Chapter 44

Nuclear Structure

44.1 Some Properties of Nuclei

44.2 Nuclear Binding Energy

44.4 Radioactivity

44.5 The Decay Processes

44.6 Natural Radioactivity

44.7 Nuclear Reactions

Milestones in the Development of Nuclear Physics

- 1896: the birth of nuclear physics
  - Becquerel discovered radioactivity in uranium compounds
- Rutherford showed the radiation had three types:
  - alpha (He nuclei)
  - beta (electrons)
  - gamma (high-energy photons)
- 1911 Rutherford, Geiger and Marsden performed scattering experiments
  - Established that the nucleus could be treated as a point mass and a point charge
  - Most of the atomic mass was contained in the nucleus
  - Nuclear force was a new type of force

44.1 Some Properties of Nuclei

- All nuclei are composed of protons and neutrons.
  - Exception is ordinary hydrogen with a single proton
- The **atomic number** Z equals the number of protons in the nucleus.
  - Sometimes called the charge number
- The **neutron number** N is the number of neutrons in the nucleus.
- The **mass number** A is the number of **nucleons** in the nucleus.
  - $A = Z + N$
  - Nucleon is a generic term used to refer to either a proton or a neutron
  - The mass number is not the same as the mass.

44.1 Some Properties of Nuclei

Symbolism

- A **nuclide** is a specific combination of atomic number and mass number that represents a nucleus.

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

  - X is the chemical symbol of the element.

- Example:

$$^{27}_{13}Al$$

» Mass number is 27

» Atomic number is 13

» Contains 13 protons

» Contains 14 (27 – 13) neutrons

44.1 Some Properties of Nuclei

More Properties

- The nuclei of all atoms of a particular element must contain the same number of protons.
- They may contain varying numbers of neutrons.
  - **Isotopes** of an element have the same Z but differing N and A values.
  - The natural abundance of isotopes can vary.
  - Isotope example:

$$^{11}_{6}C,\ ^{12}_{6}C,\ ^{13}_{6}C,\ ^{14}_{6}C$$

44.1 Some Properties of Nuclei

Charge

- The proton has a single positive charge, *e*.
- The electron has a single negative charge, - *e*.
  - $e = 1.6 \times 10^{-19}$ C
- The neutron has no charge.
  - Made it difficult to detect in early experiments
  - Easy to detect with modern devices

44.1 Some Properties of Nuclei

Mass

- It is convenient to use *atomic mass units*, u, to express masses.
  - $1\ u = 1.660\ 539 \times 10^{-27}$ kg
  - Based on definition that the mass of one atom of ^{12}C is exactly 12 u
- Mass can also be expressed in MeV/c^2.
  - From $E_R = mc^2$
  - $1\ u = 931.494\ MeV/c^2$
    - Includes conversion $1\ eV = 1.602\ 176 \times 10^{-19}$ J

44.1 Some Properties of Nuclei

Some Masses in Various Units

TABLE 44.1 *Masses of Selected Particles in Various Units*

Particle	Mass kg	Mass u	Mass MeV/c^2
Proton	$1.672\,62 \times 10^{-27}$	1.007 276	938.27
Neutron	$1.674\,93 \times 10^{-27}$	1.008 665	939.57
Electron	$9.109\,38 \times 10^{-31}$	$5.485\,79 \times 10^{-4}$	0.510 999
${}^{1}_{1}$H atom	$1.673\,53 \times 10^{-27}$	1.007 825	938.783
${}^{4}_{2}$He nucleus	$6.644\,66 \times 10^{-27}$	4.001 506	3 727.38
${}^{12}_{6}$C atom	$1.992\,65 \times 10^{-27}$	12.000 000	11 177.9

44.1 Some Properties of Nuclei

Size of Nucleus

•Since the time of Rutherford, many other experiments have concluded the following:

- Most nuclei are approximately spherical.
- Average radius is

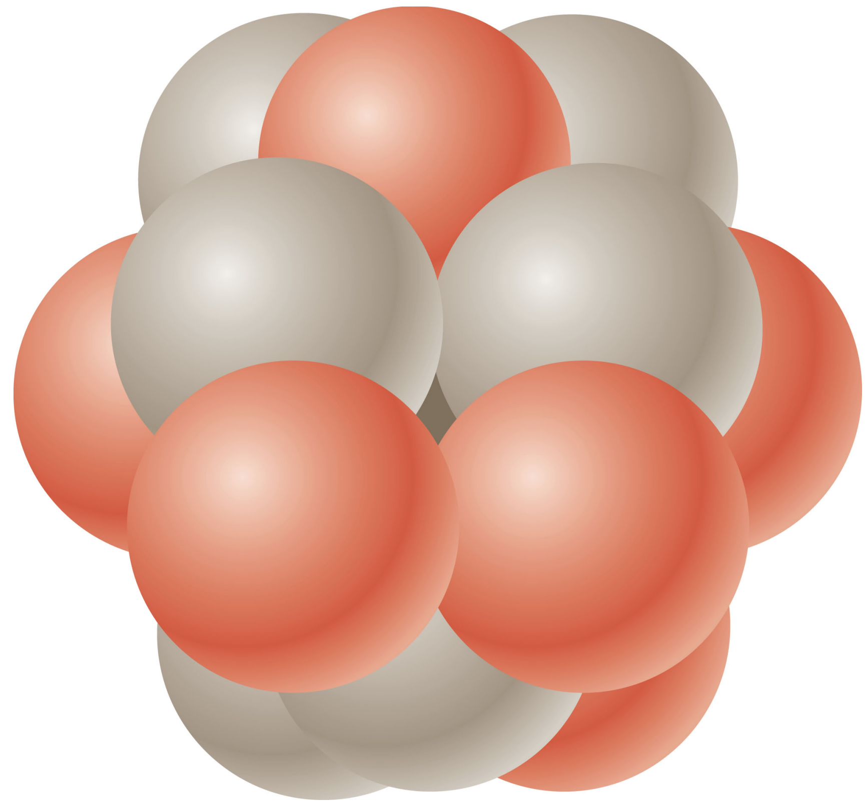
$$r = r_o A^{1/3}$$

  - $r_o = 1.2 \times 10^{-15}$ m
  - A is the mass number

44.1 Some Properties of Nuclei

Density of Nuclei

- The volume of the nucleus (assumed to be spherical) is directly proportional to the total number of nucleons.
- This suggests that *all nuclei have nearly the same density.*
- Nucleons combine to form a nucleus as though they were tightly packed spheres.



44.1 Some Properties of Nuclei

Nuclear Stability

- There are very large repulsive electrostatic forces between protons.
  - These forces should cause the nucleus to fly apart.
- The nuclei are stable because of the presence of another, short-range force, called the **nuclear force.**
  - This is an attractive force that acts between all nuclear particles.
  - The nuclear attractive force is stronger than the Coulomb repulsive force at the short ranges within the nucleus.

44.1 Some Properties of Nuclei

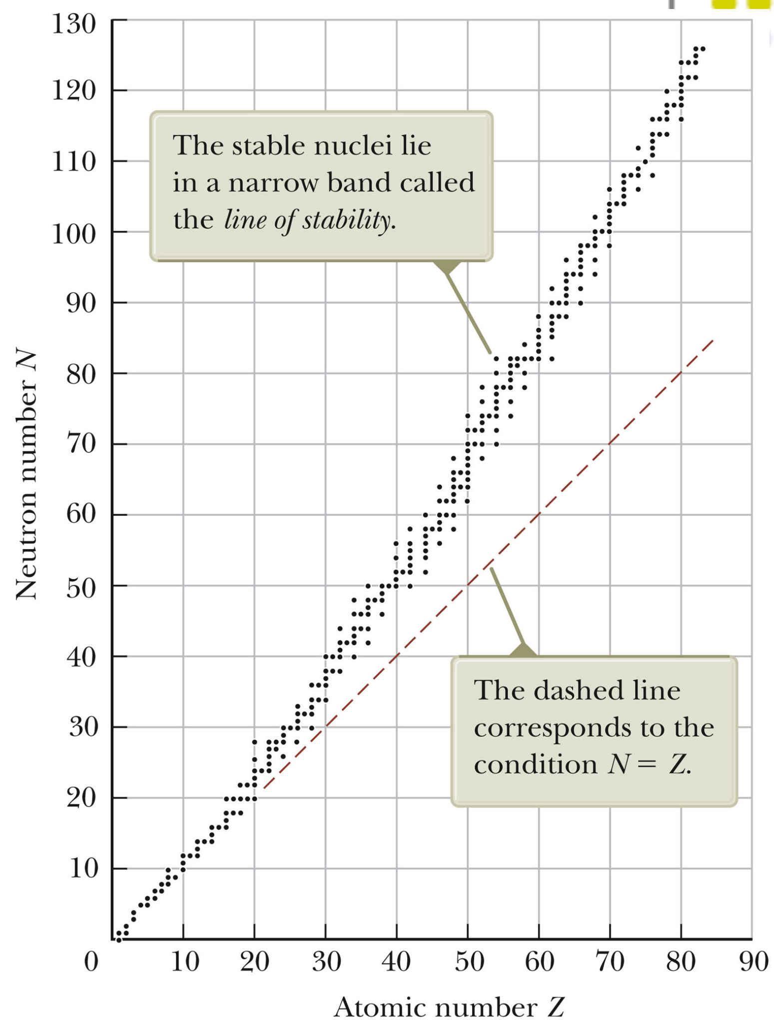
Features of the Nuclear Force

- Attractive force that acts between all nuclear particles
- Very short range
  - It falls to zero when the separation between particles exceeds about several fermis (femtometers (fm) where 1 fm = 10^{-15} m).
- Independent of charge
  - The nuclear force on p-p, p-n, n-n are all the same
  - Does not affect electrons

44.1 Some Properties of Nuclei

Nuclear Stability, cont.

- Light nuclei are most stable if $N = Z$.
- Heavy nuclei are most stable when $N > Z$.
  - Above about $Z = 20$
  - As the number of protons increases, the Coulomb force increases and so more neutrons are needed to keep the nucleus stable.
- No nuclei are stable when $Z > 83$.



44.2 Nuclear Binding

Binding Energy

•The total energy of the bound system (the nucleus) is less than the combined energy of the separated nucleons.

- This difference in energy is called the **binding energy** of the nucleus.
  - It can be thought of as the amount of energy you need to add to the nucleus to break it apart into its components.

44.4 Radioactivity

Marie Curie

- 1867 – 1934
- Polish scientist
- Shared Nobel Prize in Physics in 1903 for studies in radioactive substances
  - Shared with Pierre Curie and Becquerel
- Won Nobel Prize in Chemistry in 1911 for discovery of radium and polonium

44.4 Radioactivity

Radioactivity

- *Radioactivity* is the spontaneous emission of radiation.
  - Discovered by Becquerel in 1896
  - Many experiments were conducted by Becquerel and the Curies.
- Experiments suggested that radioactivity was the result of the decay, or disintegration, of unstable nuclei.

44.4 Radioactivity

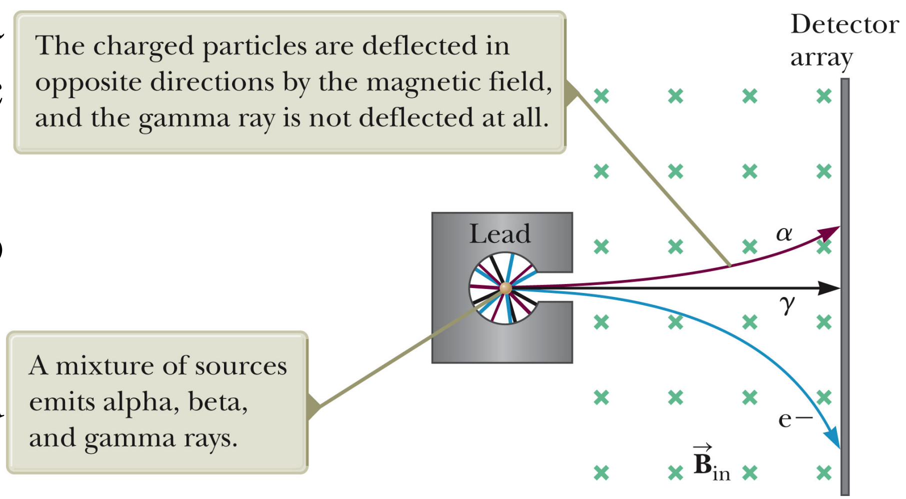
Radioactivity – Types of Decay

- Three types of radiation can be emitted.
  - Alpha particles
    - The particles are ^{4}He nuclei.
  - Beta particles
    - The particles are either electrons or positrons.
      - A **positron** is the antiparticle of the electron.
      - It is similar to the electron except its charge is +e.
  - Gamma rays
    - The “rays” are high energy photons.

44.4 Radioactivity

Distinguishing Types of Radiation

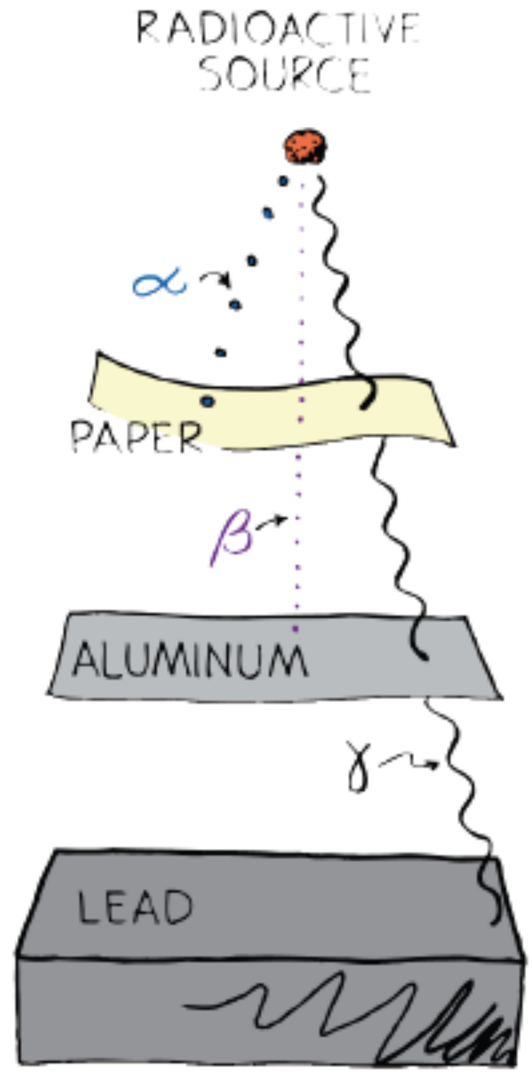
- All three types of radiation enter a region where there is a magnetic field.
- The gamma particles carry no charge.
- The alpha particles are deflected upward.
- The beta particles are deflected downward.



44.4 Radioactivity

Penetrating Ability of Particles

- Alpha particles
  - Barely penetrate a piece of paper
- Beta particles
  - Can penetrate a few mm of aluminum
- Gamma rays
  - Can penetrate several cm of lead



44.4 Radioactivity

Terminology Notes

- Radiation is the term used historically for all emanations from a radioactive nucleus.
  - Although these are not forms of electromagnetic radiation, the term radiation is still used.
- The symbol N has many uses, so be sure to consider the context in which the symbol is used.

44.4 Radioactivity

Decay Rate

•The **decay rate** R of a sample is defined as the number of decays per secor

$$R = \left|\frac{dN}{dt}\right| = \lambda N = R_o e^{-\lambda t}$$

– $R_o = N_o\lambda$ is the decay rate at $t = 0$.
  - λ is called the **decay constant** and determines the probability of decay per nucleus per second.
  - N is the number of undecayed radioactive nuclei present.
  - N_o is the number of undecayed nuclei at time $t = 0$.

– The decay rate is often referred to as the activity of the sample.

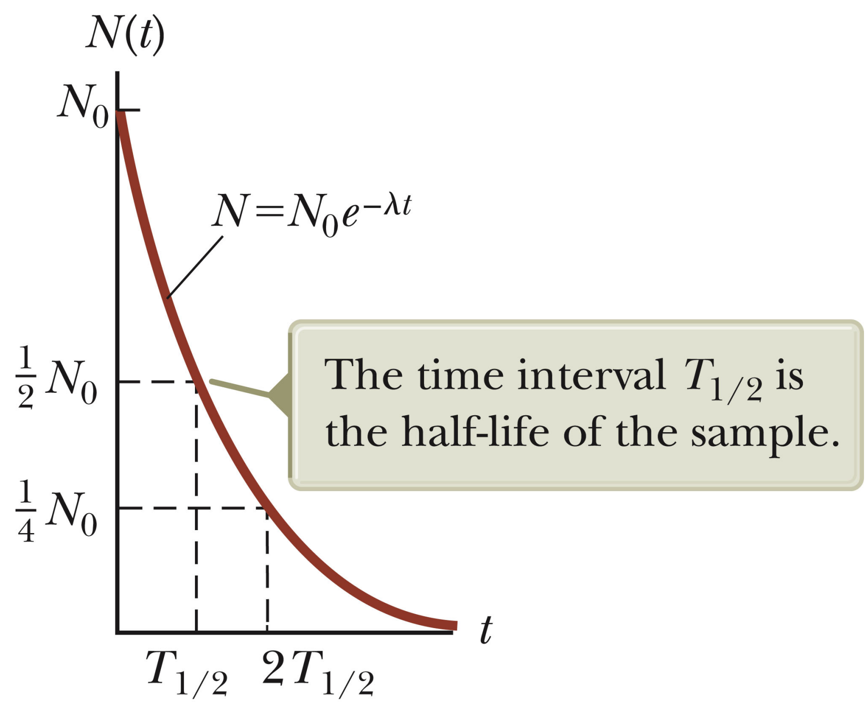
44.4 Radioactivity

Decay Curve and Half-Life

- The decay curve follows the equation $N = N_o e^{-\lambda t}$.
- The **half-life** is also a useful parameter.
  - The half-life is defined as the time interval during which half of a given number of radioactive nuclei decay.

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

  - The half-life is determined by calculating the number of atoms in a sample and the rate at which the sample decays.
  - The shorter the half-life of a substance, the faster it disintegrates, and the more active is the substance.



44.4 Radioactivity

Half-Live, cont.

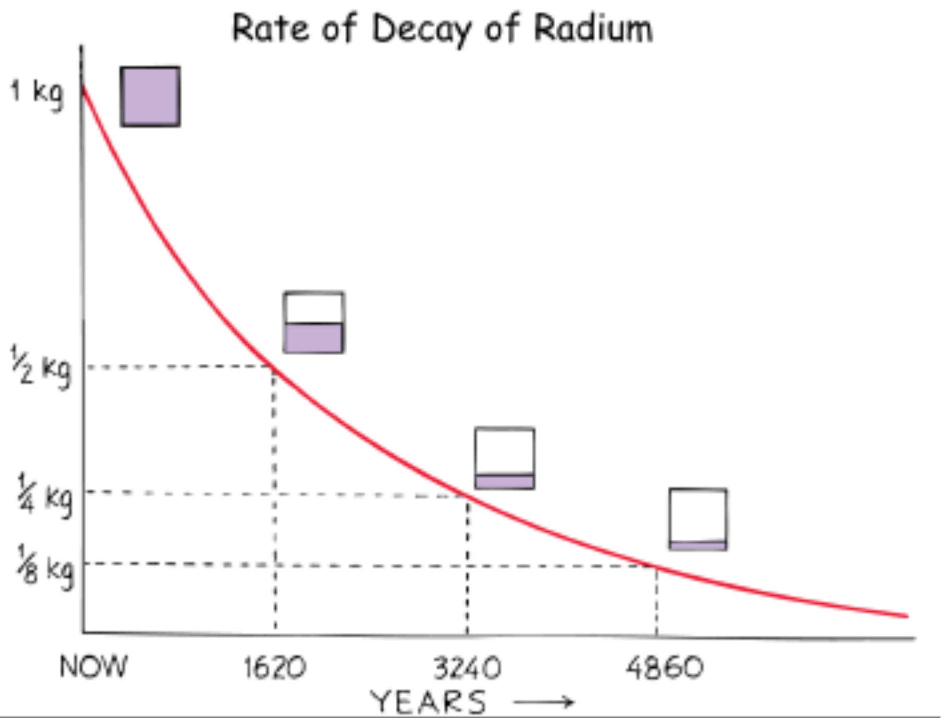
- During the first half-life, ½ of the original material will decay.
- During the second half-life, ½ of the remaining material will decay, leaving ¼ of the original material remaining.
- Summarizing, the number of undecayed radioactive nuclei remaining after *n* half-lives is $N = N_o\,(½)^n$
  - *n* can be an integer or a noninteger.

44.4 Radioactivity

half-life -Examples

Radium-226, for example, has a half-life of 1620 years.

- This means that half of any given specimen of Ra-226 will have undergone decay by the end of 1620 years.
- In the next 1620 years, half of the remaining radium decays, leaving only one fourth the original of radium atoms.



44.4 Radioactivity

half-life -Examples

- The isotopes of some elements have a half-life of less than a millionth of a second.
- U-238 has a half-life of 4.5 billion years.
- Each isotope of a radioactive element has its own characteristic half-life.
- Rates of radioactive decay appear to be absolutely constant, unaffected by any external conditions

44.4 Radioactivity

Units

- The unit of activity, R, is the **curie** (Ci)
  - $1\ Ci \equiv 3.7 \times 10^{10}$ decays/s
- The SI unit of activity is the **becquerel** (Bq)
  - $1\ Bq \equiv 1$ decay/s
    - Therefore, $1\ Ci = 3.7 \times 10^{10}\ Bq$
- The most commonly used units of activity are the millicurie and the microcurie.

44.5 The Decay Processes

Alpha Decay

- When a nucleus emits an alpha particle it loses two protons and two neutrons.
  - N decreases by 2
  - Z decreases by 2
  - A decreases by 4
- Symbolically
  - X is called the **parent nucleus.**
  - Y is called the **daughter nucleus.**

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

44.5 The Decay Processes

Decay – General Rules

- The sum of the mass numbers A must be the same on both sides of the equation.
- The sum of the atomic numbers Z must be the same on both sides of the equation.
- When one element changes into another element, the process is called **spontaneous decay** or transmutation.
- Relativistic energy and momentum of the isolated parent nucleus must be conserved.

44.5 The Decay Processes

Disintegration Energy

- The disintegration energy Q of a system is defined as

$$Q = (M_x - M_y - M_\alpha)c^2$$

- The disintegration energy appears in the form of kinetic energy in the daughter nucleus and the alpha particle .
- It is sometimes referred to as the Q value of the nuclear decay.

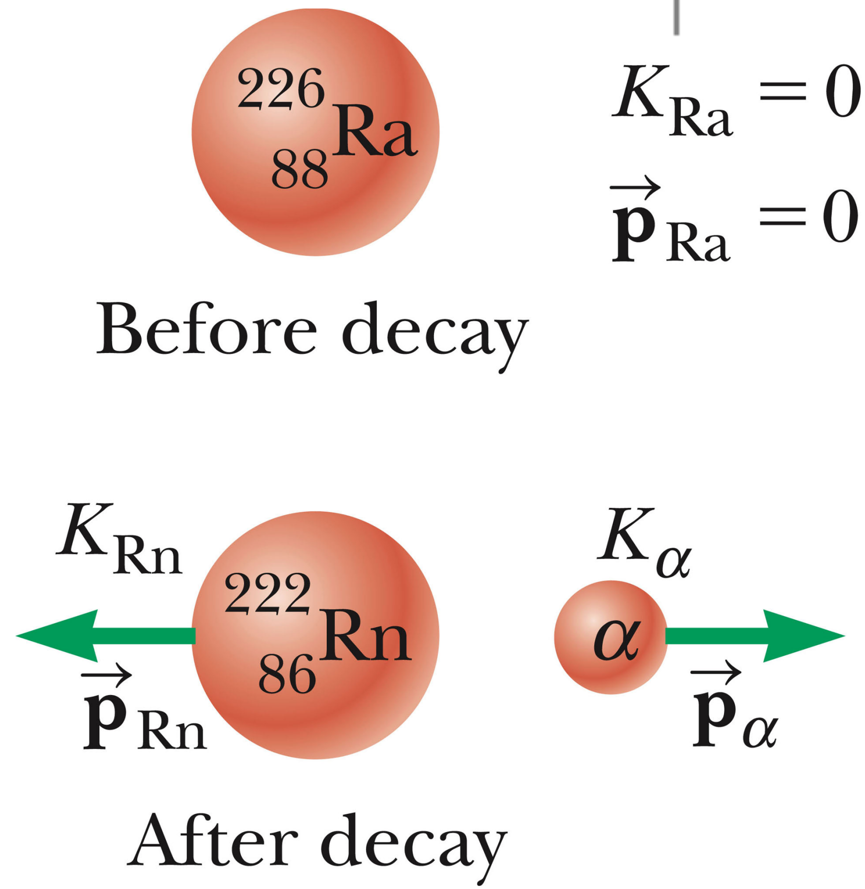
44.5 The Decay Processes

Alpha Decay, Example

- Decay of ^{226} Ra

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

- If the parent is at rest before the decay, the total kinetic energy of the products is 4.87 MeV.
- After the decay, the radon nucleus has kinetic energy K_{Rn} and momentum P_{Ra} and the alpha particle has kinetic energy K_{α} and momentum P_{α}.



44.5 The Decay Processes

Alpha Decay, Notes

- Experimental observations of alpha-particle energies show a number of discrete energies instead of a single value.
  - The daughter nucleus may be left in an excited quantum state.
  - So, not all of the energy is available as kinetic energy.
- A negative Q value indicates that such a proposed decay does not occur spontaneously.

44.5 The Decay Processes

Beta Decay

- During beta decay, the daughter nucleus has the same number of nucleons as the parent, but the atomic number is changed by one.
- Symbolically

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

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

  – Beta decay is not completely described by these equations.

44.5 The Decay Processes

Beta Decay, cont.

- The emission of the electron or positron is from the nucleus.
  - The nucleus contains protons and neutrons.
  - The process occurs when a neutron is transformed into a proton or a proton changes into a neutron.
    - The electron or positron is created in the process of the decay.
- The nucleon number and the total charge are both conserved.
- Energy of the isolated system must be conserved.
- The energy released in the decay process should almost all go to kinetic energy of the β particle.

44.5 The Decay Processes

Neutrino

$$^{14}_{6}C \rightarrow {}^{14}_{7}N + e^{-} \quad \text{(incomplete expression)}$$

$$^{12}_{7}N \rightarrow {}^{12}_{6}C + e^{+} \quad \text{(incomplete expression)}$$

- To account for this "missing" energy, in 1930 Pauli proposed the existence of another particle.
- Enrico Fermi later named this particle the neutrino.
- Properties of the neutrino:
  - Zero electrical charge
  - Mass much smaller than the electron, probably not zero
  - Very weak interaction with matter and so is difficult to detect
- The neutrino was detected experimentally in 1956.

44.5 The Decay Processes

Beta Decay – Completed

–Symbolically

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

- ν is the symbol for the neutrino.
- ν^{-} is the symbol for the antineutrino.

–To summarize, in beta decay, the following pairs of particles are emitted.

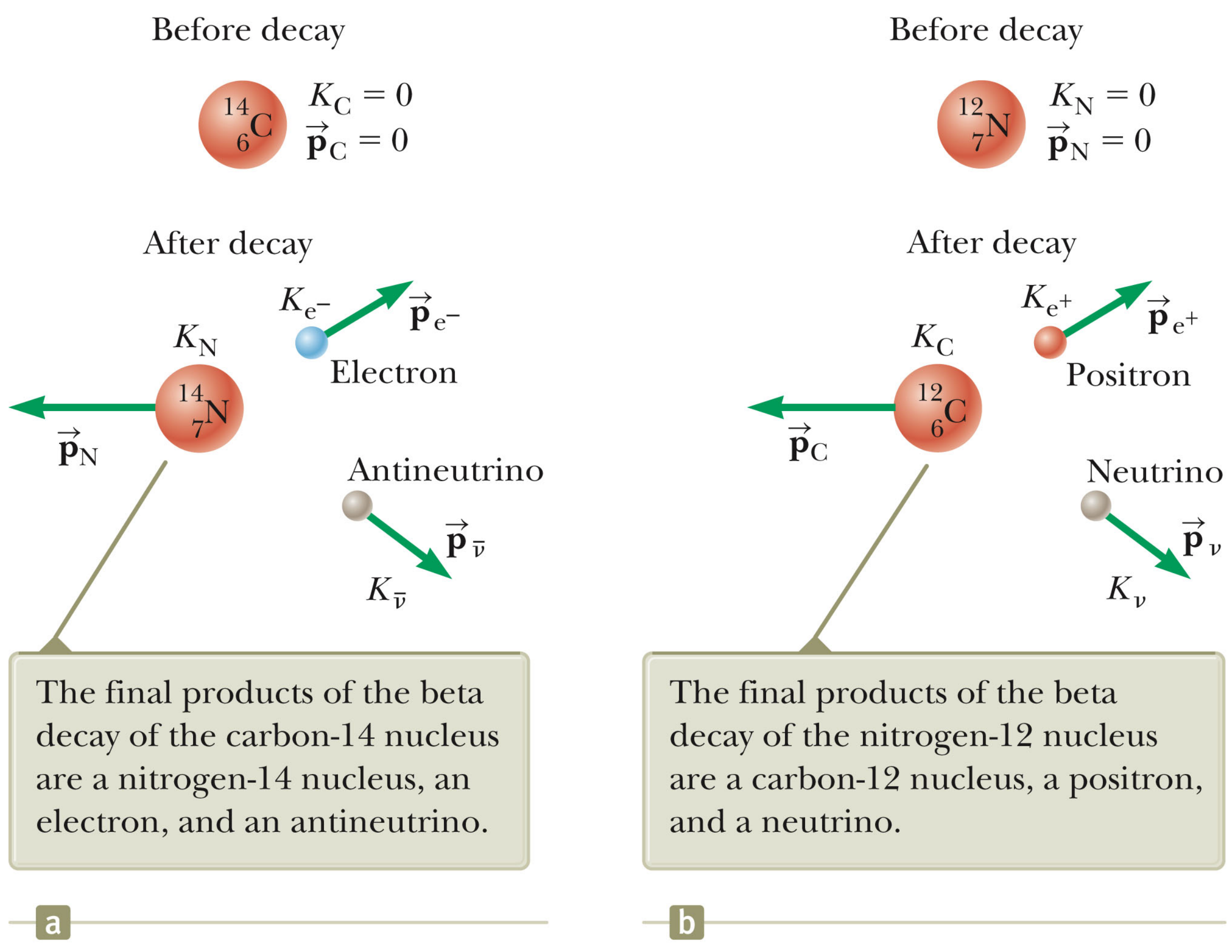
- An electron and an antineutrino
- A positron and a neutrino

44.5 The Decay Processes

Beta Decay – Examples

$$^{14}_{6}\mathrm{C} \rightarrow\ ^{14}_{7}\mathrm{N} + e^{-} + \bar{\nu} \quad \text{(complete expression)}$$

$$^{12}_{7}\mathrm{N} \rightarrow\ ^{12}_{6}\mathrm{C} + e^{+} + \nu \quad \text{(complete expression)}$$



44.5 The Decay Processes

Beta Decay, Final Notes

- The fundamental process of e^- decay is a neutron changing into a proton, an electron and an antineutrino.
- In e^+, the proton changes into a neutron, positron and neutrino.

$$n \rightarrow p + e^- + \nu^-$$

$$p \rightarrow n + e^+ + \nu^+$$

  - This can only occur within a nucleus.
  - It cannot occur for an isolated proton since its mass is less than the mass of the neutron.

44.5 The Decay Processes

Electron Capture

- **Electron capture** is a process that competes with e^+ decay.
- In this case, a parent nucleus captures one of its own orbital electrons and emits a neutrino:

$$ {}^{A}_{Z}X + {}^{0}_{-1}e \rightarrow {}^{A}_{Z-1}Y + \nu $$

  - In most cases, a K-shell electron is captured, so this is often referred to as **K capture.**
    - Because the neutrino is very hard to detect, electron capture is usually observed by the x-rays given off as higher-shell electrons cascade downward to fill the vacancy created in the K shell.

44.5 The Decay Processes

Gamma Decay

- Gamma rays are given off when an excited nucleus decays to a lower energy state.
- The decay occurs by emitting a high-energy photon called gamma-ray photons.

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

  - The X* indicates a nucleus in an excited state.
- Typical half-life is 10^{-10} s
- The only change in the nucleus is that it ends up in a lower energy state.
  - No changes in *Z*, *N* or *A* occur

44.5 The Decay Processes

Gamma Decay – Example

- Example of a decay sequence:
  - The first decay is a beta emission.
  - The second step is a gamma emission.

$$^{12}_{5}B \rightarrow {}^{12}_{6}C^{*} + e^{-} + \nu^{-}$$
$$^{12}_{6}C^{*} \rightarrow {}^{12}_{6}C + \gamma$$

  - Gamma emission doesn’t change *Z, N*, or *A*
  - The emitted photon has an energy of h*f* equal to DE between the two nuclear energy levels.

44.5 The Decay Processes

Summary of Decays

TABLE 44.3 *Various Decay Pathways*

Alpha decay	${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$
Beta decay (e^-)	${}^{A}_{Z}X \rightarrow {}_{Z+1}^{A}Y + e^- + \bar{\nu}$
Beta decay (e^+)	${}^{A}_{Z}X \rightarrow {}_{Z-1}^{A}Y + e^+ + \nu$
Electron capture	${}^{A}_{Z}X + e^- \rightarrow {}_{Z-1}^{A}Y + \nu$
Gamma decay	${}^{A}_{Z}X^* \rightarrow {}^{A}_{Z}X + \gamma$

44.6 Natural Radioactivity

Natural Radioactivity

- Classification of nuclei
  - Unstable nuclei found in nature
    - Give rise to *natural radioactivity*
  - Nuclei produced in the laboratory through nuclear reactions
    - Exhibit *artificial radioactivity*
- Three series of natural radioactivity exist.
  - Uranium
  - Actinium
  - Thorium
- Some radioactive isotopes are not part of any decay series.

44.6 Natural Radioactivity

Radioactive Series, Overview

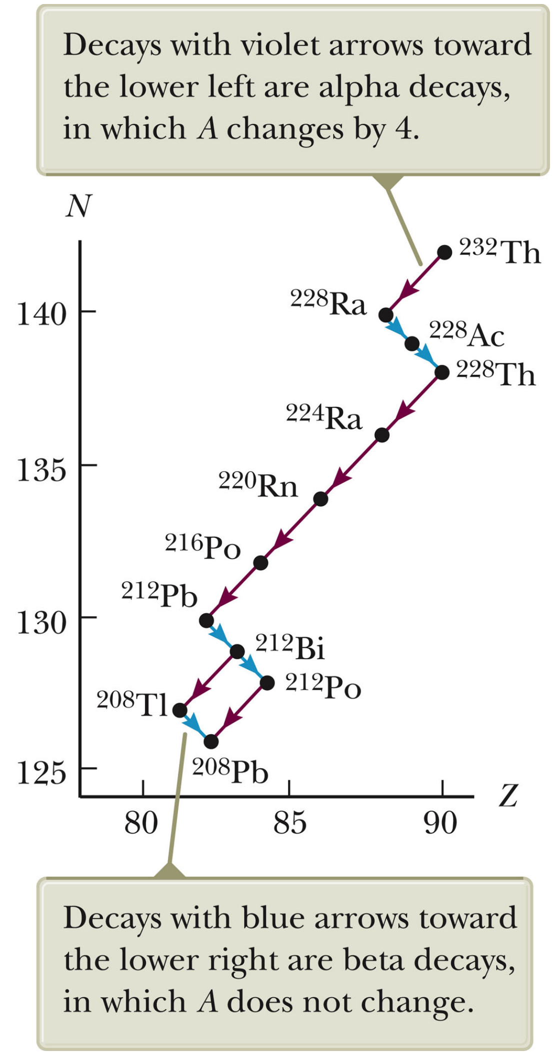
TABLE 44.4 *The Four Radioactive Series*

Series		Starting Isotope	Half-life (years)	Stable End Product
Uranium	Natural	$^{238}_{92}U$	4.47×10^9	$^{206}_{82}Pb$
Actinium	Natural	$^{235}_{92}U$	7.04×10^8	$^{207}_{82}Pb$
Thorium	Natural	$^{232}_{90}Th$	1.41×10^{10}	$^{208}_{82}Pb$
Neptunium		$^{237}_{93}Np$	2.14×10^6	$^{209}_{83}Bi$

44.6 Natural Radioactivity

Decay Series of ^{232}Th

- Series starts with ^{232}Th
- Processes through a series of alpha and beta decays
- The series branches at ^{212}Bi
- Ends with a stable isotope of lead, ^{208}Pb



44.7 Nclear Reactions

Nuclear Reactions

- The structure of nuclei can be changed by bombarding them with energetic particles.
  - The changes are called **nuclear reactions.**
- As with nuclear decays, the atomic numbers and mass numbers must balance on both sides of the equation.
- A target nucleus, X, is bombarded by a particle a, resulting in a daughter nucleus Y and an outgoing particle b.
  - $a + X \rightarrow Y + b$
- The **reaction energy** *Q* is defined as the *total change in mass-energy resulting from the reaction.*
  - $Q = (M_a + M_X - M_Y - M_b)c^2$

44.7 Nclear Reactions

Q Values for Reactions

- The Q value determines the type of reaction.
  - An **exothermic** reaction
    - There is a mass "loss" in the reaction.
    - There is a release of energy.
    - Q is positive.
  - An **endothermic** reaction
    - There is a "gain" of mass in the reaction.
    - Energy is needed, in the form of kinetic energy of the incoming particles.
    - Q is negative.

44.7 Nclear Reactions

Nuclear Reactions, final

•If a and b are identical, so that X and Y are also necessarily identical, the reaction is called a **scattering event.**

- If the kinetic energy before the event is the same as after, it is classified as *elastic scattering*.
- If the kinetic energies before and after are not the same, it is an *inelastic scattering*.

44.7 Nclear Reactions

Conservation Rules for Nuclear Reactions

•The following must be conserved in any nuclear reaction:

- Energy
- Momentum
- Total charge
- Total number of nucleons