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 $a + X \rightarrow Y + b$ is

$$Q = (M_a + M_X - M_b - M_Y)c^2 \quad \textbf{(31–1)}$$

$$= K_b + K_Y - K_a - K_X. \quad \textbf{(31–2)}$$

In **fission** a heavy nucleus such as uranium splits into two intermediate-sized nuclei after being struck by a neutron. $^{235}_{92}U$ is fissionable by slow neutrons, whereas some fissionable nuclei require fast neutrons. Much energy is released in 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 to sustain a chain reaction. In a **nuclear reactor** or nuclear bomb, a **moderator** is needed 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 is believed to originate in the fusion reactions known as the **proton–proton cycle** in which four protons fuse to form a ^4_2He nucleus producing over 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 high temperature required.

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: $1\ \text{Ci} = 3.70 \times 10^{10}$ disintegrations per second, whereas $1\ \text{Bq} = 1$ disintegration/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} J/kg of material. The SI unit of absorbed dose is the **gray**: $1\ \text{Gy} = 1\ \text{J/kg} = 100\ \text{rad}$. The **effective dose** is often specified by the **rem** = rad × QF, where QF is the "quality factor" 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 0.36 rem. The SI unit for effective dose is the **sievert**: $1\ \text{Sv} = 10^2$ rem.

[*Nuclear radiation is used in medicine as therapy and for imaging of biological processes, as well as several types of tomographic **imaging** of the human body: PET, SPET, and MRI; the latter makes use of **nuclear magnetic resonance** (NMR).]

Questions

(NOTE: Masses are found in Appendix B.)

1. Fill in the missing particles or nuclei:
(*a*) $n + ^{137}_{56}Ba \rightarrow ? + \gamma$; (*b*) $n + ^{137}_{56}Ba \rightarrow ^{137}_{55}Cs + ?$;
(*c*) $d + ^2_1H \rightarrow ^4_2He + ?$; (*d*) $\alpha + ^{197}_{79}Au \rightarrow ? + d$
where d stands for deuterium.

2. The isotope: $^{32}_{15}P$ is produced by the reaction: $n + ? \rightarrow ^{32}_{15}P + p$. What must be the target nucleus?

3. When $^{22}_{11}Na$ is bombarded by deuterons (^2_1H), an α particle is emitted. What is the resulting nuclide?

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

5. A proton strikes a $^{20}_{10}Ne$ nucleus, and an α particle is observed to emerge. What is the residual nucleus? Write down the reaction equation.

6. Are fission fragments β^+ or β^- emitters? Explain.

7. If $^{235}_{92}U$ released only 1.5 neutrons per fission on the average, would a chain reaction be possible? If so, what would be different?

8. $^{238}_{92}U$ releases an average of 2.5 neutrons per fission compared to 2.9 for $^{239}_{94}Pu$. Pure samples of which of these two nuclei do you think would have the smaller critical mass? Explain.

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

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

11. How can a neutron, with practically no kinetic energy, excite a nucleus to the extent shown in Fig. 31–2?

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

13. 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.

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

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

16. What is the reason for the "secondary system" in a nuclear reactor, Fig. 31–7? That is, why is the water heated by the fuel in a nuclear reactor not used directly to drive the turbines?

17. Why are neutrons released in a fission reaction?

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

19. A higher temperature is required for deuterium–deuterium ignition than for deuterium–tritium. Explain.

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

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

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

23. People who work around metals that emit alpha particles are trained that there is little danger from proximity or even touching the material, but that they must take extreme precautions against ingesting it. Hence, there are strong rules against eating and drinking while working, and against machining the metal. Why?