Section Summary

31.1 Nuclear Radioactivity

- Some nuclei are radioactive—they spontaneously decay destroying some part of their mass and emitting energetic rays, a process called nuclear radioactivity.
- Nuclear radiation, like x rays, is ionizing radiation, because energy sufficient to ionize matter is emitted in each decay.
- The range (or distance traveled in a material) of ionizing radiation is directly related to the charge of the emitted particle and its energy, with greater-charge and lower-energy particles having the shortest ranges.
- Radiation detectors are based directly or indirectly upon the ionization created by radiation, as are the effects of radiation on living and inert materials.

31.2 Radiation Detection and Detectors

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31.3 Substructure of the Nucleus

- Two particles, both called nucleons, are found inside nuclei. The two types of nucleons are protons and neutrons; they are very similar, except that the proton is positively charged while the neutron is neutral. Some of their characteristics are given in Table 31.2 and compared with those of the electron. A mass unit convenient to atomic and nuclear processes is the unified atomic mass unit (u), defined to be
- $1\ u = 1.6605 \times 10^{-27}$ kg $= 931.46$ MeV$/c^2$.
- A nuclide is a specific combination of protons and neutrons, denoted by
- ${}^{A}_{Z}\mathrm{X}_N$ or simply${}^{A}\mathrm{X}$,

  Z is the number of protons or atomic number, X is the symbol for the element, N is the number of neutrons, and A is the mass number or the total number of protons and neutrons,

  $A = N + Z$.
- Nuclides having the same Z but different N are isotopes of the same element.
- The radius of a nucleus, r, is approximately
- $r = r_0 A^{1/3}$,

  where $r_0 = 1.2\ fm$. Nuclear volumes are proportional to A. There are two nuclear forces, the weak and the strong. Systematics in nuclear stability seen on the chart of the nuclides indicate that there are shell closures in nuclei for values of Z and N equal to the magic numbers, which correspond to highly stable nuclei.

31.4 Nuclear Decay and Conservation Laws

- When a parent nucleus decays, it produces a daughter nucleus following rules and conservation laws. There are three major types of nuclear decay, called alpha (α), beta (β), and gamma (γ). The α decay equation is
- ${}_Z^A X_N \rightarrow {}_{Z-2}^{A-4}\,\mathrm{Y}_{N-2} + {}_2^4\,\mathrm{He}_2$.
- Nuclear decay releases an amount of energy E related to the mass destroyed Δm by
- $E = (\Delta m)c^2$.
- There are three forms of beta decay. The β^-decay equation is
- ${}_Z^A X_N \rightarrow {}_{Z+1}^{A}\,\mathrm{Y}_{N-1} + \beta^- + \bar{\nu}_e$.
- The β^+ decay equation is
- ${}_Z^A X_N \rightarrow {}_{Z-1}^{A}\,\mathrm{Y}_{N+1} + \beta^+ + \nu_e$.
- The electron capture equation is
- ${}_Z^A X_N + e^- \rightarrow {}_{Z-1}^{A}\,\mathrm{Y}_{N+1} + \nu_e$.
- β^- is an electron, β^+ is an antielectron or positron, ν_e represents an electron's neutrino, and $\bar{\nu}_e$ is an electron's antineutrino. In addition to all previously known conservation laws, two new ones arise— conservation of electron family number and conservation of the total number of nucleons. The γ decay equation is
- Z A X N * → Z A X N + 1 + 2 +

  γ is a high-energy photon originating in a nucleus.

31.5 Half-Life and Activity

- Half-life $t_{1/2}$ is the time in which there is a 50% chance that a nucleus will decay. The number of nuclei N as a function of time is
- $N = N_0 e^{-\lambda t}$,

  where N_0 is the number present at $t = 0$, and λ is the decay constant, related to the half-life by

  $\lambda = \frac{0.693}{t_{1/2}}$.

- One of the applications of radioactive decay is radioactive dating, in which the age of a material is determined by the amount of radioactive decay that occurs. The rate of decay is called the activity R:
- $R = \frac{\Delta N}{\Delta t}$.
- The SI unit for R is the becquerel (Bq), defined by
- 1 Bq = 1 decay/s.
- R is also expressed in terms of curies (Ci), where
- $1 \text{ Ci} = 3.70 \times 10^{10}$ Bq.
- The activity R of a source is related to N and $t_{1/2}$ by
- $R = \frac{0.693N}{t_{1/2}}$.
- Since N has an exponential behavior as in the equation $N = N_0 e^{-\lambda t}$, the activity also has an exponential behavior, given by
- $R = R_0 e^{-\lambda t}$,

  where R_0 is the activity at $t = 0$.

31.6 Binding Energy

- The binding energy (BE) of a nucleus is the energy needed to separate it into individual protons and neutrons. In terms of atomic masses,
- $\text{BE} = \{[\text{Zm}(^1\text{H}) + \text{Nm}_n] - m(^A\text{X})\}c^2$,

  where $m\left(^1\text{H}\right)$ is the mass of a hydrogen atom, $m\left(^A\text{X}\right)$ is the atomic mass of the nuclide, and m_n is the mass of a neutron. Patterns in the binding energy per nucleon, BE/A, reveal details of the nuclear force. The larger the BE/A, the more stable the nucleus.

31.7 Tunneling

- Tunneling is a quantum mechanical process of potential energy barrier penetration. The concept was first applied to explain α decay, but tunneling is found to occur in other quantum mechanical systems.