Hewitt/Lyons/Suchocki/Yeh

Conceptual Integrated Science

Chapter 10

NUCLEAR PHYSICS

Radioactivity

Radioactivity:
- is the phenomenon—radioactive decay is the process, whereby unstable atomic nuclei break down and emit radiation.
- has existed since Earth's origin

Radioactivity

Unstable atomic nuclei occur in atoms that have an imbalance of neutrons to protons.

Radioactivity

Most radiation we encounter is:
- natural background radiation that originates in Earth and space (cosmic rays from the Sun and stars).
- more intense at higher altitudes.

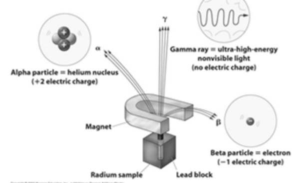
Radioactivity

Cosmic rays are of two types:
- high-energy particles.
- high-frequency electromagnetic radiation (gamma rays).

They affect us indirectly by transforming nitrogen atoms in the air to radioactive carbon-14, which ends up in plants we consume.

Alpha, Beta, and Gamma Rays

Types of radiation:
- alpha (α) carries positive electrical charge
- beta (β) carries negative electrical charge
- gamma (γ) carries no charge



Alpha, Beta, and Gamma Rays

Alpha particle:
- consists of two protons and two neutrons
- loses energy quickly during interaction
- can be stopped easily by a few pieces of paper due to its large mass and double positive charge
- does not normally penetrate lightweight material (paper, clothing)

Alpha, Beta, and Gamma Rays

Alpha particle:
- causes significant damage to the surface of a material (living tissue) due to great kinetic energy
- picks up electrons and becomes harmless helium when traveling through air
- is deflected in the presence of magnetic or electric fields

Alpha, Beta, and Gamma Rays

Beta particle:
- is an ejected electron from a neutron
- has both a smaller mass and electric charge than an alpha particle, and moves faster
- loses energy at a slower rate in air and travels farther before stopping
- can be stopped by several sheets of aluminum foil

Alpha, Beta, and Gamma Rays

Beta particle:
- penetrates fairly deeply into skin (potential for harming or killing living cells)
- once stopped becomes an ordinary electron
- is deflected in the opposite direction to an alpha particle in the presence of magnetic and electric fields

Alpha, Beta, and Gamma Rays

Gamma rays:
- are high-frequency electromagnetic radiation
- are emitted when a nucleus in an excited state moves to a lower energy state
- are more harmful than alpha or beta particles

Alpha, Beta, and Gamma Rays

Gamma rays:
- are most penetrating because they have no mass or charge
- are pure energy, greater per photon than in visible or ultraviolet light and X-rays
- are unaffected by magnetic and electric fields, and therefore interact via direct hit with an atom

Environmental Radiation

Common rock and minerals contain traces of uranium and significant quantities of radioactive isotopes

There is more exposure to radiation when residing in brick, concrete, or stone buildings, than in wooden buildings

Environmental Radiation

Units of radiation:

- measured in rads (radiation absorbed dose), a unit of absorbed energy
- 1 rad = 0.01 joule of radiant energy absorbed/kilogram of tissue
- 1 rem (roentgen equivalent man) is the radiation dosage based on potential damage

The Atomic Nucleus and the Strong Nuclear Force

Atomic nucleus:

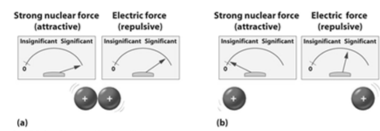
- is composed of nucleons (protons and neutrons)
- energy levels within nucleus are similar to energy levels for orbital electrons only much greater energies are involved

The Atomic Nucleus and the Strong Nuclear Force

The Strong nuclear force is an attraction between nucleons depending on distance

Stronger than the electric force for close nucleons

Weaker than the electric force for distant nucleons



The Atomic Nucleus and the Strong Nuclear Force

The presence of neutrons helps hold the nucleus together.

All nucleons, both protons and neutrons, attract one another by the strong nuclear force.

Only protons repel one another by the electric force.

Half-Life

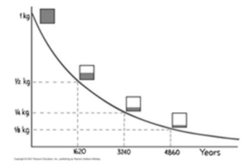
Half-life is the time required for half of an original quantity of an element to decay.

The half-life is constant and independent of any physical or chemical change the atom may undergo.

Half-Life

Radioactive isotopes decay at a rate characteristic of each isotope. Rates are described by half-life.

The shorter the half-life of a substance $\Rightarrow$ the faster it disintegrates and the more active the substance.

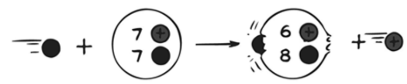


Transmutation of Elements

Transmutation of elements:

the changing of one chemical element to another occurring in

- natural events—natural transmutation
- artificially in labs—artificial transmutation



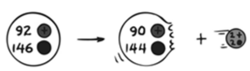
$${}^{14}_{7}\mathrm{N} + {}^{1}_{0}n \rightarrow {}^{14}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{H}$$

Transmutation of Elements

Natural transmutation:

Alpha emission from a nucleus:

- mass number decreases by 4
- atomic number decreases by 2
- resulting atom belongs to an element two places back in periodic table



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

Transmutation of Elements

Beta emission from a nucleus:

- no change in mass number - no loss in nucleons
- atomic number increases by 1
- resulting atom belongs to an element one place forward in periodic table

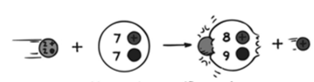
Transmutation of Elements

Gamma emission from a nucleus:

- no change in mass number
- no change in atomic number

Transmutation of Elements

Ernest Rutherford's cloud-chamber experiment in 1919 succeeded in transmuting a chemical element. After bombardment of nitrogen gas with alpha particles from a radioactive piece of ore, he found traces of oxygen and hydrogen.

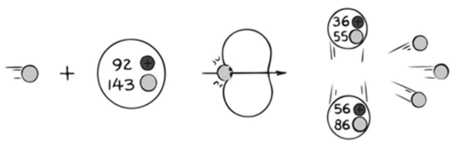


$${}^{14}_{7}\mathrm{N} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{17}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{H}$$

Nuclear Fission

Nuclear Fission:

A neutron hitting a U-235 nucleus may cause it to stretch and fly apart.

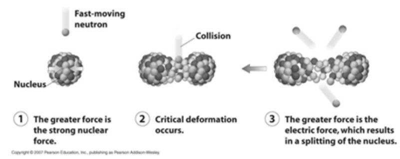


$${}^{1}_{0}n + {}^{235}_{92}\text{U} \rightarrow {}^{91}_{36}\text{Kr} + {}^{142}_{56}\text{Ba} + 3({}^{1}_{0}n)$$

Nuclear Fission

Energy released is in the form of

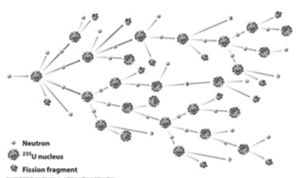
- kinetic energy of fission fragments
- kinetic energy of ejected neutrons, and
- energy of gamma radiation.



Nuclear Fission

Chain reaction:

is a self-sustaining reaction in which the products of one reaction event stimulate further reaction events.



Nuclear Fission

Critical mass:

- the minimum mass of fissionable material in a reactor or nuclear bomb that will sustain a chain reaction
- i.e. a mass large enough to sustain fission

At or above critical mass, in a large quantity of atoms, an enormous explosion can occur.

The Mass–Energy Relationship

Albert Einstein in the early 1900s:

- discovered that mass and energy are directly related.
- formulated the famous equation, $E = mc^2$, which is the key to understanding why and how energy is released in nuclear reactions.

The Mass–Energy Relationship

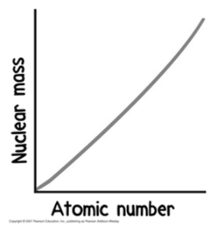
Relationship of equation terms:

- When nucleons lose mass in a nuclear reaction, the loss of mass, Δm, multiplied by the square of the speed of light is equal to the energy release : $E = \Delta mc^2$.
- Mass difference is related to the binding energy of the nucleus - how much is required to dissemble the nucleus.

The Mass–Energy Relationship

A graph of nuclear masses versus atomic number of elements from hydrogen to uranium shows:

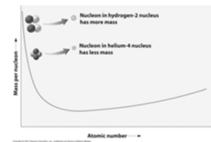
- an upward slope with increasing atomic number - elements are more massive as atomic numbers increase.
- a slightly curved slope because of disproportionally more neutrons in the more massive atoms.



The Mass–Energy Relationship

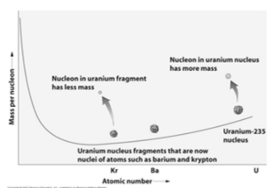
Dividing the mass of a nucleus by the number of nucleons in the nucleus gives the mass per nucleon.

Graph of nuclear mass per nucleon inside each nucleus versus atomic number from hydrogen to uranium:



The Mass–Energy Relationship

- The nucleons in a uranium nucleus have more mass than the nucleons in uranium fragments.



Nuclear Fusion

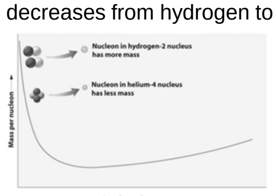
Nuclear fusion is the combination of nuclei of light atoms to form heavier nuclei with the release of much energy.

Any nuclear transformation that moves nuclei toward iron releases energy.

Iron is the “nuclear sink” for energy production.

Nuclear Fusion

A graph of mass per nucleon versus atomic number from hydrogen to iron shows how the average mass per nucleon decreases from hydrogen to iron.



Nuclear Fusion

- Nuclear fusion is produced by high temperature resulting in more tightly bound nuclei.
- Mass decreases as energy is released.
- This is the process by which stars generate energy.
- Fusion on Earth?