Summary

A **nuclear reaction** occurs when two nuclei collide and two or more other nuclei (or particles) are produced. In this process, as in radioactivity, **transmutation** (change) of elements occurs.

The **reaction energy** or **Q-value** of a reaction $\mathrm{a} + \mathrm{X} \rightarrow \mathrm{Y} + \mathrm{b}$ is

$$Q = \left(M_{\mathrm{a}} + M_{\mathrm{X}} - M_{\mathrm{b}} - M_{\mathrm{Y}}\right)c^2 \qquad \textbf{(31–2a)}$$

$$= \mathrm{KE_b} + \mathrm{KE_Y} - \mathrm{KE_a} - \mathrm{KE_X}. \qquad \textbf{(31–2b)}$$

In **fission**, a heavy nucleus such as uranium splits into two intermediate-sized nuclei after being struck by a neutron. ${}^{235}_{92}\mathrm{U}$ is fissionable by slow neutrons, whereas some fissionable nuclei require fast neutrons. Much energy is released in fission ($\approx 200\,\mathrm{MeV}$ per fission) because the binding energy per nucleon is lower for heavy nuclei than it is for intermediate-sized nuclei, so the mass of a heavy nucleus is greater than the total mass of its fission products. The fission process releases neutrons, so that a **chain reaction** is possible. The **critical mass** is the minimum mass of fuel needed so that enough emitted neutrons go on to produce more fissions and sustain a chain reaction. In a **nuclear reactor** or nuclear weapon, a **moderator** is used to slow down the released neutrons.

The **fusion** process, in which small nuclei combine to form larger ones, also releases energy. The energy from our Sun originates in the fusion reactions known as the **proton–proton chain** in which four protons fuse to form a ${}^{4}_{2}\mathrm{He}$ nucleus producing 25 MeV of energy. A useful fusion reactor for power generation has not yet proved possible because of the difficulty in containing the fuel (e.g., deuterium) long enough at the extremely high temperature required ($\approx 10^8\mathrm{K}$). Nonetheless, progress has been made in confining the collection of charged ions known as a **plasma**. The two main methods are **magnetic confinement**, using a magnetic field in a device such as the donut-shaped **tokamak**, and **inertial confinement** in which intense laser beams compress a fuel pellet of deuterium and tritium.

Radiation can cause damage to materials, including biological tissue. Quantifying amounts of radiation is the subject of **dosimetry**. The **curie** (Ci) and the **becquerel** (Bq) are units that measure the **source activity** or rate of decay of a sample: $1\,\mathrm{Ci} = 3.70 \times 10^{10}$ decays per second, whereas $1\,\mathrm{Bq} = 1\,\mathrm{decay/s}$. The **absorbed dose**, often specified in **rads**, measures the amount of energy deposited per unit mass of absorbing material: 1 rad is the amount of radiation that deposits energy at the rate of $10^{-2}\,\mathrm{J/kg}$ of material. The SI unit of absorbed dose is the **gray**: $1\,\mathrm{Gy} = 1\,\mathrm{J/kg} = 100\,\mathrm{rad}$. The **effective dose** is often specified by the **rem** = rad × RBE, where RBE is the "relative biological effectiveness" of a given type of radiation; 1 rem of any type of radiation does approximately the same amount of biological damage. The average dose received per person per year in the United States is about 360 mrem. The SI unit for effective dose is the **sievert**: $1\,\mathrm{Sv} = 100\,\mathrm{rem}$.

[*Nuclear radiation is used in medicine for cancer therapy, and for imaging of biological structure and processes. Tomographic imaging of the human body, which can provide 3-dimensional detail, includes several types: PET, SPET (= SPECT), MRI, and CT scans (discussed in Chapter 25). MRI makes use of **nuclear magnetic resonance** (NMR).]

Questions

1. Fill in the missing particles or nuclei:
(*a*) $\mathrm{n} + {}^{232}_{90}\mathrm{Th} \rightarrow\ ?\ + \gamma$;
(*b*) $\mathrm{n} + {}^{137}_{56}\mathrm{Ba} \rightarrow {}^{137}_{55}\mathrm{Cs}\ +\ ?$;
(*c*) $\mathrm{d} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He}\ +\ ?$;
(*d*) $\alpha + {}^{197}_{79}\mathrm{Au} \rightarrow\ ?\ + \mathrm{d}$
where d stands for deuterium.

2. When ${}^{22}_{11}\mathrm{Na}$ is bombarded by deuterons $\left({}^{2}_{1}\mathrm{H}\right)$, an α particle is emitted. What is the resulting nuclide? Write down the reaction equation.

3. Why are neutrons such good projectiles for producing nuclear reactions?

4. What is the Q-value for radioactive decay reactions?
(*a*) $Q < 0$. (*b*) $Q > 0$. (*c*) $Q = 0$.
(*d*) The sign of Q depends on the nucleus.

5. The energy from nuclear fission appears in the form of thermal energy—but the thermal energy of what?

6. (*a*) If ${}^{235}_{92}\mathrm{U}$ released only 1.5 neutrons per fission on average (instead of 2.5), would a chain reaction be possible? (*b*) If so, how would the chain reaction be different than if 3 neutrons were released per fission?

7. Why can't uranium be enriched by chemical means?

8. How can a neutron, with practically no kinetic energy, excite a nucleus to the extent shown in Fig. 31–3?

9. Why would a porous block of uranium be more likely to explode if kept under water rather than in air?

10. A reactor that uses highly enriched uranium can use ordinary water (instead of heavy water) as a moderator and still have a self-sustaining chain reaction. Explain.

11. Why must the fission process release neutrons if it is to be useful?

12. Why are neutrons released in a fission reaction?

13. What is the reason for the "secondary system" in a nuclear reactor, Fig. 31–8? That is, why is the water heated by the fuel in a nuclear reactor not used directly to drive the turbines?

14. What is the basic difference between fission and fusion?

15. Discuss the relative merits and disadvantages, including pollution and safety, of power generation by fossil fuels, nuclear fission, and nuclear fusion.

16. Why do gamma particles penetrate matter more easily than beta particles do?

17. Light energy emitted by the Sun and stars comes from the fusion process. What conditions in the interior of stars make this possible?

18. How do stars, and our Sun, maintain confinement of the plasma for fusion?

19. People who work around metals that emit alpha particles are trained that there is little danger from proximity or touching the material, but they must take extreme precautions against ingesting it. Why? (Eating and drinking while working are forbidden.)

20. What is the difference between absorbed dose and effective dose? What are the SI units for each?

21. Radiation is sometimes used to sterilize medical supplies and even food. Explain how it works.

***22.** How might radioactive tracers be used to find a leak in a pipe?