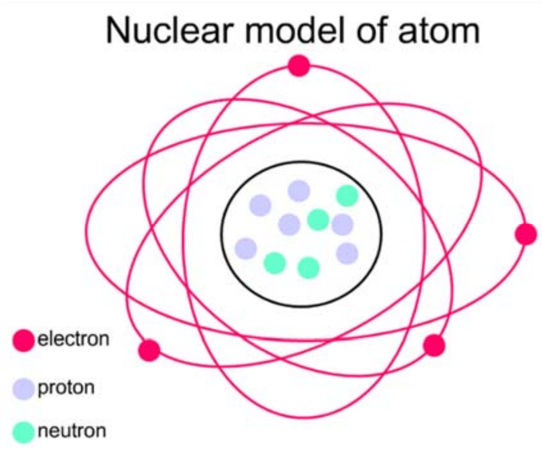
The Atom

All things around us are made of atoms.
The atom is the smallest unit of a chemical element, such as gold or carbon, which has the physical and chemical properties of the element.

Nucleus

Atoms have a dense center called a nucleus.
The nucleus is surrounded by orbiting electrons.

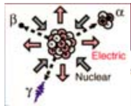
Nuclear Notation



Radiactivity

Henri Becquerel

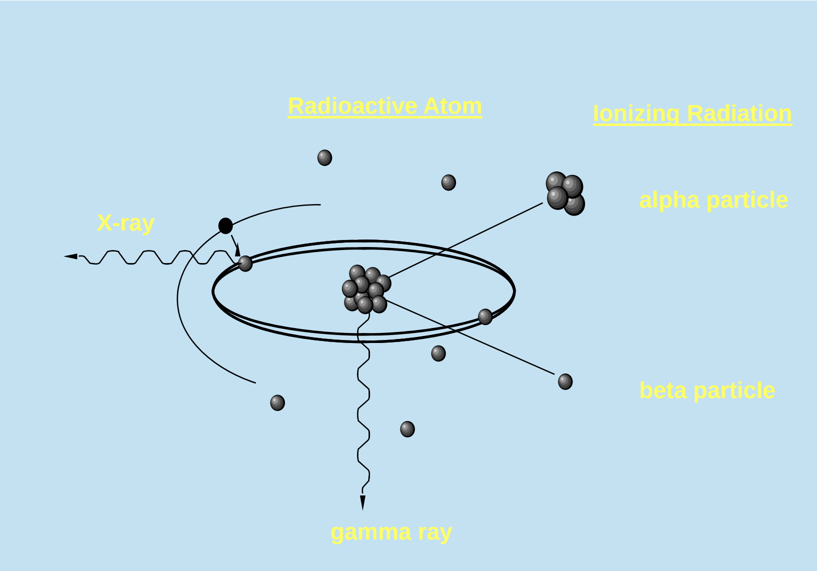
- First to discover that Uranium is radioactive
  – Left Uranium Ore in his desk next to photographic paper.
  – When developed the film had an image on it from the Uranium decaying



Radioactivity

- Radioactivity refers to the particles which are emitted from nuclei as a result of nuclear instability.
- Because the nucleus experiences the intense conflict between the two strongest forces in nature, it should not be surprising that there are many nuclear isotopes which are unstable and emit some kind of radiation.
- The most common types of radiation are called **α**, **β**, and **γ** radiation, but there are several other varieties of radioactive decay.

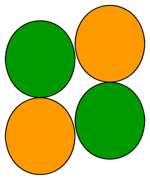
Radioactive decays are normally stated in terms of their half-lives, and the half-life of a given nuclear species is related to its radiation risk.
The radioactive half-life for a given radioisotope is a measure of the tendency of the nucleus to "decay" or "disintegrate" and as such is based purely upon probability



Radioactive Emissions

Emission	What?	Penetration
Alpha α	2 protons 2 neutrons	few cm in air. Stopped by paper
Beta β	electron	1 metre in air. Stopped by thin aluminium
Gamma γ	electromagnetic wave	few metres of concrete will reduce their energy. Difficult to stop

Alpha radiation - α



Helium nuclei

Description:

2 neutrons, 2 protons (helium nuclei)

Electric Charge:

+2

Relative Atomic Mass:

4

Penetration power:

Stopped by paper or a few cm of air

Ionisation effect:

Strongly ionising

Effects of Magnetic/Electric Field:

Weakly deflected

Alpha Particles

- Two neutrons and two protons
- Charge of +2
- Emitted from nucleus of radioactive atoms
- Transfer energy in very short distances (10 cm in air)
- Shielded by paper or layer of skin
- Primary hazard from internal exposure
- Alpha emitters can accumulate in tissue (bone, kidney, liver, lung, spleen) causing local damage

Beta radiation - β

high energy electron

Description:

High energy electron

Electric Charge:

-1

Relative Atomic Mass:

1/1860th

Penetration power:

Stopped by few mm of aluminium

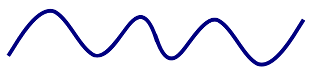
Ionisation effect:

Weakly ionising

Effects of Magnetic/Electric Field:

Strongly deflected

Gamma radiation - γ



Electromagnetic radiation

Description:

High energy electromagnetic radiation

Electric Charge:

0

Relative Atomic Mass:

0

Penetration power:

Reduced by several cm's of lead or several metres of concrete

Ionisation effect:

Very weakly ionising

Effects of Magnetic/Electric Field:

NO deflection

Gamma-rays

- Electromagnetic photons or radiation (identical to x-rays except for source)
- Emitted from nucleus of radioactive atoms – spontaneous emission
- Emitted with kinetic energy related to radioactive source
- Highly penetrating – extensive shielding required
- Serious external radiation hazard

Complete Symbols

- Contain the symbol of the element, the mass number and the atomic number.

Superscript → Mass number

X

Subscript → Atomic number

$$^{A}_{Z}X$$

A = number of protons + number of neutrons

Z = number of protons

A – Z = number of neutrons

Number of neutrons = Mass Number – Atomic Number

There are many types of uranium:

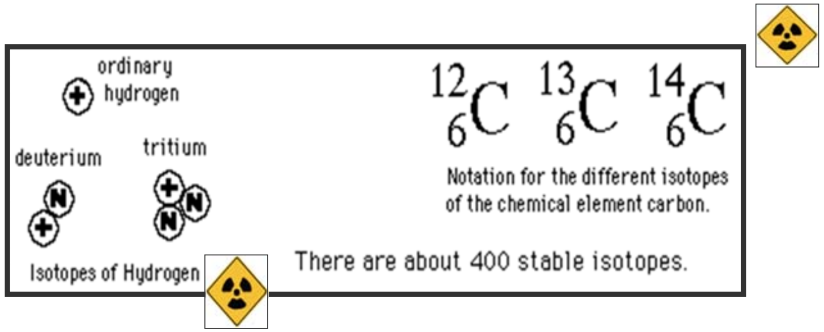
$$^{235}_{92}U \qquad ^{238}_{92}U$$

A	235
Z	92
Number of protons	92
Number of neutrons	143

A	238
Z	92
Number of protons	92
Number of neutrons	146

Isotopes of any particular element contain the same number of protons, but different numbers of neutrons.

Isotopes



Nuclear Transformation

- When the atomic nucleus undergoes spontaneous transformation, called *radioactive decay*, radiation is emitted
  - If the daughter nucleus is stable, this spontaneous transformation ends
  - If the daughter is unstable, the process continues until a stable nuclide is reached
- Most radionuclide's decay in one or more of the following ways: (a) alpha decay, (b) beta-minus emission, (c) beta-plus (positron) emission, (d) electron capture, or (e) isomeric transition.

Alpha Decay

- Alpha (α) decay is the spontaneous emission of an alpha particle (identical to a helium nucleus) from the nucleus
- Typically occurs with heavy nuclides (A > 150) and Z above 83 are unstable, often followed by gamma and characteristic x-ray emission

$${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He^{+2} + \text{transition energy}$$

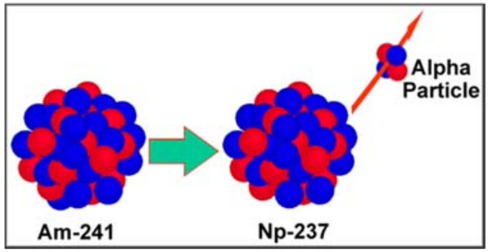
$${}^{238}_{92}U \rightarrow {}^{4}_{2}He + {}^{234}_{90}Th + 2{}^{0}_{0}\gamma$$

Alpha decay

In alpha decay, the nucleus emits an alpha particle; an alpha particle is essentially a helium nucleus, so it's a group of two protons and two neutrons. A helium nucleus is very stable .

example : $${}^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$$

$${}^{238}_{92}U \longrightarrow {}^{234}_{90}Th + {}^{4}_{2}He$$



$${}^{241}_{95}Am \xrightarrow{\alpha} {}^{237}_{93}Np + {}^{4}_{2}He$$

The half-live ranging from about 10^{-3} s to 10^{10} years , the decay processes are much slower than β

Alpha Decay

$${}^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$$

$${}^{226}_{88}Ra \longrightarrow {}^{222}_{86}Rn + {}^{4}_{2}He$$

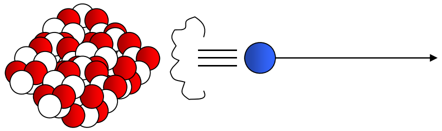
$${}^{222}_{86}Rn \longrightarrow {}^{218}_{84}Po + {}^{4}_{2}He$$

Converting protons and neutrons

- There are certain combinations of protons and neutrons that are more stable than others
- If the number of protons :neutrons is not correct the nucleus is unstable.
- The solution is to release certain types of radioactivity. Note: proton (${}^{1}_{1}p$), neutron (${}^{1}_{0}n$)
  - ${}^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e$ (β⁻ emission)
  - ${}^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{1}e$ (β⁺ emission)
  - ${}^{1}_{1}p + {}^{0}_{-1}e \rightarrow {}^{1}_{0}n$ (EC – electron capture)
- You can tell what type of reaction will occur by referring to the top of your periodic table (“Table of Selected Radioactive Isotopes”)

Beta Decay

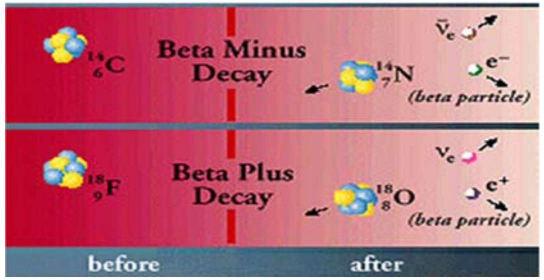
A beta particle is a fast moving electron which is emitted from the nucleus of an atom undergoing radioactive decay.



Beta decay occurs when a neutron changes into a proton and an electron.

Beta Particles

Beta Particles: Electrons or positrons having small mass and variable energy. Electrons form when a neutron transforms into a proton and an electron or:



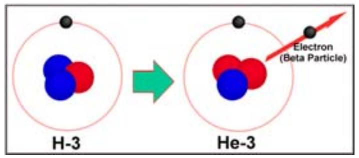
1) β decay

a nuclear neutron changes into a nuclear proton

$$n \longrightarrow P + \beta^- (e^-)$$

$$^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}Y + {}_{-1}e$$

$$^{22}_{11}Na \rightarrow {}^{0}_{1}e + {}^{22}_{10}Ne$$



$$^{3}_{1}H \xrightarrow{\beta} {}^{3}_{2}He + e^- + \bar{\upsilon}_e$$

- release of anti-neutrino (no charge, no mass)

$$^{218}_{84}Po \longrightarrow {}^{218}_{85}Rn + {}^{0}_{-1}\beta$$

$$^{234}_{90}Th \longrightarrow {}^{234}_{91}Pa + {}^{0}_{-1}\beta$$

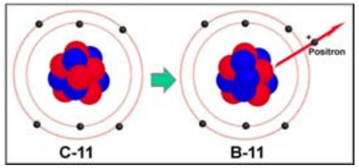
$$^{210}_{81}Tl \longrightarrow {}^{210}_{82}Pb + {}^{0}_{-1}\beta$$

2) β^+ decay

a nuclear proton changes into a nuclear neutron

$$n \longrightarrow P + \beta^+ (e^+)$$

$$^{A}_{Z}X \longrightarrow {}^{A}_{Z-1}Y + {}_{+1}e$$



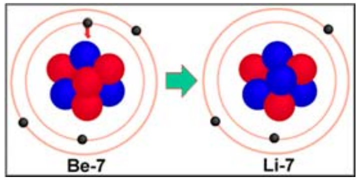
$$^{11}_{6}C \xrightarrow{\beta^+} {}^{11}_{5}B + e^+ + \upsilon_e$$

release of neutrino

3) Electron capture (EC)

In an Electron capture a parent nucleus may capture one of its orbital electrons and emit a neutrino. This is a process which competes with positron emission and has the same effect on the atomic number. Most commonly, it is a K-shell electron which is captured, and this is referred to as K-capture.

$$^{A}_{Z}X + {}_{1-}e \longrightarrow {}^{A}_{Z-1}Y + \nu$$



$$^{7}_{4}Be + {}^{0}_{-1}e \longrightarrow {}^{7}_{3}Li + \nu$$

Gamma Decay

Gamma rays are not charged particles like α and β particles.

Gamma rays are electromagnetic radiation with high frequency.

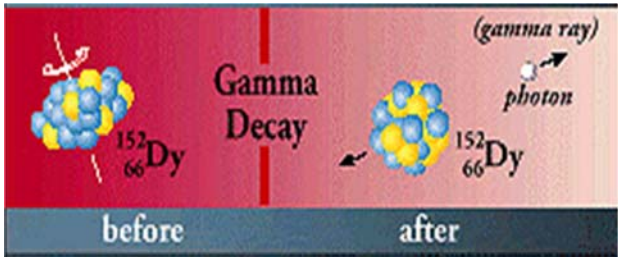
When a nucleus undergoes a transition from higher to lower energy Level ,they are equivalent to light quanta and X rays ,their energies much greater and the half live for γ decay are very short,the emitting α or β particles to form a new atom, the nuclei of the new atom formed may still have too much energy to be completely stable. The γ decay is internal conversion

This excess energy is emitted as gamma rays (gamma ray photons have energies of ~ 1 x 10^{-12} J).

Gamma Rays

Gamma Rays (or photons): Result when the nucleus releases

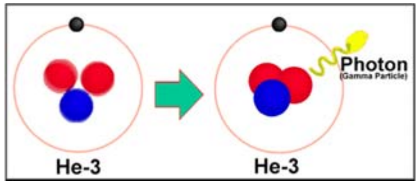
Energy, usually after an alpha, beta or positron transition



❑ *Gamma decay (γ)*

Gamma radioactivity is composed of electromagnetic rays. It is distinguished from x-rays only by the fact that it comes from the nucleus. Most gamma rays are higher in energy than x-rays and therefore are very penetrating.

$$^{A}_{Z}X^{*} \longrightarrow {}^{A}_{Z}X + {}^{o}_{o}\gamma$$



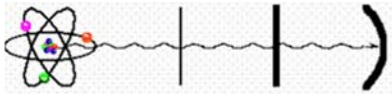
$$^{3}_{2}He^{*} \xrightarrow{\gamma} {}^{3}_{2}He + \gamma$$

X-Rays

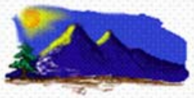
X-Rays: Occur whenever an inner shell orbital electron is removed
and rearrangement of the atomic electrons results with the release of
the elements characteristic X-Ray energy

X Ray and gamma Ray radiation

Penetrating and external hazard



stopped by lead



naturally present in soil and cosmic radiation

found in medical uses

Half-Life

☎The "half-life" (τ) is the time it takes for ***half the atoms*** of a radioactive substance to decay.

$$N = \frac{1}{2}N_0$$

$$\frac{1}{2}N_0 = N_0 e^{-\lambda\tau_{1/2}}$$

$$\ln\frac{1}{2} = -\lambda\tau_{1/2}$$

$$\ln 2 = \lambda\tau_{1/2}$$

$$T_{1/2} = \frac{\ln 2}{\lambda} \approx \frac{0.693}{\lambda} \approx 0.693\tau$$

Radioactive half-life ($T_{1/2}$); Radioactive decay constant (λ); Mean lifetime (τ)

Half-Life

☎For example, suppose we had 20,000 atoms of a radioactive substance. If the half-life is 1 hour, how many atoms of that substance would be left after:

Time	#atoms remaining	% of atoms remaining
1 hour (one lifetime) ?	**10,000**	**(50%)**
2 hours (two lifetimes) ?	**5,000**	**(25%)**
3 hours (three lifetimes) ?	**2,500**	**(12.5%)**

Nuclear Half-Life

The half life of a radioactive isotope

- The time it takes for half of a radioactive sample of an isotope to decay.
- Temperature changes do not affect the rate of nuclear decay.
- After two half lives have passed…
  - **1/8 of the original sample will remain.**

Radioactive Decay Constant

The decay constant is also sometimes called the disintegration constant.

The half-life and the decay constant give the same information, so either may be used to characterize decay.

Another useful concept in radioactive decay is the Mean lifetime. The Mean lifetime is the reciprocal of the decay constant .

$$T_{1/2} = \frac{\ln 2}{\lambda} \approx \frac{0.693}{\lambda} \approx 0.693\tau$$

Radioactive half-life ($T_{1/2}$); Radioactive decay constant (λ); Mean lifetime (τ)

Physical Half-Life

- Useful parameter related to the decay constant; defined as the time required for the number of radioactive atoms in a sample to decrease by one half

$$\lambda = \ln 2/T_{p1/2} = 0.693/T_{p1/2}$$

- Physical half-life and decay constant are inversely related and unique for each radionuclide

Radioactive Half-Life

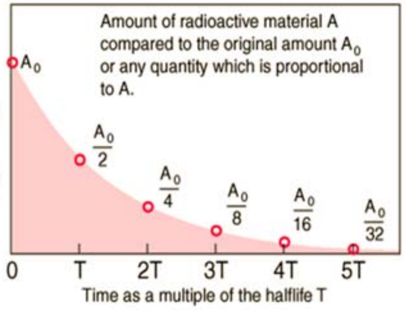
- The radioactive half-life for a given radioisotope is the time for half the radioactive nuclei in any sample to undergo radioactive decay. After two half-lives, there will be one fourth the original sample, after three half-lives one eight the original sample, and so forth.

$$A = A_0(1/2)^{t/T_{1/2}}$$

$$t = nT_{1/2}$$

$$A = A_0(1/2)^n$$

$$A = A_0 2^{\frac{-t}{T_{1/2}}}$$



Nuclear Decay Probability

- Radioactive decay is a statistical process which depends upon the instability of the particular radioisotope, but which for any given nucleus in a sample is completely unpredictable. The decay process can be described by assuming that individual nuclear decays are purely random events.
- If there are N radioactive nuclei at some time t, then the number $-\Delta N$ which would decay in any given time interval Δt would be proportional to N:

$$\Delta N = -\lambda N \Delta t$$

Where λ is a constant of proportionality (decay constant).

Nuclear Decay Probability

Without any further assumptions, this leads to the exponential radioactive decay law:

$$N = N_0 e^{-\lambda t}$$

This implies that the decay rate and amount of emitted radiation also follow the same type of relationship. The number of atoms, the mass of the substance, and the level of activity all follow the same exponential decay form:

$$R = R_0 e^{-\lambda t}$$

Example

The half life of radium Ra is 1.6×10^3 yr. If the sample contains 3.00×10^{16} nuclei. Find the activity after 4.8×10^3 yr.

$$R = \lambda N$$

After this time since the no. of nuclei is reduced by a factor of 8 the decay rate will also be reduced by a factor of 8.

$$R = 11\ \mu Ci/8 = 1.4\ \mu Ci$$

$$R = \lambda N$$

$$\lambda = \frac{0.693}{1.6\times10^{3}\times365\times24\times3600} = 1.37343\times10^{-11}$$

$$R = 3\times10^{16} e^{-2.079}$$

$$R = 3.75\times10^{15}\ decay\ /\sec$$

$$R = 1.388\,Ci$$

Example:

Tritium has a half life of 12.3 years. How many years will it take for 88.0 grams to decay to 5.50 grams

$$\lambda = \frac{0.693}{12.3} = 0.0563\,y^{-1}$$

$$N = N_0 e^{-\lambda t}$$

$$5.5 = 88 e^{-0.563t}$$

$$\frac{5.5}{88} = e^{-0.0563t}$$

$$\ln\frac{5.5}{88} = \ln 0.0625 = -0.0563t \qquad \text{t=49.25 years}$$

Fundamental Decay Equation

$$N_t = N_o e^{-\lambda t} \text{ or } R_t = R_o e^{-\lambda t}$$

where:

- N_t = number of radioactive atoms at time t
- R_t = activity at time t
- N_o = initial number of radioactive atoms
- R_o = initial activity
- e = base of natural logarithm = 2.71828...
- λ= decay constant = ln 2/$T_{p1/2}$ = 0.693/$T_{p1/2}$
- t = time

Activity

- **The activity of a radioactive substance is defined as the number of radioactive nuclei that disintegrate per second.**

$$R = |\Delta N/\Delta t|$$

$$R = \lambda N = \lambda N_o e^{-\lambda t}$$

$$Ro = \lambda N_o$$

$$R(t) = R_o e^{-\lambda t}$$

Units of Activity

- The SI unit of activity is the Becquerel [Bq]

1 Bq = 1 disintegration/sec (dps)

- The Curie [Ci] = Activity of 1g of ^{226}Ra

1 Ci = 3.7×10^{10} Bq

Units of Activity

- 1 kBq = 10^{3} Bq
- 1 MBq = 10^{6} Bq
- 1 GBq = 10^{9} Bq
- 1 TBq = 10^{12} Bq

- 1 mCi = 10^{-3} Ci
- 1 μCi = 10^{-6} Ci
- 1 nCi = 10^{-9} Ci
- 1 pCi = 10^{-12} Ci

Radioactivity and Ionizing Radiation

- **Radioactivity or radioactive decay**:
  - Emitting excess energy from the nucleus of an unstable atom
  - Radioactive decay results in the decrease of radiation levels over time
- **Ionizing radiation:** Energy released from unstable (radioactive) atoms
- NOTE: ***Radioactive*** Atoms Emit ***Radiation***

• Ionizing radiation (enough energy to ionize molecules) is characterized by high frequency and short wavelength

Three Main Types of Ionizing Radiation Emitted from Radioactive Atoms

- Alpha
- Beta
- Gamma

Effective half life τ_{eff}

The effective half life τ_{eff} is obtained by combining the biological half life τ_b and the radioactive or physical half life τ_p according to the formula

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_b} + \frac{1}{\tau_p}$$

Effective Half-Life

Physical half-life, TP [radioactive decay]

Biological half-life, TB [clearance from the body]

$$A = A_0 e^{-\lambda_{phys} t} e^{-\lambda_{biol} t}$$

$$A = A_0 e^{-(\lambda_P + \lambda_D)t} \qquad \lambda_P + \lambda_B = \lambda_E$$

$$\frac{1}{T_E} = \frac{1}{T_B} + \frac{1}{T_P} \quad or \quad T_E = \frac{T_P T_B}{T_P + T_B}$$

Effective Half-Life

E.g., for an isotope with a 6-hr half life attached to various carrier molecules with different biological half-lives.

T_P	T_B	T_E
6 hr	1 hr	0.86 hr
6 hr	6 hr	3 hr
6 hr	60 hr	5.5 hr
6 hr	600 hr	5.9 hr