REP01 RADIOACTIVITY AND RADIOACTIVE DECAY

SPH4U

CH 13 (KEY IDEAS)

- describe three types of radioactive decay
- use equations to model radioactive decay processes
- describe how particles interact
- explain the work of particle accelerators and particle detectors and analyze bubble chamber photographs
- outline the discoveries that led to our current understanding of the four fundamental forces of nature
- describe the developments that led to the classification of particles into the two families of bosons and fermions, and explain how the families are divided into the hadrons and leptons
- show how the concept of a new, fundamental particle, the quark, helped simplify and systematize particle theory
- follow some current research, including work at the Sudbury Neutrino Observatory, and understand the development of the standard model and grand unified and superstring theories

EQUATIONS

- Quantity Half-Life

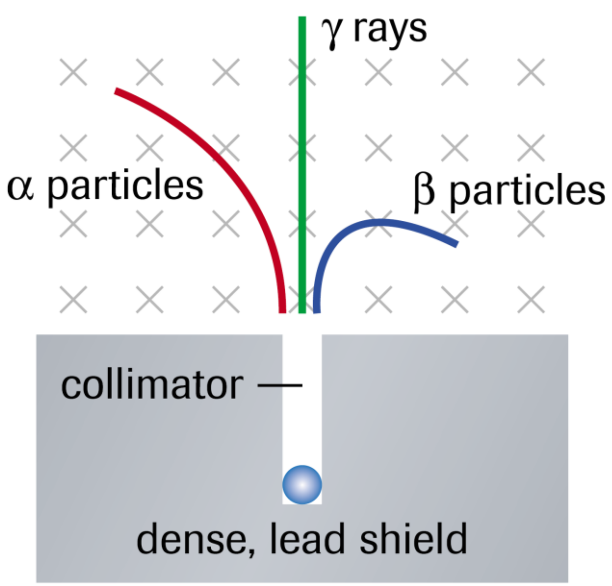
$$N = N_0 \left(\frac{1}{2}\right)^{\frac{t}{t_{1/2}}}$$

- Activity Half-Life

$$A = A_0 \left(\frac{1}{2}\right)^{\frac{t}{t_{1/2}}}$$

RADIOACTIVITY

- **Radioactivity:** the spontaneous emission of electromagnetic (gamma) radiation or particles of nonzero mass by a nucleus
  - Alpha Decay (α particles)
  - Beta Decay (β particles)
  - Gamma Decay (γ rays)
- Observing how the particles behave in a magnetic field allows us to better understand their behaviours



ALPHA DECAY

- **Alpha (α) Particle:** a form of radiation consisting of two protons and two neutrons (^4_2He), emitted during a decay
- A radioactive element loses two protons and two neutrons from one of its atoms to form an α particle, in a process called <u>transmutation</u>, resulting in a <u>daughter nucleus</u>
    - **Transmutation:** the process of changing an atom of one element into another as a result of radioactive decay
    - **Daughter Nucleus:** the nucleus of an atom created as a result of radioactive decay

ALPHA DECAY – CONT.

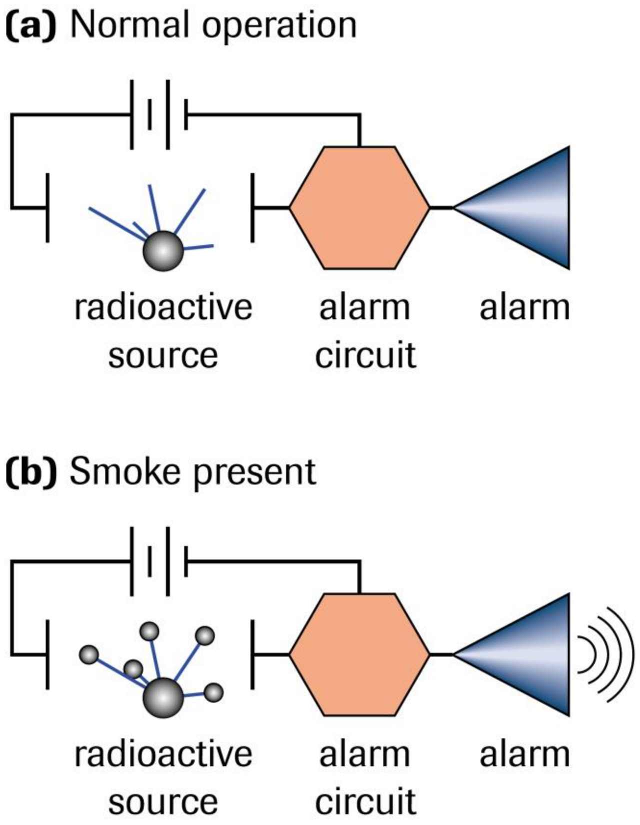
- Example: element X transmutes to element Y releasing an α particle

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

  - X – radioactive element
  - Y – daughter element
  - A – atomic mass, number of particles (nucleons) in nucleus
  - Z – atomic number, number of protons
  - $^{4}_{2}\mathrm{He}$ – α particle

ALPHA DECAY – CONT.

- Smoke detectors use alpha particles
- Tiny amounts of americium dioxide emits α particles, ionizing air molecules and connecting the circuit
- Smoke absorbs the radiation, causing the current to drop and activating the alarm circuit



PROBLEM 1

An unstable polonium atom spontaneously emits an α particle and transmutes into an atom of some other element. Show the process, including the new element, in standard nuclear-reaction notation.

PROBLEM 1 – SOLUTIONS

X = new element

$$^{218}_{84}\text{Po} \rightarrow {}^{4}_{2}\text{He} + {}^{A-4}_{Z-2}\text{X}$$

$$^{218}_{84}\text{Po} \rightarrow {}^{4}_{2}\text{He} + {}^{218-4}_{84-2}\text{X}$$

$$^{218}_{84}\text{Po} \rightarrow {}^{4}_{2}\text{He} + {}^{214}_{82}\text{X}$$

Every element has a unique atomic number. The periodic table shows the new element to be lead (Pb). The finalized equation can now be written:

$$^{218}_{84}\text{Po} \rightarrow {}^{4}_{2}\text{He} + {}^{214}_{82}\text{Pb}$$

In the nuclear reaction, polonium transmutes into lead by α decay.

BINDING ENERGY

- **Strong Nuclear Force:** the force that binds the nucleus of a stable atom
  - Stronger than the repelling electric force between protons
- **Binding Energy:** the energy required to break up the nucleus into protons and neutrons
  - Conversion between atomic mass units [u] and electron volts [eV]

$$1\ \text{u} = 931.5\ \text{MeV}/c^2$$

    - c – speed of light in a vacuum

PROBLEM 2

Molecules of “heavy water,” used both in CANDU nuclear reactors and in the Sudbury Neutrino Observatory, contain an oxygen atom, an ordinary hydrogen atom, and an atom of the rare hydrogen isotope *deuterium*. A *deuteron* is the name given to the nucleus of a deuterium atom. It is composed of a proton and a neutron. Calculate the binding energy per nucleon in a deuteron.

$$m_d = 2.013553 \text{ u}$$

$$m_p = 1.007276 \text{ u}$$

$$m_n = 1.008665 \text{ u}$$

PROBLEM 2 – SOLUTIONS

$$E = ((m_p + m_n) - m_d)c^2$$
$$= ((1.007276\text{ u} + 1.008665\text{ u}) - 2.013553\text{ u})c^2$$
$$E = (0.002388\text{ u})c^2$$

Since $1\text{ u} = 931.5\text{ MeV}/c^2$,

$$E = (0.002338\text{ u})\cancel{c^2}\left(\frac{931.5\text{ MeV}/\cancel{c^2}}{1\text{ u}}\right)$$
$$= 2.18\text{ MeV}$$
$$E = 2.18 \times 10^6\text{ eV}$$

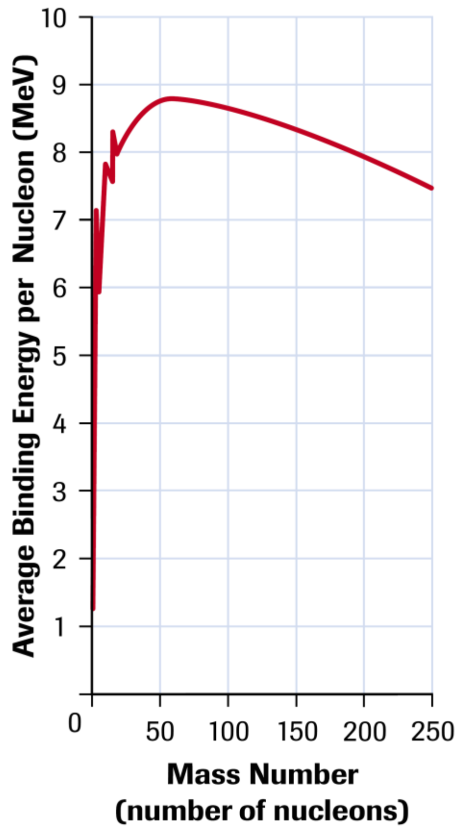
The deuteron has two nucleons (a proton and a neutron; therefore,

$$E_n = \frac{E}{2}$$
$$= \frac{2.18 \times 10^6\text{ eV}}{2}$$
$$E_n = 1.09 \times 10^6\text{ eV}$$

The binding energy per nucleon is 1.09×10^6 eV.

BINDING ENERGY – CONT.

- Binding energy increases until the distance between nucleon pairs becomes too great
- Repulsion force between protons starts to overcome the strong nuclear force in larger elements
- α particles are created when two protons and two neutrons group together, breaking off from the parent nucleus
    - Binding energy converts to kinetic energy

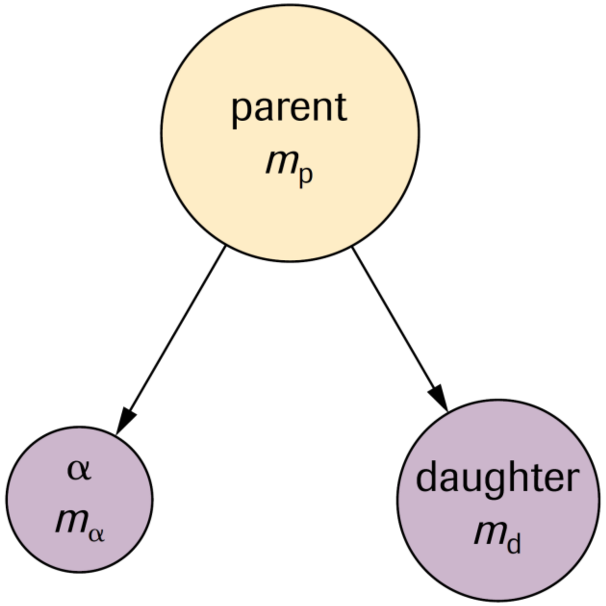


BINDING ENERGY – CONT.

- From Einstein's theory of special relativity, we know mass and energy are linked
- The combined masses of the α particle and daughter nucleus are less than the mass of the parent nucleus

$$m_p > m_\alpha + m_d$$

- Remaining mass is converted to the kinetic energy of the products



PROBLEM 3

Calculate the total kinetic energy, in electron volts, of the products when $^{236}_{92}U$ undergoes α decay to $^{232}_{90}Th$.

$m_U = 236.045562$ u

$m_{Th} = 232.038051$ u

$m_{He} = 4.002602$ u

PROBLEM 3 – SOLUTIONS

$E_K = ?$

mass of parent	${}^{236}_{92}U = 236.045562\ u$
mass of daughters	${}^{232}_{90}Th = 232.038051\ u$
	${}^{4}_{2}H = 4.002602\ u$
total mass of daughters	$232.038051\ u + 4.002602\ u = 236.040653\ u$
mass difference	$236.045562\ u - 236.040653\ u = 0.004909\ u$
energy equivalence	$0.004909\ u \times 931.5\ MeV/u = 4.572\ MeV$

The total kinetic energy of the products is 4.572 MeV.

BETA DECAY

- **Beta ($\boldsymbol{\beta}$) Particle:** negatively charged particles emitted during β^- decay (electrons); positively charged electrons (positrons) emitted in β^+ decay
- **Positron ($^{0}_{+1}\mathrm{e}$):** a particle identical to an electron ($^{0}_{-1}\mathrm{e}$) but with a positive charge; also called an antielectron
- Electrons or positrons released in beta decay are produced in the nucleus; <u>not an orbiting electron</u>
- We get electrons and positrons from the following conversions
  - β^- Decay: $^{1}_{0}\mathrm{n} \rightarrow {}^{1}_{1}\mathrm{p} + {}^{0}_{-1}\mathrm{e}$
  - β^+ Decay: $^{1}_{1}\mathrm{p} \rightarrow {}^{1}_{0}\mathrm{n} + {}^{0}_{+1}\mathrm{e}$

BETA DECAY – CONT.

- Through observation, energy and momentum are not conserved if only a daughter nucleus and β particle are released
- Neutrinos (ν) are released with positrons ($_{+1}^{0}\text{e}$)
- Antineutrinos ($\bar{\nu}$) are released with electrons ($_{-1}^{0}\text{e}$)
- β decay is therefore written as
  - β^- decay: $_{Z}^{A}\text{X} \rightarrow {}_{Z+1}^{A}\text{Y} + {}_{-1}^{0}\text{e} + \bar{\nu}$
  - β^+ decay: $_{Z}^{A}\text{X} \rightarrow {}_{Z-1}^{A}\text{Y} + {}_{+1}^{0}\text{e} + \nu$
- **Weak Nuclear Force:** the weak force in a nucleus thought to be associated with β decay

PROBLEM 4

An atom of sodium-24 can transmute into an atom of some other element by emitting a β^- particle. Represent this reaction in symbols, and identify the daughter element.

PROBLEM 4 – SOLUTIONS

$$^{24}_{11}\text{Na} \rightarrow {}^{A}_{Z+1}\text{Y} + {}^{0}_{-1}\text{e}$$

$$^{24}_{11}\text{Na} \rightarrow {}^{24}_{11+1}\text{Y} + {}^{0}_{-1}\text{e}$$

$$^{24}_{11}\text{Na} \rightarrow {}^{24}_{12}\text{Y} + {}^{0}_{-1}\text{e}$$

The periodic table reveals the new element to be magnesium:

$$^{24}_{11}\text{Na} \rightarrow {}^{24}_{12}\text{Mg} + {}^{0}_{-1}\text{e}$$

When sodium-24 undergoes β^- decay, magnesium-24 is produced.

PROBLEM 5

Calculate the energy released by the reaction in Sample Problem 4.

$$^{24}_{11}\text{Na} \rightarrow ^{24}_{12}\text{Mg} + ^{0}_{-1}\text{e}$$

$$m_{\text{Na}} = 23.990961\ \text{u}$$

$$m_{\text{Mg}} = 23.985042\ \text{u}$$

PROBLEM 5 – SOLUTIONS

$$\Delta m = m_{\text{Na}} - m_{\text{Mg}}$$

$$= (23.990961 \text{ u} - 23.985042 \text{ u})$$

$$\Delta m = 0.005937 \text{ u}$$

Since 1 u $=$ 931.5 MeV,

$$\Delta E = (0.005937 \text{ u})(931.4 \text{ MeV/u})$$

$$\Delta E = 5.5297 \text{ MeV}$$

The energy released is 5.5297 MeV.

GAMMA DECAY

- **Gamma (γ) Ray:** high-frequency emission of (massless, chargeless) photons during γ decay
  - A drop from a higher energy state to a lower energy state
  - No transmutation occurs

$$^{A}_{Z}\mathrm{Y} \rightarrow {}^{A}_{Z}\mathrm{Y} + \gamma$$

  - Often a part of α or β decay
    - α Decay: $^{A}_{Z}\mathrm{X} \rightarrow {}^{A-4}_{Z-2}\mathrm{Y} + {}^{4}_{2}\mathrm{He} + \gamma$
    - β^- Decay: $^{A}_{Z}\mathrm{X} \rightarrow {}_{Z+1}^{\;\;A}\mathrm{Y} + {}_{-1}^{\;\;0}\mathrm{e} + \bar{\nu} + \gamma$
    - β^+ Decay: $^{A}_{Z}\mathrm{X} \rightarrow {}_{Z-1}^{\;\;A}\mathrm{Y} + {}_{+1}^{\;\;0}\mathrm{e} + \nu + \gamma$

GAMMA DECAY – CONT.

- Gamma rays are similar to X-rays, though with higher energy
  - Frequency ranges overlap
  - Distinguished by how they are produced
    - X-rays – high-energy electrons interacting with matter
    - Gamma rays – produced within the nucleus through decay of matter

PROBLEM 6

Give the value of x and y in each reaction. Classify each as α, β, or γ decay.

(a) $^{212}_{82}\text{Pb} \longrightarrow {}^{212}_{x}\text{Bi} + {}^{0}_{-1}\text{e}$

(b) $^{210}_{84}\text{Po} \longrightarrow {}^{y}_{x}\text{Pb} + {}^{4}_{2}\text{He}$

(c) $^{227}_{89}\text{Ac} \longrightarrow {}^{227}_{90}\text{Th} + x$

(d) $^{226}_{88}\text{Ra} \longrightarrow {}^{y}_{x}\text{Ra} + \gamma$

PROBLEM 6 – SOLUTIONS

(a) $x = 83$. Since ${}_{-1}^{0}$e is by definition a β^- particle, the reaction is β^- decay.

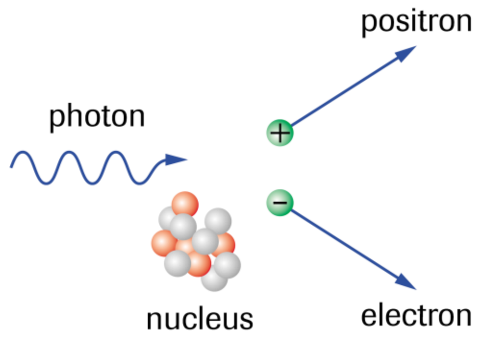
(b) $x = 82$, $y = 206$. The reaction is α decay since 2 protons and 2 neutrons are emitted as one particle.

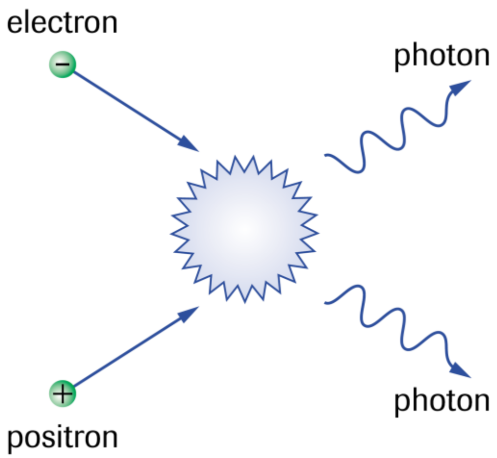
(c) $x = {}_{-1}^{0}$e. The increase by 1 in the atomic number and the lack of change in the mass number together indicate that a proton appeared; therefore this is β^- decay.

(d) $x = 88$, $y = 226$. Since the process is γ decay, neither the atomic number nor the atomic mass number is changed.

PAIR PRODUCTION & PAIR ANNIHILATION

- Carl Anderson observed high-energy radiation from deep space produced <u>pairs of particles</u> spontaneously when passing through a radiation detector
  - Radiation disappeared, replaced by the pair of particles
- Particles had equal masses and speeds, and equal but opposite charges
  - The electron and the positron
- Combining an electron and a positron results in the reverse phenomena
  - A pair of photons is produced





ANTIMATTER

- Combining special relativity with quantum mechanics, Paul Dirac adapted Einstein's equation into

$$E^2 = m^2c^4$$

- This gives us two versions of Einstein's equation:

$$E = mc^2$$

$$E = -mc^2$$

- Dirac's solution to the negative equation allowing electrons to gain negative energy with no limit is the Pauli Exclusion Principle
  - **Pauli Exclusion Principle:** states that no more than one particle can occupy any one quantum state

ANTIMATTER – CONT.

- Dirac suggested that with the creation of any particle, its antiparticle is also created
  - Electron with positron
  - Neutrino with antineutrino
  - Proton with antiproton
  - Neutron with antineutron
  - A photon is its own antiparticle; two are created together

SUMMARY – RADIATION AND RADIOACTIVE DECAY

- Alpha decay occurs when an unstable nucleus emits a particle, often denoted as ${}_{2}^{4}\mathrm{He}$, which consists of two protons and two neutrons. The resulting daughter nucleus is of a different element and has two protons and two neutrons fewer than the parent.
- Beta decay assumes two forms. In β^{-} decay, a neutron is replaced with a proton and a β^{-} particle (a high-speed electron). In β^{+} decay, a proton is replaced with a neutron and a β^{+} particle (a high-speed positron).
- The analysis of β decays reveals that additional particles, either antineutrinos or neutrinos, must be produced to satisfy the conservation of energy and linear and angular momentum.
- Gamma decay is the result of an excited nucleus that has emitted a photon and dropped to a lower state.
- The twin phenomena of pair production and pair annihilation demonstrate mass–energy equivalence.

PRACTICE

Readings

- Section 13.1 (pg 666)

Questions

- pg 676 # 1,2aceg,3ace,4,7