Summary

Nuclear physics is the study of atomic nuclei. Nuclei contain **protons** and **neutrons**, which are collectively known as **nucleons**. The total number of nucleons, A, is the nucleus's **atomic mass number**. The number of protons, Z, is the **atomic number**. The number of neutrons equals $A - Z$. **Isotopes** are nuclei with the same Z, but with different numbers of neutrons. For an element X, an isotope of given Z and A is represented by

$$^{A}_{Z}\mathrm{X}.$$

The nuclear radius is approximately proportional to $A^{\frac{1}{3}}$, indicating that all nuclei have about the same density. Nuclear masses are specified in **unified atomic mass units** (u), where the mass of $^{12}_{6}\mathrm{C}$ (including its 6 electrons) is defined as exactly 12.000000 u. In terms of the energy equivalent (because $E = mc^2$),

$$1\,\mathrm{u} = 931.5\,\mathrm{MeV}/c^2 = 1.66 \times 10^{-27}\,\mathrm{kg}.$$

The mass of a stable nucleus is less than the sum of the masses of its constituent nucleons. The difference in mass (times c^2) is the **total binding energy**. It represents the energy needed to break the nucleus into its constituent nucleons. The **binding energy per nucleon** averages about 8 MeV per nucleon, and is lowest for low mass and high mass nuclei.

Unstable nuclei undergo **radioactive decay**; they change into other nuclei with the emission of an α, β, or γ particle. An α particle is a $^{4}_{2}\mathrm{He}$ nucleus; a β particle is an electron or positron; and a γ ray is a high-energy photon. In β decay, a **neutrino** is also emitted. The transformation of **parent** nuclei into **daughter** nuclei is called **transmutation** of the elements. Radioactive decay occurs spontaneously only when the mass of the products is less than the mass of the parent nucleus. The loss in mass appears as kinetic energy of the products.

Nuclei are held together by the **strong nuclear force**. The **weak nuclear force** makes itself apparent in β decay. These two forces, plus the gravitational and electromagnetic forces, are the four known types of force.

Electric charge, linear and angular momentum, mass–energy, and **nucleon number** are **conserved** in all decays.

Radioactive decay is a statistical process. For a given type of radioactive nucleus, the number of nuclei that decay (ΔN) in a time Δt is proportional to the number N of parent nuclei present:

$$\Delta N = -\lambda N\,\Delta t; \tag{30–3a}$$

the minus sign means N *decreases* in time.

The proportionality constant λ is called the **decay constant** and is characteristic of the given nucleus. The number N of nuclei remaining after a time t decreases exponentially,

$$N = N_0 e^{-\lambda t}, \tag{30–4}$$

as does the **activity**, R = magnitude of $\Delta N/\Delta t$:

$$R = \left|\frac{\Delta N}{\Delta t}\right|_0 e^{-\lambda t}. \tag{30–5}$$

The **half-life**, $T_{\frac{1}{2}}$, is the time required for half the nuclei of a radioactive sample to decay. It is related to the decay constant by

$$T_{\frac{1}{2}} = \frac{0.693}{\lambda}. \tag{30–6}$$

Radioactive dating is the use of radioactive decay to determine the age of certain objects, such as carbon dating.

[*Alpha decay occurs via a purely quantum-mechanical process called **tunneling** through a barrier.]

Particle **detectors** include **Geiger counters**, **scintillators** with attached **photomultiplier tubes**, and **semiconductor detectors**. Detectors that can image particle tracks include **semiconductors**, photographic **emulsions, bubble chambers**, and **multiwire chambers**.

Questions

1. What do different isotopes of a given element have in common? How are they different?
2. What are the elements represented by the X in the following: (*a*) $^{232}_{92}\mathrm{X}$; (*b*) $^{18}_{7}\mathrm{X}$; (*c*) $^{1}_{1}\mathrm{X}$; (*d*) $^{86}_{38}\mathrm{X}$; (*e*) $^{252}_{100}\mathrm{X}$?
3. How many protons and how many neutrons do each of the isotopes in Question 2 have?
4. Identify the element that has 87 nucleons and 50 neutrons.
5. Why are the atomic masses of many elements (see the Periodic Table) not close to whole numbers?
6. Why are atoms much more likely to emit an alpha particle than to emit separate neutrons and protons?
7. What are the similarities and the differences between the strong nuclear force and the electric force?
8. What is the experimental evidence in favor of radioactivity being a nuclear process?
9. The isotope $^{64}_{29}\mathrm{Cu}$ is unusual in that it can decay by γ, β^-, and β^+ emission. What is the resulting nuclide for each case?
10. A $^{238}_{92}\mathrm{U}$ nucleus decays via α decay to a nucleus containing how many neutrons?
11. Describe, in as many ways as you can, the difference between α, β, and γ rays.
12. Fill in the missing particle or nucleus:
    (*a*) $^{45}_{20}\mathrm{Ca} \rightarrow\ ?\ + e^- + \bar{\nu}$
    (*b*) $^{58}_{29}\mathrm{Cu}^* \rightarrow\ ?\ + \gamma$
    (*c*) $^{46}_{24}\mathrm{Cr} \rightarrow {}^{46}_{23}\mathrm{V} +\ ?$
    (*d*) $^{234}_{94}\mathrm{Pu} \rightarrow\ ?\ + \alpha$
    (*e*) $^{239}_{93}\mathrm{Np} \rightarrow {}^{239}_{94}\mathrm{Pu} +\ ?$
13. Immediately after a $^{238}_{92}\mathrm{U}$ nucleus decays to $^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$, the daughter thorium nucleus may still have 92 electrons circling it. Since thorium normally holds only 90 electrons, what do you suppose happens to the two extra ones?
14. When a nucleus undergoes either β^- or β^+ decay, what happens to the energy levels of the atomic electrons? What is likely to happen to these electrons following the decay?
15. The alpha particles from a given alpha-emitting nuclide are generally monoenergetic; that is, they all have the same kinetic energy. But the beta particles from a beta-emitting nuclide have a spectrum of energies. Explain the difference between these two cases.