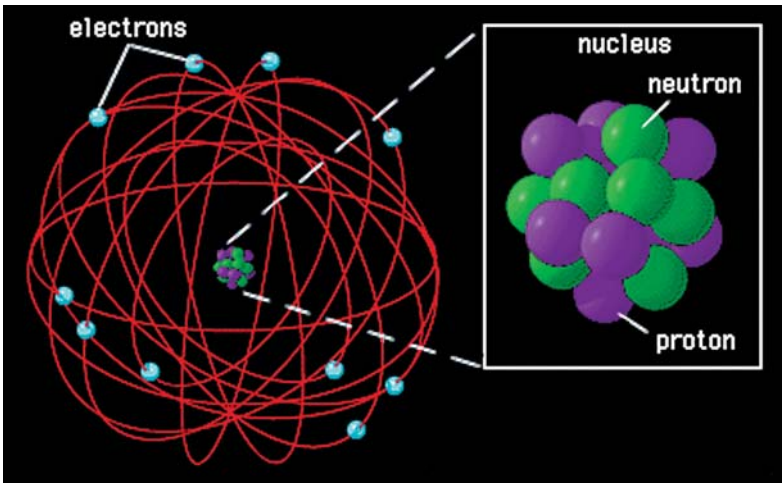


Fig. 1.4. Rutherford's nuclear atom [5]

Fig. 1.5. Ernest Rutherford (1871–1937).

These ideas were put to test by two of Rutherford's students Geiger and Marsden in 1913 [6]. In a classic experiment, they bombarded thin gold foils with alpha particles emitted from radioactive polonium. If Rutherford's ideas on the structure of the atom were correct, then most of the alpha particles would pass through the thin foils with no interaction while a few would be scattered strongly due to close contact between the projectile and the nucleus.

The experiments confirmed Rutherford's ideas by showing that a collection of atoms consisted of positively charged nuclei with diameter of 5×10^{-15} m and that these nuclei were separated by distances of approximately 10^{-10} m. It was also found that the number of unit charges in the nucleus was approximately equal to the atomic number of the atom and to about one half of the atomic weight.

Although these ideas were revolutionary at the time, there were two unsatisfactory aspects of Rutherford's proposed atomic structure. The first concerned how electrons are held in place outside the nucleus and the second how the protons can be held together in view of the strong repulsive forces of the positively charges particles. The idea of a small solar system with the electrons orbiting the positively charged nucleus seemed attractive but this was unacceptable to classical theory. According to this theory, such orbiting electrons experience a radial acceleration and should emit radiation. In doing so they would lose their kinetic energy and spiral into the nucleus.

Another limitation of the model was the fact that it could not account for the emission spectra of atoms. Emission spectra were first identified by Kirchhoff and

Bunsen who showed that spectral lines constitute a fingerprint which could be used to identify atoms.

These difficulties were to be resolved by Niels Bohr [7] who introduced a series of revolutionary ideas which were to change twentieth century science.

Bohr-Sommerfeld Model of the Atom

Bohr Atom

Rutherford's ideas were indeed irreconcilable with the classical theory of electromagnetism. Around this time new ideas were emerging on the structure of the atom. In 1913 Bohr [7] developed a model based on the new "quantum" theory proposed by Planck for radiation. In his investigations into the distribution of light from heated bodies and how this changes with temperature (blackbody radiation), Planck showed in 1900 that bodies emit radiation only in discrete amounts which are some multiple of $h\nu$, the quantum of energy, where ν is the frequency of the radiation and h is a constant known as Planck's constant. This discovery was to set the scene for the foundations of quantum theory some twenty years later. These ideas were further substantiated with the discovery of the photoelectric effect by Einstein in 1905. In his investigations of how electrons are emitted from metal plates under the action of ultraviolet light, Einstein showed that the energy of the emitted electrons depends only on the frequency of the incident light and not on its intensity – in contrast to classical theory. He showed further that the light must be composed of discrete "photons" each with energy $h\nu$.

In a series of three papers published in 1913, Bohr invoked the ideas of Planck and Einstein into a new model of the atom. He proposed that atoms are in stationary states and that any emission of energy is associated with a transition of one state to the other. On this basis, emitted radiation must satisfy the condition $h\nu = E_1 - E_2$. With this idea, Bohr resolved the difficulty of classical theories in which orbiting electrons must emit radiation continuously.

Bohr's postulates can be summarised as follows:

1. Electrons orbit around the nucleus in discrete energy states without emitting radiation.
2. The allowed states for the electron are those for which the orbital angular momentum L is an integral multiple of $h/2\pi$ i.e. $L = n \cdot h/2\pi$ where n is the quantum number for discrete energy states.
3. When an electron jumps from a higher energy E_2 state to a lower energy state E_1 radiation of frequency ν is emitted, where $h\nu = E_2 - E_1$.

A spectacular success of Bohr's model over that of Rutherford lay in the fact that it could explain the sharp line atomic spectra which results from, for example, the electrical excitation of gases. As early as 1885 Balmer had shown that the series of frequencies characteristic of spectral lines for the visible spectrum of hydrogen were governed by the relation

$$\nu = R\left(\frac{1}{i^2} - \frac{1}{j^2}\right),$$

where R is known as the Rydberg constant. The first series is given by setting $i = 1$, and $j = 1, 2, 3, \ldots$. The second series corresponds to $i = 2$, and $j = 3, 4, 5$, etc.

With Bohr's postulates, it can be shown that from conservation of energy and angular momentum the electron energy is given by

$$E_n = -\frac{1}{n^2} \cdot \frac{(2\pi)^2 k^2 q^4 m}{2h^2} = -\frac{1}{n^2} \times 13.58 \text{ eV},$$

where q and m are the electron charge and mass respectively, and $k = 2\pi/\lambda$ with λ the wavelength. For $n = 1$, $E_1 = -13.58$ eV in agreement with the ionisation energy of the hydrogen atom. Higher lying energy states are then given by [8]

$$E_n = -\frac{E_1}{4}, -\frac{E_1}{9}, -\frac{E_1}{16}, \ldots \text{etc.}$$

with $E_1 = -13.58$ eV. The energy levels are shown in Fig. 1.6. From the energy levels, the frequencies of the emissions (and absorptions) can be calculated. Bohr showed that for $n = 3$, he could reproduce the Balmer series of frequencies. For other values of n (1, 2, 4 etc.) Bohr predicted other series of frequencies not known at the time. Following Bohr's prediction, these series were also found providing a spectacular success for the theory.

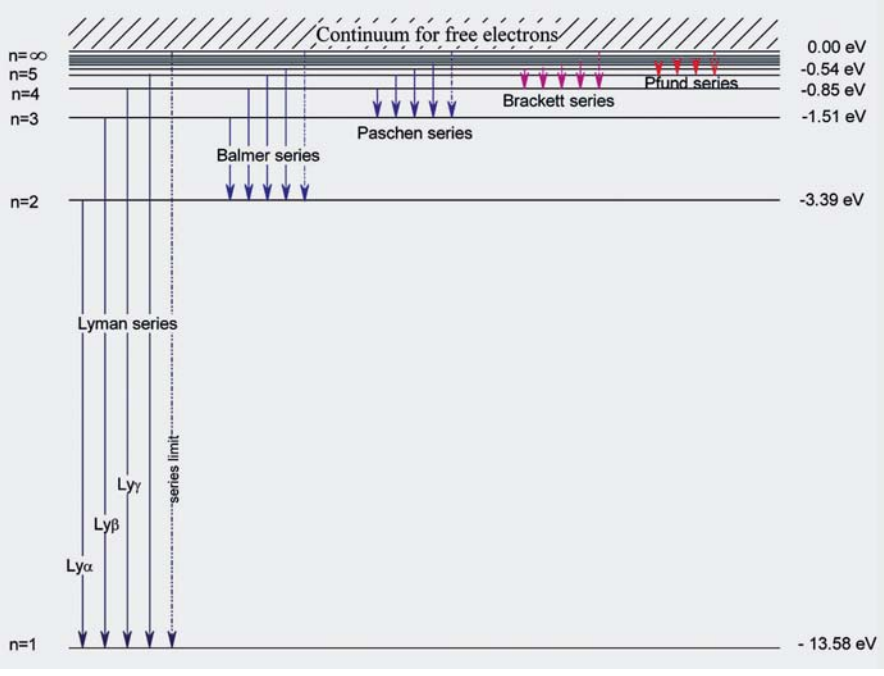


Fig. 1.6. Energy states of electrons in the hydrogen atom [8]

Sommerfeld's Extension of the Bohr Theory

In 1916, Sommerfeld extended Bohr's circular orbits, with the main or principal quantum number n, to elliptical orbits with an "azimuthal" quantum number l. Shortly later the magnetic quantum number was introduced to account for the effects of magnetic fields. These three quantum numbers n, l, m, can be regarded as giving the size, shape, and spatial orientation of the orbits.

Table 1.2. Characterisation of orbits in Bohr-Sommerfeld model

l	0	1	2	3
Orbital	*s*	*p*	*d*	*f*

These elliptical orbits, including the circular orbit, for one quantum number n have the same length of the major axes and with this the same energy levels, but different lengths of the minor axes. Different proportions between the major axes and minor axes (i.e. the eccentricity of the elliptical orbit) show different azimuthal quantum numbers l. The number of different quantum numbers l depends on the main quantum number through the relation $l_{\max} = n - 1$. The different l numbers characterise the different orbitals as shown in Table 1.2. This model is shown schematically in Fig. 1.7.

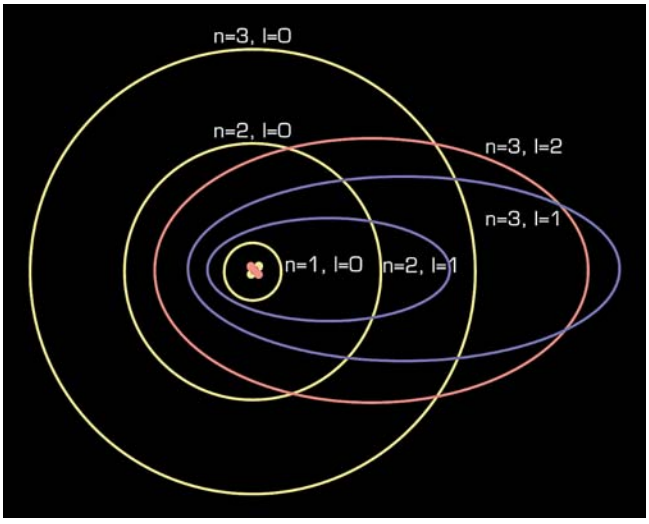


Fig. 1.7. Bohr-Sommerfeld model of the atom [5]

In general, the number of orbitals with the same azimuthal quantum number l is given through the expression $2l + 1$. Each of these orbits is characterised by the orbital magnetic moment m_l, where m_l has the values $l, l-1, l-2, \ldots, -l+1, -l$. The results are summarised in Table 1.3.

Table 1.3. Number and orbital angular momentum of orbits for a given quantum number l

l	0	1	2	3
Number of orbitals	1	3	5	7
m_l	0	1, 0, −1	2, 1, 0, −1, −2	3, 2, 1, 0, −1, −2, −3

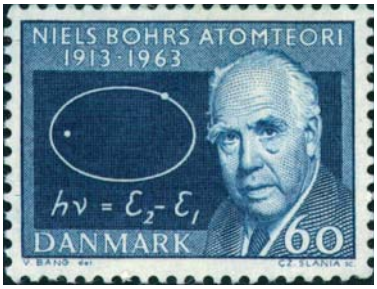


Fig. 1.8. Image of Niels Bohr (1885–1962) on a Danish stamp

To explain the very fine structure of atomic lines, it was necessary to postulate that an orbital electron can spin in one of two directions about its own axis in the same way that the earth spins about its axis as it orbits the sun. The associated spin magnetic momentum m_s can take one of two values, $+\frac{1}{2}$ and $-\frac{1}{2}$, with the condition, that the two electrons in one orbital have different spins.

The total magnetic moment, the quantum number m, is the sum of the orbital magnetic moment m_l and spin magnetic moment m_s. The magnetic moment may be positive or negative depending on the direction of the orbital motion. When the atoms of a substance are placed in a magnetic field, the electrons will arrange themselves in definite directions with respect to the applied field.

With the Bohr-Sommerfeld atomic model, all elements of the periodic table can be categorised with these four quantum numbers n, l, m_l and m_s.

The Neutron

The second difficulty of Rutherford's model of the atom was to explain how the protons can be held together in view of the strong repulsive forces of the positively charged particles. Hydrogen, the simplest atom, consists of a single proton in the nucleus. If heavier nuclei contained multiple protons, then the mass number and the atomic numbers should be the same. This was not the case. The mass numbers were found to be approximately twice the atomic number for light nuclei. Similarly, the Coulombic repulsion of these multiple proton nuclei would be enormous – what can hold the nuclei together?

These difficulties were resolved by the discovery of the neutron by Chadwick in 1932. Its presence in the nucleus explains the difference between the atomic and mass numbers. More importantly, the neutron is responsible for the cohesive force that holds the nucleus together. This *nuclear force* is attractive and extremely short range – about 2–3 $\times$ 10^{-15} m.

Fig. 1.9. James Chadwick (1891–1974). © 1999 Awards of Outstanding International Importance to Statesmen and Heroines

Because of the very short range of the nuclear force, neutrons can only interact with their nearest neighbour nucleons, in contrast to the longer-range repulsive electrical forces of the protons. For this reason, in a stable nucleus, the number of neutrons must increase more rapidly than the number of protons. The discovery of the neutron also explained the existence of isotopes discovered in 1913 by Soddy for radioactive elements.

In addition to the proton, neutron, and electron, there are considerably more than 100 other fundamental particles which have been discovered or hypothesized. The majority of these fall into one of two classes, leptons (consisting of electrons, muons, and neutrinos) or hadrons (e.g. protons and neutrons). According to the Standard Model (see Glossary), these elementary particles can be grouped in a similar manner to chemical elements in the periodic table. From these groupings, it has been proposed that hadrons are composed of three (or possibly more) simpler components called *quarks*, and that these quarks are "glued" together by gluons which carry the strong nuclear force.

Wave/Particle Duality: The de Broglie Relation and Wave Mechanics

The Bohr theory introduced the idea of characterising the states of electrons with integers (the quantum numbers). It is also known that integers are used in many branches of physics involving waves to characterise standing waves, interference, resonance etc. This is one of many considerations which led Louis de Broglie to postulate in 1924 the wave/particle duality expressed in his formula

$$\lambda = h/p\,,$$

where h is Planck's constant described in the previous section. This relation expresses the fact that associated with any particle is a wave of wavelength λ which depends on the momentum p of that particle. The remarkable aspect about this relation is that when applied to electrons in the atom, due to the wave characteristics of the electron, the quantisation rules emerge naturally. The stable orbits are those in which the circumference is an integral number of wavelengths. The relation postulated by de Broglie in 1924 was verified experimentally for electrons by Davisson, Germer, and Thomson in 1927. The wave properties of atoms were demonstrated much later in 1991.

Shortly after this postulation of de Broglie, Schrödinger introduced his "wave mechanics" to characterise the de Broglie waves in 1926. Starting from the wave equation $\nabla^2\Psi + k^2\Psi = 0$ where $k = 2\pi/\lambda$, Schrödinger replaced the wavelength by the de Broglie relation $\lambda = h/mv$. The wave amplitude or wave function is then given by

$$\nabla^2\Psi + \left(\frac{4\pi^2 m^2 v^2}{h^2}\right)\Psi = 0\,.$$

Since the total energy of the particle $E = \frac{1}{2}mv^2 + V$, it follows that $mv^2 = 2(E-V)$ and substituting in the above relation leads to

$$\nabla^2\Psi + \left(\frac{8\pi^2 m}{h^2}\right)(E - V)\Psi = 0\,,$$

which is known as the Schrödinger equation. To satisfy standard boundary conditions, this equations has solutions Ψ only for particular values of the energy E. It follows that energy quantisation and the three quantum numbers follow naturally, rather than just a postulate as in Bohr's theory. The functions Ψ are also called "orbitals" to contrast with the classical orbits describing well defined trajectories. Based on de Broglie's wave/particle relation, Schrödinger considered the wave function as a physically real property of electrons.

A completely different interpretation of the wave function, which quickly gained widespread acceptance by leading physicists, was introduced by Max Born in 1926. The real novelty in his interpretation was the introduction of a probabilistic interpretation of the wave function. This was to be a subject of great controversy for many years later.

As stated above, the solution to Schrödinger's wave equation provides the quantum numbers n, l, and m. The possible values up to $n = 4$ (a given value of n is referred to as a shell) are given in Table 1.4.

Table 1.4. Possible values of the quantum numbers n, l, m and spectroscopic notation [1]

					Electrons in orbital	
Shell	n	l	Orbital	m	Max. no.	Total no.
K	1	0	s	0	2	2
L	2	0	s	0	2	8
		1	p	$0, \pm 1$	6	
M	3	0	s	0	2	18
		1	p	$0, \pm 1$	6	
		2	d	$0, \pm 1, \pm 2$	10	
N	4	0	s	0	2	32
		1	p	$0, \pm 1$	6	
		2	d	$0, \pm 1, \pm 2$	10	
		3	f	$0, \pm 1, \pm 2, \pm 3$	14	

In addition to the three quantum numbers n, l, m, the spin quantum number has to be added to account for the rotational motion about themselves. Finally the filling of orbital by electrons is shown Table 1.5. Arrows indicate spin and anti-parallel spin. It is then straightforward to obtain the maximum number of electrons in each shell.

This filling procedure then provides the key to classification of the elements in the periodic table.

Table 1.5. Filling of orbitals by electrons [1]

	$1s$	$2s$	$2p_x$	$2p_y$	$2p_z$	
H	↑					$1s$
He	↑↓					$1s^2$
Li	↑↓	↑				$1s^2\,2s$
Be	↑↓	↑↓				$1s^2\,2s^2$
B	↑↓	↑↓	↑			$1s^2\,2s^2\,2p$
C	↑↓	↑↓	↑	↑		$1s^2\,2s^2\,2p^2$
N	↑↓	↑↓	↑	↑	↑	$1s^2\,2s^2\,2p^3$
O	↑↓	↑↓	↑↓	↑	↑	$1s^2\,2s^2\,2p^4$
F	↑↓	↑↓	↑↓	↑↓	↑	$1s^2\,2s^2\,2p^5$
Ne	↑↓	↑↓	↑↓	↑↓	↑↓	$1s^2\,2s^2\,2p^6$

Classification of the Elements

Until recently, there were 114 known chemical elements. Very recently, evidence for the existence of two new superheavy elements has been reported. Each element is characterised by atoms containing a fixed number of protons, denoted by the atomic number Z, in the nucleus and an equal number of orbital electrons to ensure electrical neutrality. In addition to protons, the nucleus contains a variable number N of electrically neutral neutrons. Atoms of an element with different numbers of neutrons but fixed number of protons are known as isotopes of that element (see inset). More than 3000 nuclides are known, but only about 10% of these are stable. The total number of protons plus neutrons is known as the mass number A of a nuclide. Nuclides with the same N and different Z are called isotones, and nuclides with the same mass number A are known as isobars. In general, an atom with atomic number Z, and neutron number N is known as a nuclide. A nuclide can be specified by the notation:

$$ {}^{A}_{Z}\mathrm{X}_{N} \ , $$

where Z is the atomic (proton) number, N is the neutron number, A is the mass number ($N + Z$), and X is the chemical element symbol.

Because of the relationships between Z, A, N ($A = Z + N$) and X, a nuclide can be uniquely specified by fewer parameters. A particular chemical element is uniquely specified by its symbol X or the proton number Z. A nuclide is uniquely specified by the element name X (or proton number Z) together with the mass number A. An example is ^{60}Co which refers to the element cobalt (chemical symbol Co) with mass number 60 (number of protons plus neutrons). A variety of ways of referring to this nuclide are in current use i.e. Co60, Co-60, Co 60, ^{60}Co, and cobalt-60.

Nuclide, $^{A}_{Z}\mathbf{X}$

Refers to a particular atom or nucleus with a specific number N of neutrons and number Z of protons. A is the mass number ($= Z + N$). Nuclides are either stable or radioactive. Radioactive nuclides are referred to as radionuclides.

Atomic Number, Z

The number of positively charged protons in the nucleus of an atom.

Neutron Number, N

The number of neutrons in the nucleus of an atom.

Isotope

One of two or more atoms of the same element that have the same number of protons (isotope) in their nucleus but different numbers of neutrons. Hydrogen $^{1}_{0}$H, deuterium $^{2}_{1}$H, and tritium $^{3}_{1}$H, are isotopes of hydrogen. Radioactive isotopes are referred to as radioisotopes.

Isotone

One of several different nuclides having the same number of neutrons (isotone) in their nuclei.

Isobar

Nuclides with the same atomic mass number $A(= Z + N)$ but with different values of N and Z e.g. ^{14}B, ^{14}C, ^{14}N.

Isomer

Atoms with the same atomic number Z and the same mass number A in different long-lived states of excitation – the higher states being metastable with respect to the ground state. For example, an isomer of ^{99}Tc is ^{99m}Tc where the m denotes the long-lived excited state.

Synthesis of the Elements in Nature

The distribution of elements in nature is by no means uniform. Studies of stars reveal that hydrogen is by far the most abundant element, accounting for approximately 75% of the mass of the universe. The remaining mass is mostly in the form of helium gas with other elements contributing only to a small extent.

The hydrogen in the universe is the driving fuel for continuous change in the chemical composition. Hydrogen is being converted to helium, which is further changed into heavier elements.

The observed abundances of elements in the universe require the postulation of at least eight different processes for their formation [9]. The main processes are:

- hydrogen burning (formation of helium-4 by the fusion of hydrogen nuclei),
- helium burning (formation of carbon-12 from helium-4-nuclei),
- s processes (slow neutron capture processes, starting from iron group nuclei, close to the stability line – see section “Nuclide Charts”, Chapter 2),

- r processes (rapid neutron capture processes, starting from iron group nuclei, produce nuclei far from the line of stability),
- rp processes (similar to the r-processes, but involve successive proton absorptions),
- X processes (spallation of heavier elements into lighter elements by cosmic rays).

Light elements were probably produced in the early history of the galaxy whereas heavy elements were formed in supernovae.

According to current theory, the universe is about 10^{10} years old and started as a "soup" of quarks at enormous temperatures and pressures. As the universe expanded, the temperature and pressure decreased rapidly to the point where neutrons and protons condensed out. Shortly after, nuclear fusion took place and led to the formation of deuterons followed by tritons and onto helium-3 nuclei and alpha particles (hydrogen burning), thereby giving rise to the present hydrogen to helium ratio of 3:1. In addition, some lithium-6 and lithium-7 were produced at this time. As the universe further expanded and cooled, the fusion reactions stopped and the gases condensed and eventually led to the formation of stars consisting of the primordial elements.

As a cloud of interstellar gas contracts and condenses to form a star, the temperature will rise as the gravitational potential energy is converted to kinetic energy. When the temperature increases to 10^7 K and beyond, fusion reactions will begin to take place and further nucleosynthesis leads to the conversion of the elements hydrogen and helium to carbon, silicon, oxygen, sulphur and heavier elements up to iron. Fusion can proceed no further than iron since this element has the high-

Fig. 1.10. Vela supernova remnant. © Anglo-Australian Observatory, photo from UK Schmidt, plates by David Malin

est binding energy. Fusion of heavier elements will consume energy rather than release it.

The synthesis of elements heavier than iron require a supernova. As stated above, the sequence of stellar burning more or less stops when the core of the star is composed of nuclei with mass numbers close to 56 (i.e. iron). At this point the central region of the star has consumed all the nuclear fuel and cannot support the star's interior against gravitational collapse into a neutron star. In this process all protons are converted into neutrons with the release of a large number of neutrinos within a short time. These neutrinos interact with the outer layers of the star resulting in a large fraction of the mass being ejected into space. In addition, large numbers of particles are produced, in particular neutrons. It is then these neutrons, which lead to the formation of heavier elements by transmutation through r(rapid)-process neutron capture events.

At least 24 elements are believed essential to living matter. The most abundant of these in the human body are, in order of importance: hydrogen, oxygen, carbon, nitrogen, calcium, phosphorus, chlorine, potassium, sulphur, sodium, magnesium, iron, copper, zinc, silicon, iodine, cobalt, manganese, molybdenum, fluorine, tin, chromium, selenium, and vanadium.

Ninety-one elements occur naturally on earth supporting the theory that heavy elements were produced during creation of the solar system. Exceptions are technetium and promethium although these are present in stars.

In the following chapter, the properties of nuclides and their constitutents are described in more detail.

2. Nuclear Energetics

Nuclear Units – Atomic Mass Unit and the Electron Volt

Most units used in nuclear science are based on the International System of Units or SI units (from the French "Système International d'Unités") [1]. The base SI units are the metre (length), kilogram (mass), second (time), ampere (electric current), kelvin (temperature), candela (luminous intensity), and the mole (quantity of substance). In nuclear science, in addition to SI, two units are commonly used for mass and energy i.e. the atomic mass unit and the electron volt.

Mass – The Atomic Mass Unit

Masses of atomic nuclei are generally less than 10^{-21} g. For this reason, it is more convenient to express the masses in so-called *atomic mass units* [2]. The atomic mass unit (abbreviated as amu or u) is defined such that the mass of a ^{12}C atom is exactly 12 u. Hence,

$$1\,\mathrm{u} = 1.6605387 \times 10^{-27}\,\mathrm{kg}\,.$$

Energy – The Electron Volt

Energies released in chemical reactions are of the order of 10^{-19} J. For such reactions, it is more convenient to use the energy unit *electron volt*, eV. By definition, the electron volt is the kinetic energy gained by an electron after acceleration through a potential difference ΔV of one volt. This kinetic energy increase of $e\Delta\mathrm{V} = (1.60217646 \times 10^{-19}\,\mathrm{C}) \cdot (1\,\mathrm{V}) = 1.60217646 \times 10^{-19}\,\mathrm{J}$. Hence

$$1\,\mathrm{eV} = 1.60217646 \times 10^{-19}\,\mathrm{J}\,.$$

The energy equivalent of the atomic mass unit is

$$E = mc^2 = 931.494013\ \mathrm{MeV}\,.$$

Nuclear and Atomic Masses

Tables of masses always give *atomic* rather than *nuclear* masses. This implies that the masses given include the extra-nuclear electrons. Atomic masses are more convenient than nuclear masses since it is always atomic masses or differences between atomic

masses that are measured experimentally. This distinction is reflected in the notation used in this book: rest mass of an *atom* is denoted by $M\left({}^{A}_{Z}\mathrm{X}\right)$ whereas the rest mass of the *nucleus* is denoted by $m\left({}^{A}_{Z}\mathrm{X}\right)$.

Notation on Masses

- rest mass of an *atom* is denoted by $M\left({}^{A}_{Z}\mathrm{X}\right)$
- rest mass of the *nucleus* is denoted by $m\left({}^{A}_{Z}\mathrm{X}\right)$

According to the above notation, the electron, neutron, and proton masses are $m\left({}^{0}_{-1}\mathrm{e}\right)$, $m\left({}^{1}_{0}\mathrm{n}\right)$, $m\left({}^{1}_{1}\mathrm{H}\right)$ respectively. For convenience, however, the notation here is simplified to m_{e}, m_{n}, m_{p}. Since combining Z electrons with the nucleus forms a neutral atom, the atomic and nuclear masses are related by

$$M\left({}^{A}_{Z}\mathrm{X}\right) = m\left({}^{A}_{Z}\mathrm{X}\right) + Zm_{\mathrm{e}} - \frac{BE_{Z\mathrm{e}}}{c^2}\,,$$

where $BE_{Z\mathrm{e}}$ is the energy released upon binding with the nucleus. The mass change corresponding to the electron binding energy in the above relation ($BE_{Z\mathrm{e}}/c^2$ for hydrogen is approximately 10^{-8} u) is negligible compared to the mass of the atom (hydrogen mass is about 1 u) and also the electron (about 5.5×10^{-4} u), such that, to a good approximation [3]

$$M\left({}^{A}_{Z}\mathrm{X}\right) \cong m\left({}^{A}_{Z}\mathrm{X}\right) + Zm_{\mathrm{e}}\,.$$

Atomic and Molecular Weights

The atomic weight $\mathscr{A}$ of an atom is the ratio of the atom's mass to 1/12th of the mass of an atom of ^{12}C in its ground state [3, 4]. The molecular weight of a molecule is the ratio of the molecular mass of one molecule to 1/12th of the mass of one atom of ^{12}C. Both the atomic and molecular weights are dimensionless. It follows that the mass of an atom measured in atomic mass units is numerically equal to the atomic weight of that atom. The atomic mass (in u) and hence the atomic weight of a nuclide is almost equal to the atomic mass number $A(= Z + N)$ such that $\mathscr{A} \cong A$.

Most naturally occurring elements consists of two or more isotopes. The isotopic abundance a_i is defined as the relative number of atoms of a particular isotope in a mixture of the isotopes of a chemical element, expressed as a fraction of all the atoms of the element. The *elemental atomic weight* $\mathscr{A}$ is the weighted average of the atomic weights $\mathscr{A}_i$ of the naturally occurring isotopes of the elements, weighted by the isotopic abundance a_i of each isotope i.e.

$$\mathscr{A} = \sum_i \frac{a_i}{100}\mathscr{A}_i\,.$$

Atomic Weight of Magnesium

Naturally occurring magnesium consists of three stable isotopes – ^{24}Mg, ^{25}Mg, ^{26}Mg – with isotopic abundances 78.99, 10, and 11.01 atom-percent respectively. The atomic weights are 23.985041700 (^{24}Mg), 24.98583692 (^{25}Mg), and 25.982592929 (^{26}Mg).

The atomic weight of magnesium $\mathscr{A}_{\mathrm{Mg}}$ is then:

$$\begin{aligned}\mathscr{A}_{\mathrm{Mg}} &= \frac{a_{24}\mathscr{A}_{24} + a_{25}\mathscr{A}_{25} + a_{26}\mathscr{A}_{26}}{100} \\ &= (0.7899 \times 23.985042) + (0.1 \times 24.985837) + (0.1101 \times 25.982593) \\ &= 24.3050\end{aligned}$$

Avogadro's Number

A mole of a substance is defined to contain as many "elementary particles" as there are atoms in 12 g of ^{12}C and is equal to 6.0221415×10^{23} (2002 CODATA recommended value). This number is known as Avogadro's number N_{a}. The mass in grams of a substance that equals the dimensionless atomic or molecular weight is called the gram atomic weight or the gram molecular weight. Hence one gram atomic weight of a substance represents one mole and contains N_{a} atoms or molecules.

Basic Relation between Mass and Number of Atoms

Consider a substance of mass $\mathscr{M}$ (in grams). This mass corresponds to $\mathscr{M}/\mathscr{A}$ moles and therefore contains $(\mathscr{M}/\mathscr{A}) \cdot N_{\mathrm{a}}$ atoms. Hence the basic relation between the *number of atoms* and the *mass of a substance* is given by:

$$N = \frac{\mathscr{M}}{\mathscr{A}} \cdot N_{\mathrm{a}}\,.$$

Calculations usually involve an initial mass or an activity of a parent nuclide. The first step is then to convert this mass to a number of atoms, N, before the solutions to the decay equations is evaluated, for example.

The activity, A, is defined by $A = kN$ where k is the decay constant $\ln 2/\tau(\mathrm{s})$. Given an activity, the number of atoms is given by

$$N = \frac{A}{k} = A \cdot \frac{\tau(\mathrm{s})}{\ln 2}$$

where $\tau(\mathrm{s})$ is the half-life in seconds. The relationship between the mass and the activity is given by

$$A \cdot \frac{\tau(\mathrm{s})}{\ln 2} = \frac{\mathscr{M}}{\mathscr{A}} \cdot N_{\mathrm{a}}$$

from which it follows

$$A = \frac{\ln 2}{\tau(\mathrm{s})} \cdot \frac{\mathscr{M}}{\mathscr{A}} \cdot N_{\mathrm{a}}$$

or

$$\mathscr{M} = A \cdot \left[\frac{\mathscr{A}}{N_{\mathrm{a}}}\right] \cdot \frac{\tau(\mathrm{s})}{\ln 2}$$

Mass of an Atom and Atomic Number Density

With Avogadro's number, the mass of an individual atom can be evaluated. One mole of a substance, with mass of $\mathscr{A}$ grams, contains N_a atoms. Hence, the mass of an individual atom is

$$M = \frac{\mathscr{A}}{N_a} \cong \frac{A}{N_a}$$

where the atomic weight has been approximated by the atomic mass number. That this approximation is good can be seen for the case of ^{208}Pb:

Approximate relation $M \cong A/N_a$

$$M(^{208}\text{Pb}) \cong \frac{208\,\text{g}}{6.022142 \times 10^{23}} = 3.4539 \times 10^{-22}\,\text{g}\,.$$

Exact relation $M = \mathscr{A}/N_a$

$$M(^{208}\text{Pb}) = \frac{207.976652\,\text{g}}{6.022142 \times 10^{23}} = 3.4535 \times 10^{-22}\,\text{g}\,.$$

Atomic masses are expressed in atomic mass units (u), based on the definition that the mass of a neutral atom of ^{12}C is exactly 12 u. All other nuclides are assigned masses relative to ^{12}C. The mass of a single atom can be computed from the fact that one mole of any substance contains 6.0221415×10^{23} atoms and has a mass equal to the atomic mass in grams. For ^{12}C, 1 mole has a mass of 12 g, hence the mass of one atom is given by:

$$M(^{12}\text{C}) = \frac{12\ \text{g}}{6.0221415 \times 10^{23}} = 1.992647 \times 10^{-23}\,\text{g}\,.$$

The atomic mass unit, u (also known as a dalton) is then

$$1\,\text{u} = \frac{1.992647 \times 10^{-23}\,\text{g}}{12} = 1.660539 \times 10^{-24}\,\text{g}\,.$$

The energy equivalent of 1 u is $E = mc^2 = 931.494013\,\text{MeV}$.

Atomic Number Density

A useful quantity in many calculations is the number density of atoms. By analogy with the basic relation between the mass and number of atoms, $N = (\mathscr{M}/\mathscr{A}) \cdot N_a$, the relation for the number density is given by

$$N(\text{atoms cm}^{-3}) = \frac{\rho}{\mathscr{A}} \cdot N_a$$

where ρ is the mass density (in g cm^{-3}).

Relativistic Mechanics and Einstein's Mass/Energy Equivalence

The fundamental relation describing motion is that the force acting on a body will result in a change of momentum i.e.

$$\boldsymbol{F} = \frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t},$$

where $\boldsymbol{p}$ is the linear momentum $m\boldsymbol{v}$ and $\boldsymbol{F}$ the force. The quantities $\boldsymbol{F}$, $\boldsymbol{p}$, and $\boldsymbol{v}$ are all vectors. In classical mechanics, the mass of a body is constant, and the above relation reduces to $\boldsymbol{F} = m\mathrm{d}\boldsymbol{v}/\mathrm{d}t = m\boldsymbol{a}$, the more familiar form of Newton's second law. In relativistic mechanics, the mass of a body changes with its speed v such that

$$\boldsymbol{F} = \frac{\mathrm{d}}{\mathrm{d}t}m\boldsymbol{v} = m\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} + v\frac{\mathrm{d}m}{\mathrm{d}t}.$$

From conservation of energy, the work done on a particle as it moves along a path of length s must equal the change in the kinetic energy ΔKE from the beginning to the end of the path. The work done by the force F on the particle as it moves through a displacement $\mathrm{d}s$ is given by $\boldsymbol{F} \cdot \mathrm{d}\boldsymbol{s}$. The resulting change in the kinetic energy is then given by [3]

$$\Delta KE = \int_0^s \boldsymbol{F} \cdot \mathrm{d}\boldsymbol{s} = \int_0^s \frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t} \cdot \mathrm{d}\boldsymbol{s} = \int_0^t \frac{\mathrm{d}p}{\mathrm{d}t} \cdot \frac{\mathrm{d}s}{\mathrm{d}t} \cdot \mathrm{d}t = \int_0^{mv} \boldsymbol{v} \cdot \mathrm{d}\boldsymbol{p},$$

where it is assumed that initially the particle is at rest $v = 0$. Using the expression for the relativistic mass

$$m = \frac{m_0}{(1 - v^2/c^2)^{1/2}}$$

and substituting in the relation for the change in kinetic energy gives

$$\Delta KE = m_0 \int_0^v v\mathrm{d}\left[\frac{v}{(1 - v^2/c^2)^{1/2}}\right].$$

Differentiation of the term in square brackets leads to

$$\begin{aligned}\Delta KE &= m_0 \int_0^v v\left[\frac{1}{(1 - v^2/c^2)^{1/2}} + \frac{v^2/c^2}{(1 - v^2/c^2)^{3/2}}\right]\mathrm{d}v \\ &= m_0 \int_0^v \frac{v}{(1 - v^2/c^2)^{3/2}}\mathrm{d}v = m_0c^2\frac{1}{(1 - v^2/c^2)^{1/2}}\Bigg|_0^v \\ &= \frac{m_0c^2}{(1 - v^2/c^2)^{1/2}} - m_0c^2\end{aligned}$$

and finally,

$$\Delta KE = mc^2 - m_0c^2.$$

This last expression can be rewritten in the form $mc^2 = m_0c^2 + \Delta KE$. The left hand side mc^2 can be regarded as the total energy of the particle consisting of the rest-mass energy m_0c^2 plus the kinetic energy of the particle. This expression for the total energy E, i.e. $E = mc^2$ shows the equivalence of mass and energy and one of

The energy equivalent of the rest mass of an electron is

$$E = m_e c^2 = (5.486 \times 10^{-4}\,\mathrm{u}) \times \frac{931.49\,\mathrm{MeV}}{\mathrm{u}} = 0.511\,\mathrm{MeV}\,.$$

An interesting example is the direct conversion of mass to energy is the electron/positron annihilation $m_{e^-} + m_{e^+} \rightarrow 2\gamma$ in which the gamma photon each has an energy of 0.511 MeV.

The energy equivalent of* 1 amu *is

$$E = m_{\mathrm{amu}} c^2 = (1\,\mathrm{u}) \times \frac{931.49\,\mathrm{MeV}}{\mathrm{u}} = 931.49\,\mathrm{MeV}\,.$$

The energy equivalent of the rest mass of a proton is

$$E = m_p c^2 = (1.007276\,\mathrm{u}) \times \frac{931.49\,\mathrm{MeV}}{\mathrm{u}} \cong 1\,\mathrm{GeV}\,.$$

the most important expressions in nuclear physics. It will be seen later that in nuclear reactions, the mass is converted into energy and vice versa. Conversion of even small amounts of mass gives rise to considerable energies.

Binding Energy of the Nucleus

The binding energy, BE, of a nucleus is the energy which must be supplied to separate the nucleus into its constituent component nucleons. The sum of the masses of the constituents, m_c, of an isotope ${}^A_Z\mathrm{X}$ is given by

$$m_c = Zm_p + (A - Z)m_n\,,$$

where Z is the atomic number, A is the atomic mass number (number of nucleons in the nucleus), m_p is the mass of a proton atom and m_n is the mass of the neutron.

Mass Defect

The mass defect is the difference between the mass of the constituents m_c and the actual mass of the nucleus $m({}^A_Z\mathrm{X})$, i.e.

$$\textit{mass defect} = m_c - m({}^A_Z\mathrm{X}) = Zm_p + (A - Z)m_n - m({}^A_Z\mathrm{X}) = \frac{BE}{c^2}\,,$$

where BE is the binding energy of the nucleus and the mass defect is equivalent of the energy required (i.e. BE/c^2) to separate the components. It should be noted that the above expression for the mass defect involves the nuclear mass $m({}^A_Z\mathrm{X})$. Since only atomic masses are available, the above relation should be expressed in atomic masses, i.e.

$$\textit{mass defect} = \frac{BE}{c^2} = Z\left[M({}^1_1\mathrm{H}) - m_e + \frac{BE_{1e}}{c^2}\right] + (A - Z)m_n - \left[M({}^A_Z\mathrm{X}) - Zm_e + \frac{BE_{Ze}}{c^2}\right]$$

or

Mass Defect and Binding Energy of $^{17}_{8}\mathrm{O}$

Using the atomic mass data in Appendix D, the mass defect is given by

$$\begin{aligned} \textit{mass defect} &= \frac{BE}{c^2} = 8M\left({}^{1}_{1}\mathrm{H}\right) + 9m_{\mathrm{n}} - M\left({}^{17}_{8}\mathrm{O}\right) \\ &= 8(1.0078250) + 9(1.0086649) - 16.9991317 = 0.1414524\,\mathrm{u}\,. \end{aligned}$$

In energy units, the binding energy BE is given by

$$BE = \textit{mass defect} \times \frac{931.5\,\mathrm{MeV}}{\mathrm{u}} \approx 131.76\,\mathrm{MeV}\,.$$

The average binding energy per nucleon $\langle BE\rangle = BE/A$ is then

$$\langle BE\rangle = \frac{131.76}{17} = 7.75\,\mathrm{MeV\ per\ nucleon}\,.$$

$$\textit{mass defect} = \frac{BE}{c^2} = ZM({}^{1}_{1}\mathrm{H}) + (A-Z)m_{\mathrm{n}} - M({}^{A}_{Z}\mathrm{X}) + \frac{1}{c^2}\left[ZBE_{1\mathrm{e}} - BE_{Z\mathrm{e}}\right].$$

The last term, $[ZBE_{1\mathrm{e}} - BE_{Z\mathrm{e}}]$, is the difference between the binding energies of Z hydrogen electrons and the Z electrons in the atom ${}^{A}_{Z}\mathrm{X}$. It is orders of magnitude less than nuclear binding energies and hence to a very good approximation

$$BE({}^{A}_{Z}\mathrm{X}) \cong \left[ZM({}^{1}_{1}\mathrm{H}) + (A-Z)m_{\mathrm{n}} - M({}^{A}_{Z}\mathrm{X})\right]c^2\,.$$

A plot of the binding energy per nucleon versus the atomic mass number shows a broad maximum in excess of 8 MeV per nucleon between mass numbers 50–100. The two dimensional plot is shown in Fig. 2.1. At lower and higher mass numbers,

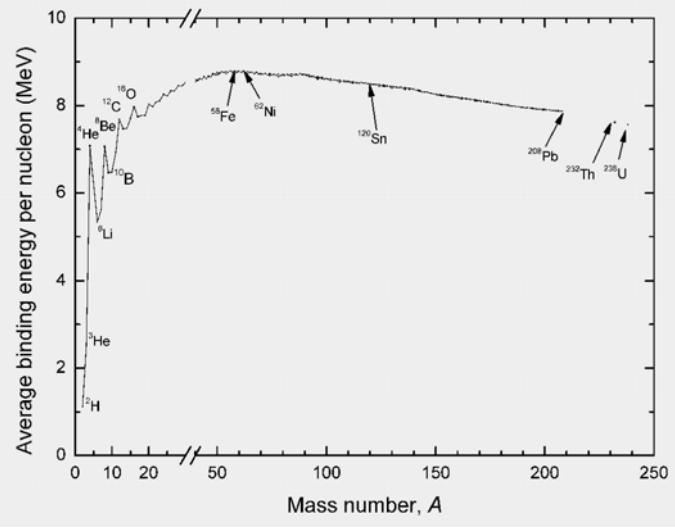


Fig. 2.1. Average binding energy per nucleon versus mass number for stable nuclides

the binding energy per nucleon is less. It is for this reason that energy can be released by splitting heavy elements or by fusing light elements.

Notable departures from the smooth behaviour of the binding energy per nucleon vs. the mass number are provided by ^{4}He, ^{12}C, ^{16}O. The binding energies per nucleon of these isotopes are higher than their immediate neighbours indicating that they are very strongly bound. These nuclei contain respectively one, three, and four sub-units of ^{4}He. This tends to suggest that nucleons form stable sub-groups of two protons and two neutrons within the nucleus.

Mass Excess

The atomic masses are often described in terms of the mass excess *ME* defined by

$$ME(^A_Z\mathrm{X}) = M(^A_Z\mathrm{X}) - A\,,$$

where the masses are expressed in atomic mass units (u). Hence, knowing the mass excess, the mass of any nuclide can be derived. Consider the example of ^{238}U. In the Nuclides.net database [5], the mass excess is given in units of keV, i.e. $ME(^{238}\mathrm{U}) = 47308.9\,\mathrm{keV}$. In a first step, this must be converted to atomic mass units using $1\,\mathrm{u} = 931.494013\,\mathrm{MeV}/c^2$ (see Appendix A), hence

$$ME(^{238}\mathrm{U}) = 0.0507882\,\mathrm{u}\,.$$

The mass of ^{238}U is then given by

$$M(^{238}\mathrm{U}) = ME(^A_Z\mathrm{X}) + A = 0.0507882\,\mathrm{u} + 238\,\mathrm{u} = 238.0507882\,\mathrm{u}\,.$$

Nucleon Separation Energy

Another useful quantity, in addition to the binding energy, is the nucleon separation energy. Whereas the binding energy is the energy required to separate the nucleus into its constituent component nucleons, the nucleon separation is the energy required to remove a single nucleon from the nucleus according to the reaction i.e. (for a neutron removal):

$$^A_Z\mathrm{X} \rightarrow {}^{A-1}_{Z}\mathrm{X} + \mathrm{n}\,.$$

The energy required to remove this neutron, denoted $S_\mathrm{n}(^A_Z\mathrm{X})$, is given by:

$$S_\mathrm{n}(^A_Z\mathrm{X}) = \left[m(^{A-1}_{Z}\mathrm{X}) + m_\mathrm{n} - m(^A_Z\mathrm{X})\right]c^2$$

or

$$\boxed{S_\mathrm{n}(^A_Z\mathrm{X}) \cong \left[M(^{A-1}_{Z}\mathrm{X}) + m_\mathrm{n} - M(^A_Z\mathrm{X})\right]c^2\,.}$$

Using the relation derived earlier for the binding energy i.e.

$$BE(^A_Z\mathrm{X}) \cong \left[ZM(^1_1\mathrm{H}) + (A-Z)m_\mathrm{n} - M(^A_Z\mathrm{X})\right]c^2\,,$$

the neutron separation energy can also be expressed as

$$S_{\mathrm{n}}({}^{A}_{Z}\mathrm{X}) = \left[BE({}^{A}_{Z}\mathrm{X}) - BE({}^{A-1}_{Z}\mathrm{X})\right]c^2 .$$

Similarly, the energy required to remove a single proton from the nucleus according to the reaction

$${}^{A}_{Z}\mathrm{X} \rightarrow {}^{A-1}_{Z-1}\mathrm{Y} + \mathrm{p} .$$

The energy required to remove this proton, denoted $S_{\mathrm{p}}({}^{A}_{Z}\mathrm{X})$, is given by:

$$S_{\mathrm{p}}({}^{A}_{Z}\mathrm{X}) = \left[m({}^{A-1}_{Z-1}\mathrm{Y}) + m_{\mathrm{p}} - m({}^{A}_{Z}\mathrm{X})\right]c^2$$

or

$$\boxed{S_{\mathrm{p}}({}^{A}_{Z}\mathrm{X}) \cong \left[M({}^{A-1}_{Z-1}\mathrm{Y}) + M({}^{1}_{1}\mathrm{H}) - M({}^{A}_{Z}\mathrm{X})\right]c^2 .}$$

Again using the relation for the binding energy, this can also be expressed as

$$S_{\mathrm{p}}({}^{A}_{Z}\mathrm{X}) = \left[BE({}^{A}_{Z}\mathrm{X}) - BE({}^{A-1}_{Z-1}\mathrm{Y})\right]c^2 .$$

Table 2.1. Comparison of the binding energy per nucleon (BE/A) with the neutron and proton separation energies for selected nuclides

Nuclide	BE/A (MeV)	S_{n} (MeV)	S_{p} (MeV)
${}^{16}_{8}\mathrm{O}$	7.98	15.66	12.13
${}^{129}_{53}\mathrm{I}$	8.44	8.83	6.80
${}^{99}_{43}\mathrm{Tc}$	8.61	8.97	6.50

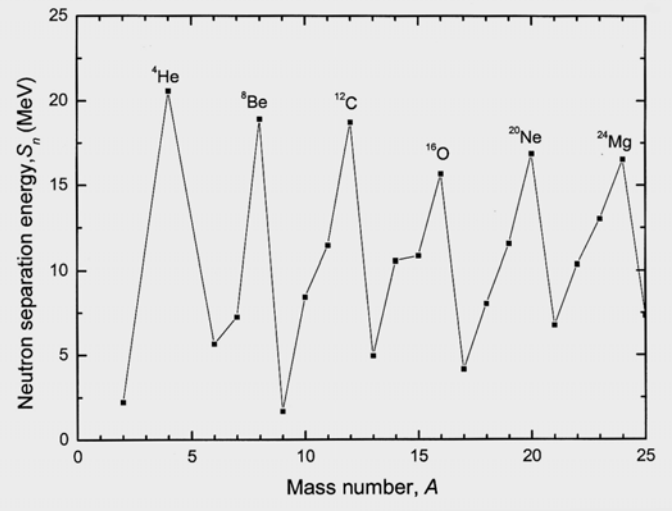


Fig. 2.2. The neutron separation energy as a function of the mass number

Some values of S_n and S_p are given in Table 2.1 and Fig. 2.2. The fact that the neutron and proton separation energies in $^{16}_{8}O$ are considerably higher than the average binding energy per nucleon, implies that this nuclide is particularly stable.

Q-Value for a Reaction

In a nuclear reaction, from conservation of energy, the total energy including the rest-mass energy must be the same before and after the reaction i.e.

$$\left(\sum_i \left[E_i + m_i c^2\right]\right)_{\text{before}} = \left(\sum_i \left[E_i + m_i c^2\right]\right)_{\text{after}} ,$$

where E_i and m_i are the kinetic energy and rest mass of particle respectively. Any change in the total kinetic energy before and after the reaction must be accompanied by an equivalent change in the total rest mass. Following [3], the Q-value of a reaction is defined the change in kinetic energy or rest mass in a reaction i.e.

$$Q = (\textit{kinetic energy})_{\text{after}} - (\textit{kinetic energy})_{\text{before}}$$

or

$$Q = (\textit{rest mass})_{\text{after}} \cdot c^2 - (\textit{rest mass})_{\text{before}} \cdot c^2 .$$

If the kinetic energy of the products is greater than that of the reactants, the reaction is exothermic and Q is positive. If energy is required to induce a reaction, the reaction is endothermic and Q is negative. In such endothermic reactions a minimum kinetic energy of reactants is required for the reaction to proceed.

In a binary nuclear reaction $a + X \rightarrow Y + b$, the Q-value is given by

$$Q = (E_Y + E_b) - (E_a + E_X) = \left[(m_a + m_X) - (m_Y + m_b)\right]c^2 .$$

In most binary reactions, the number of protons is conserved and the same number of electron masses can be added to both sides of the above reactions. Neglecting the differences in electron binding energies, the Q-value can be expressed in terms of

Q-Value for fusion [3]:

Consider the fusion reaction in which two protons fuse to form a deuteron i.e.

$$p + p \rightarrow d + \beta^+ + \nu .$$

In this reaction, the number of protons is not conserved and care is required in the evaluation of the Q-value. To obtain the Q-value in terms of the atomic masses, add two electrons to both sides of the reaction i.e.

$$^1_1H + {}^1_1H \rightarrow {}^2_1H + \beta^+ + \beta^- + \nu .$$

The Q-value is then obtained from:

$$\begin{aligned} Q &= \left[2M(^1_1H) - M(^2_1H) - 2m_e - m_\nu\right]c^2 \\ &= (2 \times 1.007825032 - 2.014101778 - 2 \times 0.00054858) \times \frac{931.5\,\text{MeV}}{\text{u}} \\ &= 0.422\,\text{MeV} , \end{aligned}$$

where the rest mass of the neutrino has been assumed to be zero.

atomic masses i.e.

$$Q = (E_Y + E_b) - (E_a + E_X) = \left[(M_a + M_X) - (M_Y + M_b)\right]c^2 .$$

In radioactive decay reactions (see Decay Energy) a parent nuclide decays to a daughter with the emission of a particle, i.e. $P \rightarrow D + d$.

The Q-value is given by $Q = (E_D + E_d)$ since the parent nuclide is at rest, hence

$$Q = (E_D + E_d) = \left[m_P - m_D - m_d\right]c^2 > 0 .$$

It should be noted that in some types of radioactive decay, such as beta decay and electron capture, the number of protons is not conserved. In such cases the evaluation of the Q-value using atomic masses may be inaccurate. For more information on the calculation of Q-values using atomic masses, the reader is referred to [3].

Threshold Energy for a Nuclear Reaction

The actual amount of energy required to bring about a nuclear reaction is slightly greater than the Q-value. This is due to the fact that not only energy but also momentum must be conserved in any nuclear reaction. From conservation of momentum, a fraction $m_a/(m_a + M_X)$ of the kinetic energy of the incident particle a must be retained by the products. This implies that only a fraction $M_X/(m_a + M_X)$ of the incident particle is available for the reaction. It follows that the threshold energy is higher than the Q-value and is given by

$$E_{th} = -\frac{Q(m_a + M_X)}{M_X} .$$

Energy Level Diagrams

Nuclear data can be displayed in the form of nuclear energy level diagrams. These diagrams are essentially a plot of the nuclear energy level versus the atomic number and are very useful for showing the nuclear transition corresponding to decay modes. From the basic decay data, energy level diagrams can be constructed according to the following procedure:

- The ground state of the daughter nucleus is chosen to have zero energy.
- If there is an increase in the atomic number (as in β^- decay), the daughter is shown to the right of the parent. The following is an example of the energy level diagram for the decay of $^{32}_{15}$P:

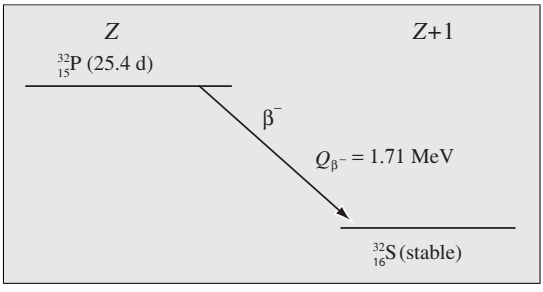


Fig. 2.3. Energy level diagram for the decay of $^{32}_{15}$P

- If the radioactive decay results in a decrease of the atomic number (e.g. alpha emission, positron emission, or electron capture) the daughter is shown to the left of the parent. The following is an example of the energy level diagram for the decay of $^{18}_{9}$F. Since the decay energy is greater than $2m_e c^2$ (1.022 MeV) positron emission (β^+) competes with electron capture (ec) to the ground state.

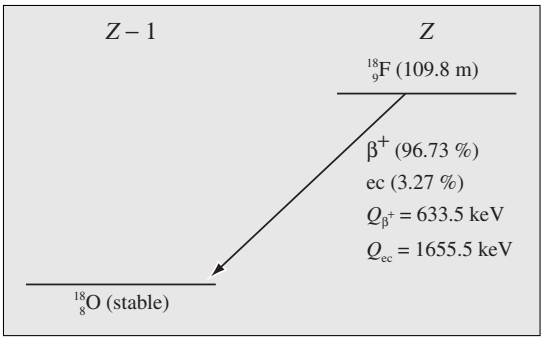


Fig. 2.4. Energy level diagram for the decay of $^{18}_{9}$F

In addition to showing the decay modes and energies, these diagrams can also be used to show half-lives, branching ratios, nuclear isomerism, etc. as in the above examples.

Nuclear Spin and Parity

Protons and neutrons have half integral spin i.e. $+\frac{1}{2}$ or $-\frac{1}{2}$. Spin, which can be loosely associated with the picture of a particle spinning, is inherently quantum mechanical in nature and related to the intrinsic angular momentum associated with the subatomic particle. Spin is a vector quantity, with a total spin and a component of spin in a specified direction. The total spin has a spin quantum number (symbol s) with value equal to an integer for a boson, and a half-integer for a fermion and the word 'spin' is often used to mean this quantum number.

The overall spin of an atomic nucleus is by virtue of the spin of each nucleon within it. The hydrogen nucleus, for example, contains one proton with a spin quan-

Table 2.2. Spin quantum number for various nuclei

Number of protons	Number of neutrons	Spin quantum number	Examples
Even	Even	0	^{12}C, ^{16}O, ^{32}S
Odd	Even	1/2	^{1}H, ^{19}F, ^{31}P
"	"	3/2	^{11}B,^{35}Cl, ^{79}Br
Even	Odd	1/2	^{13}C
"	"	3/2	^{127}I
"	"	5/2	^{17}O
Odd	Odd	1	^{2}H, ^{14}N

tum number of $\frac{1}{2}$, and this gives rise to a spin of $\frac{1}{2}$ for a hydrogen atom. The spin produces a magnetic moment, and this forms the basis of the technique of nuclear magnetic resonance.

Within a nucleus, nucleons (protons and neutrons) have a strong tendency to pair i.e. neutron with neutron or proton with proton so that their spins cancel (spins pair anti-parallel). Hence for all even-Z even-N nuclei such as ^{12}C, ^{16}O, ^{32}S, the ground state spin is always zero as shown in Table 2.2.

Nuclei with an odd number of protons, neutrons, or both, will have an intrinsic nuclear spin. Although there is the tendency for nucleons to pair up spins anti-parallel to become spin-0, the total spin is not necessarily the lowest value after pairing off – some nucleons remain unpaired and result in spins as high as $\frac{11}{2}$.

The parity of a nucleus is the sign of the spin and is either odd $(-)$ or even $(+)$. Parity is important due to the fact that it is conserved in nuclear processes (in the case of weak interactions, however, such as in beta decay, parity conservation is weakly broken).

Nuclear Isomerism

Nuclei usually exist in their ground state with the individual nucleons paired up subject to energy constraints. In some nuclides, for example resulting from radioactive decay, one or more nucleons can be excited into one or more higher spin states. These nuclei can revert back to the ground state by the emission of gamma radiation. If this emission is delayed by more than 1 μs, the nucleus is said to be a nuclear isomer and the process of releasing energy is known as isomeric transition.

There are two very different ways that such nuclei can possess spin. Either the nucleus rotates as a whole, or several nucleons can orbit the nucleus independently in a non-collective rotation. The latter case can result in the nucleons being trapped in high spin states such that they have much higher lifetimes. Nuclides with even-Z and even-N (i.e. with a whole number of ^{4}He nuclei) can also have high excess rotational spin due to alpha particles rotating independently around the nucleus. Examples here are ^{12}C, ^{16}O, ^{20}Ne, and ^{24}Mg.

^{212m}Po is an example where the isomer has a much longer half-life than the ground state. With a spin of 18, the half-life of 45 s is very much longer than the ground state half-life of 300 ns. The isomer can be considered as two neutrons and two protons orbiting around the doubly magic ^{208}Pb nucleus. The high spin state decays by alpha emission which carries off the 18 units of spin.

Other examples are ^{178n}Hf (spin 16 due to 4 of the 78 nucleons orbiting the nucleus), ^{178}W (spin 25 due to 8 unpaired nucleons orbiting the nucleus).

Nuclide Charts

The origin of the nuclide chart is somewhat uncertain. In his autobiography [6], Segrè mentions the "Segrè Chart" compiled with the help of his wife at Los Alamos in 1945. After the war it was declassified and published, selling more than 50,000 copies. Segrè also mentions that the "first modest table of isotopes was published by a student in our Rome group in the 1930s", see G. Fea [7]. One of the earliest

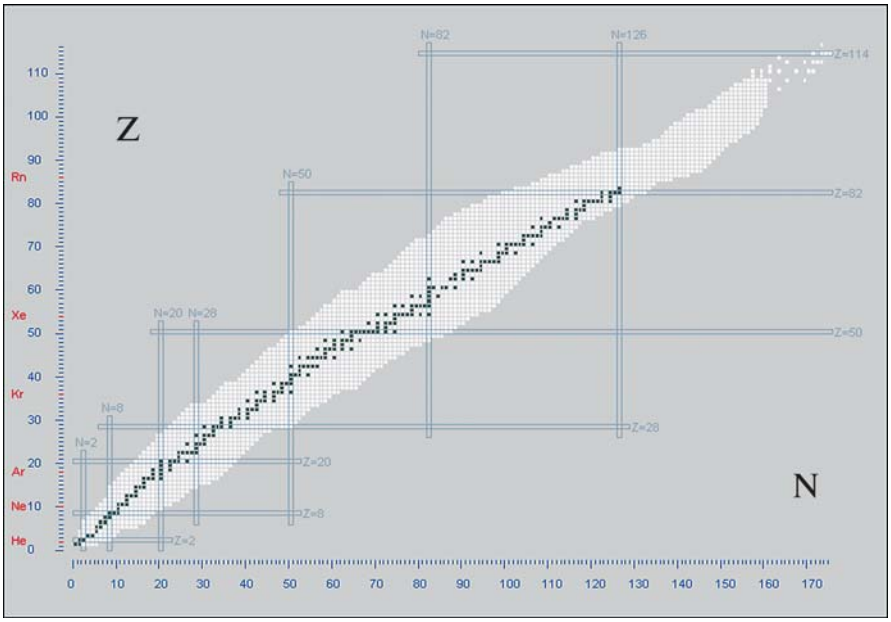


Fig. 2.5. Nuclide stability diagram. Stable nuclides (*black*) fall in a narrow range of neutron to proton ratio. Unstable nuclides (*white*) have neutron to proton ratios outside this range. Also shown are the proton and neutron magic numbers represented by the horizontal and vertical lines

nuclides charts was complied by G. Friedlander and M. Perlman and published by the General Electric Company in 1946. In contrast to the earlier charts by Fea and Segrè, this chart had the protnon number as the vertical axis and the neutron number as the horizontal axis. The current version of this chart is the 16th edition [8].

Nuclide charts are based upon the proton-neutron model of the nucleus and are essentially a plot of the number of protons versus the number of neutrons in stable and unstable nuclei. In these charts, the vertical and horizontal axes represent the number of protons and neutrons respectively in the nucleus as shown in Fig. 2.5.

The charts contain information on the basic nuclear properties of known nuclides. Each nuclide is represented by a box containing basic nuclear data. This data consists of the half-life, neutron cross-sections, main gamma lines etc. of that nuclide. An important characteristic of the charts is the use of colour to denote the mode of decay, half-life, or cross-sections. If the nuclide has one or more metastable states, the box is subdivided into smaller boxes for each state. The main nuclide charts in use world-wide are the Karlsruhe (Germany) [9], Strasbourg (France) [10], General Electric or KAPL (US) [8], and the JAERI (Japan) [11] charts.

It can be seen that stable isotopes lie within a relatively narrow range indicating that the neutron to proton ratio must have a certain value or range of values to be stable. Radioactive nuclei (white squares in Fig. 2.5) mostly lie outside this range. The plot also shows that for low atomic numbers, the neutron to proton ratio is unity.

At higher atomic numbers, this value increases indicating a higher ratio of neutrons to protons in heavy atoms.

The extremities of the white regions above and below the region of stability are known as the proton and neutron "drip-lines" beyond which nuclei are extremely unstable (i.e. if a nucleon is added it will "drip" out again). As nucleons are successively added to a nucleus on the stability line, the binding energy of the last nucleon decreases steadily until it is no longer bound and the nucleus decays by either neutron or proton emission.

Nuclei with even numbers of protons and neutrons are more stable than nuclei with other combinations of neutrons and protons. For uneven numbers of protons and neutrons, there are only very few stable nuclides. The stability of nuclei is extremely significant for special numbers of protons and neutrons. These (magic) numbers are 2, 8, 20, 28, 50, 82 and 126 and correspond to full shells in the shell model of the nucleus. The element tin with the proton number $Z = 50$, for example, has 10 stable isotopes, more than all other elements.

When the proton and neutron numbers both have magic values, the nucleus is said to be "doubly magic". Doubly magic, stable nuclides are for example ^{4}He, the alpha particle, as well as the nuclide ^{208}Pb, which is reached in several decay processes, for example in the decay chain of ^{232}Th.

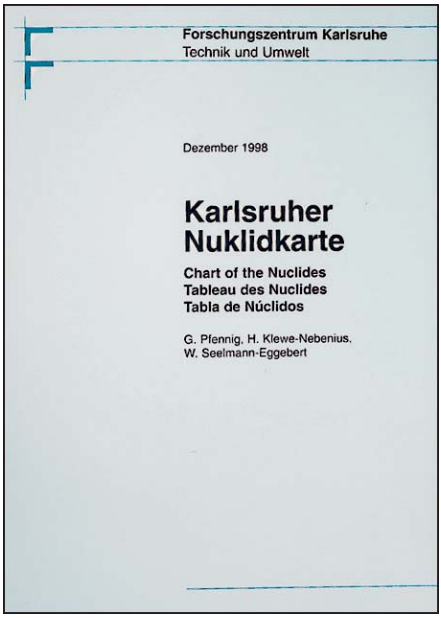
In addition to providing the most important basic nuclear data, the charts allow one to trace out radioactive decay processes and neutron reaction paths. This feature is described in more detail in the following section.

The Karlsruhe Nuclide Chart [9] is described in detail at the end of this chapter.

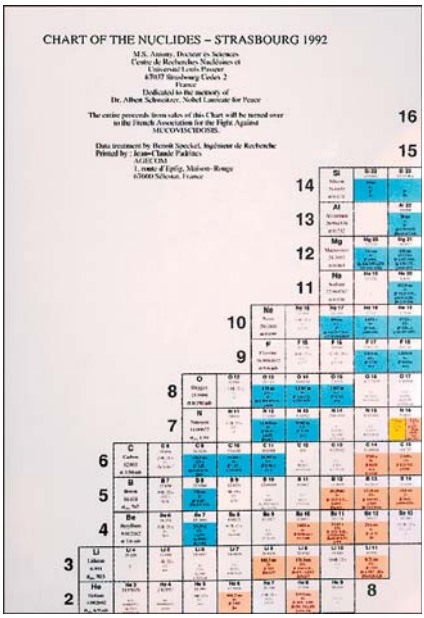
The Strasbourg Nuclide Chart [10] was developed by Dr. Mariasusai Antony from the Louis Pasteur University of Strasbourg. Approximately 5000 copies of the 1992 version were sold in more than 40 countries. This original version contained data on approximately 2550 ground states and 571 isomers. An updated version was published in 2002. The new chart displays about 2900 isotopes in the ground states and about 700 isomers. The chart is a booklet of 44 A4 formatted pages. The front cover page exhibits a stork, symbol of the region of Alsace for which Strasbourg is the capital. The colours blue, white and red (actually reddish-brown) were chosen to indicate the tri-colours of France.

Continuing a half-century tradition, Knolls Atomic Power Laboratory (KAPL) has recently published the 16th edition (2003) of its Chart of the Nuclides in both wallchart and textbook versions [8]. The first edition was published by the General Electric Company in 1946. Evaluated nuclear data is given for about 3100 known nuclides and 580 known isomers. For each nuclide the half-life, atomic mass, decay modes, relative abundances, nuclear cross-section, and other nuclear properties are detailed. The updated chart includes approximately 300 new nuclides and 100 new isomers not found in the 15th (1996) edition. There has been at least one change in more than 95% of the squares on the chart.

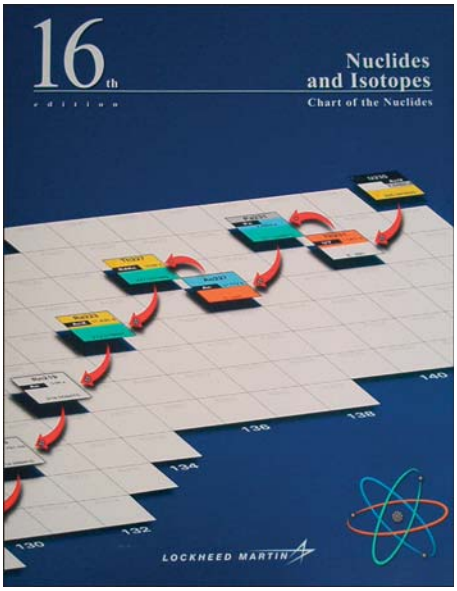
The first edition of the JAERI nuclide chart was published in February 1977. Since then the chart has been revised every 4 years, i.e. 1980, 1984, 1988, 1992, 1996, with the most recent edition appearing in 2000 [11]. In total, seven editions have been published. Approximately 2000 copies of each edition were printed, most



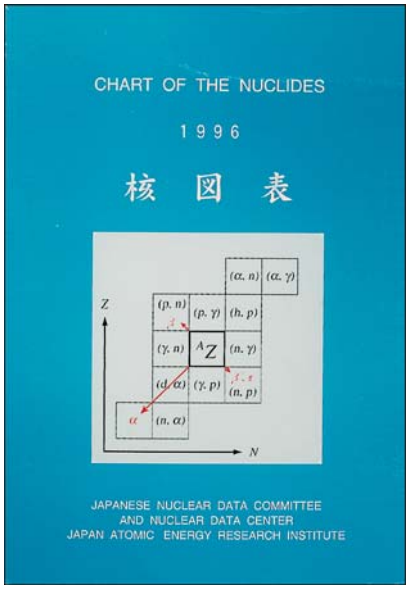
Revised 6th edition of the "Karslruher Nuklidkarte"



Strasbourg nuclide chart



KAPL nuclide chart



Japanese (JAERI) nuclide chart

Fig. 2.6. Main paper-based nuclide charts

of which are distributed to the Japanese nuclear data community and international organisations. The chart comes as an A4-sized booklet.

Decay and Reaction Processes

A small section of a nuclide chart is shown in Fig. 2.7. The central box, with co-ordinates Z, N represents a nuclide with Z protons and N neutrons. When this "parent" nuclide decays, it results in a "daughter" nuclide with co-ordinates Z', N' depending on the decay process. In Fig. 2.7, the position of the daughter nuclide is shown following decay by α, β^-, ε/β^+, n, and p decay processes. These decay processes are explained in detail in Chap. 4. With this information, the radioactive decay chain can be traced out. Starting with a parent nuclide, the position of the daughter can be found from the decay mode (given in the parent box) and the information given in Fig. 2.7. If the daughter is radioactive, it then becomes the parent for the next decay process etc. In this way the full decay chain may be traced out starting from a parent nuclide.

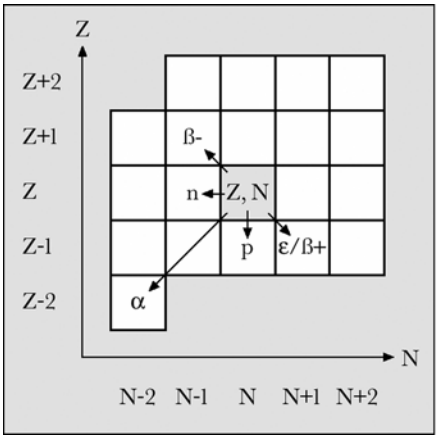
Similarly the nuclide chart may be used to trace out activation and nuclear reactions. In Fig. 2.8, a small section of the chart is shown with the nuclide Z, N at its centre.

A target nuclide of element X, with Z protons and N neutrons will transform through reaction with a particle a to an element Y, with Z' protons and N' neutrons, through the emission of a particle b.

The reaction can be written:

$$\mathrm{a} + {}^{Z+N}\mathrm{X} \rightarrow {}^{Z'+N'}\mathrm{Y} + \mathrm{b}\,,$$

or more compactly in the form



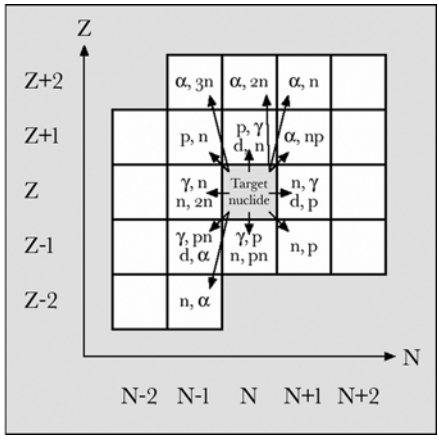


Fig. 2.7 (*left*). Nuclear decay processes on the nuclide chart. A nuclide with "co-ordinates" Z, N transforms to the nuclide Z', N' through the decay processes shown

Fig. 2.8 (*right*). Activation processes and nuclear reactions on the nuclide chart. A target nuclide with co-ordinates Z, N transforms to the nuclide Z', N' through the processes shown

$^{Z+N}\mathrm{X(a,\,b)}^{Z'+N'}\mathrm{Y}$.

The result of interaction of a variety of particles a (neutrons, alpha particles, deuterons, gamma radiation, protons etc.) with a target nuclide with co-ordinates Z, N is shown in Fig. 2.8.

Electronic Nuclide Charts

There are a variety of "electronic" nuclide charts available on the internet. Each of these resources has its own particular tool for navigating the nuclide chart efficiently and displaying the data once a particlur nuclide has been selected. These internet resources are restriced, however, to only displaying nuclear data. The main ones are shown below.

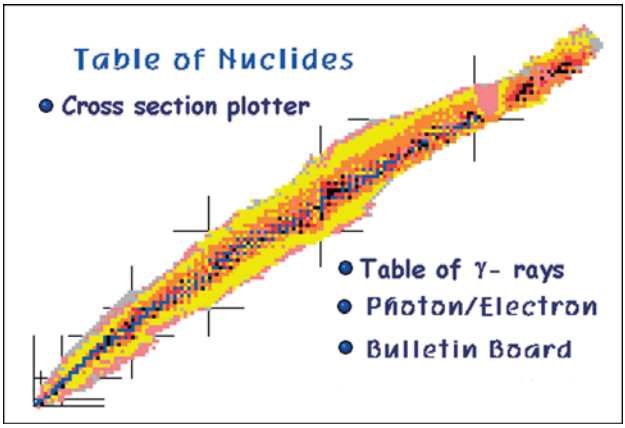


Fig. 2.9
Table of Nuclides
Korea Atomic Energy Research Institute KAERI
http://atom.kaeri.re.kr/

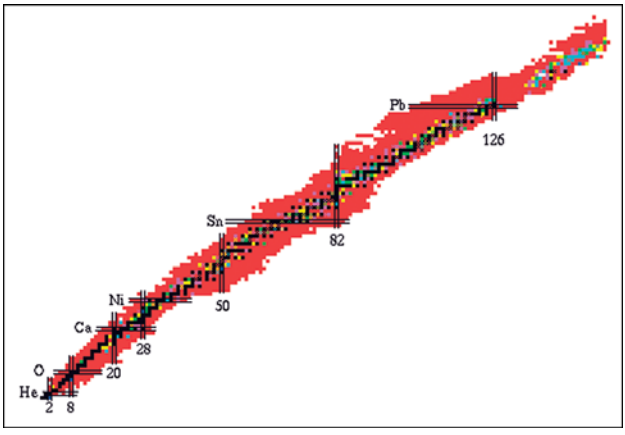


Fig. 2.10
Table of the Nuclides
Japanese Atomic Energy Research Institute (JAERI)
http://sutekh.nd.rl.ac.uk/CoN/

Each horizontal row represents one element; the coloured dots indicate the known isotopes of that element. A vertical column represents the nuclides with same neutron numbers. Heavy lines on the Chart occur for Z and N equal to 2, 8, 20, 28, 50, 82, and 126. These are the so-called "magic numbers"

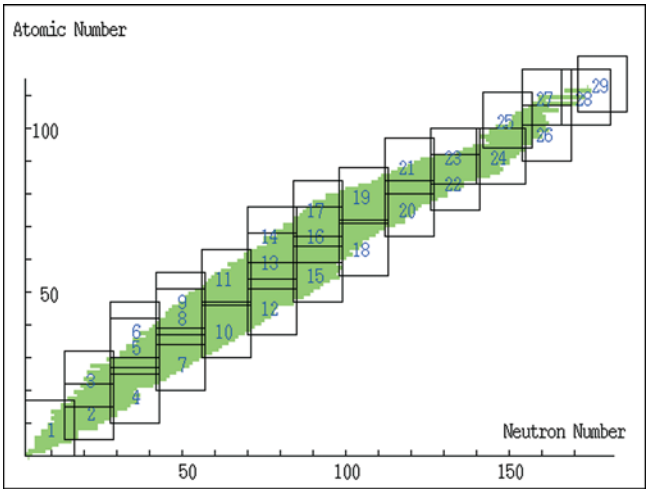


Fig. 2.11
WWW Chart of the Nuclides
Japan Atomic Energy Research Institute (JAERI)
http://wwwndc.tokai.jaeri.go.jp/CN00/

The latest version of "Chart of the Nuclides 2000" was made by T. Horiguchi, T. Tachibana, H. Koura and J. Katakura, and published by the Japanese Nuclear Data Committee (JNDC) and the JAERI Nuclear Data Center.
"WWW Chart of the Nuclides" here is based on the most recent compilation of experimental data by T. Horiguchi (Hiroshima International University) (2000)

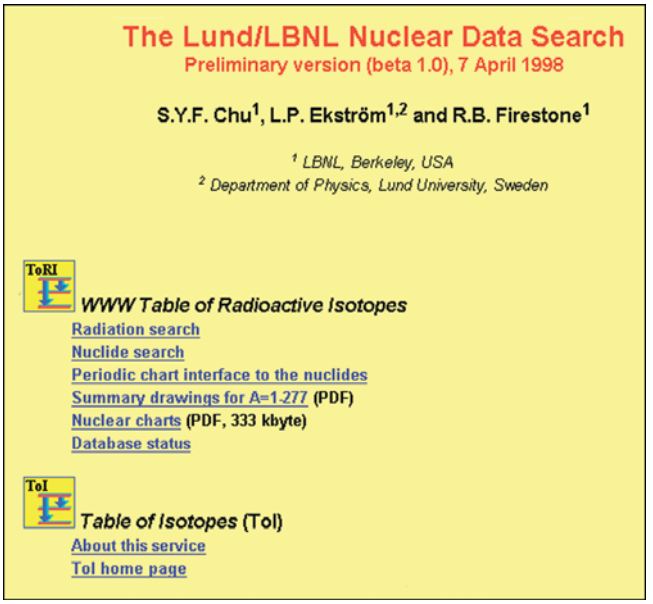


Fig. 2.12
The Lund / LBNL Nuclear Data Search
http://nucleardata.nuclear.lu.se/Database/toi/

The handbook "Table of Isotopes" has for many years been the most widely used source of information for nuclear structure and decay data. This service is intended to give convenient Web access to the Table of Isotopes data. At present only part of the decay data is implemented, but the service will eventually include search facilities, table generators, charts and drawings of all nuclear structure and decay data in the ToI book

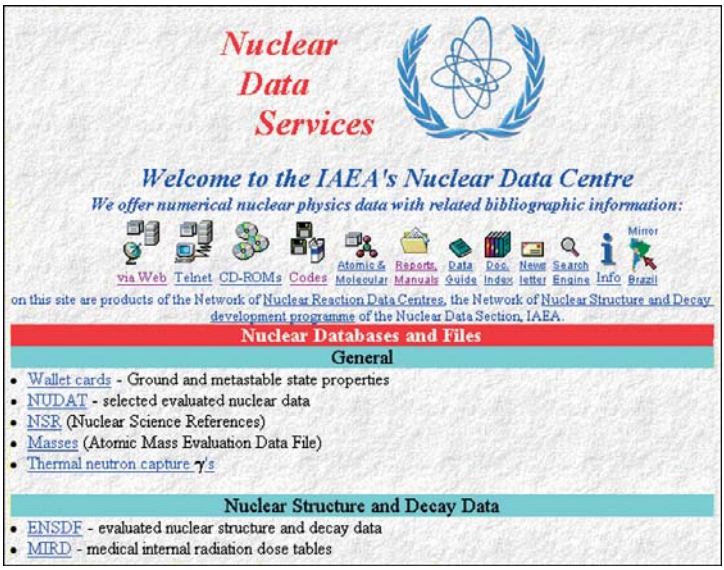


Fig. 2.13. ***IAEA's Nuclear Data Centre***, http://www-nds.iaea.or.at/

Nuclides.net [5]

The Institute for Transuranium Elements, http://www.nuclides.net/

The main user interface, Nuclide Explorer, provides access to nuclide information (data on approximately 3650 ground states and isomers, from internationally recognised sources) through nuclide charts. In addition to displaying nuclear data, various applications/calculations can be launched.

There are six main applications:

- Decay Engine – a software module for decay calculations.
- Dosimetry and Shielding – a module that allows the calculation of dose rates from both unshielded and shielded point sources. A choice of 10 shield materials is available.
- Virtual Nuclides allow the user to do decay and dosimetry and shielding calculations on mixtures of nuclides.
- Fission Yield – the module gives the user access to fission products and yields for 36 fissioning nuclides (data for spontaneous fission and neutron induced fission with thermal, fast, and 14 MeV neutrons) from the main international datafiles.
- Cross-Sections give averaged neutron cross sections from the main international datafiles. Data include the cross sections for room temperature, Maxwell averaged, resonance integral, fission averaged, and 14 MeV neutrons.
- The Universal Nuclide Chart shows the most important basic data. It can also be used to simulate decay processes and reaction paths in nuclear reactors.

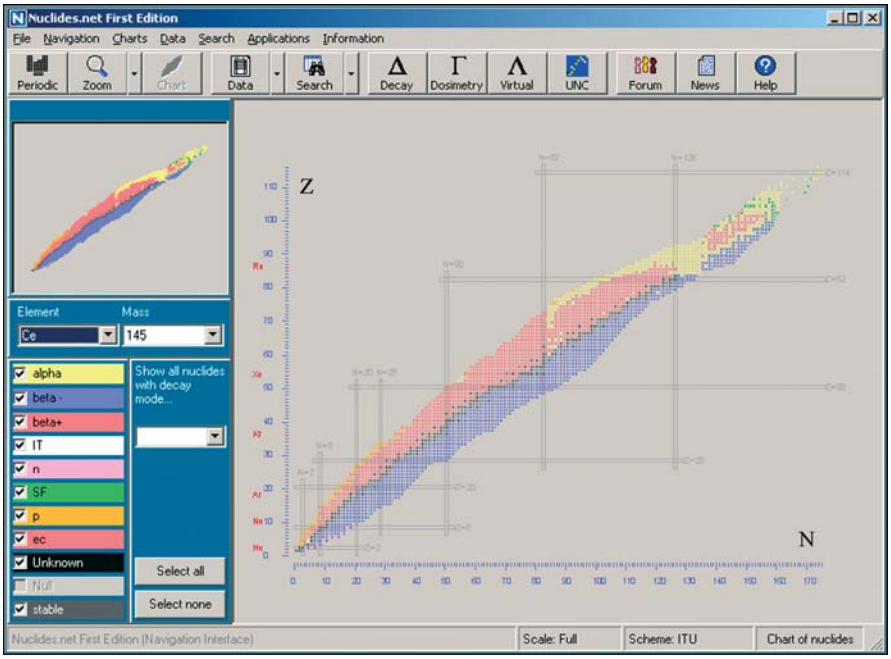


Fig. 2.14. Nuclides.net: The Nuclide Explorer

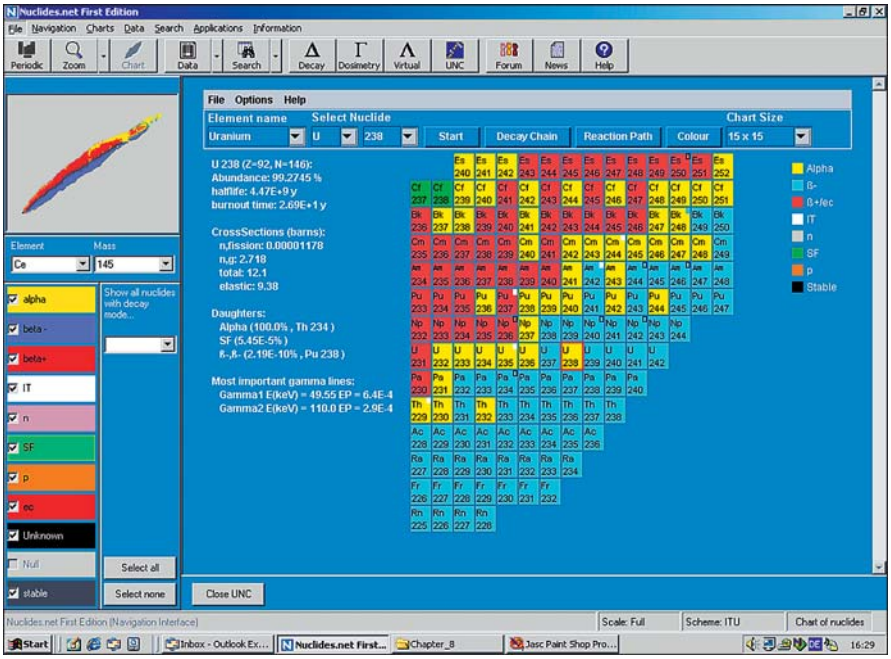


Fig. 2.15. Nuclides.net: Universal Nuclide Chart

A Short History of the Karlsruhe Nuclide Chart

The *Karlsruhe Chart of the Nuclides* was initiated by Professor Walter Seelmann-Eggebert from the Technische Hochschule (TH) Karlsruhe to display basic nuclear data (half-lives, decay modes, particle energies, and most probable gamma energies) [9, 12]. The Karlsruhe chart of the nuclides was based on an earlier chart by G. Friedlander and M. L. Pearlman in the *General Electric Chart of the Nuclides* [13].

1st Edition, 1958: The first edition appeared as a wall chart in DIN A0 format. Coloured boxes were used to indicate the decay modes (black = stable nuclide, red = β^+ decay or electron capture, blue = β^- decay, yellow = alpha decay, white = isomeric transition). In addition a DIN A4 version was available as a collection of sheets with an explanatory brochure for desktop use. It was prepared by W. Seelmann-Eggebert and G. Pfennig both from the Institute of Radiochemistry in the Karlsruhe Research Centre and the TH Karlsruhe. The data used in the chart was from the Nuclear Data Sheets of the National Research Council and the Table of Isotopes by D. Strominger, J. M. Hollander, G.T. Seaborg. The original chart contained data on 267 stable and 1030 unstable nuclides and more than 220 isomeric states from the, at that time, 102 known elements from hydrogen to nobelium.

2nd Edition, 1961: Following on the interest shown in the first edition, a second edition was published in 1961 with additional authors H. Münzel and G. Zundel – also from the Institute of Radiochemistry. A new feature was the introduction of coloured

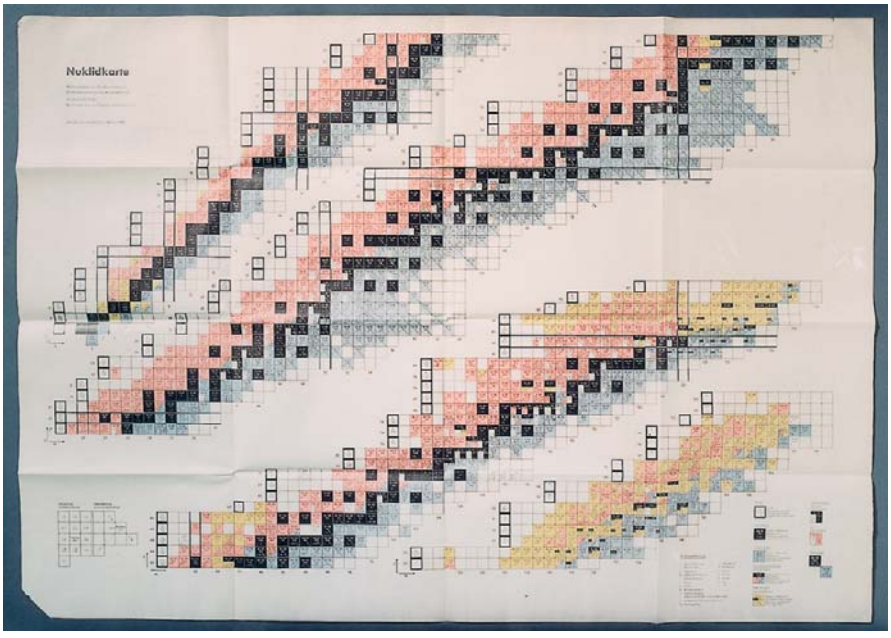


Fig. 2.16. Original Karlsruhe Chart of the Nuclides from 1958

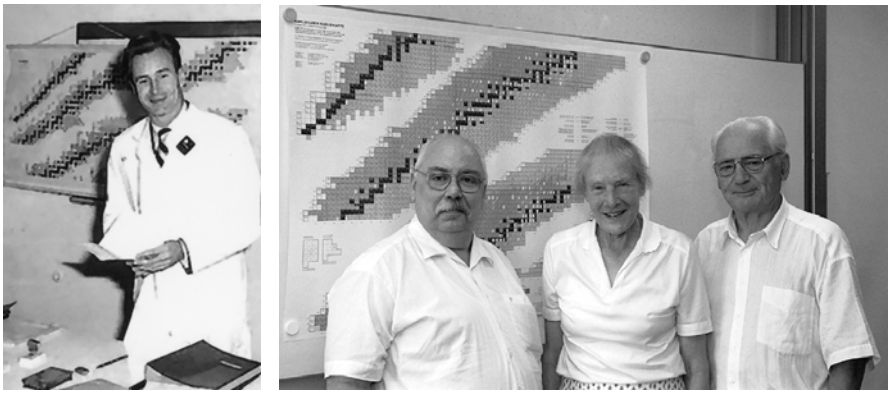


Fig. 2.17. *Left:* Prof. W. Seelmann-Eggebert with the original 1st edition (1958) of the Karlsruhe Chart of the Nuclides. *Right:* The co-authors H. Klewe-Nebenius (*left*), G. Pfennig (*centre*), H. Münzel (*right*) with the revised 6th edition (1998/2001).

corners of different size to indicate the branching ratio of the decay mode. The second edition contained information on 103 elements, and data on approximately 70 new unstable nuclides.

3rd Edition, 1968: Due to the increasing use of the Karlsruhe chart of the nuclides worldwide, a third edition was produced in 1968 with explanatory text in four languages – German, English, French and Spanish. The colour green was introduced to indicate spontaneous fission, and atomic masses were based on ^{12}C. Instead of single DIN A4 sheets, the desktop version was printed in a special arrangement in a strip folded to DIN A4 format. The third edition contained information on 105 elements and more than 1600 nuclides – an increase of 250 over the 2nd edition.

4th Edition, 1974: Much of the data in the 3rd edition had to be revised to reflect the higher accuracy data obtained from the use of Ge detectors. Owing to the improved experimental technique, new data had become available for many short-lived fission products. The 4th edition contained data on more than 1900 nuclides.

5th Edition, 1981: The fifth edition was authored by W. Seelmann-Eggebert, G. Pfennig, H. Münzel, and H. Klewe-Nebenius. New decay modes of double beta decay ($2\beta^-$) and proton decay (p, colour orange) were introduced. To discriminate between direct and β-delayed particle emission, new notations for the latter (βp,βn, β2n, βsf, etc.) were introduced. The 5th edition contained data on more than 2220 nuclides.

6th Edition, 1995: The sixth edition was published in 1995 – more than a decade after the 5th edition – by G. Pfennig and H. Klewe-Nebenius and dedicated to Professor W. Seelmann-Eggebert who died in 1988. In the meantime, four new heavy elements (108–111) had been discovered at the Gesellschaft für Schwerionenforschung (GSI) at Darmstadt. New decay modes of cluster emission e. g. C-14, O-20, Ne-24 etc. indicated by the colour violet) were added. The 6th edition contained data on approximately 2690 nuclides from 111 elements.

Revised 6th Edition, 1998/2001: the sixth edition was revised in 1998 to include data on the newly discovered element 112, new names for elements 104–108, new decay data for some transuranics and 150 mostly short-lived nuclides far from the line of stability.

Since the introduction of the Karlsruhe Chart of Nuclides, over 150,000 copies of the wall chart and 203,000 copies of the brochure with the folded chart have been printed. For the sixth edition more than 15,000 wall charts and 45,000 brochures were printed.

3. Radioactivity and Nuclear Reactions

Following the discovery of radioactivity by Henri Becquerel in 1896, two young scientists, Frederic Soddy and Ernest Rutherford then at McGill University in Canada, set about to investigate the recently discovered phenomena. In 1901, the twenty-four year-old chemist Soddy and Rutherford were attempting to identify a gas which was being released from samples of radioactive thorium oxide. They believed that this gas – they called it an "emanation" – was related to the radioactivity of the thorium sample. In order to investigate the nature of this gas, Soddy passed it over a series of powerful chemical reagents, heated white-hot. No reactions took place. Years later in his biography, he wrote [1]

I remember quite well standing there transfixed as though stunned by the colossal import of the thing and blurting out – or so it seemed at the time: "Rutherford, this is transmutation: the thorium is disintegrating and transmuting itself into argon gas". Rutherford's reply was typically aware of more practical implications, "For Mike's sake, Soddy, don't call it transmutation. They'll have our heads off as alchemists".

Fig. 3.1. Frederic Soddy (1877–1956). © The Nobel Foundation

Fig. 3.2. "The Alchymist in Search of the Philosopher's Stone", Joseph Wright (1734–1797) with permission from Derby Museums and Art Gallery

Following this discovery, Rutherford and Soddy published nine joint papers between 1902 and 1903 in a period of extremely productive research [2]. In 1902 they described their theory of radioactivity as a spontaneous disintegration of the radioactive element by the expulsion of particles with the result that new elements are formed. This was the ultimate step in the ancient alchemists' dream of transmutation.

Simple Radioactive Decay: Half-life and Decay Constant

Radioactive decay is a random process. As such, one cannot state with certainty when an unstable nuclide will decay. The probability that an atom will decay during the time $\mathrm{d}t$ is given by $k\mathrm{d}t$ where k is the constant of proportionality known as the decay constant. In a system where there are $N(0)$ atoms present initially, the number of atoms decaying in time $\mathrm{d}t$ is given by $-\mathrm{d}N = kN\mathrm{d}t$. In the limit of very small time intervals, this can be expressed as

$$\frac{\mathrm{d}N}{\mathrm{d}t} = -kN\,.$$

Integration with respect to time gives the number of atoms present at any time t, i.e.

$$N(t) = N(0)\mathrm{e}^{-kt}\,.$$

The half-life, τ, is used to denote the time at which the number of atoms has decreased to half the initial value, i.e. $\frac{1}{2} = \mathrm{e}^{-k\tau}$. Hence the half-life is related to the decay constant through the relation

$$\tau = \frac{\ln 2}{k} \approx \frac{0.693}{k}\,.$$

Activity

The number of decays per unit time interval, i.e. the activity A, is defined by

$$A = -\frac{\mathrm{d}N}{\mathrm{d}t} = kN\,.$$

It should be noted in this definition that it is assumed that N is decreasing due to decay. In general the rate equation contains a term for decay (removal) to the daughter and in-growth (production) from the parent, i.e.

$$N_{\mathrm{parent}} \xrightarrow{k_{\mathrm{parent}}} N \xrightarrow{k} N_{\mathrm{daughter}}$$

for which the rate equation becomes

$$\frac{\mathrm{d}N}{\mathrm{d}t} = -kN + k_{\mathrm{parent}}N_{\mathrm{parent}}\,.$$

A situation could arise in which $kN = k_{\mathrm{parent}}N_{\mathrm{parent}}$ and thus N is constant, i.e. $\mathrm{d}N/\mathrm{d}t = 0$. Clearly the activity is not zero. In the definition of A above only decay is considered. In the general case where decay and growth occur, A is given by $A = kN$. Hence A is the number of disintegrations per second even though N may be constant. The unit of activity is the Becquerel, i.e. $1\,\mathrm{Bq} = 1$ disintegration per second.

A technical problem arises in the evaluation of the activity in the case where the half-life is less than 1 s. The activity defined above gives the instantaneous disintegration rate. If the half-life is ≤ 1 s, a significant amount of the material has decayed in the first second. The above definition of the activity will then overestimate the emitted radiation. The difficulty can easily be overcome by defining the activity per integral second, i.e.

$$A_{1\mathrm{s}} = \int_0^1 kN\mathrm{d}t = N(0)(1 - \mathrm{e}^{-k}) ,$$

where $k = \ln 2/\tau(\mathrm{s})$ and $N(0)$ is the number of atoms at time 0. For the calculation of the specific activity, denoted *spA*, $N(0)$ is the number of atoms in 1 g i.e. $N(0) = N_\mathrm{a}/\mathscr{A}$. Hence

$$spA = \frac{N_\mathrm{a}(1 - \mathrm{e}^{-k})}{\mathscr{A}}$$

or

$$spA(\mathrm{Bq/g}) = 6.022 \times 10^{23} \cdot \frac{1 - \mathrm{e}^{-\frac{\ln 2}{\tau(\mathrm{s})}}}{\mathscr{A}} .$$

Average (Mean) Lifetime

The half-life of a nuclide is a statistical property and is a valid concept only because of the very large number of atoms involved. Any individual atom of a radionuclide may be transformed at any time, from zero to infinity. For some calculations, it is convenient to use the average life of a radionuclide. The average life is defined as the sum of the lifetimes of the individual atoms divided by the total number of atoms present originally. During a time interval from t to $t + \mathrm{d}t$, the total number of transformations is $kN\mathrm{d}t$. Each atom that decayed during this time interval had existed for a total lifetime t. The sum of the lifetimes of all atoms that were transformed during the time interval $\mathrm{d}t$, having survived from $t = 0$ is $tkN\mathrm{d}t$. The average lifetime is then given by

$$l = \frac{1}{N(0)} \int_0^\infty tkN\mathrm{d}t .$$

It is then straightforward to show that the relationship between the average or mean lifetime and the half-life is given by $l = 1.44\,\tau$.

Branching Ratios and Number of Decay Modes

Many nuclides have more than one decay mode. Consider a nuclide in which there are two decay modes. The probability that an atom will decay by process 1 in time $\mathrm{d}t$ is $k_1\mathrm{d}t$. Similarly, the probability that it will decay by process 2 in time $\mathrm{d}t$ is $k_2\mathrm{d}t$. Hence the equation governing the radioactive decay can be written as

$$\frac{\mathrm{d}N}{\mathrm{d}t} = -(k_1 + k_2)N .$$

The total decay constant for the decay of the parent nuclide is the sum of the partial decay constants i.e. $k = k_1 + k_2$. Hence, the branching ratios for modes 1 and 2 are defined as

$$BR_1 = \frac{k_1}{k}, \text{ and } BR_2 = \frac{k_2}{k}.$$

In general, the branching ratio (BR) for a particular decay mode is defined as the ratio of the number of atoms decaying by that decay mode to the number decaying in total, i.e.

$$BR_i = \frac{k_i}{(k_1 + k_2 + \ldots k_i + \ldots)} = \frac{k_i}{k}.$$

Alternatively, given the total decay constant, the "partial" decay constant is given by

$$k_i = BR_i \cdot k.$$

Number of Decay Modes

There are a number of ways in which a nuclide can decay. Usually the number of decay modes is one or two. There are nuclides, however, which have many decay modes. In Table 3.1, the seven decay modes of the nuclide ^{11}Li are listed.

Table 3.1. Decay modes, branching ratios, and daughters of ^{11}Li

Decay mode	Branching ratio	Daughters
β^-	8.07×10^{-2}	^{11}Be
β^-,d	1.30×10^{-4}	^{9}Li
$\beta^-\alpha$	1.00×10^{-2}	^{7}He
β^-n	8.49×10^{-1}	^{10}Be
β^-3n	1.90×10^{-2}	^{8}Be
β^-t	1.40×10^{-4}	^{8}Li
β^-2n	4.10×10^{-4}	^{9}Be

Decay Chains

It is very often the case that the daughter product of a nuclear decay is also radioactive. In such cases one speaks of radioactive decay "chains". As an example, consider the decay chain $N_1 \rightarrow N_2 \rightarrow N_3 \rightarrow \ldots$ in which the starting or "parent" nuclide N_1 decays to the "daughter" N_2. This daughter in turn is radioactive and decays to N_3. More generally each nuclide in the decay chain N_i can "branch", with branching ratio k_{N_i,N_j}, to more than one daughter. In addition, there may be an external source term S_i for the production of N_i (apart from the decay of the parent).

The situation for successive radioactive decay is shown schematically in Fig. 3.3. This general process of radioactive decay was first investigated systematically by Bateman [3].

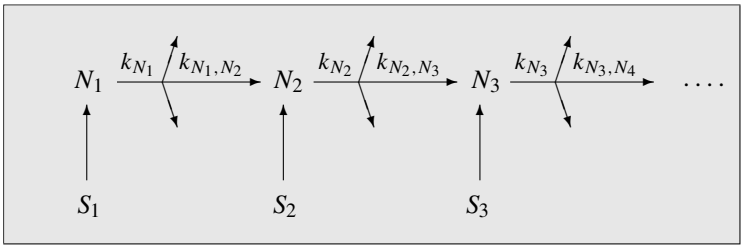


Fig. 3.3. Successive radioactive decay with branching and source terms

The differential equations governing the above processes can be written as:

$$\frac{\mathrm{d}N_1}{\mathrm{d}t} = S_1 - k_{N_1} \cdot N_1 \,,$$

$$\frac{\mathrm{d}N_2}{\mathrm{d}t} = S_2 + k_{N_1,N_2} \cdot N_1 - k_{N_2} \cdot N_2 \,,$$

$$\frac{\mathrm{d}N_i}{\mathrm{d}t} = S_i + k_{N_{i-1},N_i} \cdot N_{i-1} - k_{N_i} \cdot N_i \,,$$

$$\frac{\mathrm{d}N_\mathrm{n}}{\mathrm{d}t} = S_\mathrm{n} + k_{N_{\mathrm{n}-1},N_\mathrm{n}} \cdot N_{\mathrm{n}-1} - k_{N_\mathrm{n}} \cdot N_i \,,$$

where N_n is the number of atoms of species n present at time t, k_n is the decay constant (total removal constant) for species n ($k = \ln 2/\tau$), $k_{\mathrm{n},\mathrm{n}+1}$ is the partial decay constant (partial removal constant) and is related to the branching ratio $BR_{\mathrm{n},\mathrm{n}+1}$ through the relation $k_{\mathrm{n},\mathrm{n}+1} = BR_{\mathrm{n},\mathrm{n}+1} \cdot k_\mathrm{n}$. The solution to this system of equations is [4]

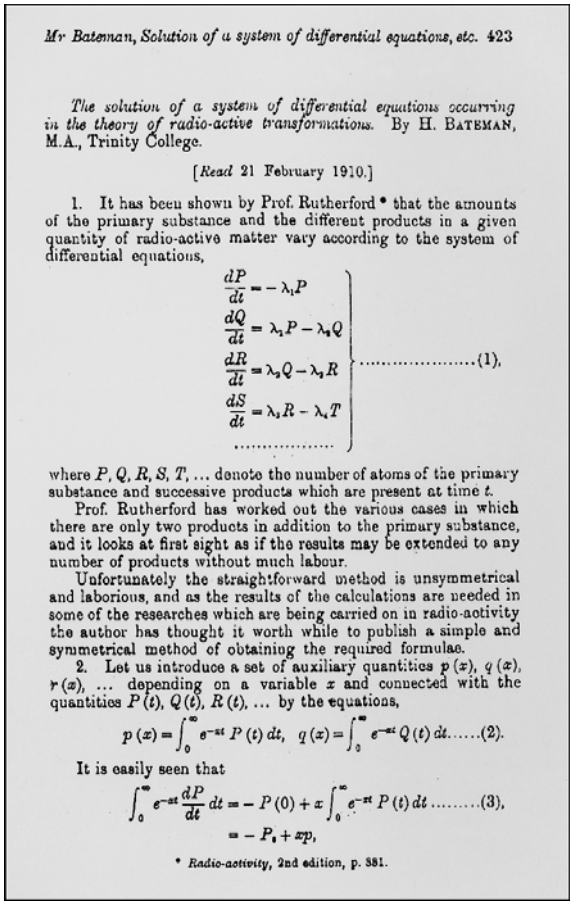
$$N_\mathrm{n}(t) = \sum_{i=1}^{i=n} \left[\left(\prod_{j=1}^{j=n-1} k_{j,j+1} \right) \times \sum_{j=i}^{j=n} \left(\frac{N_i\,(0)\,\mathrm{e}^{-k_j t}}{\prod\limits_{\substack{p=i \\ p\neq j}}^{n} \left(k_p - k_j\right)} + \frac{S_i\left(1 - \mathrm{e}^{-k_j t}\right)}{k_j \prod\limits_{\substack{p=i \\ p\neq j}}^{n} \left(k_p - k_j\right)} \right) \right] \tag{3.1}$$

for the particular case (of most interest) one is interested in the decay chain starting from a single parent nuclide with no source term S. In this case the above relation reduces to:

$$N_\mathrm{n}\,(t) = \prod_{j=1}^{j=n-1} k_{j,j+1} \sum_{j=i}^{j=n} \frac{N_i\,(0)\,\mathrm{e}^{-k_j t}}{\prod\limits_{\substack{p=i \\ p\neq j}}^{n} \left(k_p - k_j\right)} \tag{3.2}$$

It is of interest to construct the first few terms, i.e.

Fig. 3.4. H. Bateman. © 2002 University of St. Andrews; http://www-gap.dcs.st-and.ac.uk/~history/Mathematicians/Bateman.html



Mr Bateman, Solution of a system of differential equations, etc. 423

The solution of a system of differential equations occurring in the theory of radio-active transformations. By H. BATEMAN, M.A., Trinity College.

[*Read* 21 February 1910.]

1. It has been shown by Prof. Rutherford * that the amounts of the primary substance and the different products in a given quantity of radio-active matter vary according to the system of differential equations,

$$\left.\begin{aligned} \frac{dP}{dt} &= -\lambda_1 P \\ \frac{dQ}{dt} &= \lambda_1 P - \lambda_2 Q \\ \frac{dR}{dt} &= \lambda_2 Q - \lambda_3 R \\ \frac{dS}{dt} &= \lambda_3 R - \lambda_4 T \\ &\cdots\cdots\cdots\cdots \end{aligned}\right\} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (1),$$

where $P, Q, R, S, T, \ldots$ denote the number of atoms of the primary substance and successive products which are present at time t.

Prof. Rutherford has worked out the various cases in which there are only two products in addition to the primary substance, and it looks at first sight as if the results may be extended to any number of products without much labour.

Unfortunately the straightforward method is unsymmetrical and laborious, and as the results of the calculations are needed in some of the researches which are being carried on in radio-activity the author has thought it worth while to publish a simple and symmetrical method of obtaining the required formulae.

2. Let us introduce a set of auxiliary quantities $p(x)$, $q(x)$, $r(x)$, ... depending on a variable x and connected with the quantities $P(t)$, $Q(t)$, $R(t)$, ... by the equations,

$$p(x) = \int_0^\infty e^{-xt} P(t)\, dt, \quad q(x) = \int_0^\infty e^{-xt} Q(t)\, dt \cdots\cdots (2).$$

It is easily seen that

$$\int_0^\infty e^{-xt} \frac{dP}{dt}\, dt = -P(0) + x \int_0^\infty e^{-xt} P(t)\, dt \cdots\cdots (3),$$
$$= -P_0 + xp,$$

* *Radio-activity*, 2nd edition, p. 381.

Fig. 3.5. An extract from Bateman's original publication from 1910 [3]

$$\begin{aligned} N_1 &= N_1(0)\, \mathrm{e}^{-k_1 t} \\ N_2 &= k_{1,2} \left\{ \frac{N_1(0)\, \mathrm{e}^{-k_1 t}}{k_2 - k_1} + \frac{N_1(0)\, \mathrm{e}^{-k_2 t}}{k_1 - k_2} \right\} \\ N_3 &= k_{1,2} k_{2,3} \left\{ \frac{N_1(0)\, e^{-k_1 t}}{(k_2 - k_1)(k_3 - k_1)} + \frac{N_1(0)\, \mathrm{e}^{-k_2 t}}{(k_1 - k_2)(k_3 - k_2)} \right. \\ &\qquad \left. + \frac{N_1(0)\, \mathrm{e}^{-k_3 t}}{(k_1 - k_3)(k_2 - k_3)} \right\} \qquad (3.3) \\ &\ldots \end{aligned}$$

These relations allow one to update the numbers of atoms from time $t = 0$ to time t. It is also of interest to calculate the numbers at various times in the range $0, t$ (for example for plotting purposes). This can be done by specifying the total time t over which the calculation is to be made, and the number of time-steps L to reach t. The time interval for each calculation is then $\Delta t = t/L$. For $L = 1$, the numbers

are evaluated at the time t. For $L = 2$, the numbers are evaluated at $t/2$, and t. For $L = 3$, the Ns are evaluated at $t/3$, $2t/3$, t etc. From above, the relation to be used is then

$$N_{\mathrm{n}}((l+1)\Delta t) = \sum_{j=1}^{j=n} \left[\left(\prod_{j=1}^{j=n-1} k_{j,j+1} \right) \sum_{j=1}^{j=n} \frac{N_i(l\Delta t)\mathrm{e}^{-k_j \Delta t}}{\prod\limits_{\substack{p=i \\ p\neq j}}^{p=n} (k_p - k_j)} \right] \tag{3.4}$$

for $l = 1, 2, 3, \ldots L$.

Convergent and Divergent Branches

The solution to the differential equations given in equations (3.1–3.4) is valid for the various species produced in series, i.e. in a chain. If branching occurs, as indicated in Figs. 3.3 and 3.6, the solution (e.g. equation 3.2) must be applied to all possible chains. As an example, consider the radioactive decay of ^{225}Ac. The schematic decay is shown in Fig. 3.6 together with the various paths by which ^{225}Ac can decay. The breakdown into "linear chains" is shown in Fig. 3.6b. Equations (3.1–3.4) must be applied to each of these three chains. In the evaluation of the total quantities of any species, care is required not to count the same decay more than once.

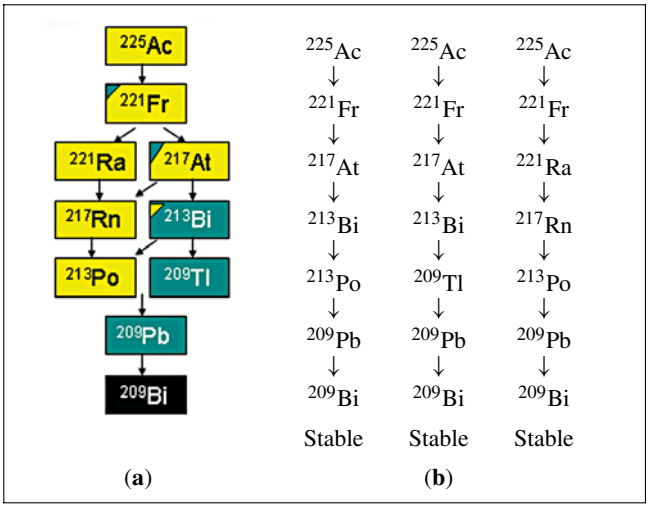


Fig. 3.6. (**a**) Schematic decay of ^{225}Ac. The colours used indicate the type of decay (yellow: alpha emission, blue: beta emission, black: stable), (**b**) the three main "linear chains" for the decay of ^{225}Ac giving the various paths by which the nuclide can decay

Radioactive Equilibria

Consider a simplified radioactive decay process involving only three nuclides, N_1, N_2, and N_3. The nuclide 1 decays into nuclide 2 which in turn decays to nuclide 3.

Nuclide 1 is the parent of nuclide 2 (or nuclide 2 is the daughter of nuclide 1). From the relations given above, the number of atoms of nuclide 2 is given by equation (3.3) [5]

$$N_2 = \frac{k_1}{k_2 - k_1} \cdot N_1(0) \cdot \left(\mathrm{e}^{-k_1 t} - \mathrm{e}^{-k_2 t}\right)$$
$$= \frac{k_1}{k_2 - k_1} \cdot N_1 \left(1 - \mathrm{e}^{-(k_1 - k_2)t}\right) \tag{3.5}$$

From Eq. (3.5) it can be seen that the time required to reach equilibrium depends on the half-life of both the parent and the daughter. Three cases can be distinguished:

1. $\tau_1 \gg \tau_2$. The half-life of the parent is much longer than that of the daughter.
2. $\tau_1 > \tau_2$. The half-life of the parent is longer than that of the daughter.
3. $\tau_1 < \tau_2$. The half-life of the parent is shorter than that of the daughter.

These will be discussed in more detail in the following sections.

Secular Equilibrium: ($\tau_1 \gg \tau_2$)

In secular equilibrium, the half-life of the parent is much longer than that of the daughter, i.e. $\tau_1 \gg \tau_2$ ($k_1 \ll k_2$). In this case Eq. (3.5) reduces to

$$N_2 = \frac{k_1}{k_2} \cdot N_1\,(0) \cdot \left(1 - \mathrm{e}^{-k_2 t}\right)$$

For times $t \gg \tau_1$, radioactive equilibrium is established and the following relation holds:

Secular Equilibrium: $$\frac{N_2}{N_1} = \frac{k_1}{k_2} = \frac{\tau_2}{\tau_1}, \text{ and } A_1 = A_2\,,$$

where A is the activity defined by $k \cdot N$. Hence in radioactive equilibrium the ratio of the numbers, and the masses are constant whereas the activities are equal as shown in Fig. 3.7.

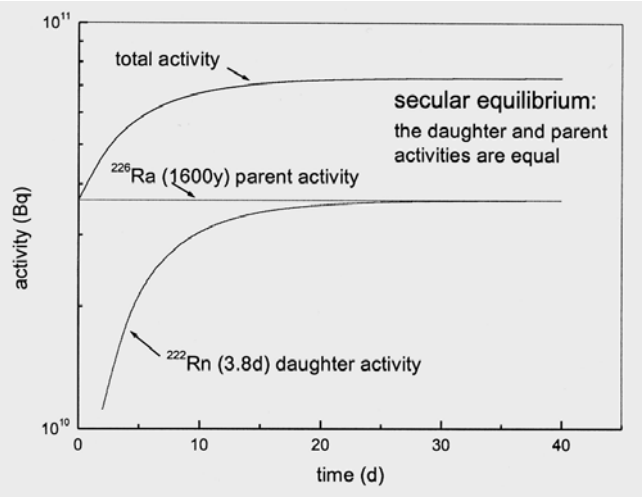


Fig. 3.7. Schematic illustration of secular equilibrium between a parent ^{226}Ra and its daughter ^{222}Rn (Radon gas): buildup of short-lived daughters from a long-lived parent

Transient Equilibrium: ($\tau_1 \geq \tau_2$)

In transient equilibrium the half-life of the daughter is of the same order but smaller than that of the parent, i.e. $\tau_1 > \tau_2$ ($k_1 < k_2$). The general equation for the daughter is from equation (3.5)

$$N_2 = \frac{\tau_2}{\tau_2 - \tau_1} \cdot N_1(0) \cdot \left(\mathrm{e}^{-k_1 t} - \mathrm{e}^{-k_2 t}\right) .$$

As an example, consider the decay of ^{140}Ba as shown in Fig. 3.8. For times $t \ll \tau_1$ (12.75 d), the first exponential term is very close to 1 and N_2 increases according to $(1 - \mathrm{e}^{-k_2 t})$ (rising part of activity of ^{140}La in Fig. 3.8). For times $t \gg \tau_2$ (1.68d), the second exponential becomes smaller than the first one with N_2 decreasing according to $\mathrm{e}^{-k_1 t}$ (see Fig. 3.8). For this decreasing part of the curve, one obtains

Transient Equilibrium: $$N_2 = \frac{\tau_2}{\tau_2 - \tau_1} \cdot N_1$$

where the relation $N_1 = N_1(0)\mathrm{e}^{-k_1 t}$ has been used. This is the condition for transient equilibrium.

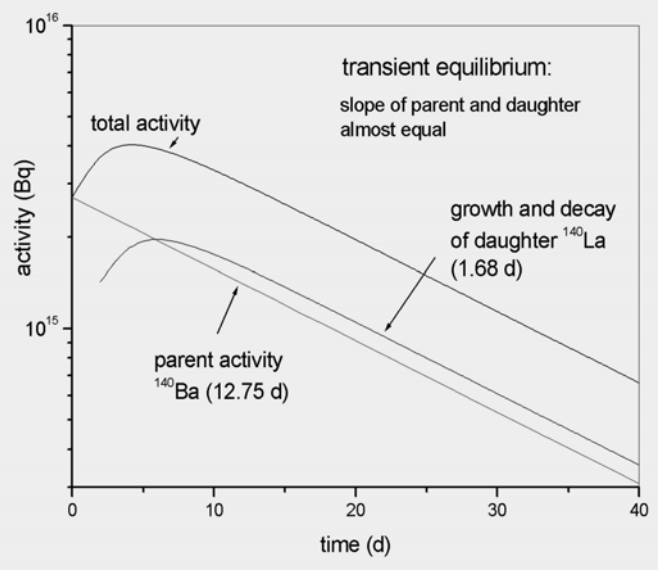


Fig. 3.8. Schematic illustration of transient equilibrium between a parent ^{140}Ba and its daughter ^{140}La: daughter and parent activities are approximately equal but change with time

No-Equilibrium: ($\tau_1 < \tau_2$)

In the case of no equilibrium, the half-life of the parent is shorter than that of the daughter. When the parent has a shorter half-life than that of the daughter, the daughter activity grows to some maximum and then decays with its own characteristic half-life. An example is shown in Fig. 3.9 for ^{146}Ce.

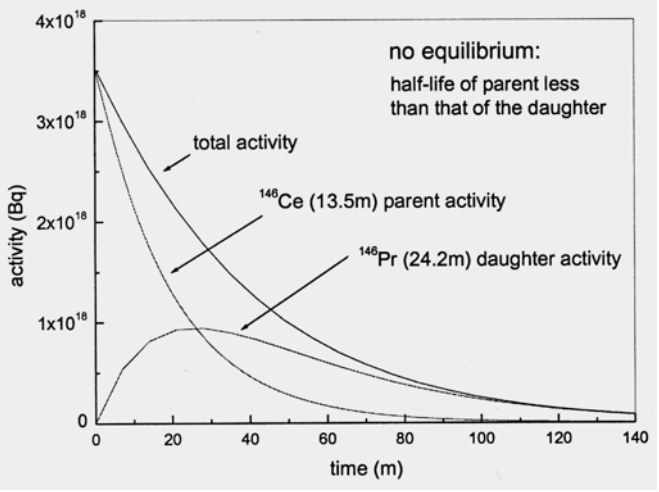


Fig. 3.9. Schematic illustration of 'no-equilibrium' between a parent ^{146}Ce and its daughter ^{146}Pr: total activity approaches the daughter activity with time

Decay Energy

The decay energy is the total energy released in a radioactive decay. A radioactive decay reaction is a special case of a binary nuclear reaction a + X → Y + b (see section *Q*-Value for a Reaction) in which there is no particle a and X is at rest. The decay energy is just the *Q*-value for this type of reaction.

Consider the radioactive decay of ^{238}U is commonly written in the form:

$$^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\alpha$$

and the Q value for this reaction as:

$$Q = M(^{238}\mathrm{U}) - M(^{234}\mathrm{Th}) - m_{\alpha}\,.$$

However, it should be noted that in all nuclear reactions, total charge must be conserved. In the above reaction, the number of electrons is not conserved. On the left hand side, the uranium atom has 92 electrons. On the right, the thorium atom has 90 electrons and the alpha particle no electrons. Before proceeding, care is required to balance the electron number. This can be done by noting that, when an alpha particle is emitted from the uranium atom, the emission of the alpha particle must be accompanied by the emission of two orbital electrons from the thorium atom. The correct reaction should be written as:

$$^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\alpha + 2\,{}^{0}_{-1}\mathrm{e}\,.$$

Conceptually the two electrons can be combined with the alpha particle to produce a He atom with two electrons (the binding energy of the two electrons in the helium atom is neglected) i.e.

$$^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}\,.$$

The Q-value can now be expressed in terms of the atomic masses as:

$$\begin{aligned} Q &= M\left({}^{238}_{92}\mathrm{U}\right) - M\left({}^{234}_{90}\mathrm{Th}\right) - M\left({}^{4}_{2}\mathrm{He}\right) \\ &= (238.050788\,\mathrm{u}) - (234.043601\,\mathrm{u}) - (4.002603\,\mathrm{u}) \\ &= 0.004584\,\mathrm{u} = 4.27\,\mathrm{MeV}. \end{aligned}$$

Alternatively, the decay energy can be obtained for the emitted alpha particles together with the recoil energy of the thorium atom. About 77% of the α particles emitted have a kinetic energy of 4.20 MeV and 23% have an energy of 4.15 MeV. The 4.20 MeV transition results in the ground state of ^{234}Th. The 4.15 MeV transition gives rise to an excited state which then decays by the emission of a 0.05 MeV photon to the ground state. Thus the total decay energy is 4.20 MeV plus the recoil energy of the thorium nucleus. From conservation of momentum, the momentum p of the alpha particle and the thorium nucleus must be equal. Since the energy E is related to the momentum by $E = p^2/2M$, it follows that the energy of the recoiling thorium nucleus is $E_{\mathrm{Th}} = (4/234) \times E_{\alpha} = 0.07$ MeV. Hence the total decay energy Q is 4.27 MeV.

Nuclear Reactions

During his investigations on the scattering of alpha particles by nuclei, Rutherford noticed that certain light elements could be disintegrated by these alpha particles. In 1919, he placed an alpha particle source inside a box that could be filled with various gases. A zinc sulphide screen was placed outside the box to detect scintillations. When the box was filled with nitrogen, scintillations were seen on the screen. These scintillations could not have been produced by alpha particles since the distance between the source and the screen was greater than the range of alpha particles in the gas. Rutherford concluded that the particles were protons ejected by the impact of the alpha particles on nitrogen nuclei. This, now famous, nuclear reaction can be written

$$\begin{aligned} {}^{14}_{7}\mathrm{N}\ (\text{nitrogen}) + {}^{4}_{2}\mathrm{He}\ (\text{alpha}) &\rightarrow \left[{}^{18}_{9}\mathrm{F}\right]^{*}\ (\text{fluorine}) \\ &\rightarrow {}^{17}_{8}\mathrm{O}(\text{oxygen}) + {}^{1}_{1}\mathrm{H}\ (\text{proton})\,. \end{aligned}$$

This transmutation of nitrogen into oxygen was the first artificially induced nuclear reaction (notice that radioactive decay is also a nuclear reaction but it occurs naturally). Nuclear reactions involve the absorption of a bombarding particle by the nucleus of the target material. Absorption of the bombarding particle first produces an excited compound nucleus (fluorine in the above example) which then decays to yield the final products. The main interactions of interest occur when the bombarding particles are alpha particles, protons, deuterons, neutrons, light nuclei, and photons. The nuclear reaction can be represented as

$$\mathrm{X} + \mathrm{a} \rightarrow [\text{compound nucleus}]^{*} \rightarrow \mathrm{Y} + \mathrm{b}\,,$$

where X is the target nucleus, a the bombarding particle, Y the product nucleus, and b the emitted particle. In condensed form this reaction can be written as

Target (projectile, emission) Product

or

$$\mathrm{X(a,\,b)Y}\,.$$

Since the total charge Z and the total number of nucleons must be the same before and after the reaction, it is customary to include these in the reaction as shown in the transmutation reaction with nitrogen above. In condensed form, this reaction can be written

$$^{14}_{7}\mathrm{N}\left(^{4}_{2}\mathrm{He},\,^{1}_{1}\mathrm{H}\right)^{16}_{8}\mathrm{O}\,.$$

Cross-sections

The likelihood of an interaction between a bombarding particle and a nucleus is described by the concept of cross-section denoted by the Greek letter σ. There is no guarantee that a particular bombarding projectile will interact with the target nucleus to bring about a given reaction – σ provides only a measure of the probability that it will occur. The cross-section depends on the properties of the target nuclei and the incident projectile.

If a target is irradiated by particles or photons, then the reduction in flux of the particles or photons after passing through the target is given by

$$-\frac{\mathrm{d}\phi}{\mathrm{d}x} = \sigma N \phi$$

where ϕ is the flux of projectiles, N is the number of target atoms per unit volume, and σ, the cross-section, is the constant of proportionality. From this relation, the units of cross-section are m^2 or cm^2. Cross-sections are usually in the range of $10^{-24}\ \mathrm{cm}^2$. Nuclear physicists use the unit of barn, abbreviated b, where:

$$1\,\mathrm{b} = 10^{-24}\ \mathrm{cm}^2\,.$$

Cross-sections are defined for all types of reaction resulting from the interaction of an incident particle and a nucleus. In the case of an absorption reaction, the de-excitation of the compound nucleus may involve the emission of an alpha particle, electrons, positrons, protons, γ-rays or, in the case of fission, fission fragments. All the different decay "paths" can be referred to by a specific cross-section such as σ_α for α emission, σ_β for β emission, σ_f for fission cross-section, etc.

To represent a particular reaction (see Table 3.2), the abbreviated symbol of the incident and emitted particles within parenthesis is used, e.g. alpha-proton (α,p), alpha-neutron (α,n), neutron-proton (n,p), gamma-proton (γ,p), proton-gamma (p,γ), neutron-fission (n,f), etc. The corresponding cross-sections are abbreviated the same way e.g. the neutron-fission cross-section is noted $\sigma_{(\mathrm{n,f})}$.

Table 3.2. Examples of nuclear reactions [6, 7]

Reaction type	Reaction	Description
(α,p)	${}^{4}_{2}\mathrm{He} + {}^{14}_{7}\mathrm{N} \rightarrow {}^{17}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{H}$ or ${}^{14}_{7}\mathrm{N}(\alpha,\mathrm{p}){}^{17}_{8}\mathrm{O}$	The first nuclear reaction reported by Rutherford in 1919. By bombarding nitrogen with alpha particles he observed the production of protons. This transmutation of nitrogen was the first artificially induced nuclear reaction.
(α,n)	${}^{4}_{2}\mathrm{He} + {}^{9}_{4}\mathrm{Be} \rightarrow {}^{12}_{6}\mathrm{C} + {}^{1}_{0}\mathrm{n}$ or ${}^{9}_{4}\mathrm{Be}(\alpha,\mathrm{n}){}^{12}_{6}\mathrm{C}$ $\alpha + {}^{9}\mathrm{Be} \rightarrow {}^{12}\mathrm{C} + \mathrm{n}$	The neutron was discovered by Chadwick in 1932 by bombarding beryllium with alpha particles.
(γ,n)	$\gamma + {}^{2}_{1}\mathrm{H} \rightarrow {}^{1}_{1}\mathrm{H} + {}^{1}_{0}\mathrm{n}$ or ${}^{2}_{1}\mathrm{H}(\gamma,\mathrm{n}){}^{1}_{1}\mathrm{H}$	Highly energetic (gamma) photons can knock neutrons directly out of the nucleus. In this case, photon irradiation of deuterium results in hydrogen with the generation of neutrons.
(p,γ)	${}^{1}_{1}\mathrm{H} + {}^{7}_{3}\mathrm{Li} \rightarrow {}^{8}_{4}\mathrm{Be} + \gamma$ or ${}^{7}_{3}\mathrm{Li}(\mathrm{p},\gamma){}^{8}_{4}\mathrm{Be}$	Protons can induce nuclear reactions. In the radiative capture of a proton, the nucleus enters into a higher energy state and de-excites with the emission of a photon. The product nucleus decays immediately into two alpha particles.
(γ,αn)	$\gamma + {}^{17}_{8}\mathrm{O} \rightarrow {}^{12}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n}$ or ${}^{17}_{8}\mathrm{O}(\gamma,\alpha\mathrm{n}){}^{12}_{6}\mathrm{C}$	High energy photon can split oxygen into carbon, an alpha particle and a neutron.
(n,p)	${}^{1}_{0}\mathrm{n} + {}^{16}_{8}\mathrm{O} \rightarrow {}^{16}_{7}\mathrm{N} + {}^{1}_{1}\mathrm{p}$ or ${}^{16}_{8}\mathrm{O}(\mathrm{n},\mathrm{p}){}^{16}_{7}\mathrm{N}$	High energy neutrons (in a fast reactor) can interact with oxygen to produce nitrogen and a proton.
(n,f)	${}^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow$ fission products	Neutron induced fission
(d,n)	${}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n}$ or $\mathrm{D} + \mathrm{T} \rightarrow \mathrm{He} + \mathrm{n}$, or T(d,n)He	Fusion reaction
(n,nT)	$\mathrm{n} + {}^{7}\mathrm{Li} \rightarrow {}^{3}\mathrm{H} + \mathrm{n}$	Tritium (denoted by T or ${}^{3}\mathrm{H}$) production
(n,p)	$\mathrm{n} + {}^{14}\mathrm{N} \rightarrow {}^{14}\mathrm{C} + \mathrm{p}$	Cosmogenic production of ${}^{14}\mathrm{C}$ by cosmic ray protons

Neutron Reactions

A special class of nuclear reactions involves neutrons. Due to the fact that they have no charge, neutrons are very effective in penetrating the nucleus producing nuclear reactions. Nuclear reactors and so-called "spallation" sources produce very high fluxes of neutrons. A list of the main neutron reactions is given in Table 3.3.

Table 3.3. Main neutron induced nuclear reactions

	n,4n	n,t
Elastic	n,p	n,^{3}He
Inelastic	n,2p	n,α
n,γ	n,np	n,nα
n,fission	n,nd	n,n2α
n,2n	n,nt	n,2nα
n,3n	n,d	n,t2α

The most common neutron reaction is radiative capture. In this process the excitation energy induced by the neutron is released by the emission of a gamma photon. The process is denoted by (n,γ) as shown in the table. In this process the mass number of the nucleus increases by one but the charge remains unchanged. Hence the process of radiative capture produces a new isotope of the target element. This new isotope may be short-lived, in which case it will decay to a new chemical element through the emission of an alpha particle etc.

Another important reaction is neutron induced fission denoted by (n,fission) in the table. In this process, the excitation energy induced by the neutron causes the nucleus to break up or "fission" into lighter elements.

Burnout Time

The half-life of a radioactive nuclide, τ, is defined as the time it takes for half of the atoms of a radioactive source to undergo transformation. If one takes the standard decay equation:

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t} = -kN\,,$$

where $N(t)$ is the number of atoms at the time t, and k is the decay constant, the solution is $N(t) = N(0)\exp(-kt)$. It follows that $\frac{1}{2} = \exp(-k\tau)$ and hence $\tau = \ln 2/k$. In a reactor, the rate of disappearance of a nuclide is given by

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t} = -\sigma_\mathrm{a} N \Phi\,,$$

where $N(t)$ is the number of atoms at the time t, σ_a the absorption cross-section and Φ the neutron flux of the reactor. The absorption cross-section is the sum of the capture and fission cross-sections i.e. $\sigma_\mathrm{a} = \sigma_{\mathrm{n},\gamma} + \sigma_{\mathrm{n,fission}}$.

Similarly to the definition of the half-life, a "burnout time" τ_{bo} can be defined as the time it takes for half the atoms to transform to the heavier isotope i.e. $\tau_{\mathrm{bo}} = \ln 2/(\sigma_{\mathrm{a}} \cdot \phi)$. The above relations can be combined to give a relation for the overall rate of change due to decay and reaction of a nuclide in a neutron flux i.e.:

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t} = -kN - \sigma_{\mathrm{a}} N \Phi = -\left(\frac{\ln 2}{\tau} + \frac{\ln 2}{\tau_{\mathrm{bo}}}\right) N\,.$$

In this equation, when $\tau \gg \tau_{\mathrm{bo}}$ (long half-life, short burnout time), one can neglect the decay process as the absorption of a neutron occurs much faster than the decay, and when $\tau_{\mathrm{bo}} \gg \tau$ (long burnout time and short half-life), one can neglect the nuclear reaction as the nuclide has decayed long before a neutron is absorbed.

In the case of a ^{238}U nucleus in a reactor, the ^{238}U will transform mainly by neutron absorption to give ^{239}U, since the burnout time for ^{238}U (26.9 y) is much shorter than its half-life of 4.47×10^9 years. This ^{239}U then decays to ^{239}Np since the half-life of ^{239}U (23.4 minutes) is shorter than its burnout time. The ^{239}Np then decays to ^{239}Pu as its half-life of 2.35 days is much shorter than its burnout time (for a standard neutron flux of 3×10^{14} neutrons cm^{-2} s^{-1}) of 2.0 years. The ^{239}Pu then absorbs neutrons and goes on to ^{240}Pu and ^{241}Pu which have a half-life of several years, so that the burnout time is much shorter and the neutron reaction takes place. The reaction path for ^{238}U in a thermal neutron flux of 3×10^{14} neutrons cm^{-2} s^{-1} is shown in Fig. 3.10.

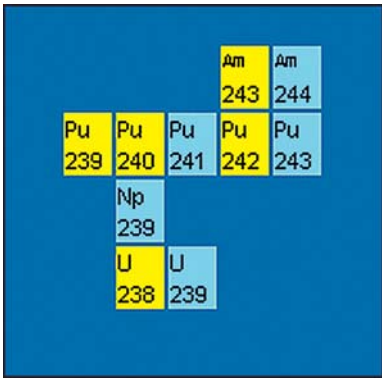


Fig. 3.10. First 9 steps of reaction path of ^{238}U (from the "Universal Nuclide Chart", App. E) [8]

One has to be careful with neglecting a particular process. If the half-life and the burnout time for the standard neutron flux of 3×10^{14} neutrons cm^{-2} s^{-1} are not very different, only a small change in the neutron flux will change the behaviour of the nuclide.

Changing the neutron flux can change the reaction path. This can be illustrated with the nuclide ^{233}Pa. This nuclide has a half-life of 26.9 days and a burnout time of 1.8 years. In this case, the ^{233}Pa decays to ^{233}U. But if the neutron flux is increased to 8×10^{15} neutrons cm^{-2} s^{-1}, the burnout time decreases to 25 days, so that the probability for the neutron reaction is higher than for the decay. This means that ^{233}Pa absorbs a neutron and gives ^{234}Pa more often than decaying to ^{233}U.

4. Types of Radioactive Decay

Decay Modes

Radioactive decay is a spontaneous nuclear transformation which results in the formation of new elements. In this process, an unstable "parent" nuclide P is transformed into a more stable "daughter" nuclide D through various processes. Symbolically the process can be described as follows:

$$P \rightarrow D + d_1 + d_2 + \ldots$$

where the light products $d_1 + d_2 + \ldots$ are the emitted particles. The process is usually accompanied by the emission of gamma radiation. If the daughter nuclide is also unstable, the radioactive decay process continues further in a decay chain until a stable nuclide is reached. Radioactive nuclides decay spontaneously by the following processes:

- Alpha (α) decay
- Beta-minus (β^-) decay
- Gamma emission (γ)
- Isomeric transitions (IT)
- Beta-plus (β^+) decay
- Electron capture (ε or ec)
- Spontaneous fission (SF)
- Proton decay (p)
- Special beta-decay processes (β^-n, $\beta^+\alpha$, β^+p)
- Heavy-ion radioactivity (^{14}C, ^{24}Ne, etc.)
- Decay of bare nuclei-bound beta decay

Radioactive decay is a nuclear process and is largely independent of the chemical and physical states of the nuclide. The actual process of radioactive decay depends on the neutron to proton ratio and on the mass-energy relationship of the parent, daughter, and emitted particle(s). As with any nuclear reactions, the various conservation laws must hold.

A summary of the pure and mixed modes is given in Tables 4.1 and 4.2 [1]. There are 8 known pure decay modes (α, β^-, β^+, ec, SF, n, p, CE). In addition to the pure decay modes listed, there are mixed modes, listed in Table 4.2, ranging from special

beta decay processes such as beta delayed neutron, alpha, or proton emission to more exotic decay modes such as two-proton (2p) emission and "cluster" emission. Cluster emission is a generic term covering a variety of rare decay processes – they are grouped together with the mixed decay modes in Table 4.2. A description of pure decay modes is given in Table 4.3.

Table 4.1. Pure decay modes

Mode	Symbol
Alpha	α
Beta minus	β^-
Beta plus	β^+
Electron capture	ec
Spontaneous fission	SF
Neutron	n
Proton	p
Cluster emission	CE

Table 4.2. Mixed decay modes

(β^-)	(β^+/ec)	(IT)	CE
$2\beta^-$	$2\beta^+$	IT,α	^{12}C
β^-,d	β^+,xa†		^{14}C
β^-,t	β^+,α	(proton)	^{20}O
β^-,xα$_\dagger$	β^+,2α	2p	^{23}F
β^-,α	β^+,3α		^{24}Ne
β^-,2α	β^+,SF	(neutron)	^{28}Mg
β^-,3α	β^+,xp†	n,xn†	^{30}Mg
β^-, xn†	β^+,p	2n (n,n)	^{32}Si
β^-,n	β^+,2p	3n (n,2n)	^{34}Si
β^-,2n	β^+,3p	4n (n,3n)	
β^-,3n	β^+,ec		^{24}Ne+^{26}Ne
β^-,4n	ec,α		^{24}Ne+^{25}Ne
β^-,SF	ec,p		^{28}Mg+^{30}Mg

† Denotes mutliple particle emission

Table 4.3. Summary of different types of radioactive decay. The parent nuclide is denoted by P and the daughter nuclide by D.

Decay type	Reaction	Description
Alpha (α)	${}^{A}_{Z}P \rightarrow {}^{A-4}_{Z-2}D + \alpha$	In proton rich nuclides, an alpha particle (${}^{4}_{2}\mathrm{He}$) can be emitted – the daughter nucleus contains two protons and two neutrons less than the parent.
Beta-minus (β^-)	${}^{A}_{Z}P \rightarrow {}^{A}_{Z+1}D + \beta^- + \overline{\nu}$	In neutron rich nuclides, a neutron in the nucleus can decay to a proton – thereby an electron (β^-) is emitted together with an anti-neutrino ($\overline{\nu}$).
Beta-plus (β^+)	${}^{A}_{Z}P \rightarrow {}^{A}_{Z-1}D + \beta^+ + \nu$	In proton rich nuclides, a proton in the nucleus changes to a neutron – thereby a positron (β^+) is emitted together with a neutrino (ν).
Electron capture (ε or ec)	${}^{A}_{Z}P + \mathrm{e}^- \rightarrow {}^{A}_{Z-1}D^* + \nu$	An orbital electron is "captured" by the nucleus and results in a proton being converted to a neutron and a neutrino (ν). The daughter nucleus is usually left in an excited state.
Gamma (γ)	${}^{A}_{Z}P^* \rightarrow {}^{A}_{Z}P + \gamma$	An atom in an excited state decays through the emission of a photon.
Isomeric transition (IT)	${}^{A\mathrm{m}}_{Z}P \rightarrow {}^{A}_{Z}P + \gamma$	Isomeric transition occurs in long-lived metastable states (isomers) of parent nuclei.
Internal conversion (IC)	${}^{A}_{Z}P^* \rightarrow \left[{}^{A}_{Z}P\right]^+ + \mathrm{e}^-$	A nucleus in an excited state ejects an orbital (usually a K-shell) electron.
Proton (p)	${}^{A}_{Z}P \rightarrow {}^{A-1}_{Z-1}D + \mathrm{p}$	A proton is ejected from the nucleus.
Neutron (n)	${}^{A}_{Z}P \rightarrow {}^{A-1}_{Z}D + \mathrm{n}$	A neutron is ejected from the nucleus.
Spontaneous fission (SF)	${}^{A}_{Z}P \rightarrow D_\mathrm{H} + D_\mathrm{L} + \upsilon\mathrm{n}$	In this process, the parent nucleus splits into heavy and light fragment daughter nuclei (D_H, D_L) with mass and charge roughly half that of the parent, and several neutrons υn.
Special beta-decay processes $\beta^-\mathrm{n}$, $\beta^+\alpha$, $\beta^+\mathrm{p}$	${}^{A}_{Z}P \rightarrow {}^{A}_{Z+1}D^* + \beta^- + \overline{\nu}$ ${}^{A}_{Z+1}D^* \rightarrow {}^{A-1}_{Z+1}D + \mathrm{n}$	Particle (neutron, alpha, proton) emission immediately follows beta decay.
Heavy-ion radioactivity	${}^{A}_{Z}P \rightarrow D_\mathrm{H} + D_\mathrm{L}$	A heavy parent decays by the emission of a light ion.

Alpha (α) Decay

In alpha decay, the parent atom ${}^{A}_{Z}P$ emits an alpha particle ${}^{4}_{2}\alpha$ and results in a daughter nuclide ${}^{A-4}_{Z-2}D$. Immediately following the alpha particle emission, the daughter atom still has the Z electrons of the parent – hence the daughter atom has two electrons too many and should be denoted by $\left[{}^{A-4}_{Z-2}D\right]^{2-}$. These extra electrons are lost soon after the alpha particle emission leaving the daughter atom electrically neutral. In addition, the alpha particle will slow down and lose its kinetic energy. At low energies

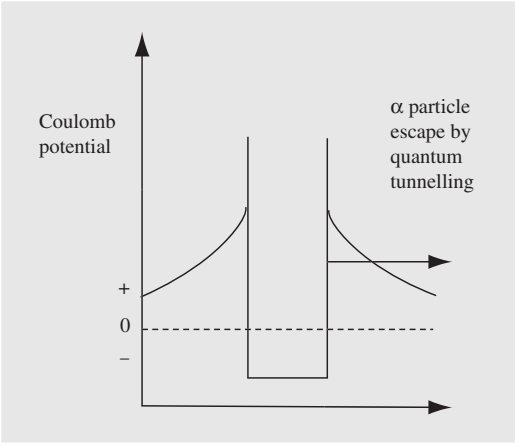
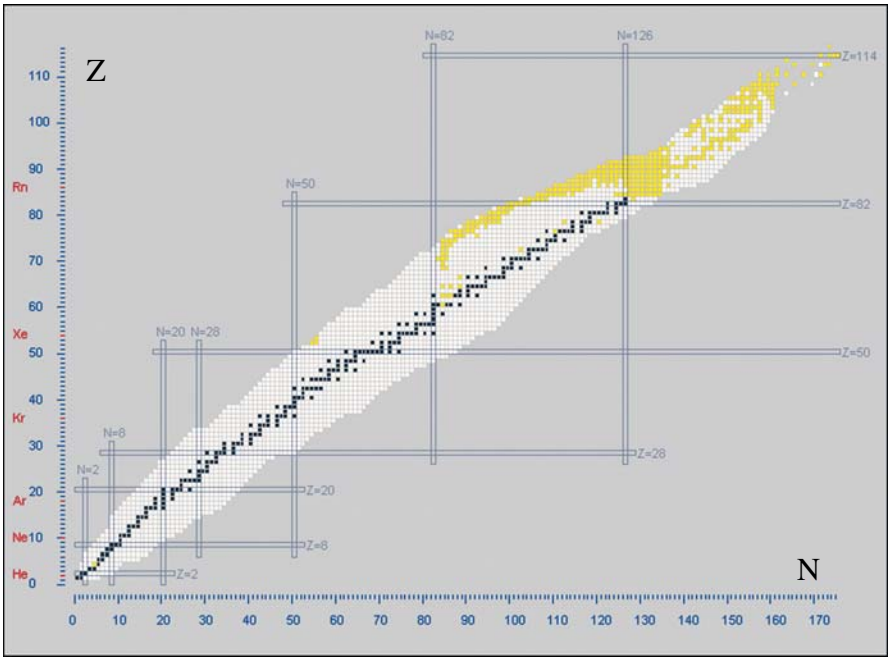


Fig. 4.1. Potential barrier near nucleus

Fig. 4.2 (*below*). Alpha emitters (*yellow*) in Nuclides.net [1]



the alpha particle will acquire two electrons to become a neutral helium atom. The alpha decay process is described by:

$$\alpha \text{ decay:} \quad {}^{A}_{Z}P \rightarrow \left[{}^{A-4}_{Z-2}D\right]^{2-} + {}^{4}_{2}\alpha \rightarrow {}^{A-4}_{Z-2}D + {}^{4}_{2}\mathrm{He}\,.$$

The process of alpha decay is found mainly in proton rich, high atomic number nuclides due to the fact that electrostatic repulsive forces increase more rapidly in heavy nuclides than the cohesive nuclear force. In addition, the emitted particle must have sufficient energy to overcome the potential barrier in the nucleus as shown in Fig. 4.1. The height of the potential barrier is about 25 MeV. Nevertheless, alpha particles can escape this barrier by the process of quantum tunnelling.

The known alpha emitters are shown in yellow in Fig. 4.2. There are in total 815 alpha emitting nuclides listed in the Nuclides.net [1] database.

Decay Energy

From Chap. 3, the Q-value for alpha decay is given by

$$\begin{aligned}\frac{Q_\alpha}{c^2} &= M({}^{A}_{Z}P) - \left[M([{}^{A-4}_{Z-2}D]^{2-}) + m({}^{4}_{2}\alpha)\right] \\ &\cong M({}^{A}_{Z}P) - \left[M({}^{A-4}_{Z-2}D) + 2m_\mathrm{e} + m({}^{4}_{2}\alpha)\right] \\ &\cong M({}^{A}_{Z}P) - \left[M({}^{A-4}_{Z-2}D) + M({}^{4}_{2}\mathrm{He})\right].\end{aligned}$$

In the above reactions, the binding energy of the two electrons on the daughter atom, as well as in the helium atom is of the order of a few eV and hence negligible in comparison to the Q-value which is of the order MeV. The Q-value in the above is now expressed in terms of tabulated atomic masses.

As an example of alpha particle emission, we consider the alpha decay from ^{238}U, i.e.

$$^{238}\mathrm{U} \rightarrow {}^{234}\mathrm{Th} + {}^{4}\mathrm{He}\,.$$

In this reaction, the neutron to proton ratio increases from 1.59 for ^{238}U to 1.6 for ^{234}Th. It is of interest to evaluate the Q-value and to determine the energy distribution among the reactions products. Hence, using the atomic masses listed in Appendix D,

$$\begin{aligned}\frac{Q_\alpha}{c^2} &= M({}^{238}\mathrm{U}) - M({}^{234}\mathrm{Th}) - M({}^{4}\mathrm{He}) \\ &= (238.050788\,\mathrm{u}) - (234.043601\,\mathrm{u}) - (4.002603\,\mathrm{u}) \\ &= 0.004584\,\mathrm{u} \mathrel{\widehat{=}} 4.27\,\mathrm{MeV}\,.\end{aligned}$$

From conservation of energy and momentum, it follows that

$$\begin{aligned}E_\alpha &= Q_\alpha \cdot \frac{M(\mathrm{Th})}{[M(\mathrm{Th}) + M(\mathrm{He})]} \\ &\cong 4.27\,\mathrm{MeV} \cdot \left(\frac{234}{238}\right) = 4.2\,\mathrm{MeV}\end{aligned}$$

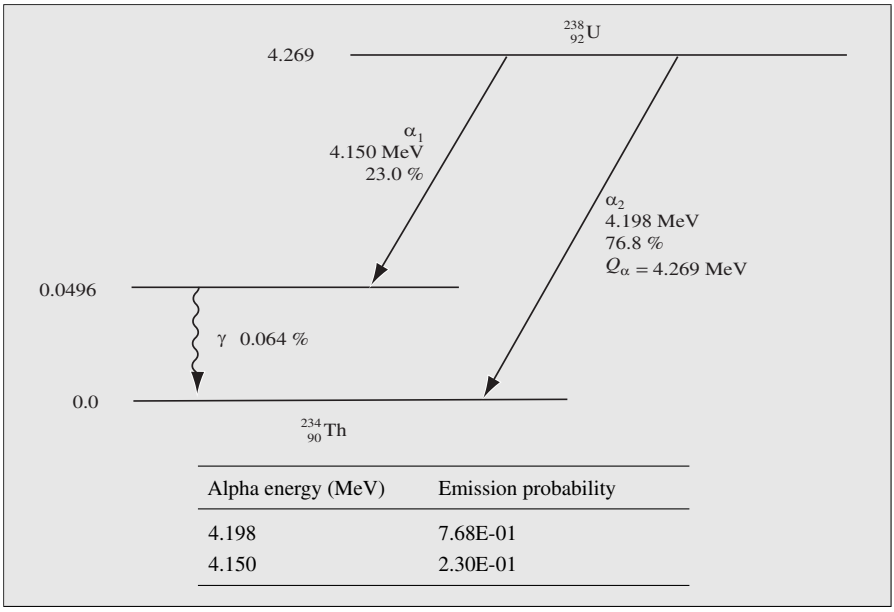
and

$$E_{\mathrm{Th}} = Q_\alpha \cdot \frac{M(\mathrm{He})}{[M(\mathrm{Th}) + M(\mathrm{He})]}$$
$$\cong 4.27\,\mathrm{MeV} \cdot \left(\frac{4}{238}\right) = 0.07\,\mathrm{MeV}$$

where it can be seen that the lighter alpha particle transports most of the kinetic energy.

Energy Level Diagram

The energy level diagram for the alpha decay from ^{238}U is shown in Fig. 4.3.



Alpha energy (MeV)	Emission probability
4.198	7.68E-01
4.150	2.30E-01

Fig. 4.3. Energy levels for alpha decay of ^{238}U showing the main α and associated γ emissions

In their interaction with matter, the alpha particles give up their energy and become neutral helium atoms. Their range in solids and liquids is very short – of the order of micrometres. In air the range is typically a few centimetres. Because of this short range, they do not normally constitute a hazard to humans. They are absorbed in the outer layers of the skin before they cause injury. If the alpha emitters are taken internally, for example by ingestion or inhalation, they are very toxic because of the large amount of energy released in a short distance within living tissue. This property can be used for killing cancer cells in such processes as alpha-immunotherapy (see Chap. 7).

Beta-minus (β^-) Decay

β^- radioactivity occurs when a nucleus emits a negative electron from an unstable radioactive nucleus. This happens when the nuclide has an excess of neutrons. The-

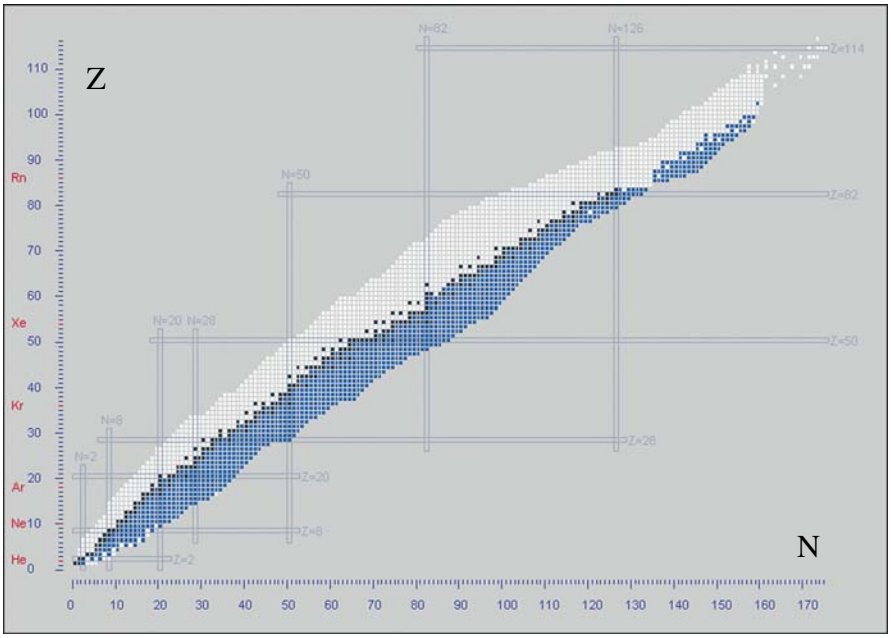


Fig. 4.4. β^- emitters (*blue*) in Nuclides.net [1]

oretical considerations (the fact that there are radionuclides which decay by both positron and negatron emission and the de Broglie wavelength of MeV electrons is much larger than nuclear dimensions), however, do not allow the existence of a negative electron in the nucleus. For this reason the beta particle is postulated to arise from the nuclear transformation of a neutron into a proton through the reaction

$$n \rightarrow p + \beta^- + \overline{\nu},$$

where $\overline{\nu}$ is an antineutrino. The ejected high energy electron from the nucleus and denoted by β^- to distinguish it from other electrons denoted by e^-.

Beta emission differs from alpha emission in that beta particles have a continuous spectrum of energies between zero and some maximum value, the endpoint energy, characteristic of that nuclide. The fact that the beta particles are not monoenergetic but have a continuous energy distribution up to a definite maximum energy, implies that there is another particle taking part i.e. the neutrino ν.

This endpoint energy corresponds to the mass difference between the parent nucleus and the daughter as required by conservation of energy. The average energy of the beta particle is approximately $\frac{1}{3}$ of the maximum energy.

More precisely, the "neutrino" emitted in β^- decay is the anti-neutrino (with the neutrino being emitted in β^+ decay). The neutrino has zero charge and almost zero mass. The maximum energies of the beta particles range from 10 keV to 4 MeV. Although beta minus particles have a greater range than alpha particles, thin layers of water, glass, metal, etc. can stop them. There are 1281 β^- emitters in the Nuclides.net database [1] (shown in Fig. 4.4).

The β^- decay process can be described by:

$$\beta^- \text{ decay:} \quad {}^A_Z P \rightarrow \left[{}^A_{Z+1} D\right]^+ + \beta^- + \bar{\nu}\,.$$

Immediately following the decay by beta emission, the daughter atom has the same number of orbital electrons as the parent atom and is thus positively charged. Very quickly, however, the daughter atom acquires an electron from the surrounding medium to become electrical neutral.

Beta radiation can be an external radiation hazard. Beta particles with less than about 200 keV have limited penetration range in tissue. However, beta particles give rise to Bremsstrahlung radiation which is highly penetrating.

Decay Energy

From Chap. 3, the Q-value for β^- decay is given by

$$\begin{aligned}\frac{Q_{\beta^-}}{c^2} &= M({}^A_Z P) - \left[M([{}^A_{Z+1} D]^+) + m_{\beta^-} + m_{\bar{\nu}}\right] \\ &\cong M({}^A_Z P) - \left[M([{}^A_{Z+1} D] - m_e) + m_{\beta^-} + m_{\bar{\nu}}\right] \\ &\cong M({}^A_Z P) - M({}^A_{Z+1} D)\,,\end{aligned}$$

where the Q-value is now expressed in terms of the atomic masses. As an example of β^- emission, we consider the beta decay of ^{14}C, i.e.

$$^{14}\mathrm{C} \rightarrow {}^{14}\mathrm{N} + \beta^- + \bar{\nu}\,.$$

From the atomic masses listed in Appendix D, the decay energy is given by

$$\begin{aligned}\frac{Q_{\beta^-}}{c^2} &= M(^{14}\mathrm{C}) - M(^{14}\mathrm{N}) = 14.003242\,\mathrm{u} - 14.003074\,\mathrm{u} \\ &= 0.000168\,\mathrm{u} \mathrel{\widehat{=}} 0.1565\,\mathrm{MeV}\,.\end{aligned}$$

Energy Level Diagram

The energy level diagram for the decay of ^{14}C is shown in Fig. 4.5. A more complicated example is shown in Fig. 4.6 for the decay of ^{38}Cl. In this case, the daughter ^{38}Ar can be produced in an excited state following β^- decay. From the figure it can be seen that the ^{38}Cl parent can decay to both the ground state and two excited states.

The decay energy to the ground state is given by

$$\begin{aligned}\frac{Q_{\beta^-}}{c^2} &= M(^{38}\mathrm{Cl}) - M(^{38}\mathrm{Ar}) = 37.968010\,\mathrm{u} - 37.962732\,\mathrm{u} \\ &= 0.005278\,\mathrm{u} \mathrel{\widehat{=}} 4.917\,\mathrm{MeV}\,.\end{aligned}$$

To evaluate the decay energy or Q-value to an energy state higher than the ground state, the mass of the daughter atom $M({}^A_{Z+1} D)$ must be replaced by the mass of the excited daughter i.e. $M({}^A_{Z+1} D^*) \cong M({}^A_{Z+1} D) + E^*/c^2$. Hence the decay energy to the excited state with energy E^* above the ground state is

$$\frac{Q_{\beta^-}}{c^2} = M({}^A_Z P) - M({}^A_{Z+1} D) - \frac{E^*}{c^2}\,.$$

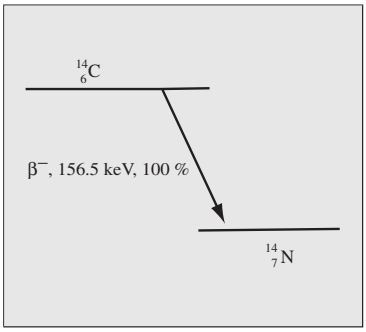


Fig. 4.5. Energy levels for beta decay of ^{14}C showing the main β^- emission

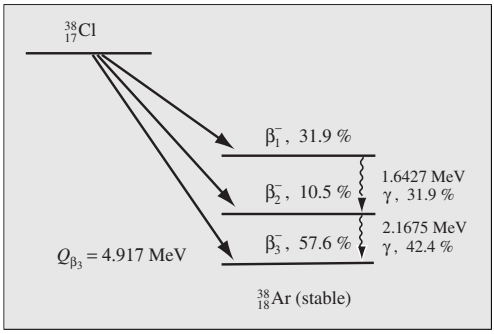


Fig. 4.6. Energy levels for beta decay of ^{38}Cl. Three groups of β^- particles are emitted [2]

Gamma Emission and Isomeric Transition (IT)

Gamma emission is not a primary decay process but usually accompanies alpha and beta decay. Typically this type of radiation arises when the daughter product resulting from alpha or beta decay is formed in an excited state. This excited state returns very rapidly ($< 10^{-9}$ s) to the ground state through the emission of a gamma photon. Instead of having a well-defined range like alpha and beta particles, gamma rays loose characteristically a certain fraction of their energy per unit distance through matter. Gamma rays are highly penetrating and can result in considerable organic damage. Gamma emitting sources require heavy shielding and remote handling.

In contrast to normal gamma emission that occurs by dipole radiation, isomeric transitions must occur by higher order multipole transitions that occur on a longer time-scale. If the lifetime for gamma emission exceeds about one nanosecond, the excited nucleus is defined to be in a metastable or isomeric state (denoted by m). The decay process from this excited state is known as an isomeric transition (IT).

The gamma decay or isomeric transition process can be described by:

$$\gamma \text{ decay:} \quad {}^{A}_{Z}P^{*} \rightarrow {}^{A}_{Z}P + \gamma$$
$$\text{IT:} \quad {}^{Am}_{Z}P \rightarrow {}^{A}_{Z}P + \gamma\,,$$

where the asterisk * denotes the excited state and m the isomeric or metastable state.

Decay Energy

From conservation of energy

$$M({}^{A}_{Z}P) = M({}^{A}_{Z}P^{*}) - \frac{E^{*}}{c^{2}}\,,$$

where E^* is the excitation energy of the nucleus. On de-excitation the energy E^* is shared between the energy of the gamma photon E_γ and the recoil energy of the atom E_P.

The decay energy or Q-value for the gamma transition is given by

$$Q_{\gamma,\mathrm{IT}} = E^* = E_\gamma + E_P \,.$$

From conservation of energy and momentum, it can be shown that

$$E_\gamma = Q_{\gamma,\mathrm{IT}} \cdot \left[1 + \frac{E_\gamma}{2M_P c^2}\right]^{-1} \,.$$

Since the photon energy has a maximum value of approximately 10 MeV, and $2M_P c^2 > 4000\,\mathrm{MeV}$, it follows that $E_\gamma \cong Q_{\gamma,\mathrm{IT}} = E^*$ such that in gamma emission or isomeric transition, the kinetic energy of the recoil nucleus is negligible in comparison to the energy of the gamma photon.

There are 473 nuclides which decay by isomeric transition in the Nuclides.net [1] database.

Internal Conversion (IC)

Alternative to gamma emission, the excited nucleus may return to the ground state by ejecting an orbital electron. This is known as internal conversion and results in the emission of an energetic electron and X-rays due to electrons cascading to lower energy levels. The ratio of internal conversion electrons to gamma emission photons is known as the internal conversion coefficient. Conversion electrons are monoenergetic.

The internal conversion process can be described by:

IC decay: $\quad {}^{A}_{Z}P^* \rightarrow [{}^{A}_{Z}P]^+ + \mathrm{e}^- \,.$

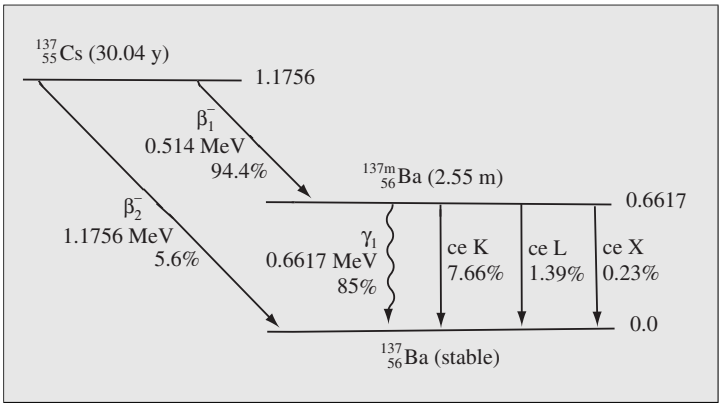


Fig. 4.7. Gamma emission and internal conversion (ce) of $^{137\mathrm{m}}$Ba in the transformation of ^{137}Cs to ^{137}Ba [2]

Decay Energy

The Q-value for internal conversion is given by

$$\begin{aligned}\frac{Q_{\mathrm{IC}}}{c^2} &= M({}^A_Z P^*) - \left[M([{}^A_Z P]^+) + m_{\mathrm{e}^-}\right] \\ &\cong \left[M({}^A_Z P) + \frac{E^*}{c^2}\right] - \left[\left\{M({}^A_Z P) - m_{\mathrm{e}} + \frac{BE_{\mathrm{e}}}{c^2}\right\} + m_{\mathrm{e}}\right] \\ &= \frac{[E^* - BE_{\mathrm{e}}]}{c^2}\,.\end{aligned}$$

From conservation on energy and momentum, this energy is shared between the daughter ion and IC electron as follows:

$$E_{\mathrm{e}} = \left[\frac{M({}^A_Z P)}{M({}^A_Z P) + m_{\mathrm{e}}}\right][E^* - BE_{\mathrm{e}}] \cong E^* - BE_{\mathrm{e}}$$

$$E_{\mathrm{ion}} = \left[\frac{m_{\mathrm{e}}}{M({}^A_Z P) + m_{\mathrm{e}}}\right][E^* - BE_{\mathrm{e}}] \cong 0\,.$$

Consider the decay of the isomeric state $^{137\mathrm{m}}$Ba.. This nuclide emits a 0.661 MeV photon which undergoes internal conversion in 11% of the transitions. These conversion electrons are seen in the beta spectrum of ^{137}Cs. Following the internal conversion, outer orbital electrons fill the deeper energy levels and result in characteristic X-ray emission. These X-rays can in turn lead to the ejection of outer electrons through an internal photoelectric effect. The low energy ejected electrons are known as Auger electrons.

Beta-plus (β^+) Decay (Positron Emission)

In nuclides where the neutron to proton ratio is low, and alpha emission is not energetically possible, the nucleus may become more stable by the emission of a positron (a positively charged electron).Within the nucleus a proton is converted into a neutron, a positron, and a neutrino i.e.

$$\mathrm{p} \rightarrow \mathrm{n} + \beta^+ + \nu\,.$$

Similarly to the β^-, the positron β^+ is continuously distributed in energy up to a characteristic maximum energy. The positron, after being emitted from the nucleus, undergoes strong electrostatic attraction with the atomic electrons. The positron and negative electrons annihilate each other and result in two photons (gamma rays) each with energy of 0.511 MeV moving in opposite directions.

There are 1496 β^+ emitters in the Nuclides.net database (shown in Fig. 4.8). The radiation hazard from positrons is similar to that from β^- particles. In addition, the gamma radiation resulting from the positron-electron annihilation presents an external radiation hazard.

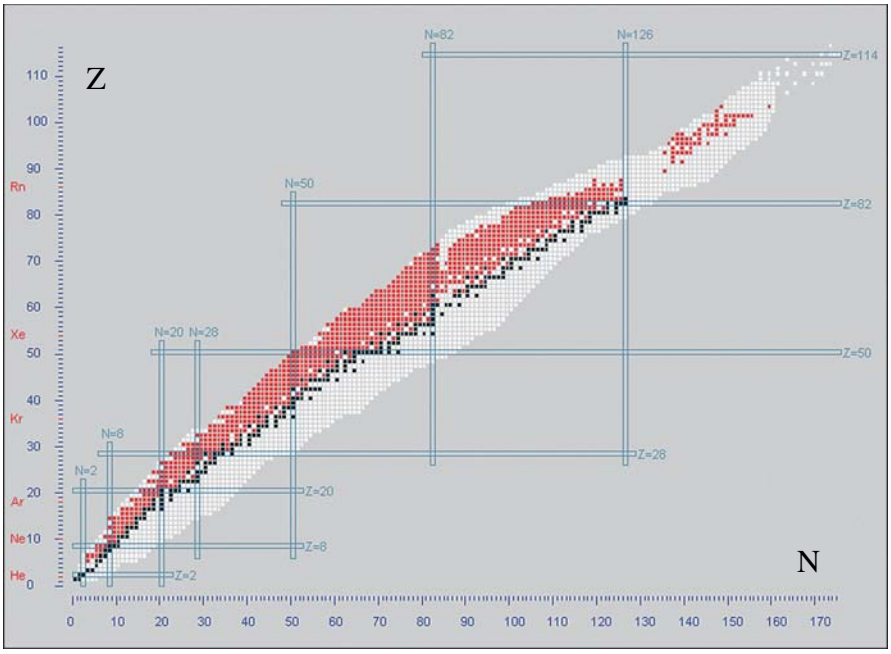


Fig. 4.8. β^+ emitters (*red*) in the Nuclides.net database

The β^+ decay process can be described by:

$$\beta^+ \text{ decay:} \quad {}^{A}_{Z}P \rightarrow \left[{}^{A}_{Z-1}D\right]^- + \beta^+ + \nu\,.$$

Immediately following the decay by positron emission, the daughter atom has the same number of orbital electrons as the parent atom and is thus negatively charged. Very quickly, however, the daughter atom loses the electron from the surrounding medium to become electrically neutral.

Decay Energy

From Chapter 3, the Q-value for β^+ decay is given by

$$\begin{aligned}\frac{Q_{\beta^+}}{c^2} &= M({}^{A}_{Z}P) - \left[M([{}^{A}_{Z-1}D]^-) + m_{\beta^+} + m_\nu\right] \\ &\cong M({}^{A}_{Z}P) - \left[\{M([{}^{A}_{Z-1}D] + m_e)\} + m_{\beta^+} + m_{\overline{\nu}}\right] \\ &= M({}^{A}_{Z}P) - M({}^{A}_{Z-1}D) - 2m_e\,,\end{aligned}$$

where the Q-value is now expressed in terms of the atomic masses and the electron mass (binding energy of the electron to the daughter ion has been neglected).

The daughter is often produced in an excited state and the decay energy is given by

$$\frac{Q_{\beta^+}}{c^2} = M({}^{A}_{Z}P) - M({}^{A}_{Z-1}D) - 2m_e - \frac{E^*}{c^2}\,,$$

where E^* is the excitation energy. Since the daughter is much heavier, the positron carries most of the kinetic energy.

Energy Level Diagram

An example is the decay of ^{22}Na:

$${}^{22}_{11}\mathrm{Na} \rightarrow {}^{22}_{10}\mathrm{Ne} + \beta^+ + \nu\,.$$

From the atomic masses listed in Appendix D, the decay energy is given by

$$\begin{aligned}\frac{Q_{\beta^+}}{c^2} &= M(^{22}\mathrm{Na}) - M(^{22}\mathrm{Ne}) - 2m_e \\ &= 21.994436\,\mathrm{u} - 21.991385\,\mathrm{u} - 2(0.000549\,\mathrm{u}) \mathrel{\widehat{=}} 1.82\,\mathrm{MeV}\,.\end{aligned}$$

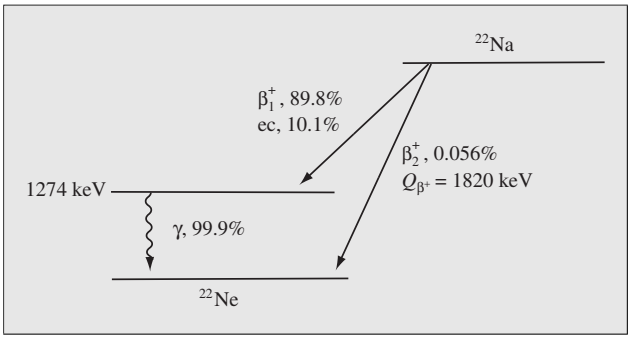


Fig. 4.9. Energy levels for beta decay of ^{22}Na showing the main β^+ emissions [2]

Electron Capture (ε or ec)

Neutron deficient nuclides can also attain stability by capturing an electron from the inner K or L shells of the atomic orbits. As a result, a proton in the nucleus transforms to a neutron i.e.

$$\mathrm{p} + \mathrm{e}^- \rightarrow \mathrm{n} + \nu\,.$$

The process is similar to β^+ decay in that the charge of the nucleus decreases by 1. The ec decay process can be described by:

$$\text{ec decay:} \quad {}^{A}_{Z}P \rightarrow {}^{A}_{Z-1}D^* + \nu$$

and the daughter is usually produced in an excited state. The resulting nucleus is unstable and decays by the ejection of an unobservable neutrino (ν) and the emission of a characteristic X-ray when the electron vacancy in the K or L shell is filled by outer orbital electrons. The Nuclides.net database lists 162 nuclides (shown in Fig. 4.10) which undergo electron capture.

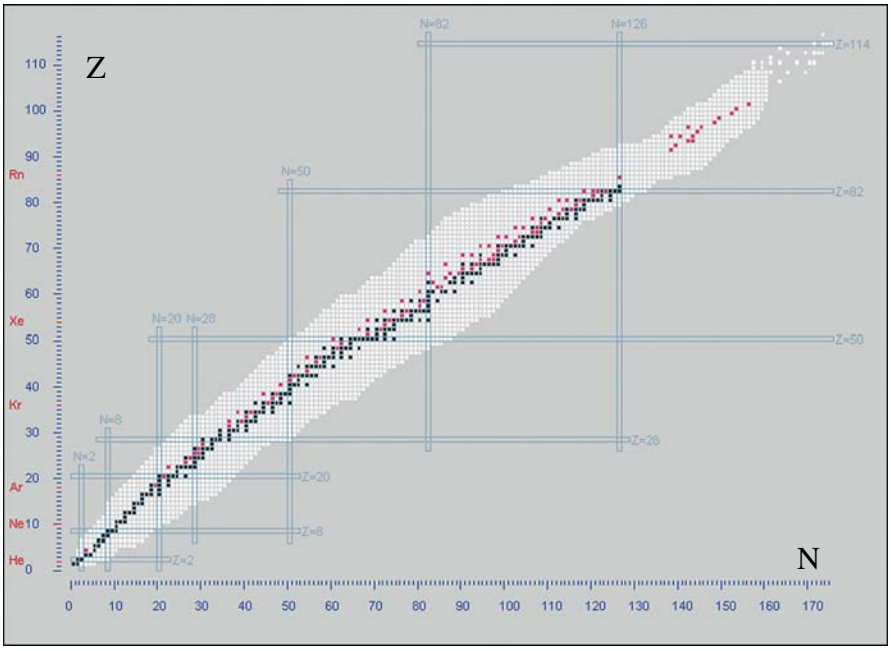


Fig. 4.10. Nuclides which undergo electron capture (*red*) in the Nuclides.net database

Decay Energy

The Q-value for ec decay is given by

$$\frac{Q_{\mathrm{ec}}}{c^2} = M({}^{A}_{Z}P) - \left[M({}^{A}_{Z-1}D) + m_\nu\right]$$
$$\cong M({}^{A}_{Z}P) - M({}^{A}_{Z-1}D)$$

If the daughter is produced in an excited state, the decay energy is given

$$\frac{Q_{\mathrm{ec}}}{c^2} = M({}^{A}_{Z}P) - M({}^{A}_{Z-1}D) - \frac{E^*}{c^2}$$

where E^* is the excitation energy.

Energy Level Diagram

An example is the electron capture process in beryllium-7 i.e.

$${}^{7}_{4}\mathrm{Be} \rightarrow {}^{7}_{3}\mathrm{Li} + \nu\,.$$

From the atomic masses listed in Appendix D, the decay energy is given by

$$\frac{Q_{\mathrm{ec}}}{c^2} = M({}^{7}\mathrm{Be}) - M({}^{7}\mathrm{Li}) = 7.016929\,\mathrm{u} - 7.016004\,\mathrm{u} \mathrel{\widehat{=}} 861.6\,\mathrm{keV}$$

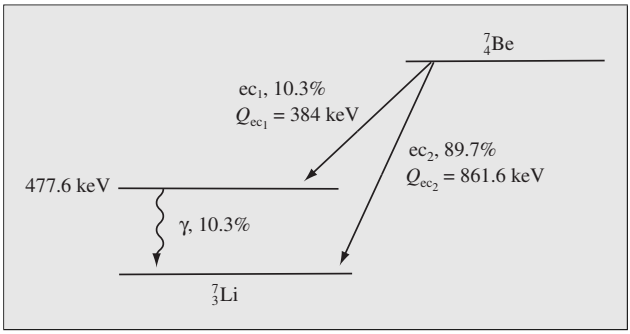


Fig. 4.11. Energy levels for decay of ^{7}Be showing the main electron captures [2]

Spontaneous Fission (SF)

The discovery of fission by neutrons is credited to Hahn and Strassmann [3], and to Meitner and Frisch [4] for their explanation of the phenomena and introduction of the term *nuclear fission*. Spontaneous fission was discovered in 1940 by Petrzak and Flerov [5].

Although the alpha emitting properties of ^{238}U were well known by that time, the much less common spontaneous fission had been "masked" due to its very small branching ratio of about one SF in 2×10^6 alpha emissions. With the exception of ^{8}Be (which decays into two alpha particles), SF has not been detected in any elements lighter than thorium. In the 1960s, sources of ^{252}Cf became available and detailed measurement of the fissioning of this system contributed much to our understanding of the process.

Actinides (Ac, Th, Pu, U, Pu, Am, Np, Cm, etc.) and trans-actinides can undergo radioactive decay by spontaneous fission. In this process the nucleus splits into two fragment nuclei, with mass and charge roughly half that of the parent, and several neutrons.

The spontaneous fission (SF) decay process can be described qualitatively by:

$$P \rightarrow D_1 + D_2 + d_1 + d_2 + \ldots$$

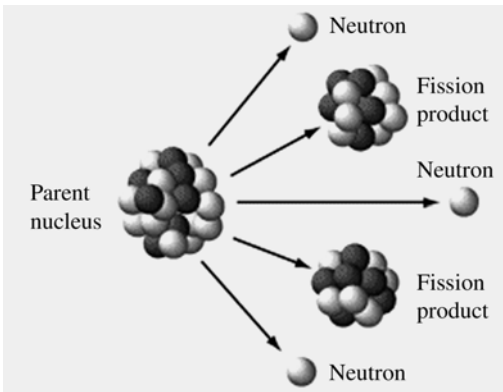


Fig. 4.12. Spontaneous fission of heavy nuclides (AJ Software & Multimedia. Used by permission. All rights reserved. www.atomicarchive.com)

and in more detail by

$$\text{SF decay:} \quad {}^{A}_{Z}P \rightarrow {}^{A'}_{Z'}D + {}^{A-A'-\upsilon}_{Z-Z'}D + \upsilon\text{n} + E^{*}\,.$$

The process is shown schematically in Fig. 4.12. A "parent" nuclide ${}^{A}_{Z}P$ splits into two "daughter" nuclides ${}^{A'}_{Z'}D$ and ${}^{A-A'-\upsilon}_{Z-Z'}D$ together with the release of υ prompt neutrons and energy E^{*}. Typically υ ranges from 2–4 and E^{*} is approximately 200 MeV. Additionally, so-called delayed neutrons may be emitted by the primary fission products. The daughter nuclides or fission products have in general different mass numbers A and atomic numbers Z.

Since there are more than two decay products, the products and their energies cannot be uniquely identified. In the case of the spontaneous fission of fermium-256, one such reaction is:

$${}^{256}_{100}\text{Fm} \rightarrow {}^{140}_{54}\text{Xe} + {}^{112}_{46}\text{Pd} + 4\text{n}$$

(this reaction represents only one of many fission product combinations). The kinetic energy release in this process, due mainly to large electrostatic repulsion of the fragments, is approximately 190 MeV.

The distribution of the energy released in fission is shown in Table 4.4. The Nuclides.net database currently lists 127 spontaneously fissioning nuclides (shown in Fig. 4.13 and Table 4.5).

About 87% of the total energy is emitted promptly with the fission fragments. Most of the neutrons released are prompt neutrons and are released within 10^{-14} s of fissioning. Some neutrons are released on a much longer timescale and are associated with the fission decay chains. Since the discovery of this process, the identification of the mass and the nuclear charge of the fission products has always been an important part of fission investigations and experiments. In the early days of fission product yields exploration, initiated by nuclear physicists such as Anderson and Fermi, radiochemical methods were used. These are being progressively replaced by more sophisticated physical methods for the determination of the yields [6–8].

Table 4.4. Energy released resulting from spontaneous fission of ^{235}U

Products	Emitted energy (MeV)
Prompt energy:	
Fission fragments	168
Fission neutrons	5
γ emission	7
Radioactivity:	
β decay (electrons)	8
β decay (neutrinos)	12
γ emission	7
Total	207

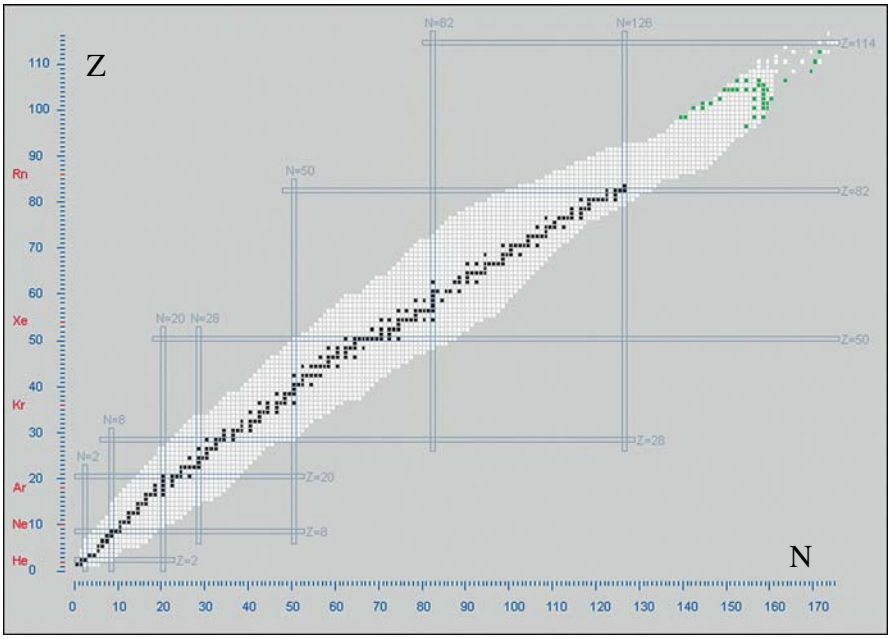


Fig. 4.13. Nuclides (*green*) in which spontaneous fission is the *main* decay mode

Although mass yield distributions have been measured with sufficient precision for most fission reactions of technical importance, the distribution of independent yields is still not completely known. The reason for this is that the mass distribution of fission products does not change with time after the fission reaction, if the small effect due to delayed neutron emission is neglected. Independent yields, however, describe the elemental distribution of fission products and undergo a rapid change after fission because of the predominance of short-lived β^--unstable nuclides.

Therefore, the methods of measuring independent yields differ from those for the measurement of chain yields, and thus require more advanced technology.

On the other hand, only a small fraction of yields, independent and/or cumulative, of approximately 900 primary products have been measured for any fission reaction. About 25% of the fission products have been measured, at best, for the fissioning systems of technical importance and usually about 1% or less for the other fission reactions. Therefore, most of the independent and cumulative yields must be estimated.

Fission yield distributions are interesting from two standpoints a) they provide information on the nature of large collective motion of nuclear matter in different energy ranges and b) low energy fission yield distributions are important for the control of nuclear reactors.

In the framework of nuclear technologies (reactor technology, safeguards, etc.), there is an even more important need of nuclear data. The cumulative fission product distribution is of great interest for practical purposes such as waste storage, control of nuclear reactors, etc. Independent yields are of importance for the fundamental

Table 4.5. Spontaneously fissioning nuclides in the Nuclides.net database

Nuclides	Half-life	Nuclides	Half-life	Nuclides	Half-life	Nuclides	Half-life
$^{230}_{90}$Th	7.5E4 y	$^{247}_{97}$Bk	1.4E3 y	$^{259}_{100}$Fm	1.5 s	$^{257}_{104}$Rf	4.7 s
$^{232}_{90}$Th	1.4E10 y	$^{249}_{97}$Bk	320 d	$^{245}_{101}$Md	900 μs	$^{258}_{104}$Rf	12 ms
$^{231}_{91}$Pa	3.3E4 y	$^{237}_{98}$Cf	2.1 s	$^{247}_{101}$Md	270 ms	$^{259}_{104}$Rf	2.7 s
$^{234}_{91}$Pa	6.7 h	$^{238}_{98}$Cf	21 ms	$^{247m}_{101}$Md	1.12 s	$^{260}_{104}$Rf	20.1 ms
$^{234m}_{91}$Pa	1.17 m	$^{240}_{98}$Cf	1.06 m	$^{255}_{101}$Md	27 m	$^{261}_{104}$Rf	1.08 m
$^{230}_{92}$U	20.8 d	$^{242}_{98}$Cf	3.49 m	$^{257}_{101}$Md	5.52 h	$^{262}_{104}$Rf	2.06 s
$^{232}_{92}$U	68.95 y	$^{246}_{98}$Cf	1.49 d	$^{258m}_{101}$Md	57 m	$^{262m}_{104}$Rf	47 ms
$^{233}_{92}$U	1.6E5 y	$^{248}_{98}$Cf	3.3E2 d	$^{259}_{101}$Md	1.6 h	$^{263}_{104}$Rf	10 m
$^{234}_{92}$U	2.5E5 y	$^{249}_{98}$Cf	3.5E2 y	$^{260}_{101}$Md	27.8 d	$^{255}_{105}$Db	1.7 s
$^{235}_{92}$U	7.0E8 y	$^{250}_{98}$Cf	13.09 y	$^{250}_{102}$No	250 μs	$^{256}_{105}$Db	3 s
$^{236}_{92}$U	2.3E7 y	$^{252}_{98}$Cf	2.65 y	$^{251}_{102}$No	800 ms	$^{257}_{105}$Db	1.4 s
$^{238}_{92}$U	4.5E9 y	$^{254}_{98}$Cf	60.5 d	$^{252}_{102}$No	2.3 s	$^{258}_{105}$Db	4.6 s
$^{237}_{93}$Np	2.1E6 y	$^{255}_{98}$Cf	1.42 h	$^{253}_{102}$No	1.7 m	$^{260}_{105}$Db	1.52 s
$^{236}_{94}$Pu	2.86 y	$^{256}_{98}$Cf	12.3 m	$^{254}_{102}$No	55 s	$^{261}_{105}$Db	1.8 s
$^{238}_{94}$Pu	87.76 y	$^{247}_{99}$Es	4.55 m	$^{256}_{102}$No	2.91 s	$^{262}_{105}$Db	34 s
$^{239}_{94}$Pu	2.4E4 y	$^{253}_{99}$Es	20.47 d	$^{258}_{102}$No	1.2 ms	$^{263}_{105}$Db	29 s
$^{240}_{94}$Pu	6.6E3 y	$^{254}_{99}$Es	2.8E2 d	$^{259}_{102}$No	58 m	$^{258}_{106}$Sg	3.3 ms
$^{241}_{94}$Pu	14.36 y	$^{254m}_{99}$Es	1.64 d	$^{260}_{102}$No	106 ms	$^{259}_{106}$Sg	580 ms
$^{242}_{94}$Pu	3.7E5 y	$^{255}_{99}$Es	39.8 d	$^{262}_{102}$No	5 ms	$^{260}_{106}$Sg	3.8 ms
$^{244}_{94}$Pu	8.1E7 y	$^{242}_{100}$Fm	800 μs	$^{252}_{103}$Lr	1 s	$^{261}_{106}$Sg	230 ms
$^{241}_{95}$Am	4.3E2 y	$^{243}_{100}$Fm	210 ms	$^{253}_{103}$Lr	1.5 s	$^{263}_{106}$Sg	800 ms
$^{242m}_{95}$Am	1.4E2 y	$^{244}_{100}$Fm	3.3 ms	$^{254}_{103}$Lr	13 s	$^{265}_{106}$Sg	16 s
$^{242n}_{95}$Am	14 ms	$^{245}_{100}$Fm	4.2 s	$^{255}_{103}$Lr	22 s	$^{266}_{106}$Sg	20 s
$^{243}_{95}$Am	7.4E3 y	$^{246}_{100}$Fm	1.1 s	$^{256}_{103}$Lr	28 s	$^{269}_{106}$Sg	22 s
$^{240}_{96}$Cm	27 d	$^{248}_{100}$Fm	36 s	$^{257}_{103}$Lr	646 ms	$^{261}_{107}$Bh	13 ms
$^{242}_{96}$Cm	1.6E2 d	$^{250}_{100}$Fm	30 m	$^{259}_{103}$Lr	6.3 s	$^{262}_{107}$Bh	102 ms
$^{243}_{96}$Cm	29.12 y	$^{252}_{100}$Fm	1.06 d	$^{260}_{103}$Lr	3 m	$^{262m}_{107}$Bh	8 ms
$^{244}_{96}$Cm	18.11 y	$^{254}_{100}$Fm	3.24 h	$^{261}_{103}$Lr	39 m	$^{277}_{108}$Hs	11 m
$^{245}_{96}$Cm	8.5E3 y	$^{255}_{100}$Fm	20.07 h	$^{253}_{104}$Rf	13 ms	$^{266}_{109}$Mt	6 ms
$^{246}_{96}$Cm	4.7E3 y	$^{256}_{100}$Fm	2.63 h	$^{254}_{104}$Rf	23 μs	$^{280}_{110}$Ds	7.5 s
$^{248}_{96}$Cm	3.4E5 y	$^{257}_{100}$Fm	1.0E2 d	$^{255}_{104}$Rf	1.5 s	$^{283}_{112}$Uub	12.7 s
$^{250}_{96}$Cm	9.0E3 y	$^{258}_{100}$Fm	360 μs	$^{256}_{104}$Rf	6.7 ms		

understanding of the corresponding nuclear reactions, but also for short-term practical purposes in reactor operation.

In the fission process, the probability of measuring the production of an isotope or a nuclide is generally expressed as the yield (given in units of production per unit fission or in percent).

Proton Decay

As one moves further to the left of the line of stability, the proton to neutron ratio increases with increasing distance (see Fig. 4.14) and the nuclides are increasingly proton rich. In such proton rich nuclides, positron (β^+) decay is usually energetically more favourable. However, as the binding energy of these protons decreases further, there comes a point in which proton emission becomes energetically possible. More often, proton emission follows positron emission in a two-stage process i.e. β^+ decay results in an daughter in an excited state which then de-excites by proton emission.

A review of the early theoretical speculations on the subject of proton emission has been given by Goldansky in 1966 [9]. The first observation of proton emission was reported by Jackson et al. in 1970 [10] with the nuclide ^{53m}Co. This decay process, is exhibited by the metastable state of cobalt-53, i.e.

$$^{53m}_{27}\mathrm{Co} \begin{cases} \nearrow\ ^{52}_{26}\mathrm{Fe} + \mathrm{p} \\ \searrow\ ^{53}_{26}\mathrm{Fe} + \beta^+ + \nu \end{cases}$$

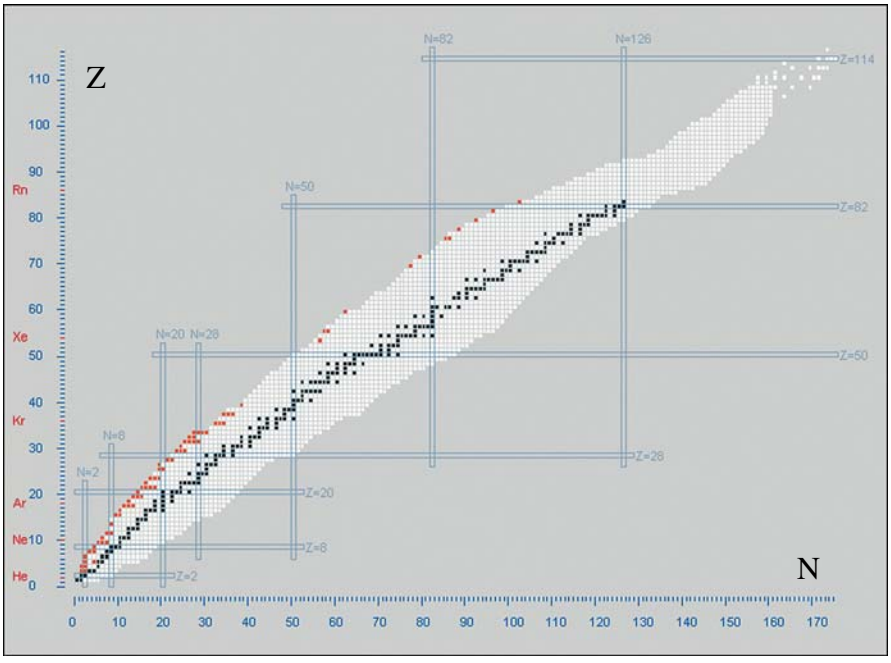


Fig. 4.14. Proton emitters (*brown*) in the Nuclides.net database

Table 4.6. Proton emitters in the Nuclides.net database

Nuclide	Half-life	Nuclide	Half-life	Nuclide	Half-life
$^{4}_{3}$Li	9.1E-14 ns	$^{45}_{25}$Mn	70 ns	$^{109}_{53}$I	100 µs
$^{5}_{3}$Li	3.0E-13 ns	$^{45}_{26}$Fe	350 ns	$^{112}_{55}$Cs	500 µs
$^{5}_{4}$Be		$^{48}_{27}$Co		$^{113}_{55}$Cs	17 µs
$^{7}_{5}$B	3.5E-13 ns	$^{49}_{27}$Co	35 ns	$^{117}_{57}$La	500 ms
$^{9}_{5}$B	8.0E-10 ns	$^{53m}_{27}$Co	247 ms	$^{121}_{59}$Pr	600 ms
$^{10}_{7}$N		$^{52}_{29}$Cu		$^{128}_{61}$Pm	800 ms
$^{11}_{7}$N	5.0E-13 ns	$^{53}_{29}$Cu	300 ns	$^{132}_{63}$Eu	400 ms
$^{14}_{9}$F		$^{54}_{29}$Cu	75 ns	$^{138}_{65}$Tb	400 ms
$^{15}_{9}$F	4.6E-13 ns	$^{55}_{29}$Cu	200 ns	$^{142}_{67}$Ho	300 ms
$^{16}_{9}$F	1.1E-11 ns	$^{56}_{31}$Ga		$^{146}_{69}$Tm	235 ms
$^{18}_{11}$Na		$^{57}_{31}$Ga		$^{146m}_{69}$Tm	72 ms
$^{19}_{11}$Na	40 ns	$^{58}_{31}$Ga		$^{147}_{69}$Tm	580 ms
$^{21}_{13}$Al	35 ns	$^{58m}_{31}$Ga		$^{150}_{71}$Lu	35 ms
$^{24}_{15}$P		$^{59}_{31}$Ga		$^{151m}_{71}$Lu	85 ms
$^{25}_{15}$P	30 ns	$^{60}_{33}$As		$^{156}_{73}$Ta	144 ms
$^{28}_{17}$Cl		$^{60m}_{33}$As		$^{156m}_{73}$Ta	360 ms
$^{29}_{17}$Cl	20 ns	$^{61}_{33}$As		$^{160}_{75}$Re	790 µs
$^{30}_{17}$Cl	30 ns	$^{62}_{33}$As		$^{161}_{75}$Re	
$^{30}_{18}$Ar	20 ns	$^{63}_{33}$As		$^{165}_{77}$Ir	1 µs
$^{32}_{19}$K		$^{67}_{35}$Br		$^{165m}_{77}$Ir	300 µs
$^{33}_{19}$K	25 ns	$^{68}_{35}$Br	1.2 µs	$^{166}_{77}$Ir	10.5 ms
$^{34}_{19}$K	40 ns	$^{69}_{35}$Br	24 ns	$^{166m}_{77}$Ir	15.1 ms
$^{34}_{20}$Ca	35 ns	$^{71}_{37}$Rb		$^{167}_{77}$Ir	35.2 ms
$^{36}_{21}$Sc		$^{72}_{37}$Rb	1.2 µs	$^{167m}_{77}$Ir	30 ms
$^{37}_{21}$Sc		$^{72m}_{37}$Rb		$^{171}_{79}$Au	10 µs
$^{38}_{21}$Sc	300 ns	$^{73}_{37}$Rb	< 30 ns	$^{171m}_{79}$Au	1.02 ms
$^{38m}_{21}$Sc		$^{77}_{39}$Y	1.2 µs	$^{172}_{79}$Au	4.7 ms
$^{39}_{21}$Sc	300 ns	$^{81}_{41}$Nb	800 ms	$^{177}_{81}$Tl	1 µs
$^{40}_{23}$V		$^{85}_{43}$Tc	500 ms	$^{177m}_{81}$Tl	
$^{41}_{23}$V		$^{104}_{51}$Sb	470 ms	$^{185}_{83}$Bi	2 ms
$^{42}_{23}$V	55 ns	$^{105}_{51}$Sb	1.12 s	$^{185m}_{83}$Bi	44 µs
$^{44}_{25}$Mn	105 ns	$^{108}_{53}$I	36 ms		

with branching ratios of 1.5% (p mode) and 98.5% (β^+ mode). Proton radioactivity from a ground state, i.e. ^{151}Lu, was first reported by Hofmann et al. in 1981 [11]. In the following three years, three more proton emitters were observed in the region of nuclei near ^{151}Lu with ^{147}Tm, ^{147m}Tm, ^{150}Lu, and two in the region near ^{100}Sn i.e. ^{113}Cs and ^{109}I. This work is summarised in the review article by Hofmann in 1995 [12]. More recently, due to various experimental improvements, proton transitions have been found in nuclei near to $N = 82$ (^{146}Tm, ^{146m}Tm, ^{156}Ta, ^{160}Re) and also in ^{165,166,167}Ir, ^{171}Au, ^{185}Bi and ^{105}Sb. As of 1995, 21 proton transitions have been established definitively. Since then more proton emitters have been either claimed or identified. The Nuclides.net database contains 95 proton emitters (shown in Fig. 4.14 and Table 4.6).

The phenomena of two-proton radioactivity has been discussed by Brown [13]. In total there are 13 two-proton emitters in the Nuclides.net database.

The proton decay process can be described by:

$$\text{p decay:} \quad {}^{A}_{Z}P \rightarrow [{}^{A-1}_{Z-1}D^*]^- + {}^{1}_{1}\text{p}$$

following emission of the proton, the daughter atom has an extra electron which is rapidly ejected to the surrounding media in order to balance the charge.

Decay Energy

The Q-value for proton decay is given by

$$\begin{aligned}
\frac{Q_\text{p}}{c^2} &= M({}^{A}_{Z}P) - \left\{ M([{}^{A-1}_{Z-1}D^*]^-) + m_\text{p} \right\} \\
&\cong M({}^{A}_{Z}P) - \left\{ [M({}^{A-1}_{Z-1}D^*) + m_\text{e}] + m_\text{p} \right\} \\
&\cong M({}^{A}_{Z}P) - \left\{ [M({}^{A-1}_{Z-1}D) + \frac{E^*}{c^2} + m_\text{e}] + m_\text{p} \right\} \\
&\cong M({}^{A}_{Z}P) - M({}^{A-1}_{Z-1}D) - M({}^{1}_{1}\text{H}) - \frac{E^*}{c^2}
\end{aligned}$$

For proton decay to the ground state

$$\frac{Q_\text{p}}{c^2} = M({}^{A}_{Z}P) - M({}^{A-1}_{Z-1}D) - M({}^{1}_{1}\text{H})$$

Special Beta-Decay Processes

To the right of the line of stability, the nuclides are neutron rich and neutron emission can be expected in this region by analogy with proton emission from proton rich nuclides. Neutron emission from a ground state nuclide has not been observed although it is energetically possible for some nuclides.

Neutron Emission

Neutron emission immediately following β^- emission (beta delayed neutron emission denoted β^-n) has been observed in many neutron-rich nuclides. The phenomena of delayed neutron emission is very important in the control of nuclear reactors since neutron emission occurs on a timescale much longer than that associated with fission – this allows a response time long enough to move control rods and thereby control the fission reactor. An example of this type of emission is given by ^{17}N i.e.

$$^{17}_{7}\mathrm{N} \rightarrow {}^{17}_{8}\mathrm{O}^* + \beta^- + \bar{\nu}\,,$$

$$^{17}_{8}\mathrm{O}^* \rightarrow {}^{16}_{8}\mathrm{O} + \mathrm{n}\,,$$

where the asterisk denotes the short-lived intermediate excited states of oxygen-17. The effective half-life for this process is 4.17 s. There are 279 (β^-n) emitters in the Nuclides.net database. The delayed neutron emission from the β^- decay of ^{87}Br is shown in Fig. 4.15.

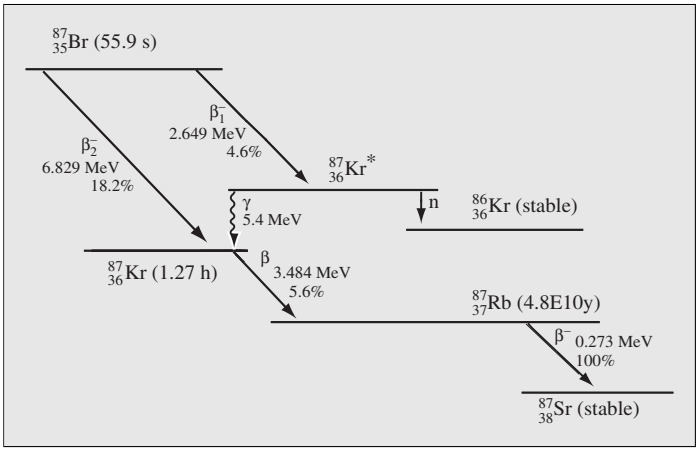


Fig. 4.15. Decay scheme of ^{87}Br showing the delayed neutron emission from $^{87}_{36}\mathrm{Kr}^*$ [2]

Alpha and Proton Emission

Some positron emitters in the light-element region beta decay partly to excited states that are unstable with respect to emission of an alpha particle ($\beta^+\alpha$). Both the positron decay from boron-8 and negatron decay from lithium-8 ($\beta^-2\alpha$) are beta-delayed alpha emission, because ground as well as excited states of beryllium-8 are unstable with respect to breakup into two alpha particles. Another example is the decay of ^{20}Na, i.e.

$$^{20}_{11}\mathrm{Na} \rightarrow {}^{20}_{10}\mathrm{Ne}^* + \beta^+ + \nu\,,$$

$$^{20}_{10}\mathrm{Ne}^* \rightarrow {}^{16}_{8}\mathrm{O} + \alpha\,.$$

There are 39 $\beta^+\alpha$ emitters listed in the Nuclides.net database.

In a few cases, positron decay leads to an excited nuclear state not able to bind a proton. In these cases, proton radiation appears with the half-life of the beta transition. One example of this is the decay of ^{111}Te, i.e.

$$^{111}_{52}\mathrm{Te} \rightarrow {}^{111}_{51}\mathrm{Sb}^{*} + \beta^{+} + \nu\,,$$

$$^{111}_{51}\mathrm{Sb}^{*} \rightarrow {}^{110}_{50}\mathrm{Sn} + \mathrm{p}\,.$$

There are 177 β^{+}p in the Nuclides.net database. An example of proton emission following the β^{-} decay of ^{73}Kr is shown in Fig. 4.16.

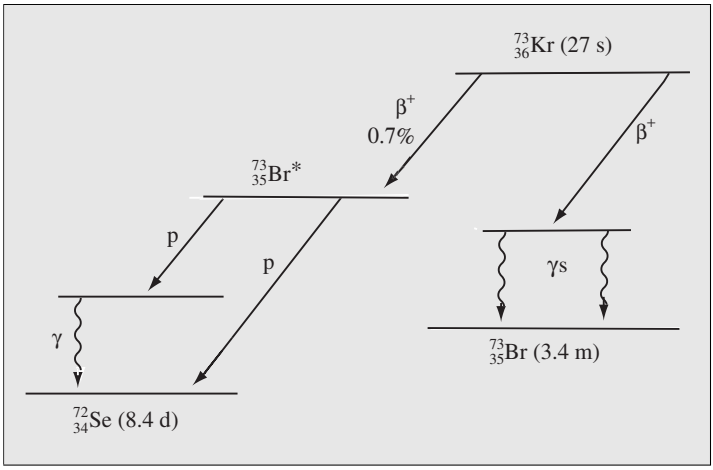


Fig. 4.16. Proton emission in the decay of ^{73}Kr in which 0.7% of the β^{+} transitions are to the metastable state $^{73}_{35}$Br* which then decay by proton emission [2]

Heavy-Ion or Cluster Radioactivity

In 1984, Rose and Jones [14] at Oxford University announced the discovery of a new rare type of radioactive decay in the nuclide ^{223}Ra. Their article entitled "A new kind of natural radioactivity" was published in *Nature*. The possibility that such a decay process, intermediate between alpha decay and spontaneous fission, may exist was postulated by A. Sandulescu, D. N. Poenaru, and W. Greiner a few years earlier in 1980. Rose and Jones showed that part of the ^{223}Ra parent nuclide decays directly to ^{209}Pb by the emission of a 30 MeV ^{14}C ion i.e.

$$^{223}\mathrm{Ra} \rightarrow {}^{209}\mathrm{Pb} + {}^{14}\mathrm{C}\,.$$

It is of interest to calculate value of the decay energy for this process i.e.

$$\frac{Q_{\mathrm{p}}}{c^2} = M(^{223}\mathrm{Ra}) - M(^{209}\mathrm{Pb}) - M(^{14}\mathrm{C})$$
$$= 223.018502\,\mathrm{u} - 208.981090 - 14.003241\,\mathrm{u} \mathrel{\widehat{=}} 31.8\,\mathrm{MeV}\,.$$

This calculated value of the decay energy is in agreement with the observed kinetic energy of the carbon ion.

Observations also have been made of carbon-14 from radium-222, radium-224, and radium-226, as well as neon-24 from thorium-230, protactinium-231, and uranium-232. Such heavy-ion radioactivity, like alpha decay and spontaneous fission, involves quantum-mechanical tunnelling through the potential-energy barrier. Shell effects play a major role in this phenomenon and in all cases observed to date the heavy partner of carbon-14 or neon-24 is close to doubly magic lead-208, a region of higher stability.

The ratio of carbon-14 decay to alpha decay is about 5.5×10^{-10}. This low value explains why the spontaneous decay mode had not been observed earlier. Since the probability of cluster emission is expected to be greatest when the daughter nuclide configuration is close to that of a full shell, attempts have been made to observe the phenomenon with parent nuclides near $Z = 88$ ($Z = 82$ corresponds to a magic proton line). Hence the search has concentrated on the elements francium and actinium with potential daughter of thallium and bismuth, e.g.

$$^{221}\mathrm{Fr} \rightarrow {}^{207}\mathrm{Tl}\,, \text{ and } {}^{225}\mathrm{Ac} \rightarrow {}^{211}\mathrm{Bi}\,.$$

Oxygen cluster emission was discovered by Hussonois et al. [15] in the decay of thorium, i.e.

$$^{226}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + {}^{18}\mathrm{O}\,.$$

Similarly, ^{34}Si cluster should result from the decay of ^{241}Am and ^{240}Pu.

Magic Radioactivity

The discovery of trans-tin cluster emitters may confirm the idea of "magic radioactivity" proposed by Sandulescu in 1989 [16]. Magic numbers in the trans-tin region are at $N = 50$ and 82 and $Z = 50$. The doubly magic closed shell nuclides ^{132}Sn and ^{100}Sn lie far from the line of stability as can be seen in Fig. 4.17. In the proton rich region around Ba–Sm cluster emission would lead to nuclides close to the doubly magic ^{100}Sn. Expected cluster emission reactions could be

$$^{114}\mathrm{Ba} \rightarrow {}^{102}\mathrm{Sn} + {}^{12}\mathrm{C},\ {}^{128}\mathrm{Sm} \rightarrow {}^{100}\mathrm{Cd} + {}^{28}\mathrm{Si}\,.$$

Sandulescu has also proposed the idea of cold fission as a special case of cluster radioactivity where the fission fragments lie in the $Z = 50$ region. An example is the decay of fermium i.e.

$$^{264}\mathrm{Fm} \rightarrow {}^{132}\mathrm{Sn} + {}^{132}\mathrm{Sn}\,,$$

in which the neutron rich fermium splits into two identical doubly magic tin fragments with a probability comparable to that of alpha decay.

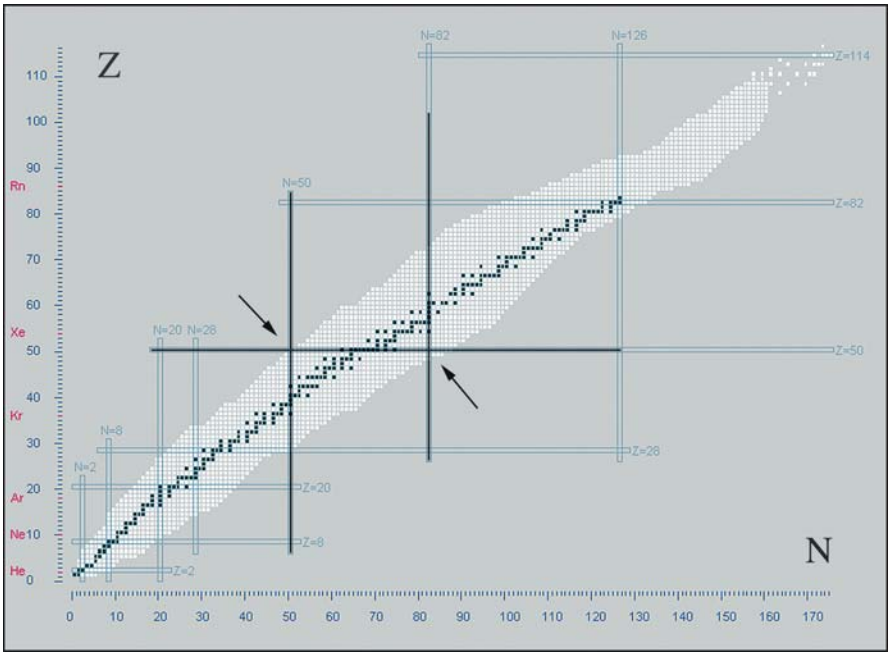


Fig. 4.17. Magic numbers in the trans-tin region are at $N = 50$ and 82 and $Z = 50$. The location of doubly magic tin nuclides ^{132}Sn and ^{100}Sn are indicated

Decay of Bare Nuclei – Bound Beta Decay

The effect of external physical conditions on the nuclear decay rate has been of interest for many decades (see "How Constant is the Decay Constant?" in Chapter 5). Many attempts have been made to alter the decay rate by varying the temperature, pressure, chemical environment etc. [17] but only small effects have been observed. This situation has now changed with the observation that the half-lives of highly charged ions can be increased from 10% to 670% [18].

When a stable atom is fully ionised, the resulting ion may be unstable. These nuclei give rise to a special kind of β^- emission in which an electron is liberated from the nucleus, through transformation of a neutron to a proton, and captured into one of the empty energy shells of the atom (Figs. 4.18, 4.19 [19]). This "bound beta decay" was predicted in 1947 by the French physicists Daudel et al. [20] but was observed for the first time only in 1992 [21] at the Institute of Heavy Ion Research (GSI) at Darmstadt.

A bound beta isotope, denoted β_b, is an isotope which is (nearly) stable as a neutral atom, but which decays by β_b decay when fully ionized. There are now four such isotopes known in nature: ^{163}Dy, ^{187}Re, ^{193}Ir, and ^{205}Tl. The isotope ^{187}Re is included because of its extremely long beta decay half-life (43 Gy).

Bound beta decay was first observed with highly ionised ions of the stable nuclide ^{163}Dy [21] and ^{187}Re [23] provided by the synchrotron and stored in the storage

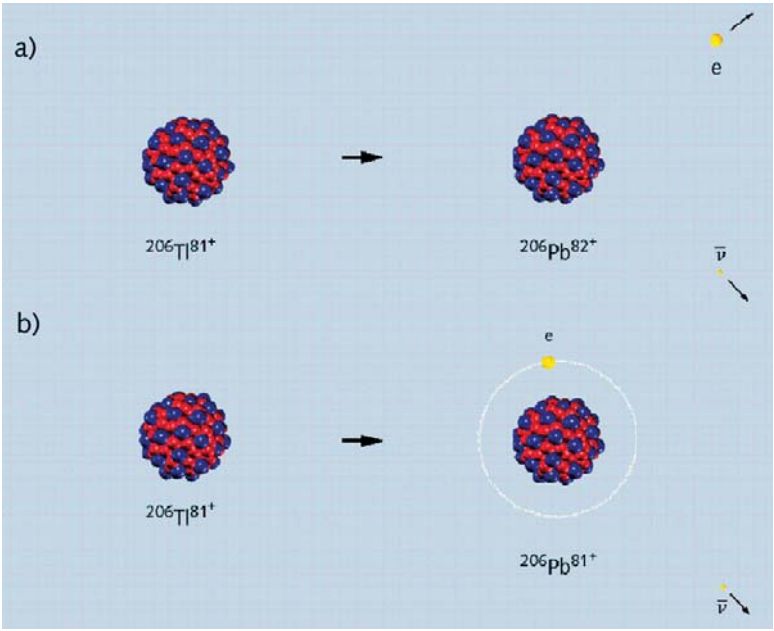


Fig. 4.18. While in usual β decay the electron goes into a continuum state (a), it is captured and bound in an inner atomic shell in bound beta decay β_b (b). (Courtesy GSI [19])

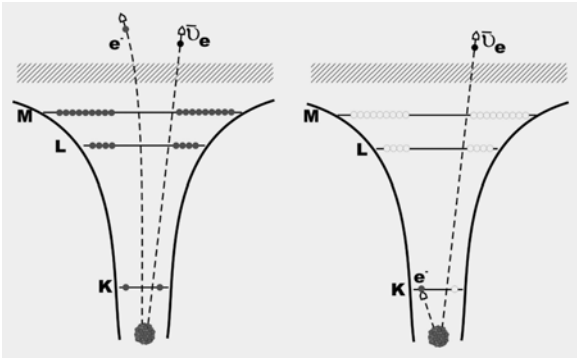


Fig. 4.19. Energy level diagrams for the bare (*left*) and bound beta decay (*right*) for highly charged ions (HCI). (Courtesy F. Bosch, GSI Darmstadt [22])

cooler ring at GSI [24, 25]. The ionised $[^{163}\mathrm{Dy}]^{66+}$ is observed to decay with a half-life of 47 d by β^- emission to ^{163}Ho. For the almost stable ^{187}Re, the fully ionised $[^{187}\mathrm{Re}]^{75+}$ ion shows a decrease in the half-life of 9 orders of magnitude. In addition to the $^{163}\mathrm{Dy}/^{163}\mathrm{Ho}$ transmutation under extreme conditions, other such reactions pairs are $^{205}\mathrm{Tl}/^{205}\mathrm{Pb}$ and $^{193}\mathrm{Ir}/^{193}\mathrm{Pt}$ and these may have an impact in stellar nucleosynthesis where terrestrial and stellar half-lives may be different.

Through the recent developments in high intensity lasers, it may become possible to investigate such reactions which until now could only be studied in a very limited way in terrestrial laboratories (see section on "Laser Transmutation" in Chapter 5).

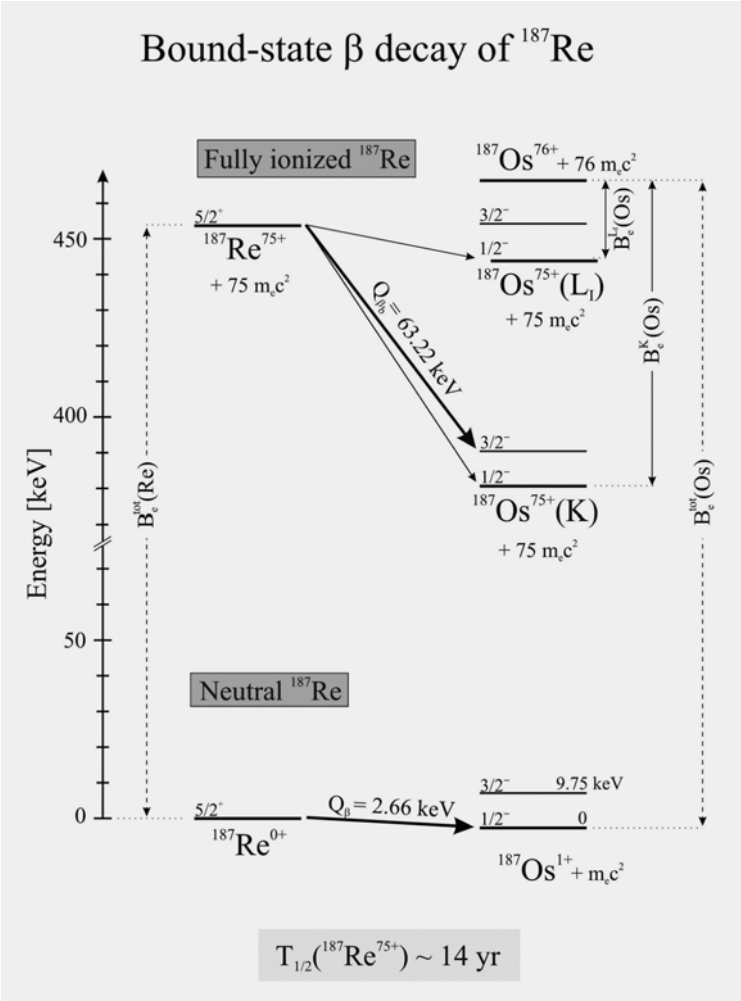


Fig. 4.20. Energy level diagram for the decay of bare and neutral ^{187}Re. The half-life of bare ^{187}Re has been determined to be only 33 years, i.e. by more than 9 orders of magnitude shorter than in the neutral charge state. (Courtesy F. Bosch, GSI Darmstadt)

Table 4.7. Measured half-lives for bare isomers. The hindrance factors $T_{½}$ (bare)/$T_{½}$ (neutral) are shown in the last column

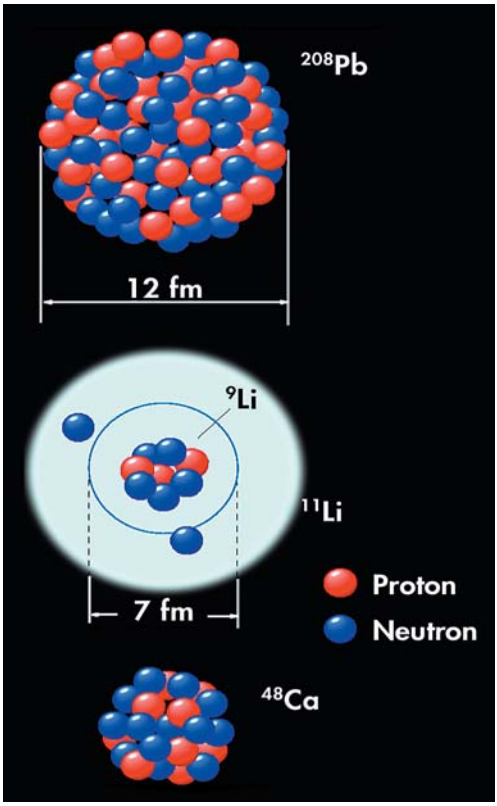
Isomer	$T_{½}$ bare, s	$T_{½}$ neutral, s	Hindrance factor
^{151m}Er	19(3)	0.58(2)	33(5)
^{149m}Dy	11(1)	0.49(2)	22(2)
^{144m}Tb	12(2)	4.25(15)	2.8(5)

Very recently quite the opposite effect has been demonstrated [18] in that instead of the nuclear decay process being accelerated in bare atoms, it has been hindered in bare isomers. The main decay channel of the isomeric states of neutral atoms is internal conversion. The results, showing an increase of the half-life by up to a factor 30, are shown in Table 4.7 for the bare isomers $[^{151m}\mathrm{Er}]^{68+}$, $[^{149m}\mathrm{Dy}]^{75+}$, and $[^{144m}\mathrm{Tb}]^{65+}$.

Halo Nuclides

For most nuclides, the density of nucleons in the nucleus is more or less uniform. However near the neutron dripline, some neutrons are only weakly bound to the inner core nucleons. In this recently discovered phenomena, the nuclei consist of a normal nucleus surrounded by a halo of extra neutrons with a diameter very much larger than the core nucleus. The halo neutrons are mostly outside the region of the strong nuclear force between the nucleons. Typically half-lives of these nuclei are around 100 ms.

One such example of a halo nuclide is ^{11}Li. It consists of a ^{9}Li core surrounded by a halo of two loosely bound neutrons requiring only 0.3 MeV to remove them. The ^{11}Li nucleus is similar in size to that of ^{48}Ca which has a neutron binding energy



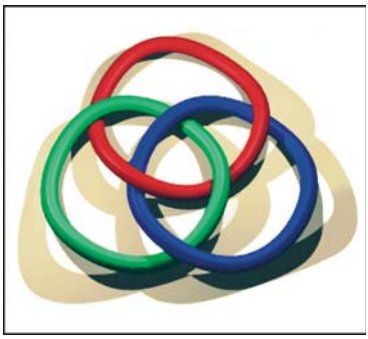


Fig. 4.22 (*above*)
The Borromean rings provide an analogy for the structure of halo nuclei in which the removal of any one of the three major components breaks the whole system. Courtesy Wilton Catford, from the SIRIUS Science Booklet [26]

Fig. 4.21 (*left*)
The neutron halo in ^{11}Li extends to fill the volume equivalent to ^{208}Pb, with very dilute, pure neutron matter. Courtesy Wilton Catford, from the SIRIUS Science Booklet [26]

of about 8 MeV. Other examples of halo nuclei are ^{6}He (^{4}He + 2n), ^{8}He (^{4}He + 4n), ^{11}Be (^{10}Be+1n), ^{14}Be, ^{17}B and ^{19}Ca.

Proton halo nuclides may also exist for nuclei near the proton dripline. Possible nuclides are ^{8}B, ^{13}N, and ^{17}F.

Borromean Nuclei

In Borromean nuclei, three separate parts of the nucleus are bound together in such a way that if any one is removed, the remaining two become unbound. The expression originates from the Borromean Rings which consist of interlocking rings.

^{12}C, in its excited state, is one example of a Borromean nucleus. It consists of three sub-units of ^{4}He. If one is removed, the result is ^{8}Be which is not bound. Other examples are ^{6}He, ^{11}Li, ^{14}Be, and ^{22}C.

5. Transmutation Research

Transmutation – the idea of changing one element into another – is almost as old as time itself. In the middle-Ages, the alchemists tried to turn base metals into gold. Transmutation, however, only became a reality in the last century with the advent of nuclear reactors and particle accelerators.

One of the main interests today in transmutation is in the field of nuclear waste disposal. Nuclear waste is a radioactive by-product formed during normal reactor operation through the interaction of neutrons with the fuel and container materials. Some of these radioactive by-products are very long-lived (long half-lives) and if untreated, must be isolated from the biosphere for very long times in underground repositories. Various concepts are being investigated worldwide on how to separate out (partition) these long-lived by-products from the waste and convert (transmute) them into shorter-lived products thereby reducing the times during which the waste must be isolated from the biosphere.

In the following sections, a brief history of attempts made to modify the decay constant, and thereby enhance the transmutation rate, is outlined. A particularly interesting application of transmutation is in the synthesis of super-heavy elements in which lighter elements are fused with heavier ones and transmutated to new elements. Finally, a new technique – laser transmutation – is described in which very high intensity laser radiation is used to produce high energy photons, and particles which can be used for transmutation studies.

How Constant is the Decay Constant?

Following the discovery of radioactivity, many attempts to modify α decay rates were made by changing temperature, pressure, magnetic fields, and gravitational fields (experiments in mines and on the top of mountains, using centrifuges). In one attempt, Rutherford [1] actually used a bomb to produce temperatures of 2500 °C and pressures of 1000 bar albeit for a short period of time. No effect on the decay constant was detected.

Only through Gamow theory of alpha decay could one understand why the above experiments to modify the decay constant were negative. Gamow showed that quantum-mechanical tunnelling through the Coulomb barrier was responsible for alpha emission. Even if the entire electron cloud surrounding a nucleus were removed, this would change the potential barrier by only a very small factor. Changes of the order of $\delta k/k \approx 10^{-7}$ are to be expected.

In 1947, Segrè [2] suggested that the decay constant of atoms undergoing electron capture (ec) could be modified by using different chemical compounds of the substance. Different compounds will have different electron configurations and this should lead to small differences in the ec decay rate. This idea was confirmed experimentally using ^{7}Be. This nuclide has a half-life of 53.3 d and decay by ec is accompanied by the emission of a 477.6 keV gamma photon. A comparison of BeF_2 and Be revealed a difference in the decay rate $\delta k/k = 7 \times 10^{-4}$. These chemically induced changes in the decay constant are small but measurable.

It is also to be expected that the decay constant can be modified by pressure. As the pressure increases, the electron density near the nucleus should increase and manifest itself in an increase in the decay rate (for ec). Experiments [3, 4] on ^{99m}Tc, ^{7}Be, ^{131}Ba, and ^{90m}Nb have shown that this is indeed the case. The fractional change in the decay constant is $\delta k/k \approx 10^{-8}$ per bar. At pressures of 100 kbar, which can be relatively easily produced in laboratory conditions, $\delta k/k = 10^{-3}$ and the change in the decay constant is still small. Extrapolation to very high pressures would give $\delta k/k \approx 10$ at 1 Gbar and $\delta k/k \approx 10^{3}$ at 100 Gbar. With regard to β^- decay, it is also expected that screening effects can also modify the decay constant [5, 6].

Recently fissioning of ^{238}U has been demonstrated using very high power laser radiation (see section on "Laser Transmutation"). The fact that through laser induced fission one can significantly alter the rate of fission is however not achieved through modifying the environment. It arises indirectly through bremsstrahlung and electron induced reactions with the nucleus. In the focal region, the beam diameter is 1 μm and the penetration depth is 20 nm. In this region there are approximately 10^{9} atoms of ^{238}U. On average, every 10 y one of these atoms will decay by alpha emission. Spontaneous fission will occur on a timescale approximately six orders of magnitude longer, i.e. 10^{7} y. Under irradiation by the laser, typically 8000 fissions are produced per pulse.

Natural Transmutation by Radioactive Decay

Recently, ten years old $^{244}Cm_2O_3$ particles of approximately 1 mm size have been analysed [7]. As the half-life of ^{244}Cm is 18.1 years, approximately 55 to 60% of the initial curium had decayed into ^{240}Pu producing an equal atomic fraction of helium (produced from the alpha particles). Now, even for a small inert atom such as helium, concentrations of this order of magnitude are hardly conceivable in the form of gas-in-solid; therefore, some form of bubble precipitation was expected to occur. Yet, the experiment showed that much more dramatic changes took place in the sample during ageing.

The microscopic observations of the sample, as well as the thermal annealing experiments on helium release reveal drastic restructuring phenomena. The initial granular structure has totally disappeared, and, though still geometrically compact, the sample consists of an intricate, spongeous agglomeration of small globular particles of sizes of the order of a few microns.

Surprisingly, a number of morphologically diverse phases are formed during production of α-damage. Some of them preserve traces of the original grains, others,

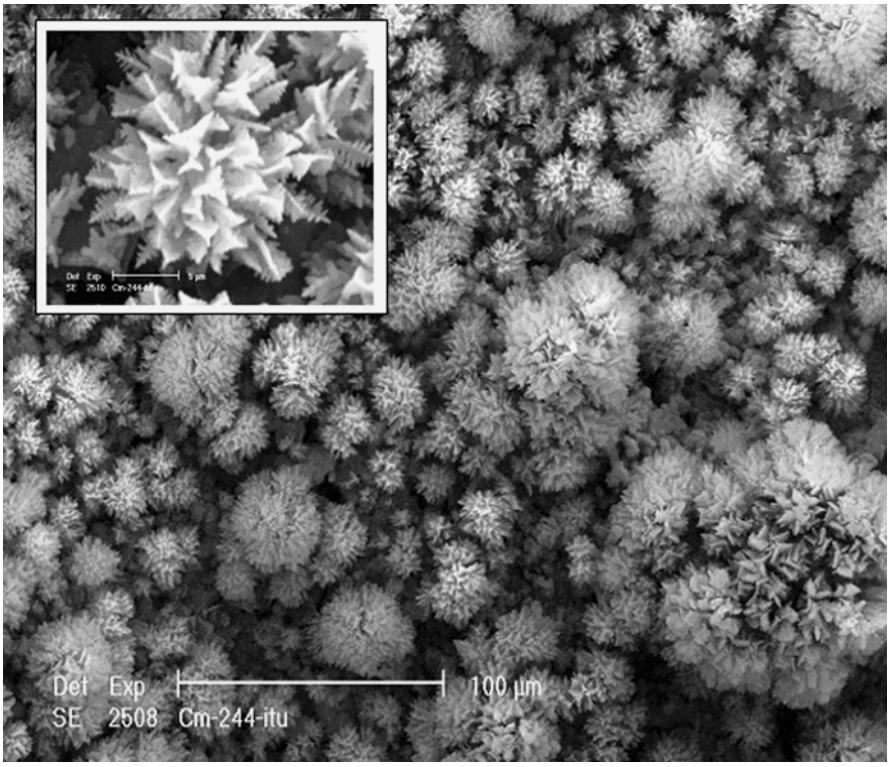


Fig. 5.1. Surface features of the curium oxide sample. Colonies of dendritic crystals are formed, likely due to re-deposition of recoil atoms. The inset shows a magnification of the dendrites [7]

formed on the sample outer surface, assumed coral-like configurations consisting of groups of regularly arranged platelets which often display a pronounced pine-tree dendrite shape (Fig. 5.1).

The "cauliflower" structure of Fig. 5.1, and the dendrites, can only originate from re-deposition of vaporised atoms produced by energetic recoils and sputtering events. This structure of the curium oxide sample is an example of natural transmutation on a macroscopic scale by radioactive decay.

Synthesis of Superheavy Elements by Transmutation

The idea of the existence of a group of stable elements outwith the main nuclear "island" dates back to the 1930s and received considerable attention in the 1960s. The location of a smaller island of stability at $Z = 114$, $N = 184$ was suggested in 1966 and, at this time, prompted an intensive search for superheavy elements in nature. The isotope $Z = 114$, $N = 184$ has a doubly magic configuration with both the protons and neutrons being in complete shells. In addition, the idea of creating superheavy elements experimentally through heavy ion collisions led to a number

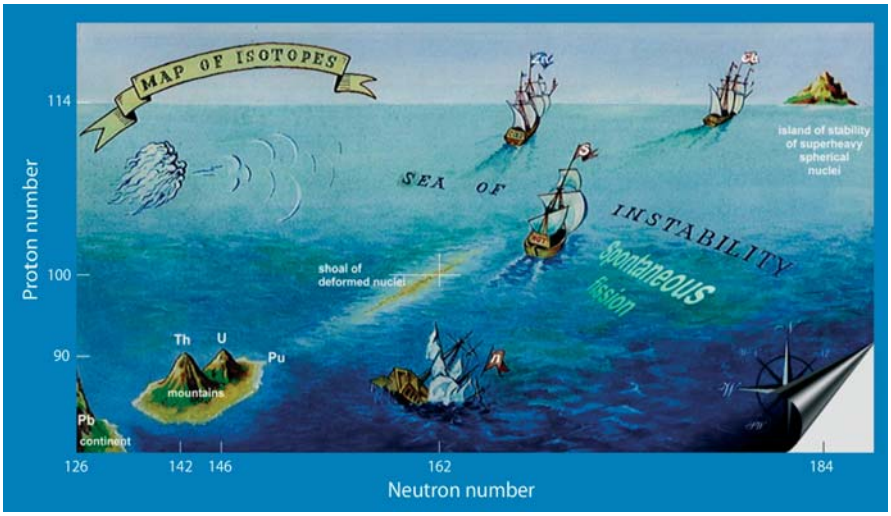


Fig. 5.2. The nuclide chart as depicted by Prof. Flerov in 1974. The ships, which are afloat, represent the different laboratory strategies and facilities dedicated to this endeavour (picture by Prof. G. N. Flerov, Dubna, USSR) [15]

of laboratories being set up to investigate this [8–10]. The wave of enthusiasm, at the time depicted in Professor Flerov's Nuclide Chart shown in Fig. 5.2, continues to this day.

In the years 1981–84, the GSI group at Darmstadt, Germany, reported the synthesis of elements 107 (Bohrium), 108 (Hassium), and 109 (Meitnerium). In 1994 elements 110 (recently named Darmstadtium, Ds) and 111 (suggested name Roentgenium, Rg) were reported by the same group [11–13]. In 1998, a Russian team in Dubna claimed to have synthesized for the first time element 114 [14]. This was achieved by bombarding (fusing) nuclei of plutonium-242 with calcium-48. The scientists had to bombard the plutonium with calcium nuclei for a period of six weeks to produce a single nucleus of element 114. The reaction gives rise to a compound nucleus, $^{289}114$ shown below, which decays by alpha emission. The compound nucleus of element 114 had the remarkably "long" half-life of 30 s before undergoing a series of alpha decays to element 108 over a time period of approximately 30 minutes.

$$\text{Fusion}: \quad {}^{48}_{20}\text{Ca} + {}^{242}_{94}\text{Pu} = {}^{289}114 + \text{n}$$

$$\text{Decay}: \quad {}^{289}114 \rightarrow {}^{285}112 \rightarrow {}^{281}110 \rightarrow {}^{277}108 \rightarrow \ldots$$

In 1999, researchers from the University of California at Berkeley and Oregon State University claimed to have detected three atoms of element 118 in collisions between high-energy krypton ions and a lead target. The results, however, were later retracted.

Laser Transmutation

Recent advances in laser technology now make it possible to induce nuclear reactions with light beams [16–18]. When focussed to an area of a few tens of square microns,

Fig. 5.3. *Left:* Giant pulse VULCAN laser. Courtesy CCLRC Rutherford Appleton Laboratory. *Right:* High intenisty Jena tabletop laser. Courtesy Institut für Optik und Quantenelektronik, Friedrich-Schiller-Universität, Jena

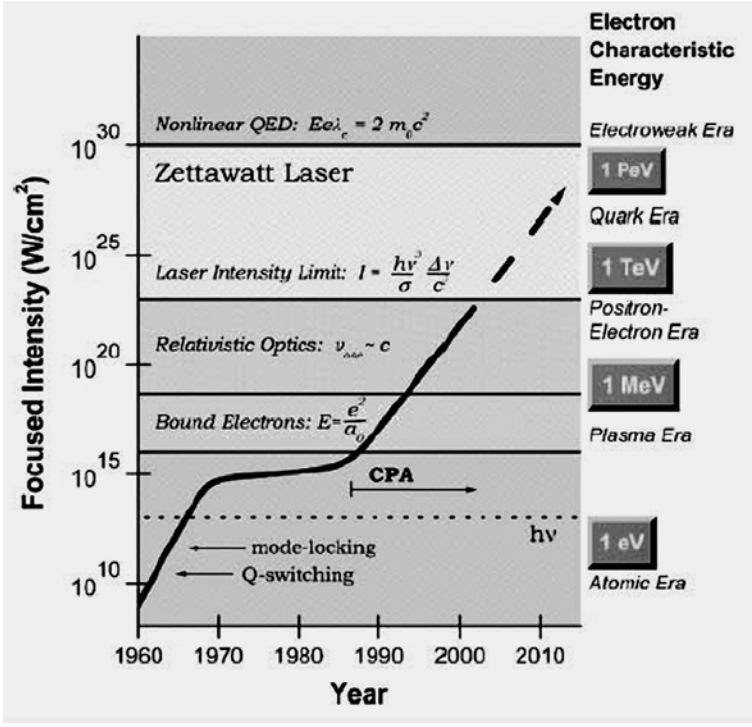


Fig. 5.4. Dramatic increase in focussed laser intensity over the past few decades for tabletop systems [19]. With the development of chirped pulse amplification (CPA) techniques in the mid-eighties, a new era of laser matter interactions has become possible

the laser radiation can reach intensities greater than 10^{20} W cm^{-2}. By focusing such a laser onto a target, the beam generates a plasma with temperatures of ten billion degrees (10^{10} K) – comparable to conditions that occurred one second after the 'big bang'.

With the help of modern compact high intensity lasers, it is now possible to produce highly relativistic plasma in which nuclear reactions such as fusion, photonuclear reactions and fission of nuclei have been demonstrated to occur. Two decades ago, such reactions induced by a laser beam were believed to be impossible. This new development opens the path to a variety of highly interesting applications, the realisations of which require continued investigation of fundamental processes by both theory and experiment and in parallel the study of selected applications.

The possibility of accelerating electrons in focussed laser fields was first discussed by Feldman and Chiao [20] in 1971. The mechanism of the interaction of charged particles in intense electromagnetic fields, e.g. in the solar corona, had, however, been considered much earlier in astrophysics as the origin of cosmic rays. In this early work, it was shown that in a single pass across the diffraction limited focus of a laser power of 10^{12} W, the electron could gain 30 MeV, and become relativistic within an optical cycle. With a very high transverse velocity, the magnetic field of the wave bends the particle trajectory through $\boldsymbol{v} \times \boldsymbol{B}$ Lorentz force into the direction of the travelling wave. In very large fields, the particle velocity approaches the speed of light and the electron will tend to travel with the wave, gaining energy as it does so.

Dramatic improvements in laser technology since 1984 have revolutionised high power laser technology [21]. Application of chirped-pulse amplification techniques [22, 23] has resulted laser intensities in excess of $10^{19}\,\mathrm{W\,cm^{-2}}$. In 1985, C. K. Rhodes [23] discussed the possibility of laser intensities of $\approx 10^{21}\,\mathrm{W\,cm^{-2}}$ using a pulse length of 0.1 ps and 1 J of energy. At this intensity, the electric field is $10^{14}\,\mathrm{V\,cm^{-1}}$ a value which is over 100 times the coulomb field binding atomic

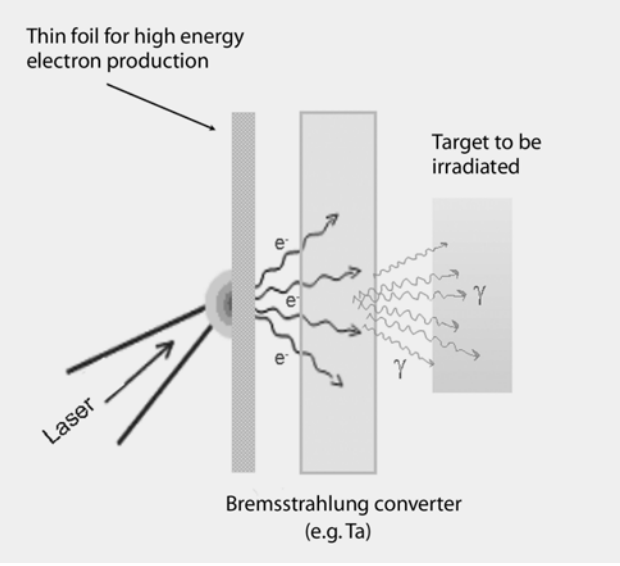


Fig. 5.5. Schematic setup of the laser experiments for high energy electron and photon generation

electrons. In this field, a uranium atom will lose 82 electrons in the short duration of the pulse. The resulting energy density of the pulse is comparable to a 10 keV blackbody (equivalent light pressure ≈ 300 Gbar) and comparable to thermonuclear conditions (thermonuclear ignition in DT occurs at about 4 keV). In 1988, K. Boyer et al. [24] investigated the possibility that such laser beams could be focussed onto solid surfaces and cause nuclear transitions. In particular, irradiation of a uranium target could induce electro- and photo-fission in the focal region.

These developments open the possibility of "switching" nuclear reactions on and off by high intensity ultraviolet laser radiation and providing a bright point source of fission products and neutrons.

Laser-Induced Radioactivity

When a laser pulse of intensity $10^{19}\,\mathrm{W\,cm^{-2}}$ interacts with solid targets, electrons of energies of some tens of MeV are produced. In a tantalum target, the electrons generate an intense highly directional γ-ray beam that can be used to carry out photo-nuclear reactions. The isotopes ^{11}C, ^{38}K, ^{62,64}Cu, ^{63}Zn, ^{106}Ag, ^{140}Pr, and ^{180}Ta have been produced by (γ, n) reactions using the VULCAN laser beam.

Laser-Induced Photo-Fission of Actinides – Uranium and Thorium

The first demonstrations were made with the giant pulse VULCAN laser in the U. K. using uranium metal and with the high repetition rate laser at the University of Jena with thorium samples. Both experiments were carried out in collaboration with the Institute for Transuranium Elements in Karlsruhe. Actinide photo-fission

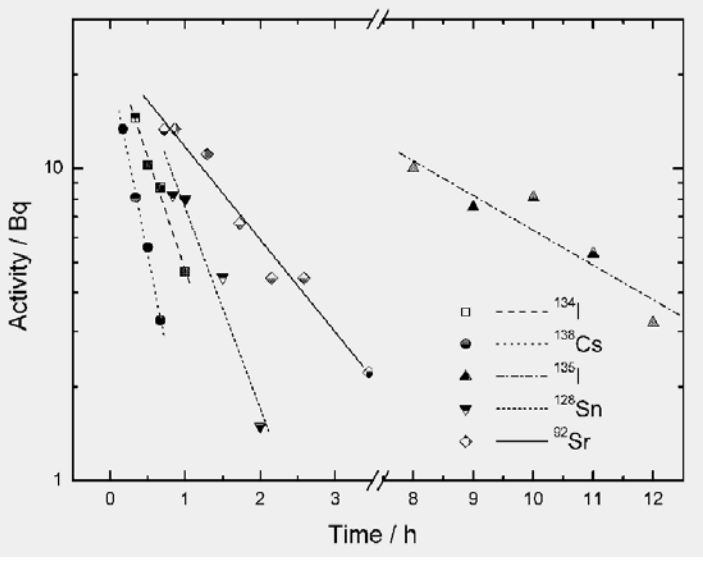


Fig. 5.6. Decay characteristics of fission products from bremsstrahlung-induced fission of ^{232}Th.The deduced half-lives are in good agreement with literature values. Symbols indicate experimental data

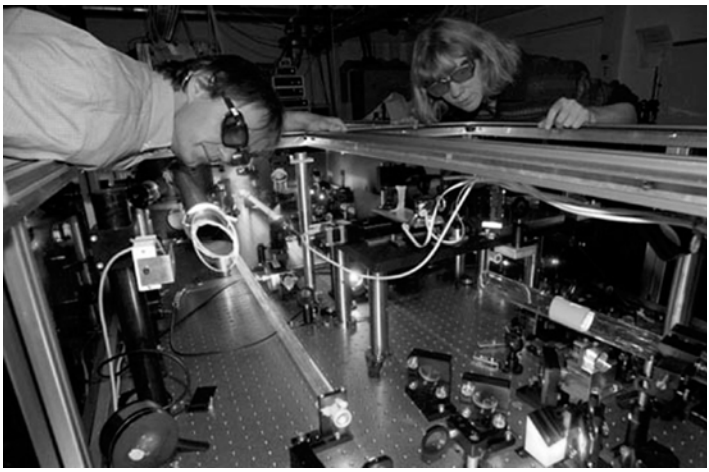


Fig. 5.7. Jena high repetition rate tabletop laser

was achieved in both U and Th using the high-energy bremsstrahlung radiation produced by laser acceleration of electrons. The fission products were identified by time-resolved γ-spectroscopy.

Laser-Driven Photo-Transmutation of Iodine-129

The first successful laser induced transmutation of ^{129}I, one of the key radionuclides in the nuclear fuel cycle was reported recently [25–27]. ^{129}I with a half-life of 15.7

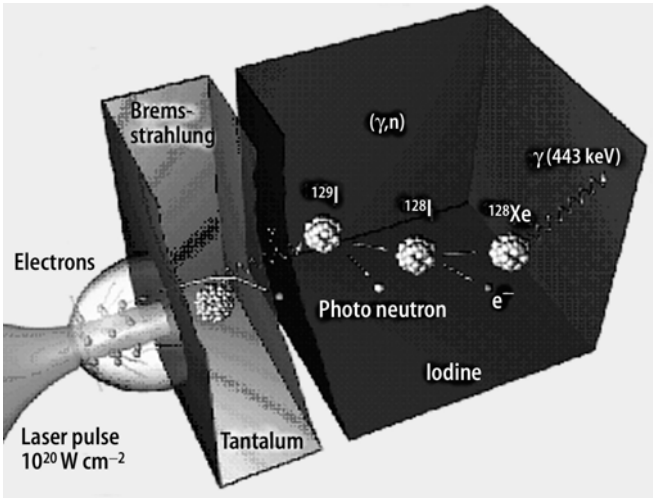


Fig. 5.8. The high intensity laser pulse produces a hot plasma on the surface of a tantalum foil. Relativistic electrons are stopped in the foil, efficiently generating high-energy Bremsstrahlung. The ^{129}I in the radioactive target is transformed into ^{128}I due to a (γ,n)-reaction

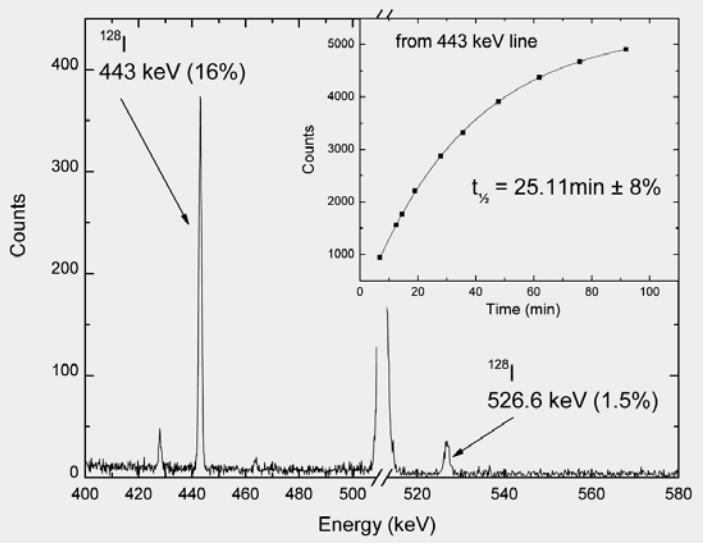


Fig. 5.9. Gamma emission spectra from one of the iodine samples measured before and after laser irradiation of the gold target. Characteristic emission lines of ^{128}I at 443.3 keV and 527.1 keV are clearly observed, alongside peaks from the decay of ^{125}Sb impurity and a peak at 511 keV from positron annihilation

million years is transmuted into ^{128}I, with a half-life of 25 min through a (γ,n)-reaction using laser generated Bremsstrahlung.

Laser-Induced Heavy Ion Fusion

In a recent series of experiments with the VULCAN laser, at intensities of 10^{19} W cm^{-2}, beams of energetic ions were produced by firing the laser onto a thin foil primary target (Fig. 5.10).

The resulting ion beam then interacts with a secondary target. If the ions have enough kinetic energy, it is possible to produce fusion of the ions in the beam with

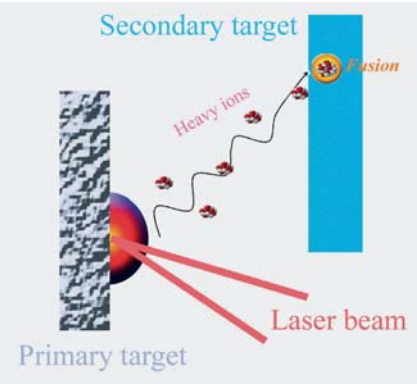


Fig. 5.10. Setup of the heavy ion fusion experiment. The laser is focussed onto a primary target (Al, C or other), where it generates a hot plasma on the surface. Heavy ions accelerated in the plasma are blown-off into the secondary target (Al, Ti, Zn, or other) inducing a fusion reaction

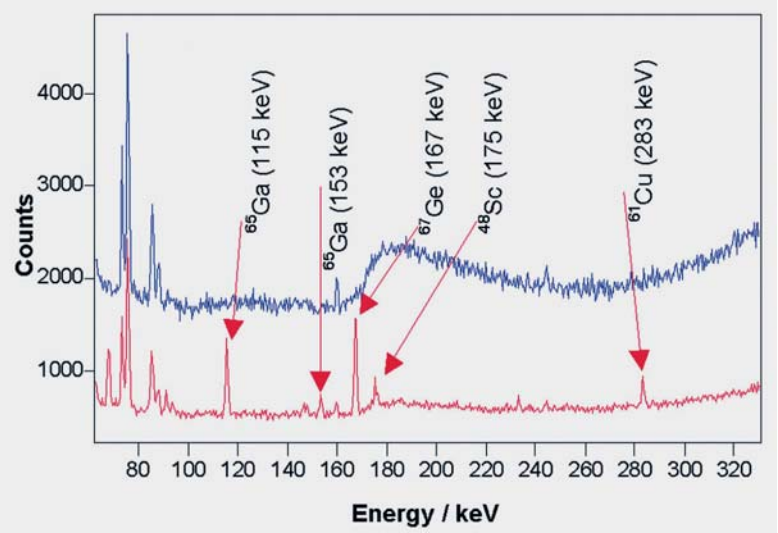


Fig. 5.11. The main reaction products identified by their characteristic gamma emission for a Ti plate exposed to Al blow-off. Blue spectrum: "cold" target, red spectrum, heated target (391 °C). Fusion products are much more evident in the heated target

atoms in the secondary target. Heavy ion beams were generated from primary targets of aluminium and carbon. Secondary target material consisted of aluminium, titanium, iron and zinc niobium and silver. The heavy ion "blow-off" fused with the atoms in the secondary target creating compound nuclei in highly excited states. The compound nuclei then de-excited to create fusion products in the secondary target foils. These foils were then examined in a high efficiency germanium detector to

Table 5.1. Heavy ions fusion measurement. The primary and secondary target materials are given, with some of the measured and identified fusion products

Primary target material	Secondary target	Nuclides identified in preliminary analysis
Al	Al	^{49}Cr, ^{27}Mg, ^{28}Al, ^{43}Sc, ^{34m}Cl
Al (heated)	Ti	^{48}V, ^{44}Sc, ^{48}Sc, ^{65}Ga, ^{67}Ge, ^{61}Cu, ^{70}As
C	Fe	^{65,66}Ga, ^{67}Ge, ^{60}Cu, ^{63}Zn
C	Ag	^{117}Te, ^{115}Te, ^{119}I

measure the characteristic gamma radiation produced by the radioactive decay of short-lived fusion product nuclides. Typical spectra are shown in Fig. 5.11.

Figure 5.11 shows the results of experiments involving cold and heated targets. The target here was aluminium, and the secondary titanium. The spectrum in blue is that taken for the aluminium target at room temperature, and the red spectrum is that of an aluminium target heated to 391 °C. For the heated target, many more fusion products are evident which are not observed in the cold target. This is attributed to the heating of the target to remove hydrocarbon impurities. When these layers are removed, heavier ions are accelerated more readily and to higher energies.

Laser-Driven (p,xn)-Reactions on Lead

Recently, (p,xn) reactions on lead with the use of very high intensity laser radiation has been demonstrated. Laser radiation is focused onto a thin foil to an intensity of $10^{20}\,\mathrm{W\,cm^{-2}}$ to produce a beam of high-energy protons. These protons interact with a lead target to produce (p,xn) reactions. The (p,xn) process is clearly visible through the production of a variety of bismuth isotopes with natural lead. Such experiments may provide useful basic nuclear data for transmutation in the energy range 20–250 MeV without recourse to large accelerator facilities.

Spallation nuclear reactions refer to non-elastic interactions induced by a high-energy particle in which mainly neutrons are "spalled," or knocked out of the nucleus directly, followed by the evaporation of low energy particles as the excited nucleus heats up. At low energies ($\leq$ 50 MeV), the de Broglie wavelength of the proton is larger than the size of individual nucleons. The proton then interacts with the entire nucleus and a compound nucleus is formed. At high proton energies ($\geq$ 50 MeV), the de Broglie wavelength is of the order of the nucleon dimensions. The proton can interact with single or a few nucleons and results in direct reactions. These latter reactions are referred to as spallation nuclear reactions and refer to non-elastic interactions induced by a high-energy particle in which mainly light charged particles and neutrons are "spalled," or knocked out of the nucleus directly, followed by the evaporation of low energy particles as the excited nucleus heats up. Current measurements on the feasibility of proton induced spallation of lead and similar materials focus around the need to measure nuclear reaction cross-sections relevant to accelerator driven systems desirable for use in the transmutation of long-lived radioactive products in nuclear waste. The neutron production from the spallation reaction is important for defining the proton beam energy and target requirements. However the measurements being undertaken require high power accelerators to generate the proton beam. In the present work, the proton beam is generated by a high-intensity laser rather than by an accelerator.

The recently developed petawatt arm of the VULCAN Nd:glass laser at the Rutherford Appleton Laboratory, UK, was used in this experiment. The 60 cm beam was focused to a 7.0 μm diameter spot using a 1.8 m focal length off-axis parabolic mirror, in a vacuum chamber evacuated to $\sim 10^{-4}$ mbar (Fig. 5.12). P-polarised laser pulses with energy up to 400 J, wavelength $\sim$1 μm and average duration 0.7 ps, were focused onto foil targets at an angle of 45° and to an intensity of the order of

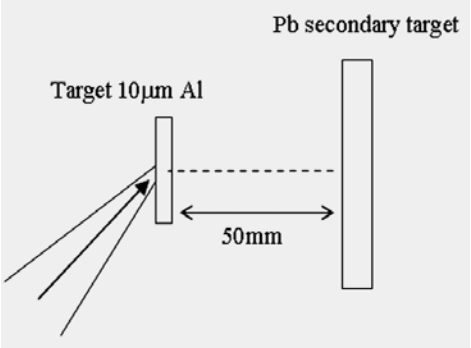


Fig. 5.12. Experimental setup for the laser production of protons and ions. The protons or Al ions generated from the laser irradiation of the target foil are used for nuclear activation in the secondary target

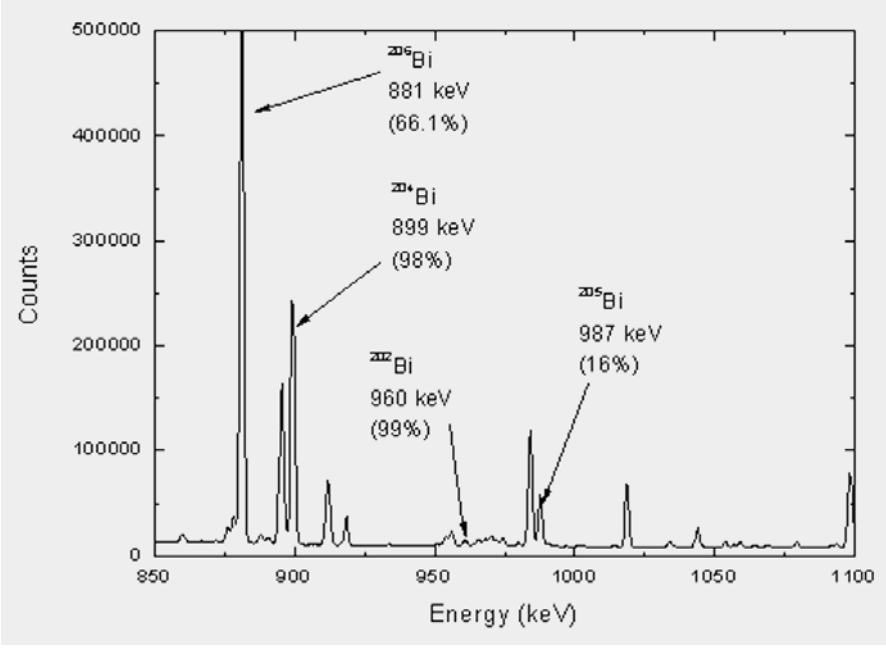


Fig. 5.13. Preliminary identification of bismuth isotopes produced through (p,xn) reactions in lead

$4 \times 10^{20}\,\mathrm{W\,cm^{-2}}$. A typical spectrum resulting from the proton activation of lead to produce bismuth isotopes is shown in Fig. 5.13 (the relevant section of the nuclide chart is shown in Fig. 5.14).

The protons originate from H_2O and hydrocarbon contamination layers on the surface of solid targets. Secondary catcher activation samples were positioned at the front of the target (the 'blow-off' direction). Energetic protons accelerated from the primary target foil can induce nuclear reactions in these activation samples.

From the proton induced reactions on lead, the isotopes $^{202-206}$Bi were identified using the main emission lines.

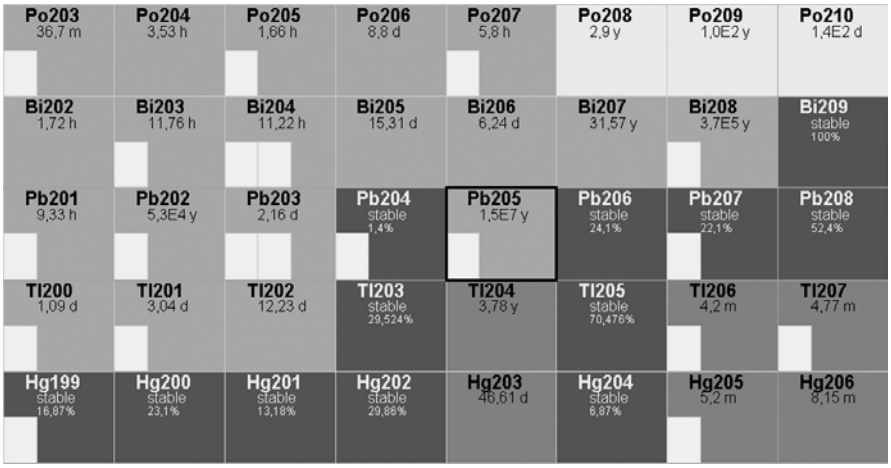


Fig. 5.14. Nuclide chart [31] showing the location of lead and bismuth isotopes

Laser Activation of Micro-Spheres

Nano-encapsulation of chemical agents is well known in the pharmaceutical field. Nano-radiotherapy is a technique in which nano-particles can be made radioactive and then used in cancer therapy [28–29]. Nano-spheres are relatively easy to manufacture and the isotope to be activated is chosen depending on the type and size of the tumour. The particles are activated by neutron irradiation in a nuclear reactor. Typically, durable ceramic micro-spheres containing a large amount of yttrium and/or phosphorus are useful for *in situ* radiotherapy of cancer, since the stable ^{89}Y

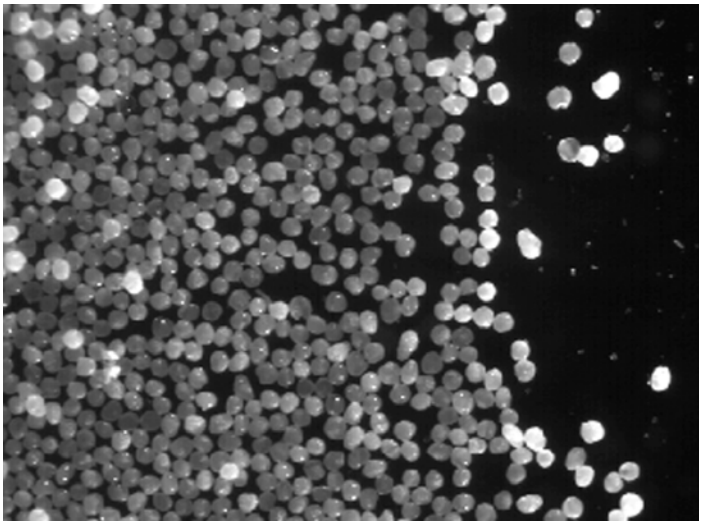


Fig. 5.15. Zirconium oxide micro-particles. The particle diameters are in the range 95–110 μm

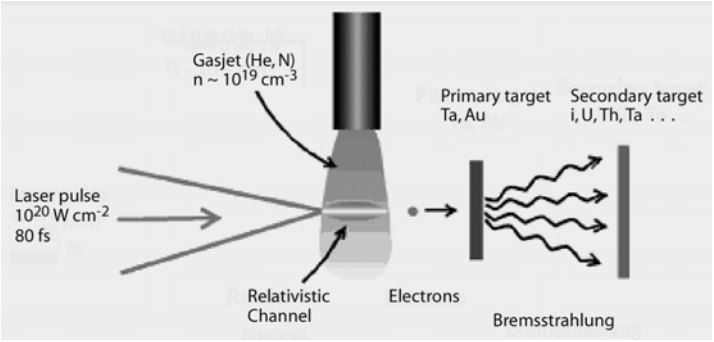


Fig. 5.16. Setup for the laser micro-particle irradiation experiments

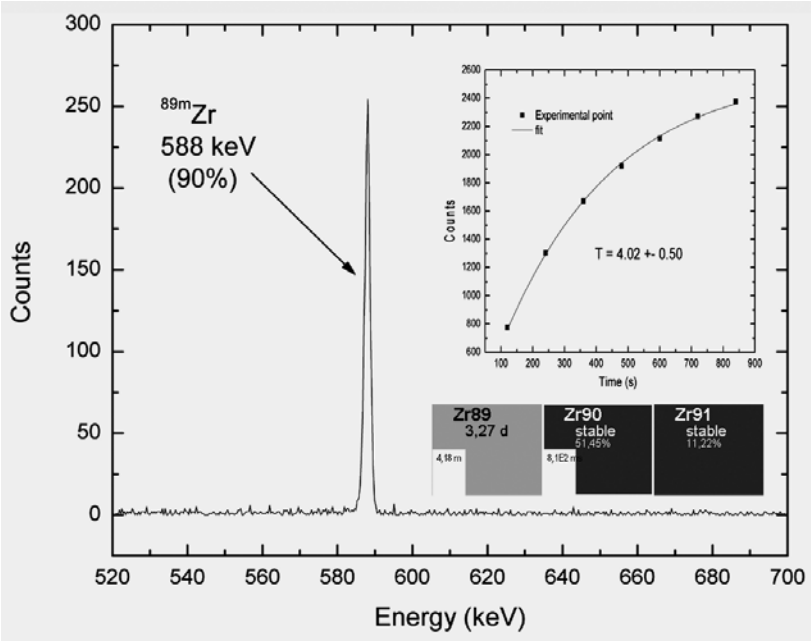


Fig. 5.17. Spectra taken 10 min. after the Zr irradiation showing the main line of ^{89m}Zr from the ^{90}Zr(γ,n)^{89m}Zr reaction. The inset shows the position of the isotopes in the nuclide chart (from Nuclides.net [31])

and/or ^{31}P in the micro-spheres can be activated to β-emitters ^{90}Y with a half-life: 2.7 d and/or ^{32}P with a half-life of 14.3 d.

Recently, micro-particles have been activated in a ultra high intensity laser field for the first time [30]. Micro-particles of ZrO_2 and HfO_2, with diameters of approximately 80 μm, were irradiated using the high repetition rate laser at the University of Jena (see Fig. 5.15).

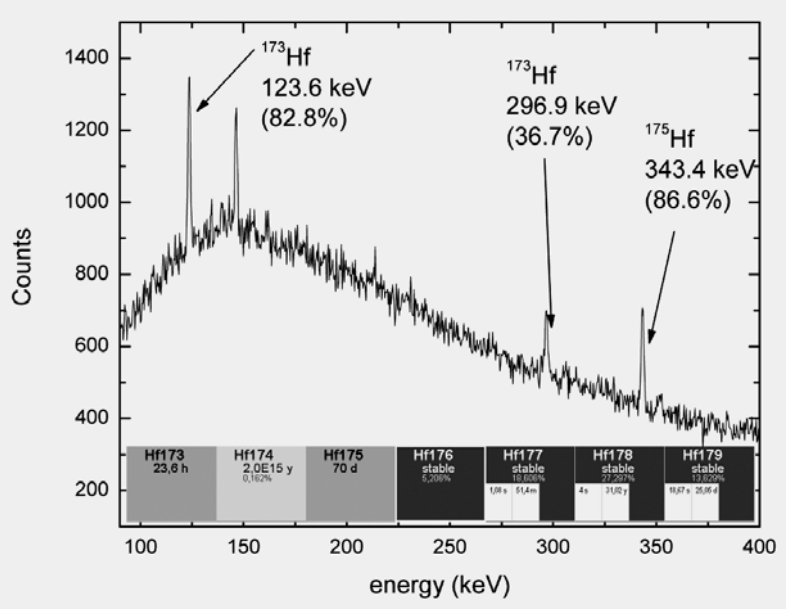


Fig. 5.18. Spectrum showing the lines of the ^{173}Hf and ^{175}Hf from the laser irradiation of the HfO_2. The inset shows the position of the hafnium isotopes in the nuclide chart (from Nuclides.net [31])

Focussing the laser beam in the gas jet (Fig. 5.16) results in a high temperature plasma. Relativistic self-focussing of the electrons gives rise to a directed, pulsed, high-energetic electron beam which interacts with the primary target to produce high-energy bremsstrahlung. This bremsstrahlung is then used for the particle activation. The results are shown for both the zirconium and hafnium micro-particles in Figs. 5.17 and 5.18.

The future development of the field of laser transmutation will benefit from the currently fast evolution of high intensity laser technology. Within a few years, compact and efficient laser systems will emerge, capable of producing intensities exceeding $10^{22}\,\mathrm{W\,cm^{-2}}$ with repetition rates of 1 shot per minute and higher. These laser pulses will generate electron and photon temperatures in the range of the giant dipole resonances and open the possibility of obtaining nuclear data in this region. These laser experiments may offer a new approach to studying material behaviour under neutral and charged particle irradiation without resource to nuclear reactors or particle accelerators.

6. Archaeology and Dating

Radioactive Dating

Radioactive dating methods are based on the temporal decrease of the number of radioactive atoms and/or on the related ingrowth of radioactive or stable daughter nuclides. These changes are described by the radioactive decay laws and in particular by the decay constant or half-life. Because the half-life of a given radioisotope is not affected by temperature, physical or chemical state, or any other influence of the environment outside the nucleus (apart, of course, from nuclear reactions), then radioactive samples continue to decay at a predictable rate. This makes several types of radioactive dating feasible [1, 2].

Fig. 6.1. The Dead Sea scrolls were dated to 1900 y BP (before present) using ^{14}C dating [3].

Comparison of Present and Initial Radioactivity

The simplest form of isotopic age computation is where there are no daughter atoms present initially and where no mass has been lost from the sample. The equation for the time-dependence of the parent is given by:

$$P(t) = P(0)\mathrm{e}^{-kt} ,$$

where $P(t)$ is the quantity of parent isotope present at time t, $P(0)$ the initial amount and k the decay constant $k = \ln 2/\tau$. It follows that the age can be obtained from

$$\text{Age} = t = \frac{1}{k} \cdot \ln\left[\frac{P(0)}{P(t)}\right] .$$

^{14}C *Dating*

Carbon-14 is produced at almost a constant rate in the atmosphere by interactions of cosmic rays with nitrogen i.e. ^{14}N(n,p)^{14}C. Following production the carbon atoms are oxidised to form $^{14}CO_2$ which then follows the CO_2 cycle. Following the death of an organism, the CO_2 exchange is terminated and the ^{14}C starts to decay. Since the initial activity is known (activity of ^{14}C in the atmosphere), and the present value of ^{14}C in the organism can be measured, the age can be determined.

Example: Take the present ^{14}C activity to be 900 Bq per gram. In the sample the activity is 6 Bq per gram. The age of the sample is then

$$\text{Age} = \left(\frac{5730\,\text{y}}{0.693}\right) \cdot \ln\left[\frac{900}{6}\right] = 41400\,\text{y}\,.$$

Archaeological dating by radiocarbon is limited to about ten half-lives i.e. to about 50,000 BP (before present). Longer-lived nuclides such as ^{10}Be (1.6 million years), ^{26}Al (760,000 years) and ^{41}Ca (100,000) can be used to date older samples.

So from a knowledge of the parent concentrations at different times, the age can be evaluated. This age determination can be applied to many of the radionuclides produced in the atmosphere by the cosmic radiation (cosmogenic radionuclides). The best known example is ^{14}C (see inset).

Since the parent atoms decay to daughter atoms, the number of daughter atoms $D(t) = P(0) - P(t)$ or $P(0) = P(t) + D(t)$, the "age" t can be obtained from

$$\text{Age} = t = \frac{1}{k} \cdot \ln\left[1 + \frac{D(t)}{P(t)}\right]\,.$$

From a measurement of the parent and daughter concentrations, and the time t, the age can be evaluated (assuming the decay constant is known).

Radioactive Parent and Stable Decay Product

In this case a parent nuclide decays to a stable daughter. In general one has to account for the fact that the (stable) daughter nuclide is already present such that the following relation holds:

$$D(t) + P(t) = D(0) + P(0)\,.$$

Since this now adds an additional unknown, $D(0)$, additional information is required before the age can be determined. There are two main assumptions in the dating process:

- The amount of daughter isotope at the time of formation of the sample is zero (or known independently and can be compensated for).
- No parent isotope or daughter isotope has entered or left the sample since its time of formation.

If one of these assumptions has been violated, the simple computation above yields an incorrect age.

Isochron Methodology

Isochron methods avoid the problems which can potentially result from both of the above assumptions. Such information can be obtained in cases where there are other stable isotopes of the elements involved in the sample. This stable, non-radiogenic nuclide can then be used as a reference nuclide. Denoting the concentration of the stable, non-radiogenic daughter nuclide by D_s, then the above equation can be written in the form of ratios [4, 5] e.g.

$$\frac{D(t) + P(t)}{D_s} = \frac{D(0) + P(0)}{D_s} .$$

Substituting $P(0) = P(t)e^{+kt}$, the relation can be expressed as

$$\frac{D(t)}{D_s} = \frac{P(t)}{D_s}[e^{kt} - 1] + \frac{D(0)}{D_s} .$$

From which the age is given by

$$\text{Age} = \frac{1}{k} \ln \left[1 + \frac{(D(t)/D_s - D(0)/D_s)}{P(t)/D_s} \right] .$$

The equation for $D(t)/D_s$ above has the form

$$y = x \cdot [e^{kt} - 1] + y_0 .$$

On a plot of y vs. x, the slope is $dy/dx = e^{kt} - 1$. The age can then be determined by

$$\text{Age} = \frac{1}{k} \cdot \ln \left[1 + \frac{dy}{dx} \right] .$$

If the samples have the same age, a plot of D/D_s against P/D_s will give a straight line with slope $(e^{kt} - 1)$ intersecting the ordinate at $D(0)/D_s$. Such a plot is called an isochron and is particularly useful for age determinations on samples of the same age.

Rubidium-Strontium Dating

In the Rb/Sr method, determination of the parent (^{87}Rb) and the daughter (^{87}Sr) are compared to to the stable isotope ^{86}Sr which is used as the reference nuclide. Application of the isochron method to the Rb/Sr system gives

$$\left(\frac{^{87}\text{Sr}}{^{86}\text{Sr}} \right)_t = \left(\frac{^{87}\text{Rb}}{^{86}\text{Sr}} \right)_0 (e^{kt} - 1) + \left(\frac{^{87}\text{Sr}}{^{86}\text{Sr}} \right)_0 .$$

A plot of ^{87}Sr/^{86}Sr against ^{87}Rb/^{86}Sr for various samples of the same age is shown in Fig. 6.1. From the relation above, using $1/k = \tau/0.693$, the age can then be determined i.e.

$$\text{Age} = \frac{47.5\,\text{Gy}}{(0.693)} \cdot \ln \left[1 + \frac{0.3}{4.51} \right] = \underline{4.41\,\text{Gy}} .$$

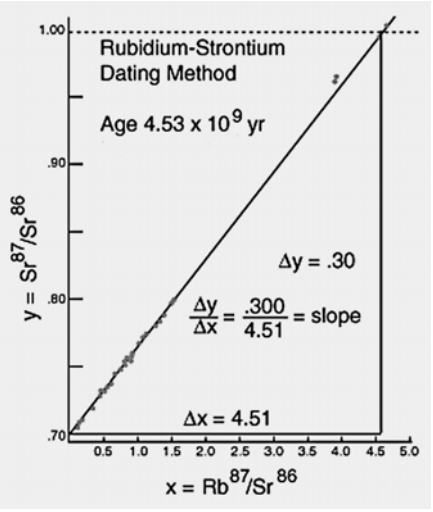


Fig. 6.2. Rb/Sr dating method [2], HyperPhysics, © C. R. Nave, 2003

Radioactive Disequilibrium

Radioactive disequilbria may arise in a variety of situations in which the parent and daughter nuclides do not remain together. Following chemical processing, it is possible to separate the parent and daughter nuclides. Following this separation, the daughter nuclide will start to grow in again. Information on the time of this processing or separation may be obtained by comparing the ratio of the parent to daughter nuclides. An example of this is given later in this chapter for the determination of the age of plutonium particles. Fresh plutonium particles will, in general, contain the isotopes ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, and ^{242}Pu depending on the production route. With time, these nuclides decay to ^{234}U, ^{235}U, ^{236}U, ^{241}Am, and ^{238}U, respectively. From the ratios of the parent to daughter nuclides, one can deduce the elapsed time and hence the age of the particle.

Fission Tracks

Fission tracks, which result from spontaneous fission or by neutron induced fission, can be used for dating purposes. The method is really only applicable to ^{238}U where there is a measurable density of tracks. In a first step, the tracks naturally produced in minerals by ^{238}U spontaneous fission are counted. In the second step, the uranium in the sample is determined by ^{235}U fission tracks in a reactor with a well characterised thermal flux. The age of the sample is obtained from the ratios of the tracks, the reactor neutron flux, etc.

In the following sections, various examples of dating techniques based on radioactive decay are described in more detail.

An Astrophysical Clock

Heavy elements such as uranium formed in a supernova more than 6000 million years ago. From the supernova remnants, the solar system was born around 4600

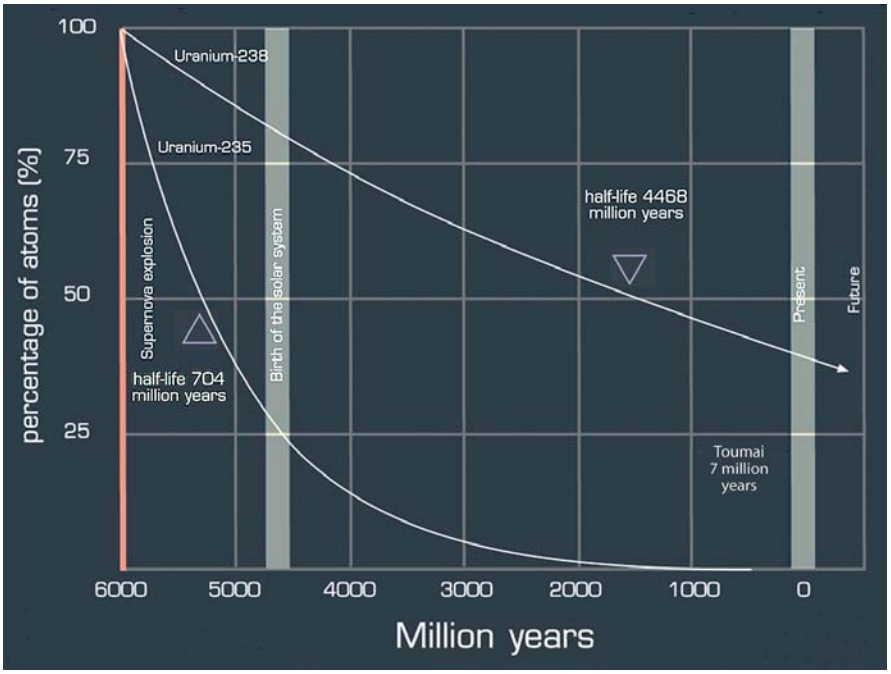


Fig. 6.3. The Astrophysical Clock

million years ago. Assuming uranium isotopes were produced in equal amounts in the supernova the ratios of uranium isotopes can be used as an astrophysical clock. Today, the natural abundance of ^{235}U ratio is 0.71%. The natural reactors at Oklo in Africa occurred around 2000 million years ago at which time the natural abundance of ^{235}U was around 3%. Evidence indicates that the natural uranium deposits achieved nuclear criticality and operated for tens of thousands of years or longer. The absence of ^{236}U, which has a half-life of 2.342×10^7 y indicates that induced fission stopped at least 10^8 years ago. The recently discovered "Toumai" has been dated to around 7 million years. In the above diagram this time is almost indistinguishable from the present time.

Age of the Earth

Towards the end of the 19th century, the age of the Earth was of great scientific controversy [6]. Lord Kelvin had estimated the age to be around 20 million years based on the rate of cooling assuming that the Earth was originally in a molten state. Already by 1840, from the work of Hutton and Lyell, it was known that rocks were laid down on top of one another in an orderly manner. This gave rise to age estimates based on sedimentation geology. Darwin had estimated the age of the Earth at 300 million years from cliff erosion assuming an erosion rate of 1 inch per century.

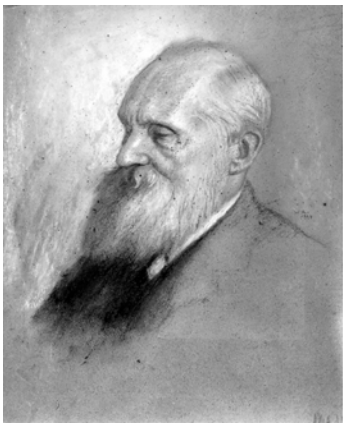


Fig. 6.4. Portrait of Lord Kelvin (1824–1907) by W. Rothenstein. © Hunterian Art Gallery, University of Glasgow

Shortly after the discovery of radioactivity by Becquerel in 1896, Rutherford and Soddy showed that through radioactive decay, one element could be transformed into another (see page 43), e.g. radium (a metal) became radon (a gas). They suggested also that the observed presence of helium in rocks might be due to radioactive "decay". The same authors first established the "decay chain" of the unstable "parent" uranium. They identified the 14 stages in the decay of uranium, shown in Fig. 6.5, producing 8 atoms of helium.

Based on these observations, Rutherford and Soddy concluded that if the amount of helium in a rock could be measured, one could estimate how long this process

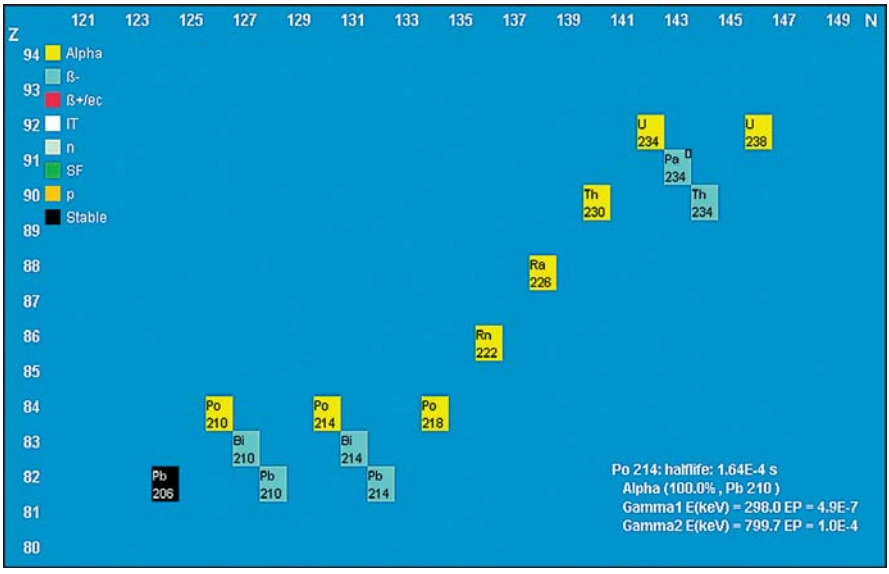


Fig. 6.5. Decay chain of uranium with the 14 stages established by Rutherford (from the "Universal Nuclide Chart", Appendix E)

took i.e. the age of the rock. In particular, by measuring the amount of radium and helium, Rutherford dated the age of a rock at 500 million years. The problem with this method was, however, that helium gas could escape from the rock and that an age determination would result in a minimum age. From these results, Kelvin's age determination was clearly too low. In 1907, Boltwood had observed that along with helium, large amounts of lead were found in rocks containing radioactivity. He postulated that lead was the stable product in the decay of uranium. Based on this, Arthur Holmes proposed that the age could be determined by measuring the amount of lead, rather than helium i.e. on a uranium/lead technique. The basic assumption here was that the "ordinary" lead in a rock was present in much smaller quantities than the amount produced by the decay of uranium.

Around this time, Soddy discovered "isotopes" – nuclides which had different atomic masses. The existence of these isotopes would complicate matters considerably in the development of age techniques – they would, however, ultimately result in an accurate dating technique. Not only did lead have four such isotopes ^{208}Pb (parent ^{232}Th), ^{207}Pb (parent ^{235}U), ^{206}Pb (parent ^{238}U), ^{204}Pb ("ordinary" lead) but natural uranium had also three isotopes (^{238}U, ^{235}U, ^{234}U with relative abundancies of 99.28%, 0.72% and 0.0055%, respectively). Following the discovery of the new isotope of uranium ^{235}U, which decayed much faster than ^{238}U, Rutherford in 1929 determined the age of the Earth by assuming that, at formation, equal amounts of ^{238}U and ^{235}U were present. The result obtained, 3400 million years, was the first age determination based on isotope ratios.

It also followed from this new isotope of uranium, that the uranium-lead pathways contained two geological "clocks" that could be used to check one another i.e. the decay rate of ^{238}U to ^{206}Pb and the decay rate of ^{235}U to ^{207}Pb. In addition, a third "clock" based on the ratios of the isotopes ^{206}Pb, ^{207}Pb relative to the constant value of ^{204}Pb was proposed. This new lead-lead method is still used today in age dating techniques. The first estimates of the age of the Earth based on these lead ratios (the isochron method) are due to Paterson in the 1950s. The current value of the age of the Earth is 4550 ± 70 million years.

Prehistoric Cave Art at Altamira, Northern Spain

The most famous of the Altamira paintings are on the plafond – a low ceiling in one of the caves to the left from the entrance [7]. The total area of the ceiling is about 100 m^2. Here the artist skilfully combined pigment painting with the ceiling relief. The majority of more than 20 animal figures are bison (though there is also a horse, a boar and a deer). The most common pigments used in these paintings were red Fe_2O_3, black MnO_2 and charcoal. Rather than dating the sample by traditional ^{14}C techniques of β activity measurements (where sample requirements would damage the artwork), accelerator mass spectrometry was used to count individual carbon isotopes thereby reducing the amount of sample required to a minimum. To obtain the carbon needed for dating, a scalpel was used to scratch off approximately 20–40 mg from a dark section of the painting. Radiocarbon dating of the charcoal

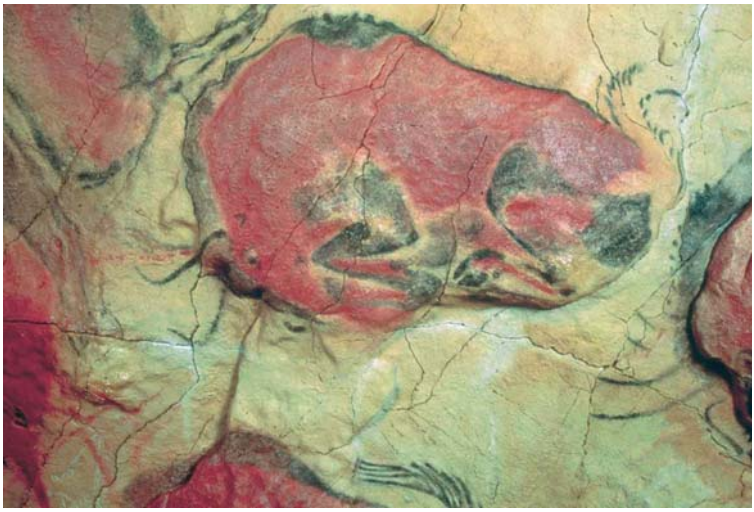


Fig. 6.6. Prehistoric cave art at Altamira, Northern Spain. © Museo de Altamira

used to draw the bison shown above found the drawing to be $14{,}000 \pm 400$ years old [8].

The Age of Groundwater – The Oasis Ballad Seet

Groundwater provides one of the most important sources of drinking water worldwide. In dry climates, in deserts, etc., groundwater is often the only permanent source of water. Important information for the sustainable cultivation of groundwater resources is the residence time of the water underground i.e. the "age" of the groundwater. Groundwater is an archive of historical environmental conditions. Following infiltration, the water can spend thousands of years in the ground, isolated from the atmosphere. Valuable information can be obtained from the dissolved noble gases in the water. Heavy noble gases can give information on the temperature which existed when the water first entered into the ground [9–11].

One of the most reliable methods for dating "young" groundwater (up to ages of 50 y) is based on the rare "stable" isotope ^{3}He. This isotope is created in water through the radioactive decay of the hydrogen isotope tritium ^{3}H (half-life 2.34 y) contained in the water molecules. This tritium is produced in nature in very small amounts by cosmic radiation through the reaction $^{14}\mathrm{N} + \mathrm{n} \rightarrow {}^{12}\mathrm{C} + {}^{3}\mathrm{H}$. Tritium was produced in very much larger quantities in the 1950s and 1960s through atmospheric nuclear explosions. The resulting "tritium peak" in rainfall was used in the following years as a useful "marker" in hydrology. Today, the tritium levels have almost returned to their natural constant values. For this reason, little information can be gained on residence times of water by measuring the tritium content alone.

Of considerably more interest, however, is the combined measurement of ^{3}H and ^{3}He. Following infiltration of rainwater, groundwater becomes isolated from the

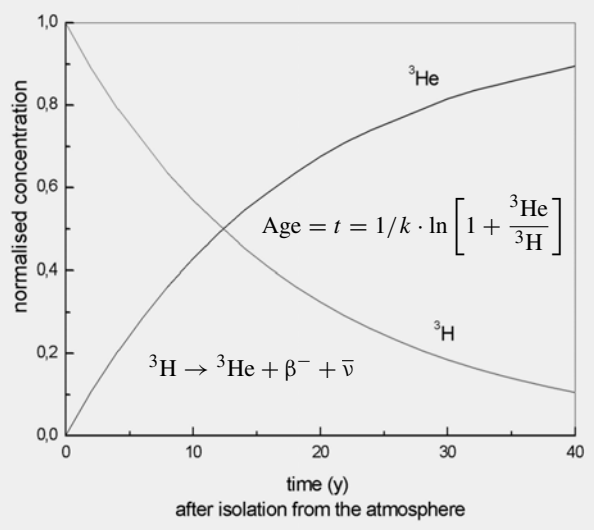


Fig. 6.7. Time evolution of the concentrations of ^{3}H and ^{3}He in water isolated from the atmosphere

atmosphere and the concentration of ^{3}He increases through the radioactive decay of ^{3}H. From the ratio of the ^{3}H and ^{3}He concentrations, the "age" of the water can be calculated.

The "age" of the groundwater refers to the time elapsed since the isolation of the groundwater from the atmosphere. Surface waters, whose dissolved gases are in solution equilibrium with the atmosphere, have age zero. After isolation from the atmosphere, for example water at the bottom of lakes or in groundwater, the gas exchange is no longer possible and helium gas accumulates in the water.

Even the presence of tritium in such water can be useful information since it establishes that the formation of groundwater inside the previous 50 y. From the concentrations of the ^{3}H and ^{3}He, the history of the tritium in groundwater can

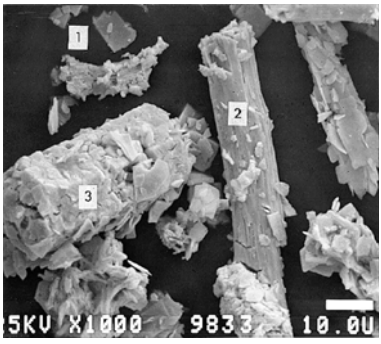
Fig. 6.8. The Oasis Ballad Seet in Oman [9] – how did the irrigation work?
© Resa Asarschahab – Source: ZDF

be reconstructed. From this information, rates of groundwater formation can be established and used to estimate available water resources. For "older" groundwater, the ^{14}C-method can be used for age determination.

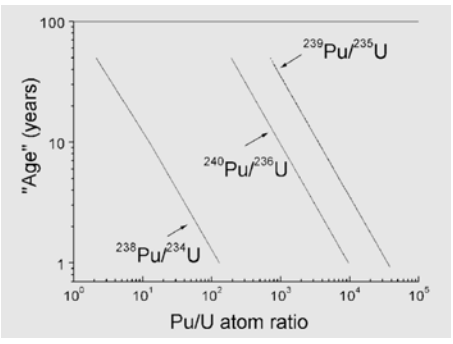
Recently, water from the oasis Ballad Seet in Oman in the south east of the Arabian peninsula has been analysed. How was it possible in a region consisting of desert and sterile mountains that such a rich and powerful culture could develop in this oasis? The analysis showed that the water age in the oasis was 5–6 years old. This was the length of time required for the water from the plateau to seep through to the groundwater almost 1000 meters below. The oasis inhabitants knew that a single rainfall every five years would be sufficient to guarantee their water supply from the oasis.

Nuclear Forensic Science – Age of Plutonium Particles

At the Institute for Transuranium Elements, a range of analytical techniques is being developed for verification and detection purposes to check nation state compliance with their non-proliferation commitments. As part of these activities, a technique is being developed to determine the "age" of plutonium particles [12, 13]. The "age"



Sample F19A: Experimental isotope ratios and the deduced particle "Age" from decay correlation



Pu/U atom ratios vs. "Age".

F19A	Expt. ratio	"Age" (y)		
^{238}Pu/^{234}U:	109.4	1.18		^{238}Pu/^{234}U: $\log(\text{Age}) = 2.0228 - 0.9563 \log(\text{Pu/U})$
^{239}Pu/^{235}U:	670.9	51.9	$\Leftarrow$	^{239}Pu/^{235}U: $\log(\text{Age}) = 4.541 - 0.9994 \log(\text{Pu/U})$
^{240}Pu/^{236}U:	476.3	19.9		^{240}Pu/^{241}U: $\log(\text{Age}) = 3.9744 - 0.9563 \log(\text{Pu/U})$

Fig. 6.9. "Age" determination of plutonium particles: since the uranium contamination is significant in sample F19A, the ages determined from the ratios disagree largely. The most accurate value of 19.9 y is expected from the ^{240}Pu/^{236}U ratio since there is no ^{236}U present in natural uranium from the ^{240}Pu/^{236}U ratio, i.e. 19.9 y, since there is no ^{236}U present in natural uranium.

of a particle is defined as the time elapsed since the last chemical separation of daughter nuclides from the parent. The particles to be analysed can be obtained from the environment or from "swipes" taken at nuclear installations where clandestine activities are suspected. In view of the pending international agreement to stop the production of weapon materials, the age of such "suspected" particles is of course of great interest for verification purposes.

For bulk samples, gamma spectroscopy can be used. However, for very small particles, because of the low activity, this technique is not possible. Fresh plutonium particles will in general contain the isotopes ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, and ^{242}Pu in different amounts, depending on the production route. With time, these nuclides decay to ^{234}U, ^{235}U, ^{236}U, ^{241}Am, ^{238}U respectively. By determining the ratios of parent to daughter (^{238}Pu/^{234}U, ^{239}Pu/^{235}U, ^{240}Pu/^{236}U, ^{241}Pu/^{241}Am, ^{242}Pu/^{238}U) one can deduce the elapsed time and therefore the age of the particle. Because these ratios are measured by secondary ion mass spectrometry (SIMS), one cannot obtain the ratio ^{241}Pu/^{241}Am. In addition, if the particle has some uranium contamination, one cannot use the ratio ^{242}Pu/^{238}U. This leaves the three ratios ^{238}Pu/^{234}U, ^{239}Pu/^{235}U, ^{240}Pu/^{236}U which are suitable for age determination. The correlation between the atom ratios and the age as calculated is shown in Fig. 6.9. The time scale of interest is in the range 1–50 years. The correlation between the "age" of a particle and the Pu/U atom ratio was obtained with Nuclides.net. Since the uranium contamination is significant, the ages determined from the ratios disagree largely. The most accurate is expected from the ^{240}Pu/^{236}U ratio, i.e. 19.9 y, since there is no ^{236}U present in natural uranium.

7. Radioisotopes in Medicine

Radionuclides were first used for therapeutic purposes almost 100 years following the observation by Pierre Curie that radium sources brought into contact with the skin produced burns. Already by 1915, sealed sources of radium-226 and radon-222 were in use. By the 1950s radiotherapy had become much more widespread due to the development of remote source handling techniques and the availability of reactor produced radionuclides such as cobalt-60.

Ionising radiation from radionuclides kills cells by damaging the DNA thereby inhibiting cellular reproduction. The energy of the radiation (in the form of photons, electrons, heavy particle, etc.) required to damage DNA should be greater than a few electron volts (eV) corresponding to the binding energy of the outer electrons [1].

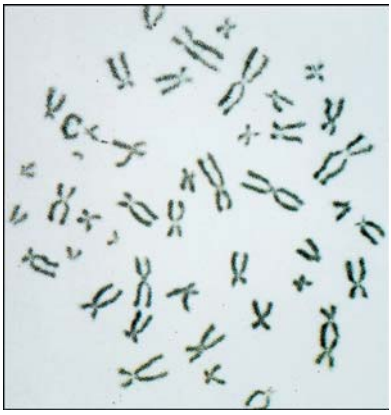


Fig. 7.1. A collection of normal chromosomes with their single centres (indicated by a X shape). An anomalous chromosome with a double centre (XX) can be seen at the bottom right-hand corner. © CEA-IPSN

Imaging

Nuclear diagnostic imaging techniques provide information about physiological and biochemical processes and compliment other imaging methods such as conventional radiology, nuclear magnetic resonance, and ultrasound. They have a very important role to play in identification of heart disease, brain disorder, lung and kidney function, and a range of cancers.

Gamma Imaging

One of the main applications in medical applications is the use of gamma cameras to detect diseases in the heart, brain, bone, lung, and the thyroid. More than 20,000

Table 7.1. Main isotopes used for gamma imaging

Organ	Nuclide
Lung	^{81m}Kr, ^{99m}Tc, ^{133}Xe
Bone	^{99m}Tc
Thyroid	^{99m}Tc, ^{123}I, ^{131}I
Kidney	^{99m}Tc, ^{111}In,, ^{131}I
Brain	^{99m}Tc, ^{123}I, ^{133}Xe
Liver, pancreas	^{99m}Tc, ^{111}In
Abdomen	^{67}Ga, ^{99m}Tc
Blood	^{99m}Tc, ^{111}In
Heart	^{82}Rb, ^{99m}Tc, ^{201}Tl

gamma cameras are in use throughout the world in some 8500 nuclear medicine departments [2]. The main radionuclide in use is ^{99m}Tc, however other nuclides are also in use as summarised in Table 7.1.

Positron Emission Tomography (PET)

There are some 250 PET cameras in use today mainly for the diagnosis of cancer. The radio-pharmaceutical mostly used is the ^{18}F compound fluoro-deoxy-glucose which is similar to glucose in behaviour, ahough the development of alternatives based on ^{64}Cu, ^{86}Y, and ^{124}I is underway.

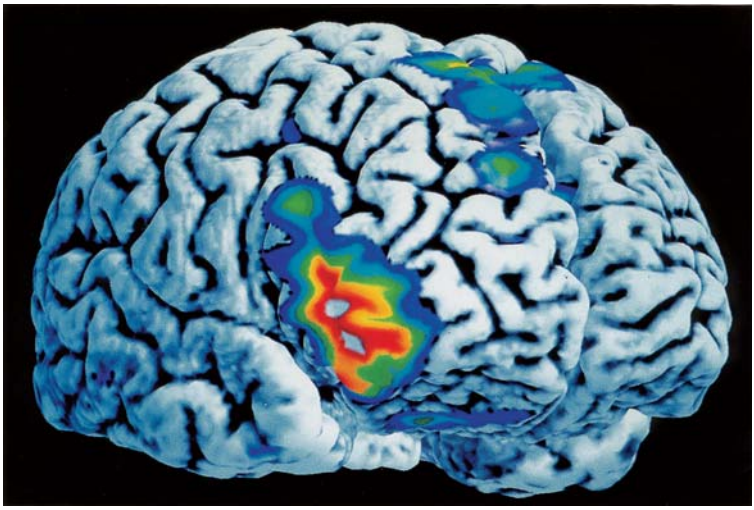


Fig. 7.2. Superposition of magnetic resonance imaging (which shows the morphology of the brain) and positron emission tomography showing the active areas (coloured zones) in the brain. Courtesy of the Montréal Neurological Institute, McGill University

External Beam Radiotherapy

In external beam radiotherapy, where radiation is delivered from outside the body, photon energies of millions of electron volts are required to penetrate the tissue and reach the tumours inside the body. Radiotherapy is also being carried out with sealed sources of ^{60}Co with some 1500 units in operation. A new process, known as the Gamma Knife, is being introduced especially for brain tumour treatment.

Brachytherapy

Today, hundreds of thousand of patients are treated each year based on brachytherapy (Brachys is the Greek word for near) in which sealed sources of radiation are brought into the body and placed in or near the tumour to be treated leaving the surrounding healthy tissue undamaged. Using these brachytherapy implants, radionuclides with photons energies as low as 20 keV can be used. The radionuclide palladium-103, for example, used for prostate implantation has an average energy of only 21 keV. Some gamma ray emitters commonly used are ^{192}Ir, ^{137}Cs, ^{125}I, ^{103}Pd and have an effective range of a few centimetres. Beta emitters include ^{90}Y, ^{188}Re, and ^{32}P with effective ranges of a few millimetres in tissue [3].

The technique is particularly successful for the treatment of prostate cancer at an early stage. In the U.S. almost 57,000 patients were treated for prostate cancer in 1999 using brachytherapy seed implants based on ^{103}Pd, ^{125}I, ^{137}Cs and ^{192}Ir.

Immunotherapy

In the last ten years, the technique known as radio-immunotherapy has been under investigation. In this technique, a radionuclide is chemically attached to an antibody which is then injected into the bloodstream. The antibodies go to the source of the tumour and the attached radionuclides, for example ^{131}I, emit charged particles to kill the tumour cells. The development of therapeutic substances for radiotherapy is being actively pursued by many companies and research organisations. Techniques are being developed which combine the radioisotopes ^{90}Y, ^{131}I, ^{153}Sm, and ^{213}Bi with monoclonal antibodies and smaller molecules such as peptides. The three main applications of radionuclides for therapeutic purposes, however, remain a) sealed sources for prostrate therapy, b) sources for intravascular therapy and c) radio-pharmaceutical therapy. It is expected that these therapies will see rapid growth in the near future.

Ion Beam Therapy

In December 1997, the GSI heavy ion radiotherapy started with the irradiation of the first two patients. The distribution of biological effective dose (isodose contours from carbon ion deposition) is shown in Fig. 7.3 superimposed on the image of the brain. The tumour, situated in the centre of the brain, is treated directly by depositing the ion beam energy in this region.

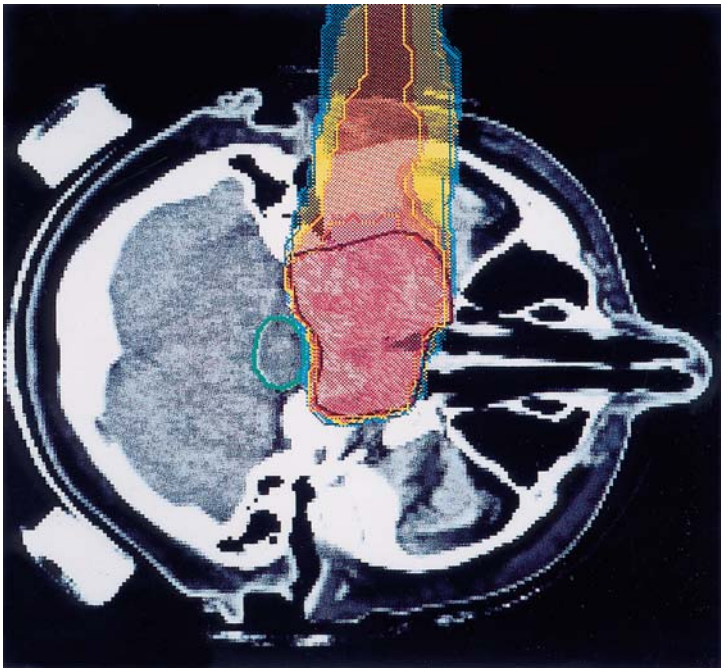


Fig. 7.3. Distribution of biological effective dose (isodose contours from carbon ion deposition) is shown superimposed on the image of the brain. © Gesellschaft für Schwerionenforschung mbH

Boron Neutron Capture Therapy

In Boron Neutron Capture Therapy (BNCT), a boron containing compound is administered intravenously to the patient. The boron accumulates preferentially in the malignant tumour. The patient is then irradiated with a beam of intermediate energy neutrons of a few keV, directed towards the tumour bed. The neutrons lose their energy through neutron scatter in the overlying tissue, whereby the thermalised neutrons are then captured by the ^{10}B atoms. These immediately disintegrate into two highly energetic particles: Li- and He-nuclei, which in principle can destroy the cancer cells, whilst sparing the healthy cells.

The American biophysicist G. L. Locher first came up with the idea of the NCT treatment in 1936. Pioneering work in the development of BNCT was carried out in the 1950s and 1960s at Brookhaven and MIT in the USA.

However, initial clinical results were disappointing. With hindsight, this was due to the non-accumulation in the tumour of the boron compounds used at the time and also the use of low energy neutrons, which in order to be able to give a high enough dose at depth, produced very high doses at shallower depths in healthy tissue. Nevertheless, in the late 1960s and early 1970s, improvements in both drug delivery and construction of higher energy neutron beams, led to a major improvement in this therapy [4].

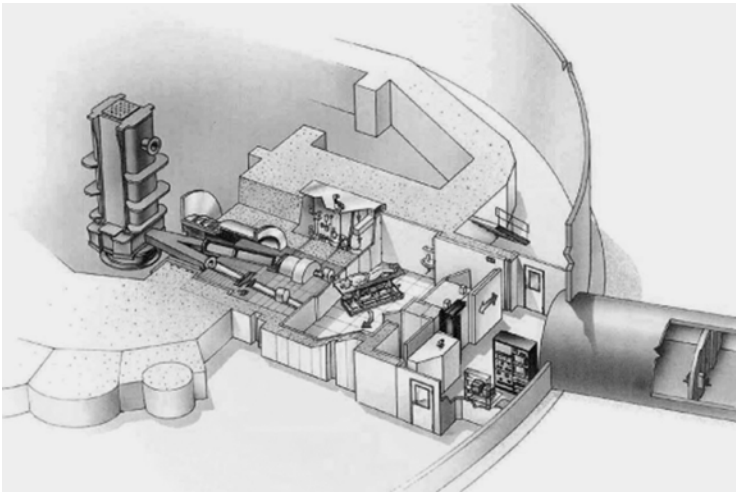


Fig. 7.4. BNCT: Clinical facility in Petten, showing the irradiation room, which has been built to reflect as closely as possible, a hospital-type environment. The clinical facilities have been installed at the High Flux Reactor (HFR) of the Joint Research Centre of the European Union (EU) in Petten. Courtesy R. Moss

Since October 1997, the first European clinical trial on BNCT is being performed at the High Flux Reactor of the Joint Research Centre of the European Commission, under the guidance of clinicians from the University of Essen and in collaboration with NRG Petten and five other hospitals. A Phase I clinical trial for the post-operative BNCT treatment of patients with glioblastoma multiforme, targets this highly aggressive brain tumour, which affects around 15,000 people in Europe every year.

The trial is the first of its type in Europe and is also the first time that a clinical application has been realised on a completely multi-national scale, whereby a unique facility localised in one country (The Netherlands), is operated by radiotherapists from another country (Germany), and treats patients coming from different countries (France, Germany, Austria, Switzerland and The Netherlands).

Since the start of BNCT trials at Petten, four other centres are performing BNCT in Europe (in Finland, Sweden, Czech Republic and Italy). Elsewhere in the world, BNCT is also carried out in Japan, USA and Argentina.

Radioactive “Bullets” – Alpha-Immunotherapy

Form the early 1980s, a new form of treatment for cancer therapy based on the use of radioactice isotope “bullets” in diseased cells began to attract increasing interest. Previouly, treatment mainly involved the use of relatively low energy beta emitters. More recently, isotopes emitting alpha particles have been recognised as more effective and selective against blood-borne cancers, widespread tumours, and residual cells remaining after surgical intervention. Production of suitable alpha emitters,

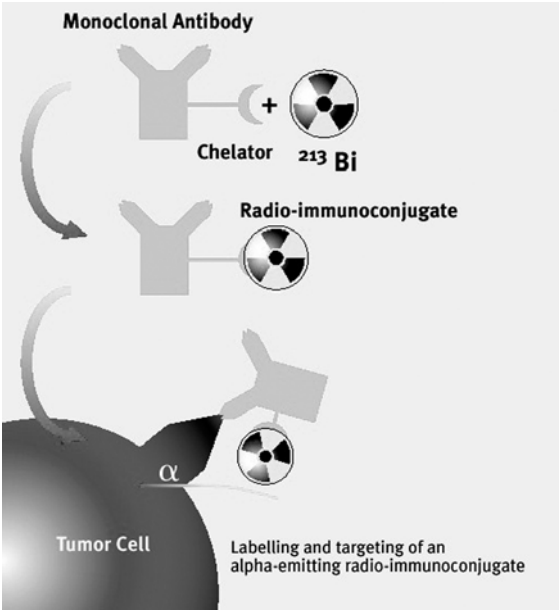


Fig. 7.5. ^{213}Bi is coupled to a monoclinical antibody using a chelation agent. The alpha emitting radionuclide is then close enough to the cancerous cell to destroy it with little damage to the surrounding tissue.

their stable coupling to suitable carriers, and safe use of such tools in hospitals have become the main goals.

Treatment of cancer by radio-immunotherapy involves injecting the patient with a radioactive isotope "bullet" connected to a specific carrier such as a monoclonal antibody, with the aim of selectively destroying targeted tumour cells. During radioactive decay, photons, electrons, or even heavier particles are emitted and damage or kill cells along their trajectory.

Alpha-emitting radionuclides are amongst the most promising radionuclides for the treatment of blood-borne cancers and micro-metastatic cancers cells. Because of their short range (60 to 100 micrometer) and high linear energy transfer values, alpha-emitters can deliver such a high radiation dose over the distance of a few cell diameters that they will effectively kill the cells. When alpha-emitters are conjugated to tumour-seeking monoclonal antibodies (a protein molecule that attaches to the cell), the resulting product is expected to be an efficient cancer drug. Other smaller molecular weight carriers such as peptides and fragments of the antibodies are being investigated because they can enter into larger sized tumours.

A number of alpha-emitting isotopes have been considered, but most gave rise to various drawbacks that preclude large-scale implementation. The preferred option today is the use of bismuth-213 (^{213}Bi), which has a half-life of 45 minutes. Actually ^{213}Bi is mainly a beta emitter with half-life of 46 m. This nuclide decays however to ^{213}Po, a very short-lived (half-life 4.2 μs) nuclide, which decays by alpha emission. So effectively ^{213}Bi is an alpha emitter with a half-life of 46 m. Actinium-225 (^{225}Ac), which has a half-life of 10 days and is the parent nuclide of ^{213}Bi, does not occur

in nature. The actinium isotope can, however, be obtained in small quantities from nuclear waste.

The first European clinical trials of such alpha-immunotherapy started in April 2000 in Basel on patients with glioblastoma and, since early 2001, in Heidelberg on patients with non-Hodgkin’s-lymphoma. The results vary from highly promising indications to cautious optimism, depending on the type and status of the disease. At the Memorial Sloan-Kettering Cancer Center in New York, clinical trilas are also continuing on patients with acute myeloid leukaemia. Other aspects of pre-clinical trials are being studied in Germany, Belgium and France. Clinical trial on leukaemia patients showed that the alpha particles were 100–1000 times more cytotoxic than beta particles, which have also been used, and caused much less damage to surrounding healthy tissue [5].

8. Scientific and Industrial Applications

A key property of radionuclides which makes them invaluable is that they can be deteced in tiny amounts. It is claimed that George de Hevesy, a colleague of Rutherford and one of the pioneers of radioisotope tracers, first used a radioisotopes to test his food [1]. Hevesy lived in a boarding house and was suspicious that the stew his landlady was serving was made from the previous day leftovers. To test his hypothesis, he placed a small mount of radioisotope in his uneaten food. The following day, he examined the stew with a detector and established that some of the food had indeed come from the previous day leftovers. George de Hevesy won the Nobel Prize in Chemistry 1943 for his work on the use of isotopes as tracers in the study of chemical tracers.

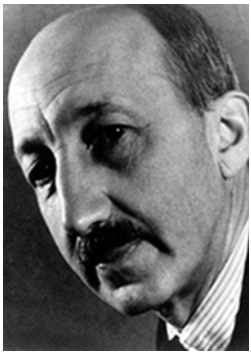


Fig. 8.1. George de Hevesy (1885–1966). © The Nobel Foundation

In addition to nuclear power, there are the so-called "non-power" applications of radionuclides in areas such as medicine, agriculture, industry, environmental protection, public safety and space applications. These non-power applications of nuclear technology in the US alone generated sales in excess of $ 300 billion and provided 4 million jobs (as of 1995). For comparison, nuclear power at the same time generated $ 900 million in sales and provided 44 000 jobs [2]. In Japan, the economic value of non-power and power applications are about equal at $ 50 billion per year. By far the largest contributor to non-power applications is in medicine. Here gamma rays are used on a very large scale to sterilise surgical dressings, structures, catheters, and syringes. In addition, more than 80% of all new drugs are tested with radioactive tagging before receiving government approval.

In the field of agriculture, pests reduce the world food production by 20–25% To reduce this, the sterile insects technique (SIT) is being used to control pest populations. Med flies have been eradicated in California, Chile, Argentina, and Peru. Tsetse and screwworm flies are also candidates for this treatment. Radiation is now used to enhance crop yields, provide improved nutrition, improve processing capabilities and disease resistance. Since the 1920s, radiation has been used to develop more than 2000 new crop varieties. In China, for example, more than one quarter of the crops for food produce is due to radiation.

Food irradiation is also receiving increased attention. With 76 million cases of food poisoning in the US each year, these numbers could be lowered by food irra-

diation before consumption. Recently, in the US, the supermarket chains have been introducing irradiated foods onto their shelves.

In industry, radiation is used in process controls for thickness gauges and density/level gauges (see below). For materials testing and inspection radiation is used to detect engine wear, check weld defects and corrosion in metals. For personal hygiene, radiation is used on contact lens solutions, bandages, cosmetics etc.

In space applications, NASA generates electricity from the radioactive decay of plutonium-238 for electricity and heating. The first space reactor, the SNAP-10A, was launched in April 1965 and functioned for 43 days before an electrical problem resulted in shutdown. The spacecraft, however, did indeed demonstrate that nuclear powered electrical sources were feasible. Recently there has been renewed interest in the use of nuclear propulsion to send a spacecraft to the moons of Jupiter (Project Prometheus). The so-called Jupiter Icy Moon Orbiter (JIMO) will orbit the three moons of Jupiter – Callisto, Ganymede, and Europa.

There is nowadays such a wide range of applications of radionuclides [3, 4, 5], that it is necessary to use some kind of classification system. In the following sections, the system used is based on the properties that make the radioisotopes useful. Following [1] these properties are:

1. Radiation traces Materials – Radioisotope Tracers
2. Materials affect Radiation – Radiography and Gauging
3. Radiation affects Materials – Radiation Processing
4. Radiation uses Energy – Nuclear Batteries

There are four main classes of application of radionuclides and radiation in industry: Radiosotope Tracers, Radiography and Gauging, Radiation Processing, Nuclear Batteries. Each of these will be described.

Radioisotope Tracers

The use of radionuclide tracers dates to the early days of radioactivity, when de Hevesy, a student of Rutherford, added the beta emitting nuclide ^{210}Pb to bulk lead to trace the solubility of lead salts. The use of so-called "tag" or "tracer" techniques using radionuclides is based on the fact that radiation can be detected with very high sensitivity. A very small number of "tagged" or "labelled" molecules added to a material allows one to monitor chemical and physical behaviour at both macro- and microscopic levels without disturbing the carrier material. Pesticides and insecticides, for example, are tagged using ^{14}C to monitor product degradation in the biosphere. In other areas of biochemistry, radioactive hydrogen (tritium) ^{3}H is used. Tiny amounts of about 10^{-15}g of the isotope ^{32}P are used implants to monitor the uptake of phosphorus in plants. A wide variety of radionuclide tracers are available for a variety of tasks. Some of these are outlined in more detail below.

Leak Detection

A common problem in the oil industry is the detection of leaks. For this purpose radionuclide tracers can be inserted into the pipe flow and will leak where the structure is damaged. If the pipe is not too deeply buried in the ground, the leak position can

be identified from the gamma emission from the tracer radionuclide from above the soil.

Common Pipelines

Many pipelines carry oil from different producers at different times. To differentiate oil from from various producers, the oil soluble radionuclides can be used. Radiation monitors can then be used to identify different batches of oil.

Flow Patterns and Rates

By monitoring the diffusion of tagged radionuclide tracers, information on complex flows can be obtained [6]. This is particularly useful for studies on ocean currents, atmospheric pollution dispersion, sand movement on beaches, etc. For sand movement studies, for example, small glass beads are synthesised with particles sizes and densities matching those of the sand. The glass beads contain appropriate target material such as lanthanum oxide, iridium, or silver metal which is activated in a nuclear reactor to produce the radiotracers ^{140}La (1.7d), ^{192}Ir (74 d)), or ^{110m}Ag (250 d). The tracers are chosen such that their half-lives correspond to the timescale of interest (1 week, 1 season, annual cycle etc.). Radionuclides can also be used as tracers for flow rate measurement in complex systems such as in rivers.

Tracer Dilution

By injecting radionuclide tracers into unknown volumes of fluids, the volume of the fluid can be determined from the dilution of the tracer. If the unknown volume is V, then this is obtained from $V = V_0(C_0/C)$ where V_0 is the volume of tracer injected with concentration C_0 and C is the concentration in the unknown volume. This method can be used to determine, for example, the total amount of blood in a person's body, or the amount of catalyst in a chemical process etc.

Wear Analyses

A particularly important application of radionuclide tracers is in the study of wear, friction, corrosion, etc. The wear on piston rings in an engine, for example, can be analysed by tagging the rings with suitable radionuclides. By measuring the rate of appearance of the tag in the engine oil, the wear of the piston rings can be determined.

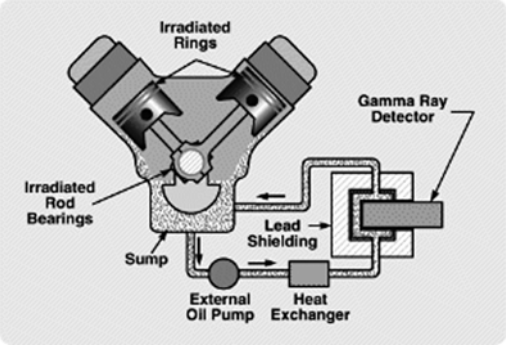


Fig. 8.2. A gamma ray detector, placed in the test engine's lubrication stream, detects and analyzes the presence of radioactive tracers emitted by abraded metal particles from irradiated engine parts [7]. © Southwest Research Institute

Mixing Times

An important problem in many industrial batch mixing processes is to ensure that the complete mixing occurs. By measuring the concentration of a tagged component at various times, the time required for mixing can be obtained.

Radiography and Gauging

The interaction of radiation with material generally results in a change in intensity or energy of the radiation. The penetration of radiation through a material depends on the density and thickness of the materials and the energy of the radiation. The resulting decrease in the intensity can be used as a basis for measuring thicknesses, finding voids, testing welds, detecting concealed objects, etc. The three main applications are *radiography*, *gauging* and *activation*.

X-Ray and Gamma Ray Radiography

One of the most spectacular applications of radiation was Roentgen's X-ray of his wife's hand in 1895. The image produced on a photographic plate placed beneath the hand showed clearly the underlying bones. Nowadays the technique of radiography is very well developed. X-rays of teeth and other parts of the body are now everyday procedures in practices and hospitals all over the world. In this technique, high energy electrons are directed on to a high-Z target material where they are slowed down thereby producing high energy photons or bremsstrahlung radiation. As these

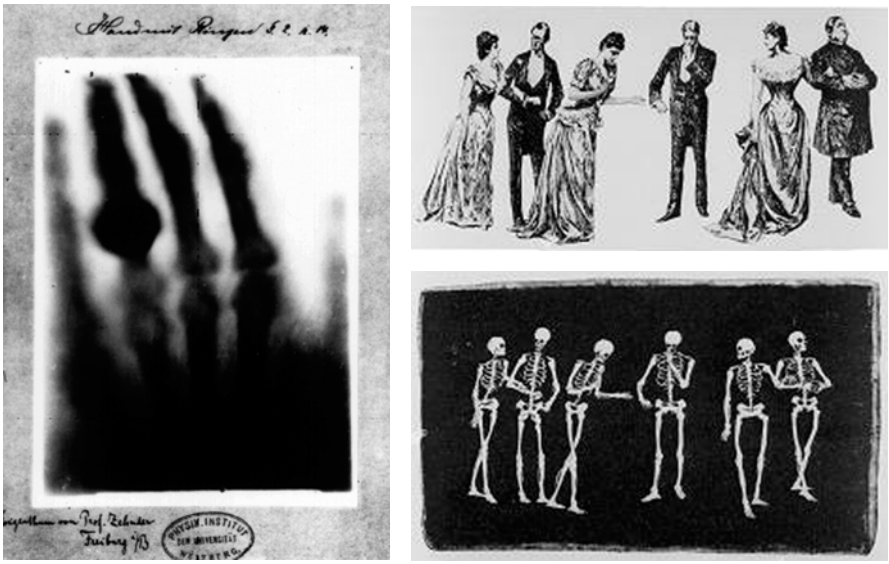


Fig. 8.3. (*Left*) The first X-ray picture: the radiograph of the hand of Roentgen's wife made by Roentgen on 22 Dec. 1895 [8], (*right*) Contemporary humour on X-rays in the magazine Life No. 27 of 6th April 1896, p. 313 [8]. © Deutsches Museum, Munich

high energy photons pass through tissue, dense objects absorb or scatter the photons preferentially resulting in less photons reaching the photographic plate. In situations where X-ray machines are impractical, the photon radiation can be obtained from radioisotopes. Such small scale radioisotope gamma sources are very reliable.

Neutron Radiography

Radioactive sources are too weak to produce images with the right quality. Neutron beam-lines from nuclear reactors or spallation sources [9] can also be used for radiography if the object has different neutron cross-sections. Because materials such as water and hydrocarbons are very effective at scattering thermal neutrons, in contrast to gases, voids, metals etc., neutron radiographs are ideal for analysing the density variations in neutron absorbing and scattering materials.

Most of the existing neutron radiography facilities are reactor-based. At the Paul Scherrer Institute (PSI) in Switzerland [9], however, the neutrons are produced in the SINQ spallation source. Neutron radiography stations are almost exclusively large stationary installations. This makes them unsuitable for "in situ" measurements.

Since X-rays interact with atomic electrons, the interaction probability is greatest with high atomic number Z as shown in Fig. 8.4. Neutrons have no electric charge and interact only with the atomic nucleus. Neutron interactions do not vary systematically with Z as do X-rays – however certain low Z materials (such as hydrogen, boron) show strong interaction probabilities.

A neutron transmission radiography setup, Fig. 8.5, consists of a neutron source, a collimatior to guide the neutons to the sample and an neutron detector to collect the transmitted neutrons behind the sample.

Thermal neutron fluxes in the range 10^5–$10^7\,\mathrm{cm^{-2}\,s^{-1}}$ are used in neutron radiography. Exposure times for the detection of neutrons and X-rays are only a few seconds. Thermal neutrons are preferrred due to their hight interactions probability with the observed materials, but also with the detection materials (^{11}B, ^{6}Li, ^{155,157}Gd). The most important detections reactions are (for thermal and cold neutrons) [9]:

$$^{3}\mathrm{He} + {}^{1}\mathrm{n} \rightarrow {}^{3}\mathrm{H} + {}^{1}\mathrm{p} + 0.77\,\mathrm{MeV}$$

$$^{6}\mathrm{Li} + {}^{1}\mathrm{n} \rightarrow {}^{3}\mathrm{H} + {}^{4}\mathrm{He} + 4.79\,\mathrm{MeV}$$

$$^{10}\mathrm{B} + {}^{1}\mathrm{n} \xrightarrow{(7\%)} {}^{7}\mathrm{Li} + {}^{4}\mathrm{He} + 2.78\,\mathrm{MeV}$$

$$^{10}\mathrm{B} + {}^{1}\mathrm{n} \xrightarrow{(93\%)} {}^{7}\mathrm{Li}^{*} + {}^{4}\mathrm{He} + 2.30\,\mathrm{MeV} \rightarrow {}^{7}\mathrm{Li} + {}^{4}\mathrm{He} + \gamma\,(0.48\,\mathrm{MeV})$$

$$^{155}\mathrm{Gd} + {}^{1}\mathrm{n} \rightarrow {}^{156}\mathrm{Gd} + \gamma + \text{conversion electrons}\ (7.9\,\mathrm{MeV})$$

$$^{157}\mathrm{Gd} + {}^{1}\mathrm{n} \rightarrow {}^{158}\mathrm{Gd} + \gamma + \text{conversion electrons}\ (8.5\,\mathrm{MeV})$$

X-ray and neutron transmission images look different and provide complimentary information. In the camera images shown in Fig. 8.6, the metallic parts are revelaed clearly in the X-ray images, whereas plastic components are shown clearly with the neutrom images.

The neutron radiography facility at the Paul Scherrer Institute (PSI) in Switzerland – the Neutron Transmission Radiography NEUTRA (NEUtron Transmission

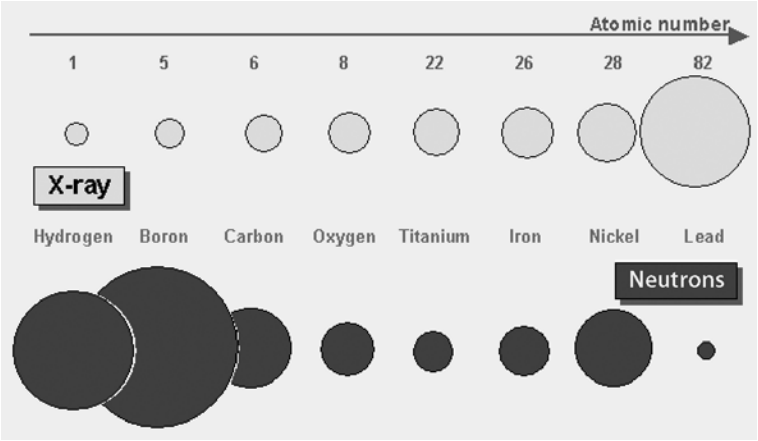


Fig. 8.4. Neutron matter interaction probability: comparsion between neutrons an X-ray. Circles with larger diameters have higher interaction probabilities or cross-sections [9]

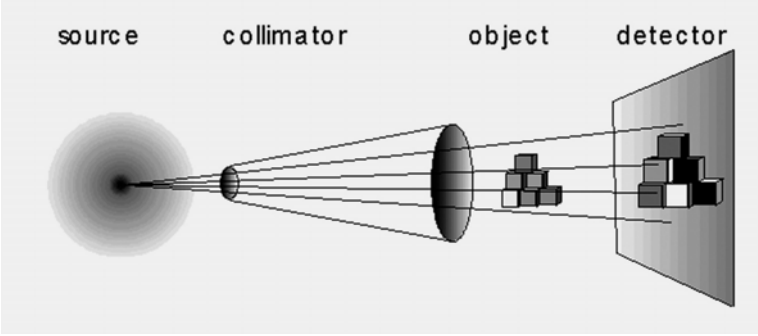
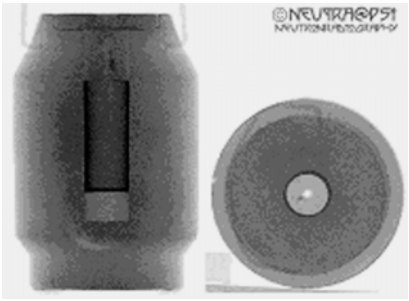


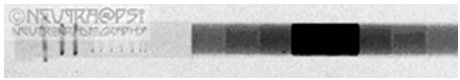
Fig. 8.5. Principle of neutron radiography [9]

Fig. 8.6. Unlike X-rays, neutrons interact significantly with some light materials and penetrate easily some heavy materials, making it a complementary technique to X-ray radiography. While X-rays are attenuated more effectively by heavier materials like metals, neutrons make it possible to image some light materials such as hydrogenous substances with high contrast: in the X-ray image (left), the metal parts of the photo apparatus are seen clearly, while the neutron radiograph (right) shows details of the plastic parts [9]

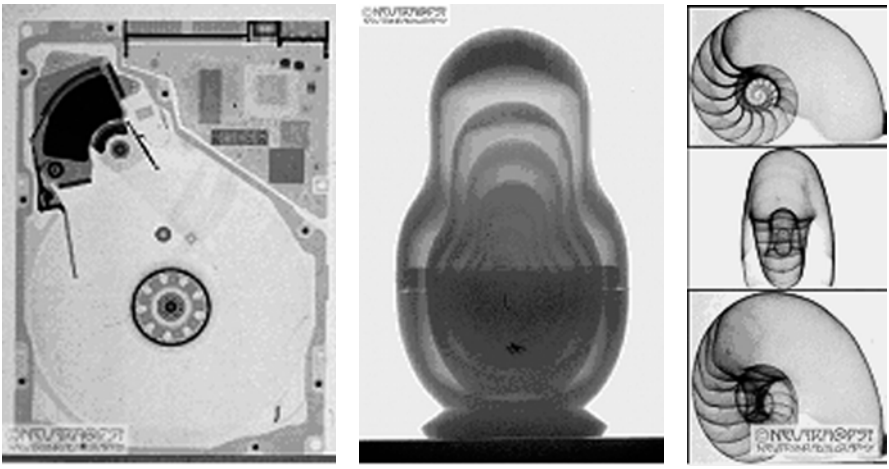
RAdiography) – station has been in operation at the spallation source SINQ since 1997. The aim of NEUTRA is to provide a state-of-the-art tool for scientific and industrial neutron radiography applications. Typical applications of neutron radiography are shown in Fig. 8.7.



(**a**) Neutrons can penetrate lead provided it is not too thick. The container shown contained possibly dangerous material. By neutron inspection it was verified easily that it is empty and only a plastic cylinder was inside.



(**b**) Uranium can be transmitted by thermal neutrons and the enrichment of the isotope U-235 can be measured (and visualized) due to the higher attenuation compared to U-238. The "black" areas in the image are pellets with the "burnable poison" Gadolinium.



(**c**) Hard-disks are electro-mechanical devices which are sealed and cannot easily be opened for inspection. Non-invasive investigation can help to evaluate the status of enclosed componenets with a high resolution.

(**d**) The wooden puppet (very popular Russian "Matroschka") contains several "daughters".

(**e**) The very interesting inner structure of the (empty) shell of a Nautilus scrobiculatus can be visualised by neutrons due to the relative high contrast of the shell material. The size of this object is about 20 cm.

Fig. 8.7a–e. Various applications of neutron radiography. © NEUTRA@PSI

Level Gauging

Properties of the material can be determined from changes in the radiation using "gauges" (or nucleonic gauges) consisting of a radioactive source and a detector such as a NaI crystal. In many industrial processes there is a need to determine the level of a liquid in a container. A simple gauge consists of a source of radiation and a detector with a line of axis near the surface (either above or below) of the liquid. If the surface level of the liquid moves, the detector signal changes accordingly. In the drinks industry, this technique is used to ensure that cans on high-speed conveyor belts are properly filled.

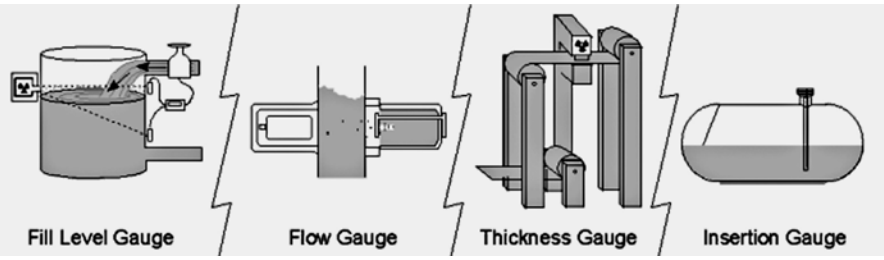


Fig. 8.8. Examples of several different types of fixed gauges [10]

Thickness Gauging

Thickness gauging is used in processes involving continuous sheets of materials such as adhesive tape, floor coverings, paper production etc. The thickness of the material is determined from the measurement of the transmitted or reflected radiation.

Density Gauging

Density gauges are used to measure the density of material between the source and detector based on the radiation attenuation in the material. The basic relation used is

$$I_t = I_0 \mathrm{e}^{-\mu_\mathrm{m} \rho t}$$

where I_0 and I_t are the gamma ray intensities before and after attenuation through a material of thickness t, ρ is the density of the material and μ_m is the mass attenuation coefficient.

Neutron Activation Analysis

Neutron activation analysis is used to detect very small amounts of impurities or trace elements in a sample. Small samples undergo neutron irradiation whereby the neutrons activate the stable atoms to radioactive atoms. Following the irradiation, the sample is analysed using gamma spectroscopy to identify the emission and thus determine the origin of the radiation. The technique is widely used in nuclear forensic science to obtain a "fingerprint" of the material. The technique has potential applications for example to plastic explosive detection at airports or detecting buried landmines.

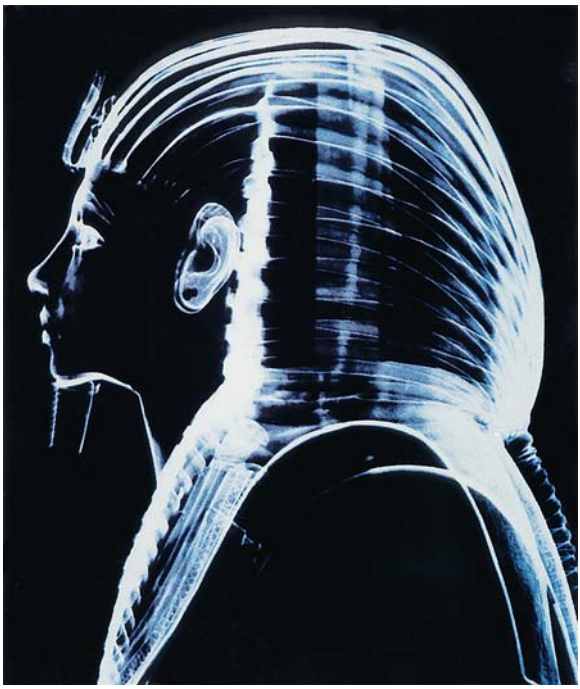


Fig. 8.9. Gamma radiography of the gold mask of Tutankhamon made for the Exhibition "Toutankhamon et son Temps", Paris 1967.

Radiation Processing

In the same way that overexposure to sunlight can lead to sunburn, overexposure to radiation from radioisotopes can result in cell damage. At lower dose levels, radiation induced mutation of DNA cells can occur. At sufficiently high dose levels, radiation can be used to kill bacteria and insects. This is the basis of using radiation for sterilisations of materials and foods. In the following section, processes are described in which radiation is used to modify the properties of materials. In specific cases, because large volumes requiring treatment, very large doses of radiation may be required.

Radiation-Induced Mutation

Through the process of stochastic mutation of DNA cells by radiation, plants exhibiting desired features can be selected. As a result new genetic lines of, for example, garlic, wheat, bananas, beans, avocado and peppers can be produced which are more resistant to pests and climate. Using the technique of radiation-induced mutation, the shape, size and colour of flowers can be changed (see Fig. 8.10). Recently bioluminescent flowers have been developed by genetic modification using a gene from fireflies. These flowers produce constant light, visible to the human eye, for up to five hours. The bioluminescent plants use their own energy to create light, and radiate a greenish-white glow from all parts of the orchid, including roots, stem, leaves and petals.

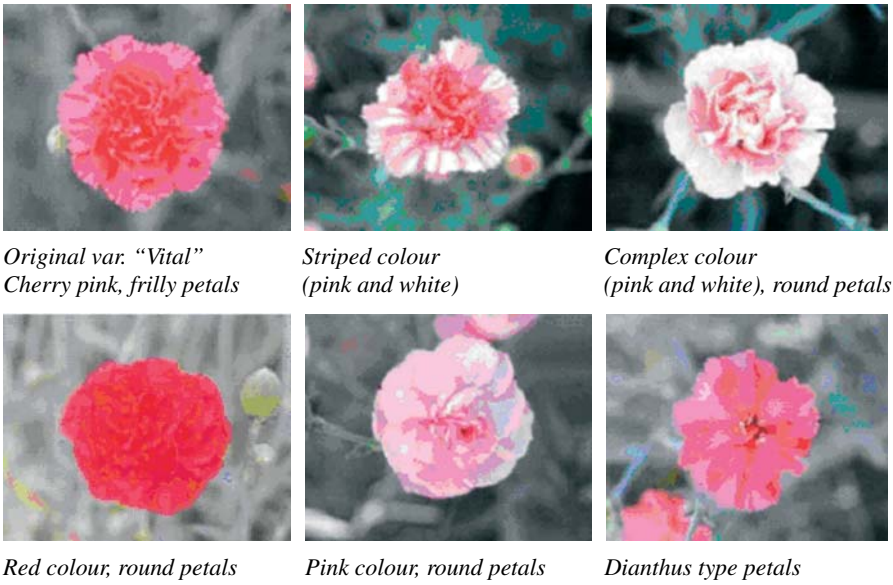


Fig. 8.10. Mutant carnation flowers. Irradiation with carbon ions resulted in various changes on both flower colour and shape. From the original variety "Vital" (*left top*), flowers with stripes, bi-colour/round shape, red/round shape, pink/round shape, and Dianthus type shape were obtained [11]

Food Irradiation

Radiation can be used to reduce the high losses of food due to insect infestation and spoilage, reduce concern over food-borne illness and help to increase international trade in food products. At present over 30 countries have permission to irradiate around 40 different foodstuffs ranging from fruits and vegetables to seafood, meat and poultry. An advantage of radiation processing of food over thermal pasteurisation processes is that the former does not change the flavour of the food product. Typical gamma or X-ray doses required are in the range of kGy to hundreds of Gy (Fig. 8.11).

Sterilisation

Radiation sterilising is based on the use of gamma rays and accelerated electrons to destroy bacteria, fungi and viruses. It works through the sealed packaging of the material, without raising the temperature or requiring the addition of any chemical. It is particularly of interest for medical supplies many of which cannot withstand high temperatures (e.g. plastic syringes). Recently it has been proposed to destroy anthrax bacterium sent in mail by the use of such radiation.

Insect Control

Insect control using radiation consists of irradiating laboratory male insects before hatching, to sterilise them. The sterilised males are then released to the environment

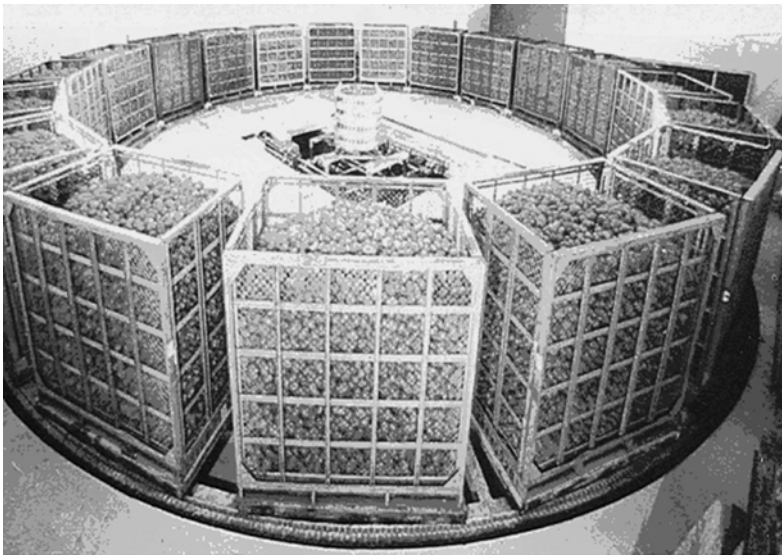


Fig. 8.11. Shihoro Potato irradiation facility located in Hokkaido, Japan [12]. In Japan 10,000 tons of potatoes are irradiated per year to inhibit sprouting

in the infested areas. Following mating with females, no offspring are produced. Repeated releases of sterilised males in the affected area will result in almost complete elimination of the insect pest. Successful operations have been carried out in Mexico against the Medfly (Mediterranean fruit fly) and the screwworm.

Nuclear Batteries

Using the energy released from the radioactive decay of radionuclides for the purpose of heating, lighting, or electricity production is an attractive concept. Devices using such energy sources could operate for long periods without human intervention. One problem, however, is that that relativley large quantities of radioactive materials are required to generate powers in excess of a few watts. One of the SNAP thermoelectric generators with an output power of 68 W contained 2.25×10^5 Ci of ^{90}Sr. Another problem is that such large amounts of radioactive material is a considerable health hazard.

Conversion of Radioactive Decay Energy to Electricity

There are basically two ways to convert radioactive decay energy to electricity:

1. The decay energy is converted to thermal energy which is then further converted to electrical energy.
2. The emitted radiation (charged particle or photon) is converted directly to electrical energy

In the first case, electrical energy generation is based on a thermal cycle using radionuclide heat sources (RHSs). Although there are many methods for the conver-

sion, the most suitable for RHSs are the dynamic, thermionic, and thermoelectric methods [13]. In the *dynamic* method, the generator is driven by a circulating fluid in a closed system which is evaporated by the radionuclide source. The conversion efficiency of such systems is typically 10–15%.

In the *thermionic* method, heat from the source is used to generate electrons via thermoelectric emission. The efficiency is around 20%. The most practical method for thermoelectric conversion, however, is the *thermoelectric* method first proposed by Ioffe in 1929. In this method thermal energy is converted to electrical energy based on the thermo-electromotive force arising from a temperature gradient between two sides of an electrical circuit consisting of different conductors or semiconductors. The hot junctions are in thermal contact with the source. The cold junctions are cooled by heat removal. The maximum efficiency is around 6%.

In the second case, electrical energy is produced directly via direct charge, direct conversion, or indirect conversion methods. In the *direct charge battery*, the charge particles are collected directly onto a battery electrode. These give rise to typically large voltage low current systems. The first battery based on this idea was suggested by Mosely in 1913. A thin walled spherical quartz ampule filled with radium was used as the emitter. The alpha particles were retained by the walls and the beta particles were transmitted through the walls. An electrode was used to collect the beta particles. These direct charge batteries produce high voltage (10–100 kV) and deliver powers in the range micro-milliwatt at high efficiency (typically 75%). In *direct conversion batteries*, the radiation (alpha, beta etc.) is used to ionise a gas filling the space between two metal electrodes with different work functions. The electrodes contact potential difference creates the electric field for the charged particles. The energy conversion in these systems, however, is only around 0.5% due to the high energy required for ion pair formation (around 30 eV).

In indirect conversion batteries, the energy released by the radioactive decay is transformed to light radiation using radioluminescent methods. The light energy is later converted to electrical energy by photovoltaic methods.

Nuclear Batteries Based on Beta-Emitters

Beta-emitters with stable daughters are the least hazardous sources since they can shielded relatively easily – even in significant amounts. These are suitable for light or electricity production but not for heat production since not much heat is generated (typically beta energies are 200–300 keV). As energy sources, the half-lives of the isotopes should be a few years. From the more than 3000 known radionuclides, only a few are beta emitters with stable daughters and suitable half-lives such as ^{3}H, ^{14}C, ^{45}Ca, and ^{63}Ni. Other nuclides of interest are ^{55}Fe (Auger electron emitter), ^{147}Pm (with soft gammas) and ^{204}Tl (high energy beta). Some of their characteristics are listed in Table 8.1.

The specific power, P_{sp}, per Curie of activity is defined as

$$P_{sp} = 3.7 \times 10^{10} \cdot \int_{0}^{\varepsilon_{max}} w(\varepsilon_\beta) \cdot \varepsilon_\beta \cdot d\varepsilon_\beta = 3.7 \times 10^{10} \cdot \varepsilon_{av}$$

Table 8.1. Characteristics of radionuclides of interest as energy sources [13]

Nuclide	^{3}H	^{14}C	^{45}Ca	^{55}Fe	^{63}Ni	^{147}Pm	^{204}Tl
Halflife y	12.3	5710	0.44	2.7	100	2.7	3.8
Radiation	β^-	β^-	β^-	e^-, X	β^-	β^-, weak γ	β^-, X
Average energy, keV	5.7	49	77	e^--5.2	17.6	62	243
P_{sp}, μW Ci^{-1}	34	290	456	e^--18, X-10	100	367	1440

where ε_β is the kinetic energy of the beta particle, $w(\varepsilon_\beta)$ is the distribution function and ε_{av} is the average energy. When the ε_{av} is measured in keV, and P_{sp} in μW Ci^{-1} then

$$P_{sp} = 5.92\ \varepsilon_{av}\ .$$

Tritium is of special interest for light generation. From Table 8.1, the average beta energy is 5.7 keV implying a maximum beta energy of (3 × average) approximately 18 keV. This is also the energy of the electrons in cathode ray tubes in televison sets. The paths length for electrons in solids with this energy is only a few microns implying that heavy shielding is not required. Tritium is used in many different forms for radioluminescent light sources e.g. metal tritides, tritium loaded silicon, tritium containing zeolites and aerogels, selected organic tritium containing compounds.

Nuclear Batteries for Microelctromechanical Systems (MEMS)

Using microelectromechanical systems (MEMS) technology, also known as nanotechnology or micromechanics, tiny devices can be produced which can perform precise functions in applications such as medical equipment, environmental management, and in automobiles. A common application for MEMS is as tiny sensors in airbags in cars [14].

One possibility to power these tiny systems is with nuclear batteries. A fundamental advantage of power units based on radionuclides lies in their power density and longevity [15]. In Table 8.2 a list of potential candidate nuclides for such applications is shown. The data is taken from the Nuclides.net database. The heat generation resulting from radioactive decay is also shown. A characteristic of these MEMS is that they require power sources that are both lightweight and intense.

Normally, exposure to radioactive materials is hazardous and their use must be closely regulated. However the amounts of materials required (to produce power in the range of nanowatts to microwatts (nW-μW) is so small that they may not pose safety risks or require regulation. In addition these radioactive energy sources would be encapsulated to withhold the radiation.

Table 8.2. Potential candidate nuclides for nuclear powered MEMS [15]

Nuclide	Half-life	Isotopic power	Quality	Energy
^{3}H	12.3 y	300 W g^{-1}	Low energy β^-, no gammas	18.57 keV (β^-)
^{14}C	5730 y	1.3 mW g^{-1}	Low energy β^-, no gammas	156.5 keV (β^-)
^{32}Si	132 y	34.5 mW g^{-1}	Low energy β^-, no gammas	225 keV (β^-)
^{63}Ni	100.1 y	5.7 mW g^{-1}	Low energy β^-, no gammas	65.87 keV (β^-)
^{90}Sr	28.84 y	160 mW g^{-1}	Low energy β^-, no gammas	546 keV (β^-)
^{121}Sn	1.13 d	642 W g^{-1}	Low energy β^-, no gammas	383 keV (β^-)
^{134}Cs	2.06 y	1.32 W g^{-1}	β^-, and gamma emission	Range (β^-, γ)
^{147}Pm	2.62 y	340 mW g^{-1}	Low energy β^-, no gammas	224.5 keV (β^-)
^{151}Sm	90 y	4 mW g^{-1}	β^-, and gamma emission	76.3 keV (β^-), 21.5 keV (γ)
^{204}Tl	3.78 y	3.4 mW g^{-1}	β^-, low energy gammas	349 keV (β^-)
^{210}Po	138.4 d	144 W g^{-1}	High energy α, low energy γ	5.3 MeV (α, γ)
^{228}Ra	5.75 y	38 mW g^{-1}	β^-, low energy gammas	39 keV (β^-)
^{241}Am	432.2 y	115 mW g^{-1}	High energy α, low energy γ	Range (α, γ)
^{242}Cm	162.8 d	122 W g^{-1}	High energy α, low energy γ	Range (α, γ)
^{244}Cm	18.1 y	2.8 W g^{-1}	High energy α, low energy γ	Range (α, γ)

9. Radiation and the Environment

Biological Effects of Ionising Radiation

When ionising radiation passes through tissue, the component atoms may be ionised or excited. As a result the structure of molecules may change and result in damage to the cell. In particular, the genetic material of the cell, the DNA (deoxyribonic acid) may be changed. Two categories of radiation-induced injury are recognised: deterministic effects and stochastic effects. Deterministic effects are usually associated with high doses and are characterised by a threshold. Above this threshold the damage increases with dose. Stochastic effects are associated with lower doses and have no threshold. The main stochastic effect is cancer.

The radiation dose depends on the intensity, energy and type of the radiation, the exposure time, the area exposed and the depth of energy deposition. Various quantities such as the absorbed dose, the equivalent dose and the effective dose have been introduced to specify the dose received and the biological effectiveness of that dose [1].

Absorbed Dose

The absorbed dose (D) is the amount of radiation absorbed per unit mass of material. The modern SI unit of absorbed dose is the gray (Gy) where one gray is one joule per kilogram $1\,\mathrm{Gy} = 1\,\mathrm{J\,kg^{-1}}$. In dosimetry, it is useful to define an average dose for a tissue or organ D_T. The absorbed dose to the mass δm_T, is defined as the imparted energy δE_T per unit mass of the tissue or organ, i.e.

$$D_\mathrm{T} = \frac{\delta E_\mathrm{T}}{\delta m_\mathrm{T}}\,.$$

The absorbed dose rate is the rate at which an absorbed dose is received. The units are $\mathrm{Gy\,s^{-1}}$, $\mathrm{mGy\,hr^{-1}}$, etc. Biological effects depend not only on the total dose to the tissue but also on the rate at which this dose was received. In organisms, mechanisms exist which enable molecules such as deoxyribonucleic acid (DNA) to recover if they have not been too badly damaged. Hence it is possible for organs to recover from a potentially lethal dose provided that the dose was supplied at a sufficiently slow rate. This phenomena can be exploited in cancer radiotherapy.

Quality or Weighting Factor

The biological effect of radiation is not directly proportional to the energy deposited by radiation in an organism. It depends, in addition, on the way in which the energy is deposited along the path of the radiation, and this in turn depends on the type of radiation and its energy. Thus the biological effect of the radiation increases with the linear energy transfer (LET) defined as the mean energy deposited per unit path length in the absorbing material (units keV μm^{-1}). Thus for the same absorbed dose, the biological effect from high LET radiation such as α particles or neutrons is much greater than that from low LET radiation such as β or γ rays. The quality or weighting factor, w_R, is introduced to account for this difference in the biological effects of different types of radiation. The weighting factors for the various types of radiation and energies is given in Table 9.1.

Table 9.1. The ICRP radiation weighting factors [2]

Type of radiation, R	Energy range	Quality or weighting factor, w_R
Photons, electrons	All energies	1
Neutrons	<10 keV	5
	10–100 keV	10
	100 keV–2 MeV	20
	2–20 MeV	10
	>20 MeV	5
Protons	<20 MeV	5
Alpha particles, fission fragments, heavy nuclei		20

Equivalent Dose, H_T

To reflect the damage done in biological systems from different types of radiation, the equivalent dose is used. It is defined in terms of the absorbed dose multiplied by a weighting factor which depends on the type of radiation i.e.

$$H_{T,R} = w_R D_{T,R} ,$$

where $H_{T,R}$ is the equivalent dose in tissue T and w_R is the radiation weighting factor. The ICRP weighting factors are given in Table 9.1.

Equal equivalent doses from different sources of radiation delivered to a point in the body should produce approximately the same biological effect. However, a given equivalent dose will in general produce different effects in different parts of the body. A dose to the hand is, for example, considerably less serious than the same dose to blood forming organs. If there are several types of radiation present, then the equivalent dose is the weighted sum over all contributions, i.e.

$$H_T = \sum_R \left(w_R D_{T,R} \right) .$$

The SI unit of dose is the Sievert, Sv (1 Sv = 1 J kg^{-1}, the old unit is the rem, 1 Sv = 100 rem). This is the equivalent dose arising from an absorbed dose of 1 Gy. Hence

for γ rays, where $w_R = 1$, an absorbed dose of 1 Gy gives an equivalent dose of 1 Sv. The same absorbed dose for α particles, where $w_R = 20$, gives an equivalent dose of 20 Sv. The equivalent dose rate is the rate at which an equivalent dose is received, i.e.

$$dH_{T,R}/dt = w_R dD_{T,R}/dt \ .$$

The equivalent dose rate is expressed in Sv s^{-1} or mSv hr^{-1}.

The sievert, Sv, is the unit describing the biological effect of radiation deposited in an organism. The biological effect of radiation is not just directly proportional to the energy absorbed in the organism but also by a factor describing the *quality* of the radiation. An energy deposition of 6 J per kg due to gamma radiation (quality = 1), i.e. 6 Sv is lethal. This same energy deposited in the form of heat (quality = 0) will only increase the body temperature by 1 mK and is therefore completely harmless. The difference between the two types of radiation is due to the fact that biological damage arises from ionisation.

Effective Dose, *E*

In general, cells which undergo frequent cell divisions, and organs and tissue in which cells are replaced slowly, exhibit high radiation sensitivity. This is why different tissues show different sensitivities to radiation. The thyroid, for example, is much less sensitive than bone marrow. In order to take these effects into account, equivalent doses in different tissues must be weighted. The resulting effective dose is obtained using

$$E = \sum_T (w_T H_T) \ ,$$

where H_T is the equivalent dose in tissue or organ T and w_T is the tissue weighting factor. The ICRP tissue weighting factors are shown in Table 9.2.

Table 9.2. ICRP Tissue weighting factors [2]

Tissue	Weighting factors, w_T
Gonads	0.20
Red bone marrow	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder	0.05

Committed Effective Dose, $E(\tau)$

A person irradiated by gamma radiation outside the body will receive a dose only during the period of irradiation. However, following an intake by ingestion or inhalation, some radionuclides persist in the body and irradiate the various tissues for many years. The total radiation dose in such cases depends on the half-life of the radionuclide, its distribution in the body, and the rate at which it is expelled from the body. Detailed mathematical models allow the dose to be calculated for each year following intake. The resulting total effective dose delivered over a lifetime (70 years for infants, 50 y for adults) is called the committed effective dose. The name arises from the fact that once a radionuclide has been taken up into the body, the person is "committed" to receiving the dose [1]. The ICRP has published values for committed doses following intake of 1 Bq of radionuclide via ingestion and inhalation. These are known as the effective dose coefficients $e(\tau)$ and have been calculated for intake by members of the public at six standard ages, and for intake by adult workers. The unit of the effective dose coefficient is Sv/Bq.

Collective Effective Dose

On the assumption that radiation effects are directly proportional to the radiation dose without a threshold, then the sum of all doses to all individuals in a population is the collective effective dose with unit manSv. As an example, in a population consisting of 10,000 persons, each receives a dose of 0.1 mSv. The collective dose is the $10\,000 \times 0.0001 = 1$ manSv. The effects of various doses to man are listed in Table 9.3.

Table 9.3. Effects of radiation exposure to man [3]

Dose (whole body irradiation)	Effects
< 0.25 Sv	No clinically recognizable damage
0.25 Sv	Decrease in white blood cells
0.5 Sv	Increasing destruction of the leukocyte-forming organs (causing decreasing resistance to infection)
1 Sv	Marked changes in the blood picture (decrease in the leukocytes and neutrophils)
2 Sv	Nausea and other symptoms
5 Sv	Damage to the gastrointestinal tract causing bleeding and ≈ 50% death
10 Sv	Destruction of the neurological system and ≈ 100% death within 24 h

Radiotoxicity and Annual Limits of Intake

Radiotoxicity of an isotope refers to its potential capacity to cause damage to living tissue as the result of being deposited inside the body. This damage potential is

Committed Effective Dose, $E(\tau)$

The sum of the products of the committed organ or tissue equivalent doses and the appropriate organ or tissue weighting factors (w_T), where τ is the integration time in years following the intake. The integration time for adults is 50 years.

Effective Dose Coefficient, $e(\tau)$

The committed effective dose per unit acute intake where τ is the time period in years over which the dose is calculated (e.g. $e(50)$).

Intake

Activity that enters the respiratory or gastrointestinal tract from the environment.

governed by the type and energy of the radioactive disintegration, the physical half-life, the rate at which the body excretes the material, and the radio-sensitivity of the critical organ.

The radiotoxicity is defined here in terms of dose received by a population ingesting all the radioactive materials present at a given time, taking into account the nature and energy of the emitted radiation and its effect on biological organisms. For this purpose it is suitable to use the Committed Effective Dose $E(\tau)$ – see inset – as a measure of the radiotoxicity, hence

$$\text{Radiotoxicity} = E(\tau)\,.$$

The committed effective dose of a radionuclide is given by the effective dose coefficient multiplied by the activity of the radionuclide at the time of intake, hence

$$\text{Radiotoxicity} = A \cdot e(\tau)\,,$$

where A is the activity of the radionuclide at the moment of intake.

It should be noted that many radionuclides decay to nuclides that are themselves radioactive (radioactive daughters). The effective dose coefficients take into account the ingrowth of daughters in all regions of the body following an intake of unit activity of the parent nuclide. They do not take into account any activity of daughter nuclides in the initial intake.

The activity is just the number of disintegrations per second and is measured in units of becquerel, Bq (1 Bq = 1 disintegration per second). The effective dose coefficient e is a measure of the damage done by ionising radiation associated with the radioactivity of an isotope. It accounts for radiation and tissue weighting factors, metabolic and biokinetic information. It is measured in units of sievert per becquerel (Sv/Bq) where the sievert is a measure of the dose arising from the ionisation energy absorbed.

The Annual Limit of Intake (ALI) of an isotope is defined as the activity required to give a particular annual dose. Publication 60 of the ICRP recommends a committed effective dose limit of 20 mSv per year, hence

$$ALI = \frac{(0.02)\,\text{Sv}}{e(50)}\,.$$

The *ALI* is a calculated value based on the primary dose limit and gives only the annual limit of intake. It is sometimes more useful to establish the limits on the concentration of a radionuclide in air or water which would lead to this intake. For this purpose the derived air concentration (*DAC*) is introduced for airborne contaminants. The *DAC* is the average atmospheric concentration of the radionuclide which would lead to the *ALI* in a reference person as a consequence of exposure at the *DAC* for a 2000 h working year. A reference person inhales 20 litres of air per minute or 2400 m^3 during the working year. The derived air concentration is

$$DAC\left(\frac{\mathrm{Bq}}{\mathrm{m}^3}\right) = \frac{ALI_{\mathrm{inh}}(\mathrm{Bq})}{2400\,\mathrm{m}^3}\,.$$

^{137}Cs, for example, has an $ALI_{\mathrm{inh}} = 3.0 \times 10^6$ Bq. It follows that the *DAC* = 1.2 Bq/m^3. Similarly the derived water concentration (*DWC*) is given by

$$DWC\left(\frac{\mathrm{Bq}}{\mathrm{litre}}\right) = \frac{ALI_{\mathrm{ing}}(\mathrm{Bq})}{913\,\mathrm{litre}}$$

based on a water intake of 2.5 litre per day. For members of the public, the values obtained for the *DAC* and *DWC* should be further reduced by a factor 20 corresponding to a dose limit of 1 mSv per year.

Table 9.4. Annual Limits of Intake (*ALI*) for ingestion which results in a dose of 0.02 Sv for the main radioactive by-products of nuclear waste. The values are given in both becquerel and mass units

Isotope	Annual Limit of Intake (becquerel)	Annual Limit of Intake (mass)
Plutonium-239	8.0×10^4	30 μg
Minor actinides MA		
Neptunium-237	1.82×10^5	7 mg
Americium-241	1.00×10^5	0.8 μg
Curium-244	1.67×10^5	0.06 μg
Selected fission fragments		
Technetium-99	3.13×10^7	40 mg
Iodine-129	1.82×10^5	30 mg
Caesium-135	1.00×10^7	0.2 g

Radiation Hormesis and the Linear Non-Threshold (LNT) Model

Although it is generally believed that low doses arising from chemicals, pharmaceuticals, radiation, etc. produce effects proportional to high doses, there is evidence to suggest that this is incorrect and that low doses may have a beneficial effect to biolog-

ical systems. This positive effect arising from low doses is referred to as "hormesis" from the Greek word "hormaein" which means "to excite". Radiation hormesis refers to the stimulation of biological functions by low doses of radiation.

The first observation of hormesis dates to the 1940s where it was reported that low doses of Oak bark extract stimulated fungi growth (in contrast to inhibiting growth at high doses). In the 1980s, the first complete report on radiation hormesis was published [4].

Toxicology, and in particular the dose response relation, is very important in many medical and public-health issues. Predictions based on this relationship have major implications for risk assessment and risk communication to the public. At issue here is the known hormetic (beneficial or positive) response of cells and organisms to radiation dose.

It has been claimed recently [5] that the toxicological models in current use by regulatory authorities to extrapolate dose response at low doses of carcinogens are incorrect. Traditionally, the dose-response relationship used for risk assessment to obtain the risk from low doses of carcinogens is the so-called "linear non-threshold model" (LNT) shown in Fig. 9.1b. There is increasing evidence, however, that the dose-response relation is actually "U" shaped or "J" shaped as shown in Fig. 9.1c. This "U" shape is a manifestation of hormesis where a response stimulation occurs at low doses.

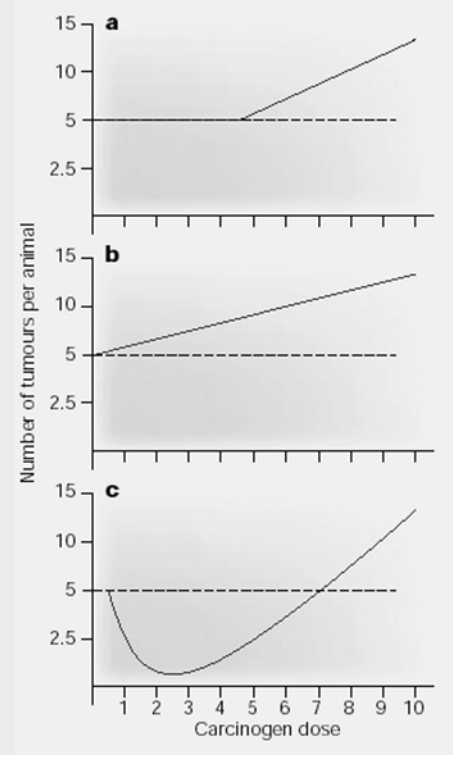


Fig. 9.1. Hypothetical curves depicting (**a**) threshold, (**b**) linear non-threshold, and (**c**) hormetic dose-response models using cancer (number of tumours per animal) as the endpoint. The reduction in number of tumours per animal at the lower doses (1–6) compared to the number of tumours per animal (5 tumours per animal) in the control indicates a reduced risk of cancer. (Reprinted by permission from Nature [5]. © 2003 Macmillan Publishers Ltd.)

Current radiation protection standards are based on the assumption that all doses, no matter how small, can result in health detriment and the likelihood is directly proportional to dose received; i.e. the accepted dose response relationship for estimating harm is the linear non-threshold (LNT) model. According to the Health Physics Society, there is increasing scientific evidence that this model represents an oversimplification of the biological mechanisms involved and that it results in an overestimation of health risks in the low dose range. The Health Physics Society notes that radiogenic health effects (primarily excess cancers) are observed in human epidemiology studies only at doses in excess of 0.1 Sv delivered at high dose rates. Below this dose, estimation of adverse health effects is speculative.

UNSCEAR is also showing increasing reservation toward the use of dose commitment (individual dose integrated over infinite time) and collective dose. Both are consequences of the linear non-threshold model of radiation effects. Recent radiobiological and epidemiological studies suggest that this model has lost credibility [6]. The organisation is proposing to spend more time and resources to learn the effect of anthropogenic radiation on individual plants and animals. It is well known, for example, that in Kerala, India, where the natural radiation level (up to about 400 millisieverts per year) is much higher than the average global one (2.4 mSv), black rats for 800 to 1000 generations have shown no adverse biological effects [6, 7].

High Background Radiation Areas Around the World

According to the UNSCEAR 2000 report, in the seaside city of Guarapari (80,000 inhabitants), Brazil, peak dose rate measurements on the beach are as high as 40 μSv/h – about 200 times higher than the average natural background radiation level in other areas of the world. In Ramsar, northern Iran, some inhabited areas have the highest known natural radiation levels (up to 260 mSv/y) [7].The radiation in Ramsar is due primarily to radium dissolved in mineral water.

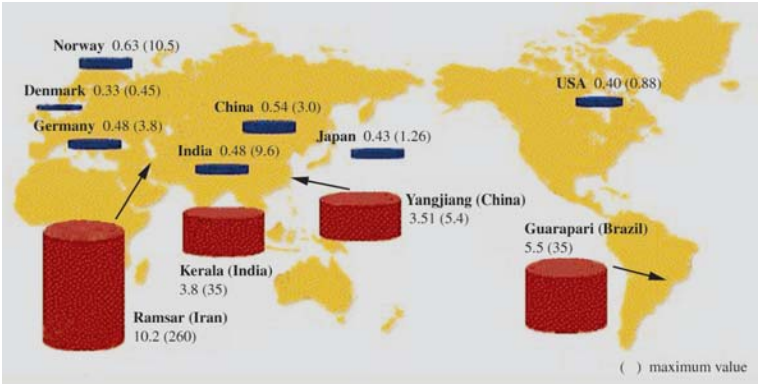


Fig. 9.2. Average (and maximum) dose rates in mSv/y worldwide. Figure adapted from Health Research Foundation, Kyoto, Japan. With courtesy to S. M. Javad Mortazavi, Biology Division, Kyoto University of Education, Kyoto, Japan

Radon: A Test for the LNT Hypothesis?

What is Radon?

Radon (^{222}Rn) is a colourless, odourless, tasteless, radioactive noble gas which occurs naturally from the decay of uranium in the earth. It arises from the radioactive decay of ^{226}Ra (itself a decay product of uranium) and has a half-life of 3.8 days. Its short-lived daughter products include the alpha emitters ^{210,214,218}Po.

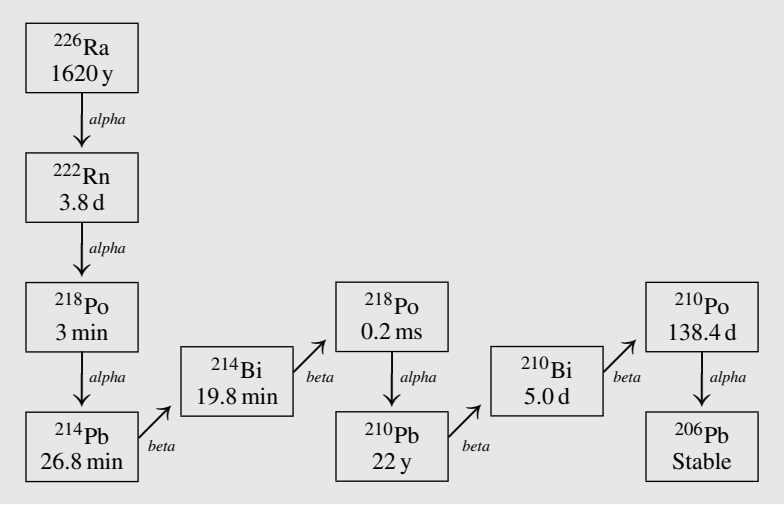


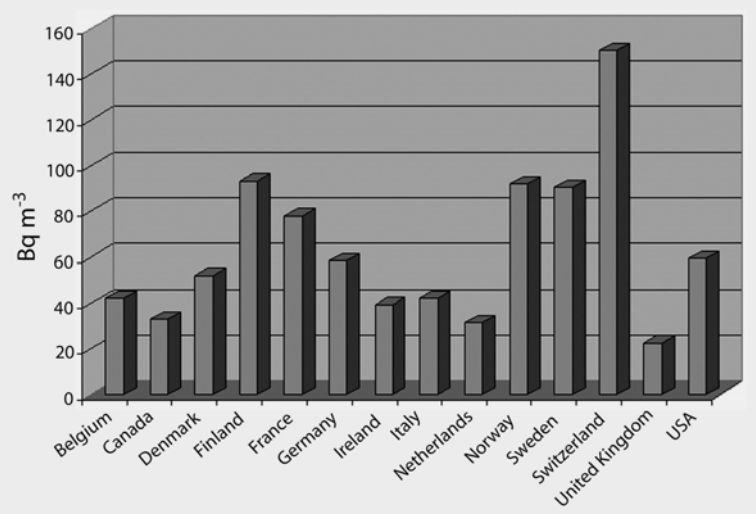
Fig. 9.3. Decay chain of ^{226}Ra

Radon gas can be found where uranium is present in the ground. The gas concentration builds up in caves and in the cellars of buildings. Of the naturally ocurring radiation sources giving rise to a total radiation dose of 2.4 mSv/y, radon gas is the largest contributor with a value of 1.3 mSv/y [8]. It has been estimated that between 5% and 15% of all lung cancer cases are attributed to radon inhalation.

For centuries, it has been known that some underground miners suffered from higher rates of lung cancer than the general population. The link between ^{222}Rn exposure and lung cancer was first postulated in 1556 when Agricola described high mortality rates among underground miners in the Erz Mountains of Central Europe. Since then many studies of miners have confirmed this link. In the 1950s, the cause of lung cancer was attributed to the radon progeny (the daughters of ^{222}Rn). These radioactive daughters are electrically charged and can attach themselves to tiny dust particles in indoor air. Particles inhaled adhere to the lung linings where they cause radiation damage to the cells by disrupting the cell DNA whch can eventually lead to cancer.

In 1998 the National Academy of Sciences (NAS) estimated that between 3000–32,000 lung cancers deaths per year in the U.S. are attributable to to residential ^{222}Rn progeny [9]. The authors, however, cautioned that there is considerable uncertainty

Table 9.5. Average concentration of radon in Europa and North America: Exposure to radiation from natural sources can be significant. The radon in the domestic environment can give rise to annual doses that exceed the ICRP dose limits for occupational exposure. A value of 50 Bq/m^3 corresponds to an averaged equivalent dose of 15 mSv/y



in these figures because of limited knowledge on the effects of low levels of exposure and that from the evidence now available, a threshold exposure, that is, a level of exposure below which there is no effect of radon, cannot be excluded.

Current EU limit is 200 Bq/m^3 for new and 400 Bq/m^3 for old houses. These values, however, are exceeded in many countries. The ICRP suggests 500 Bq/m^3 for homes and 1000 Bq/m^3 for the workplace [10].

Therapeutic Effects of Radon

Observations of the beneficial effects of radon on human health date back to prehistoric times [11]. There is archaeological evidence that radon sources were in use in Gastein, Austria thousands of years ago. The ancient Romans used radon spas and in Ischia, Italy, the therapetic baths have been in use for over 2000 years. The springs of Misasa in Japan have been in use for 800 years.

Today there are many therapeutic radon centres in use: in Germany, in Austria (most well known is Bad Gastein, Fig. 9.4), Czech Republic, France, Italy, Ukraine, Russia, Japan, and the U.S. Currently some 75,000 patients are treated annually in German and Austrian radon spas mostly for painful inflamatory joint diseases such as rheumatism, arthritic problems, Morbus Bechterew, psoriasis, gout, chronic bronchitis, asthma etc.

Following a three week treatment period, beneficial effects are claimed to last for periods of six months or more. Treatment involves inhaling radon in high concentration. In Bad Gastein's Heilstollen the radon concentration is 170,000 Bq/m^3 (almost

Fig. 9.4. Therapy zone in Bad Gastein (Austria) healing gallery

a thousand times higher than the current legilsation) or by drinking or bathing in radon water.

In view of the claimed contribution to the population dose and the associated risk of lung cancer (indoor radon claimed to cause about 20,000 lung cancer deaths annually in the U.S.) it is suprising to note that the costs for the radon therapy are partly covered by the medical health insurance schemes.

A Test for LNT?

Because of the claimed large contribution to the total population dose, the effects of radon should be considered as a test for the validity of the LNT hypothesis. It has, for example, been claimed recently [11] that radon studies provide evidence against the LNT hypothesis.

Radiation Exposure in High-Flying Aircraft

The radiation exposure to passengers and crew in high-flying aircraft is caused by energetic photons and particles such as neutrons, protons, electrons, muons, and pions. These radiation types are produced as a result of the interaction with the Earth's

Cosmic Rays

These comprise 85% protons, 14% alpha particles, and 1% heavier ions covering the full range of elements, some of the more abundant being, for example, carbon and iron nuclei. They are partly kept out by the earth's magnetic field and have easier access at the poles compared with the equator. From the point of view of space systems it is particles in the energy range 1–20 GeV per nucleon which have most influence.

atmosphere of high-energy particles (primarily protons and alpha particles) that come from a variety of cosmic sources in our galaxy, with a lesser contribution from our own sun. The galactic component of this incoming cosmic radiation is always present; the solar contribution varies in intensity over an approximately eleven-year cycle. In fact, the galactic component is greatest at solar minimum and is reduced at solar maximum by solar particle interactions with irregularities in the magnetic field associated with the "solar wind."

There are four main factors that affect the increased radiation dose received by travellers on long-distance airflights: altitude, latitude, hours aloft, and solar activity [12, 13].

Altitude

The amount of cosmic radiation doubles approximately with every 2000-metre increase in altitude. In most commercial aircraft, which fly at 10,000 or 12,000 metres, cosmic radiation is approximately 100 times higher than on the ground [13]. In flights on the Concorde at a height of 18,000 metres, passengers received a radiation dose twice as intense as on subsonic flights. However, since the flight time is shorter, the dose received during a flight is virtually identical to the one received during a subsonic flight on any given route.

Latitude

The Earth's magnetic field creates a barrier which causes cosmic radiation to be concentrated at high latitudes near to the north and south magnetic poles. The dose rate at 70 degrees north or south latitude is about four times as much as at 25 degrees [12]. Thus, flights over polar routes will result in higher radiation dose rates than those at lower latitudes.

Flight Duration

The total dose of cosmic radiation received is directly proportional to the duration of exposure, and thus with the duration of the flight. For occasional travellers, rather than frequent flyers, this increased radiation does not present a significant risk. Airplane crew, however, with 1000 hours flying time, would receive a dose in the range 5–10 mSv depending on the route.

Solar Activity

Solar flares can increase the cosmic radiation level. Unlike the stable radiation of galactic origin, the sun is the source of an unpredictable component of cosmic radiation. It constantly ejects particles with an intensity which varies according to an 11-year cycle as shown in Fig. 9.5.

Typical annual doses received by cabin personnel, frequent and occasional flyers are shown in Table 9.6. Further information on cosmic radiation and the calculation of the dose received in high-flying aircraft can be found at the SIEVERT website [13].

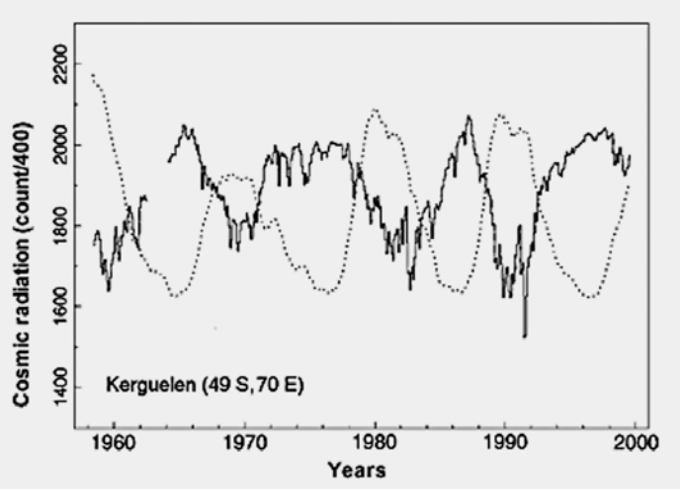


Fig. 9.5. Variation in the intensity of galactic cosmic radiation observed on the ground from 1959 to 2000, compared with that of the index of sunspots (dotted line). During periods of high solar activity, the cosmic radiation is less intense, as the particles have more difficulty reaching the Earth. Source: IPEV and Paris Observatory [13]

Table 9.6. Annual dose received in high-flying aircraft (based on a flying altitude of 10,000 m – at this height the radiation dose rate is 52 mSv/y, corresponding to 6 μSv/h) [11]

	Cabin personnel	Frequent flyers	Occasional flyers
Flight duration	40 days per year	10 days per year	2 days per year
Dose	$52 \cdot (40/365)$ $= 5.7$ mSv	$52 \cdot (10/365)$ $= 1.4$ mSv	$52 \cdot (2/365)$ $= 0.3$ mSv

In the recommendations of both the NCRP and ICRP, two population groups are identified i.e. members of the general public, and "radiation workers" who are exposed to radiation through their occupation. For this latter group, government standards give an occupational exposure limit which is 20 to 50 times greater than those for the general public (Table 9.7). The rationale for this distinction is that

Table 9.7. Maximum permissable doses (MPD) to radiation workers and members of the public

		NCRP	**ICRP**
General public:	Annual MPD	1 mSv	1 mSv
Radiation workers:	Annual MPD	50 mSv	20 mSv
	Cumulative MPD	10 mSv × age	–
	MPD during pregnancy	5 mSv	2 mSv

"radiation workers" presumably accept the increased risk in exchange for the benefits of employment. Note that in addition to its annual MPD for occupationally exposed radiation workers, the NCRP recommends a cumulative lifetime limit (in mSv) equal to 10 times a worker's age. So, for instance, a pilot who retires at age 60 should not be exposed to more than 600 mSv over his entire flying career. Assuming that career lasts 30 years, average annual exposure should not exceed 20 mSv.

Conan the Bacterium

The bacterium *Deinococcus radiodurans* or *D. radiodurans*, which means "strange berry that withstands radiation", was first identified in 1956. It was isolated from a can of beef which had been radiation sterilised. Normally bacteria do not withstand the radiation processing. This was not the case, however, with *D. radiodurans* now affectionately known among scientists as Conan the Bacterium [14, 15].

Not only does the bacterium show resistance to toxic chemicals, but *D. radiodurans* is extremely resistant to massive doses of ionising radiation. Following a radiation dose in excess of 10,000 Sv (thousands of times higher than the lethal radiation dose in humans), the radiation damaged the bacterium's genetic material by breaking each of the chromosomes into more than one hundred pieces. Due to a a unique repair system which efficiently repairs the damage to its DNA the bacterium returns to normal within a few hours.

The bacterium is believed to be as old as the Earth and could have been one of the earliest forms of life on the planet. Due to its radiation repair abilities it could even have come from space.

An interesting application is to use a genetic manipulation of the bacteria to break down toxic organic chemicals at radioactive waste sites. In particular, the task is to engineer radiation-resistant microbes that degrade or transform this waste into less hazardous forms. Using bacteria for such purposes is known as bioremediation. In the US, some 3000 sites have been contaminated due to nuclear related activities. In many of the sites, the waste contains a mixture of organic pollutants with radioisotopes of

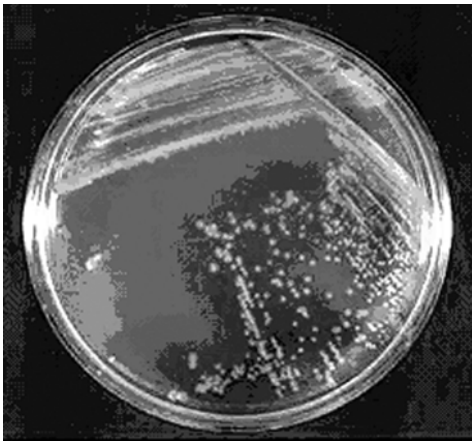


Fig. 9.6. Colonies of *D. radiodurans* growing in a petri dish.
Courtesy Michael Daly

uranium and plutonium. Traditional physicochemical cleaning methods would take decades and prove very costly. Bioremediation techniques could be considerably less expensive than the conventional methods.

Packaging and Transport of Radioactive Materials

Each year more than 10 million packages of radioactive materials are transported worldwide. Radionuclides are used for a variety of purposes e.g. in nuclear medicine, materials testing, oil exploration etc. For these purposes, radioactive materials must be packaged and transported to the location of interest. Before these materials can be shipped, care must be taken that the regulations have been strictly followed. The purpose of these regulations, of course, is to ensure safety by containing the radioactivity to make sure that there is no negative effect on the environment, to control the radiation emitted from the package, make sure that nuclear fission criticality conditions cannot be met, and to dissipate any heat generated within the package.

For the purpose of transportation, radioactive materials were previously defined as those materials which spontaneously emit ionising radiation and have a specific activity in excess of 0.002 microcuries per gram (0.002 μCi/g or 74 Bq/g) of material. In 2001, new regulations on the transport of radioactive materials were introduced with lower limits on the specific activity of individual nuclides [16].

The choice of packaging depends on the radionuclides involved, the amounts of radioactivity to be shipped and the form of the radionuclides. Restrictions on the amounts of material are determined by the so-called "$A1$" and "$A2$" values [16]. "$A1$" is the maximum amount of activity for a special form radionuclide that is allowed in Type A packaging, whereas "$A2$" refers to the maximum amount of activity in a Type A package for normal form materials. Usually the $A1$ or $A2$ values can not exceed 37 terabecquerels (37×10^{12} Bq) or 1000 curies (Ci). For some materials, however, the limits have been set to 40 TBq or more (in the case of ^{238}U).

Example. As an example, consider the radionuclides ^{137}Cs and ^{60}Co. The $A1$ and $A2$ values are shown in Table 9.8 where it can be seen that the values for ^{137}Cs are quite different and for ^{60}Co are the same.

Table 9.8. Maximum activities for special ($A1$) and normal form ($A2$) materials

Nuclide	$A1$ (special form)	$A2$ (normal form)
^{137}Cs	2 TBq	0.6 TBq
^{60}Co	0.4 TBq	0.4 TBq
^{238}U	No limit	No limit

In the case of ^{60}Co, this means that even if five different exposure pathways are considered, there is no greater risk than if only the external gamma radiation pathway were considered. This is not the case with ^{137}Cs which does indeed depend on the exposure pathway.

The special form referred to above refers to the fact that if the material were released from the package, the only hazard would be from external gamma radiation. An example of such a special form is that of a sealed (encapsulated) source of radiation. Here the durable metal capsule with high physical integrity ensures that the radioactivity will not disperse. In addition, only solid materials are classified as "special form". Special form encapsulation is designed such that the capsule cannot be opened unless it is destroyed.

In contrast to special form materials, normal form materials may be solid, liquid, or gaseous. Examples here are waste materials in a plastic bag, a liquid-containing bottle housed with a metal contained, powder in a glass or plastic bottle, contaminated soil in a drum, or gas in a cylinder.

A1

The values of the quantity $A1$ arise through worst-case assumptions with regard to external gamma radiation from a known source at a certain distance. More exactly, the $A1$ value for a particular radionuclide is that quantity of radionuclide which will give rise to a dose rate of 0.1 Sv/h at a distance of 1 m from the package. Since only external radiation is considered, it is assumed that the radioactive material inside the package will not be dispersed if the package is damaged.

A2

The $A2$ value also relates to the worst-case assumptions, but five different exposure pathways are considered rather than just the single pathway associated with the $A1$ value. The five pathways are:

- external gamma radiation
- external beta radiation to the skin
- inhalation
- ingestion
- external gamma radiation from immersion in a gaseous cloud of radioactive material released from a damaged package

It is important to note that the $A2$ values refer to normal form radioactive materials and to both external and internal exposure. In contrast to the $A1$ value, the $A2$ value assumes that dispersal and contamination of the package content is probable. On this basis, the $A2$ values are always lower than the $A1$ values.

Packaging

Type A packaging is required for shipping radioactive materials when the radioactivity inside the package does not exceed the $A1$ or $A2$ values. If the radioactivity is higher, type A packaging, which is foreseen for normal transportation conditions and minor accidents only, cannot be used. The basic purpose of type A packaging is to prevent loss or dispersal of the package contents while maintaining proper radiation shielding under normal transportation conditions. Type A packaging must withstand water spray, drop, puncture and crash tests.

When the level of radioactivity exceeds the $A1$ and $A2$ values, type B or type C packaging is required. Type B and C packaging must meet all the conditions of

type A packaging and in addition have the ability to withstand serious accidents. Examples of type B packaging are spent nuclear fuel casks.

Transport Index

The Transport Index "*TI*" is the dose rate in units of millisieverts per hour (mSv/h) at a distance of one meter from the external surface of a package containing radioactivity, multiplied by a factor 100. The Transport Index is printed on the label of a package so that interested persons can assess the relative radiation hazard and the control to be exercised upon handling. In special cases (tanks, big containers), an additional multiplication factor must be used.

Nuclear Waste Disposal

Nuclear waste disposal is a problem of radioactive material "packaging" in the extreme. One of the challenges facing the nuclear industry is to demonstrate that an underground repository can contain nuclear waste for very long periods of times and that any releases that might take place in the future will pose no significant health or environment risk. It must be taken into account that the engineered barriers which initially contain the wastes will degrade, and that some residual radionuclides may return to the surface in low concentrations at some time in the future due to groundwater movement and environmental change.

One way of building confidence in engineered barriers is by studying the processes which operate in natural and archaeological systems and by making appropriate parallels with a repository. These studies are called "natural analogues" [17]. The natural analogues are particularly relevant in the event that nuclear waste transmutation is introduced[1].

Natural Analogues

There are many radioactive materials which occur naturally and can be found in rocks, sediments etc. In particular, uranium which is the main component in nuclear fuel, occurs in nature. By studying the distribution in nature, information can be obtained on the movement of uranium in rocks and ground waters.

Natural analogues provide a way of informing the wider public on the principles on which repositories are built, without using complex mathematical demonstrations of "safety" and "risk". One of the concepts which can be presented using analogues is the very slow degradation of materials over thousands of years. Some notable natural analogues are:

[1] Recently proposals have been put forward to introduce transmutation of nuclear waste reduce the burden of underground repositories [18]. Through transmutation, the mass and the radiotoxicity of the waste are significantly reduced as is also the time needed to reach the radioactivity level in natural ores. The proposed schemes lead to the radiotoxicity of the waste reaching reference levels in about 500–700 years rather than hundreds of thousands of years in the natural decay process.

• **The Inchtuthil Roman Nails:** The most northerly fortress in the Roman Empire at Inchtuthill in Perthshire, Scotland had to be abandoned hastily in 87 AD. In an attempt to hide metal objects which could be used for weapons, the Romans buried over one million nails in a 5 m deep pit and covered them with 3 m of compacted earth. These nails were discovered in the 1950s.

Fig. 9.7. A Roman nail found at Inchtuthil, Scotland. © Glasgow Steel Nail Co. Ltd.

It was found that the outermost nails were badly corroded and had formed a solid iron oxide crust. The innermost nails, however, showed only very limited corrosion. This was attributed to the fact that the outer nails removed the oxygen from the infiltrating groundwater such that by the time they came into contact with the innerlying nails the waters were less corrosive. In the same way, the large volumes of iron in waste canisters are expected to maintain chemically reducing conditions in an environment which is oxygen rich due to the radiolytic decomposition of water.

• **The Kronan Cannon:** The Kronan was a Swedish warship built in 1668 and which sank in 1676 during the Battle of Öland [19]. One of the bronze cannon on board the Kronan had remained partly buried in a vertical position, muzzle down in clay sediments since the ship sank. This cannon is a good analogue for canisters to be used in the Swedish and Finnish spent fuel repositories which have a copper outer shell since the cannon had a very high content of copper (96.3%). From an analysis of the cannon surface, a corrosion rate of 0.15 μm/y was established. At this rate of corrosion, it would take some 70,000 years to corrode 1 cm thickness of copper. This provides evidence for the very long life of copper spent fuel canisters in the repository.

• **Hadrian's Wall:** In AD 122 Emperor Hadrian ordered construction of a wall to separate the lands of the Britons from that of the Picts to the north. Hadrian's Wall was over 100 km long and 5 m high and was built from stone blocks cemented together. The Wall is of interest as an analogue due to the longevity of Roman cement used to bind the stones together. Modern Portland cement is very similar chemically and mineralogically. From these studies, conclusions can be drawn with regard to the stability and longevity of modern cements in repositories.

• **The Dunarobba Forest:** In the Dunarobba forest near Todi in Italy, dead tree trunks approximately 2 million years old have been found in their original upright position [20]. Remarkably, in contrast to typical fossilised trees, the Dunarobba trees are still composed of wood. The wood has been preserved due to the surrounding clay. This clay stopped oxygenated waters reaching the wood thereby limiting the aerobic decomposition. The Dunarobba trees are of relevance in repository concepts since the wood is considered to be analogous to the organic/cellulosic materials which comprise a large part of the waste.

Fig. 9.8. The Dunarobba Forest, Italy. © CRIDEA (ref. 20)

• **The Needle's Eye:** This site in south-west Scotland, close to a natural rock arch known as the Needle's eye, comprises a sea-cliff in which the mineralised veins of uranium and other metals are partly exposed [21]. Uranium is present as pitchblende (UO_2) associated with secondary minerals.

Fig. 9.9. The Needle's Eye, Scotland. Courtesy Michael E. Brookfield

The pitchblende has undergone dissolution by two processes. In the first, slow leaching results in a preferential loss of ^{234}U relative to ^{238}U. The second is dissolution by oxidising waters. The mobilised uranium is redeposited in close proximity to the vein as stable oxidised uranium minerals. In contrast to uranium, the dissolution and transport of thorium is negligible.

The Needle's Eye is ideal for investigating radionuclide migration behaviour and for testing geochemical codes in simulation exercises.

• **The Oklo Natural Fission Reactors:** In 1972 scientists in France found that the ^{235}U content of ore being processed to make nuclear fuel pellets had been depleted from the normal 0.72% to 0.62%. The ore had been obtained from Oklo in the south-

east part of the Republic of Gabon in West Africa. Further investigations revealed that nuclear fission had taken place. The uranium ore bodies at Oklo are the only known examples of natural fission reactors. The criticality took place approximately 2 billion years ago as a result of dissolution, mobilisation and accumulation of uranium in sufficient mass to achieve criticality. Natural uranium had a much higher content of ^{235}U at that time. The chemistry of the uranium is such that it is practically insoluble in water under oxygen-free conditions, but readily soluble in water in the presence of oxygen. The fission reactions operated intermittently for between 10^5 and 10^6 years.

Fig. 9.10. Remains of one of the Oklo reactors. © CEA

The natural fission reactors at Oklo can be considered as analogues for very old radioactive waste repositories and can be used to study the transport behaviour of transuranic nuclides and stability of uranium minerals which have undergone criticality.

Nuclear Tests in the South Pacific

France began atmospheric nuclear testing in the South Pacific at the atolls of Mururoa and Fangataufa atolls in 1966 [22]. These French Polynesian atolls, were chosen because of their relative isolation and geological characteristics as shown in Fig. 9.11.

The first tests conducted at the Mururoa and Fangataufa sites were atmospheric. Underground testing started in June 1975. In total 41 atmospheric and 134 borehole tests were conducted between 1960 and 1991. A final series of eight tests were conducted between September 1995 and May 1996 after which France signed the Comprehensive Nuclear Test Ban Treaty (CTBT) [23].

Geological and radiological surveillance of the Mururoa and Fangataufa atolls will continue on a periodic basis for many years. Radioactivitiy measurements in air and water will be made together with measurements in soil and sediment and in plants, fish, plankton, shellfish under the auspices of the IAEA.

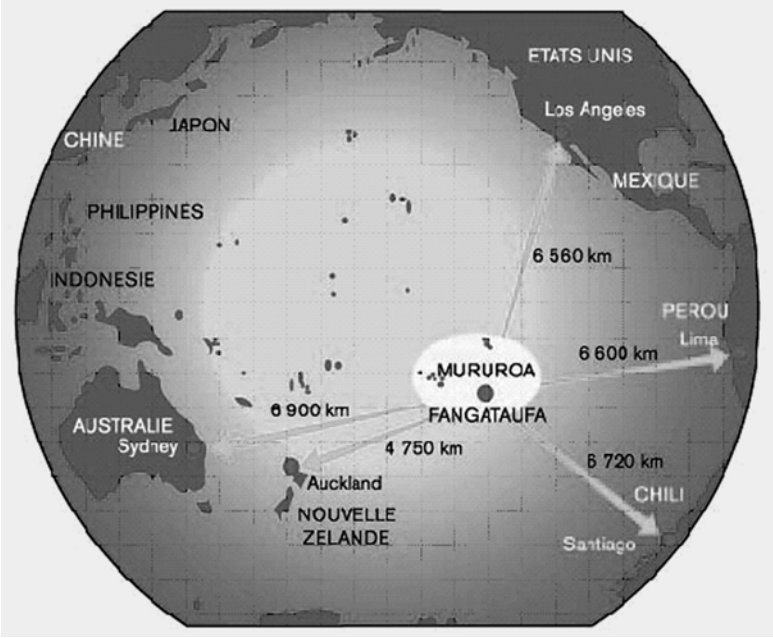


Fig. 9.11. French map showing the location of the Mururoa and Fangataufa atolls [22]

Atoll Geology

Atoll are ring-shaped coral reefs a few metres in height enclosing a lagoon (Fig. 9.12). They are the result of volcanic eruptions that occurred millions of years ago. Fuelled by a hotspot in the Earth's crust, these volcanoes grew some four kilometres in height from the sea floor until they reached the ocean surface where they were capped with several hundreds of metres of carbonate rock from coral accretions. During glaciation periods, the sea level dropped some hundred metres below the top rim of the extinct volcano.

Fig. 9.12. Pacific atoll of Mururoa

Underground Nuclear Explosions

The nuclear tests were carried out at depths of between 500 and 1100 m in the volcanic rock. An underground nuclear explosion generates, apart from radioactivity, intense heat and a shock wave [24]. The rock in the vicinity is melted and vaporized forming a roughly spherical cavity and a pool of molten rock. On cooling, the molten mass in the cavity forms a glass-like lava that contains most of the radioactivity.

The confinement of the radioactivity in the solidified rocks is efficient. The water in the cavities formed contains some thousandths of the total $\beta\gamma$-activity and less than one millionth of the total α-activity. Basaltic glasses have existed for millions of years and show very good stability against the phenomena of natural leaching. Leaching rates of the order of 1 μm per 1000 years have been observed. Leaching rates of similar order of magnitude have been observed in laboratory studies of vitrified nuclear waste.

Radionuclide Inventory

The inventory of long-lived radionuclides resulting from the underground nuclear explosions is shown in Table 9.9. The activities have been estimated from the yields

Table 9.9. Inventory of selected long-lived radionuclides at Mururoa and Fangataufa atolls [25, 26]

	Study data (TBq)		
Radionuclide	Mururoa	Fangataufa	Total
Tritium	232 000	48 000	280 000
Carbon-14	25	2.6	28
Chlorine-36	1.3	0.4	1.7
Calcium-41	1.0	0.3	1.3
Nickel-59	2.9	0.9	3.8
Nickel-63	340	110	450
Selenium-79	0.008	0.003	0.011
Krypton-85	670	380	1 000
Strontium-90	7 300	3 500	10 800
Zirconium-93	0.23	0.09	0.32
Technetium-99	1.9	0.6	2.5
Palladium-107	0.18	0.03	0.21
Iodine-129	0.0047	0.0014	0.0061
Caesium-135	0.20	0.07	0.27
Caesium-137	10 700	4 100	14 800
Neptunium-237	0.22	0.03	0.25
Plutonium-238	185	15	200
Plutonium-239	1 030	70	1 100
Plutonium-240	280	20	300
Plutonium-241	6 200	620	6 800
Americium-241	350	30	380

of the explosions together with reasonable assumptions regarding the proportion of energy from ^{239}Pu, ^{235}U, ^{238}U fission and from fusion of hydrogen isotopes [25].

Following the nuclear tests in the south Pacific atolls of Mururoa and Fangataufa, detailed measurements revealed that the predominant nuclides in marine and terrestrial environments were caesium-137, plutonium-239, and plutonium-240. It was established that the concentrations of radionuclides in coconuts, fish, and shellfish did not exceed a few becquerels per kilogram. Although modelling of the total inventory of radionuclides retained underground indicated that releases will peak in approximately 2500 years, it was concluded that no adverse radiological health effects will arise as a result of the addition of radioactivity to the environment.

The Chernobyl Accident

The Chernobyl power plant is about 7 km from the border with Belarus, with Kiev, the capital of Ukraine, about 100 km to the south with a population of 3.1 million. In the night of 25 April 1986, the explosion of the reactor released one hundred times more

Table 9.10. Current estimate of radionuclide releases during the Chernobyl accident [27, 28]

	Core inventory on 26 April 1986		**Total release during the accident**	
Nuclide	Half-life	Activity (PBq)*	Percent inventory	Activity (PBq)*
^{33}Xe	5.3 d	6 500	100	6 500
^{131}I	8.0 d	3 200	50–60	~1 760
^{134}Cs	2.0 y	180	20–40	~54
^{137}Cs	30.0 y	280	20–40	~85
^{132}Te	78.0 h	2 700	25–60	~1150
^{89}Sr	52.0 d	2 300	4–6	~115
^{90}Sr	28.0 y	200	4–6	~10
^{140}Ba	12.8 d	4 800	4–6	~240
^{95}Zr	65.0 d	5 600	3.5	196
^{99}Mo	67.0 h	4 800	>3.5	>168
^{103}Ru	39.6 h	4 800	>3.5	>168
^{106}Ru	1.0 y	2 100	>3.5	>73
^{141}Ce	33.0 d	5 600	3.5	196
^{144}Ce	285.0 d	3 300	3.5	~196
^{239}Np	2.4 d	27 000	3.5	~95
^{238}Pu	86.0 y	1	3.5	0.035
^{239}Pu	24 400.0 y	0.85	3.5	0.03
^{240}Pu	6 580.0 y	1.2	3.5	0.042
^{241}Pu	13.2 y	170	3.5	~6
^{2421}Cm	163.0 d	26	3.5	~0.9

* 1 PBq = 10^{15} Bq.

radiation than the atom bombs dropped over Hiroshima and Nagasaki. In addition to the reactor's immediate surroundings – an area with a radius of about 30 km – other regions were contaminated, particularly in Belarus, Russia and Ukraine.

The radionuclide releases from the damaged reactor occurred mainly over a 10-day period [27, 28]. From the radiological point of view, ^{131}I and ^{137}Cs were responsible for most of the radiation exposure received by the general population. The releases of ^{131}I and ^{137}Cs are estimated to have been 1760 and 85 PBq, respectively (1 PBq = 10^{15} Bq). The three main areas of contamination, defined as those with ^{137}Cs deposition density greater than 37 kBq/m^2 were in Belarus, the Russian Federation and Ukraine. In northern and eastern Europe, there were many areas with a ^{137}Cs deposition density in the range 37–200 kBq/m^2.

The Chernobyl accident is to date the only nuclear accident to be assigned a 7 on the INES (international nuclear event scale). This rating implies significant health consequences in addition to psychological effect. Of the 600 workers present during the accident, 134 received high doses in the range 0.7–13 Gy and suffered radiation illness. In the few months following the accident, 30 of the high dose victims died. Following the accident, around 200,000 recovery operations workers received doses between 0.01 and 0.5 Gy. Since 1986, the population in the neighbouring territories have been subjected to external and internal exposure from deposited radionuclides.

The Goiânia Radiation Incident – a Benchmark for Radiological Dispersion Devices (RDDs)

The Goiânia Radiation Incident is the most serious event recorded to date involving a medical radiation source [29–31]. Goiânia is the capital of the Brazilian state of Goiás in south-central Brazil with a population of 700,000 (1980). In September 1987, approximately one year after the Chernobyl accident, a radiation source contained in a metal canister was stolen from a radiotherapy machine in an abandoned cancer clinic and sold to a scrap dealer. Some five days later, the dealer opened the metal canister to find a fluorescent powder which was radioactive cesium (^{137}Cs) chloride. The source had a strength of 50 TBq (approx. 1400 Ci). The blue glow from the powder, caused by the absorption of the gamma rays by chlorine and emission of visible light, made it appear valuable. In the following days, the powder was also circulated among family and friends. A six-year-old girl rubbed the powder onto her body and ate a sandwich contaminated with the powder from her hands. In total 244 persons were exposed, and four died. Approximately 100,000 people were screened for contamination. The incident in Goiânia was the second largest radiological accident after Chernobyl and is regarded as a benchmark when discussing the potential consequences of radiological dispersion devices (RDD or "dirty bombs"). The socio-economic impact was such that tourism suffered greatly and it took five years for the gross domestic product to return to pre-1987 levels.

In order to illustrate the potential consequences of such radiological incidents, two idealised cases, involving a) external radiation exposure and b) internal exposure through inhalation, are considered in detail.

External Exposure Due to Radiation from a ^{60}Co Source

Consider a source of ^{60}Co located somewhere in the centre of a city. Since the radioactivity is not dispersed, population exposure occurs only through external radiation. As a source of ^{60}Co, we consider a capsule (used in radiotherapy) containing 1.7 g corresponding to an activity of 7.4×10^{13} Bq (2000 Ci). The gamma dose rate at various distances from the source is shown in Fig. 9.13 neglecting attenuation by buildings (calculated with the Γ-Dose module in Nuclides.net [32]). Results for three calculations are given: in "vacuum" (no absorption by air, no scattering), in air (absorption, no scattering), and in air (absorption and scattering). At 1 m from source the Γ-dose rate is 24.9 Sv h^{-1}. At a distance of approximately 200 m from the source, the dose rate has the value of 0.5 mSv h^{-1}. For an exposure time of 2 h (considered below) the dose received is 1 mSv, the limit for members of the public.

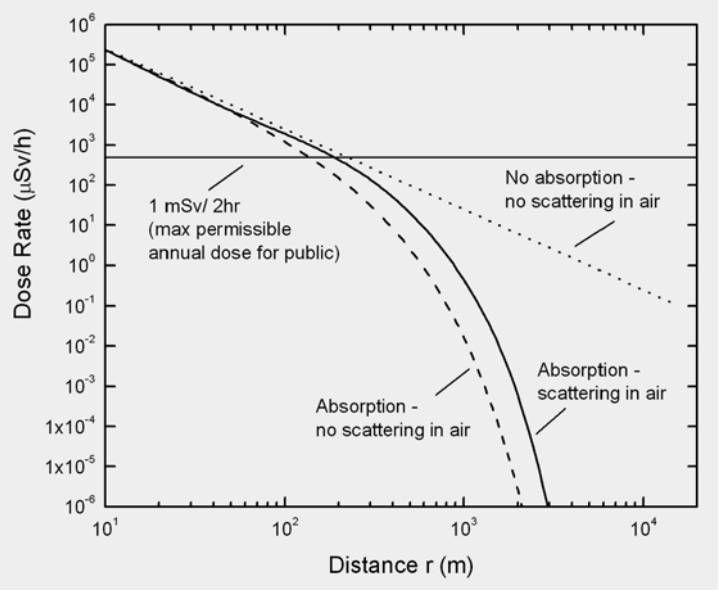


Fig. 9.13. Long-range radiological effects of a ^{60}Co source (7.4×10^{13} Bq). Beyond 100 m, the effects of air attenuation and scattering become important

Such a concealed radioactive source in an open area of high population density could lead to a significant radiation exposure. On the assumption that radiation effects are directly proportional to the radiation dose without threshold, then the sum of all doses to all exposed individuals is the collective effective dose, *CD*. This can be calculated as follows.

The dose rate $\mathrm{d}H(r)/\mathrm{d}t$ is received by the total number of people in a small ring of thickness $\mathrm{d}r$ at distance r. The number of people is this ring is then $\mathrm{d}N = 2\pi r \cdot \mathrm{d}r \cdot \rho_\mathrm{p}$ where ρ_p is the population density (inhabitants per square kilometre). The collective dose is then obtained by integrating this over the area of interest i.e.

$$CD = \sum_i \frac{\mathrm{d}H(r_i)}{\mathrm{d}t} \cdot \mathrm{d}N_i \cdot \Delta t = \sum_i \frac{\mathrm{d}H(r_i)}{\mathrm{d}t} \cdot 2\pi r_i \Delta r_i \rho_\mathrm{p} \Delta t$$

where Δt is the exposure time. For the above source (2000 Ci of ^{60}Co): $A = 7.4 \times 10^{13}$ Bq, an exposure time of 2 hours, a population density of 2600 inh/km^2, $R = 200$ m. Neglecting air attenuation and multiple scattering implies that the dose rate has the form $\mathrm{d}H(r)/\mathrm{d}t = kA/r^2$, where k is the specific gamma dose rate constant. This gives an upper limit to the dose rate as shown in Fig. 9.13 and allows one to obtain a simple expression for the collective dose, i.e.

$$CD = \int_{r_0}^{R} \left(\frac{kA}{r^2}\right) 2\pi r \mathrm{d}r \rho_\mathrm{p} \Delta t = 2\pi k A \rho_\mathrm{p} \Delta t \ln\left(\frac{R}{r_0}\right) ,$$

where the lower limit r_0 has been used to avoid the divergence at $r = 0$. The upper limit for integration R is where the equivalent dose rate reaches the limit for members of the public. Inserting the values $k = 3.37 \times 10^{-7}$ μSv m^2/h Bq [32] leads to the collective dose $CD = 5.3$ manSv. This is within a factor 2 of the more accurate value obtained by numerical integration.

The relationship between the radiation dose and the likelihood of incurring a stochastic effect can be expressed as a risk factor i.e. the likelihood of incurring a stochastic effect = collective dose (Sv)×Risk Factor (Sv^{-1}). The total number of excess cancers is the risk factor multiplied by the collective dose i.e.

$$\text{Total number of cancers} = 0.05\,\mathrm{Sv}^{-1} \times 5.3\,\text{manSv} = 0.27\,\text{persons}\,.$$

Internal Exposure Due to Inhalation of ^{60}Co Dispersed in a Radioactive Cloud

In this scenario, it is assumed that following the detonation of an RDD, radioactive material is dispersed into the atomosphere. To understand the dispersion of this radioactivity under given wind conditions, a simple dispersion model has been developed. It is assumed that as a result of the detonation, the activity S_T has been dispersed uniformly in fine (~ 1 μm) aerosol form resulting in a cylindrical radioactive cloud of radius $r(t)$ and height h. The cloud radius is given by $r(t) = vt$ where v is the horizontal dispersion velocity. This assumption of a cloud consisting of finely dispersed particle aerosol can be considered as a worst case. In reality, following an explosion, only a small percentage of the airborne activity would be in a form of fine (1 μm) aerosol. The dose by inhalation depends on the particle size distribution, and the larger the particle size the lower the dose (particles with aerodynamic diameter of more than 10 μm cannot reach the lungs). In a real case the fraction of radionuclides which is deposited into the lungs is likely below 10% (AMAD 5 μm = 5.8% deposit in the lung; AMAD 1 μm = 11% deposit in the lung).

The cloud location is a function of time and is given by the wind speed w, and the dispersion velocity v as shown in Fig. 9.14. The cloud height is the plume height resulting from detonation. The volume activity $A_\mathrm{V}(t)$ in the cloud is $A_\mathrm{V}(t) = S_\mathrm{T}/(\pi r^2 h) = S_\mathrm{T}/(\pi h v^2 t^2)$. It is assumed that the dose arises from internal exposure due to inhalation (this is usually many orders of magnitude higher than exposure due to external radiation).

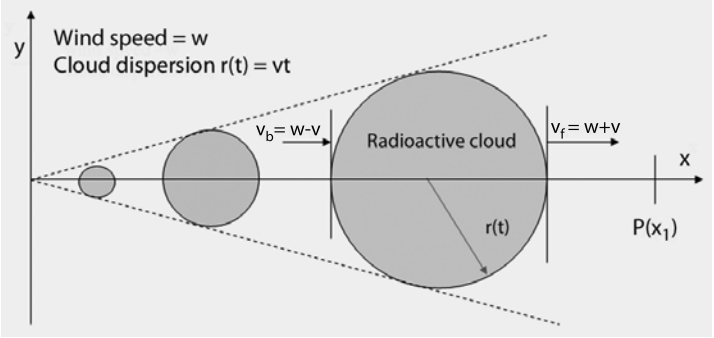


Fig. 9.14. Simplified cloud dispersion model. The cloud is moving with wind speed w (along the x-axis). Dispersion occurs radially such that the cloud radius r at any time t is given by $r(t) = vt$. It is assumed that the aerosol concentration is uniform within the cloud

At any time t, the contribution to the committed effective dose $\mathrm{d}E$ (dose generated by inhaled radioactive material within the next 50 years) received by a person in the cloud due to inhalation in time $\mathrm{d}t$ is given by

$$\mathrm{d}E(t) \equiv e_{\mathrm{inh}} \cdot \mathrm{d}A(t) = e_{\mathrm{inh}} A_V(t) R_{\mathrm{inh}} \mathrm{d}t = e_{\mathrm{inh}} (S_{\mathrm{T}}/\pi h v^2) R_{\mathrm{inh}} (1/t^2) \mathrm{d}t \quad (9.1)$$

where $\mathrm{d}A$ is the total activity intake, and e_{inh} the effective dose coefficient for inhalation. The total activity intake in time $\mathrm{d}t$ is $A_{\mathrm{V}} R_{\mathrm{inh}} \mathrm{d}t$ where A_{V} is the activity per unit volume and $\mathrm{R_{inh}}$ is the inhalation rate ($R_{\mathrm{inh}} = 1.2\,\mathrm{m^3/h}$). Integration leads to the total dose received by a person at x due to the passing cloud, i.e.

$$E(x) = \frac{e_{\mathrm{inh}} S_{\mathrm{T}} R_{\mathrm{inh}}}{\pi h v^2} \int_{t_1}^{t_2} \frac{1}{t^2} \mathrm{d}t = \frac{e_{\mathrm{inh}} S_{\mathrm{T}} R_{\mathrm{inh}}}{\pi h v^2} \left(\frac{1}{t_1} - \frac{1}{t_2} \right), \quad (9.2)$$

where t_1 and t_2 are the times at which the cloud front and back surfaces cross the point x. The cloud front surface has a speed of $w + v$ such that $t_1 = x/(w + v)$. For $w > v$, the cloud back surface moves along the x-axis such that $t_2 = x/(w - v)$. For $w \leq v$ (very low wind speeds), the cloud back surface is either stationary or moves along the negative x-axis such that $t_2 = \infty$. Hence:

for $t > x/(w + v)$ and $w > v$:

$$E(x,t) = \frac{e_{\mathrm{inh}} S_{\mathrm{T}} R_{\mathrm{inh}}}{\pi h v^2} \frac{(w+v)}{x} \left[1 - \frac{x}{(w+v) \min\left(t, \frac{x}{w-v}\right)} \right], \quad (9.3)$$

for $t > x/(w + v)$ and $w = v$:

$$E(x,t) = \frac{e_{\mathrm{inh}} S_{\mathrm{T}} R_{\mathrm{inh}}}{\pi h v^2} \frac{(w+v)}{x} \left[1 - \frac{x}{(w+v)t} \right]. \quad (9.4)$$

The expressions for the committed effective dose given in equations (9.3–9.4) are applied to the dispersion of ^{60}Co. The result are shown in Fig. 9.15 for a wind

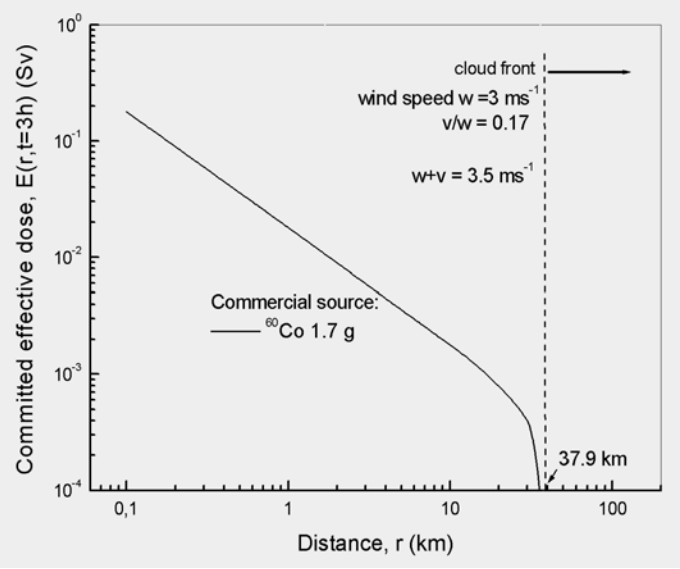


Fig. 9.15. Committed effective dose as a function of distance x from the detonation point in a moving radioactive cloud (wind speed $w = 3\,\mathrm{m\,s^{-1}}$, dispersion speed $v = 0.5\,\mathrm{m\,s^{-1}}$). It is assumed that the fine aerosol is dispersed uniformly in a cylindrical cloud with radius $r(t)$ and height h (see Fig. 9.14).

speed of $3\,\mathrm{m\,s^{-1}}$ and a radial dispersion speed of $0.5\,\mathrm{m\,s^{-1}}$. The simple analytical model can reproduce the more sophisticated code results very well.

A number of studies have already addressed the problem of RDDs fabricated from isotopes destined for medical and industrial purposes [33–40], such as ^{60}Co, ^{90}Sr, ^{137}Cs, ^{192}Ir, etc. The amount of radioactive material contained in such sources varies considerably but can be as high as tens of thousands of curies. These studies conclude that the consequences of an RDD using such radioactive materials are much less severe than those of a nuclear explosion. Compared to fission or fusion devices, the amount of radioactivity disperse is much less as is the energy released from detonation. The main consequence is social and economic disruption with limited casualties [41] and that expensive and time consuming decontamination will be required.

References

Chapter 1. Origins and Discovery

General References

R. Bimbot, A. Bonnin, R. Deloche, C. Lapeyre: *Cent ans après – La Radioactivité, Le Rayonnement d'une découverte.* EDP Sciences, 1999

One Hundred Years after the Discovery of Radioactivity. Radiochimica Acta (Special Issue), vol. 70/71. Oldenbourg Verlag, München 1995

X-Ray & Radioactivity Centennial Calendar. Health Physics Society's History Committee, 1995

H. Cember: *Introduction to Health Physics.* Third edition. McGraw-Hill, 1996

J. K. Shultis, R. E. Faw: *Fundamentals of Nuclear Science and Engineering.* Marcel Dekker, New York 2002

1. B. Pullman: *The Atom in the History of Human Thought.* Oxford University Press, 1998
2. J. J. Thomson: *The Corpuscular Theory of Matter.* Constable & Co., Ltd., London, 1907
3. Kelvin-Thomson "plum pudding" model of the atom. http://www.angelfire.com/sc2/atomtheory/main.html
4. E. Rutherford: Phil. Mag. **21**, 669 (1911)
5. Rutherford's nuclear atom. http://www.angelfire.com/sc2/atomtheory/main.html
6. H. Geiger, E. Marsden: Phil. Mag. **25**, 604 (1913)
7. N. Bohr: Phil. Mag. **26**, 1 (1913); **26**, 476 (1913)
8. J. E. Martin: *Physics for Radiation Protection.* John Wiley, 2000
9. Handbook of Chemistry and Physics, 78th edition, D. R. Lide (ed.). CRC Press, Boca Raton, Florida, 1997

Chapter 2. Nuclear Energetics

1. More information on the International System of Units (SI) can be found at: http://www.bipm.org/en/si/. See also the NIST website at http://physics.nist.gov/cuu/Units/
2. A good explanation of the atomic mass unit is given in: *Atomic, molecular, and formula masses*, see http://www.carlton.paschools.pa.sk.ca/chemical/molemass/
3. J. K. Shultis, R. E. Faw: *Fundamentals of Nuclear Science and Engineering.* Marcel Dekker, New York 2002
4. A list of atomic weights and isotopic abundances can be found at: Commission on Atomic Weights and Isotopic Abundances, http://www.physics.curtin.edu.au/iupac/
5. J. Magill: *Nuclides.net. An Integrated Environment for Computations on Radionuclides and their Radiation.* Springer, Heidelberg 2003. http://www.nuclides.net
6. E. Segrè: *A Mind Always in Motion. The Autobiography of Emilio Segrè.* University of California Press, Berkeley 1993, page 190

7. G. Fea: Nuovo cimento **12**, 368–407 (1935)
8. *Nuclides and Isotopes: Chart of the Nuclides*, 16th edition, E. M. Baum, H. D. Knox, T. R. Miller, Lockheed Martin, 2002
9. *Karlsruhe Chart of the Nuclides*, 6th edition 1995, revised reprint 1998, G. Pfennig, H. Klewe-Nebenius, and W. Seelmann-Eggebert
10. *Strasbourg Nuclide Chart 2002*, M. S. Antony, Centre de Recherches Nucleaires et Universite Louis Pasteur, Strasbourg, France
11. *JAERI Chart of the Nuclides 1996*. Japanese Nuclear Data Committee and Nuclear Data Center, JAERI, T. Horiguchi, T. Tachibana, J. Katakura
12. G Pfennig: Zur Geschichte der Karlsruher Nuklidkarte. Forschungszentrum Karlsruhe, Hausmitteilungen **1**, 25–26 (2003)
13. G. Friedlander, M. L. Pearlman: *General Electric Chart of the Nuclides*, 4th Edition 1956

Chapter 3. Radioactivity and Nuclear Reactions

1. M. Howarth: *Pioneer Research on the Atom.* London 1958, pp. 83–84
2. A. Fleck: 'Frederic Soddy' in Biographical Memoirs of Fellows of the Royal Society **3** 203–216 (1957)
3. H. Bateman: Proc. Camb. Phil. Soc. **16**, 423 (1910)
4. K. Skrable et al.: Health Physics **27**, 155–157 (1972)
5. K. H. Lieser: *Nuclear and Radiochemistry: Fundamentals and Applications.* VCH/Wiley, 1997
6. K. Shultis, R. E. Faw: *Fundamentals of Nuclear Science and Engineering*. Marcel Dekker, New York 2002
7. R. M. Mayo: *Introduction to Nuclear Concepts for Enngineers.* American Nuclear Society, 2001
8. J. Magill: *Nuclides.net: An Integrated Environment for Computation on Radionuclides and their Radiation.* Springer, Heidelberg 2003, http://www.nuclides.net

Chapter 4. Types of Radioactive Decay

1. J. Magill: *Nuclides.net. An Integrated Envvironment for Computations on Radionuclides and their Radiation.* Springer, Berlin Heidelberg 2003
2. J. E. Martin: *Physics for Radiation Protection.* John Wiley & Sons, 2000
3. O. Hahn, F. Strassmann: Naturwiss. **26**, 756 (1938).
4. L. Meitner, O. Frisch: Nature **143**, 239 (1939)
5. K. A. Petrzhak, G. N. Flerov: C. R. (Dokl.) Akad. Sci. URSS **28**, 500; J. Phys. USSR **3**, 275 (1940)
6. J. Galy: Investigation of the fission yields of the fast neutron-induced fission of ^{233}U. Thesis submitted for the degree of Doctor of Philosophy (September 1999)
7. H. O. Denschlag in: *Experimental Techniques in Nuclear Physics*, D. N. Poenaru, W. Greiner (eds.). Walter de Gruyter, Berlin 1997
8. F. Gönnenwein in: *The Nuclear Fission Process*, C.Wagemans (ed.). CRC Press, Boca Raton 1991
9. V. I. Goldansky: Ann. Rev. Nucl. Sci. **16**, 1 (1966)
10. K. P. Jackson et al.: Phys. Lett. **33B**, 281 (1970)
11. S. Hofmann et al., in: Proc. 4th Int. Conf. on Nuclei Far from Stability, CERN 81-09, Geneva, 111 (1982)
12. S. Hofmann: Proton Radioactivity. Radiochimica Acta **70/71**, 93–105 (1995)

13. B. A. Brown: Phys. Rev. C **43**, 1513–1517 (1991)
14. H. J. Rose, G. A. Jones: Nature **307**, 245 (1984)
15. M. Hussonis et al.: Phys. Rev. C **43**, 2599 (1991)
16. J. Sandulescu: Phys. G: Nucl. Part. Phys. **15**, 529 (1989)
17. G. T. Emery: Perturbation of nuclear decay rates. Ann. Rev. Nucl. Sci. **22**, 165 (1972)
18. Yu. A. Litvinov et al.: Observation of a dramatic hindrance of the nuclear decay of isomeric states for fully ionized atoms. Phys. Lett. B **573**, 80–85 (2003), http://mev.btg.cc/BTG-Library/files/yuri03plb.pdf
19. GSI-Nachrichten 1/01, Direct Observation of Bound Beta Decay at FRS/ESR, http://www.gsi.de/documents/DOC-2003-Jun-28-1.pdf
20. R. Daudel et al.: C. R. Acad. Sci. (Paris) **224**, 1427 (1947). See also R. Daudel, M. Jean, M. J. Lecoin: Phys. Radium **8**, 238 (1947)
21. M. Jung et al.: Phys. Rev. Lett. **69**, 2164 (1992)
22. F. Bosch et al.: Beta Decay of Highly Charged Ions, http://www-ap.gsi.de/research/posters/betadecay/
23. F. Bosch et al.: Phys. Rev. Lett. **77**, 5190 (1996)
24. K. Blasche, B. Franczak, in: Proc. of the 3rd European Accelerator Conf., Berlin, 1992, Vol. 9. Editions Frontières, Dreux, France
25. B. Franzke et al.: Nucl. Instrum. Methods **24/25**, 18 (1987)
26. The Sirius Science Booklet, http://www.ph.surrey.ac.uk/npg/sirius/SIRIUSver3.pdf

Chapter 5. Transmutation Research

1. E. Rutherford, J. E. Petavel: Brit. Assoc. Advan. Sci. Rep. A, 456 (1906)
2. E. Segrè: Phys. Rev. **71**, 274 (1947)
3. G. T. Emery: Perturbation of Nuclear Decay Rates. Ann. Rev. Nucl. Sci. **22**, 165 (1972).
4. H. Mazaki: J. Phys. E, Sci. Instrum. **11**, 739–741 (1978)
5. K. Ader, G. Bauer, V. Raff: Helv. Phys. Acta **44**, 514 (1971)
6. W. Rubinson, M. L. Perlman: Phys. Lett. B **40**, 352 (1972)
7. C. Ronchi: Institute for Transuranium Elements, Activity Report 2002, EUR 20658 EN, pp. 14–15
8. Y. Oganessian: Superheavy Elements. Physics World (July 2004), 25–29
9. S. Grevy et al.: Production of Super Heavy Elements at GANIL: Present Status and Perspectives. Journal of Nuclear and Radiochemical Sciences **3**, no. 1, pp. 9–12 (2002)
10. S. Hoffmann, G. Münzenberg: The Discovery of the Heaviest Elements. Revs. Mod. Phys. **72**, 733–767 (2000)
11. Element 110. http://www.gsi.de/portrait/Pressemeldungen/02122003.html
12. Element 111. http://www.gsi.de/portrait/Pressemeldungen/18052004.html
13. Element 111 and 112. S. Hofmann et al.: Eur. Phys. J. **A14**, 147–157 (2002)
14. P. J. Karol et al.: Pure Appl. Chem. **75** (10), 1601–1611 (2003). http://www.iupac.org/publications/pac/2003/pdf/7510x1601.pdf
15. Map of Isotopes. Flerov Laboratory, http://159.93.28.88/linkc/coop/index.html
16. K.W. D. Ledingham et al.: Science **300**, 1107–1111 (2003).
17. K.W. D. Ledingham et al.: Phys. Rev. Lett. **84**, 899 (2000)
18. H. Schwoerer et al.: Europhys. Lett. **61**, 47 (2003)
19. T. Tajima, G. Mouron: Phys. Rev. Special Topics – Accelerators and Beams **5**, 031301-1 (2002)
20. M. J. Feldman, R.Y. Chiao: Phys. Rev **A4**, 352–358 (1971)
21. O. E. Martinez et al.: J. Opt. Soc. Amer. **A1** 1003–1006 (1984)
22. P. Main et al.: IEEE J. Quant. Electr. **24**, 398–403 (1988)

23. C. K. Rhodes: Science **229**, 1345–1351 (1985)
24. K. Boyer, T. S. Luk, C. K. Rhodes: Phys. Rev. Lett. **60**, 557–560 (1988)
25. J. Magill et al.: Appl. Phys. **B**, 1–4 (2003)
26. K. W. D. Ledingham et al.: J. Phys. D: Appl. Phys. **36**, L79–L82 (2003)
27. F. Ewald et al.: Plasma Phys. Control. Fusion **45** 1–9 (2003)
28. See http://www.ualberta.ca/∼csps/JPPS3(2)/M.Kumar/particles.htm
29. See http://www.nea.fr/html/pt/docs/iem/madrid00/Proceedings/Paper41.pdf
30. J. Magill et al.: Joint Research Centre Technical Report JRC-ITU-TN-2003/08, March 2003
31. J. Magill: *Nuclides.net. An Integrated Environment for Computations on Radionuclides and their Radiation.* Springer, Heidelberg 2003. http://www.nuclides.net

Chapter 6. Archaeology and Dating

1. H. R. von Gunten: Radioactivity: A tool to explore the past. Radiochemica Acta **70/71**, 305–316 (1995)
2. Clocks in the Rocks: http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/clkroc.html#c1
3. Scrolls from the Dead Sea, http://www.ibiblio.org/expo/deadsea.scrolls.exhibit/intro.html
4. Isochron Dating: http://www.talkorigins.org/faqs/isochron-dating.html#generic
5. Watching a Rock Age on an Isochron Diagram: http://www.talkorigins.org/faqs/isochron-dating/AnimatedIsochron.html
6. C. Lewis: *The Dating Game – one Man's Search for the Age of the Earth*. Cambridge University Press, Cambridge 2000
7. H. Valladas et al.: Direct radiocarbon dates for prehistoric paintings at the Altamira, El Castillo and Niaux caves. Nature **357**, 68–70 (1992)
8. Dating of French cave art: http://www.culture.gouv.fr/culture/arcnat/chauvet/fr/
9. "Humboldts Erben" – Atlantis der Wüste. http://www.dfg.de/aktuelles_presse/termine/humboldts_erben_2/index.html#3
10. W. Aeschbach-Hertig: Klimaarchiv im Grundwasser. Physik in unserer Zeit **33** (4) 160 (2002)
11. EAWAG: Environmental Isotopes Group: http://www.eawag.ch/research_e/w+t/UI/waterage.html
12. J. Magill, R. Schenkel, L. Koch: Verification of Nuclear Materials and Sites, Detection of Clandestine Activities, and Assessment of the Proliferation Resistance of New Reactors and Fuel Cycle Concepts. Fachsitzung zum Thema "Abrüstung und Verification", Dresden 22–23 März, 2000
13. M. Wallenius, K. Mayer: 'Age' determination of plutonium material in nuclear forensics by thermal ionisation spectrometry. Fresenius J. Anal. Chem. **366**, 234–238 (2000)

Chapter 7. Radioisotopes in Medicine

1. K. Bethge, G. Kraft, P. Kreisler, G. Walter: *Medical Applications of Nuclear Physics.* Springer 2004
2. Benefits Uses and Production of Isotopes, 2000 Update. Nuclear Energy Agency, OECD 2000
3. B. Coursey, R. Nath: Radionuclide therapy. Physics Today on the Web, http://www.aip.org/pt/apr00/coursey.html
4. International Society for Neutron Capture, http://www.jrc.nl/isnct/
5. C. Apostolidis, R. Carlos-Marquez, W. Janssens, R. Molinet, A. Ouadi: Cancer treatment using Bi-213 and Ac-225 in radioimmunotherapy. Nuclear News **29–33** (Dec. 2001). See also http://ituwebpage.fzk.de/alpha_immuno/index.htm

Chapter 8. Scientific and Industrial Applications

1. P. S. Baker, D. A. Fuccillo, M. W. Gerrard, R. H. Lafferty: Radioisotopes in Industry. US-AEC, Washington D.C. 1965
2. Nuclear News, pp. 56–57, January 2004
3. Benefits Uses and Production of Isotopes, 2000 Update, Nuclear Energy Agency, OECD 2000
4. G. C. Lowenthal, P. L. Airey: *Practical Applications of Radioactivity and Nuclear Radiations.* Cambridge University Press, 2001
5. J. K. Shultis, R. E. Faw: *Fundamentals of Nuclear Science and Engineering.* Marcel Dekker, New York, 2002
6. A. Dassargues (ed.): Tracers and Modelling in Hydrogeology. IAHS Publication no. 262 (2000)
7. M. B. Treuhaft, X. Tao: Tracing Engine Wear. See http://www.swri.edu/3pubs/ttoday/spring98/trace.htm
8. Deutsches Museum. See http://www.deutsches-museum.de/ausstell/meister/e_roent.htm
9. Paul Scherrer Institute, http://www.psi.ch/
   NEUTRA homepage http://neutra.web.psi.ch/
10. Examples of Several Different Types of Fixed Gauges. See http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1556/v4/fig004.html
11. Mutant carnation flowers, http://www.kenkyubu.taka.jaeri.go.jp/j643/j643work_e.html, see also http://www.jaeri.go.jp/english/press/2002/021112/
12. Shihoro Potato irradiation facility located in Hokkaido, Japan.
    See http://wwwsoc.nii.ac.jp/aesj/publication/JNST2002/No.10/39_1106-1113.pdf
13. K. E. Bower, Y. A. Barbanel, Y. G. Shreter, G. W. Bohnert: *Polymers, Phosphors, and Voltaics for Radioisotope Batteries.* CRC Press, Boca Raton 2002
14. J. W. Gardner, V. K. Varadan, O. O. Awadelkarim: *Microsensors, MEMS, and Smart Devices.* John Wiley 2001
15. K. H. Lieser: *Nuclear and Radiochemistry: Fundamentals and Applications.* VCH/Wiley 1997

Chapter 9. Radiation and the Environment

1. J. R. Cooper, K. Randle, R. S. Sokhi: *Radioactive Releases in the Environment: Impact and Assessment.* Wiley 2003
2. ICRP Publication 72. Annals of the ICRP **26** (1996) Pergamon Press
3. K. H. Lieser: *Nuclear and Radiochemistry: Fundamentals and Applications.* VCH/Wiley 1997
4. T. D. Luckey: *Radiation Hormesis.* CRC Press, Boca Raton, 1991
5. E. J. Calabrese, L. A. Baldwin: Nature **421**, 691 (2003). See also Z. Jaworowski: "Radiation folly" in Environment and Health, Myths and Realities, K. Okonski and J. Morris (eds.), International Policy Network, 2004
6. R. E. J. Mitchel, D. R. Boreham: Proc. of the International Radiation Protection Association, 10th Quadrennial Meeting, Hiroshima, Japan, 15–19 May 2000, Plenary Session 1
7. P. C. Kesavan, in: High Levels of Natural Radiation, L. Wei, T. Sugahara, Z. Tao (eds.). Elsevier, Amsterdam 1996, p. 111
8. UNSCEAR, 1993. Sources and Effects of Ionising Radiation. Report of the United Nations Scientific Committee on the Effects of Atomic Radiation to the General Assembly.
9. Biological Effects of Ionizing Radiation (BEIR) VI Report: "The Health Effects of Exposure to Indoor Radon", National Academy Press, 1999. http://www.epa.gov/iaq/radon/beirvi1.html

10. ICRP Publication 65: Protection Against Radon-222 at Home and at Work. Annals of the ICRP **23/2**. Pergamon, 1994
11. K. Becker: Health Effects of High Radon Environments in Central Europe: Another Test for the LNT Hypothesis? Nonlinearity in Biology, Toxicology, and Medicine **1**, No. 1, 3–35 (2003)
12. R. J. Barish: *The Invisible Passenger: Radiation Risks for People Who Fly.* Advanced Medical Publishing, 1996
    Aircraft Radiation Exposure, http://hps.org/publicinformation/ate/cat38.html. See also http://www.avweb.com/news/aeromed/181873-1.html
13. Sievert: this website gives further information on cosmic radiatiion and allows one to calcluate the dose received in high-flying aircraft.
    http://www.sievert-system.org/WebMasters/en/
14. P. Huyghe: Conan the Bacterium. The Sciences, July/August 1998, New York Academy of Sciences
15. C. C. Lange, L. P. Wackett, K. W. Minton, M. J. Daly: Engineering a recombinant *Deinococcus radiodurans* for organopollutant degradation in radioactive mixed waste environment. Nature Biotechnology **16**, 929 (1998). The abstract can be obtained online at: http://www.nature.com/nbt/wilma/v16n10.906565782.html
16. ADR 2001: Gefahrgutverordnung Straße/Eisenbahn (Entwurf) Anlagen A und B zum ADR, K. Ridder, J. Holzhäuser, 3. Ausgabe, Landsberg/Lech: ecomed, 2001 (European Agreement Concerning the International Carriage of Dangerous Goods by Road)
17. William Miller et al.: *Geological Disposal of Wastes and Natural Analogues: Lessons from Nature and Archaeology.* Pergamon Press, 2000
18. A European Roadmap for Developing Accelerator Driven Systems (ADS) for Nuclear Waste Incineration. The European Technical Working Group on ADS, April 2001, ENEA, Rome. http://itumagill.fzk.de/ADS/publications.htm
19. Kronan cannon, http://www.kalmarlansmuseum.se/kronan/english/finds/cannon.html
20. Dunarobba forest, http://www.regione.umbria.it/cridea/cea/dunarobba.htm
21. Needle's eye, http://www.uoguelph.ca/∼mbrookfi/hutton3.htm
22. Mururoa Fangataufa, http://www.defense.gouv.fr/actualites/dossier/d60/sommaire.html
23. Radiological Situation at the Atolls of Mururoa and Fangataufa: Main Report (Radiological Assessment Reports Series). IAEA, 1998
24. E. T. Brown: The Consequences of Underground Nuclear Testing in French Polynesia. http://www.atse.org.au/index.php?sectionid=388
25. R. Fry, D. Levins, E. Warneke: Radionuclide Migration through the Geosphere. http://www.iaea.or.at/Publications/Magazines/Bulletin/Bull404/article7.pdf
26. Yu. A. Izrael: *Radioactive Fallout after Nuclear Explosions and Accidents.* Elsevier 2002
27. Sources and Effects of Ionizing Radiation, United Nations Scientific Committee on the Effects of Atomic Radiation, UNSCEAR 2000 Report to the General Assembly, with Scientific Annexes, Volume 2: Effects. ISBN 92-1-422396: Exposures and effects of the Chernobyl accident. http://www.unscear.org/pdffiles/annexj.pdf
28. CHERNOBYL Assessment of Radiological and Health Impacts: 2002 Update of Chernobyl: Ten Years On. Nuclear Energy Agency Organisation for Economic Co-operation and Development. http://www.nea.fr/html/rp/reports/2003/nea3508-chernobyl.pdf
29. IAEA, Dosimetric and medical aspects of the radiological accident in Goiânia in 1987, IAEA-TECDOC-1009. IAEA, June 1998
30. The Goiânia Radiation Accident, Health Physics, 60 Jan. 1991
31. Radiation Protection Dosimetry **25** (3) 217 (1988)

32. J. Magill: *Nuclides.net. An Integrated Environment for Computations on Radionuclides and their Radiation.* Springer, Berlin Heidelberg 2002. ISBN 3-540-43448-8. For further information, see the Nuclides.net website at http://www.nuclides.net/
33. Testimony of Dr. Henry Kelly, President Federation of American Scientists before the Senate Committee on Foreign Relations, USA, 2002. http://www.fas.org/ssp/docs/kelly_testimony_030602.pdf
34. M. A. Levi, H. C. Kelly: Weapons of Mass Disruption. Scientific American **77** (Nov. 2002). http://www.fas.org/ssp/docs/021000-sciam.pdf
35. C. D. Ferguson, T. Kazi, J. Perera: Commercial Radioactive Sources. Center for Nonproliferation Studies, Monterey Institute of International Studies, Monterey, USA, Occasional Paper Nr. 11, 2003. http://cns.miis.edu/pubs/opapers/op11/op11.pdf
36. The DOE/NRC Interagency Working Group, Radiological Dispersion Devices, Report to the Nuclear Regulatory Commission and the Secretary of State, May 2003. http://www.energy.gov/engine/doe/files/dynamic/1222004142719_RDDRPTF14MAY03.pdf
37. M. Bunn, A. Wier, J. P. Holdren: Controlling Nuclear Warheads and Materials, Washington, D.C., Nuclear Threat Initiative and the Project on Managing the Atom, Harvard University, 2003. http://www.nti.org/e_research/cnwm/cnwm.pdf
38. M. M. Hart: Disabling Radiological Dispersal Terror, Lawrence Livermore National Laboratory, Report UCRL-JC-150849, Nov. 8, 2002. http://eed.llnl.gov/ans/2002/hart/hart_ans_2002.pdf
39. IAEA, Updating IAEA-TECDOC-953. Method for developing arrangements for response to a nuclear or radiological emergency – Updating IAEA-TECDOC-953, IAEA-TECDOC-953, IAEA October 2003. http://www-pub.iaea.org/MTCD/publications/PubDetails.asp?pubId=6750
40. NCRP, Management of terrorist events involving radioactive material. NCRP Report No. 138. NCRP 2001. http://www.ncrp.com/138press.html
41. D. Elcock, G. A. Klemic, A. L. Taboas: Environ. Sci. Technol. **38**, 2505–2512 (2004)

Recommended Reading and Weblinks

Reading

1. R. Bimbot, A. Bonnin, R. Deloche and C. Lapeyre: Cent ans après – La Radioactivité, Le Rayonnement d'une découverte. EDP Sciences, 1999
2. One Hundred Years after the Discovery of Radioactivity. Radiochimica Acta (Special Issue), vol. 70/71. Oldenbourg Verlag, München 1995
3. X Ray & Radioactivity Centennial Calendar. Health Physics Society's History Committee, 1995
4. Herman Cember: Introduction to Health Physics. Third edition. McGraw-Hill, 1996
5. Cherry Lewis: The Dating Game – one Man's Search for the Age of the Earth. Cambridge University Press, Cambridge 2000
6. W. Miller, R. Alexander, Neil Chapman, Ian McKinley, and John Smellie: Geological Disposal of Radioactive Wastes and Natural Analogues – Lessons from Nature and Archaeology. Pergamon, Amsterdam 2000
7. C. Grupen: Grundkurs Strahlenschutz. Vieweg, Braunschweig 2000
8. H. V. Klapdor-Kleingrothaus: Sixty Years of Double Beta Decay – From Nuclear Physics to Beyond Standard Model Particle Physics. World Scientific, 2001
9. James E. Martin: Physics for Radiation Protection. John Wiley & Sons, 2000
10. Benefits Uses and Production of Isotopes, 2000 Update. Nuclear Energy Agency, OECD 2000
11. J. K. Shultis, R. E. Faw: Fundamentals of Nuclear Science and Engineering. Marcel Dekker, New York 2002
12. G. C. Lowenthal and P. L. Airey: Practical Applications of Radioactivity and Nuclear Radiations – An Introductory Text for Engineers, Scientists, Teachers and Students. Cambridge University Press, 2001
13. J. S. Lilley: Nuclear Physics – Principles and Applications. John Wiley & Sons, 2001
14. K. H. Lieser: Nuclear and Radiochemistry: Fundamentals and Applications. VCH / Wiley, 1997
15. G. R. Chopin, J. Liljenzin, and J. Rydberg: Radiochemistry and Nuclear Chemistry. Butterworth-Heinemann 2002
16. R. D. Evans: The Atomic Nucleus. McGraw-Hill, 1965
17. J. Emsley: The Elements. Clarendon Press, Oxford 1998
18. B. Coursey and R. Nath: Radionuclide Therapy. Physics Today on the Web, http://www.aip.org/pt/apr00/coursey.html
19. B. Schlein, L. A. Slaback, Jr., and B. Kent Birky: The Health Physics and Radiological Health Handbook. Third edition. Scinta, Silver Spring, MD 1998
20. S. Hoffmann and G. Münzenberg: The Discovery of the Heaviest Elements. Rev. Mod. Phys. **72**, 733–767 (2000)

21. P. J. Mohr and B. N. Taylor: The 1998 CODATA Recommended Values of the Fundamental Physical Constants, Web Version 3.1, available at physics.nist.gov/constants. National Institute of Standards and Technology, Gaithersburg, MD 20899, 3 December 1999
22. K. Ridder, J. Holzhäuser: ADR 2001: Gefahrgutverordnung Straße / Eisenbahn (Entwurf) Anlagen A und B zum ADR, 3. Ausgabe. ecomed, Landsberg/Lech 2001. (European Agreement Concerning the International Carriage of Dangerous Goods by Road)
23. J. Kenneth Schultis and Richard E. Faw: Radiation Shielding. American Nuclear Society, 2000
24. E. Browne and R. B. Firestone: Tables of Radioactive Isotopes. Wiley, New York 1986
25. J. R. Cooper, K. Randle, R. S. Sochi: Radioactive Releases in the Environment: Impact and Assessment. Wiley 2003
26. K. Bethge, G. Lraft, P. Kreisler, G. Walter: Medical Applications of Nuclear Physics. Springer 2004
27. Z. Jaworowski: "Radiation folly" in Environment and Health, Myths and Realities, K. Okonski and J. Morris (eds.), International Policy Network, 2004

Weblinks

Nuclear Data Services on the Internet

1. Atomic Mass Data Center: http://www-csnsm.in2p3.fr/AMDC/web/nubase_en.html
2. Table of Isotopes: http://ie.lbl.gov./toi.html
   http://nucleardata.nuclear.lu.se/NuclearData/toi/
3. Display of nuclear data: http://ie.lbl.gov/isoexpl/isoexpl.htm
4. National Nuclear Data Center, Brookhaven National Laboratory:
   http://www.nndc.bnl.gov/
5. Nuclear cross section data, Los Alamos: http://t2.lanl.gov/data/data.html
6. JEF Nuclear Data Services: http://www.nea.fr/html/dbdata/
7. Photon mass attenuation coefficients and the mass energy-absorption coefficients:
   http://physics.nist.gov/PhysRefData/XrayMassCoef/cover.html
8. International Commission for Radiological Protection: http://www.icrp.org/
9. Centre for Photonuclear Experimental Data, Moscow State University:
   http://depni.npi.msu.su/cdfe/services/index.html
10. International Atomic Energy Agency (IAEA) Nuclear Data Section:
    http://www-nds.iaea.or.at
11. Korean Atomic Energy Research Institute Nuclear Data Evaluation Laboratory:
    http://atom.kaeri.re.kr/
12. Petersburg Nuclear Physics Institute Data Center:
    http://georg.pnpi.spb.ru/english/RNDC.html
13. National Council on Radiation Protection and Measurement (NCRP):
    http://www.ncrp.com
14. International Commission on Radiation Units and Measurements (ICRU):
    http://www.icru.org
15. The German Institute of Radiation Protection: http://www.gsf.de/index_en.phtml
16. National Radiological Protection Board: http://www.nrpb.org
17. Health Physics Society: http://www.hps.org/
18. Laradioactivite.com. EDP Sciences, 2001: http://www.laradioactivite.com
19. Integrated Environment Management, Inc. (IEM): http://www.iem-inc.com/Index.html
20. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR),
    http://www.UNSCEAR.org/
21. National Radiological Protection Board, UK (NRPB), http://www.nrpb.org/

Glossary

***A*1, *A*2**
Values for the classification of radioactive sources for transportation purposes.

Absorbed Dose
The amount of energy deposited in any substance by ionizing radiation per unit mass of the substance. The SI unit for absorbed dose is the gray, symbol Gy. One gray is one joule of absorbed energy per kilogram of the material.

Actinide(s)
Any nuclide belonging to a series of 15 consecutive elements in the periodic table from actinium to lawrencium (atomic numbers 89 to 103). As a group they are significant largely because of their toxicity. Although several members of the group including uranium occur naturally, most are man-made.

Acute Exposure
A large exposure (typically greater than 0.1 Gy) received over a short period of time (< 1 d).

ADR
This European agreement concerning the international carriage of dangerous goods by road, popularly known as the ADR, aims to ensure that dangerous goods arriving at a frontier in or on a road vehicle have been suitably packed and are being carried safely. The system of classification of dangerous goods under ADR is based on the Recommendations of the United Nations Committee of Experts of the Transport of Dangerous Goods, published in the Orange Book.

Alpha Decay
Radioactive decay resulting in the emission of an alpha particle.

Alpha Particle
Nucleus of a helium atom of mass number four. It consists of two protons and two neutrons and therefore has a double positive charge.

AMAD
Acitivity Median Aerodynamic Diameter (for aerosol particles).

Annual Limit of Intake (*ALI*)
For occupational exposures, the 1990 recommendations of the ICRP limit the effective dose to 100 mSv in a 5 y period (giving an annual value of 20 mSv). The derived limit, *ALI*, for the amount of radioactive material taken into the body of an adult by inhalation or ingestion in a year is then

$$ALI = 0.02/e(50)\,,$$

where $e(50)$ is the effective dose coefficient.

Antimatter
Quantum mechanics predicts that each subatomic matter particle has an antimatter partner (of opposite electric charge if the particle is charged).

Antineutrino
The antineutrino is the antimatter partner of the neutrino.

Atomic Number
The number of positively charged protons in the nucleus of an atom.

Barn
Unit of effective cross-sectional area of a nucleus equal to 10^{-28} m^2.

Becquerel (Bq)
The unit of radioactive decay equal to 1 disintegration per second.
37 billion (3.7×10^{10}) becquerels = 1 curie (Ci).

Beta Decay
Radioactive disintegration with the emission of an electron or positron accompanied by an uncharged antineutrino or neutrino. The mass number of the nucleus remains unchanged but the atomic number is increased by one or decreased by one depending on whether an electron or positron is emitted.

Beta Particle
An electron or positron emitted in beta decay from a radioactive isotope.

Big Bang
The universe is believed to have been born in a "Big Bang" explosion about 15 billion years ago.

Binding Energy
The minimum energy required to separate a nucleus into its component neutrons and protons.

BNCT (Boron Neutron Capture Therapy)
is a binary therapy. In the first stage, boron selectively accumulates in the tumour cells. In the second stage, the tumour is irradiated with neutrons, which react with the atomic nuclei of the boron to yield short-range radiation.

Boson
Elementary particles with integer spin angular momentum. Bosons have total spin angular momentum of $n \cdot h/2\pi$, where $n = 0, 1, 2$ and h is Planck's constant.

Bremsstrahlung
Electromagnetic radiation emitted when a charged particle changes its velocity. When electrons collide with a target and undergo large deceleration, the radiation emitted constitutes a continuous Bremsstrahlung spectrum.

CODATA
Committee for Data on Science and Technology.

Collective Effective Dose
On the assumption that radiation effects are directly proportional to the radiation dose without a threshold, then the sum of all doses to all individuals in a population is the collective effective dose with unit manSv. As an example, in a population consisting of 10,000 persons, each receives a dose of 0.1 mSv. The collective dose is then $10\,000 \times 0.0001 = 1$ manSv.

Committed Effective Dose, $E(\tau)$
A person irradiated by gamma radiation outside the body will receive a dose only during the period of irradiation. However, following an intake by ingestion or inhalation, some radionuclides persist in the body and irradiate the various tissues for many years. The total radiation dose in such cases depends on the half-life of the radionuclide, its distribution in the body, and the rate at which it is expelled from the body. Detailed mathematical models allow the dose to be calculated for each year following intake. The resulting total effective dose delivered over a lifetime (70 years for infants, 50 y for adults) is called the committed effective dose. The name arises from the fact that once a radionuclide has been taken up into the body, the person is "committed" to receiving the dose. The ICRP has published values for committed doses following intake of 1 Bq of radionuclide via ingestion and inhalation. These are known as the effective dose coefficients and have been calculated for intake by members of the public at six standard ages, and for intake by adult workers.

Committed Equivalent Dose, $H_T(\tau)$
The time integral of the equivalent dose rate in a particular tissue or organ that will be received by in individual following intake of radioactive material into the body, where τ is the integration time in years following the intake. The integration time is 50 y for adults.

Compton Effect
The elastic scattering of photons by electrons. If λ_s and λ_i are respectively the wavelengths associated with scattered and incident photons, the Compton shift is given by $\lambda_s - \lambda_i = \lambda_0(1-\cos\theta)$ where θ is the angle between the directions of the incident and scattered photons and λ_0 is the Compton wavelength ($\lambda_0 = 0.00243$ nm) of the electron. The effect is only significant for incident X-ray and γ-ray photons.

Cosmogenic radionuclides
Radionuclides produced by the interation of cosmic radiation with the Earth's atmosphere. The nuclides ^{14}C and ^{3}H (tritium) are examples.

Cumulative Dose
The total dose resulting from repeated exposures of ionizing radiation to an occupationally exposed worker to the same portion of the body, or to the whole body, over a period of time.

Curie (Ci)
The old unit used to describe the intensity of radioactivity in a sample of material. The curie is equal to 37 billion (3.7×10^{10}) disintegrations per second (Bq), which is approximately the activity of 1 gram of radium. A curie is also a quantity of any radionuclide that decays at a rate of 37 billion disintegrations per second. It is named after Marie and Pierre Curie, who discovered radium in 1898.

Daughter Product
A nuclide that originates from a radioactive disintegration of another parent nuclide.

Decontamination
The process of removing or reducing radioactive contamination from a surface.

Disintegration
A process in which a nucleus ejects one or more particles applied especially, but not only, to spontaneous radioactive decay.

Dose
The absorbed dose, given in grays (or in the old system of units, rads), represents the energy absorbed from the radiation in a gram of any material. Furthermore, the biological dose or

dose equivalent, given in sieverts or rems, is a measure of the biological damage to living tissue from the radiation exposure.

Dose Coefficient, $e(\tau)$
Committed effective dose per unit intake, $e(\tau)$, where τ is the time in years over which the dose is calculated (typically 50 y for adults). For dose coefficients for inhalation of nuclides it is assumed that for non-gaseous radionuclides that the inhaled material is in the form of 1 μm AMAD (Activity Mean Aerodynamic Diameter) particles.

Drip-lines
The drip-lines are the outer boundaries of the chart of the nuclides, terminating isobaric chains on both sides of the valley of stability. Beyond the drip-lines, the nucleus can no longer bind another particle.

Effective Dose, E
The equivalent dose is a measure of the harm from radiation to a particular tissue. A dose of 1 mSv, for example, to the liver will give rise to the same cancer risk regardless of the type of radiation concerned.

However, different tissues show different sensitivities to radiation. The thyroid is less sensitive than other tissues. In addition, following intake, some radionuclides will buildup in particular organs and irradiate them preferentially. Iodine isotopes, for example, concentrate in the thyroid whereas plutonium concentrates in the liver and bone. In order to take these effects into account, equivalent doses in different tissues must be weighted. The resulting effective dose is obtained using

$$E = \sum_{\mathrm{T}} (w_{\mathrm{T}} \cdot H_{\mathrm{T}}) \,,$$

where H_T is the equivalent dose in tissue or organ T and w_{T} is the tissue weighting factor. The ICRP weighting factors are shown in Table 9.2.

Electron
A fundamental particle with negative electric charge of 1.602×10^{-19} coulombs and mass 9.109×10^{-31} kg. Electrons are a basic constituent of the atom; they are distributed around the nucleus in shells and the electronic structure is responsible for the chemical properties of the atom. Electrons also exist independently and are responsible for many electric effects in materials. Due to their small mass, the wave properties and relativistic effects of electrons are marked. The positron, the antiparticle of the electron, is an equivalent particle but with positive charge. Either electrons or positrons may be emitted in β decay. Electrons belong to a group of fundamental particles called leptons.

Epithermal Neutrons
are neutrons with energy in the range 0.5 eV to 10 keV. These neutrons are effectively slowed down by interactions with the nuclei of hydrogen atoms in water molecules in the tissue, while causing minimal radiation damage.

Equivalent Dose, H_{T}
The absorbed dose does not give an accurate indication of the harm that radiation can do. Equal absorbed doses do not necessarily have the same biological effects. An absorbed dose of 0.1 Gy of alpha radiation, for example, is more harmful than an absorbed dose of 0.1 Gy or beta or gamma radiation. To reflect the damage done in biological systems from different types of radiation, the equivalent dose is used. It is defined in terms of the absorbed dose weighted by a factor which depends on the type of radiation i.e.

$$H_{\mathrm{T,R}} = w_{\mathrm{R}} \cdot D_{\mathrm{T,R}}$$

where $H_{T,R}$ is the equivalent dose in tissue T and w_R is the radiation weighting factor. The ICRP weighting factors are given in Table 9.1. The total equivalent dose, H_T is the sum of $H_{T,R}$ over all radiation types i.e.

$$H_T = \sum_R H_{T,R}$$

Fermion
Elementary particles with half-integer angular momentum of $\left(n + \frac{1}{2}\right) \cdot h/2\pi$, where $n = 0, 1, 2 \ldots$ and h is Planck's constant.

Fission *see* **Nuclear Fission**
The spontaneous or induced disintegration of a heavy atomic nucleus into two or more lighter fragments. The energy released in the process is referred to as nuclear energy.

Fundamental Forces
All forces known in the universe can be reduced to four fundamental forces: gravitational, electromagnetic, weak and strong nuclear forces.

Gamma Radiation
Electromagnetic radiation emitted by excited atomic nuclei during the process of passing to a lower excitation state. Gamma radiation ranges in energy from about 10^{-15} to 10^{-10} joule (10 keV to 10 MeV) corresponding to a wavelength range of about 10^{-10} to 10^{-14} metre.

Geological Repository
An underground site, excavated from surrounding rock formation, designed to isolate nuclear waste from the biosphere over long periods of time.

Glioblastoma
The most malignant of the brain tumours, which originates from the supportive brain tissue, known as glial cells. This tumour is the most common of all brain tumours and mainly affects adults.

Gluon
The particle (boson) that mediates the strong force.

Gray, (Gy)
The special name for the SI unit of absorbed dose. 1 Gy = 1 J kg^{-1}.

Hadron
Any of a class of subatomic particles that interact by the strong interaction. The class includes protons, neutrons and pions. (*See* Leptons).

Half-life
The time in which one half of the atoms of a particular radioactive substance disintegrates into another nuclear form. Measured half-lives vary from millionths of a second to billions of years. Also called physical or radiological half-life.

IAEA
International Atomic Energy Agency

ICRP
Internation Commission on Radiological Protection.

INES
International nuclear event scale. The Chernobyl accident was assigned a "7" on this scale.

Internal Conversion
An excited nucleus may return to the ground state by ejecting an orbital electron. This is known as internal conversion and results in an energetic electron and X-rays due to electrons cascading to lower energy levels. The ratio of internal conversion electrons to gamma emission photons is known as the internal conversion coefficient.

Isomer
Atoms with the same atomic number Z and the same mass number A in different states of excitation, the higher states being metastable with respect to the ground state.

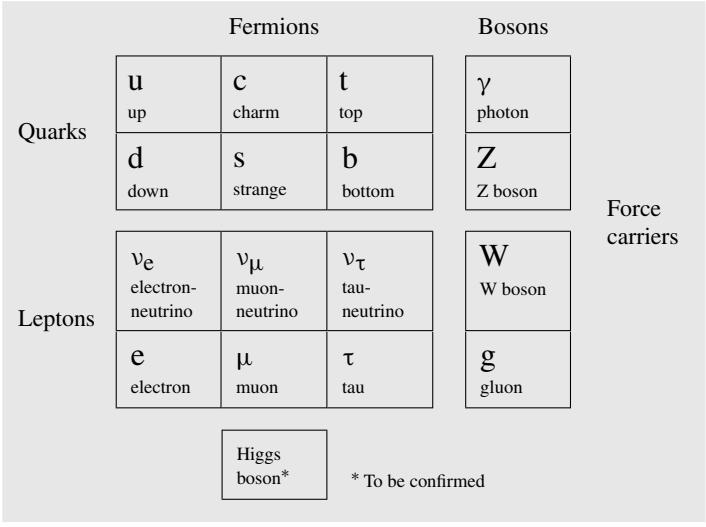
Isotone
One of several different nuclides having the same number of neutrons (isotone) in their nuclei.

Isotope
(Greek: at the same place). One of two or more atoms of the same element that have the same number of protons (isotope) in their nucleus but different numbers of neutrons. Hydrogen, deuterium and tritium are isotopes of hydrogen. Most elements in nature consists of a mixture of isotopes.

Leaching
Leaching generally refers to the removal of a substance from a solid via a liquid extraction media.

Lepton
Any of a class of fundamental particles that consists of the electron, muon, tau particle and three types of neutrino. For each lepton there is an equivalent antiparticle.

Table G.1. The Standard model and fundamental particles



The antileptons have a charge opposite that of the leptons; the antineutrinos, like the neutrinos, have no charge. The electron, muon and tau all have a charge of -1. These three particles differ from each other only in mass: the muon is 200 times more massive than the electron and the tau is 3500 times more massive than the electron. Leptons interact by the electromagnetic interaction and the weak interaction.

Lethal Dose
(Lethal Dose 50/30). The dose of radiation expected to cause death to an exposed population within 30 days to 50 percent of those exposed. Typically, the LD 50/30 is in the range from 4 to 5 Sieverts received over a very short period of time.

Table G.2. Range of doses causing death from deterministic effects

Whole-body dose (Gy)	Principal effects causing death	Time of exposure (h)
3–10	Damage to bone marrow	30–60
10–50	Damage to gastrointestinal tract and lungs	10–20
>50	Damage to nervous system	1–5

Magic Numbers
Numbers of neutrons or protons that occur in atomic nuclei to produce very stable structures. The magic numbers for both protons and neutrons are 2, 8, 20, 28, 50 and 82. For neutrons, 126 and 184 are also magic numbers and for protons, 114 is a magic number. The relationship between stability and magic numbers led to a nuclear shell model in analogy to the electron shell model of the atom.

Mass Defect
The difference between the rest mass of an atomic nucleus and the sum of the rest masses of its individual nucleons in the unbound state. It is thus the mass equivalent of the binding energy on the basis of the mass-energy equation.

Mass Number
The number of nucleons (neutrons and protons) in the nucleus of an atom.

Minor Actinides
Refers mainly to the elements neptunium, americium, and curium. These minor actinides (MA) are produced as radioactive by-products in nuclear reactors. The term "minor" refers to the fact that they are produced in smaller quantities in comparison to the "major" actinide plutonium.

Neutrino
A lepton (*see* Lepton) that exists in three forms, one in association with the electron, one with the muon and one with the tau particle. Each form has its own antiparticle.

Neutron
A neutral particle (hadron) that is stable in the atomic nucleus but decays into a proton, an electron and an antineutrino with a mean life of 12 minutes outside the nucleus. Its rest mass is slightly greater than that of the proton, being $1.6749286(10) \times 10^{-27}$ kg. Neutrons occur in all atomic nuclei except normal hydrogen. The neutron was first reported in 1932 by James Chadwick.

Nuclear Fission
A nuclear reaction in which a heavy nucleus (such as uranium) splits into two or more parts (fission products) which subsequently emit either two or three neutrons, releasing a quantity of energy equivalent to the difference between the rest mass of the neutrons and the fission products and that of the original nucleus.

Nucleons
Protons and neutrons.

Nucleosynthesis
The processes in stars by which increasingly heavy nuclei are made from protons and neutrons to create the elements in nature.

Nucleus
The central core of an atom that contains most of its mass. Experiments performed in 1909 by Geiger and Marsden (under the direction of Rutherford) led to the discovery of a nuclear structure. The nucleus is positively charged and contains one or more nucleons (protons or neutrons). The positive charge of the nucleus is determined by the number of protons it contains; in the neutral atom this positive charge is balanced by an equal number of negatively charged electrons orbiting the nucleus in a comparatively large region outside it.

Pair Production
The creation of an electron and a positron from a photon in a strong electric field, such as that surrounding an atomic nucleus. The electron and the positron each have a mass of about 9×10^{-31} kg, which is equivalent on the basis of the mass-energy equation to a total of 16×10^{-14} J. The frequency associated with a photon of this energy is 2.5×10^{20} Hz. Pair production thus requires photons of high quantum energy (Bremsstrahlung or gamma rays). Any excess energy is taken up as kinetic energy of the products.

Photon
A particle with zero rest mass consisting of a quantum of electromagnetic radiation. The photon may also be regarded as a unit of energy equal to hf, where h is the Planck constant and f is the frequency of the radiation in hertz. Photons travel at the speed of light. They are required to explain the photoelectric effect and other phenomena that require light to have particle character.

Planck's Constant
The fundamental constant in nature that relates the energy and wavelength of quantum particles.

Positron
The antiparticle of the electron.

Primordial Radionuclides
Naturally occurring radionuclides with very long half-lives.

Proton
An elementary particle that is stable, bears a positive charge equal in magnitude to that of the electron and has a mass of 1.672614×10^{-27} kg, which is 1836.12 times that of the electron. The proton occurs in all atomic nuclei.

Quality Factor
The factor by which the absorbed dose (gray or rad) is to be multiplied to obtain a quantity that expresses, on a common scale for all ionizing radiation, the biological damage (sievert or rem) to an exposed individual. It is used because some types of radiation, such as alpha particles, are more biologically damaging internally than other types.

Quark
There are six kinds of quark and they interact via the strong, weak, and electromagnetic forces. Particles such as protons and neutrons are made up of these elementary quarks.

r-Process (Rapid Process)
The explosive process believed to occur in type II supernovae in which nuclei rapidly capture neutrons on a timescale fast in comparison with the beta decay process. As a result several neutrons can be captured before beta decay occurs.

Rad
The old unit of absorbed dose of ionising radiation (1 rad = 0.01 Gy, see Gray).

Radiation Weighting Factor, w_R
The radiation weighting factor is a dimensionless factor to derive the equivalent dose from the absorbed dose averaged over a tissue or organ and is based on the quality of the radiation.

Radioactive Equilibrium
The equilibrium reached by a radioactive series in which the rate of decay of each nuclide is equal to its rate of production. It follows that all rates of decay of the different nuclides within the sample are equal when radioactive equilibrium is achieved. For example, in the uranium series, uranium-238 decays to thorium-234. Initially, the rate of production of thorium will exceed the rate at which it is decaying and the thorium content of the sample will rise. As the amount of thorium increases, its activity increases; eventually a situation is reached in which the rate of production of thorium is equal to its rate of decay. The proportion of thorium in the sample will then remain constant. Thorium decays to produce protactinium-234; some time after the stabilisation of the thorium content, the protactinium content will also stabilise. When the whole radioactive series attains stabilisation, the sample is said to be in radioactive equilibrium.

Radioactive Series
A series of radioactive nuclides in which each member of the series is formed by the decay of the nuclide before it. The series ends with a stable nuclide. Three radioactive series occur naturally, those headed by thorium-232 (thorium series), uranium-235 (actinium series), and uranium-238 (uranium series). All three series end with an isotope of lead. The neptunium series starts with the artificial isotope plutonium-241, which decays to neptunium-237, and ends with bismuth-209.

Radioactivity
The spontaneous disintegration of certain atomic nuclei accompanied by the emission of alpha-particles (helium nuclei), beta-particles (electrons or positrons), or gamma radiation (short-wavelength electromagnetic waves).

Radioisotope
An isotope of an element that is radioactive.

Radionuclide
A nuclide that is radioactive.

RDD
Radiological Dispersion Devices, also known as “Dirty Bombs”, make use of conventional explosive to disperse radioactive material in the atmosphere.

RDE
Radiological Dispersion Event.

Reference Man
A person with the anatomical and physiological characteristics of an average individual which is used in calculations assessing internal dose (also may be called “Standard Man”).

Rem

The old unit of equivalent dose (1 rem $\simeq$ 0.01 sievert, see Sievert).

Rest Energy

The rest mass of a body expressed in energy terms according to the relationship $E = m_0c^2$, where m_0 is the rest mass of the body and c is the speed of light.

Rest Mass

The mass of a body at rest when measured by an observer who is at rest in the same frame of reference.

Risk factor

The relationship between the radiation dose and the likelihood of incurring a stochastic effect can be expressed as a risk factor i.e.

$$\textit{likelihood of incurring a stochastic effect} = \textit{Dose}\ (\mathrm{Sv}) \cdot \textit{Risk Factor}\ (\mathrm{Sv}^{-1})$$

ICRP risk factors for stochastic effects (ICRP 60)

Exposed population	Fatal cancers	Non-fatal cancers	Heredirory effect	Total
Adult workers	0.04	0.01	0.01	0.06
Whole population	0.05	0.01	0.01	0.07

Roentgen (R)

The roentgen is the amount of exposure that will create 2.58×10^{-4} C of singly charged ions in 1 kg of air at STP. Since about 34 eV of energy is needed to produce one ion pair, 1 R corresponds to an energy absorption per unit mass of 0.0088 J kg^{-1}.

s-Process (Slow Process)

The process of nucleosysthesis in red giants whereby nuclei capture neutrons on a timescale that is slower compared with beta decay.

Shell Model of the Nucleus

A model of the atomic nucleus in which nucleons are assumed to move under the influence of a central field in shells that are analogous to atomic electron shells. The model provides a good explanation of the stability of nuclei that have magic numbers.

SI Units

Système International d'Unités: the internationl system of units recommended for scientific purposes.

Sievert (Sv)

The new international system (SI) unit for dose equivalent equal to 1 Joule/kilogram. 1 sievert = 100 rem. The equivalent dose in sieverts is equal to the absorbed dose in grays multiplied by the quality factor.

SNAP

Systems for Nuclear Auxiliary Power.

Spent Fuel
Nuclear fuel which has been used for energy production in a nuclear reactor and whose nuclide composition has been (partially) modified by fission and neutron capture processes and subsequent radioactivity decay.

Spontaneous Emission
The emission of a photon by an atom as it makes a transition from an excited state to the ground state. Spontaneous emission occurs independently of any external electromagnetic radiation; the transition is caused by interactions between atoms and vacuum fluctuations of the quantised electromagnetic field. The process of spontaneous emission, which cannot be described by nonrelativistic quantum mechanics, as given by formulations such as the Schrödinger equation, is responsible for the limited lifetime of an excited state of an atom before it emits a photon.

Standard Model of Particle Physics *see* **Lepton**

Stochastic Effects
For stochastic effects, the probability of occurrence (but not the severity) depends on the radiation dose. The main type of stochastic effects following exposure are the incidence of cancer and of hereditary disease in their descendents.

STP
Standard temperature ($T = 273.15\,\mathrm{K}$) and pressure ($p = 0.1\,\mathrm{MPa}$).

Strong Interaction
The strong interaction, some 100 times stronger than the electromagnetic interaction, functions only between hadrons and is responsible for the force between nucleons that gives the atomic nucleus its great stability. It operates at very short range inside the nucleus (as little as 10^{-15} metre) and is visualised as an exchange of virtual mesons.

Supernovae Type II
Refers to massive stars (10 to 30 times the mass of our sun) which end their life in a gigantic explosion.

Thomson Scattering
The scattering of electromagnetic radiation by free charged particles, especially electrons, when the photon energy is small compared with the energy equivalent of the rest mass of the charged particles. The energy lost by the radiation is accounted for by classical theory as a result of the radiation transmitted by the charged particles when they are accelerated in the transverse electric field of the radiation. It is named after Sir J. J. Thomson.

Tissue Weighting Factor, w_T
The factor by which the equivalent dose in a tissue or organ is weighted to represent the relative contribution of that tissue or organ to the total detriment resulting from uniform irradiation of the body.

Transmutation
The transformation of an atomic nucleus into another nucleus by radioactive decay or by nuclear reactions.

Uncertainty Principle
An intrinsic characteristic of quantum mechanics whereby the precision with which linked variables such as position and momentum, or energy and time, can be determined simultaneously is limited.

UNSCEAR
United Nations Scientific Committee on the Effects of Atomic Radiation.

Reference

Many definitions can be found on the website:
http://physics.about.com/cs/glossary/a/glossary.htm

Appendices

Appendix A
Physical Constants, Conversion Factors, Prefixes, Greek Alphabet

Table A.1. Physical constants*

Quantity	Symbol	Value
Electron rest mass	m_e	$9.109\,381\,88(72) \times 10^{-31}$ kg $5.485\,799\,110(12) \times 10^{-4}$ u $0.510\,998\,902(21)$ MeV c^{-2}
Electron charge	e	$1.602\,176\,462(63) \times 10^{-19}$ C
Proton rest mass	m_p	$1.672\,621\,58(13) \times 10^{-27}$ kg $1.007\,276\,466\,88(13)$ u $938.271\,998(38)$ MeV c^{-2}
Neutron rest mass	m_n	$1.674\,927\,16(13) \times 10^{-27}$ kg $1.008\,664\,915\,78(55)$ u $939.565330(38)$ MeV c^{-2}
Alpha particle mass	m_α	$4.001\,506\,1747(10)$ u
Atomic mass unit $(1\,\text{u} = M(^{12}\text{C})/12)$	u	$1.660\,538\,73(13) \times 10^{-27}$ kg $931.494\,013(37)$ MeV c^{-2}
Speed of light	c	$2.997\,924\,58 \times 10^{8}$ m s^{-1}
Avogadro's number	N_a	$6.022\,141\,99(47) \times 10^{23}$ mol^{-1}
Boltzmann constant	k	$1.380\,6503(24) \times 10^{-23}$ J K^{-1}
Planck's constant	h	$6.626\,0688 \times 10^{-34}$ J s $4.135\,6673 \times 10^{-15}$ eV s

Reference

* P. J. Mohr and B. N. Taylor: The 1998 CODATA Recommended Values of the Fundamental Physical Constants, Web Version 3.1, available at physics.nist.gov/cuu/index.html (National Institute of Standards and Technology, Gaithersburg, MD 20899, 3 December 1999)

Table A.2. Conversion factors

1 year (365.25 days)	3.15576×10^7 s
1 month **	2.6298×10^6 s
1 week	6.048×10^5 s
1 day	8.640×10^4 s
1 curie	3.7×10^{10} Bq

** 1 month = 1 year/12 = 2.6298×10^6 s

Table A.3. Radiation dose, dose rate, and conversion factors

Dose	Symbol	Unit	Abbreviation SI unit	SI unit
Absorbed dose	D	gray (formerly rad)	Gy (rd)	1 Gy = 1 J kg^{-1} (1 rd = 0.01 Gy)
Equivalent dose	H	sievert (formerly rem)	Sv (rem)	1 Sv $\cong$ 1 J kg^{-1} (1 rem $\cong$ 0.01 Sv)
Absorbed dose rate	$\mathrm{d}D/\mathrm{d}t$	Gy/s (Gy/h) (rd/s)		1 Gy/s = 1 J kg^{-1} s^{-1} (1 rd/s = 0.01 Gy/s)
Equivalent dose rate	$\mathrm{d}H/\mathrm{d}t$	Sv/s (Sv/h) (rem/s)		1 Sv/s = 1 J kg^{-1} s^{-1} (1 rem/s = 0.01 Gy/s)

Table A.4. List of prefixes

Prefix	Unit	Factor	Prefix	Unit	Factor	Prefix	Unit	Factor
yotta	Y	10^{24}	kilo	k	10^3	nano	n	10^{-9}
zetta	Z	10^{21}	hecto	h	10^2	pico	p	10^{-12}
exa	E	10^{18}	deka	da	10^1	femto	f	10^{-15}
peta	P	10^{15}	deci	d	10^{-1}	atto	a	10^{-18}
tera	T	10^{12}	centi	c	10^{-2}	zepto	z	10^{-21}
giga	G	10^9	milli	m	10^{-3}	yocto	y	10^{-24}
mega	M	10^6	micro	μ	10^{-6}			

Table A.5. The Greek alphabet

A, α	alpha	I, ι	iota	P, ρ	rho
B, β	beta	K, κ	kappa	Σ, σ	sigma
Γ, γ	gamma	Λ, λ	lambda	T, τ	tau
Δ, δ	delta	M, μ	mu	Y, υ	upsilon
E, ε	epsilon	N, ν	nu	Φ, ϕ	phi
Z, ζ	zeta	Ξ, ξ	xi	X, χ	chi
H, η	eta	O, o	omicron	Ψ, ψ	psi
Θ, θ	theta	Π, π	pi	Ω, ω	omega

Appendix B
Table of the Elements

Reference

Elementymology Elements Multidict, Peter van der Krogt, see website at http://www.vanderkrogt.net/elements/

		English	German	French	Spanish	Russian
Symbol	*Z*	Name	Name	Nom	Nombre	Название
Ac	89	Actinium	Actinium	Actinium	Actinio	Актиний
Ag	47	Silver	Silber	Argent	Plata	Серебро
Al	13	Aluminium	Aluminium	Aluminium	Aluminio	Алюминий
Am	95	Americium	Americium	Américium	Americio	Америций
Ar	18	Argon	Argon	Argon	Argón	Аргон
As	33	Arsenic	Arsen	Arsenic	Arsénico	Мышъяк
At	85	Astatine	Astat	Astate	Astatino	Астатин
Au	79	Gold	Gold	Or	Oro	Золото
B	5	Boron	Bor	Bore	Boro	Бор
Ba	56	Barium	Barium	Baryum	Bario	Барий
Be	4	Beryllium	Beryllium	Béryllium	Berilio	Бериллий
Bh	107	Bohrium	Bohrium	Bohrium	Bohrio	Борий
Bi	83	Bismuth	Bismut	Bismuth	Bismuto	Висмут
Bk	97	Berkelium	Berkelium	Berkélium	Berkelio	Беркелий
Br	35	Bromine	Brom	Brome	Bromo	Бром
C	6	Carbon	Kohlenstoff	Carbone	Carbono	Углерод
Ca	20	Calcium	Calcium	Calcium	Calcio	Кальций
Cd	48	Cadmium	Cadmium	Cadmium	Cadmio	Кадмий
Ce	58	Cerium	Cer	Cérium	Cerio	Церий
Cf	98	Californium	Californium	Californium	Californio	Калифорний
Cl	17	Chlorine	Chlor	Chlore	Cloro	Хлор
Cm	96	Curium	Curium	Curium	Curio	Кюрий
Co	27	Cobalt	Cobalt	Cobalt	Cobalto	Кобальт
Cr	24	Chromium	Chrom	Chrome	Cromo	Хром
Cs	55	Caesium	Caesium	Caesium	Cesio	Цезий
Cu	29	Copper	Kupfer	Cuivre	Cobre	Медь
Db	105	Dubnium	Dubnium	Dubnium	Dubnio	Дубний
Ds	110	Darmstadtium	Darmstadtium	Darmstadtium	Darmstadtium	Дармцтадий
Dy	66	Dysprosium	Dysprosium	Dysprosium	Disprosio	Диспрозий
Er	68	Erbium	Erbium	Erbium	Erbio	Эрбий
Es	99	Einsteinium	Einsteinium	Einsteinium	Einsteinio	Эйнштейний
Eu	63	Europium	Europium	Europium	Europio	Европий
F	9	Fluorine	Fluor	Fluor	Flúor	Фтор
Fe	26	Iron	Eisen	Fer	Hierro	Железо
Fm	100	Fermium	Fermium	Fermium	Fermio	Фермий
Fr	87	Francium	Francium	Francium	Francio	Франций

		English	German	French	Spanish	Russian
Symbol	Z	Name	Name	Nom	Nombre	Название
Ga	31	Gallium	Gallium	Gallium	Galio	Галлий
Gd	64	Gadolinium	Gadolinium	Gadolinium	Gadolinio	Гадолиний
Ge	32	Germanium	Germanium	Germanium	Germanio	Германий
H	1	Hydrogen	Wasserstoff	Hydrogène	Hydrógeno	Водород
He	2	Helium	Helium	Helium	Helio	Гелий
Hf	72	Hafnium	Hafnium	Hafnium	Hafnio	Гафний
Hg	80	Mercury	Quecksilber	Mercure	Mercurio	Ртуть
Ho	67	Holmium	Holmium	Holmium	Holmio	Гольмий
Hs	108	Hassium	Hassium	Hassium	Hassio	Хассий
I	53	Iodine	Iod	Iode	Yodo	Йод
In	49	Indium	Indium	Indium	Indio	Индий
Ir	77	Iridium	Iridium	Iridium	Iridio	Иридий
K	19	Potassium	Kalium	Potassium	Potasio	Калий
Kr	36	Krypton	Krypton	Krypton	Criptón	Криптон
La	57	Lanthanum	Lanthan	Lanthane	Lantano	Лантан
Li	3	Lithium	Lithium	Lithium	Litio	Литий
Lr	103	Lawrencium	Lawrencium	Lawrencium	Lawrencio	Лоуренсий
Lu	71	Lutetium	Lutetium	Lutétium	Lutecio	Лютеций
Md	101	Mendelevium	Mendelevium	Mendélévium	Mendelevio	Менделевий
Mg	12	Magnesium	Magnesium	Magnésium	Magnesio	Магний
Mn	25	Manganese	Mangan	Manganèse	Manganeso	Марганец
Mo	42	Molybdenum	Molybdän	Molybdène	Molibdeno	Молибден
Mt	109	Meitnerium	Meitnerium	Meitnerium	Meitnerio	Майтнерий
N	7	Nitrogen	Stickstoff	Azote	Nitrógeno	Азот
Na	11	Sodium	Natrium	Sodium	Sodio	Натрий
Nb	41	Niobium	Niob	Niobium	Niobio	Ниобий
Nd	60	Neodymium	Neodym	Néodyme	Neodimio	Неодим
Ne	10	Neon	Neon	Néon	Neón	Неон
Ni	28	Nickel	Nickel	Nickel	Níquel	Никель
No	102	Nobelium	Nobelium	Nobélium	Nobelio	Нобелий
Np	93	Neptunium	Neptunium	Neptunium	Neptunio	Нептуний
O	8	Oxygen	Sauerstoff	Oxygène	Oxígeno	Кислород
Os	76	Osmium	Osmium	Osmium	Osmio	Осмий
P	15	Phosphorus	Phosphor	Phosphore	Fósforo	Фосфор
Pa	91	Protactinium	Protactinium	Protactinium	Protactinio	Протактиний
Pb	82	Lead	Blei	Plomb	Plomo	Свинец
Pd	46	Palladium	Palladium	Palladium	Paladio	Палладий
Pm	61	Promethium	Promethium	Prométhium	Prometio	Прометий
Po	84	Polonium	Polonium	Polonium	Polonio	Полоний
Pr	59	Praseodymium	Praseodym	Praséodyme	Praseodimio	Празеодим
Pt	78	Platinium	Platin	Platine	Platino	Платина
Pu	94	Plutonium	Plutonium	Plutonium	Plutonio	Плутоний

		English	German	French	Spanish	Russian
Symbol	Z	Name	Name	Nom	Nombre	Название
Ra	88	Radium	Radium	Radium	Radio	Радий
Rb	37	Rubidium	Rubidium	Rubidium	Rubidio	Рубидий
Re	75	Rhenium	Rhenium	Rhénium	Renio	Рений
Rf	104	Rutherfordium	Rutherfordium	Rutherfordium	Rutherfordio	Рутерфордий
Rh	45	Rhodium	Rhodium	Rhodium	Rodio	Родий
Rn	86	Radon	Radon	Radon	Radón	Радон
Ru	44	Ruthenium	Ruthenium	Ruthénium	Rutenio	Рутений
S	16	Sulfur	Schwefel	Soufre	Azufre	Сера
Sb	51	Antimony	Antimon	Antimoine	Antimonio	Сурьма
Sc	21	Scandium	Scandium	Scandium	Escandio	Скандий
Se	34	Selenium	Selen	Sélénium	Selenio	Селен
Sg	106	Seaborgium	Seaborgium	Seaborgium	Seaborgio	Сиборгий
Si	14	Silicon	Silicium	Silicium	Silicio	Кремний
Sm	62	Samarium	Samarium	Samarium	Samario	Самарий
Sn	50	Tin	Zinn	Etain	Estaño	Олово
Sr	38	Strontium	Strontium	Strontium	Estroncio	Стронций
Ta	73	Tantalum	Tantal	Tantale	Tántalo	Тантал
Tb	65	Terbium	Terbium	Terbium	Terbio	Тербий
Tc	43	Technetium	Technetium	Technétium	Tecnecio	Технеций
Te	52	Tellurium	Tellur	Tellure	Telurio	Теллур
Th	90	Thorium	Thorium	Thorium	Torio	Торий
Ti	22	Titanium	Titan	Titane	Titanio	Титан
Tl	81	Thallium	Thallium	Thallium	Talio	Таллий
Tm	69	Thulium	Thulium	Thulium	Tulio	Тулий
U	92	Uranium	Uran	Uranium	Uranio	Уран
Uuu	111	Unununium	Unununium	Unununium	Unununium	
Uub	112	Ununbium	Ununbium	Ununbium	Ununbium	
Uut	113	Ununtrium	Ununtrium	Ununtrium	Ununtrium	
Uuq	114	Ununquadium	Ununquadium	Ununquadium	Ununquadium	
Uuh	116	Ununhexium	Ununhexium	Ununhexium	Ununhexium	
Uuo	118	Ununoctium	Ununoctium	Ununoctium	Ununoctium	
V	23	Vanadium	Vanadium	Vanadium	Vanadio	Ванадий
W	74	Tungsten	Wolfram	Tungstène	Volframio	Вольфрам
Xe	54	Xenon	Xenon	Xénon	Xenón	Ксенон
Y	39	Yttrium	Yttrium	Yttrium	Itrio	Иттрий
Yb	70	Ytterbium	Ytterbium	Ytterbium	Iterbio	Иттербий
Zn	30	Zinc	Zink	Zinc	Cinc	Цинк
Zr	40	Zirconium	Zirconium	Zirconium	Circonio	Цирконий

Appendix C
Properties of the Elements

Atomic weights apply to elements as they exist on Earth. In the case of thorium and protactinium, the atomic weights refer to the isotopes which have the longest half-lives. The values in parentheses are the mass numbers for the longest-lived isotopes. Densities are given at 25°C, unless otherwise indicated in adjacent column. Densities for gaseous elements are for the liquids at their boiling points (from Handbook of Chemistry and Physics, 78th edition, D. R. Lide (editor). CRC Press, Boca Raton, Florida 1997.

[a] Calculated [b] Estimated [t] Critical temperature [s] Sublimation temperature

Z	El	Element	Density (g cm^{-3})	Melting point (°C)	Boiling point (°C)	Critical point (°C)	Ionisation potential (eV)
1	H	Hydrogen	0.0708	–259.34	–252.87	–240.18	13.598
2	He	Helium	0.124901	–272.2	–268.93	–267.96	24.587
3	Li	Lithium	0.534	180.5	1342		5.392
4	Be	Beryllium	1.85	1287	2471		9.323
5	B	Boron	2.37	2075	4000		8.298
6	C	Carbon	2.267 15°	4492 t	3842 s		11.26
7	N	Nitrogen	0.807	–210	–195.79	–146.94	14.534
8	O	Oxygen	1.141	–218.79	–182.95	–118.56	13.618
9	F	Fluorine	1.5	–219.62	–188.12	–129.02	17.423
10	Ne	Neon	1.204	–248.59	–246.08	–228.7	21.565
11	Na	Sodium	0.97	97.8	883		5.139
12	Mg	Magnesium	1.74	650	1090		7.646
13	Al	Aluminum	2.7	660.32	2519		5.986
14	Si	Silicon	2.3296	1414	3265		8.152
15	P	Phosphorus	1.82	44.15	280.5	721	10.487
16	S	Sulfur	2.067	115.21	444.6	1041	10.36
17	Cl	Chlorine	1.56	–101.5	–34.04	143.8	12.968
18	Ar	Argon	1.396	–189.35	–185.85	–122.28	15.76
19	K	Potassium	0.89	63.38	759		4.341
20	Ca	Calcium	1.54	842	1484		6.113
21	Sc	Scandium	2.99	1541	2836		6.561
22	Ti	Titanium	4.5	1668	3287		6.828
23	V	Vanadium	6	1910	3407		6.746
24	Cr	Chromium	7.15	1907	2671		6.767
25	Mn	Manganese	7.3	1246	2061		7.434
26	Fe	Iron	7.875	1538	2861		7.902
27	Co	Cobalt	8.86	1495	2927		7.881
28	Ni	Nickel	8.912	1455	2913		7.64
29	Cu	Copper	8.933	1084.62	2562		7.726
30	Zn	Zinc	7.134	419.53	907		9.394
31	Ga	Gallium	5.91	29.76	2204		5.999
32	Ge	Germanium	5.323	938.25	2833		7.9
33	As	Arsenic	5.776 26°	817 t	614 s	1400	9.815

Z	El	Element	Density ($g\ cm^{-3}$)		Melting point (°C)	Boiling point (°C)	Critical point (°C)	Ionisation potential (eV)
34	Se	Selenium	4.809	26°	221	685	1493	9.752
35	Br	Bromine	3.11		–7.2	58.8	315	11.814
36	Kr	Krypton	2.418		–157.36	–153.22	–63.74	14
37	Rb	Rubidium	1.53		39.31	688		4.177
38	Sr	Strontium	2.64		777	1382		5.695
39	Y	Yttrium	4.47		1522	3345		6.217
40	Zr	Zirconium	6.52		1855	4409		6.634
41	Nb	Niobium	8.57		2477	4744		6.759
42	Mo	Molybdenum	10.2		2623	4639		7.092
43	Tc	Technetium	11		2157	4265		7.28
44	Ru	Ruthenium	12.1		2334	4150		7.361
45	Rh	Rhodium	12.4		1964	3695		7.459
46	Pd	Palladium	12		1554.9	2963		8.337
47	Ag	Silver	10.501		961.78	2162		7.576
48	Cd	Cadmium	8.69		321.07	767		8.994
49	In	Indium	7.31		156.6	2072		5.786
50	Sn	Tin	7.287	26°	231.93	2602		7.344
51	Sb	Antimony	6.685	26°	630.63	1587		8.64
52	Te	Tellurium	6.232		449.51	988		9.01
53	I	Iodine	4.93	20°	113.7	184	546	10.451
54	Xe	Xenon	2.953		–111.75	–108.04	16.58	12.13
55	Cs	Cesium	1.93		28.44	671		3.894
56	Ba	Barium	3.62		727	1897		5.212
57	La	Lanthanum	6.15		918	3464		5.577
58	Ce	Cerium	8.16		798	3443		5.539
59	Pr	Praseodymium	6.77		931	3520		5.464
60	Nd	Neodymium	7.01		1021	3074		5.525
61	Pm	Promethium	7.26		1042	3000		5.55
62	Sm	Samarium	7.52		1074	1794		5.644
63	Eu	Europium	5.24		822	1596		5.67
64	Gd	Gadolinium	7.9		1313	3273		6.15
65	Tb	Terbium	8.23		1356	3230		5.864
66	Dy	Dysprosium	8.55		1412	2567		5.939
67	Ho	Holmium	8.8		1474	2700		6.022
68	Er	Erbium	9.07		1529	2868		6.108
69	Tm	Thulium	9.32		1545	1950		6.184
70	Yb	Ytterbium	6.9		819	1196		6.254
71	Lu	Lutetium	9.84		1663	3402		5.426
72	Hf	Hafnium	13.3		2233	4603		6.825
73	Ta	Tantalum	16.4		3017	5458		7.89
74	W	Tungsten	19.3		3422	5555		7.98
75	Re	Rhenium	20.8		3186	5596		7.88
76	Os	Osmium	22.5		3033	5012		8.7
77	Ir	Iridium	22.5		2446	4428		9.1

Z	El	Element	Density ($g\ cm^{-3}$)		Melting point (°C)	Boiling point (°C)	Critical point (°C)	Ionisation potential (eV)
78	Pt	Platinum	21.46		1768.4	3825		9
79	Au	Gold	19.282		1064.18	2856		9.226
80	Hg	Mercury	13.5336		–38.83	356.73	1477	10.438
81	Tl	Thallium	11.8		304	1473		6.108
82	Pb	Lead	11.342		327.46	1749		7.417
83	Bi	Bismuth	9.807		271.4	1564		7.289
84	Po	Polonium	9.32		254	962		8.417
85	At	Astatine			302			
86	Rn	Radon	4.4		–71	–61.7	104	10.749
87	Fr	Francium			27			
88	Ra	Radium	5		700			
89	Ac	Actinium	10.07	a	1051	3198		
90	Th	Thorium	11.72		1750	4788		
91	Pa	Protactinium	15.37	a	1572			
92	U	Uranium	18.95		1135	4131		
93	Np	Neptunium	20.25	20°	644			
94	Pu	Plutonium	19.84		640	3228		6.06
95	Am	Americium	13.69	20°	1176	2011		5.993
96	Cm	Curium	13.51	a	1345			6.02
97	Bk	Berkelium	14	b	1050			6.23
98	Cf	Californium			900			6.3
99	Es	Einsteinium			860			6.42
100	Fm	Fermium			1527			6.5
101	Md	Mendelevium			827			6.58
102	No	Nobelium			827			6.65
103	Lr	Lawrencium			1627			
104	Rf	Rutherfordium						
105	Ha	Hahnium						
106	Sg	Seaborgium						
107	Ns	Nielsbohrium						
108	Hs	Hassium						
109	Mt	Meitnerium						
110	Ds	Darmstadtium						
111		Element-111						

Appendix D
Table of Atomic Masses

In this appendix, atomic mass data is taken from the recent 2003 evaluation by Audi et al.*. The atomic masses are given for 3177 nuclides (ground states). In addition the table below includes atomic mass data for 977 excited isomeric states. These have been calculated from the excess mass data from the Nubase 2003 file**.

Isomers (defined as excited states with half-lives greater than 100 ns) are given in order of increasing excitation energy and identified by appending 'm', 'n', 'p' or 'q' to the nuclide name, e.g. ^{90}Nb for the ground state, ^{90}Nb^{m} for the first excited state, ^{90}Nb^{n} for the second excited state etc.

In this evaluation the provisional symbols Ea, Eb, ... Ei are used for elements 110, 111, ... 118. Recently, IUPAC has adopted the name Darmstadtium with symbol Ds for element 110, and this is used in the table below.

* G. Audi, O. Bersillon, J. Blacot, A. H. Wapstra: Nuclear Physics **A 729**, 337–676 (2003).

** G. Audi, O. Bersillon, J. Blacot, A. H. Wapstra: The NUBASE evaluation of nuclear and decay properties. Nuclear Physics **A 729**, 3–128 (2003).

N	*Z*	*A*	El	Atomic mass (μu)	*N*	*Z*	*A*	El	Atomic mass (μu)	*N*	*Z*	*A*	El	Atomic mass (μu)
1	0	1	n	1 008664.9157	4	5		B	9 013328.8	5	9		F	14 035060
0	1		H	1 007825.03207	3	6		C	9 031036.7	11	4	15	Be	15 053460
1	1	2	H	2 014101.7778	8	2	10	He	10 052400	10	5		B	15 031103
2	1	3	H	3 016049.2777	7	3		Li	10 035481	9	6		C	15 010599.3
1	2		He	3 016029.3191	7	3		Li^{m}	10 035695	8	7		N	15 000108.8982
0	3		Li	3 030780	7	3		Li^{n}	10 035996	7	8		O	15 003065.6
3	1	4	H	4 027810	6	4		Be	10 013533.8	6	9		F	15 018010
2	2		He	4 002603.25415	5	5		B	10 012937.0	12	4	16	Be	16 061920
1	3		Li	4 027190	4	6		C	10 016853.2	11	5		B	16 039810
4	1	5	H	5 035310	3	7		N	10 041650	10	6		C	16 014701
3	2		He	5 012220	8	3	11	Li	11 043798	9	7		N	16 006101.7
2	3		Li	5 012540	7	4		Be	11 021658	8	8		O	15 994914.61956
1	4		Be	5 040790	6	5		B	11 009305.4	7	9		F	16 011466
5	1	6	H	6 044940	5	6		C	11 011433.6	6	10		Ne	16 025761
4	2		He	6 018889.1	4	7		N	11 026090	12	5	17	B	17 046990
3	3		Li	6 015122.795	9	3	12	Li	12 053780	11	6		C	17 022586
2	4		Be	6 019726	8	4		Be	12 026921	10	7		N	17 008450
1	5		B	6 046810	7	5		B	12 014352.1	9	8		O	16 999131.70
6	1	7	H	7 052750	6	6		C	12 000000.0	8	9		F	17 002095.24
5	2		He	7 028021	5	7		N	12 018613.2	7	10		Ne	17 017672
4	3		Li	7 016004.55	4	8		O	12 034405	13	5	18	B	18 056170
3	4		Be	7 016929.83	9	4	13	Be	13 035690	12	6		C	18 026760
2	5		B	7 029920	8	5		B	13 017780.2	11	7		N	18 014079
6	2	8	He	8 033922	7	6		C	13 003354.8378	10	8		O	17 999161.0
5	3		Li	8 022487.36	6	7		N	13 005738.61	9	9		F	18 000938.0
4	4		Be	8 005305.10	5	8		O	13 024812	8	10		Ne	18 005708.2
3	5		B	8 024607.2	10	4	14	Be	14 042890	7	11		Na	18 025970
2	6		C	8 037675	9	5		B	14 025404	14	5	19	B	19 063730
7	2	9	He	9 043950	8	6		C	14 003241.989	13	6		C	19 034810
6	3		Li	9 026789.5	7	7		N	14 003074.0048	12	7		N	19 017029
5	4		Be	9 012182.2	6	8		O	14 008596.25	11	8		O	19 003580

N	Z	A	El	Atomic mass (μu)
10	9		F	18 998403.22
9	10		Ne	19 001880.2
8	11		Na	19 013877
7	12		Mg	19 035470
14	6	20	C	20 040320
13	7		N	20 023370
12	8		O	20 004076.7
11	9		F	19 999981.32
10	10		Ne	19 992440.1754
9	11		Na	20 007351
8	12		Mg	20 018863
15	6	21	C	21 049340
14	7		N	21 027110
13	8		O	21 008656
12	9		F	20 999949.0
11	10		Ne	20 993846.68
10	11		Na	20 997655.2
9	12		Mg	21 011713
8	13		Al	21 028040
16	6	22	C	22 057200
15	7		N	22 034390
14	8		O	22 009970
13	9		F	22 002999
12	10		Ne	21 991385.114
11	11		Na	21 994436.4
11	11		Na^m	21 995062.3
10	12		Mg	21 999573.8
9	13		Al	22 019520
8	14		Si	22 034530
16	7	23	N	23 041220
15	8		O	23 015690
14	9		F	23 003570
13	10		Ne	22 994466.90
12	11		Na	22 989769.2809
11	12		Mg	22 994123.7
10	13		Al	23 007267
9	14		Si	23 025520
17	7	24	N	24 051040
16	8		O	24 020470
15	9		F	24 008120
14	10		Ne	23 993610.8
13	11		Na	23 990962.78
13	11		Na^m	23 991469.73
12	12		Mg	23 985041.700
11	13		Al	23 999938.9
11	13		Al^m	24 000396.0
10	14		Si	24 011546
9	15		P	24 034350
18	7	25	N	25 060660
17	8		O	25 029460
16	9		F	25 012100
15	10		Ne	24 997737
14	11		Na	24 989954.0
13	12		Mg	24 985836.92
12	13		Al	24 990428.1
11	14		Si	25 004106
10	15		P	25 020260
18	8	26	O	26 038340
17	9		F	26 019620
16	10		Ne	26 000461
15	11		Na	25 992633
14	12		Mg	25 982592.929
13	13		Al	25 986891.69
13	13		Al^m	25 987136.78
12	14		Si	25 992330
11	15		P	26 011780
10	16		S	26 027880
19	8	27	O	27 048260
18	9		F	27 026760
17	10		Ne	27 007590
16	11		Na	26 994077
15	12		Mg	26 984340.59
14	13		Al	26 981538.63
13	14		Si	26 986704.91
12	15		P	26 999230
11	16		S	27 018830
20	8	28	O	28 057810
19	9		F	28 035670
18	10		Ne	28 012070
17	11		Na	27 998938
16	12		Mg	27 983876.8
15	13		Al	27 981910.31
14	14		Si	27 976926.5325
13	15		P	27 992315
12	16		S	28 004370
11	17		Cl	28 028510
20	9	29	F	29 043260
19	10		Ne	29 019390
18	11		Na	29 002861
17	12		Mg	28 988600
16	13		Al	28 980445.0
15	14		Si	28 976494.700
14	15		P	28 981800.6
13	16		S	28 996610
12	17		Cl	29 014110
21	9	30	F	30 052500
20	10		Ne	30 024800
19	11		Na	30 008976
18	12		Mg	29 990434
17	13		Al	29 982960
16	14		Si	29 973770.17
15	15		P	29 978313.8
14	16		S	29 984903
13	17		Cl	30 004770
12	18		Ar	30 021560
22	9	31	F	31 060430
21	10		Ne	31 033110
20	11		Na	31 013590
19	12		Mg	30 996546
18	13		Al	30 983947
17	14		Si	30 975363.23
16	15		P	30 973761.63
15	16		S	30 979554.7
14	17		Cl	30 992410
13	18		Ar	31 012120
22	10	32	Ne	32 040020
21	11		Na	32 020470
20	12		Mg	31 998975
19	13		Al	31 988120
19	13		Al^m	31 989157
18	14		Si	31 974148.08
18	14		Si^m	31 980141.7
17	15		P	31 973907.27
16	16		S	31 972071.00
15	17		Cl	31 985690
14	18		Ar	31 997638.0
14	18		Ar^m	32 003650
13	19		K	32 021920
23	10	33	Ne	33 049380
22	11		Na	33 026720
21	12		Mg	33 005254
20	13		Al	32 990840
19	14		Si	32 978000
18	15		P	32 971725.5
17	16		S	32 971458.76
16	17		Cl	32 977451.9
15	18		Ar	32 989925.7
14	19		K	33 007260
24	10	34	Ne	34 057030
23	11		Na	34 035170
22	12		Mg	34 009460

N	Z	A	El	Atomic mass (μu)
21	13		Al	33 996850
20	14		Si	33 978576
19	15		P	33 973636
18	16		S	33 967866.90
17	17		Cl	33 973762.82
17	17		Cl^{m}	33 973919.94
16	18		Ar	33 980271.2
15	19		K	33 998410
14	20		Ca	34 014120
24	11	35	Na	35 042490
23	12		Mg	35 017340
22	13		Al	34 999860
21	14		Si	34 984580
20	15		P	34 973314.1
19	16		S	34 969032.16
18	17		Cl	34 968852.68
17	18		Ar	34 975257.6
16	19		K	34 988010
15	20		Ca	35 004940
25	11	36	Na	36 051480
24	12		Mg	36 023000
23	13		Al	36 006210
22	14		Si	35 986600
21	15		P	35 978260
20	16		S	35 967080.76
19	17		Cl	35 968306.98
18	18		Ar	35 967545.106
17	19		K	35 981292
16	20		Ca	35 993090
15	21		Sc	36 014920
26	11	37	Na	37 059340
25	12		Mg	37 031400
24	13		Al	37 010680
23	14		Si	36 992940
22	15		P	36 979610
21	16		S	36 971125.57
20	17		Cl	36 965902.59
19	18		Ar	36 966776.32
18	19		K	36 973375.89
17	20		Ca	36 985870
16	21		Sc	37 003050
26	12	38	Mg	38 037570
25	13		Al	38 017230
24	14		Si	37 995630
23	15		P	37 984160
22	16		S	37 971163
21	17		Cl	37 968010.43
21	17		Cl^{m}	37 968731.16
20	18		Ar	37 962732.4
19	19		K	37 969081.2
18	20		Ca	37 976318
17	21		Sc	37 994700
17	21		Sc^{m}	37 995416
16	22		Ti	38 009770
27	12	39	Mg	39 046770
26	13		Al	39 022970
25	14		Si	39 002070
24	15		P	38 986180
23	16		S	38 975130
22	17		Cl	38 968008.2
21	18		Ar	38 964313
20	19		K	38 963706.68
19	20		Ca	38 970719.7
18	21		Sc	38 984790
17	22		Ti	39 001610
28	12	40	Mg	40 053930
27	13		Al	40 031450
26	14		Si	40 005870
25	15		P	39 991300
24	16		S	39 975450
23	17		Cl	39 970420
22	18		Ar	39 962383.1225
21	19		K	39 963998.48
20	20		Ca	39 962590.98
19	21		Sc	39 977967
18	22		Ti	39 990500
17	23		V	40 011090
28	13	41	Al	41 038330
27	14		Si	41 014560
26	15		P	40 994340
25	16		S	40 979580
24	17		Cl	40 970680
23	18		Ar	40 964500.6
22	19		K	40 961825.76
21	20		Ca	40 962278.06
20	21		Sc	40 969251.13
19	22		Ti	40 983150
18	23		V	40 999780
29	13	42	Al	42 046890
28	14		Si	42 019790
27	15		P	42 001010
26	16		S	41 981020
25	17		Cl	41 973250
24	18		Ar	41 963046
23	19		K	41 962402.81
22	20		Ca	41 958618.01
21	21		Sc	41 965516.43
21	21		Sc^{m}	41 966178.03
20	22		Ti	41 973031
19	23		V	41 991230
18	24		Cr	42 006430
29	14	43	Si	43 028660
28	15		P	43 006190
27	16		S	42 987150
26	17		Cl	42 974050
25	18		Ar	42 965636
24	19		K	42 960716
23	20		Ca	42 958766.6
22	21		Sc	42 961150.7
22	21		Sc^{m}	42 961313.2
21	22		Ti	42 968522
21	22		Ti^{m}	42 968859
21	22		Ti^{n}	42 971814
20	23		V	42 980650
19	24		Cr	42 997710
30	14	44	Si	44 035260
29	15		P	44 012990
28	16		S	43 990210
27	17		Cl	43 978280
26	18		Ar	43 964924.0
25	19		K	43 961560
24	20		Ca	43 955481.8
23	21		Sc	43 959402.8
23	21		Sc^{m}	43 959693.6
23	21		Sc^{n}	43 959559.7
22	22		Ti	43 959690.1
21	23		V	43 974110
20	24		Cr	43 985550
19	25		Mn	44 006870
30	15	45	P	45 019220
29	16		S	44 996510
28	17		Cl	44 980290
27	18		Ar	44 968040.0
26	19		K	44 960699
25	20		Ca	44 956186.6
24	21		Sc	44 955911.9
24	21		Sc^{m}	44 955925.2
23	22		Ti	44 958125.6
22	23		V	44 965776
21	24		Cr	44 979640
21	24		Cr^{m}	44 979689

N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)
20	25		Mn	44 994510	29	20		Ca	48 955674	25	27		Co^m	51 963993
19	26		Fe	45 014580	28	21		Sc	48 950024	24	28		Ni	51 975680
31	15	46	P	46 027380	27	22		Ti	48 947870.0	23	29		Cu	51 997180
30	16		S	46 000750	26	23		V	48 948516.1	35	18	53	Ar	53 004940
29	17		Cl	45 984210	25	24		Cr	48 951335.7	34	19		K	52 987120
28	18		Ar	45 968090	24	25		Mn	48 959618	33	20		Ca	52 970050
27	19		K	45 961977	23	26		Fe	48 973610	32	21		Sc	52 959610
26	20		Ca	45 953692.6	22	27		Co	48 989720	31	22		Ti	52 949730
25	21		Sc	45 955171.9	21	28		Ni	49 009660	30	23		V	52 944338
25	21		Sc^m	45 955324.9	33	17	50	Cl	50 007840	29	24		Cr	52 940649.4
24	22		Ti	45 952631.6	32	18		Ar	49 984430	28	25		Mn	52 941290.1
23	23		V	45 960200.5	31	19		K	49 972780	27	26		Fe	52 945307.9
22	24		Cr	45 968359	30	20		Ca	49 957519	27	26		Fe^m	52 948572.0
21	25		Mn	45 986720	29	21		Sc	49 952188	26	27		Co	52 954219
21	25		Mn^m	45 986881	29	21		Sc^m	49 952463	26	27		Co^m	52 957652
20	26		Fe	46 000810	28	22		Ti	49 944791.2	25	28		Ni	52 968470
31	16	47	S	47 008590	27	23		V	49 947158.5	24	29		Cu	52 985550
30	17		Cl	46 988710	26	24		Cr	49 946044.2	35	19	54	K	53 994200
29	18		Ar	46 972190	25	25		Mn	49 954238.2	34	20		Ca	53 974350
28	19		K	46 961678	25	25		Mn^m	49 954484	33	21		Sc	53 963260
27	20		Ca	46 954546.0	24	26		Fe	49 962990	33	21		Sc^m	53 963381
26	21		Sc	46 952407.5	23	27		Co	49 981540	32	22		Ti	53 951050
26	21		Sc^m	46 953230.7	22	28		Ni	49 995930	31	23		V	53 946440
25	22		Ti	46 951763.1	34	17	51	Cl	51 014490	30	24		Cr	53 938880.4
24	23		V	46 954908.9	33	18		Ar	50 991630	29	25		Mn	53 940358.9
23	24		Cr	46 962900	32	19		K	50 976380	28	26		Fe	53 939610.5
22	25		Mn	46 976100	31	20		Ca	50 961500	28	26		Fe^m	53 946617.4
21	26		Fe	46 992890	30	21		Sc	50 953603	27	27		Co	53 948459.6
21	26		Fe^m	46 993720	29	22		Ti	50 946615.0	27	27		Co^m	53 948671.6
20	27		Co	47 011490	28	23		V	50 943959.5	26	28		Ni	53 957910
32	16	48	S	48 014170	27	24		Cr	50 944767.4	25	29		Cu	53 976710
31	17		Cl	47 994950	26	25		Mn	50 948210.8	24	30		Zn	53 992950
30	18		Ar	47 974540	25	26		Fe	50 956820	36	19	55	K	54 999710
29	19		K	47 965514	24	27		Co	50 970720	35	20		Ca	54 980550
28	20		Ca	47 952534	23	28		Ni	50 987720	34	21		Sc	54 968240
27	21		Sc	47 952231	34	18	52	Ar	51 996780	33	22		Ti	54 955270
26	22		Ti	47 947946.3	33	19		K	51 982610	32	23		V	54 947230
25	23		V	47 952253.7	32	20		Ca	51 965100	31	24		Cr	54 940839.7
24	24		Cr	47 954032	31	21		Sc	51 956680	30	25		Mn	54 938045.1
23	25		Mn	47 968520	30	22		Ti	51 946897	29	26		Fe	54 938293.4
22	26		Fe	47 980500	29	23		V	51 944775.5	28	27		Co	54 941999.0
21	27		Co	48 001760	28	24		Cr	51 940507.5	27	28		Ni	54 951330
20	28		Ni	48 019750	27	25		Mn	51 945565.5	26	29		Cu	54 966050
33	16	49	S	49 023620	27	25		Mn^m	51 945971.0	25	30		Zn	54 983980
32	17		Cl	49 000320	26	26		Fe	51 948114	36	20	56	Ca	55 985570
31	18		Ar	48 980520	26	26		Fe^m	51 955426	35	21		Sc	55 972870
30	19		K	48 967450	25	27		Co	51 963590	34	22		Ti	55 958200

N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)
33	23		V	55 950530	29	30		Zn	58 949260	31	31		Ga	61 944175
32	24		Cr	55 940653.1	28	31		Ga	58 963370	31	31		Ga^{m}	61 945053
31	25		Mn	55 938904.9	27	32		Ge	58 981750	30	32		Ge	61 954650
30	26		Fe	55 934937.5	39	21	60	Sc	59 995710	29	33		As	61 973200
29	27		Co	55 939839.3	38	22		Ti	59 976760	41	22	63	Ti	62 994420
28	28		Ni	55 942132	37	23		V	59 965030	40	23		V	62 977550
27	29		Cu	55 958560	36	24		Cr	59 950080	39	24		Cr	62 961860
26	30		Zn	55 972380	35	25		Mn	59 942910	38	25		Mn	62 950240
25	31		Ga	55 994910	35	25		Mn^{m}	59 943199	37	26		Fe	62 940370
37	20	57	Ca	56 992360	34	26		Fe	59 934072	36	27		Co	62 933612
36	21		Sc	56 977790	33	27		Co	59 933817.1	35	28		Ni	62 929669.4
35	22		Ti	56 963990	33	27		Co^{m}	59 933880.0	35	28		Ni^{m}	62 929762.8
34	23		V	56 952560	32	28		Ni	59 930786.4	34	29		Cu	62 929597.5
33	24		Cr	56 943613.0	31	29		Cu	59 937365.0	33	30		Zn	62 933211.6
32	25		Mn	56 938285.4	30	30		Zn	59 941827	32	31		Ga	62 939294.2
31	26		Fe	56 935394.0	29	31		Ga	59 957060	31	32		Ge	62 949640
30	27		Co	56 936291.4	28	32		Ge	59 970190	30	33		As	62 963690
29	28		Ni	56 939793.5	27	33		As	59 993130	41	23	64	V	63 983470
28	29		Cu	56 949211	27	33		As^{m}	59 993194	40	24		Cr	63 964410
27	30		Zn	56 964790	39	22	61	Ti	60 983200	39	25		Mn	63 954250
26	31		Ga	56 982930	38	23		V	60 968480	39	25		Mn^{m}	63 954385
37	21	58	Sc	57 983710	37	24		Cr	60 954720	38	26		Fe	63 941200
36	22		Ti	57 966970	36	25		Mn	60 944650	37	27		Co	63 935810
35	23		V	57 956830	35	26		Fe	60 936745	36	28		Ni	63 927966.0
34	24		Cr	57 944350	35	26		Fe^{m}	60 937670	35	29		Cu	63 929764.2
33	25		Mn	57 939980	34	27		Co	60 932475.8	34	30		Zn	63 929142.2
33	25		Mn^{m}	57 940053	33	28		Ni	60 931056.0	33	31		Ga	63 936838.7
32	26		Fe	57 933275.6	32	29		Cu	60 933457.8	33	31		Ga^{m}	63 936884.7
31	27		Co	57 935752.8	31	30		Zn	60 939511	32	32		Ge	63 941650
31	27		Co^{m}	57 935779.5	31	30		Zn^{m}	60 939606	31	33		As	63 957570
31	27		Co^{n}	57 935809.8	31	30		Zn^{n}	60 939960	42	23	65	V	64 987920
30	28		Ni	57 935342.9	31	30		Zn^{p}	60 940323	41	24		Cr	64 970160
29	29		Cu	57 944538.5	30	31		Ga	60 949450	40	25		Mn	64 956340
28	30		Zn	57 954590	30	31		Ga^{m}	60 949543	39	26		Fe	64 945380
27	31		Ga	57 974250	29	32		Ge	60 963790	39	26		Fe^{m}	64 945765
27	31		Ga^{m}	57 974278	28	33		As	60 980620	38	27		Co	64 936478
26	32		Ge	57 991010	40	22	62	Ti	61 987490	37	28		Ni	64 930084.3
38	21	59	Sc	58 989220	39	23		V	61 973780	37	28		Ni^{m}	64 931171.8
37	22		Ti	58 972930	38	24		Cr	61 956610	36	29		Cu	64 927789.5
36	23		V	58 960210	37	25		Mn	61 948430	35	30		Zn	64 929241.0
35	24		Cr	58 948590	37	25		Mn^{m}	61 948427	35	30		Zn^{m}	64 929298.8
35	24		Cr^{m}	58 949125	36	26		Fe	61 936767	34	31		Ga	64 932734.8
34	25		Mn	58 940440	35	27		Co	61 934051	33	32		Ge	64 939440
33	26		Fe	58 934875.5	35	27		Co^{m}	61 934074	32	33		As	64 949560
32	27		Co	58 933195.0	34	28		Ni	61 928345.1	31	34		Se	64 964660
31	28		Ni	58 934346.7	33	29		Cu	61 932584	42	24	66	Cr	65 973380
30	29		Cu	58 939498.0	32	30		Zn	61 934330	41	25		Mn	65 961080

N	Z	A	El	Atomic mass (μu)
40	26		Fe	65 946780
39	27		Co	65 939760
39	27		Co^m	65 939946
39	27		Co^n	65 940451
38	28		Ni	65 929139.3
37	29		Cu	65 928868.8
36	30		Zn	65 926033.4
35	31		Ga	65 931589
34	32		Ge	65 933840
33	33		As	65 944710
33	33		As^m	65 946172
33	33		As^n	65 947955
32	34		Se	65 955210
43	24	67	Cr	66 979550
42	25		Mn	66 964140
41	26		Fe	66 950950
41	26		Fe^m	66 951347
40	27		Co	66 940890
39	28		Ni	66 931569
39	28		Ni^m	66 932650
38	29		Cu	66 927730.3
37	30		Zn	66 927127.3
36	31		Ga	66 928201.7
35	32		Ge	66 932734
35	32		Ge^m	66 932753
35	32		Ge^n	66 933541
34	33		As	66 939190
33	34		Se	66 950090
32	35		Br	66 964790
43	25	68	Mn	67 969300
42	26		Fe	67 953700
41	27		Co	67 944870
41	27		Co^m	67 945035
40	28		Ni	67 931869
40	28		Ni^m	67 933769
40	28		Ni^n	67 934927
39	29		Cu	67 929610.9
39	29		Cu^m	67 930385.6
38	30		Zn	67 924844.2
37	31		Ga	67 927980.1
37	31		Ga^m	67 929300.5
36	32		Ge	67 928094
35	33		As	67 936770
35	33		As^m	67 937230
34	34		Se	67 941800
33	35		Br	67 958520
44	25	69	Mn	68 972840
43	26		Fe	68 958780
42	27		Co	68 946320
41	28		Ni	68 935610
41	28		Ni^m	68 935954
41	28		Ni^n	68 938510
40	29		Cu	68 929429.3
40	29		Cu^m	68 932372.7
39	30		Zn	68 926550.3
39	30		Zn^m	68 927021.1
38	31		Ga	68 925573.6
37	32		Ge	68 927964.5
37	32		Ge^m	68 928057.7
37	32		Ge^n	68 928391.7
36	33		As	68 932270
35	34		Se	68 939560
35	34		Se^m	68 939602
35	34		Se^n	68 940171
34	35		Br	68 950110
34	35		Br^m	68 950145
34	35		Br^n	68 950714
33	36		Kr	68 965180
44	26	70	Fe	69 961460
43	27		Co	69 951000
43	27		Co^m	69 951218
42	28		Ni	69 936500
42	28		Ni^m	69 939570
41	29		Cu	69 932392.3
41	29		Cu^m	69 932500.5
41	29		Cu^n	69 932652.2
40	30		Zn	69 925319.3
39	31		Ga	69 926022.0
38	32		Ge	69 924247.4
37	33		As	69 930920
37	33		As^m	69 930960
36	34		Se	69 933390
35	35		Br	69 944790
35	35		Br^m	69 947246
34	36		Kr	69 955260
45	26	71	Fe	70 966720
44	27		Co	70 952900
43	28		Ni	70 940740
42	29		Cu	70 932676.8
42	29		Cu^m	70 935636
41	30		Zn	70 927722
41	30		Zn^m	70 927891
40	31		Ga	70 924701.3
39	32		Ge	70 924951.0
39	32		Ge^m	70 925164.0
38	33		As	70 927112
37	34		Se	70 932240
37	34		Se^m	70 932292
37	34		Se^n	70 932517
36	35		Br	70 938740
35	36		Kr	70 949630
34	37		Rb	70 965320
34	37		Rb^m	70 965378
34	37		Rb^n	70 965604
46	26	72	Fe	71 969620
45	27		Co	71 957810
44	28		Ni	71 942090
43	29		Cu	71 935820.3
43	29		Cu^m	71 936110
42	30		Zn	71 926858
41	31		Ga	71 926366.3
41	31		Ga^m	71 926494.8
40	32		Ge	71 922075.8
40	32		Ge^m	71 922818.1
39	33		As	71 926752
38	34		Se	71 927112
37	35		Br	71 936640
37	35		Br^m	71 936747
36	36		Kr	71 942092
35	37		Rb	71 959080
35	37		Rb^m	71 959184
46	27	73	Co	72 960240
45	28		Ni	72 946470
44	29		Cu	72 936675
43	30		Zn	72 929780
43	30		Zn^m	72 929994
43	30		Zn^n	72 930037
42	31		Ga	72 925174.7
41	32		Ge	72 923458.9
41	32		Ge^m	72 923473.3
41	32		Ge^n	72 923530.6
40	33		As	72 923825
39	34		Se	72 926765
39	34		Se^m	72 926793
38	35		Br	72 931690
37	36		Kr	72 939289
37	36		Kr^m	72 939755
36	37		Rb	72 950560
36	37		Rb^m	72 951025
35	38		Sr	72 965970
47	27	74	Co	73 965380

N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)
46	28		Ni	73 948070	47	30		Zn^m	76 937788	39	40		Zr	78 949160
45	29		Cu	73 939875	46	31		Ga	76 929154.3	51	29	80	Cu	79 960870
44	30		Zn	73 929460	45	32		Ge	76 923548.6	50	30		Zn	79 944340
43	31		Ga	73 926946	45	32		Ge^m	76 923720.1	49	31		Ga	79 936520
43	31		Ga^m	73 927010	44	33		As	76 920647.3	48	32		Ge	79 925370
42	32		Ge	73 921177.8	44	33		As^m	76 921157.6	47	33		As	79 922534
41	33		As	73 923928.7	43	34		Se	76 919914.0	46	34		Se	79 916521.3
40	34		Se	73 922476.4	43	34		Se^m	76 920087.8	45	35		Br	79 918529.3
39	35		Br	73 929891	42	35		Br	76 921379	45	35		Br^m	79 918621.4
39	35		Br^m	73 929906	42	35		Br^m	76 921493	44	36		Kr	79 916379.0
38	36		Kr	73 933084.4	41	36		Kr	76 924670.0	43	37		Rb	79 922519
38	36		Kr^m	73 933629	40	37		Rb	76 930408	43	37		Rb^m	79 923049
37	37		Rb	73 944265	39	38		Sr	76 937945	42	38		Sr	79 924521
36	38		Sr	73 956310	38	39		Y	76 949650	41	39		Y	79 934280
48	27	75	Co	74 968330	50	28	78	Ni	77 963180	40	40		Zr	79 940400
47	28		Ni	74 952870	49	29		Cu	77 951960	51	30	81	Zn	80 950480
46	29		Cu	74 941900	48	30		Zn	77 938440	50	31		Ga	80 937750
45	30		Zn	74 932940	48	30		Zn^m	77 941309	49	32		Ge	80 928820
44	31		Ga	74 926500.2	47	31		Ga	77 931608.2	49	32		Ge^m	80 929554
43	32		Ge	74 922858.9	46	32		Ge	77 922853	48	33		As	80 922132
43	32		Ge^m	74 923009.0	45	33		As	77 921827	47	34		Se	80 917992.5
42	33		As	74 921596.5	44	34		Se	77 917309.1	47	34		Se^m	80 918103.1
42	33		As^m	74 921922.7	43	35		Br	77 921146	46	35		Br	80 916290.6
41	34		Se	74 922523.4	43	35		Br^m	77 921340	46	35		Br^m	80 916866.2
40	35		Br	74 925776	42	36		Kr	77 920364.8	45	36		Kr	80 916592.0
39	36		Kr	74 930946	41	37		Rb	77 928141	45	36		Kr^m	80 916796.7
38	37		Rb	74 938570	41	37		Rb^m	77 928260	44	37		Rb	80 918996
37	38		Sr	74 949950	40	38		Sr	77 932180	44	37		Rb^m	80 919088
48	28	76	Ni	75 955330	39	39		Y	77 943610	43	38		Sr	80 923212
47	29		Cu	75 945275	38	40		Zr	77 955230	42	39		Y	80 929130
47	29		Cu^m	75 945271	50	29	79	Cu	78 954560	41	40		Zr	80 937210
46	30		Zn	75 933290	49	30		Zn	78 942650	40	41		Nb	80 949030
45	31		Ga	75 928827.6	48	31		Ga	78 932890	52	30	82	Zn	81 954420
44	32		Ge	75 921402.6	47	32		Ge	78 925400	51	31		Ga	81 942990
43	33		As	75 922394.0	47	32		Ge^m	78 925603	50	32		Ge	81 929550
43	33		As^m	75 922441.7	46	33		As	78 920948	49	33		As	81 924500
42	34		Se	75 919213.6	46	33		As^m	78 921777	49	33		As^m	81 924771
41	35		Br	75 924541	45	34		Se	78 918499.1	48	34		Se	81 916699.4
41	35		Br^m	75 924652	45	34		Se^m	78 918601.9	47	35		Br	81 916804.1
40	36		Kr	75 925910	44	35		Br	78 918337.1	47	35		Br^m	81 916853.4
39	37		Rb	75 935072.2	44	35		Br^m	78 918560.0	46	36		Kr	81 913483.6
39	37		Rb^m	75 935412.5	43	36		Kr	78 920082	45	37		Rb	81 918208.6
38	38		Sr	75 941770	43	36		Kr^m	78 920222	45	37		Rb^m	81 918282.8
37	39		Y	75 958450	43	36		Kr^n	78 920240	44	38		Sr	81 918402
49	28	77	Ni	76 960550	42	37		Rb	78 923989	43	39		Y	81 926790
48	29		Cu	76 947850	41	38		Sr	78 929708	42	40		Zr	81 931090
47	30		Zn	76 936960	40	39		Y	78 937350	41	41		Nb	81 943130

N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)
53	30	83	Zn	82 961030	48	37		Rb	84 911789.738	53	35		Br	87 924070
52	31		Ga	82 946980	47	38		Sr	84 912933	53	35		Br^m	87 924358
51	32		Ge	82 934620	47	38		Sr^m	84 913189.0	52	36		Kr	87 914447
50	33		As	82 924980	46	39		Y	84 916433	51	37		Rb	87 911315.59
49	34		Se	82 919118	45	40		Zr	84 921470	50	38		Sr	87 905612.1
49	34		Se^m	82 919363	45	40		Zr^m	84 921782	49	39		Y	87 909501.1
48	35		Br	82 915180	44	41		Nb	84 927910	48	40		Zr	87 910227
48	35		Br^m	82 918475	44	41		Nb^m	84 928727	47	41		Nb	87 918330
47	36		Kr	82 914136	43	42		Mo	84 936550	47	41		Nb^m	87 918378
47	36		Kr^m	82 914146.2	42	43		Tc	84 948830	46	42		Mo	87 921953
47	36		Kr^n	82 914180.8	55	31	86	Ga	85 963120	45	43		Tc	87 932680
46	37		Rb	82 915110	54	32		Ge	85 946490	45	43		Tc^m	87 932678
46	37		Rb^m	82 915155	53	33		As	85 936500	44	44		Ru	87 940260
45	38		Sr	82 917557	52	34		Se	85 924272	57	32	89	Ge	88 963830
45	38		Sr^m	82 917835	51	35		Br	85 918798	56	33		As	88 949390
44	39		Y	82 922350	50	36		Kr	85 910610.73	55	34		Se	88 936450
43	40		Zr	82 928650	49	37		Rb	85 911167.42	54	35		Br	88 926390
43	40		Zr^m	82 928706	49	37		Rb^m	85 911764.36	53	36		Kr	88 917630
43	40		Zr^n	83 000000	48	38		Sr	85 909260.2	52	37		Rb	88 912278
42	41		Nb	82 936710	48	38		Sr^m	85 912433.3	51	38		Sr	88 907450.7
41	42		Mo	82 948740	47	39		Y	85 914886	50	39		Y	88 905848.3
53	31	84	Ga	83 952650	46	40		Zr	85 916470	49	40		Zr	88 908890
52	32		Ge	83 937470	45	41		Nb	85 925040	49	40		Zr^m	88 909521
51	33		As	83 929060	45	41		Nb^m	85 925303	48	41		Nb	88 913418
51	33		As^m	83 929060	44	42		Mo	85 930700	48	41		Nb^m	88 913419
50	34		Se	83 918462	43	43		Tc	85 942880	47	42		Mo	88 919480
49	35		Br	83 916479	43	43		Tc^m	85 944487	47	42		Mo^m	88 919895
49	35		Br^m	83 916843	55	32	87	Ge	86 952510	46	43		Tc	88 927170
49	35		Br^n	83 916917	54	33		As	86 939900	46	43		Tc^m	88 927235
48	36		Kr	83 911507	53	34		Se	86 928520	45	44		Ru	88 936110
48	36		Kr^m	83 914980.7	52	35		Br	86 920711	44	45		Rh	88 948840
47	37		Rb	83 914385	51	36		Kr	86 913354.86	57	33	90	As	89 955500
47	37		Rb^m	83 914882.5	50	37		Rb	86 909180.527	56	34		Se	89 939960
46	38		Sr	83 913425	49	38		Sr	86 908877.1	55	35		Br	89 930630
45	39		Y	83 920390	49	38		Sr^m	86 909294.2	54	36		Kr	89 919517
44	40		Zr	83 923250	48	39		Y	86 910875.7	53	37		Rb	89 914802
43	41		Nb	83 933570	47	40		Zr	86 914816	53	37		Rb^m	89 914916
43	41		Nb^m	83 933934	47	40		Zr^m	86 915177	52	38		Sr	89 907738
42	42		Mo	83 940090	46	41		Nb	86 920360	51	39		Y	89 907151.9
54	31	85	Ga	84 957000	46	41		Nb^m	86 920364	50	40		Zr	89 904704.4
53	32		Ge	84 943030	45	42		Mo	86 927330	50	40		Zr^m	89 907193.9
52	33		As	84 932020	44	43		Tc	86 936530	50	40		Zr^n	89 908557.8
51	34		Se	84 922250	44	43		Tc^m	86 936554	49	41		Nb	89 911265
50	35		Br	84 915608	43	44		Ru	86 949180	49	41		Nb^m	89 911396
49	36		Kr	84 912527.3	56	32	88	Ge	87 956910	49	41		Nb^n	89 911399
49	36		Kr^m	84 912854.6	55	33		As	87 944940	49	41		Nb^p	89 911449
49	36		Kr^n	84 914665.6	54	34		Se	87 931420	49	41		Nb^q	89 911675

N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)
48	42		Mo	89 913937	58	35		Br	92 943050	54	41		Nb	94 906835.8
48	42		Mo^m	89 917024	57	36		Kr	92 931270	54	41		Nb^m	94 907088.8
47	43		Tc	89 923560	56	37		Rb	92 922042	53	42		Mo	94 905842.1
47	43		Tc^m	89 923886	56	37		Rb^m	92 922313	52	43		Tc	94 907657
46	44		Ru	89 929890	55	38		Sr	92 914026	52	43		Tc^m	94 907699
45	45		Rh	89 942870	54	39		Y	92 909583	51	44		Ru	94 910413
45	45		Rh^m	89 942866	53	40		Zr	92 906476.0	50	45		Rh	94 915900
58	33	91	As	90 960430	52	41		Nb	92 906378.1	50	45		Rh^m	94 916478
57	34		Se	90 945960	52	41		Nb^m	92 906411.1	49	46		Pd	94 924690
56	35		Br	90 933970	51	42		Mo	92 906813	49	46		Pd^m	94 926688
55	36		Kr	90 923450	51	42		Mo^m	92 909416	48	47		Ag	94 935480
54	37		Rb	90 916537	50	43		Tc	92 910249	48	47		Ag^m	94 935845
53	38		Sr	90 910203	50	43		Tc^m	92 910669	48	47		Ag^n	94 938196
52	39		Y	90 907305	50	43		Tc^n	92 912594	48	47		Ag^p	94 940697
51	40		Zr	90 905645.8	49	44		Ru	92 917050	47	48		Cd	94 949870
51	40		Zr^m	90 909046.0	49	44		Ru^m	92 917831	61	35	96	Br	95 958530
50	41		Nb	90 906996	49	44		Ru^n	92 919280	60	36		Kr	95 943070
50	41		Nb^m	90 907109	48	45		Rh	92 925740	59	37		Rb	95 934270
50	41		Nb^n	90 909180	47	46		Pd	92 935910	59	37		Rb^m	95 934267
49	42		Mo	90 911750	46	47		Ag	92 949780	58	38		Sr	95 921697
49	42		Mo^m	90 912451	60	34	94	Se	93 960490	57	39		Y	95 915891
48	43		Tc	90 918430	59	35		Br	93 948680	56	40		Zr	95 908273.4
48	43		Tc^m	90 918582	58	36		Kr	93 934360	55	41		Nb	95 908101
47	44		Ru	90 926290	57	37		Rb	93 926405	54	42		Mo	95 904679.5
47	44		Ru^m	90 926376	56	38		Sr	93 915361	53	43		Tc	95 907871
46	45		Rh	90 936550	55	39		Y	93 911595	53	43		Tc^m	95 907908
45	46		Pd	90 949110	54	40		Zr	93 906315.2	52	44		Ru	95 907598
59	33	92	As	91 966800	53	41		Nb	93 907283.9	51	45		Rh	95 914461
58	34		Se	91 949920	53	41		Nb^m	93 907327.8	51	45		Rh^m	95 914517
57	35		Br	91 939260	52	42		Mo	93 905088.3	50	46		Pd	95 918160
56	36		Kr	91 926156	51	43		Tc	93 909657	50	46		Pd^m	95 920880
55	37		Rb	91 919729	51	43		Tc^m	93 909737	49	47		Ag	95 930680
54	38		Sr	91 911038	50	44		Ru	93 911360	49	47		Ag^m	95 930681
53	39		Y	91 908949	50	44		Ru^m	93 914199	49	47		Ag^n	95 930681
52	40		Zr	91 905040.8	49	45		Rh	93 921700	48	48		Cd	95 939770
51	41		Nb	91 907194	49	45		Rh^m	93 922018	62	35	97	Br	96 962800
51	41		Nb^m	91 907339.4	48	46		Pd	93 928770	61	36		Kr	96 948560
51	41		Nb^n	91 907436.2	48	46		Pd^m	93 934009	60	37		Rb	96 937350
51	41		Nb^p	91 909559.3	47	47		Ag	93 942780	59	38		Sr	96 926153
50	42		Mo	91 906811	47	47		Ag^m	93 944229	59	38		Sr^m	96 926484
50	42		Mo^m	91 909774	47	47		Ag^n	93 949758	59	38		Sr^n	96 927045
49	43		Tc	91 915260	60	35	95	Br	94 952870	58	39		Y	96 918134
49	43		Tc^m	91 915550	59	36		Kr	94 939840	57	40		Zr	96 910953.1
48	44		Ru	91 920120	58	37		Rb	94 929303	56	41		Nb	96 908098.6
47	45		Rh	91 931980	57	38		Sr	94 919359	56	41		Nb^m	96 908896.6
46	46		Pd	91 940420	56	39		Y	94 912821	55	42		Mo	96 906021.5
59	34	93	Se	92 956290	55	40		Zr	94 908042.6	54	43		Tc	96 906365

N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)
54	43		Tc^m	96 906470	51	48		Cd	98 925010	63	39		Y	101 933560
53	44		Ru	96 907555	50	49		In	98 934220	62	40		Zr	101 922980
52	45		Rh	96 911340	50	49		In^m	98 934653	61	41		Nb	101 918040
52	45		Rh^m	96 911615	49	50		Sn	98 949330	61	41		Nb^m	101 918174
51	46		Pd	96 916480	49	50		Sn^m	98 949758	60	42		Mo	101 910297
50	47		Ag	96 923970	64	36	100	Kr	99 961140	59	43		Tc	101 909215
50	47		Ag^m	96 926484	63	37		Rb	99 949870	59	43		Tc^m	101 909236
49	48		Cd	96 934940	62	38		Sr	99 935350	58	44		Ru	101 904349.3
48	49		In	96 949540	61	39		Y	99 927760	57	45		Rh	101 906843
62	36	98	Kr	97 951910	60	40		Zr	99 917760	57	45		Rh^m	101 906995
61	37		Rb	97 941790	59	41		Nb	99 914182	56	46		Pd	101 905609
61	37		Rb^m	97 942093	59	41		Nb^m	99 914684	55	47		Ag	101 911690
60	38		Sr	97 928453	58	42		Mo	99 907477	55	47		Ag^m	101 911695
59	39		Y	97 922203	57	43		Tc	99 907657.8	54	48		Cd	101 914460
58	40		Zr	97 912735	57	43		Tc^m	99 907873.3	53	49		In	101 924090
57	41		Nb	97 910328	57	43		Tc^n	99 907919.8	52	50		Sn	101 930300
57	41		Nb^m	97 910418	56	44		Ru	99 904219.5	52	50		Sn^m	101 932463
56	42		Mo	97 905408.2	55	45		Rh	99 908122	65	38	103	Sr	102 948950
55	43		Tc	97 907216	55	45		Rh^m	99 908238	64	39		Y	102 936730
55	43		Tc^m	97 907313	54	46		Pd	99 908506	63	40		Zr	102 926600
54	44		Ru	97 905287	53	47		Ag	99 916100	62	41		Nb	102 919140
53	45		Rh	97 910708	53	47		Ag^m	99 916124	61	42		Mo	102 913210
53	45		Rh^m	97 910767	52	48		Cd	99 920290	60	43		Tc	102 909181
52	46		Pd	97 912721	52	48		Cd^m	99 923027	59	44		Ru	102 906323.8
51	47		Ag	97 921570	51	49		In	99 931110	59	44		Ru^m	102 906579.5
51	47		Ag^m	97 921749	50	50		Sn	99 939040	58	45		Rh	102 905504
50	48		Cd	97 927400	64	37	101	Rb	100 953200	58	45		Rh^m	102 905547.0
50	48		Cd^m	97 930005	63	38		Sr	100 940520	57	46		Pd	102 906087
49	49		In	97 942140	62	39		Y	100 930310	57	46		Pd^m	102 906929.8
49	49		In^m	97 942136	61	40		Zr	100 921140	56	47		Ag	102 908973
63	36	99	Kr	98 957600	60	41		Nb	100 915252	56	47		Ag^m	102 909117
62	37		Rb	98 945380	59	42		Mo	100 910347	55	48		Cd	102 913419
61	38		Sr	98 933240	58	43		Tc	100 907315	54	49		In	102 919914
60	39		Y	98 924636	58	43		Tc^m	100 907538	54	49		In^m	102 920593
59	40		Zr	98 916512	57	44		Ru	100 905582.1	53	50		Sn	102 928100
58	41		Nb	98 911618	57	44		Ru^m	100 906148.4	52	51		Sb	102 939690
58	41		Nb^m	98 912010	56	45		Rh	100 906164	66	38	104	Sr	103 952330
57	42		Mo	98 907711.9	56	45		Rh^m	100 906332	65	39		Y	103 941050
57	42		Mo^m	98 907816.9	55	46		Pd	100 908289	64	40		Zr	103 928780
56	43		Tc	98 906254.7	54	47		Ag	100 912800	63	41		Nb	103 922460
56	43		Tc^m	98 906408.0	54	47		Ag^m	100 913097	63	41		Nb^m	103 922694
55	44		Ru	98 905939.3	53	48		Cd	100 918680	62	42		Mo	103 913760
54	45		Rh	98 908132	52	49		In	100 926340	61	43		Tc	103 911450
54	45		Rh^m	98 908201	52	49		In^m	100 926935	61	43		Tc^m	103 911518
53	46		Pd	98 911768	51	50		Sn	100 936060	60	44		Ru	103 905433
52	47		Ag	98 917600	65	37	102	Rb	101 958870	59	45		Rh	103 906656
52	47		Ag^m	98 918142	64	38		Sr	101 943020	59	45		Rh^m	103 906794.0

N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)
58	46		Pd	103 904036	65	42		Mo	106 921690	61	48		Cd^{n}	108 905480
57	47		Ag	103 908629	65	42		Mo^{m}	106 921771	60	49		In	108 907151
57	47		Ag^{m}	103 908637	64	43		Tc	106 915080	60	49		In^{m}	108 907848
56	48		Cd	103 909849	64	43		Tc^{m}	106 915158	60	49		In^{n}	108 909407
55	49		In	103 918300	63	44		Ru	106 909910	59	50		Sn	108 911283
55	49		In^{m}	103 918389	62	45		Rh	106 906748	58	51		Sb	108 918132
54	50		Sn	103 923140	62	45		Rh^{m}	106 907036	57	52		Te	108 927420
53	51		Sb	103 936470	61	46		Pd	106 905133	56	53		I	108 938150
67	38	105	Sr	104 958580	61	46		Pd^{m}	106 905364	70	40	110	Zr	109 952870
66	39		Y	104 944870	60	47		Ag	106 905097	69	41		Nb	109 942440
65	40		Zr	104 933050	60	47		Ag^{m}	106 905196	68	42		Mo	109 929730
64	41		Nb	104 923940	59	48		Cd	106 906618	67	43		Tc	109 923820
63	42		Mo	104 916970	58	49		In	106 910295	66	44		Ru	109 914140
62	43		Tc	104 911660	58	49		In^{m}	106 911023	65	45		Rh	109 911140
61	44		Ru	104 907753	57	50		Sn	106 915640	65	45		Rh^{m}	109 911069
60	45		Rh	104 905694	56	51		Sb	106 924150	64	46		Pd	109 905153
60	45		Rh^{m}	104 905833	55	52		Te	106 935010	63	47		Ag	109 906107
59	46		Pd	104 905085	69	39	108	Y	107 959480	63	47		Ag^{m}	109 906233.4
58	47		Ag	104 906529	68	40		Zr	107 943960	62	48		Cd	109 903002.1
58	47		Ag^{m}	104 906555	67	41		Nb	107 934840	61	49		In	109 907165
57	48		Cd	104 909468	66	42		Mo	107 923450	61	49		In^{m}	109 907232
56	49		In	104 914674	65	43		Tc	107 918460	60	50		Sn	109 907843
56	49		In^{m}	104 915397	64	44		Ru	107 910170	59	51		Sb	109 916750
55	50		Sn	104 921350	63	45		Rh	107 908730	58	52		Te	109 922410
54	51		Sb	104 931490	63	45		Rh^{m}	107 908663	57	53		I	109 935240
53	52		Te	104 943640	62	46		Pd	107 903892	56	54		Xe	109 944280
67	39	106	Y	105 949790	61	47		Ag	107 905956	70	41	111	Nb	110 945650
66	40		Zr	105 935910	61	47		Ag^{m}	107 906072	69	42		Mo	110 934410
65	41		Nb	105 927970	60	48		Cd	107 904184	68	43		Tc	110 925690
64	42		Mo	105 918137	59	49		In	107 909698	67	44		Ru	110 917700
63	43		Tc	105 914358	59	49		In^{m}	107 909730	66	45		Rh	110 911590
62	44		Ru	105 907329	58	50		Sn	107 911925	65	46		Pd	110 907671
61	45		Rh	105 907287	57	51		Sb	107 922160	65	46		Pd^{m}	110 907856
61	45		Rh^{m}	105 907434	56	52		Te	107 929440	64	47		Ag	110 905291
60	46		Pd	105 903486	55	53		I	107 943480	64	47		Ag^{m}	110 905355
59	47		Ag	105 906669	69	40	109	Zr	108 949240	63	48		Cd	110 904178.1
59	47		Ag^{m}	105 906766	68	41		Nb	108 937630	63	48		Cd^{m}	110 904603.5
58	48		Cd	105 906459	67	42		Mo	108 927810	62	49		In	110 905103
57	49		In	105 913465	66	43		Tc	108 919980	62	49		In^{m}	110 905679
57	49		In^{m}	105 913497	65	44		Ru	108 913200	61	50		Sn	110 907734
56	50		Sn	105 916880	64	45		Rh	108 908737	61	50		Sn^{m}	110 908008
55	51		Sb	105 928790	63	46		Pd	108 905950	60	51		Sb	110 913160
55	51		Sb^{m}	105 929865	63	46		Pd^{m}	108 906153	59	52		Te	110 921110
54	52		Te	105 937500	62	47		Ag	108 904752	58	53		I	110 930280
68	39	107	Y	106 954140	62	47		Ag^{m}	108 904846.7	57	54		Xe	110 941600
67	40		Zr	106 940750	61	48		Cd	108 904982	57	54		Xe^{m}	111 000000
66	41		Nb	106 930310	61	48		Cd^{m}	108 905047	71	41	112	Nb	111 950830

N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)
70	42		Mo	111 936840	67	47		Ag^{m}	113 909017	67	49		In^{m}	115 905396
69	43		Tc	111 929150	66	48		Cd	113 903358.5	67	49		In^{n}	115 905571
68	44		Ru	111 918970	65	49		In	113 904914	66	50		Sn	115 901741
67	45		Rh	111 914390	65	49		In^{m}	113 905118	65	51		Sb	115 906794
67	45		Rh^{m}	111 914750	65	49		In^{n}	113 905453	65	51		Sb^{m}	115 907203
66	46		Pd	111 907314	65	49		In^{p}	113 905603	64	52		Te	115 908460
65	47		Ag	111 907005	64	50		Sn	113 902779	63	53		I	115 916810
64	48		Cd	111 902757.8	64	50		Sn^{m}	113 906093	62	54		Xe	115 921581
63	49		In	111 905532	63	51		Sb	113 909270	61	55		Cs	115 933370
63	49		In^{m}	111 905701	63	51		Sb^{m}	113 909801	61	55		Cs^{m}	115 933472
63	49		In^{n}	111 905909	62	52		Te	113 912090	60	56		Ba	115 941380
63	49		In^{p}	111 906192	61	53		I	113 921850	74	43	117	Tc	116 946480
62	50		Sn	111 904818	60	54		Xe	113 927980	73	44		Ru	116 935580
61	51		Sb	111 912398	59	55		Cs	113 941450	72	45		Rh	116 925980
60	52		Te	111 917010	58	56		Ba	113 950680	71	46		Pd	116 917840
59	53		I	111 927970	73	42	115	Mo	114 950290	71	46		Pd^{m}	116 918056
58	54		Xe	111 935620	72	43		Tc	114 938690	70	47		Ag	116 911680
57	55		Cs	111 950300	71	44		Ru	114 928690	70	47		Ag^{m}	116 911712
72	41	113	Nb	112 954700	70	45		Rh	114 920330	69	48		Cd	116 907219
71	42		Mo	112 941880	69	46		Pd	114 913680	69	48		Cd^{m}	116 907365
70	43		Tc	112 931590	69	46		Pd^{m}	114 913784	68	49		In	116 904514
69	44		Ru	112 922490	68	47		Ag	114 908760	68	49		In^{m}	116 904852
69	44		Ru^{m}	112 922630	68	47		Ag^{m}	114 908802	67	50		Sn	116 902952
68	45		Rh	112 915530	67	48		Cd	114 905431.0	67	50		Sn^{m}	116 903289.3
67	46		Pd	112 910150	67	48		Cd^{m}	114 905625.3	66	51		Sb	116 904836
67	46		Pd^{m}	112 910241	66	49		In	114 903878	65	52		Te	116 908645
67	46		Pd^{n}	113 000000	66	49		In^{m}	114 904239	65	52		Te^{m}	116 908962
66	47		Ag	112 906567	65	50		Sn	114 903342	65	52		Te^{n}	116 908939
66	47		Ag^{m}	112 906612	65	50		Sn^{m}	114 904000.2	64	53		I	116 913650
65	48		Cd	112 904401.7	65	50		Sn^{n}	114 904108.5	63	54		Xe	116 920359
65	48		Cd^{m}	112 904684.5	64	51		Sb	114 906598	62	55		Cs	116 928670
64	49		In	112 904058	63	52		Te	114 911900	62	55		Cs^{m}	116 928835
64	49		In^{m}	112 904478	63	52		Te^{m}	114 911912	61	56		Ba	116 938500
63	50		Sn	112 905171	63	52		Te^{n}	114 912202	60	57		La	116 950070
63	50		Sn^{m}	112 905253	62	53		I	114 918050	60	57		La^{m}	116 950220
62	51		Sb	112 909372	61	54		Xe	114 926294	75	43	118	Tc	117 951480
61	52		Te	112 915890	60	55		Cs	114 935910	74	44		Ru	117 937820
60	53		I	112 923640	59	56		Ba	114 947370	73	45		Rh	117 930070
59	54		Xe	112 933340	73	43	116	Tc	115 943370	72	46		Pd	117 918980
58	55		Cs	112 944490	72	44		Ru	115 930810	71	47		Ag	117 914580
72	42	114	Mo	113 944920	71	45		Rh	115 924060	71	47		Ag^{m}	117 914718
71	43		Tc	113 935880	71	45		Rh^{m}	115 924272	70	48		Cd	117 906915
70	44		Ru	113 924280	70	46		Pd	115 914160	69	49		In	117 906354
69	45		Rh	113 918810	69	47		Ag	115 911360	69	49		In^{m}	117 906462
69	45		Rh^{m}	113 919023	69	47		Ag^{m}	115 911443	69	49		In^{n}	117 906612
68	46		Pd	113 910363	68	48		Cd	115 904756	68	50		Sn	117 901603
67	47		Ag	113 908804	67	49		In	115 905260	67	51		Sb	117 905529

N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)
67	51		Sb^{m}	117 905798	68	52		Te	119 904020	66	56		Ba	121 919900
67	51		Sb^{n}	117 905584	67	53		I	119 910048	65	57		La	121 930710
66	52		Te	117 905828	66	54		Xe	119 911784	64	58		Ce	121 937910
65	53		I	117 913074	65	55		Cs	119 920677	63	59		Pr	121 951810
64	54		Xe	117 916179	65	55		Cs^{m}	119 920783	77	46	123	Pd	122 934930
63	55		Cs	117 926559	64	56		Ba	119 926040	76	47		Ag	122 924900
63	55		Cs^{m}	117 926666	63	57		La	119 938070	75	48		Cd	122 917000
62	56		Ba	117 933040	62	58		Ce	119 946640	75	48		Cd^{m}	122 917348
61	57		La	117 946730	76	45	121	Rh	120 938720	74	49		In	122 910438
75	44	119	Ru	118 942840	75	46		Pd	120 928870	74	49		In^{m}	122 910790
74	45		Rh	118 932110	74	47		Ag	120 919850	73	50		Sn	122 905720.8
73	46		Pd	118 923110	73	48		Cd	120 912980	73	50		Sn^{m}	122 905747.2
72	47		Ag	118 915670	73	48		Cd^{m}	120 913204	72	51		Sb	122 904214.0
72	47		Ag^{m}	118 915684	72	49		In	120 907846	71	52		Te	122 904270.0
71	48		Cd	118 909920	72	49		In^{m}	120 908182	71	52		Te^{m}	122 904535.8
71	48		Cd^{m}	118 910080	71	50		Sn	120 904235.5	70	53		I	122 905589
70	49		In	118 905845	71	50		Sn^{m}	120 904242.2	69	54		Xe	122 908482
70	49		In^{m}	118 906180	71	50		Sn^{n}	120 906381.3	69	54		Xe^{m}	122 908680
69	50		Sn	118 903308	70	51		Sb	120 903815.7	68	55		Cs	122 912996
69	50		Sn^{m}	118 903403.7	69	52		Te	120 904936	68	55		Cs^{m}	122 913164
68	51		Sb	118 903942	69	52		Te^{m}	120 905252	67	56		Ba	122 918781
68	51		Sb^{m}	118 907004	68	53		I	120 907367	66	57		La	122 926240
67	52		Te	118 906404	67	54		Xe	120 911462	65	58		Ce	122 935400
67	52		Te^{m}	118 906684	66	55		Cs	120 917229	64	59		Pr	122 945960
66	53		I	118 910070	66	55		Cs^{m}	120 917303	78	46	124	Pd	123 936880
65	54		Xe	118 915411	65	56		Ba	120 924050	77	47		Ag	123 928640
64	55		Cs	118 922377	64	57		La	120 933010	77	47		Ag^{m}	123 928642
64	55		Cs^{m}	118 922426	63	58		Ce	120 943420	76	48		Cd	123 917650
63	56		Ba	118 930660	62	59		Pr	120 955360	75	49		In	123 913180
62	57		La	118 940990	77	45	122	Rh	121 943210	75	49		In^{m}	123 913150
61	58		Ce	118 952760	76	46		Pd	121 930550	74	50		Sn	123 905273.9
76	44	120	Ru	119 945310	75	47		Ag	121 923530	74	50		Sn^{m}	123 907769.9
75	45		Rh	119 936410	75	47		Ag^{m}	121 923617	74	50		Sn^{n}	123 908125.9
74	46		Pd	119 924690	74	48		Cd	121 913330	73	51		Sb	123 905935.7
73	47		Ag	119 918790	73	49		In	121 910280	73	51		Sb^{m}	123 905947.4
73	47		Ag^{m}	119 919001	73	49		In^{m}	121 910316	73	51		Sb^{n}	123 905975.2
72	48		Cd	119 909850	73	49		In^{n}	121 910585	73	51		Sb^{p}	123 905979.5
71	49		In	119 907960	72	50		Sn	121 903439.0	72	52		Te	123 902817.9
71	49		In^{m}	119 908008	71	51		Sb	121 905173.7	71	53		I	123 906209.9
71	49		In^{n}	119 908276	71	51		Sb^{m}	121 905349.3	70	54		Xe	123 905893.0
70	50		Sn	119 902194.7	71	51		Sb^{n}	121 905321.2	69	55		Cs	123 912258
70	50		Sn^{m}	119 904858.8	70	52		Te	121 903043.9	69	55		Cs^{m}	123 912755
70	50		Sn^{n}	119 905310.3	69	53		I	121 907589	68	56		Ba	123 915094
69	51		Sb	119 905072	68	54		Xe	121 908368	67	57		La	123 924570
69	51		Sb^{m}	119 905077	67	55		Cs	121 916110	67	57		La^{m}	123 924680
69	51		Sb^{n}	119 905157	67	55		Cs^{m}	121 916258	66	58		Ce	123 930410
69	51		Sb^{p}	119 907572	67	55		Cs^{n}	121 916253	65	59		Pr	123 942960

N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)
64	60		Nd	123 952230	79	48		Cd	126 926440	82	47		Ag^{m}	128 943693
78	47	125	Ag	124 930430	78	49		In	126 917350	81	48		Cd	128 932150
77	48		Cd	124 921250	78	49		In^{m}	126 917852	81	48		Cd^{m}	128 932152
77	48		Cd^{m}	124 921298	77	50		Sn	126 910360	80	49		In	128 921700
76	49		In	124 913600	77	50		Sn^{m}	126 910365	80	49		In^{m}	128 922104
76	49		In^{m}	124 913988	76	51		Sb	126 906924	80	49		In^{n}	128 923510
75	50		Sn	124 907784.1	75	52		Te	126 905226.3	79	50		Sn	128 913480
75	50		Sn^{m}	124 907813.7	75	52		Te^{m}	126 905321.1	79	50		Sn^{m}	128 913516
74	51		Sb	124 905253.8	74	53		I	126 904473	78	51		Sb	128 909148
73	52		Te	124 904430.7	73	54		Xe	126 905184	78	51		Sb^{m}	128 911135
73	52		Te^{m}	124 904586.2	73	54		Xe^{m}	126 905502	78	51		Sb^{n}	128 911146
72	53		I	124 904630.2	72	55		Cs	126 907418	78	51		Sb^{p}	128 911444
71	54		Xe	124 906395.5	72	55		Cs^{m}	126 907903	77	52		Te	128 906598.2
71	54		Xe^{m}	124 906666.6	71	56		Ba	126 911094	77	52		Te^{m}	128 906711.5
70	55		Cs	124 909728	71	56		Ba^{m}	126 911179	76	53		I	128 904988
70	55		Cs^{m}	124 910014	70	57		La	126 916375	75	54		Xe	128 904779.4
69	56		Ba	124 914473	70	57		La^{m}	126 916391	75	54		Xe^{m}	128 905032.9
68	57		La	124 920816	69	58		Ce	126 922730	74	55		Cs	128 906064
68	57		La^{m}	124 920931	69	58		Ce^{m}	126 922726	73	56		Ba	128 908679
67	58		Ce	124 928440	68	59		Pr	126 930830	73	56		Ba^{m}	128 908688
66	59		Pr	124 937830	68	59		Pr^{m}	126 931476	72	57		La	128 912693
65	60		Nd	124 948880	67	60		Nd	126 940500	72	57		La^{m}	128 912878
79	47	126	Ag	125 934500	66	61		Pm	126 951630	71	58		Ce	128 918100
78	48		Cd	125 922350	81	47	128	Ag	127 941170	71	58		Ce^{m}	128 918218
77	49		In	125 916460	80	48		Cd	127 927760	70	59		Pr	128 925100
77	49		In^{m}	125 916575	79	49		In	127 920170	70	59		Pr^{m}	128 925507
76	50		Sn	125 907653	79	49		In^{m}	127 920440	69	60		Nd	128 933190
76	50		Sn^{m}	125 910036	79	49		In^{n}	127 920515	68	61		Pm	128 943160
76	50		Sn^{n}	125 910406	78	50		Sn	127 910537	67	62		Sm	128 954640
75	51		Sb	125 907250	78	50		Sn^{m}	127 912781	83	47	130	Ag	129 950450
75	51		Sb^{m}	125 907267	77	51		Sb	127 909169	82	48		Cd	129 933900
75	51		Sb^{n}	125 907289	77	51		Sb^{m}	127 909179	81	49		In	129 924970
75	51		Sb^{p}	125 907353	76	52		Te	127 904463.1	81	49		In^{m}	129 925024
74	52		Te	125 903311.7	76	52		Te^{m}	127 907459.0	81	49		In^{n}	129 925399
73	53		I	125 905624	75	53		I	127 905809	80	50		Sn	129 913967
72	54		Xe	125 904274	74	54		Xe	127 903531.3	80	50		Sn^{m}	129 916057
71	55		Cs	125 909452	74	54		Xe^{m}	127 906523.6	79	51		Sb	129 911656
71	55		Cs^{m}	125 909745	73	55		Cs	127 907749	79	51		Sb^{m}	129 911661
71	55		Cs^{n}	125 910092	72	56		Ba	127 908318	78	52		Te	129 906224.4
70	56		Ba	125 911250	71	57		La	127 915590	78	52		Te^{m}	129 908528.7
69	57		La	125 919510	71	57		La^{m}	127 915695	78	52		Te^{n}	129 909082
69	57		La^{m}	125 919742	70	58		Ce	127 918910	78	52		Te^{p}	129 910921.6
68	58		Ce	125 923970	69	59		Pr	127 928790	77	53		I	129 906674
67	59		Pr	125 935310	68	60		Nd	127 935390	76	54		Xe	129 903508.0
66	60		Nd	125 943220	67	61		Pm	127 948420	75	55		Cs	129 906709
65	61		Pm	125 957520	66	62		Sm	127 958080	75	55		Cs^{m}	129 906884
80	47	127	Ag	126 936770	82	47	129	Ag	128 943690	74	56		Ba	129 906320.8

N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)
74	56		Ba^{m}	129 908977.9	76	56		Ba	131 905061.3	78	56		Ba	133 904508.4
73	57		La	129 912369	75	57		La	131 910100	77	57		La	133 908514
72	58		Ce	129 914740	75	57		La^{m}	131 910305	76	58		Ce	133 908925
72	58		Ce^{m}	129 917370	74	58		Ce	131 911460	75	59		Pr	133 915710
71	59		Pr	129 923590	74	58		Ce^{m}	131 913974	75	59		Pr^{m}	133 915716
71	59		Pr^{m}	129 923692	73	59		Pr	131 919260	74	60		Nd	133 918790
70	60		Nd	129 928510	73	59		Pr^{m}	131 919259	74	60		Nd^{m}	133 921252
69	61		Pm	129 940450	72	60		Nd	131 923321	73	61		Pm	133 928350
68	62		Sm	129 948920	71	61		Pm	131 933750	73	61		Pm^{m}	133 928352
67	63		Eu	129 963570	70	62		Sm	131 940690	72	62		Sm	133 933970
83	48	131	Cd	130 940670	69	63		Eu	131 954370	71	63		Eu	133 946510
82	49		In	130 926850	84	49	133	In	132 937810	70	64		Gd	133 955370
82	49		In^{m}	130 927224	84	49		In^{m}	132 938164	86	49	135	In	134 949330
82	49		In^{n}	130 931250	83	50		Sn	132 923830	85	50		Sn	134 934730
81	50		Sn	130 917000	82	51		Sb	132 915252	84	51		Sb	134 925170
81	50		Sn^{m}	130 917090	81	52		Te	132 910955	83	52		Te	134 916450
80	51		Sb	130 911982	81	52		Te^{m}	132 911313	83	52		Te^{m}	134 918110
79	52		Te	130 908523.9	80	53		I	132 907797	82	53		I	134 910048
79	52		Te^{m}	130 908719.4	79	54		Xe	132 905910.7	81	54		Xe	134 907227
78	53		I	130 906124.6	79	54		Xe^{m}	132 906161.1	81	54		Xe^{m}	134 907793
77	54		Xe	130 905082.4	78	55		Cs	132 905451.933	80	55		Cs	134 905977.0
77	54		Xe^{m}	130 905258.3	77	56		Ba	132 906007.5	80	55		Cs^{m}	134 907729.9
76	55		Cs	130 905464	77	56		Ba^{m}	132 906316.8	79	56		Ba	134 905688.6
75	56		Ba	130 906941	76	57		La	132 908220	79	56		Ba^{m}	134 905976.5
75	56		Ba^{m}	130 907142.0	76	57		La^{m}	132 908794	78	57		La	134 906977
74	57		La	130 910070	75	58		Ce	132 911515	77	58		Ce	134 909151
74	57		La^{m}	130 910398	75	58		Ce^{m}	132 911555	77	58		Ce^{m}	134 909630
73	58		Ce	130 914420	74	59		Pr	132 916331	76	59		Pr	134 913112
73	58		Ce^{m}	130 914481	74	59		Pr^{m}	132 916536	76	59		Pr^{m}	134 913496
73	58		Ce^{n}	130 914589	73	60		Nd	132 922350	75	60		Nd	134 918181
72	59		Pr	130 920260	73	60		Nd^{m}	132 922490	75	60		Nd^{m}	134 918251
72	59		Pr^{m}	130 920418	73	60		Nd^{n}	132 922544	74	61		Pm	134 924880
71	60		Nd	130 927250	72	61		Pm	132 929780	74	61		Pm^{m}	134 924927
71	60		Nd^{m}	130 927630	72	61		Pm^{m}	132 929919	73	62		Sm	134 932520
70	61		Pm	130 935870	71	62		Sm	132 938670	73	62		Sm^{m}	134 932517
69	62		Sm	130 946110	70	63		Eu	132 949240	72	63		Eu	134 941820
68	63		Eu	130 957750	85	49	134	In	133 944150	71	64		Gd	134 952570
84	48	132	Cd	131 945550	84	50		Sn	133 928290	86	50	136	Sn	135 939340
83	49		In	131 932990	83	51		Sb	133 920380	85	51		Sb	135 930350
82	50		Sn	131 917816	83	51		Sb^{m}	133 920461	85	51		Sb^{m}	135 930531
81	51		Sb	131 914467	82	52		Te	133 911369	84	52		Te	135 920100
81	51		Sb^{m}	131 914685	82	52		Te^{m}	133 913185	83	53		I	135 914650
80	52		Te	131 908553	81	53		I	133 909744	82	54		Xe	135 907219
79	53		I	131 907997	80	54		Xe	133 905394.5	82	54		Xe^{m}	135 909250
78	54		Xe	131 904153.5	80	54		Xe^{m}	133 907504.5	81	55		Cs	135 907311.6
78	54		Xe^{m}	131 907108.2	79	55		Cs	133 906718.475	81	55		Cs^{m}	135 907867
77	55		Cs	131 906434.3	79	55		Cs^{m}	133 906867.424	80	56		Ba	135 904575.9

N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)
80	56		Ba^{m}	135 906755.8	81	57		La^{m}	137 907190	80	60		Nd	139 909550
79	57		La	135 907640	80	58		Ce	137 905991	80	60		Nd^{m}	139 911936
79	57		La^{m}	135 907901	80	58		Ce^{m}	137 908276	79	61		Pm	139 916040
78	58		Ce	135 907172	79	59		Pr	137 910755	79	61		Pm^{m}	139 916497
78	58		Ce^{m}	135 910495	79	59		Pr^{m}	137 911129	78	62		Sm	139 918995
77	59		Pr	135 912692	78	60		Nd	137 911950	77	63		Eu	139 928090
77	59		Pr^{m}	135 913331	78	60		Nd^{m}	137 915359	77	63		Eu^{m}	139 928309
76	60		Nd	135 914976	77	61		Pm	137 919548	76	64		Gd	139 933670
75	61		Pm	135 923570	77	61		Pm^{m}	137 919580	75	65		Tb	139 945810
75	61		Pm^{m}	135 923703	77	61		Pm^{n}	138 000000	74	66		Dy	139 954010
74	62		Sm	135 928276	76	62		Sm	137 923244	74	66		Dy^{m}	139 956339
74	62		Sm^{m}	135 930707	75	63		Eu	137 933710	73	67		Ho	139 968540
73	63		Eu	135 939600	74	64		Gd	137 940120	89	52	141	Te	140 944650
73	63		Eu^{m}	135 939602	74	64		Gd^{m}	137 942512	88	53		I	140 935030
72	64		Gd	135 947340	73	65		Tb	137 953160	87	54		Xe	140 926650
71	65		Tb	135 961380	72	66		Dy	137 962490	86	55		Cs	140 920046
87	50	137	Sn	136 945990	88	51	139	Sb	138 945980	85	56		Ba	140 914411
86	51		Sb	136 935310	87	52		Te	138 934730	84	57		La	140 910962
85	52		Te	136 925320	86	53		I	138 926100	83	58		Ce	140 908276.3
84	53		I	136 917871	85	54		Xe	138 918793	82	59		Pr	140 907652.8
83	54		Xe	136 911562	84	55		Cs	138 913364	81	60		Nd	140 909610
82	55		Cs	136 907089.5	83	56		Ba	138 908841.3	81	60		Nd^{m}	140 910422
81	56		Ba	136 905827.4	82	57		La	138 906353.3	80	61		Pm	140 913555
81	56		Ba^{m}	136 906537.8	81	58		Ce	138 906653	80	61		Pm^{m}	140 914229
80	57		La	136 906494	81	58		Ce^{m}	138 907463	79	62		Sm	140 918476
79	58		Ce	136 907806	80	59		Pr	138 908938	79	62		Sm^{m}	140 918665
79	58		Ce^{m}	136 908078	79	60		Nd	138 911978	78	63		Eu	140 924931
78	59		Pr	136 910705	79	60		Nd^{m}	138 912226	78	63		Eu^{m}	140 925033
78	59		Pr^{m}	136 911308	78	61		Pm	138 916804	77	64		Gd	140 932126
77	60		Nd	136 914567	78	61		Pm^{m}	138 917008	77	64		Gd^{m}	140 932532
77	60		Nd^{m}	136 915125	77	62		Sm	138 922297	76	65		Tb	140 941450
76	61		Pm	136 920479	77	62		Sm^{m}	138 922787	76	65		Tb^{m}	140 941449
76	61		Pm^{m}	136 920644	76	63		Eu	138 929792	75	66		Dy	140 951350
75	62		Sm	136 926970	75	64		Gd	138 938240	74	67		Ho	140 963100
75	62		Sm^{m}	136 927160	75	64		Gd^{m}	138 938507	74	67		Ho^{m}	140 963177
74	63		Eu	136 935570	74	65		Tb	138 948290	90	52	142	Te	141 949080
73	64		Gd	136 945020	73	66		Dy	138 959540	89	53		I	141 940180
72	65		Tb	136 955980	88	52	140	Te	139 938850	88	54		Xe	141 929710
87	51	138	Sb	137 940790	87	53		I	139 931000	87	55		Cs	141 924299
86	52		Te	137 929220	86	54		Xe	139 921640	86	56		Ba	141 916453
85	53		I	137 922350	85	55		Cs	139 917282	85	57		La	141 914079
84	54		Xe	137 913950	84	56		Ba	139 910605	84	58		Ce	141 909244
83	55		Cs	137 911017	83	57		La	139 909477.6	83	59		Pr	141 910044.8
83	55		Cs^{m}	137 911103	82	58		Ce	139 905438.7	83	59		Pr^{m}	141 910048.8
82	56		Ba	137 905247.2	82	58		Ce^{m}	139 907701.5	82	60		Nd	141 907723.3
82	56		Ba^{m}	137 907491.5	81	59		Pr	139 909076	81	61		Pm	141 912874
81	57		La	137 907112	81	59		Pr^{m}	139 909895	81	61		Pm^{m}	141 913822

N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)
80	62		Sm	141 915198	81	63		Eu^{m}	143 920027	80	66		Dy	145 932845
79	63		Eu	141 923430	80	64		Gd	143 922960	80	66		Dy^{m}	145 935997
79	63		Eu^{m}	141 923933	79	65		Tb	143 933050	79	67		Ho	145 944640
78	64		Gd	141 928120	79	65		Tb^{m}	143 933471	78	68		Er	145 952000
77	65		Tb	141 938740	79	65		Tb^{n}	143 933556	77	69		Tm	145 966430
77	65		Tb^{m}	141 939044	79	65		Tb^{p}	143 933600	77	69		Tm^{m}	145 966505
76	66		Dy	141 946370	78	66		Dy	143 939250	93	54	147	Xe	146 953560
75	67		Ho	141 959770	77	67		Ho	143 951480	92	55		Cs	146 944160
90	53	143	I	142 944560	76	68		Er	143 960380	91	56		Ba	146 934950
89	54		Xe	142 935110	91	54	145	Xe	144 944070	90	57		La	146 928240
88	55		Cs	142 927352	90	55		Cs	144 935526	89	58		Ce	146 922670
87	56		Ba	142 920627	89	56		Ba	144 927630	88	59		Pr	146 918996
86	57		La	142 916063	88	57		La	144 921650	87	60		Nd	146 916100.4
85	58		Ce	142 912386	87	58		Ce	144 917230	86	61		Pm	146 915138.5
84	59		Pr	142 910816.9	86	59		Pr	144 914512	85	62		Sm	146 914897.9
83	60		Nd	142 909814.3	85	60		Nd	144 912573.6	84	63		Eu	146 916746
82	61		Pm	142 910933	84	61		Pm	144 912749	83	64		Gd	146 919094
82	61		Pm^{m}	142 911963	83	62		Sm	144 913410	83	64		Gd^{m}	146 928314
81	62		Sm	142 914628	83	62		Sm^{m}	144 922842.8	82	65		Tb	146 924045
81	62		Sm^{m}	142 915438	82	63		Eu	144 916265	82	65		Tb^{m}	146 924099
81	62		Sm^{n}	142 917628	82	63		Eu^{m}	144 917034	81	66		Dy	146 931092
80	63		Eu	142 920298	81	64		Gd	144 921709	81	66		Dy^{m}	146 931897
80	63		Eu^{m}	142 920717	81	64		Gd^{m}	144 922514	80	67		Ho	146 940060
79	64		Gd	142 926750	80	65		Tb	144 929270	79	68		Er	146 949490
79	64		Gd^{m}	142 926913	80	65		Tb^{m}	144 929275	79	68		Er^{m}	146 949597
78	65		Tb	142 935120	79	66		Dy	144 937430	78	69		Tm	146 960960
78	65		Tb^{m}	142 935126	79	66		Dy^{m}	144 937552	78	69		Tm^{m}	146 961030
77	66		Dy	142 943830	78	67		Ho	144 947200	93	55	148	Cs	147 949220
77	66		Dy^{m}	142 944165	78	67		Ho^{m}	144 947310	92	56		Ba	147 937720
76	67		Ho	142 954610	77	68		Er	144 957390	91	57		La	147 932230
75	68		Er	142 966340	76	69		Tm	144 970070	90	58		Ce	147 924430
91	53	144	I	143 949990	92	54	146	Xe	145 947750	89	59		Pr	147 922135
90	54		Xe	143 938510	91	55		Cs	145 940290	89	59		Pr^{m}	147 922190
89	55		Cs	143 932077	90	56		Ba	145 930220	88	60		Nd	147 916893
89	55		Cs^{m}	143 932399	89	57		La	145 925790	87	61		Pm	147 917475
88	56		Ba	143 922953	89	57		La^{m}	145 925936	87	61		Pm^{m}	147 917623
87	57		La	143 919600	88	58		Ce	145 918760	86	62		Sm	147 914822.7
86	58		Ce	143 913647	87	59		Pr	145 917640	85	63		Eu	147 918086
85	59		Pr	143 913305	86	60		Nd	145 913116.9	84	64		Gd	147 918115
85	59		Pr^{m}	143 913368	85	61		Pm	145 914696	83	65		Tb	147 924272
84	60		Nd	143 910087.3	84	62		Sm	145 913041	83	65		Tb^{m}	147 924369
83	61		Pm	143 912591	83	63		Eu	145 917206	83	65		Tb^{n}	147 933525
83	61		Pm^{m}	143 913494	83	63		Eu^{m}	145 917921	82	66		Dy	147 927150
83	61		Pm^{n}	143 921819	82	64		Gd	145 918311	81	67		Ho	147 937720
82	62		Sm	143 911999	81	65		Tb	145 927250	81	67		Ho^{m}	147 938142
82	62		Sm^{m}	143 914493.9	81	65		Tb^{m}	145 927407	81	67		Ho^{n}	147 938454
81	63		Eu	143 918817	81	65		Tb^{n}	145 928244	80	68		Er	147 944550

N	Z	A	El	Atomic mass (μu)
79	69		Tm	147 957840
78	70		Yb	147 967420
94	55	149	Cs	148 952930
93	56		Ba	148 942580
92	57		La	148 934730
91	58		Ce	148 928400
90	59		Pr	148 923720
89	60		Nd	148 920149
88	61		Pm	148 918334
88	61		Pm^{m}	148 918592
87	62		Sm	148 917184.7
86	63		Eu	148 917931
85	64		Gd	148 919341
84	65		Tb	148 923246
84	65		Tb^{m}	148 923285
83	66		Dy	148 927305
83	66		Dy^{m}	148 930162
83	66		Dy^{n}	148 935340
82	67		Ho	148 933775
82	67		Ho^{m}	148 933828
81	68		Er	148 942310
81	68		Er^{m}	148 943102
80	69		Tm	148 952720
79	70		Yb	148 964040
95	55	150	Cs	149 958170
94	56		Ba	149 945680
93	57		La	149 938770
92	58		Ce	149 930410
91	59		Pr	149 926673
90	60		Nd	149 920891
89	61		Pm	149 920984
88	62		Sm	149 917275.5
87	63		Eu	149 919702
87	63		Eu^{m}	149 919747
86	64		Gd	149 918659
85	65		Tb	149 923660
85	65		Tb^{m}	149 924150
84	66		Dy	149 925585
83	67		Ho	149 933496
83	67		Ho^{m}	149 933483
83	67		Ho^{n}	149 933483
82	68		Er	149 937914
81	69		Tm	149 949960
81	69		Tm^{m}	149 950112
81	69		Tm^{n}	149 950832
80	70		Yb	149 958420
79	71		Lu	149 973230
79	71		Lu^{m}	149 973269
96	55	151	Cs	150 962190
95	56		Ba	150 950810
94	57		La	150 941720
93	58		Ce	150 933980
92	59		Pr	150 928319
91	60		Nd	150 923829
90	61		Pm	150 921207
89	62		Sm	150 919932.4
89	62		Sm^{m}	150 920212.7
88	63		Eu	150 919850.2
88	63		Eu^{m}	150 920060.8
87	64		Gd	150 920348
86	65		Tb	150 923103
86	65		Tb^{m}	150 923209
85	66		Dy	150 926185
84	67		Ho	150 931688
84	67		Ho^{m}	150 931732
83	68		Er	150 937449
83	68		Er^{m}	150 940224
82	69		Tm	150 945483
82	69		Tm^{m}	150 945582
82	69		Tm^{n}	150 948335
81	70		Yb	150 955400
81	70		Yb^{m}	150 956210
81	70		Yb^{n}	150 957327
81	70		Yb^{p}	150 958035
80	71		Lu	150 967580
80	71		Lu^{m}	150 967654
96	56	152	Ba	151 954270
95	57		La	151 946250
94	58		Ce	151 936540
93	59		Pr	151 931500
92	60		Nd	151 924682
91	61		Pm	151 923497
91	61		Pm^{m}	151 923650
91	61		Pm^{n}	151 923768
90	62		Sm	151 919732.4
89	63		Eu	151 921744.5
89	63		Eu^{m}	151 921793.5
89	63		Eu^{n}	151 921903.3
88	64		Gd	151 919791.0
87	65		Tb	151 924070
87	65		Tb^{m}	151 924616
86	66		Dy	151 924718
85	67		Ho	151 931714
85	67		Ho^{m}	151 931886
85	67		Hon	151 934956
84	68		Er	151 935050
83	69		Tm	151 944420
83	69		Tm^{m}	151 944530
82	70		Yb	151 950290
81	71		Lu	151 964120
97	56	153	Ba	152 959610
96	57		La	152 949620
95	58		Ce	152 940580
94	59		Pr	152 933840
93	60		Nd	152 927698
92	61		Pm	152 924117
91	62		Sm	152 922097.4
91	62		Sm^{m}	152 922203.0
90	63		Eu	152 921230.3
89	64		Gd	152 921749.5
89	64		Gd^{m}	152 921851.8
89	64		Gd^{n}	152 921933.4
88	65		Tb	152 923435
88	65		Tb^{m}	152 923610
87	66		Dy	152 925765
86	67		Ho	152 930199
86	67		Ho^{m}	152 930273
85	68		Er	152 935063
84	69		Tm	152 942012
84	69		Tm^{m}	152 942059
83	70		Yb	152 949480
83	70		Yb^{m}	152 952378
82	71		Lu	152 958770
82	71		Lu^{m}	152 958851
82	71		Lu^{n}	152 961589
81	72		Hf	152 970690
81	72		Hf^{m}	152 971497
97	57	154	La	153 954500
96	58		Ce	153 943420
95	59		Pr	153 937520
94	60		Nd	153 929480
94	60		Nd^{m}	153 929994
94	60		Nd^{n}	153 930928
93	61		Pm	153 926460
93	61		Pm^{m}	153 926591
92	62		Sm	153 922209.3
91	63		Eu	153 922979.2
91	63		Eu^{m}	153 923135.2
90	64		Gd	153 920865.6
89	65		Tb	153 924680
89	65		Tb^{m}	153 924691

N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)
89	65		Tb^{n}	153 924895	91	65		Tb^{n}	155 924841	91	67		Ho	157 928941
88	66		Dy	153 924424	90	66		Dy	155 924283	91	67		Ho^{m}	157 929013
87	67		Ho	153 930602	89	67		Ho	155 929840	91	67		Ho^{n}	157 929135
87	67		Ho^{m}	153 930857	89	67		Ho^{m}	155 929898	90	68		Er	157 929893
86	68		Er	153 932783	89	67		Ho^{n}	155 929951	89	69		Tm	157 936980
85	69		Tm	153 941568	88	68		Er	155 931065	89	69		Tm^{m}	157 937037
85	69		Tm^{m}	153 941642	87	69		Tm	155 938980	88	70		Yb	157 939866
84	70		Yb	153 946394	87	69		Tm^{m}	155 939199	87	71		Lu	157 949313
83	71		Lu	153 957520	87	69		Tm^{n}	156 000000	86	72		Hf	157 954799
83	71		Lu^{m}	153 957584	86	70		Yb	155 942818	85	73		Ta	157 966700
83	71		Lu^{n}	153 959957	85	71		Lu	155 953030	85	73		Ta^{m}	157 966849
82	72		Hf	153 964860	85	71		Lu^{m}	155 953269	84	74		W	157 974560
98	57	155	La	154 958350	84	72		Hf	155 959360	100	59	159	Pr	158 955500
97	58		Ce	154 948040	84	72		Hf^{m}	155 961470	99	60		Nd	158 946090
96	59		Pr	154 940120	83	73		Ta	155 972300	98	61		Pm	158 938970
95	60		Nd	154 932930	83	73		Ta^{m}	155 972410	97	62		Sm	158 933210
94	61		Pm	154 928100	99	58	157	Ce	156 956340	96	63		Eu	158 929089
93	62		Sm	154 924640.2	98	59		Pr	156 947430	95	64		Gd	158 926388.7
92	63		Eu	154 922893.3	97	60		Nd	156 939030	94	65		Tb	158 925346.8
91	64		Gd	154 922622.0	96	61		Pm	156 933040	93	66		Dy	158 925739.2
91	64		Gd^{m}	154 922751.9	95	62		Sm	156 928360	93	66		Dy^{m}	158 926117.9
90	65		Tb	154 923505	94	63		Eu	156 925424	92	67		Ho	158 927712
89	66		Dy	154 925754	93	64		Gd	156 923960.1	92	67		Ho^{m}	158 927933
89	66		Dy^{m}	154 926005	92	65		Tb	156 924024.6	91	68		Er	158 930684
88	67		Ho	154 929103	91	66		Dy	156 925466	91	68		Er^{m}	158 930881
88	67		Ho^{m}	154 929256	91	66		Dy^{m}	156 925680	91	68		Er^{n}	158 931145
87	68		Er	154 933209	90	67		Ho	156 928256	90	69		Tm	158 934980
86	69		Tm	154 939199	89	68		Er	156 931920	89	70		Yb	158 940050
86	69		Tm^{m}	154 939244	89	68		Er^{m}	156 932082	88	71		Lu	158 946630
85	70		Yb	154 945782	88	69		Tm	156 936970	88	71		Lu^{m}	158 946741
84	71		Lu	154 954316	87	70		Yb	156 942628	87	72		Hf	158 953995
84	71		Lu^{m}	154 954338	86	71		Lu	156 950098	86	73		Ta	158 963018
84	71		Lu^{n}	154 956228	86	71		Lu^{m}	156 950121	86	73		Ta^{m}	158 963086
83	72		Hf	154 963390	85	72		Hf	156 958400	85	74		W	158 972920
82	73		Ta	154 974590	84	73		Ta	156 968190	100	60	160	Nd	159 949090
98	58	156	Ce	155 951260	84	73		Ta^{m}	156 968212	99	61		Pm	159 942990
97	59		Pr	155 944270	84	73		Ta^{n}	156 969898	98	62		Sm	159 935140
96	60		Nd	155 935020	99	59	158	Pr	157 951980	97	63		Eu	159 931970
96	60		Nd^{m}	155 936554	98	60		Nd	157 941600	96	64		Gd	159 927054.1
95	61		Pm	155 931060	97	61		Pm	157 936560	95	65		Tb	159 927167.6
94	62		Sm	155 925528	96	62		Sm	157 929990	94	66		Dy	159 925197.5
94	62		Sm^{m}	155 927029	95	63		Eu	157 927850	93	67		Ho	159 928729
93	63		Eu	155 924752	94	64		Gd	157 924103.9	93	67		Ho^{m}	159 928794
92	64		Gd	155 922122.7	93	65		Tb	157 925413.1	93	67		Ho^{n}	159 928941
92	64		Gd^{m}	155 924417.5	93	65		Tb^{m}	157 925531.6	92	68		Er	159 929083
91	65		Tb	155 924747	93	65		Tb^{n}	157 925830.1	91	69		Tm	159 935260
91	65		Tb^{m}	155 924805	92	66		Dy	157 924409	91	69		Tm^{m}	159 935340

N	Z	A	El	Atomic mass (μu)
90	70		Yb	159 937552
89	71		Lu	159 946030
89	71		Lu^{m}	159 946033
88	72		Hf	159 950684
87	73		Ta	159 961490
87	73		Ta^{m}	159 961825
86	74		W	159 968480
85	75		Re	159 982120
101	60	161	Nd	160 953880
100	61		Pm	160 945860
99	62		Sm	160 938830
98	63		Eu	160 933680
97	64		Gd	160 929669.2
96	65		Tb	160 927569.9
95	66		Dy	160 926933.4
94	67		Ho	160 927855
94	67		Ho^{m}	160 928081
93	68		Er	160 929995
93	68		Er^{m}	160 930420
92	69		Tm	160 933550
92	69		Tm^{m}	160 933556
91	70		Yb	160 937902
90	71		Lu	160 943570
90	71		Lu^{m}	160 943746
89	72		Hf	160 950275
88	73		Ta	160 958420
88	73		Ta^{m}	160 958471
87	74		W	160 967360
86	75		Re	160 977590
86	75		Re^{m}	160 977724
101	61	162	Pm	161 950290
100	62		Sm	161 941220
99	63		Eu	161 937040
98	64		Gd	161 930985
97	65		Tb	161 929490
96	66		Dy	161 926798.4
95	67		Ho	161 929096
95	67		Ho^{m}	161 929209
94	68		Er	161 928778
93	69		Tm	161 933995
93	69		Tm^{m}	161 934138
92	70		Yb	161 935768
91	71		Lu	161 943280
91	71		Lu^{m}	161 943403
91	71		Lu^{n}	161 943596
90	72		Hf	161 947210
89	73		Ta	161 957290
88	74		W	161 963497
87	75		Re	161 976000
87	75		Re^{m}	161 976189
86	76		Os	161 984430
102	61	163	Pm	162 953680
101	62		Sm	162 945360
100	63		Eu	162 939210
99	64		Gd	162 933990
98	65		Tb	162 930648
97	66		Dy	162 928731.2
96	67		Ho	162 928733.9
96	67		Ho^{m}	162 929053.8
95	68		Er	162 930033
95	68		Er^{m}	162 930511
94	69		Tm	162 932651
93	70		Yb	162 936334
92	71		Lu	162 941180
91	72		Hf	162 947090
90	73		Ta	162 954330
89	74		W	162 962520
88	75		Re	162 972081
88	75		Re^{m}	162 972204
87	76		Os	162 982690
102	62	164	Sm	163 948280
101	63		Eu	163 942990
100	64		Gd	163 935860
99	65		Tb	163 933350
98	66		Dy	163 929174.8
97	67		Ho	163 930233.5
97	67		Ho^{m}	163 930383.6
96	68		Er	163 929200
95	69		Tm	163 933560
95	69		Tm^{m}	163 933571
94	70		Yb	163 934489
93	71		Lu	163 941340
92	72		Hf	163 944367
91	73		Ta	163 953530
90	74		W	163 958954
89	75		Re	163 970320
89	75		Re^{m}	163 970456
88	76		Os	163 978040
87	77		Ir	163 992200
87	77		Ir^{m}	163 992485
103	62	165	Sm	164 952980
102	63		Eu	164 945720
101	64		Gd	164 939380
100	65		Tb	164 934880
99	66		Dy	164 931703.3
99	66		Dy^{m}	164 931819.5
98	67		Ho	164 930322.1
97	68		Er	164 930726
96	69		Tm	164 932435
95	70		Yb	164 935280
94	71		Lu	164 939407
93	72		Hf	164 944570
92	73		Ta	164 950773
91	74		W	164 958280
90	75		Re	164 967089
90	75		Re^{m}	164 967139
89	76		Os	164 976760
88	77		Ir	164 987520
88	77		Ir^{m}	164 987719
103	63	166	Eu	165 949970
102	64		Gd	165 941600
101	65		Tb	165 937990
100	66		Dy	165 932806.7
99	67		Ho	165 932284.2
99	67		Ho^{m}	165 932290.6
98	68		Er	165 930293.1
97	69		Tm	165 933554
97	69		Tm^{m}	165 933685
96	70		Yb	165 933882
95	71		Lu	165 939860
95	71		Lu^{m}	165 939892
95	71		Lu^{n}	165 939903
94	72		Hf	165 942180
93	73		Ta	165 950510
92	74		W	165 955027
91	75		Re	165 965810
91	75		Re^{m}	165 965969
90	76		Os	165 972691
89	77		Ir	165 985820
89	77		Ir^{m}	165 986012
88	78		Pt	165 994860
104	63	167	Eu	166 953210
103	64		Gd	166 945570
102	65		Tb	166 940050
101	66		Dy	166 935660
100	67		Ho	166 933133
100	67		Ho^{m}	166 933410
99	68		Er	166 932048.2
99	68		Er^{m}	166 932271.3
98	69		Tm	166 932851.6
98	69		Tm^{m}	166 933044.3

N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)
98	69		Tm^{n}	166 933166.0	93	76		Os	168 967019	92	79		Au	170 991879
97	70		Yb	166 934950	92	77		Ir	168 976295	92	79		Au^{m}	170 992147
96	71		Lu	166 938270	92	77		Ir^{m}	168 976460	91	80		Hg	171 003760
96	71		Lu^{m}	166 938271	91	78		Pt	168 986720	106	66	172	Dy	171 948760
95	72		Hf	166 942600	90	79		Au	168 998080	105	67		Ho	171 944820
94	73		Ta	166 948090	105	65	170	Tb	169 950250	104	68		Er	171 939356
93	74		W	166 954816	104	66		Dy	169 942390	103	69		Tm	171 938400
92	75		Re	166 962600	103	67		Ho	169 939620	102	70		Yb	171 936381.5
92	75		Re^{m}	166 962737	103	67		Ho^{m}	169 939731	101	71		Lu	171 939086
91	76		Os	166 971550	102	68		Er	169 935464.3	101	71		Lu^{m}	171 939131
90	77		Ir	166 981665	101	69		Tm	169 935801.4	101	71		Lu^{n}	171 939203
90	77		Ir^{m}	166 981854	101	69		Tm^{m}	169 935998.1	100	72		Hf	171 939448
89	78		Pt	166 992980	100	70		Yb	169 934761.8	100	72		Hf^{m}	171 941601
104	64	168	Gd	167 948360	100	70		Yb^{m}	169 936112.8	99	73		Ta	171 944900
103	65		Tb	167 943640	99	71		Lu	169 938475	98	74		W	171 947290
102	66		Dy	167 937130	99	71		Lu^{m}	169 938575	97	75		Re	171 955420
101	67		Ho	167 935520	98	72		Hf	169 939610	97	75		Re^{m}	171 955426
101	67		Ho^{m}	167 935577	97	73		Ta	169 946180	96	76		Os	171 960023
100	68		Er	167 932370.2	96	74		W	169 949228	95	77		Ir	171 970460
99	69		Tm	167 934173	95	75		Re	169 958220	95	77		Ir^{m}	171 970757
98	70		Yb	167 933897	94	76		Os	169 963577	94	78		Pt	171 977347
97	71		Lu	167 938740	93	77		Ir	169 974970	93	79		Au	171 990040
97	71		Lu^{m}	167 938937	93	77		Ir^{m}	169 975255	92	80		Hg	171 998830
96	72		Hf	167 940570	92	78		Pt	169 982495	107	66	173	Dy	172 953000
95	73		Ta	167 948050	91	79		Au	169 996120	106	67		Ho	172 947290
94	74		W	167 951808	91	79		Au^{m}	169 996414	105	68		Er	172 942400
93	75		Re	167 961570	106	65	171	Tb	170 953300	104	69		Tm	172 939604
93	75		Re^{m}	168 000000	105	66		Dy	170 946200	104	69		Tm^{m}	172 939945
92	76		Os	167 967804	104	67		Ho	170 941470	103	70		Yb	172 938210.8
91	77		Ir	167 979880	103	68		Er	170 938029.8	103	70		Yb^{m}	172 938639.0
91	77		Ir^{m}	167 979935	103	68		Er^{m}	170 938243.0	102	71		Lu	172 938930.6
90	78		Pt	167 988150	102	69		Tm	170 936429.4	102	71		Lu^{m}	172 939063.4
105	64	169	Gd	168 952870	102	69		Tm^{m}	170 936885.7	101	72		Hf	172 940510
104	65		Tb	168 946220	101	70		Yb	170 936325.8	100	73		Ta	172 943750
103	66		Dy	168 940310	101	70		Yb^{m}	170 936428.1	99	74		W	172 947690
102	67		Ho	168 936872	101	70		Yb^{n}	170 936457.2	98	75		Re	172 953240
101	68		Er	168 934590.4	100	71		Lu	170 937913.1	97	76		Os	172 959808
100	69		Tm	168 934213.3	100	71		Lu^{m}	170 937989.5	96	77		Ir	172 967502
99	70		Yb	168 935190	99	72		Hf	170 940490	96	77		Ir^{m}	172 967773
99	70		Yb^{m}	168 935216	99	72		Hf^{m}	170 940516	95	78		Pt	172 976440
98	71		Lu	168 937651	98	73		Ta	170 944480	94	79		Au	172 986237
98	71		Lu^{m}	168 937683	97	74		W	170 949450	94	79		Au^{m}	172 986467
97	72		Hf	168 941260	96	75		Re	170 955720	93	80		Hg	172 997240
96	73		Ta	168 946010	95	76		Os	170 963185	107	67	174	Ho	173 951150
95	74		W	168 951779	94	77		Ir	170 971630	106	68		Er	173 944230
94	75		Re	168 958790	94	77		Ir^{m}	170 971819	105	69		Tm	173 942170
94	75		Re^{m}	168 958947	93	78		Pt	170 981240	104	70		Yb	173 938862.1

N	Z	A	El	Atomic mass (μu)
103	71		Lu	173 940337.5
103	71		Lu^{m}	173 940520.8
102	72		Hf	173 940046
102	72		Hf^{m}	173 941976
101	73		Ta	173 944450
100	74		W	173 946080
99	75		Re	173 953120
98	76		Os	173 957062
97	77		Ir	173 966861
97	77		Ir^{m}	173 967068
96	78		Pt	173 972819
95	79		Au	173 984760
95	79		Au^{m}	173 985142
94	80		Hg	173 992864
108	67	175	Ho	174 954050
107	68		Er	174 947770
106	69		Tm	174 943840
105	70		Yb	174 941276.5
105	70		Yb^{m}	174 941829.3
104	71		Lu	174 940771.8
104	71		Lu^{m}	174 942265
103	72		Hf	174 941509
102	73		Ta	174 943740
101	74		W	174 946720
100	75		Re	174 951380
99	76		Os	174 956946
98	77		Ir	174 964113
97	78		Pt	174 972421
96	79		Au	174 981270
96	79		Au^{m}	174 981492
95	80		Hg	174 991420
108	68	176	Er	175 950080
107	69		Tm	175 946990
106	70		Yb	175 942571.7
106	70		Yb^{m}	175 943698.9
105	71		Lu	175 942686.3
105	71		Lu^{m}	175 942818.2
104	72		Hf	175 941408.6
103	73		Ta	175 944860
103	73		Ta^{m}	175 944959
103	73		Ta^{n}	175 947879
102	74		W	175 945630
101	75		Re	175 951620
100	76		Os	175 954810
99	77		Ir	175 963649
98	78		Pt	175 968945
97	79		Au	175 980100
97	79		Au^{m}	175 980268
96	80		Hg	175 987355
95	81		Tl	176 000590
109	68	177	Er	176 954050
108	69		Tm	176 949040
107	70		Yb	176 945260.8
107	70		Yb^{m}	176 945616.7
106	71		Lu	176 943758.1
106	71		Lu^{m}	176 944799.6
106	71		Lu^{n}	176 947945
106	71		Lu^{p}	176 943919.6
106	71		Lu^{q}	176 944369.7
105	72		Hf	176 943220.7
105	72		Hf^{m}	176 944632.9
105	72		Hf^{n}	176 946162.2
105	72		Hf^{p}	176 944661.8
104	73		Ta	176 944472
104	73		Ta^{m}	176 944672
104	73		Ta^{n}	176 945927
104	73		Ta^{p}	176 944550
104	73		Ta^{q}	176 949470
103	74		W	176 946640
102	75		Re	176 950330
102	75		Re^{m}	176 950419
101	76		Os	176 954965
100	77		Ir	176 961302
99	78		Pt	176 968469
99	78		Pt^{m}	176 968628
98	79		Au	176 976865
98	79		Au^{m}	176 977097
98	79		Au^{n}	176 977356
97	80		Hg	176 986280
96	81		Tl	176 996427
96	81		Tl^{m}	176 997294
109	69	178	Tm	177 952640
108	70		Yb	177 946647
107	71		Lu	177 945955
107	71		Lu^{m}	177 946088
106	72		Hf	177 943698.8
106	72		Hf^{m}	177 944930.5
106	72		Hf^{n}	177 946324.3
106	72		Hf^{p}	177 946461.5
105	73		Ta	177 945778
105	73		Ta^{m}	177 945883
105	73		Ta^{n}	177 947461
105	73		Ta^{p}	177 948996
104	74		W	177 945876
103	75		Re	177 950990
102	76		Os	177 953251
101	77		Ir	177 961082
100	78		Pt	177 965649
99	79		Au	177 976030
98	80		Hg	177 982483
97	81		Tl	177 994900
96	82		Pb	178 003830
110	69	179	Tm	178 955340
109	70		Yb	178 950170
108	71		Lu	178 947327
108	71		Lu^{m}	178 947963
107	72		Hf	178 945816.1
107	72		Hf^{m}	178 946218.8
107	72		Hf^{n}	178 947003.3
106	73		Ta	178 945929.5
106	73		Ta^{m}	178 947343.7
106	73		Ta^{n}	178 948763.0
105	74		W	178 947070
104	75		Re	178 949988
104	75		Re^{m}	178 950058
103	76		Os	178 953816
102	77		Ir	178 959122
101	78		Pt	178 965363
100	79		Au	178 973213
99	80		Hg	178 981834
98	81		Tl	178 991090
98	81		Tl^{m}	178 992013
97	82		Pb	179 002150
110	70	180	Yb	179 952330
109	71		Lu	179 949880
109	71		Lu^{m}	179 949887
108	72		Hf	179 946550.0
108	72		Hf^{m}	179 947775.4
107	73		Ta	179 947464.8
107	73		Ta^{m}	179 947545.7
107	73		Ta^{n}	179 949022.5
106	74		W	179 946704
105	75		Re	179 950789
104	76		Os	179 952379
103	77		Ir	179 959229
102	78		Pt	179 963031
101	79		Au	179 972521
100	80		Hg	179 978266
99	81		Tl	179 989910
98	82		Pb	179 997918
111	70	181	Yb	180 956150

N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)
110	71		Lu	180 951970	107	76		Os^{m}	182 953312	107	78		Pt	184 960620
109	72		Hf	180 949101.2	106	77		Ir	182 956846	107	78		Pt^{m}	184 960730
109	72		Hf^{m}	180 949740	105	78		Pt	182 961597	106	79		Au	184 965789
109	72		Hf^{n}	180 950218	105	78		Pt^{m}	182 961634	106	79		Au^{m}	184 965894
109	72		Hf^{p}	180 950967	104	79		Au	182 967593	105	80		Hg	184 971899
108	73		Ta	180 947995.8	104	79		Au^{m}	182 967671	105	80		Hg^{m}	184 972011
108	73		Ta^{m}	180 948002.5	104	79		Au^{p}	182 967841	104	81		Tl	184 978790
108	73		Ta^{n}	180 949590	103	80		Hg	182 974450	104	81		Tl^{m}	184 979281
108	73		Ta^{p}	180 950389	103	80		Hg^{m}	182 974707	104	81		Tl^{n}	184 979860
107	74		W	180 948197	103	80		Hg^{p}	182 974662	103	82		Pb	184 987610
106	75		Re	180 950068	102	81		Tl	182 982193	103	82		Pb^{m}	184 987676
105	76		Os	180 953240	102	81		Tl^{m}	182 982883	102	83		Bi	184 997630
105	76		Os^{m}	180 953301	102	81		Tl^{n}	182 983241	102	83		Bi^{m}	184 997699
104	77		Ir	180 957625	101	82		Pb	182 991870	114	72	186	Hf	185 960890
103	78		Pt	180 963097	101	82		Pb^{m}	182 991975	113	73		Ta	185 958550
102	79		Au	180 970079	113	71	184	Lu	183 960910	112	74		W	185 954364.1
101	80		Hg	180 977819	113	71		Lu^{m}	184 000000	111	75		Re	185 954986.1
100	81		Tl	180 986257	112	72		Hf	183 955450	111	75		Re^{m}	185 955146
100	81		Tl^{m}	180 987178	112	72		Hf^{m}	183 956811	110	76		Os	185 953838.2
99	82		Pb	180 996620	111	73		Ta	183 954008	109	77		Ir	185 957946
99	82		Pb^{m}	181 000000	110	74		W	183 950931.2	109	77		Ir^{m}	185 957947
111	71	182	Lu	181 955040	109	75		Re	183 952521	108	78		Pt	185 959351
110	72		Hf	181 950554	109	75		Re^{m}	183 952722	107	79		Au	185 965953
110	72		Hf^{m}	181 951813	108	76		Os	183 952489.1	107	79		Au^{m}	185 966197
109	73		Ta	181 950151.8	107	77		Ir	183 957480	107	79		Au^{p}	186 000000
109	73		Ta^{m}	181 950169.3	107	77		Ir^{m}	183 957718	106	80		Hg	185 969362
109	73		Ta^{n}	181 950709.6	106	78		Pt	183 959922	106	80		Hg^{m}	185 971742
108	74		W	181 948204.2	106	78		Pt^{m}	183 961897	105	81		Tl	185 978330
107	75		Re	181 951210	105	79		Au	183 967452	105	81		Tl^{m}	185 978664
107	75		Re^{m}	181 951274	105	79		Au^{m}	183 967524	105	81		Tl^{n}	185 979065
106	76		Os	181 952110	105	79		Au^{n}	183 967696	104	82		Pb	185 984239
105	77		Ir	181 958076	104	80		Hg	183 971713	103	83		Bi	185 996600
104	78		Pt	181 961171	103	81		Tl	183 981870	103	83		Bi^{m}	185 996887
103	79		Au	181 969618	103	81		Tl^{m}	183 981975	115	72	187	Hf	186 964590
102	80		Hg	181 974690	103	81		Tl^{n}	183 982405	114	73		Ta	186 960530
101	81		Tl	181 985670	102	82		Pb	183 988142	113	74		W	186 957160.5
101	81		Tl^{m}	181 985776	101	83		Bi	184 001120	112	75		Re	186 955753.1
101	81		Tl^{p}	181 986312	101	83		Bi^{m}	184 001288	111	76		Os	186 955750.5
100	82		Pb	181 992672	113	72	185	Hf	184 958820	110	77		Ir	186 957363
112	71	183	Lu	182 957570	112	73		Ta	184 955559	110	77		Ir^{m}	186 957563
111	72		Hf	182 953530	112	73		Ta^{m}	184 956962	109	78		Pt	186 960590
110	73		Ta	182 951372.6	111	74		W	184 953419.3	108	79		Au	186 964568
110	73		Ta^{m}	182 951451.2	110	75		Re	184 952955.0	108	79		Au^{m}	186 964698
109	74		W	182 950223.0	110	75		Re^{m}	184 955235.1	107	80		Hg	186 969814
108	75		Re	182 950820	109	76		Os	184 954042.3	107	80		Hg^{m}	186 969877
108	75		Re^{m}	182 952868	109	76		Os^{m}	184 954152.0	106	81		Tl	186 975906
107	76		Os	182 953130	108	77		Ir	184 956700	106	81		Tl^{m}	186 976265

N	Z	A	El	Atomic mass (μu)
105	82		Pb	186 983918
105	82		Pb^{m}	186 983930
104	83		Bi	186 993158
104	83		Bi^{m}	186 993267
104	83		Bi^{n}	186 993429
116	72	188	Hf	187 966850
115	73		Ta	187 963700
114	74		W	187 958489
113	75		Re	187 958114.4
113	75		Re^{m}	187 958299.2
112	76		Os	187 955838.2
111	77		Ir	187 958853
111	77		Ir^{m}	187 959892
110	78		Pt	187 959395
109	79		Au	187 965324
108	80		Hg	187 967577
108	80		Hg^{m}	187 970501
107	81		Tl	187 976010
107	81		Tl^{m}	187 976052
107	81		Tl^{n}	187 976341
106	82		Pb	187 980874
106	82		Pb^{m}	187 983642
106	82		Pb^{n}	187 983787
106	82		Pb^{p}	187 983875
105	83		Bi	187 992270
105	83		Bi^{m}	187 992485
104	84		Po	187 999422
116	73	189	Ta	188 965830
115	74		W	188 961910
114	75		Re	188 959229
113	76		Os	188 958147.5
113	76		Os^{m}	188 958180.5
112	77		Ir	188 958719
112	77		Ir^{m}	188 959118
112	77		Ir^{n}	188 961224
111	78		Pt	188 960834
111	78		Pt^{m}	188 961040
110	79		Au	188 963948
110	79		Au^{m}	188 964213
109	80		Hg	188 968190
109	80		Hg^{m}	188 968278
108	81		Tl	188 973588
108	81		Tl^{m}	188 973892
107	82		Pb	188 980810
107	82		Pb^{m}	188 980848
106	83		Bi	188 989200
106	83		Bi^{m}	188 989393
106	83		Bi^{n}	188 989587
105	84		Po	188 998481
117	73	190	Ta	189 969230
116	74		W	189 963180
115	75		Re	189 961820
115	75		Re^{m}	189 962039
114	76		Os	189 958447.0
114	76		Os^{m}	189 960277.9
113	77		Ir	189 960546.0
113	77		Ir^{m}	189 960574.0
113	77		Ir^{n}	189 960950.0
113	77		Ir^{p}	189 960584.8
113	77		Ir^{q}	189 960886.9
112	78		Pt	189 959932
111	79		Au	189 964700
111	79		Au^{m}	189 964917
110	80		Hg	189 966322
109	81		Tl	189 973880
109	81		Tl^{m}	189 974020
109	81		Tl^{n}	189 974192
109	81		Tl^{p}	189 974321
108	82		Pb	189 978082
108	82		Pb^{m}	189 980889
108	82		Pb^{n}	189 980892
108	82		Pb^{p}	189 980935
107	83		Bi	189 988300
107	83		Bi^{m}	189 988746
107	83		Bi^{n}	189 989039
106	84		Po	189 995101
117	74	191	W	190 966600
116	75		Re	190 963125
115	76		Os	190 960929.7
115	76		Os^{m}	190 961009.6
114	77		Ir	190 960594.0
114	77		Ir^{m}	190 960777.8
114	77		Ir^{n}	190 962866
113	78		Pt	190 961677
113	78		Pt^{m}	190 961837
112	79		Au	190 963700
112	79		Au^{m}	190 963993
111	80		Hg	190 967157
111	80		Hg^{m}	190 967289
110	81		Tl	190 971786
110	81		Tl^{m}	190 972105
109	82		Pb	190 978270
109	82		Pb^{m}	190 978281
108	83		Bi	190 985786
108	83		Bi^{m}	190 986044
107	84		Po	190 994574
107	84		Po^{m}	190 994611
118	74	192	W	191 968170
117	75		Re	191 965960
116	76		Os	191 961480.7
116	76		Os^{m}	191 963644.3
115	77		Ir	191 962605.0
115	77		Ir^{m}	191 962665.9
115	77		Ir^{n}	191 962785.5
114	78		Pt	191 961038.0
113	79		Au	191 964813
113	79		Au^{m}	191 964957
113	79		Au^{n}	191 965276
112	80		Hg	191 965634
111	81		Tl	191 972230
111	81		Tl^{m}	191 972399
111	81		Tl^{p}	191 972416
110	82		Pb	191 975785
110	82		Pb^{m}	191 978556
110	82		Pb^{n}	191 978603
110	82		Pb^{p}	191 978730
109	83		Bi	191 985460
109	83		Bi^{m}	191 985616
108	84		Po	191 991335
108	84		Po^{m}	191 994128
118	75	193	Re	192 967470
117	76		Os	192 964151.6
116	77		Ir	192 962926.4
116	77		Ir^{m}	192 963012.5
115	78		Pt	192 962987.4
115	78		Pt^{m}	192 963148.2
114	79		Au	192 964150
114	79		Au^{m}	192 964461
113	80		Hg	192 966665
113	80		Hg^{m}	192 966817
112	81		Tl	192 970670
112	81		Tl^{m}	192 971068
111	82		Pb	192 976170
111	82		Pb^{m}	192 976318
110	83		Bi	192 982960
110	83		Bi^{m}	192 983291
109	84		Po	192 991030
109	84		Po^{m}	192 991133
108	85		At	192 999840
119	75	194	Re	193 970420
118	76		Os	193 965182.1

N	Z	A	El	Atomic mass (μu)
117	77		Ir	193 965078.4
117	77		Ir^{m}	193 965236.3
117	77		Ir^{n}	193 965475
116	78		Pt	193 962680.3
115	79		Au	193 965365
115	79		Au^{m}	193 965480
115	79		Au^{n}	193 965876
114	80		Hg	193 965439
113	81		Tl	193 971200
113	81		Tl^{m}	193 971519
112	82		Pb	193 974012
111	83		Bi	193 982830
111	83		Bi^{m}	193 982952
111	83		Bi^{n}	193 983081
110	84		Po	193 988186
110	84		Po^{m}	193 990896
109	85		At	193 998730
109	85		At^{m}	193 999237
119	76	195	Os	194 968130
118	77		Ir	194 965979.6
118	77		Ir^{m}	194 966087
117	78		Pt	194 964791.1
117	78		Pt^{m}	194 965069.6
116	79		Au	194 965034.6
116	79		Au^{m}	194 965376.7
115	80		Hg	194 966720
115	80		Hg^{m}	194 966909
114	81		Tl	194 969774
114	81		Tl^{m}	194 970293
113	82		Pb	194 974542
113	82		Pb^{m}	194 974760
112	83		Bi	194 980651
112	83		Bi^{m}	194 981080
111	84		Po	194 988110
111	84		Po^{m}	194 988230
110	85		At	194 996268
110	85		At^{m}	194 996304
109	86		Rn	195 005440
109	86		Rn^{m}	195 005494
120	76	196	Os	195 969640
119	77		Ir	195 968400
119	77		Ir^{m}	195 968621
118	78		Pt	195 964951.5
117	79		Au	195 966570
117	79		Au^{m}	195 966661
117	79		Au^{n}	195 967210
116	80		Hg	195 965833
115	81		Tl	195 970481
115	81		Tl^{m}	195 970904
114	82		Pb	195 972774
114	82		Pb^{m}	195 974640
113	83		Bi	195 980667
113	83		Bi^{m}	195 980846
113	83		Bi^{n}	195 980956
112	84		Po	195 985535
112	84		Po^{m}	195 988208
111	85		At	195 995790
111	85		At^{m}	195 995760
111	85		At^{n}	195 995963
110	86		Rn	196 002115
120	77	197	Ir	196 969653
120	77		Ir^{m}	196 969777
119	78		Pt	196 967340.2
119	78		Pt^{m}	196 967769.2
118	79		Au	196 966568.7
118	79		Au^{m}	196 967007.8
117	80		Hg	196 967213
117	80		Hg^{m}	196 967534
116	81		Tl	196 969575
116	81		Tl^{m}	196 970227
115	82		Pb	196 973431
115	82		Pb^{m}	196 973774
115	82		Pb^{n}	196 975486
114	83		Bi	196 978864
114	83		Bi^{m}	196 979603
113	84		Po	196 985660
113	84		Po^{m}	196 985915
112	85		At	196 993190
112	85		At^{m}	196 993244
111	86		Rn	197 001580
111	86		Rn^{m}	197 001793
121	77	198	Ir	197 972280
120	78		Pt	197 967893
119	79		Au	197 968242.3
119	79		Au^{m}	197 968577.5
119	79		Au^{n}	197 969113.7
118	80		Hg	197 966769.0
117	81		Tl	197 970480
117	81		Tl^{m}	197 971068
117	81		Tl^{n}	197 971283
116	82		Pb	197 972034
116	82		Pb^{m}	197 974333
115	83		Bi	197 979210
115	83		Bi^{m}	197 979511
115	83		Bi^{n}	197 979778
114	84		Po	197 983389
114	84		Po^{m}	197 985379
114	84		Po^{n}	197 986144
114	84		Po^{p}	197 986279
113	85		At	197 992840
113	85		At^{m}	197 993194
112	86		Rn	197 998679
112	86		Rn^{m}	198 000000
122	77	199	Ir	198 973800
121	78		Pt	198 970593
121	78		Pt^{m}	198 971049
120	79		Au	198 968765.2
120	79		Au^{m}	198 969354.5
119	80		Hg	198 968279.9
119	80		Hg^{m}	198 968851.5
118	81		Tl	198 969880
118	81		Tl^{m}	198 970683
117	82		Pb	198 972917
117	82		Pb^{m}	198 973377
117	82		Pb^{n}	198 975669
116	83		Bi	198 977672
116	83		Bi^{m}	198 978388
115	84		Po	198 983666
115	84		Po^{m}	198 984001
114	85		At	198 990530
113	86		Rn	198 998370
113	86		Rn^{m}	198 998568
112	87		Fr	199 007260
122	78	200	Pt	199 971441
121	79		Au	199 970730
121	79		Au^{m}	199 971766
120	80		Hg	199 968326.0
119	81		Tl	199 970963
119	81		Tl^{m}	199 971772
118	82		Pb	199 971827
117	83		Bi	199 978132
117	83		Bi^{m}	199 978239
117	83		Bi^{n}	199 978591
116	84		Po	199 981799
115	85		At	199 990351
115	85		At^{m}	199 990472
115	85		At^{n}	199 990720
114	86		Rn	199 995699
113	87		Fr	200 006570
113	87		Fr^{m}	200 006635
123	78	201	Pt	200 974510

N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)
122	79		Au	200 971657	117	86		Rn^{m}	202 993776	124	82		Pb^{n}	205 978788.8
121	80		Hg	200 970302.3	116	87		Fr	203 000925	123	83		Bi	205 978499
121	80		Hg^{m}	200 971124.8	115	88		Ra	203 009270	123	83		Bi^{m}	205 978563
120	81		Tl	200 970819	115	88		Ra^{m}	203 009512	123	83		Bi^{n}	205 979621
120	81		Tl^{m}	200 971806	125	79	204	Au	203 977720	122	84		Po	205 980481
119	82		Pb	200 972885	124	80		Hg	203 973493.9	122	84		Po^{m}	205 982183
119	82		Pb^{m}	200 973560	123	81		Tl	203 973863.5	122	84		Po^{n}	205 982909
118	83		Bi	200 977009	123	81		Tl^{m}	203 975048.7	121	85		At	205 986667
118	83		Bi^{m}	200 977917	123	81		Tl^{n}	203 976543	121	85		At^{m}	205 987533
117	84		Po	200 982260	123	81		Tl^{p}	203 977617	120	86		Rn	205 990214
117	84		Po^{m}	200 982715	122	82		Pb	203 973043.6	119	87		Fr	205 998670
116	85		At	200 988417	122	82		Pb^{m}	203 975390.2	119	87		Fr^{m}	205 998875
115	86		Rn	200 995630	121	83		Bi	203 977813	119	87		Fr^{n}	205 999445
115	86		Rn^{m}	200 995931	121	83		Bi^{m}	203 978677	118	88		Ra	206 003827
114	87		Fr	201 003860	121	83		Bi^{n}	203 980854	117	89		Ac	206 014500
124	78	202	Pt	201 975740	120	84		Po	203 980318	117	89		Ac^{m}	206 014589
123	79		Au	201 973810	119	85		At	203 987251	117	89		Ac^{n}	206 014815
122	80		Hg	201 970643.0	119	85		At^{m}	203 987882	127	80	207	Hg	206 982590
121	81		Tl	201 972106	118	86		Rn	203 991429	126	81		Tl	206 977419
121	81		Tl^{m}	201 973126	117	87		Fr	204 000653	126	81		Tl^{m}	206 978866
120	82		Pb	201 972159	117	87		Fr^{m}	204 000706	125	82		Pb	206 975896.9
120	82		Pb^{m}	201 974488	117	87		Fr^{n}	204 001003	125	82		Pb^{m}	206 977650.4
119	83		Bi	201 977742	116	88		Ra	204 006500	124	83		Bi	206 978470.7
119	83		Bi^{m}	201 978402	126	79	205	Au	204 979870	124	83		Bi^{m}	206 980726.8
118	84		Po	201 980758	125	80		Hg	204 976073	123	84		Po	206 981593
118	84		Po^{m}	201 983578	125	80		Hg^{m}	204 977745	123	84		Po^{m}	206 983078
117	85		At	201 988630	124	81		Tl	204 974427.5	123	84		Po^{n}	206 982790
117	85		At^{m}	201 988834	124	81		Tl^{m}	204 977960.1	122	85		At	206 985784
117	85		At^{n}	201 989254	123	82		Pb	204 974481.8	121	86		Rn	206 990734
116	86		Rn	201 993263	123	82		Pb^{m}	204 975570.1	121	86		Rn^{m}	206 991699
115	87		Fr	202 003370	123	82		Pb^{n}	204 977912.4	120	87		Fr	206 996950
115	87		Fr^{m}	202 003725	122	83		Bi	204 977389	119	88		Ra	207 003800
114	88		Ra	202 009890	121	84		Po	204 981203	119	88		Ra^{m}	207 004396
124	79	203	Au	202 975155	121	84		Po^{m}	204 982772	118	89		Ac	207 011950
123	80		Hg	202 972872.5	121	84		Po^{n}	204 982148	128	80	208	Hg	207 985940
123	80		Hg^{m}	202 973874.2	120	85		At	204 986074	127	81		Tl	207 982018.7
122	81		Tl	202 972344.2	120	85		At^{m}	204 988289	126	82		Pb	207 976652.1
122	81		Tl^{m}	202 975996	120	85		At^{n}	204 988586	126	82		Pb^{m}	207 981907.0
121	82		Pb	202 973391	119	86		Rn	204 991720	125	83		Bi	207 979742.2
121	82		Pb^{m}	202 974276	118	87		Fr	204 998594	125	83		Bi^{m}	207 981428.9
121	82		Pb^{n}	202 976556	117	88		Ra	205 006270	124	84		Po	207 981245.7
120	83		Bi	202 976876	117	88		Ra^{m}	205 006602	123	85		At	207 986590
120	83		Bi^{m}	202 978055	126	80	206	Hg	205 977514	122	86		Rn	207 989642
119	84		Po	202 981420	125	81		Tl	205 976110.3	121	87		Fr	207 997140
119	84		Po^{m}	202 982108	125	81		Tl^{m}	205 978947.8	120	88		Ra	208 001840
118	85		At	202 986942	124	82		Pb	205 974465.3	120	88		Ra^{m}	208 003768
117	86		Rn	202 993387	124	82		Pb^{m}	205 976827.2	119	89		Ac	208 011550

N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)
119	89		Ac^{m}	208 012086	123	88		Ra	211 000898	132	83		Bi	215 001770
129	80	209	Hg	208 991040	122	89		Ac	211 007730	132	83		Bi^{m}	215 003217
128	81		Tl	208 985359	121	90		Th	211 014930	131	84		Po	214 999420.0
127	82		Pb	208 981090.1	131	81	212	Tl	211 998230	130	85		At	214 998653
126	83		Bi	208 980398.7	130	82		Pb	211 991897.5	129	86		Rn	214 998745
125	84		Po	208 982430.4	130	82		Pb^{m}	211 993331	128	87		Fr	215 000341
124	85		At	208 986173	129	83		Bi	211 991285.7	127	88		Ra	215 002720
123	86		Rn	208 990415	129	83		Bi^{m}	211 991551	127	88		Ra^{m}	215 004736
123	86		Rn^{m}	208 991675	129	83		Bi^{n}	211 993645	127	88		Ra^{n}	215 005133
122	87		Fr	208 995954	128	84		Po	211 988868.0	126	89		Ac	215 006454
121	88		Ra	209 001990	128	84		Po^{m}	211 991992	125	90		Th	215 011730
120	89		Ac	209 009490	127	85		At	211 990745	124	91		Pa	215 019190
119	90		Th	209 017720	127	85		At^{m}	211 990988	133	83	216	Bi	216 006306
130	80	210	Hg	209 994510	127	85		At^{n}	211 995868	132	84		Po	216 001915.0
129	81		Tl	209 990074	126	86		Rn	211 990704	131	85		At	216 002423
128	82		Pb	209 984188.5	125	87		Fr	211 996202	131	85		At^{m}	216 002866
128	82		Pb^{m}	209 985561	124	88		Ra	211 999794	130	86		Rn	216 000274
127	83		Bi	209 984120.4	124	88		Ra^{m}	212 001897	129	87		Fr	216 003198
127	83		Bi^{m}	209 984411.6	123	89		Ac	212 007810	128	88		Ra	216 003533
127	83		Bi^{n}	209 984585.7	122	90		Th	212 012980	127	89		Ac	216 008720
126	84		Po	209 982873.7	121	91		Pa	212 023200	127	89		Ac^{m}	216 008767
126	84		Po^{m}	209 984545.2	131	82	213	Pb	212 996581	126	90		Th	216 011062
125	85		At	209 987148	130	83		Bi	212 994385	126	90		Th^{m}	216 013254
125	85		At^{m}	209 989885	129	84		Po	212 992857	126	90		Th^{n}	216 013893
125	85		At^{n}	209 991472	128	85		At	212 992937	125	91		Pa	216 019110
125	85		At^{p}	209 994618	127	86		Rn	212 993883	134	83	217	Bi	217 009470
124	86		Rn	209 989696	126	87		Fr	212 996189	133	84		Po	217 006335
124	86		Rn^{m}	209 991510	125	88		Ra	213 000384	132	85		At	217 004719
124	86		Rn^{n}	209 993815	125	88		Ra^{m}	213 002283	131	86		Rn	217 003928
124	86		Rn^{p}	209 996667	124	89		Ac	213 006610	130	87		Fr	217 004632
123	87		Fr	209 996408	123	90		Th	213 013010	129	88		Ra	217 006320
122	88		Ra	210 000495	122	91		Pa	213 021110	128	89		Ac	217 009347
122	88		Ra^{m}	210 002426	132	82	214	Pb	213 999805.4	128	89		Ac^{m}	217 011507
121	89		Ac	210 009440	131	83		Bi	213 998712	127	90		Th	217 013114
120	90		Th	210 015075	130	84		Po	213 995201.4	126	91		Pa	217 018320
130	81	211	Tl	210 993480	129	85		At	213 996372	126	91		Pa^{m}	217 020322
129	82		Pb	210 988737.0	129	85		At^{m}	213 996436	125	92		U	217 024370
128	83		Bi	210 987269	129	85		At^{n}	213 996623	135	83	218	Bi	218 014320
128	83		Bi^{m}	210 988587	128	86		Rn	213 995363	134	84		Po	218 008973.0
128	83		Bi^{n}	210 988619	128	86		Rn^{m}	213 997107	133	85		At	218 008694
127	84		Po	210 986653.2	127	87		Fr	213 998971	132	86		Rn	218 005601.3
127	84		Po^{m}	210 988223	127	87		Fr^{m}	213 999104	131	87		Fr	218 007578
127	84		Po^{n}	210 988945	126	88		Ra	214 000108	131	87		Fr^{m}	218 007672
127	84		Po^{p}	210 991885	125	89		Ac	214 006902	130	88		Ra	218 007140
126	85		At	210 987496.3	1 24	90		Th	214 011500	129	89		Ac	218 011640
125	86		Rn	210 990601	123	91		Pa	214 020920	129	89		Ac^{m}	218 011798
124	87		Fr	210 995537	133	82	215	Pb	215 004810	129	89		Ac^{n}	218 012260

N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)
128	90		Th	218 013284	137	87		Fr	224 023250	136	93		Np	229 036260
127	91		Pa	218 020042	136	88		Ra	224 020211.8	135	94		Pu	229 040150
126	92		U	218 023540	135	89		Ac	224 021723	143	87	230	Fr	230 042510
135	84	219	Po	219 013740	134	90		Th	224 021467	142	88		Ra	230 037056
134	85		At	219 011162	133	91		Pa	224 025626	141	89		Ac	230 036290
133	86		Rn	219 009480.2	132	92		U	224 027605	140	90		Th	230 033133.8
132	87		Fr	219 009252	139	86	225	Rn	225 028440	139	91		Pa	230 034541
131	88		Ra	219 010085	138	87		Fr	225 025570	138	92		U	230 033940
130	89		Ac	219 012420	137	88		Ra	225 023612	137	93		Np	230 037830
129	90		Th	219 015540	136	89		Ac	225 023230	136	94		Pu	230 039650
128	91		Pa	219 019880	135	90		Th	225 023951	144	87	231	Fr	231 045440
127	92		U	219 024920	134	91		Pa	225 026130	143	88		Ra	231 041220
136	84	220	Po	220 016600	133	92		U	225 029391	143	88		Ra^m	231 041299
135	85		At	220 015410	132	93		Np	225 033910	142	89		Ac	231 038560
134	86		Rn	220 011394.0	140	86	226	Rn	226 030890	141	90		Th	231 036304.3
133	87		Fr	220 012327	139	87		Fr	226 029390	140	91		Pa	231 035884.0
132	88		Ra	220 011028	138	88		Ra	226 025409.8	139	92		U	231 036294
131	89		Ac	220 014763	137	89		Ac	226 026098	138	93		Np	231 038250
130	90		Th	220 015748	136	90		Th	226 024903	137	94		Pu	231 041101
129	91		Pa	220 021880	135	91		Pa	226 027948	136	95		Am	231 045560
128	92		U	220 024720	134	92		U	226 029339	145	87	232	Fr	232 049770
136	85	221	At	221 018050	133	93		Np	226 035150	144	88		Ra	232 043640
135	86		Rn	221 015537	141	86	227	Rn	227 035410	143	89		Ac	232 042030
134	87		Fr	221 014255	140	87		Fr	227 031840	142	90		Th	232 038055.3
133	88		Ra	221 013917	139	88		Ra	227 029177.8	141	91		Pa	232 038592
132	89		Ac	221 015590	138	89		Ac	227 027752.1	140	92		U	232 037156.2
131	90		Th	221 018184	137	90		Th	227 027704.1	139	93		Np	232 040110
130	91		Pa	221 021880	136	91		Pa	227 028805	138	94		Pu	232 041187
129	92		U	221 026400	135	92		U	227 031156	137	95		Am	232 046590
137	85	222	At	222 022330	134	93		Np	227 034960	145	88	233	Ra	233 048060
136	86		Rn	222 017577.7	142	86	228	Rn	228 037990	144	89		Ac	233 044550
135	87		Fr	222 017552	141	87		Fr	228 035730	143	90		Th	233 041581.8
134	88		Ra	222 015375	140	88		Ra	228 031070.3	142	91		Pa	233 040247.3
133	89		Ac	222 017844	139	89		Ac	228 031021.1	141	92		U	233 039635.2
133	89		Ac^m	222 018057	138	90		Th	228 028741.1	140	93		Np	233 040740
132	90		Th	222 018468	137	91		Pa	228 031051	139	94		Pu	233 043000
131	91		Pa	222 023740	136	92		U	228 031374	138	95		Am	233 046350
130	92		U	222 026090	135	93		Np	228 036180	137	96		Cm	233 050770
138	85	223	At	223 025190	134	94		Pu	228 038740	146	88	234	Ra	234 050700
137	86		Rn	223 021790	142	87	229	Fr	229 038450	145	89		Ac	234 048420
136	87		Fr	223 019735.9	141	88		Ra	229 034958	144	90		Th	234 043601
135	88		Ra	223 018502.2	140	89		Ac	229 033020	143	91		Pa	234 043308
134	89		Ac	223 019137	139	90		Th	229 031762	143	91		Pa^m	234 043392
133	90		Th	223 020811	139	90		Th^m	229 031762.4	142	92		U	234 040952.1
132	91		Pa	223 023960	138	91		Pa	229 032096.8	141	93		Np	234 042895
131	92		U	223 027740	138	91		Pa^m	229 032109.3	140	94		Pu	234 043317
138	86	224	Rn	224 024090	137	92		U	229 033506	139	95		Am	234 047810

N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)
138	96		Cm	234 050160	144	95		Am^m	239 055706	143	100		Fm	243 074350
146	89	235	Ac	235 051230	143	96		Cm	239 054960	151	93	244	Np	244 067850
145	90		Th	235 047510	142	97		Bk	239 058280	150	94		Pu	244 064204
144	91		Pa	235 045440	141	98		Cf	239 062420	149	95		Am	244 064284.8
143	92		U	235 043929.9	149	91	240	Pa	240 060980	149	95		Am^m	244 064379.9
142	93		Np	235 044063.3	148	92		U	240 056592	148	96		Cm	244 062752.6
141	94		Pu	235 045286	147	93		Np	240 056162	148	96		Cm^m	244 063869.3
140	95		Am	235 047950	147	93		Np^m	240 056184	147	97		Bk	244 065181
139	96		Cm	235 051430	146	94		Pu	240 053813.5	146	98		Cf	244 066001
138	97		Bk	235 056580	145	95		Am	240 055300	145	99		Es	244 070880
147	89	236	Ac	236 055300	144	96		Cm	240 055529.5	144	100		Fm	244 074080
146	90		Th	236 049870	143	97		Bk	240 059760	151	94	245	Pu	245 067747
145	91		Pa	236 048680	142	98		Cf	240 062300	150	95		Am	245 066452
144	92		U	236 045568.0	141	99		Es	240 068920	149	96		Cm	245 065491.2
143	93		Np	236 046570	149	92	241	U	241 060330	149	96		Cm^m	245 065873.3
143	93		Np^m	236 046634	148	93		Np	241 058250	148	97		Bk	245 066361.6
142	94		Pu	236 046058.0	147	94		Pu	241 056851.5	147	98		Cf	245 068049
141	95		Am	236 049580	147	94		Pu^m	241 057025.0	146	99		Es	245 071320
140	96		Cm	236 051410	147	94		Pu^n	241 059217	145	100		Fm	245 075390
139	97		Bk	236 057330	146	95		Am	241 056829.1	144	101		Md	245 080830
147	90	237	Th	237 053890	146	95		Am^m	241 059195	144	101		Md^m	245 081042
146	91		Pa	237 051150	145	96		Cm	241 057653.0	152	94	246	Pu	246 070205
145	92		U	237 048730.2	144	97		Bk	241 060230	151	95		Am	246 069775
144	93		Np	237 048173.4	143	98		Cf	241 063730	151	95		Am^m	246 069807
143	94		Pu	237 048409.7	142	99		Es	241 068540	150	96		Cm	246 067223.7
143	94		Pu^m	237 048565.9	142	99		Es^p	241 068964	149	97		Bk	246 068670
142	95		Am	237 050000	150	92	242	U	242 062930	148	98		Cf	246 068805.3
141	96		Cm	237 052900	149	93		Np	242 061640	147	99		Es	246 072900
140	97		Bk	237 057000	149	93		Np^m	242 061643	146	100		Fm	246 075300
139	98		Cf	237 062070	148	94		Pu	242 058742.6	145	101		Md	246 081890
148	90	238	Th	238 056500	147	95		Am	242 059549.2	145	101		Md^m	246 082115
147	91		Pa	238 054500	147	95		Am^m	242 059601.3	153	94	247	Pu	247 074070
146	92		U	238 050788.2	147	95		Am^n	242 061911	152	95		Am	247 072090
145	93		Np	238 050946.4	146	96		Cm	242 058835.8	151	96		Cm	247 070354
145	93		Np^m	238 053420	145	97		Bk	242 061980	150	97		Bk	247 070307
144	94		Pu	238 049559.9	145	97		Bk^m	242 062201	149	98		Cf	247 071001
143	95		Am	238 051980	144	98		Cf	242 063700	148	99		Es	247 073660
143	95		Am^m	238 054665	143	99		Es	242 069750	147	100		Fm	247 076850
142	96		Cm	238 053030	142	100		Fm	242 073430	147	100		Fm^m	247 000000
141	97		Bk	238 058280	150	93	243	Np	243 064280	146	101		Md	247 081640
140	98		Cf	238 061410	149	94		Pu	243 062003	146	101		Md^m	247 081772
148	91	239	Pa	239 057260	149	94		Pu^m	243 062416	153	95	248	Am	248 075750
147	92		U	239 054293.3	148	95		Am	243 061381.1	152	96		Cm	248 072349
146	93		Np	239 052939.0	147	96		Cm	243 061389.1	151	97		Bk	248 073090
145	94		Pu	239 052163.4	146	97		Bk	243 063008	151	97		Bk^m	248 073119
145	94		Pu^m	239 052583.8	145	98		Cf	243 065430	150	98		Cf	248 072185
144	95		Am	239 053024.5	144	99		Es	243 069550	149	99		Es	248 075470

N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)
149	99		Es^m	248 000000	156	97	253	Bk	253 086880	153	104		Rf^m	257 103114
148	100		Fm	248 077195	155	98		Cf	253 085133	152	105		Db	257 107720
147	101		Md	248 082820	154	99		Es	253 084824.7	152	105		Db^m	257 107838
146	102		No	248 086600	153	100		Fm	253 085185	159	99	258	Es	258 099520
154	95	249	Am	249 078480	152	101		Md	253 087280	158	100		Fm	258 097080
153	96		Cm	249 075953	151	102		No	253 090680	157	101		Md	258 098431
153	96		Cm^m	249 076006	151	102		No^m	253 090811	157	101		Md^m	258 098433
152	97		Bk	249 074986.7	150	103		Lr	253 095210	156	102		No	258 098210
152	97		Bk^m	249 074996.1	150	103		Lr^m	253 095234	155	103		Lr	258 101810
151	98		Cf	249 074853.5	149	104		Rf	253 100690	154	104		Rf	258 103490
151	98		Cf^m	249 075009.2	149	104		Rf^m	253 100902	153	105		Db	258 109230
150	99		Es	249 076410	157	97	254	Bk	254 090600	153	105		Db^m	258 109298
149	100		Fm	249 079030	156	98		Cf	254 087323	152	106		Sg	258 113170
148	101		Md	249 083010	155	99		Es	254 088022	159	100	259	Fm	259 100600
148	101		Md^m	249 083125	155	99		Es^m	254 088112	158	101		Md	259 100510
147	102		No	249 087830	154	100		Fm	254 086854.2	157	102		No	259 101030
154	96	250	Cm	250 078357	153	101		Md	254 089660	156	103		Lr	259 102900
153	97		Bk	250 078317	153	101		Md^m	254 089705	156	103		Lr^p	259 103275
153	97		Bk^m	250 078355	152	102		No	254 090955	155	104		Rf	259 105640
153	97		Bk^n	250 078407	152	102		No^m	254 091487	154	105		Db	259 109610
152	98		Cf	250 076406.1	151	103		Lr	254 096450	153	106		Sg	259 114500
151	99		Es	250 078610	150	104		Rf	254 100180	160	100	260	Fm	260 102680
151	99		Es^m	250 078830	157	98	255	Cf	255 091050	159	101		Md	260 103650
150	100		Fm	250 079521	156	99		Es	255 090273	158	102		No	260 102640
150	100		Fm^m	250 081128	155	100		Fm	255 089962	157	103		Lr	260 105500
149	101		Md	250 084420	154	101		Md	255 091083	156	104		Rf	260 106440
148	102		No	250 087510	153	102		No	255 093241	155	105		Db	260 111300
155	96	251	Cm	251 082285	152	103		Lr	255 096680	154	106		Sg	260 114420
154	97		Bk	251 080760	151	104		Rf	255 101340	153	107		Bh	260 121970
154	97		Bk^m	251 080799	151	104		Rf^m	255 101257	160	101	261	Md	261 105720
153	98		Cf	251 079587	150	105		Db	255 107400	159	102		No	261 105750
152	99		Es	251 079992	158	98	256	Cf	256 093440	158	103		Lr	261 106880
151	100		Fm	251 081575	157	99		Es	256 093600	157	104		Rf	261 108770
151	100		Fm^m	251 081780	157	99		Es^m	256 093602	157	104		Rf^m	261 108847
150	101		Md	251 084840	156	100		Fm	256 091773	157	104		Rf^p	261 108879
149	102		No	251 089010	155	101		Md	256 094060	156	105		Db	261 112060
149	102		No^m	251 089136	154	102		No	256 094283	155	106		Sg	261 116120
148	103		Lr	251 094360	153	103		Lr	256 098630	154	107		Bh	261 121660
156	96	252	Cm	252 084870	152	104		Rf	256 101166	161	101	262	Md	262 108870
155	97		Bk	252 084310	151	105		Db	256 108130	160	102		No	262 107300
154	98		Cf	252 081626	158	99	257	Es	257 095980	159	103		Lr	262 109630
153	99		Es	252 082980	157	100		Fm	257 095105	158	104		Rf	262 109930
152	100		Fm	252 082467	156	101		Md	257 095541	158	104		Rf^m	262 110564
151	101		Md	252 086560	155	102		No	257 096877	157	105		Db	262 114080
150	102		No	252 088977	154	103		Lr	257 099560	157	105		Db^p	262 114214
149	103		Lr	252 095370	154	103		Lr^p	257 099722	156	106		Sg	262 116400
149	103		Lr^p	252 095696	153	104		Rf	257 102990	155	107		Bh	262 122890

N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)	N	Z	A	El	Atomic mass (μu)
155	107		Bh^m	262 123221	164	105	269	Db	269 127460	168	109		Mt	277 152420
161	102	263	No	263 110550	163	106		Sg	269 128760	167	110		Ds	277 155650
160	103		Lr	263 111290	162	107		Bh	269 130690	166	111		Eb	277 159520
159	104		Rf	263 112550	161	108		Hs	269 134060	165	112		Ec	277 163940
158	105		Db	263 114990	160	109		Mt	269 139060	169	109	278	Mt	278 154810
157	106		Sg	263 118320	159	110		Ds	269 145120	168	110		Ds	278 156470
157	106		Sg^m	263 118433	165	105	270	Db	270 130710	167	111		Eb	278 161600
156	107		Bh	263 123040	164	106		Sg	270 130330	166	112		Ec	278 164310
155	108		Hs	263 128560	163	107		Bh	270 133620	170	109	279	Mt	279 156190
162	102	264	No	264 112350	162	108		Hs	270 134650	169	110		Ds	279 158860
161	103		Lr	264 114040	161	109		Mt	270 140660	168	111		Eb	279 162470
160	104		Rf	264 113990	160	110		Ds	270 144720	167	112		Ec	279 166550
159	105		Db	264 117400	160	110		Ds^m	270 145938	170	110	280	Ds	280 159800
158	106		Sg	264 118930	165	106	271	Sg	271 133470	169	111		Eb	280 164470
157	107		Bh	264 124600	164	107		Bh	271 135180	168	112		Ec	280 167040
156	108		Hs	264 128390	163	108		Hs	271 137660	171	110	281	Ds	281 162060
162	103	265	Lr	265 115840	162	109		Mt	271 141140	170	111		Eb	281 165370
161	104		Rf	265 116700	161	110		Ds	271 146060	169	112		Ec	281 169290
160	105		Db	265 118600	161	110		Ds^m	271 146099	171	111	282	Eb	282 167490
159	106		Sg	265 121110	166	106	272	Sg	272 135160	170	112		Ec	282 169770
158	107		Bh	265 125150	165	107		Bh	272 138030	172	111	283	Eb	283 168420
157	108		Hs	265 130090	164	108		Hs	272 139050	171	112		Ec	283 171790
157	108		Hs^m	265 130414	163	109		Mt	272 143740	170	113		Ed	283 176450
156	109		Mt	265 136150	162	110		Ds	272 146320	172	112	284	Ec	284 172380
163	103	266	Lr	266 119310	161	111		Eb	272 153620	171	113		Ed	284 178080
162	104		Rf	266 117960	167	106	273	Sg	273 138220	173	112	285	Ec	285 174110
161	105		Db	266 121030	166	107		Bh	273 139620	172	113		Ed	285 178730
160	106		Sg	266 122070	165	108		Hs	273 141990	171	114		Ee	285 183700
159	107		Bh	266 126940	164	109		Mt	273 144910	173	113	286	Ed	286 180480
158	108		Hs	266 130100	163	110		Ds	273 148860	172	114		Ee	286 183860
157	109		Mt	266 137300	163	110		Ds^m	273 149083	174	113	287	Ed	287 181050
157	109		Mt^m	266 138616	162	111		Eb	273 153680	173	114		Ee	287 185600
163	104	267	Rf	267 121530	167	107	274	Bh	274 142440	172	115		Ef	287 191190
162	105		Db	267 122380	166	108		Hs	274 143130	174	114	288	Ee	288 185690
161	106		Sg	267 124430	165	109		Mt	274 147490	173	115		Ef	288 192490
160	107		Bh	267 127650	164	110		Ds	274 149490	175	114	289	Ee	289 187280
159	108		Hs	267 131790	163	111		Eb	274 155710	174	115		Ef	289 192720
159	108		Hs^m	267 000000	168	107	275	Bh	275 144250	173	116		Eg	289 198860
158	109		Mt	267 137310	167	108		Hs	275 145950	175	115	290	Ef	290 194140
157	110		Ds	267 144340	166	109		Mt	275 148650	174	116		Eg	290 198590
164	104	268	Rf	268 123640	165	110		Ds	275 152180	176	115	291	Ef	291 194380
163	105		Db	268 125450	164	111		Eb	275 156140	175	116		Eg	291 200010
162	106		Sg	268 125610	168	108	276	Hs	276 147210	174	117		Eh	291 206560
161	107		Bh	268 129760	167	109		Mt	276 151160	176	116	292	Eg	292 199790
160	108		Hs	268 132160	166	110		Ds	276 153030	175	117		Eh	292 207550
159	109		Mt	268 138730	165	111		Eb	276 158490	175	118	293	Ei	293 214670
158	110		Ds	268 143800	169	108	277	Hs	277 149840					

Appendix E
Universal Nuclide Chart

Computer System Requirements

The Universal Nuclide Chart (UNC) has been developed using Java applet software technology and will run under various operating systems. Installation software has been developed to run on most platforms including Windows, MacOS X, Solaris/Sparc, Solaris/x86, Linux, HP-UX.

From the CD, the user can run the appropriate installation file corresponding to the operating system. In some systems, such as Windows, the installation can start automatically following insertion of the CD. The program will install the Java applet and the required files to run it on a virtual Java machine. For the installation, 68 MB of free hard-disk is required. For optimum performance, computers with 256 MB of RAM and processor speeds in excess of 500 MHz are recommended.

A "Quick tour" in Macromedia flash is part of the program and requires the browser flash plug-in. The user will be prompted to download the plug-in if this is not already installed.

Starting the Applet

Following the installation, the applet can be accessed by double clicking on the Universal Nuclide Chart (UNC) icon. All program and information files can be found in the UNC

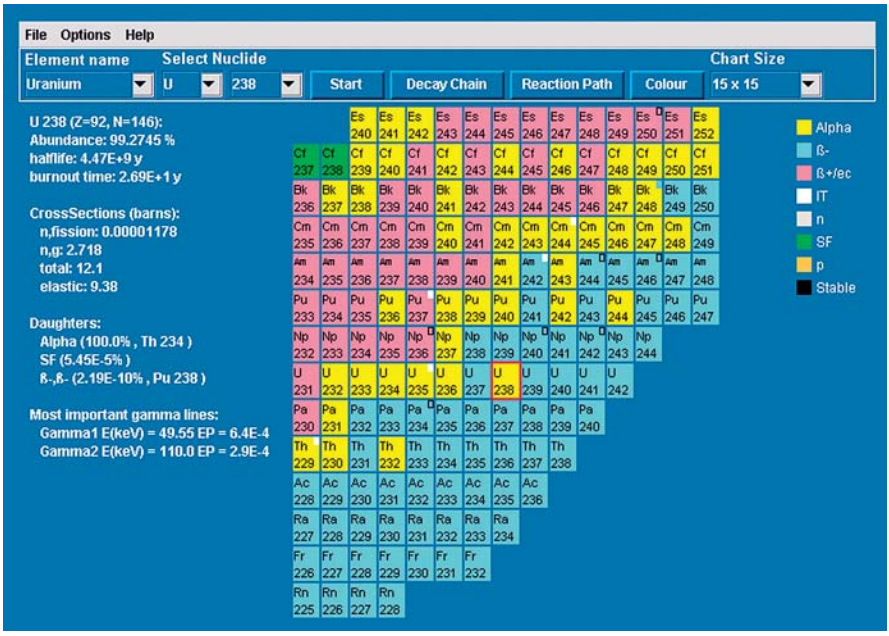


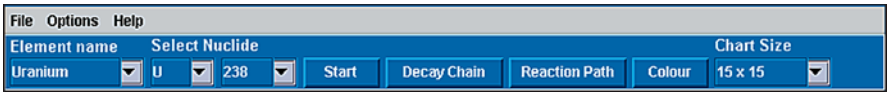
Fig E.1. The Universal Nuclide Chart main user interface. The Nuclide Chart Viewer shows a section of the nuclide chart centred on U238. The window opens with "U238" as default nuclide, "Karlsruhe" as default colour scheme, and "15 × 15" as the default chart size. The basic decay and cross-section data are also shown

directory. The "Quick Tour" Macromedia flash animation describing the applet is also located in the directory. This application can also be launched over the “Start” button on Windows platforms for example.

User Interface

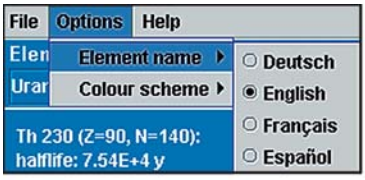
The program module is resident on the user computer. The data required for the program are contained in a “thin” database which comes with the CD. In addition to displaying basic data in nuclide charts, the Universal Nuclide Chart can be used to simulate decay chains of nuclides and reaction paths in nuclear reactors. The main user interface is shown in Fig. E.1.

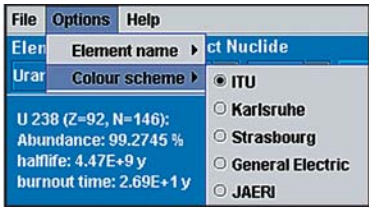
In the Nuclide Chart Viewer taskbar, shown below, there are various user definable settings. These are described in the following sections.



Basic Settings

There are several basic settings which can be made under the Options button on the taskbar. The first is the choice of language for the element names. The element names shown in the taskbar can be set to English, German, French, and Spanish. The second refers to the colour scheme to be shown in the nuclide chart. In addition to the ITU scheme, the Karlsruhe, Strasbourg, General Electric, and JAERI schemes can be selected corresponding to the paper-based nuclide charts.





In the File button on the taskbar, there are six nuclides listed – Uub283, Fm251, Re185, Sn118, Mn55, and N15. These nuclides are located at key positions in the nuclide chart. Selection of one of these nuclides will allow fast access to the region of interest. In addition, the last six nuclides used are listed below the separator. This is useful for returning quickly to a nuclide previously selected.

View Basic Decay and Cross-Section Data

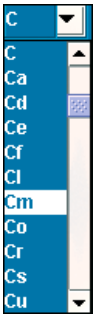
It can be seen from Fig. E.1. that the selected nuclide is highlighted with a red border. The basic decay and cross-section data is also shown to the left of the nuclide chart. To view the basic data for other nuclides one need only place the mouse cursor over the nuclide of interest (without pressing the mouse button). The following data is given as far as available for approximately 3000 nuclides and some 600 isomers: half-life, decay modes, daughter products, branching ratios, abundances, two most important gamma lines and emission probabilites, thermal neutron cross-sections, burnout-time. For likely fission products, the chain yield of the isobar is given for the thermal fission of ^{233}U, ^{235}U and ^{239}Pu.

Navigation

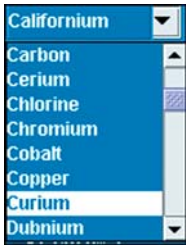
Navigation through the nuclide chart can be performed in two different ways. The first method is to place the mouse cursor over the nuclide in the top right or bottom left corner of the nuclide chart and press the left or right mouse button. A new selection of the nuclide chart is then shown, centred on the selected nuclide. By repeating this process one can quickly scan through the nuclide chart to the region of interest. Alternatively, the nuclide can be selected directly in the Select Nuclide list boxes as explained in the following section.

Select Nuclide

The default values can of course be changed by the user. To select an element, the user should place the cursor over the black triangle in the element box below the Select Nuclide button and click the left mouse button. By typing in the first letter of the chemical symbol, the list box will contain all elements arranged in alphabetical order with this as starting letter. If the chemical symbol is not known, the element name can be selected in one of four languages from the element name list box.



Select Nuclide



Element name

The element can then be selected from this list. Once the element has been selected, the isotope mass box will contain a list of all isotopes of this element for which there is data. On placing the cursor over the black triangle in the isotope mass list box and clicking the left mouse button, the user can then select the appropriate isotope. The m or n after the mass indicates that this is the metastable state of the isotope. Once the nuclide has been selected, its position is shown centred in the nuclide chart by pressing the Start button.

Colour Scheme

Five different colour schemes are available from the Colour Scheme button corresponding to the paper-based nuclide charts in use in various parts of the world:

- Karlsruhe Colour Scheme, where the colours depend on the main mode of decay (alpha, β^-, β^+, IT, n, SF, p, ec, stable).
- Strasbourg Colour Scheme in which different colours are used for the decay processes.
- General Electric Colour Scheme. Here the colours depend on the half-lives of the nuclides ($<$1 d, 1–10 d, 10–100 d, 100d–10 y, 10y–5 $\times$ 10^8 y, Stable), not on the decay mode.
- JAERI Colour Scheme, where different colours are used for half-lives under 10 minutes, between 10 minutes and 30 days, 30 days and 5 $\times$ 10^8 years and stable nuclides.
- ITU Colour Scheme, which shows the main mode of decay as in the Karlsruhe Colour Scheme.

The default colour scheme is Karlsruhe.

Chart Size

A variety of chart sizes can be selected ranging from 5×5 (showing maximum 25 nuclides) to 15×15 (where up to 225 nuclides can be shown e.g. Er-162). Clearly, it is desirable to show as many nuclides as possible. With more powerful computers, the user can select the 15×15 chart without noticing the time it requires to "load" this data. On less powerful machines, this time can be significant, and it is recommended that the user select a smaller section chart with fewer nuclides.

Colour

The possibility of changing the background colour has been implemented. This is useful, for example, if the user needs to make a screenshot of the application with a specific background colour. The background colour selector is shown in Fig. E.2.

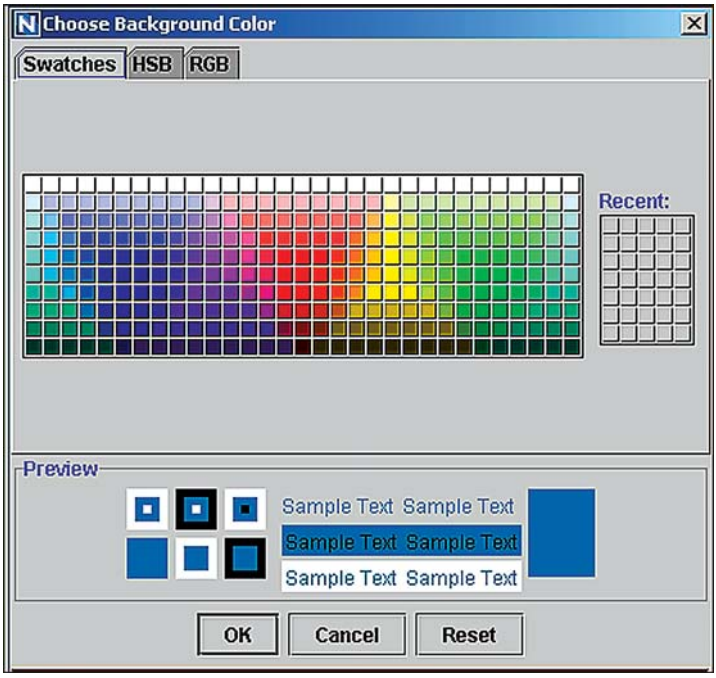


Fig. E.2. The background colour selector

Radioactive Decay Chain Simulator

Decay Chain and Reaction Path

Two applications can be reached from the chart window in Fig. E.1 by clicking on one of the dedicated buttons: the Decay Chain Simulator (button Decay Chain) and the Neutron Reaction Path Simulator (button Reaction Path). These two applications are treated in more detail below.

The radioactive decay chain simulator window is shown in Fig. E.3. The application simulates radioactive decay for over 3000 nuclides in two different arrangements (normal and compact plots) and with five different standard colour schemes. The Selected Nuclide, in this case ^{238}U selected from the Nuclide Chart Viewer in Fig. E.1, is shown in the box in the top left hand side of the window. The decay chain for this nuclide is shown in the main frame of the window. The decay process is simulated on a Z vs. N nuclide chart, labelled Normal Plot in the taskbar, with the Z and N axes shown. Alternatively, a more compact description of the decay process based on a plot of $A - 2Z$ vs. Z, can be selected through Compact Plot.

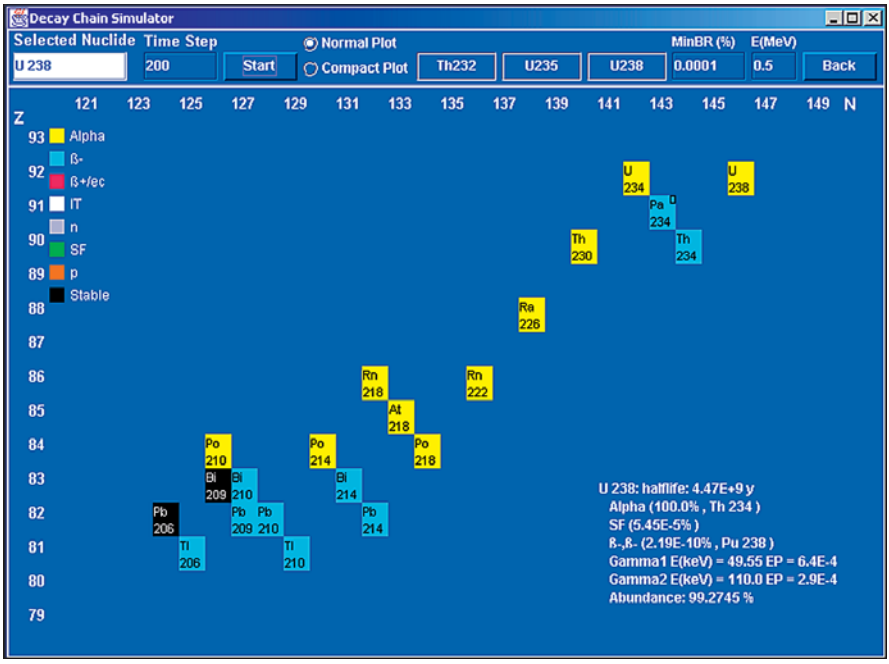


Fig. E.3. Decay Chain Simulator showing the decay of ^{238}U

In the same manner as in the Nuclide Chart Viewer, to view the basic data one need only place the mouse cursor over the nuclide of interest (without pressing the mouse button). In the following, the input selectors in the taskbar are described in more detail.

Time Step

Here the user can "see" the decay process in "slow motion" by changing the time interval in which the daughters are painted onto the screen. The value is given in milliseconds with a

default value of 200 ms. By increasing the time interval to 600, for example, the decay process will be painted at one third of the default speed onto the screen.

Start/Stop

With the Start button, the user starts the simulation with the chosen selections. During the simulation, the applet can be stopped at any time by pressing the Stop button. With the simulation halted, it is only possible to change the time-step, and then to restart. As soon as the simulation is completed, the Stop button is automatically changed to a Start button and all input and selection fields are again enabled.

Plot

As mentioned above, there are two different ways of showing the simulation. The first one is the Normal Plot where the number of protons Z in the nuclide is shown as a function of the number of neutrons N. The second plot is the Compact Plot. In this case the quantity $A-2Z$ is shown as a function of the number of protons Z, where A is the atomic number $(N+Z)$. This leads to a more compact representation of the decay scheme as shown in Fig. E.4.

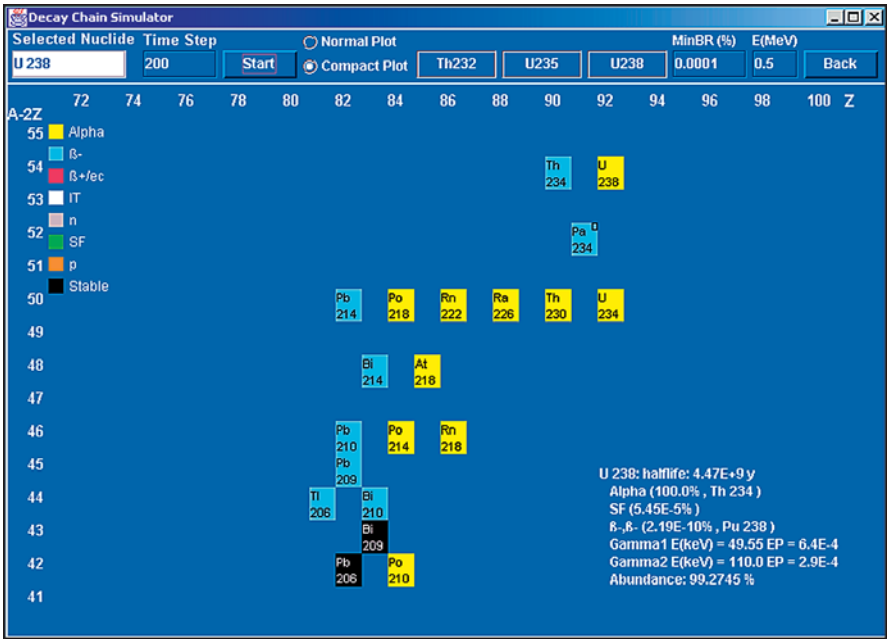


Fig. E.4. Decay Chain Simulator: decay of ^{238}U – Compact Plot

Th232/U235/U238

With these buttons the user can simulate the three natural decay families (Th232, U235 and U238) directly. These nuclides can of course also be selected through the use of the drop-down menus.

MinBR (%) (Minimum Branching Ratio)

The branching ratio refers to the fraction of daughter nuclides produced from a parent nuclide in the decay process. For some processes, such as cluster emission (discovered in the 1980s),

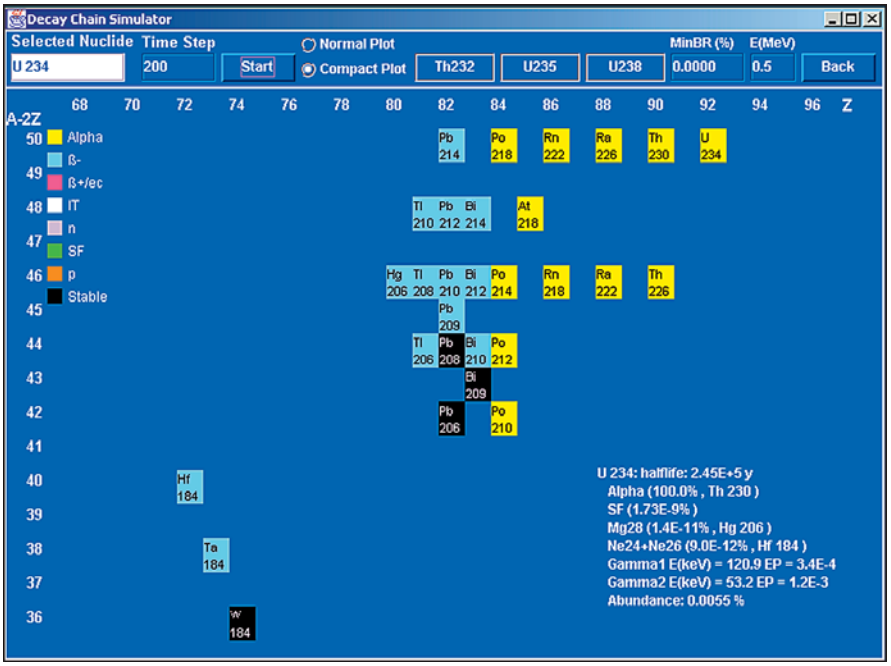


Fig. E.5. Decay of U234 with MinBR $= 0$, i.e. showing all decay processes such as cluster emission. Cluster emission of Ne24+Ne26 from U234 gives rise to Hf184

the branching ratios are extremely small. In the decay of a parent nuclide, if all daughters are shown, the decay chain will show many nuclides some of which are only present in tiny amounts. For this reason a minimum branching ratio, MinBR, can be set which allows the user to "see" only daughters with branching ratios higher than MinBR. If MinBR is set to zero, all daughters are shown including extremely rare events such as cluster emission. In Fig. E.5 the decay of U234 is shown. As can be seen from the basic decay data, U234 shows cluster emission of both Mg28 and Ne24+Ne26 to give Hg206 and Hf184 respectively. The default value is MinBR $= 10^{-4}$ %.

E(MeV)

Nuclides with high gamma activity can be indicated in the Decay Chain Simulator through "blinking". The field E(MeV) shows the threshold gamma energy per disintegration in mega electron volt (MeV) to initiate "blinking". This can be changed also while the simulation is running. As decimal separator, a point (.) must be used. The default value is 0.5 MeV, and this is also used when the user deletes the contents of the field.

Metastable states of nuclides are indicated by a small insert in the top right corner of the element box. If they have the same colour, a black border around the metastable state is used to differentiate it from the ground state. If only the metastable state is part of the decay chain, this is shown in the correct colour and the rest of the box is transparent. If there is no information available on a daughter product, this is shown transparent and the decay scheme ends there. Also, if all branching ratios of a nuclide are less than the threshold value for the branching ratio or the branching ratios are not known, the nuclide is shown transparent with no further daughters.

Neutron Reaction Path Simulator

The Neutron Reaction Path Simulator window is shown in Fig. E.6. This application indicates the main neutron reactions likely to occur with the selected nuclide in a nuclear reactor with a thermal neutron spectrum, i.e. in most light water reactors (LWRs). The neutron reactions occurring are based on the cross-sections, the burnout time and the half-life of the selected nuclide.

The Selected Nuclide, in this case Th232 selected from the Nuclide Chart Viewer, is shown in the box in the top left hand side of the window in Fig. E.6. The neutron reaction path for this nuclide is shown in the main frame of the window.

Neutron Flux

The neutron flux can be set in the taskbar in Fig. E.6. The default value of the neutron flux is 3×10^{14} neutrons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ typical of light water reactors.

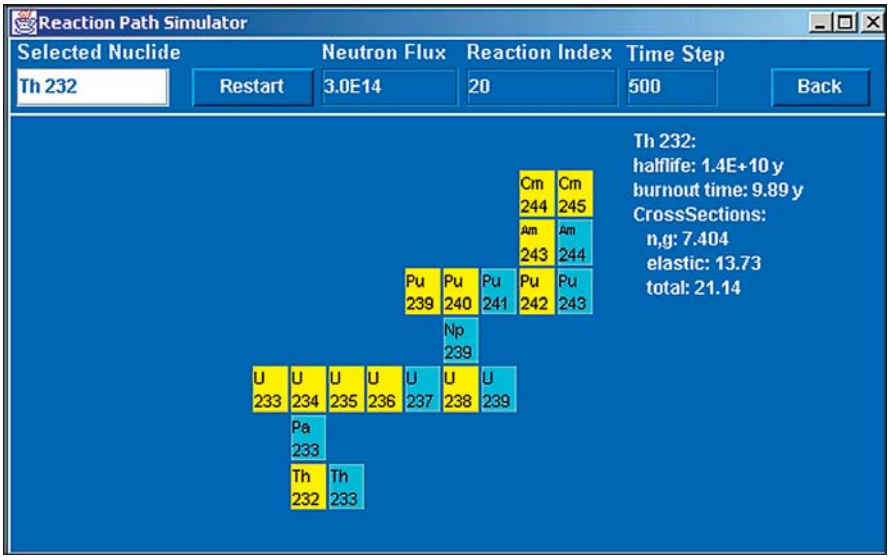


Fig. E.6. Neutron Reaction Path Simulator: transmutation of Th232 in a thermal neutron flux

Reaction Index

The reaction index, which can also be set in the taskbar, indicates the number of activation products to be taken into account. In Fig. E.6, this value is set to 20 and the first 20 activation products are shown in the main window. The default value is 10.

Time Step

Here the user can "see" the activation or transmutation process in "slow motion" by changing the time interval in which the products are painted onto the screen. The value is given in milliseconds with a default value of 500 ms. By increasing the time interval to 1500, for example, the transmutation will be painted at one third of the default speed onto the screen.

As explained in Chapter 3 (page 54), depending on the thermal neutron flux, there is a competition between decay and burnout processes. Consider the case of Th232 in a thermal

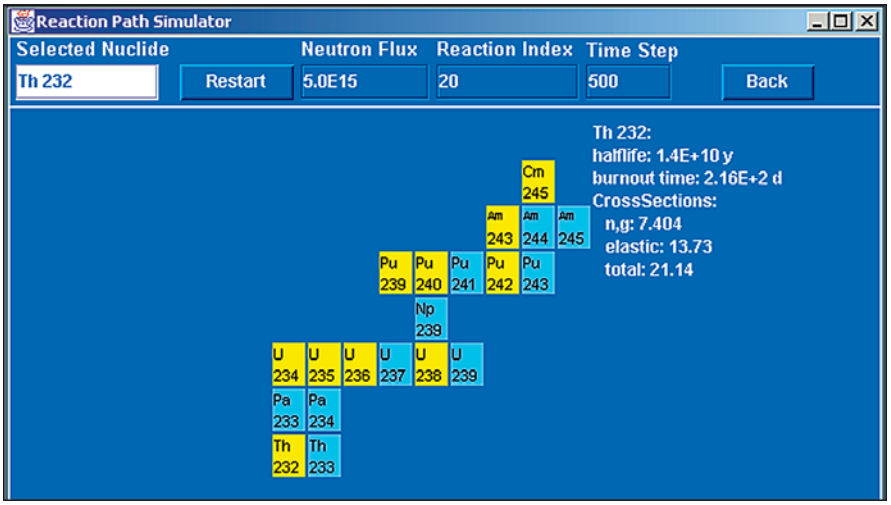


Fig. E.7. The reaction path of Th232 in a high thermal flux. Notice that the production of U233 as shown in Fig. E.6 is bypassed

neutron flux. With a half-life of 1.4×10^{10} y and a burnout time of 9.9 y, the nuclide will transmute to Th233. This nuclide has a half-life (22 m) shorter than the burnout time (18 d) and will decay to Pa233. This protactinium isotope has a half-life of 27 d and a burnout time of 1.8 y. It will therefore decay preferentially to the fissile isotope U233. This uranium isotope is highly desirable in the thermal reactor since it fissions to produce energy. If however the flux in the reactor increases, the burnout time decreases. This implies that more Pa234 (which decays to U234) is produced at the expense of U233. This can be demonstrated by setting the flux to a very high value of 5×10^{15} neutrons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ and restarting the calculation. The reaction path in this very high flux is shown in Fig. E.7.

On the other hand, in a low thermal neutron flux the decay process will predominate over the burnout process. The reaction path will be essentially the decay chain.

Reaction Products

In general, a nuclide in a nuclear reactor can transform via three main processes:

- by radioactive decay – to one or more daughter products
- by neutron (radiative) capture – to a nuclide with a mass increase of 1
- by neutron induced fission – to fission products

In some cases, all three processes can occur. As an example consider the nuclide Pu241. The nuclide has a half-life of $\tau = 14.3$ y, and capture and fission cross-sections of 361.6 b and 1013 b respectively. In a neutron flux of $\varphi = 3 \times 10^{14}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, the burnout time is $\tau_{\mathrm{bo}} = 19.4$ d. The branching ratios for decay, capture, and fission are:

$$BR_{\mathrm{decay}} = \lambda/[\lambda + (\sigma_{\mathrm{c}} + \sigma_{\mathrm{f}}) \cdot \varphi] = 0.004 \text{ or } 0.4\%$$
$$BR_{\mathrm{capture}} = \sigma_{\mathrm{f}} \cdot \varphi/[\lambda + (\sigma_{\mathrm{c}} + \sigma_{\mathrm{f}}) \cdot \varphi] = 0.263 \text{ or } 26.3\%$$
$$BR_{\mathrm{fission}} = \sigma_{\mathrm{c}} \cdot \varphi/[\lambda + (\sigma_{\mathrm{c}} + \sigma_{\mathrm{f}}) \cdot \varphi] = 0.733 \text{ or } 73.3\%$$

with the sum of the branching ratios equal to 1. In this example of Pu241, the reaction products are U237 (through alpha decay), Pu242 (through neutron capture), and fission products. Clearly, a single nuclide can give rise to a number of reaction products. These reaction prod-

ucts will also transform in the reactor through the above processes and quickly give rise to a great number of nuclides.

In the Reaction Path Simulator, painting all these nuclides onto the screen would just lead to confusion. In most cases, however, the branching ratios for many of these reaction products are quite small and the corresponding processes can be neglected. For this reason, in the Reaction Path Simulator, only the main reaction product with the highest branching ratio (in the above example this is Pu242) is shown.

Acknowledgements

This chapter was compiled with the assistance of Ms. Yvonne Galla and Dr. Jean Galy. Ms. Galla developed the Universal Nuclide Chart program module.

References

1. J. Magill, Y. Galla, J. Galy: *The Universal Nuclide Chart: An Interactive Java-based Chart*, Technical Report JRC-ITU-TN-2001/29, Institute for Transuranium Elements, 2001

Appendix F
Periodic Table of the Elements

The *Periodic Table of the Elements* as shown on the next two pages has been reproduced (and slightly modified) with permission from

The version reproduced is dated 7 November 2003.
For updates to this table see http://www.iupac.org/reports/periodic_table/.

PERIODIC TABLE

1																	
1 **H** hydrogen 1.007 94(7)	2	Key: atomic number **Symbol** name standard atomic weight															
3 **Li** lithium 6.941(2)	4 **Be** beryllium 9.012 182(3)																
11 **Na** sodium 22.989 770(2)	12 **Mg** magnesium 24.3050(6)	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
19 **K** potassium 39.0983(1)	20 **Ca** calcium 40.078(4)	21 **Sc** scandium 44.955 910(8)	22 **Ti** titanium 47.867(1)	23 **V** vanadium 50.9415(1)	24 **Cr** chromium 51.9961(6)	25 **Mn** manganese 54.938 049(9)	26 **Fe** iron 55.845(2)	27 **Co** cobalt 58.933 200(9)	28 **Ni** nickel 58.6934(2)	29 **Cu** copper 63.546(3)	30 **Zn** zinc 65.409(4)	31 **Ga** gallium 69.723(1)	32 **Ge** germanium 72.64(1)	33 **As** arsenic 74.921 60(2)	34 **Se** selenium 78.96(3)	35 **Br** bromine 79.904(1)	36 **Kr** krypton 83.798(2)
37 **Rb** rubidium 85.4678(3)	38 **Sr** strontium 87.62(1)	39 **Y** yttrium 88.905 85(2)	40 **Zr** zirconium 91.224(2)	41 **Nb** niobium 92.906 38(2)	42 **Mo** molybdenum 95.94(2)	43 **Tc** technetium [97.9072]	44 **Ru** ruthenium 101.07(2)	45 **Rh** rhodium 102.905 50(2)	46 **Pd** palladium 106.42(1)	47 **Ag** silver 107.8682(2)	48 **Cd** cadmium 112.411(8)	49 **In** indium 114.818(3)	50 **Sn** tin 118.710(7)	51 **Sb** antimony 121.760(1)	52 **Te** tellurium 127.60(3)	53 **I** iodine 126.904 47(3)	54 **Xe** xenon 131.293(6)
55 **Cs** caesium 132.905 45(2)	56 **Ba** barium 137.327(7)	57-71 lanthanoids	72 **Hf** hafnium 178.49(2)	73 **Ta** tantalum 180.9479(1)	74 **W** tungsten 183.84(1)	75 **Re** rhenium 186.207(1)	76 **Os** osmium 190.23(3)	77 **Ir** iridium 192.217(3)	78 **Pt** platinum 195.078(2)	79 **Au** gold 196.966 55(2)	80 **Hg** mercury 200.59(2)	81 **Tl** thallium 204.3833(2)	82 **Pb** lead 207.2(1)	83 **Bi** bismuth 208.980 40(1)	84 **Po** polonium [208.9824]	85 **At** astatine [209.9871]	86 **Rn** radon [222.0176]
87 **Fr** francium [223.0197]	88 **Ra** radium [226.0254]	89-103 actinoids	104 **Rf** rutherfordium [261.1088]	105 **Db** dubnium [262.1141]	106 **Sg** seaborgium [266.1219]	107 **Bh** bohrium [264.12]	108 **Hs** hassium [277]	109 **Mt** meitnerium [268.1388]	110 **Ds** darmstadtium [271]	111 **Rg** roentgenium [272]	112 **Cn** copernicium [285]	113 **Nh** nihonium [284]	114 **Fl** flerovium [289]	115 **Mc** moscovium [288]	116 **Lv** livermorium [293]	117 **Ts** tennessine [294]	118 **Og** oganesson [294]

57 **La** lanthanum 138.9055(2)	58 **Ce** cerium 140.116(1)	59 **Pr** praseodymium 140.907 65(2)	60 **Nd** neodymium 144.24(3)	61 **Pm** promethium [144.9127]	62 **Sm** samarium 150.36(3)	63 **Eu** europium 151.964(1)
89 **Ac** actinium [227.0277]	90 **Th** thorium 232.0381(1)	91 **Pa** protactinium 231.035 88(2)	92 **U** uranium 238.028 91(3)	93 **Np** neptunium [237.0482]	94 **Pu** plutonium [244.0642]	95 **Am** americium [243.0614]

Notes

- Aluminum and cesium are commonly used English-language spellings for aluminium and caesium.
- IUPAC 2001 standard atomic weights (mean relative atomic masses) are listed with uncertainties in the last figure in parentheses [R. D. Loss: Pure Appl. Chem. **75**, 1107–1122 (2003)]. These values correspond to current best knowledge of the elements in natural terrestrial sources. For elements with no IUPAC assigned standard value, the atomic mass (in unified atomic mass units) or the mass number of the nuclide with the longest known half-life is listed between square brackets.
- Element with atomic number 111 has not yet been named. The IUPAC provisional name is shown.
- Element with atomic numbers 112, 114, and 116 have been reported but not fully authenticated.

OF THE ELEMENTS (IUPAC)

10	11	12	13	14	15	16	17	18
								2 **He** helium 4.002 602(2)
			5 **B** boron 10.811(7)	6 **C** carbon 12.0107(8)	7 **N** nitrogen 14.0067(2)	8 **O** oxygen 15.9994(3)	9 **F** fluorine 18.998 4032(5)	10 **Ne** neon 20.1797(6)
			13 **Al** aluminium 26.981 538(2)	14 **Si** silicon 28.0855(3)	15 **P** phosphorus 30.973 761(2)	16 **S** sulfur 32.065(5)	17 **Cl** chlorine 35.453(2)	18 **Ar** argon 39.948(1)
28 **Ni** nickel 58.6934(2)	29 **Cu** copper 63.546(3)	30 **Zn** zinc 65.409(4)	31 **Ga** gallium 69.723(1)	32 **Ge** germanium 72.64(1)	33 **As** arsenic 74.921 60(2)	34 **Se** selenium 78.96(3)	35 **Br** bromine 79.904(1)	36 **Kr** krypton 83.798(2)
46 **Pd** palladium 106.42(1)	47 **Ag** silver 107.8682(2)	48 **Cd** cadmium 112.411(8)	49 **In** indium 114.818(3)	50 **Sn** tin 118.710(7)	51 **Sb** antimony 121.760(1)	52 **Te** tellurium 127.60(3)	53 **I** iodine 126.904 47(3)	54 **Xe** xenon 131.293(6)
78 **Pt** platinum 195.078(2)	79 **Au** gold 196.966 55(2)	80 **Hg** mercury 200.59(2)	81 **Tl** thallium 204.3833(2)	82 **Pb** lead 207.2(1)	83 **Bi** bismuth 208.980 38(2)	84 **Po** polonium [208.9824]	85 **At** astatine [209.9871]	86 **Rn** radon [222.0176]
110 **Ds** darmstadtium [271]	111 **Uuu** unununium [272]							

64 **Gd** gadolinium 157.25(3)	65 **Tb** terbium 158.925 34(2)	66 **Dy** dysprosium 162.500(1)	67 **Ho** holmium 164.930 32(2)	68 **Er** erbium 167.259(3)	69 **Tm** thulium 168.934 21(2)	70 **Yb** ytterbium 173.04(3)	71 **Lu** lutetium 174.967(1)
96 **Cm** curium [247.0704]	97 **Bk** berkelium [247.0703]	98 **Cf** californium [251.0796]	99 **Es** einsteinium [252.0830]	100 **Fm** fermium [257.0951]	101 **Md** mendelevium [258.0984]	102 **No** nobelium [259.1010]	103 **Lr** lawrencium [262.1097]

Appendix G
Karlsruhe Chart of the Nuclides – Karlsruher Nuklidkarte

6th edition 1995, revised reprint December 1998

Authors:
G. Pfennig, H. Klewe-Nebenius, W. Seelmann-Eggebert

Explanation of the Chart of the Nuclides

The data given in the chart were taken from the following sources:

Decay Data:

$A = 3$: D. R. Tilley, H. R. Weller, H. H. Hasan: Nuclear Physics **A474**, 1 (1987)

$A = 4$: D. R. Tilley, H. R. Weller, G. M. Hale: Nuclear Physics **A541**, 1 (1992)

$A = 5$–15: F. Ajzenberg-Selove: Nuclear Physics **A490**, 1 (1988); **A506**, 1 (1990); **A523**, 1 (1991)

$A = 16$–17: D. R. Tilley, H. R. Weller, C. M. Cheves: Nuclear Physics **A564**, 1 (1993)

$A = 18$–20: F. Ajzenberg-Selove: Nuclear Physics **A475**, 1 (1987)

$A = 21$–44: P. M. Endt: Nuclear Physics **A521**, 1 (1990)

$A \geq 45$: Nuclear Data Sheets (incl. Recent References) **1–75**, 1 (1966–1995)

In addition, original publications up to October 1998 were taken into account.

Neutron Cross Sections:

N. E. Holden: Table of Isotopes (Revised 1991). CRC Handbook of Chemistry and Physics, 72nd edition (1991–1992), pp. **11**–28, D. R. Lide (ed.). CRC Press, Boca Ration, Florida

Natural Isotopic Abundances and Atomic Weights:

J. R. De Laeter: IUPAC, Commission on Atomic Weights and Isotopic Abundances: Pure and Applied Chemistry **63**, 991 (1991)

K. G. Heumann: Pure and Applied Chemistry **66**, 2423 (1994)

Cumulative Chain Yields for the Thermal Neutron Fission of ^{235}U*:*

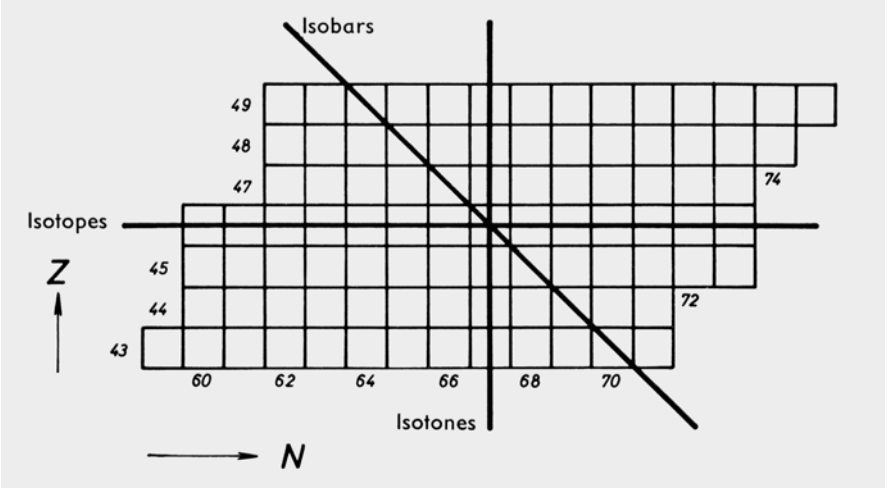
M. F. James, R. W. Mills, D. R. Weaver: Report AEA-TRS-1018 (1991)

General

In this chart of nuclides each *experimentally* observed nuclide is represented by a square containing the symbol of the element and the number of nucleons. If no half-life is given, the respective nuclide is either unstable with regard to particle emission (white field specifying the emitted particles), or a radionuclide with unknown decay properties, which has been detected as shortlived reaction product only. Metastable states, which do not undergo α-, or β-decay, or spontaneous fission, thus, decaying exclusively to the ground state of the same nuclide, are included only, if their half-life is larger than 1 s.

For isomers, which decay exclusively via spontaneous fission, no decay data are given. A compilation of the half-lives, which are all less than 14 ms can be found e.g. in W. B. Ewbank et al., Nucl. Data Sheets **26**, 1 (1979).

In the chart the nuclides are arranged in such a way that the proton number Z is given on the ordinate and the neutron number $N = A - Z$ on the abscissa, respectively. This arrangement was originally proposed by E. Segrè.



Decay Modes: Colours and Symbols

Stable nuclides

Primordial radionuclides, i. e. those formed in the build-up of the terrestrial matter and still present today.

ϵ β+	β−	α

β^+	Positron decay
ε	Electron capture
β^-	Negatron decay
α	Alpha decay

sf	p	C12

sf	Spontaneous fission
p	Proton decay
C12	Cluster emission

Iγ

The data given in the left part apply to the metastable state, those in the right part to the ground state. Iγ denotes γ-quanta due to the decay to the ground state of the same nuclide (isomeric decay).

⟷ The assignment of decay properties to the metastable or ground state is uncertain.

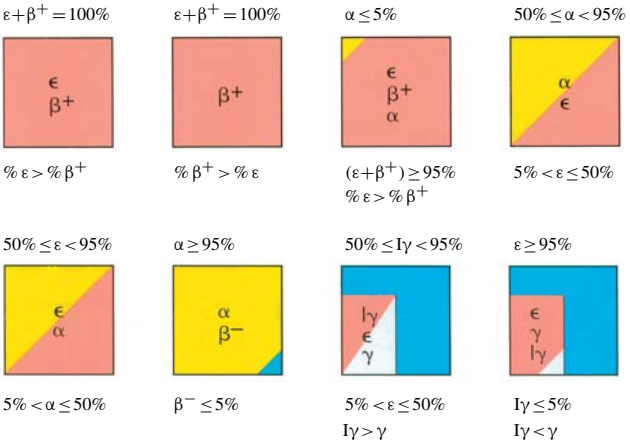
One or more shortlived states, for which only decay via spontaneous fission has been observed (spontaneously fissioning isomers) are indicated by a vertical green bar.

γ	Emission of γ-quanta; they are always listed together with the respective parent nuclide.
e^-	Emission of conversion electrons; the symbol is quoted only, if more conversion electrons than γ-quanta are emitted.
βxp; βxn; βd; βt; βxα; βsf	Emission of the specified particles or spontaneous fission from an excited level of the daughter nuclide, populated via β-decay ("β-delayed particle emission or fission").
$2\beta^-$	Simultaneous emission of two β-particles ("double β-decay", e.g. $^{130}Te \rightarrow {}^{130}Xe$).
p; n 2p; 2α	Emission of the specified particles from a particle-unstable nuclide (white field without indication of the half-life, e.g. ^5Li, ^7He). Simultaneous emission of two particles is indicated only, if one-particle-emission is excluded for energetical reasons (e.g. $^8Be \rightarrow 2\alpha$).

Abundance and Energy of the Emitted Radiation

The relative *abundances* of the decay modes and the emitted radiation are indicated by 3 different sizes of the coloured sections and by the sequence of the symbols and energy values.

Examples:



The symbols for the particle emitting decay modes are quoted first according to decreasing abundances, followed by the γ-quanta and conversion electrons. The data for the isomeric decay have been arranged corresponding to the abundance of this decay mode. β-delayed particles or fission (βn, βp, βsf) precede or follow the γ-quanta according to their relative intensities.

For a given type of radiation the sequence of the energies corresponds to the relative intensities (in decreasing order) of the respective radiation. In case of β-decay a slightly different rule is used (see below).

...	Points indicate further transitions of the same type with lower intensities.

Energies are given in keV for γ-quanta, in MeV for all kinds of particles. A radiation symbol without energy value indicates that the radiation occurs but the energy has not been measured.

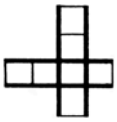
β^+ 2.7... β^- 1.2; 1.9...	Endpoint energy of the most abundant β-transition. In case further transitions with higher energies exist, the second number corresponds to the highest endpoint energy observed.
β^-... β^+...	β-transitions with known energies, for which the sum of their abundances is less than 1%.
ε	Electron capture is specified only, if it is more probable than β^+-decay.
α 3.75; 4.43... p 1.56 βp 4.5	Particle energies listed according to decreasing abundances of the respective transitions. At least one energy is given, even if the abundance of the most prominent group is less than 1%.
γ 815; 1711... γ (1340)	Energies of the strongest γ-quanta arranged in order of decreasing intensities. Intensities less than 1% are given in brackets.
γ 815*	γ-Energies followed by an asterisk denote transitions after β-delayed particle emission.
γ 291–1319	Several γ-quanta of unknown intensities within the energy interval 291–1319 keV.
e^-	Conversion electrons are specified only if they are more abundant than the γ-quanta. Energies are not quoted.

Cross Sections

All cross sections are given in barn (10^{-24} cm^2) and refer to reactions with thermal neutrons (0.0253 eV).

σ	Cross section for the (n,γ) reaction. If two values are given, the first refers to the formation of the product nucleus in the metastable, the second to the formation in the ground state.
σ_f	Fission cross section
$\sigma_{n,p}$	(n,p) cross section
$\sigma_{n,\alpha}$	(n,α) cross section
σ_{abs}	Absorption cross section

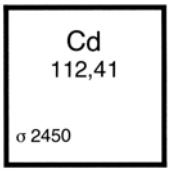
Additional Symbols and Abbreviations

↖ 1.92	Cumulative chain yield (%) for the thermal neutron fission of ^{235}U.
	Nuclides with a closed neutron or proton shell are characterized by heavy vertical or horizontal lines.

m; g	The symbols "m" and/or "g" indicate that the metastable and/or ground state of the daughter nuclide is populated, respectively. The symbols are presented in order of decreasing probability. Branches with probabilities less than 5 % are not shown.
?	Data or assignment uncertain.
ns, μs, ms, s, m, h, d, a	Nanosecond, microsecond, millisecond, second, minute, hour, day, year

Arrangement of Symbols and Data

Elements



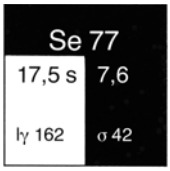
Symbol of the element
Standard atomic weight based on $^{12}C = 12$

Absorption cross section for thermal neutrons (b)

Stable Nuclides

Symbol of the element, number of nucleons
Abundance in naturally occuring element (atom %)

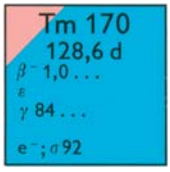
(n,γ)-cross sections for the formation of the metastable and the ground state of ^{127}Te by thermal neutrons (b)



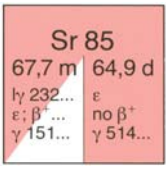
Symbol of the element, number of nucleons
Left hand side: half-life of metastable state;
γ-energy (keV) of the isomeric transition

Right hand side: abundance in the natural element (atom %)
(n,γ)-cross section for thermal neutrons (b)

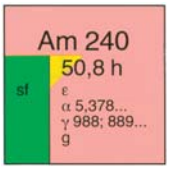
Unstable Nuclides



Symbol of the element, number of nucleons
Half-life
Modes of decay, endpoint energy of β^- radiaton (MeV)
γ-energy (keV)
Conversion electrons, (n,γ)-cross section (b)



Symbol of the element, number of nucleons
Half-lives
Both states decay by electron capture; the metastable state also to the ground state $5\% < I\gamma < 95\%$



Symbol of the element, number of nucleons
Left hand side: spontaneous fission isomer, $T < 0.1$ s
Right hand side: decay data of the ground state. "g" indicates that the daughter ^{240g}Pu is formed to at least 95%; a population of ^{240m}Pu up to 5% cannot be excluded.

Special thanks are due to Prof. Dr. H. J. Ache for promoting and support of this work. Furthermore, we express our gratitude to all colleagues who supported this work by presentation of unpublished results or by discussions.

Index