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

$$Q = \left(M_a + M_X - M_b - M_Y\right)c^2 \qquad \textbf{(31–2a)}$$

$$= \mathrm{KE}_b + \mathrm{KE}_Y - \mathrm{KE}_a - \mathrm{KE}_X. \qquad \textbf{(31–2b)}$$

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?

MisConceptual Questions

1. In a nuclear reaction, which of the following is *not* conserved?
   (*a*) Energy.
   (*b*) Momentum.
   (*c*) Electric charge.
   (*d*) Nucleon number.
   (*e*) None of the above.

2. Fission fragments are typically
   (*a*) β^+ emitters.
   (*b*) β^- emitters.
   (*c*) Both.
   (*d*) Neither.

3. Which of the following properties would decrease the critical mass needed to sustain a nuclear chain reaction?
   (*a*) Low boiling point.
   (*b*) High melting point.
   (*c*) More neutrons released per fission.
   (*d*) Low nuclear density.
   (*e*) Filled valence shell.
   (*f*) All of the above.

4. Rather than having a maximum at about $A \approx 60$, as shown in Fig. 31–12, suppose the average binding energy per nucleon continually increased with increasing mass number. Then,
   (*a*) fission would still be possible, but not fusion.
   (*b*) fusion would still be possible, but not fission.
   (*c*) both fission and fusion would still be possible.
   (*d*) neither fission nor fusion would be possible.

5. Why is a moderator needed in a normal uranium fission reactor?
   (*a*) To increase the rate of neutron capture by uranium-235.
   (*b*) To increase the rate of neutron capture by uranium-238.
   (*c*) To increase the rate of production of plutonium-239.
   (*d*) To increase the critical mass of the fission fuel.
   (*e*) To provide more neutrons for the reaction.
   (*f*) All of the above.

6. What is the difference between nuclear fission and nuclear fusion?
   (*a*) Nuclear fission is used for bombs; nuclear fusion is used in power plants.
   (*b*) There is no difference. Fission and fusion are different names for the same physical phenomenon.
   (*c*) Nuclear fission refers to using deuterium to create a nuclear reaction.
   (*d*) Nuclear fusion occurs spontaneously, as happens to the C^{14} used in carbon dating.
   (*e*) In nuclear fission, a nucleus splits; in nuclear fusion, nucleons or nuclei and nucleons join to form a new nucleus.

7. A primary difficulty in energy production by fusion is
   (*a*) the scarcity of necessary fuel.
   (*b*) the disposal of radioactive by-products produced.
   (*c*) the high temperatures necessary to overcome the electrical repulsion of protons.
   (*d*) the fact that it is possible in volcanic regions only.

8. If two hydrogen nuclei, ${}^{2}_{1}\mathrm{H}$, each of mass m_{H}, fuse together and form a helium nucleus of mass m_{He},
   (*a*) $m_{\mathrm{He}} < 2m_{\mathrm{H}}$.
   (*b*) $m_{\mathrm{He}} = 2m_{\mathrm{H}}$.
   (*c*) $m_{\mathrm{He}} > 2m_{\mathrm{H}}$.
   (*d*) All of the above are possible.

9. Which radiation induces the most biological damage for a given amount of energy deposited in tissue?
   (*a*) Alpha particles.
   (*b*) Gamma radiation.
   (*c*) Beta radiation.
   (*d*) All do the same damage for the same deposited energy.

10. Which would produce the most energy in a single reaction?
    (*a*) The fission reaction associated with uranium-235.
    (*b*) The fusion reaction of the Sun (two hydrogen nuclei fused to one helium nucleus).
    (*c*) Both (*a*) and (*b*) are about the same.
    (*d*) Need more information.

11. The fuel necessary for fusion-produced energy could be derived from
    (*a*) water.
    (*b*) superconductors.
    (*c*) uranium.
    (*d*) helium.
    (*e*) sunlight.

12. Which of the following is true?
    (*a*) Any amount of radiation is harmful to living tissue.
    (*b*) Radiation is a natural part of the environment.
    (*c*) All forms of radiation will penetrate deep into living tissue.
    (*d*) None of the above is true.

13. Which of the following would reduce the cell damage due to radiation for a lab technician who works with radioactive isotopes in a hospital or lab?
    (*a*) Increase the worker's distance from the radiation source.
    (*b*) Decrease the time the worker is exposed to the radiation.
    (*c*) Use shielding to reduce the amount of radiation that strikes the worker.
    (*d*) Have the worker wear a radiation badge when working with the radioactive isotopes.
    (*e*) All of the above.

14. If the same dose of each type of radiation was provided over the same amount of time, which type would be most harmful?
    (*a*) X-rays.
    (*b*) γ rays.
    (*c*) β rays.
    (*d*) α particles.

15. ${}^{235}_{92}\mathrm{U}$ releases an average of 2.5 neutrons per fission compared to 2.9 for ${}^{239}_{94}\mathrm{Pu}$. Which has the smaller critical mass?
    (*a*) ${}^{235}_{92}\mathrm{U}$.
    (*b*) ${}^{239}_{94}\mathrm{Pu}$.
    (*c*) Both the same.

For assigned homework and other learning materials, go to the MasteringPhysics website.

Problems

(NOTE: Masses are found in Appendix B.)

31–1 Nuclear Reactions, Transmutation

1. (I) Natural aluminum is all $^{27}_{13}\text{Al}$. If it absorbs a neutron, what does it become? Does it decay by β^+ or β^-? What will be the product nucleus?

2. (I) Determine whether the reaction $^{2}_{1}\text{H} + ^{2}_{1}\text{H} \rightarrow ^{3}_{2}\text{He} + \text{n}$ requires a threshold energy, and why.

3. (I) Is the reaction $\text{n} + ^{238}_{92}\text{U} \rightarrow ^{239}_{92}\text{U} + \gamma$ possible with slow neutrons? Explain.

4. (II) (*a*) Complete the following nuclear reaction, $\text{p} + ? \rightarrow ^{32}_{16}\text{S} + \gamma$. (*b*) What is the Q-value?

5. (II) The reaction $\text{p} + ^{18}_{8}\text{O} \rightarrow ^{18}_{9}\text{F} + \text{n}$ requires an input of energy equal to 2.438 MeV. What is the mass of $^{18}_{9}\text{F}$?

6. (II) (*a*) Can the reaction $\text{n} + ^{24}_{12}\text{Mg} \rightarrow ^{23}_{11}\text{Na} + \text{d}$ occur if the bombarding particles have 18.00 MeV of kinetic energy? (d stands for deuterium, $^{2}_{1}\text{H}$.) (*b*) If so, how much energy is released? If not, what kinetic energy is needed?

7. (II) (*a*) Can the reaction $\text{p} + ^{7}_{3}\text{Li} \rightarrow ^{4}_{2}\text{He} + \alpha$ occur if the incident proton has kinetic energy = 3100 keV? (*b*) If so, what is the total kinetic energy of the products? If not, what kinetic energy is needed?

8. (II) In the reaction $\alpha + ^{14}_{7}\text{N} \rightarrow ^{17}_{8}\text{O} + \text{p}$, the incident α particles have 9.85 MeV of kinetic energy. The mass of $^{17}_{8}\text{O}$ is 16.999132 u. (*a*) Can this reaction occur? (*b*) If so, what is the total kinetic energy of the products? If not, what kinetic energy is needed?

9. (II) Calculate the Q-value for the "capture" reaction $\alpha + ^{16}_{8}\text{O} \rightarrow ^{20}_{10}\text{Ne} + \gamma$.

10. (II) Calculate the total kinetic energy of the products of the reaction $\text{d} + ^{13}_{6}\text{C} \rightarrow ^{14}_{7}\text{N} + \text{n}$ if the incoming deuteron has kinetic energy $\text{KE} = 41.4\text{ MeV}$.

11. (II) Radioactive $^{14}_{6}\text{C}$ is produced in the atmosphere when a neutron is absorbed by $^{14}_{7}\text{N}$. Write the reaction and find its Q-value.

12. (II) An example of a **stripping** nuclear reaction is $\text{d} + ^{6}_{3}\text{Li} \rightarrow \text{X} + \text{p}$. (*a*) What is X, the resulting nucleus? (*b*) Why is it called a "stripping" reaction? (*c*) What is the Q-value of this reaction? Is the reaction endothermic or exothermic?

13. (II) An example of a **pick-up** nuclear reaction is $^{3}_{2}\text{He} + ^{12}_{6}\text{C} \rightarrow \text{X} + \alpha$. (*a*) Why is it called a "pick-up" reaction? (*b*) What is the resulting nucleus? (*c*) What is the Q-value of this reaction? Is the reaction endothermic or exothermic?

14. (II) Does the reaction $\text{p} + ^{7}_{3}\text{Li} \rightarrow ^{4}_{2}\text{He} + \alpha$ require energy, or does it release energy? How much energy?

15. (II) Calculate the energy released (or energy input required) for the reaction $\alpha + ^{9}_{4}\text{Be} \rightarrow ^{12}_{6}\text{C} + \text{n}$.

31–2 Nuclear Fission

16. (I) What is the energy released in the fission reaction of Eq. 31–4? (The masses of $^{141}_{56}\text{Ba}$ and $^{92}_{36}\text{Kr}$ are 140.914411 u and 91.926156 u, respectively.)

17. (I) Calculate the energy released in the fission reaction $\text{n} + ^{235}_{92}\text{U} \rightarrow ^{88}_{38}\text{Sr} + ^{136}_{54}\text{Xe} + 12\text{n}$. Use Appendix B, and assume the initial kinetic energy of the neutron is very small.

18. (I) How many fissions take place per second in a 240-MW reactor? Assume 200 MeV is released per fission.

19. (I) The energy produced by a fission reactor is about 200 MeV per fission. What fraction of the mass of a $^{235}_{92}\text{U}$ nucleus is this?

20. (II) Suppose that the average electric power consumption, day and night, in a typical house is 960 W. What initial mass of $^{235}_{92}\text{U}$ would have to undergo fission to supply the electrical needs of such a house for a year? (Assume 200 MeV is released per fission, as well as 100% efficiency.)

21. (II) Consider the fission reaction

$$^{235}_{92}\text{U} + \text{n} \rightarrow ^{133}_{51}\text{Sb} + ^{98}_{41}\text{Nb} + ?\text{n}.$$

(*a*) How many neutrons are produced in this reaction? (*b*) Calculate the energy release. The atomic masses for Sb and Nb isotopes are 132.915250 u and 97.910328 u, respectively.

22. (II) How much mass of $^{235}_{92}\text{U}$ is required to produce the same amount of energy as burning 1.0 kg of coal (about 3×10^7 J)?

23. (II) What initial mass of $^{235}_{92}\text{U}$ is required to operate a 950-MW reactor for 1 yr? Assume 34% efficiency.

24. (II) If a 1.0-MeV neutron emitted in a fission reaction loses one-half of its kinetic energy in each collision with moderator nuclei, how many collisions must it make to reach thermal energy $\left(\frac{3}{2}kT = 0.040\text{ eV}\right)$?

25. (II) Assuming a fission of $^{236}_{92}\text{U}$ into two roughly equal fragments, estimate the electric potential energy just as the fragments separate from each other. Assume that the fragments are spherical (see Eq. 30–1) and compare your calculation to the nuclear fission energy released, about 200 MeV.

26. (III) Suppose that the neutron multiplication factor is 1.0004. If the average time between successive fissions in a chain of reactions is 1.0 ms, by what factor will the reaction rate increase in 1.0 s?

31–3 Nuclear Fusion

27. (I) What is the average kinetic energy of protons at the center of a star where the temperature is 2×10^7 K? [*Hint*: See Eq. 13–8.]

28. (II) Show that the energy released in the fusion reaction $^{2}_{1}\text{H} + ^{3}_{1}\text{H} \rightarrow ^{4}_{2}\text{He} + \text{n}$ is 17.59 MeV.

29. (II) Show that the energy released when two deuterium nuclei fuse to form $^{3}_{2}\text{He}$ with the release of a neutron is 3.27 MeV (Eq. 31–8b).

30. (II) Verify the Q-value stated for each of the reactions of Eqs. 31–6. [*Hint*: Use Appendix B; be careful with electrons (included in mass values except for p, d, t).]

31. (II) (*a*) Calculate the energy release per gram of fuel for the reactions of Eqs. 31–8a, b, and c. (*b*) Calculate the energy release per gram of uranium $^{235}_{92}\mathrm{U}$ in fission, and give its ratio to each reaction in (*a*).

32. (II) How much energy is released when $^{238}_{92}\mathrm{U}$ absorbs a slow neutron (kinetic energy ≈ 0) and becomes $^{239}_{92}\mathrm{U}$?

33. (II) If a typical house requires 960 W of electric power on average, what minimum amount of deuterium fuel would have to be used in a year to supply these electrical needs? Assume the reaction of Eq. 31–8b.

34. (II) Suppose a fusion reactor ran on "d–d" reactions, Eqs. 31–8a and b in equal amounts. Estimate how much natural water, for fuel, would be needed per hour to run a 1150-MW reactor, assuming 33% efficiency.

35. (III) Show that the energies carried off by the $^{4}_{2}\mathrm{He}$ nucleus and the neutron for the reaction of Eq. 31–8c are about 3.5 MeV and 14 MeV, respectively. Are these fixed values, independent of the plasma temperature?

36. (III) How much energy (J) is contained in 1.00 kg of water if its natural deuterium is used in the fusion reaction of Eq. 31–8a? Compare to the energy obtained from the burning of 1.0 kg of gasoline, about 5×10^{7} J.

37. (III) (*a*) Give the ratio of the energy needed for the first reaction of the *carbon cycle* to the energy needed for a deuterium–tritium reaction (Example 31–9). (*b*) If a deuterium–tritium reaction actually requires a temperature $T \approx 3 \times 10^{8}$ K, estimate the temperature needed for the first carbon-cycle reaction.

31–5 Dosimetry

38. (I) 350 rads of α-particle radiation is equivalent to how many rads of X-rays in terms of biological damage?

39. (I) How many rads of slow neutrons will do as much biological damage as 72 rads of fast neutrons?

40. (II) How much energy is deposited in the body of a 65-kg adult exposed to a 2.5-Gy dose?

41. (II) A cancer patient is undergoing radiation therapy in which protons with an energy of 1.2 MeV are incident on a 0.20-kg tumor. (*a*) If the patient receives an effective dose of 1.0 rem, what is the absorbed dose? (*b*) How many protons are absorbed by the tumor? Assume RBE ≈ 1.

42. (II) A 0.035-μCi sample of $^{32}_{15}\mathrm{P}$ is injected into an animal for tracer studies. If a Geiger counter intercepts 35% of the emitted β particles, what will be the counting rate, assumed 85% efficient?

43. (II) About 35 eV is required to produce one ion pair in air. Show that this is consistent with the two definitions of the roentgen given in the text.

44. (II) A 1.6-mCi source of $^{32}_{15}\mathrm{P}$ (in $\mathrm{NaHPO_4}$), a β emitter, is implanted in a tumor where it is to administer 32 Gy. The half-life of $^{32}_{15}\mathrm{P}$ is 14.3 days, and 1.0 mCi delivers about 10 mGy/min. Approximately how long should the source remain implanted?

45. (II) What is the mass of a 2.50-μCi $^{14}_{6}\mathrm{C}$ source?

46. (II) $^{57}_{27}\mathrm{Co}$ emits 122-keV γ rays. If a 65-kg person swallowed 1.55 μCi of $^{57}_{27}\mathrm{Co}$, what would be the dose rate (Gy/day) averaged over the whole body? Assume that 50% of the γ-ray energy is deposited in the body. [*Hint*: Determine the rate of energy deposited in the body and use the definition of the gray.]

47. (II) Ionizing radiation can be used on meat products to reduce the levels of microbial pathogens. Refrigerated meat is limited to 4.5 kGy. If 1.6-MeV electrons irradiate 5 kg of beef, how many electrons would it take to reach the allowable limit?

48. (III) Huge amounts of radioactive $^{131}_{53}\mathrm{I}$ were released in the accident at Chernobyl in 1986. Chemically, iodine goes to the human thyroid. (It can be used for diagnosis and treatment of thyroid problems.) In a normal thyroid, $^{131}_{53}\mathrm{I}$ absorption can cause damage to the thyroid. (*a*) Write down the reaction for the decay of $^{131}_{53}\mathrm{I}$. (*b*) Its half-life is 8.0 d; how long would it take for ingested $^{131}_{53}\mathrm{I}$ to become 5.0% of the initial value? (*c*) Absorbing 1 mCi of $^{131}_{53}\mathrm{I}$ can be harmful; what mass of iodine is this?

49. (III) Assume a liter of milk typically has an activity of 2000 pCi due to $^{40}_{19}\mathrm{K}$. If a person drinks two glasses (0.5 L) per day, estimate the total effective dose (in Sv and in rem) received in a year. As a crude model, assume the milk stays in the stomach 12 hr and is then released. Assume also that roughly 10% of the 1.5 MeV released per decay is absorbed by the body. Compare your result to the normal allowed dose of 100 mrem per year. Make your estimate for (*a*) a 60-kg adult, and (*b*) a 6-kg baby.

50. (III) Radon gas, $^{222}_{86}\mathrm{Rn}$, is considered a serious health hazard (see discussion in text). It decays by α-emission. (*a*) What is the daughter nucleus? (*b*) Is the daughter nucleus stable or radioactive? If the latter, how does it decay, and what is its half-life? (See Fig. 30–11.) (*c*) Is the daughter nucleus also a noble gas, or is it chemically reactive? (*d*) Suppose 1.4 ng of $^{222}_{86}\mathrm{Rn}$ seeps into a basement. What will be its activity? If the basement is then sealed, what will be the activity 1 month later?

31–9 NMR

51. (II) Calculate the wavelength of photons needed to produce NMR transitions in free protons in a 1.000-T field. In what region of the spectrum is this wavelength?

General Problems

52. Consider a system of nuclear power plants that produce 2100 MW. (*a*) What total mass of $^{235}_{92}\mathrm{U}$ fuel would be required to operate these plants for 1 yr, assuming that 200 MeV is released per fission? (*b*) Typically 6% of the $^{235}_{92}\mathrm{U}$ nuclei that fission produce strontium–90, $^{90}_{38}\mathrm{Sr}$, a β^- emitter with a half-life of 29 yr. What is the total radioactivity of the $^{90}_{38}\mathrm{Sr}$, in curies, produced in 1 yr? (Neglect the fact that some of it decays during the 1-yr period.)

53. J. Chadwick discovered the neutron by bombarding $^{9}_{4}\mathrm{Be}$ with the popular projectile of the day, alpha particles. (*a*) If one of the reaction products was the then unknown neutron, what was the other product? (*b*) What is the *Q*-value of this reaction?

54. Fusion temperatures are often given in keV. Determine the conversion factor from kelvins to keV using, as is common in this field, $\overline{\mathrm{KE}} = kT$ without the factor $\frac{3}{2}$.

55. One means of enriching uranium is by diffusion of the gas UF_6. Calculate the ratio of the speeds of molecules of this gas containing $^{235}_{92}\mathrm{U}$ and $^{238}_{92}\mathrm{U}$, on which this process depends.

56. (*a*) What mass of $^{235}_{92}\mathrm{U}$ was actually fissioned in the first atomic bomb, whose energy was the equivalent of about 20 kilotons of TNT (1 kiloton of TNT releases 5×10^{12} J)? (*b*) What was the actual mass transformed to energy?

57. The average yearly background radiation in a certain town consists of 32 mrad of X-rays and γ rays plus 3.4 mrad of particles having a RBE of 10. How many rem will a person receive per year on average?

58. A shielded γ-ray source yields a dose rate of 0.048 rad/h at a distance of 1.0 m for an average-sized person. If workers are allowed a maximum dose of 5.0 rem in 1 year, how close to the source may they operate, assuming a 35-h work week? Assume that the intensity of radiation falls off as the square of the distance. (It actually falls off more rapidly than $1/r^2$ because of absorption in the air, so your answer will give a better-than-permissible value.)

59. In the net reaction, Eq. 31–7, for the proton–proton chain in the Sun, the neutrinos escape from the Sun with energy of about 0.5 MeV. The remaining energy, 26.2 MeV, is available to heat the Sun. Use this value to calculate the "heat of combustion" per kilogram of hydrogen fuel and compare it to the heat of combustion of coal, about 3×10^7 J/kg.

60. Energy reaches Earth from the Sun at a rate of about 1300 W/m^2. Calculate (*a*) the total power output of the Sun, and (*b*) the number of protons consumed per second in the reaction of Eq. 31–7, assuming that this is the source of all the Sun's energy. (*c*) Assuming that the Sun's mass of 2.0×10^{30} kg was originally all protons and that all could be involved in nuclear reactions in the Sun's core, how long would you expect the Sun to "glow" at its present rate? See Problem 59. [*Hint*: Use $1/r^2$ law.]

61. Radon gas, $^{222}_{86}\mathrm{Rn}$, is formed by α decay. (*a*) Write the decay equation. (*b*) Ignoring the kinetic energy of the daughter nucleus (it's so massive), estimate the kinetic energy of the α particle produced. (*c*) Estimate the momentum of the alpha and of the daughter nucleus. (*d*) Estimate the kinetic energy of the daughter, and show that your approximation in (*b*) was valid.

62. Estimate how many solar neutrinos pass through a 180-m^2 ceiling of a room, at latitude 44°, for an hour around midnight on midsummer night. [*Hint*: See Problems 59 and 60.]

63. Estimate how much total energy would be released via fission if 2.0 kg of uranium were enriched to 5% of the isotope $^{235}_{92}\mathrm{U}$.

64. Some stars, in a later stage of evolution, may begin to fuse two $^{12}_{6}\mathrm{C}$ nuclei into one $^{24}_{12}\mathrm{Mg}$ nucleus. (*a*) How much energy would be released in such a reaction? (*b*) What kinetic energy must two carbon nuclei each have when far apart, if they can then approach each other to within 6.0 fm, center-to-center? (*c*) Approximately what temperature would this require?

65. An average adult body contains about 0.10 μCi of $^{40}_{19}\mathrm{K}$, which comes from food. (*a*) How many decays occur per second? (*b*) The potassium decay produces beta particles with energies of around 1.4 MeV. Estimate the dose per year in sieverts for a 65-kg adult. Is this a significant fraction of the 3.6-mSv/yr background rate?

66. When the nuclear reactor accident occurred at Chernobyl in 1986, 2.0×10^7 Ci were released into the atmosphere. Assuming that this radiation was distributed uniformly over the surface of the Earth, what was the activity per square meter? (The actual activity was not uniform; even within Europe wet areas received more radioactivity from rainfall.)

67. A star with a large helium abundance can burn helium in the reaction $^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{12}_{6}\mathrm{C}$. What is the *Q*-value for this reaction?

68. A 1.2-μCi $^{137}_{55}\mathrm{Cs}$ source is used for 1.4 hours by a 62-kg worker. Radioactive $^{137}_{55}\mathrm{Cs}$ decays by β^- decay with a half-life of 30 yr. The average energy of the emitted betas is about 190 keV per decay. The β decay is quickly followed by a γ with an energy of 660 keV. Assuming the person absorbs *all* emitted energy, what effective dose (in rem) is received?

69. If a 65-kg power plant worker has been exposed to the maximum slow-neutron radiation for a given year, how much total energy (in J) has that worker absorbed? What if he were exposed to fast protons?

70. A large amount of ${}^{90}_{38}\mathrm{Sr}$ was released during the Chernobyl nuclear reactor accident in 1986. The ${}^{90}_{38}\mathrm{Sr}$ enters the body through the food chain. How long will it take for 85% of the ${}^{90}_{38}\mathrm{Sr}$ released during the accident to decay? See Appendix B.

71. Three radioactive sources have the same activity, 35 mCi. Source A emits 1.0-MeV γ rays, source B emits 2.0-MeV γ rays, and source C emits 2.0-MeV alphas. What is the relative danger of these sources?

72. A 55-kg patient is to be given a medical test involving the ingestion of ${}^{99\mathrm{m}}_{43}\mathrm{Tc}$ (Section 31–7) which decays by emitting a 140-keV gamma. The half-life for this decay is 6 hours. Assuming that about half the gamma photons exit the body without interacting with anything, what must be the initial activity of the Tc sample if the whole-body dose cannot exceed 50 mrem? Make the rough approximation that biological elimination of Tc can be ignored.

Search and Learn

1. Referring to Section 31–3, (*a*) why can small nuclei combine to form larger ones, releasing energy in the process? (*b*) Why does the first reaction in the proton–proton chain limit the rate at which the Sun produces energy? (*c*) What are the heaviest elements for which energy is released if the elements are created by fusion of lighter elements? (*d*) What keeps the Sun and stars together, allowing them to sustain fusion? (*e*) What two methods are currently being investigated to contain high-temperature plasmas on the Earth to create fusion in the laboratory?

2. Deuterium makes up 0.0115% of natural hydrogen on average. Make a rough estimate of the total deuterium in the Earth's oceans and estimate the total energy released if all of it were used in fusion reactors.

3. The energy output of massive stars is believed to be due to the *carbon cycle* (see text). (*a*) Show that no carbon is consumed in this cycle and that the net effect is the same as for the proton–proton chain. (*b*) What is the total energy release? (*c*) Determine the energy output for each reaction and decay. (*d*) Why might the carbon cycle require a higher temperature $\left(\approx 2 \times 10^7\,\mathrm{K}\right)$ than the proton–proton chain $\left(\approx 1.5 \times 10^7\,\mathrm{K}\right)$?

4. (*a*) Explain how each of the following can cause damage to materials: beta particles, alpha particles, energetic neutrons, and gamma rays. (*b*) How might metals be damaged? (*c*) How can the damage affect living cells?

ANSWERS TO EXERCISES

A: ${}^{138}_{56}\mathrm{Ba}$.
B: 3 neutrons.
C: 2×10^{17}.
D: (*e*).
E: (*b*).