Technicians are looking at an MRI image of sections through a patient's body. MRI is one of several powerful types of medical imaging based on physics used by doctors to diagnose illnesses.

This Chapter opens with basic and important physics topics of nuclear reactions, nuclear fission, and nuclear fusion, and how we obtain nuclear energy. Then we examine the health aspects of radiation—dosimetry, therapy, and imaging: MRI, PET, and SPECT.

CHAPTER 31

Nuclear Energy; Effects and Uses of Radiation

CONTENTS

CHAPTER-OPENING QUESTION—Guess now!

The Sun is powered by

(a) nuclear alpha decay.
(b) nuclear beta decay.
(c) nuclear gamma decay.
(d) nuclear fission.
(e) nuclear fusion.

We continue our study of nuclear physics in this Chapter. We begin with a discussion of nuclear reactions, and then we examine the important huge energy-releasing processes of fission and fusion. We also deal with the effects of nuclear radiation passing through matter, particularly biological matter, and how radiation is used medically for therapy, diagnosis, and imaging techniques.

31–1 Nuclear Reactions and the Transmutation of Elements

When a nucleus undergoes α or β decay, the daughter nucleus is a different element from the parent. The transformation of one element into another, called **transmutation**, also occurs via nuclear reactions. A **nuclear reaction** is said to occur when a nucleus is struck by another nucleus, or by a simpler particle such as a γ ray, neutron, or proton, and an interaction takes place. Ernest Rutherford was the first to report seeing a nuclear reaction. In 1919 he observed that some of the α particles passing through nitrogen gas were absorbed and protons emitted. He concluded that nitrogen nuclei had been transformed into oxygen nuclei via the reaction

$$^{4}_{2}\text{He} + ^{14}_{7}\text{N} \rightarrow ^{17}_{8}\text{O} + ^{1}_{1}\text{H},$$

where $^{4}_{2}\text{He}$ is an α particle, and $^{1}_{1}\text{H}$ is a proton.

Since then, a great many nuclear reactions have been observed. Indeed, many of the radioactive isotopes used in the laboratory are made by means of nuclear reactions. Nuclear reactions can be made to occur in the laboratory, but they also occur regularly in nature. In Chapter 30 we saw an example: ${}^{14}_{6}C$ is continually being made in the atmosphere via the reaction $n + {}^{14}_{7}N \rightarrow {}^{14}_{6}C + p$.

Nuclear reactions are sometimes written in a shortened form: for example,

$$n + {}^{14}_{7}N \rightarrow {}^{14}_{6}C + p$$

can be written

$${}^{14}_{7}N\,(n,\ p)\,{}^{14}_{6}C.$$

The symbols outside the parentheses on the left and right represent the initial and final nuclei, respectively. The symbols inside the parentheses represent the bombarding particle (first) and the emitted small particle (second).

In any nuclear reaction, both electric charge and nucleon number are conserved. These conservation laws are often useful, as the following Example shows.

CONCEPTUAL EXAMPLE 31–1 **Deuterium reaction.** A neutron is observed to strike an ${}^{16}_{8}O$ nucleus, and a deuteron is given off. (A **deuteron**, or **deuterium**, is the isotope of hydrogen containing one proton and one neutron, ${}^{2}_{1}H$; it is sometimes given the symbol d or D.) What is the nucleus that results?

RESPONSE We have the reaction $n + {}^{16}_{8}O \rightarrow ? + {}^{2}_{1}H$. The total number of nucleons initially is $1 + 16 = 17$, and the total charge is $0 + 8 = 8$. The same totals apply after the reaction. Hence the product nucleus must have $Z = 7$ and $A = 15$. From the Periodic Table, we find that it is nitrogen that has $Z = 7$, so the nucleus produced is ${}^{15}_{7}N$.

EXERCISE A Determine the resulting nucleus in the reaction $n + {}^{137}_{56}Ba \rightarrow ? + \gamma$.

Energy and momentum are also conserved in nuclear reactions, and can be used to determine whether or not a given reaction can occur. For example, if the total mass of the final products is less than the total mass of the initial particles, this decrease in mass (recall $\Delta E = \Delta m\, c^2$) is converted to kinetic energy (KE) of the outgoing particles. But if the total mass of the products is greater than the total mass of the initial reactants, the reaction requires energy. The reaction will then not occur unless the bombarding particle has sufficient kinetic energy. Consider a nuclear reaction of the general form

$$a + X \rightarrow Y + b, \qquad \textbf{(31–1)}$$

where particle a is a moving projectile particle (or small nucleus) that strikes nucleus X, producing nucleus Y and particle b (typically, p, n, α, γ). We define the **reaction energy**, or ***Q*-value**, in terms of the masses involved, as

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

For a γ ray, $M = 0$. If energy is released by the reaction, $Q > 0$. If energy is required, $Q < 0$.

Because energy is conserved, Q has to be equal to the change in kinetic energy (final minus initial):

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

If X is a target nucleus at rest (or nearly so) struck by incoming particle a, then $\text{KE}_X = 0$. For $Q > 0$, the reaction is said to be *exothermic* or *exoergic*; energy is released in the reaction, so the total kinetic energy is greater after the reaction than before. If Q is negative, the reaction is said to be *endothermic* or *endoergic*: an energy input is required to make the reaction happen. The energy input comes from the kinetic energy of the initial colliding particles (a and X).

EXAMPLE 31–2 **A slow-neutron reaction.** The nuclear reaction

$$n + {}^{10}_{5}B \rightarrow {}^{7}_{3}Li + {}^{4}_{2}He$$

is observed to occur even when very slow-moving neutrons (mass $M_n = 1.0087$ u) strike boron atoms at rest. For a particular reaction in which $\text{KE}_n \approx 0$, the outgoing helium ($M_{He} = 4.0026$ u) is observed to have a speed of 9.30×10^6 m/s. Determine (*a*) the kinetic energy of the lithium ($M_{Li} = 7.0160$ u), and (*b*) the Q-value of the reaction.

APPROACH Since the neutron and boron are both essentially at rest, the total momentum before the reaction is zero; momentum is conserved and so must be zero afterward as well. Thus,

$$M_{\text{Li}} v_{\text{Li}} = M_{\text{He}} v_{\text{He}}.$$

We solve this for v_{Li} and substitute it into the equation for kinetic energy. In (*b*) we use Eq. 31–2b.

SOLUTION (*a*) We can use classical kinetic energy with little error, rather than relativistic formulas, because $v_{\text{He}} = 9.30 \times 10^6\,\text{m/s}$ is not close to the speed of light *c*. And v_{Li} will be even less because $M_{\text{Li}} > M_{\text{He}}$. Thus we can write the KE of the lithium, using the momentum equation just above, as

$$\text{KE}_{\text{Li}} = \frac{1}{2} M_{\text{Li}} v_{\text{Li}}^2 = \frac{1}{2} M_{\text{Li}} \left(\frac{M_{\text{He}} v_{\text{He}}}{M_{\text{Li}}} \right)^2 = \frac{M_{\text{He}}^2 v_{\text{He}}^2}{2M_{\text{Li}}}.$$

We put in numbers, changing the mass in u to kg and recall that $1.60 \times 10^{-13}\,\text{J} = 1\,\text{MeV}$:

$$\text{KE}_{\text{Li}} = \frac{(4.0026\,\text{u})^2 (1.66 \times 10^{-27}\,\text{kg/u})^2 (9.30 \times 10^6\,\text{m/s})^2}{2(7.0160\,\text{u})(1.66 \times 10^{-27}\,\text{kg/u})}$$

$$= 1.64 \times 10^{-13}\,\text{J} = 1.02\,\text{MeV}.$$

(*b*) We are given the data $\text{KE}_{\text{a}} = \text{KE}_{\text{X}} = 0$ in Eq. 31–2b, so $Q = \text{KE}_{\text{Li}} + \text{KE}_{\text{He}}$, where

$$\text{KE}_{\text{He}} = \tfrac{1}{2} M_{\text{He}} v_{\text{He}}^2 = \tfrac{1}{2}(4.0026\,\text{u})(1.66 \times 10^{-27}\,\text{kg/u})(9.30 \times 10^6\,\text{m/s})^2$$

$$= 2.87 \times 10^{-13}\,\text{J} = 1.80\,\text{MeV}.$$

Hence, $Q = 1.02\,\text{MeV} + 1.80\,\text{MeV} = 2.82\,\text{MeV}$.

EXAMPLE 31–3 **Will the reaction "go"?** Can the reaction

$$\text{p} + {}^{13}_{6}\text{C} \rightarrow {}^{13}_{7}\text{N} + \text{n}$$

occur when ${}^{13}_{6}\text{C}$ is bombarded by 2.0-MeV protons?

APPROACH The reaction will "go" if the reaction is exothermic $(Q > 0)$ and even if $Q < 0$ if the input momentum and kinetic energy are sufficient. First we calculate Q from the difference between final and initial masses using Eq. 31–2a, and look up the masses in Appendix B.

SOLUTION The total masses before and after the reaction are:

Before		After	
$M({}^{13}_{6}\text{C})$ =	13.003355	$M({}^{13}_{7}\text{N})$ =	13.005739
$M({}^{1}_{1}\text{H})$ =	1.007825	$M(\text{n})$ =	1.008665
	14.011180		14.014404

(We must use the mass of the ${}^{1}_{1}\text{H}$ atom rather than that of the bare proton because the masses of ${}^{13}_{6}\text{C}$ and ${}^{13}_{7}\text{N}$ include the electrons, and we must include an equal number of electron masses on each side of the equation.) The products have an excess mass of

$$(14.014404 - 14.011180)\,\text{u} = 0.003224\,\text{u} \times 931.5\,\text{MeV/u} = 3.00\,\text{MeV}.$$

Thus $Q = -3.00\,\text{MeV}$, and the reaction is endothermic. This reaction requires energy, and the 2.0-MeV protons do not have enough to make it go.

NOTE The incoming proton in this Example would need more than 3.00 MeV of kinetic energy to make this reaction go; 3.00 MeV would be enough to conserve energy, but a proton of this energy would produce the ${}^{13}_{7}\text{N}$ and n with no kinetic energy and hence no momentum. Since an incident 3.0-MeV proton has momentum, conservation of momentum would be violated. A calculation using conservation of energy *and* of momentum, as we did in Examples 30–7 and 31–2, shows that the minimum proton energy, called the **threshold energy**, is 3.23 MeV in this case.

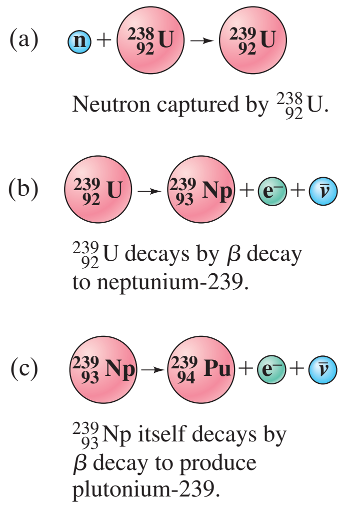


FIGURE 31–1 Neptunium and plutonium are produced in this series of reactions, after bombardment of $^{238}_{92}$U by neutrons.

Neutron Physics

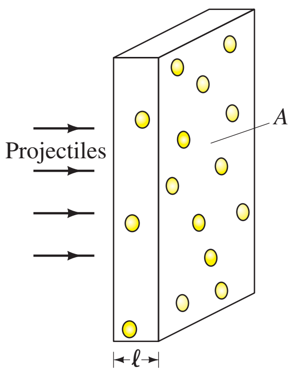
The artificial transmutation of elements took a great leap forward in the 1930s when Enrico Fermi realized that neutrons would be the most effective projectiles for causing nuclear reactions and in particular for producing new elements. Because neutrons have no net electric charge, they are not repelled by positively charged nuclei as are protons or alpha particles. Hence the probability of a neutron reaching the nucleus and causing a reaction is much greater than for charged projectiles,[†] particularly at low energies. Between 1934 and 1936, Fermi and his co-workers in Rome produced many previously unknown isotopes by bombarding different elements with neutrons. Fermi realized that if the heaviest known element, uranium, is bombarded with neutrons, it might be possible to produce new elements with atomic numbers greater than that of uranium. After several years of hard work, it was suspected that two new elements had been produced, neptunium ($Z = 93$) and plutonium ($Z = 94$). The full confirmation that such "transuranic" elements could be produced came several years later at the University of California, Berkeley. The reactions are shown in Fig. 31–1.

It was soon shown that what Fermi had actually observed when he bombarded uranium was an even stranger process—one that was destined to play an extraordinary role in the world at large. We discuss it in Section 31–2.

*Cross Section

Some reactions have a higher probability of occurring than others. The reaction probability is specified by a quantity called the collision **cross section**. Although the size of a nucleus, like that of an atom, is not a clearly defined quantity since the edges are not distinct like those of a tennis ball or baseball, we can nonetheless define a *cross section* for nuclei undergoing collisions by using an analogy. Suppose that projectile particles strike a stationary target of total area A and thickness ℓ, as shown in Fig. 31–2. Assume also that the target is made up of identical objects (such as marbles or nuclei), each of which has a cross-sectional area σ, and we assume the incoming projectiles are small by comparison. We assume that the target objects are fairly far apart and the thickness ℓ is so small that we don't have to worry about overlapping. This is often a reasonable assumption because nuclei have diameters on the order of 10^{-14} m but are at least 10^{-10} m (atomic size) apart even in solids. If there are n nuclei per unit volume, the total cross-sectional area of all these tiny targets is

FIGURE 31–2 Projectile particles strike a target of area A and thickness ℓ made up of n nuclei per unit volume.



$$A' = nA\ell\sigma$$

since $nA\ell = (n)(\text{volume})$ is the total number of targets and σ is the cross-sectional area of each. If $A' \ll A$, most of the incident projectile particles will pass through the target without colliding. If R_0 is the rate at which the projectile particles strike the target (number/second), the rate at which collisions occur, R, is

$$R = R_0 \frac{A'}{A} = R_0 \frac{nA\ell\sigma}{A}$$

so

$$R = R_0 n\ell\sigma.$$

Thus, by measuring the collision rate, R, we can determine σ:

$$\sigma = \frac{R}{R_0 n\ell}.$$

The cross section σ is an "effective" target area. It is a *measure of the probability of a collision or of a particular reaction occurring* per target nucleus, independent of the dimensions of the entire target. The concept of cross section is useful

[†]That is, positively charged particles. Electrons rarely cause nuclear reactions because they do not interact via the strong nuclear force.

because σ depends only on the properties of the interacting particles, whereas R depends on the thickness and area of the physical (macroscopic) target, on the number of particles in the incident beam, and so on.

31–2 Nuclear Fission; Nuclear Reactors

In 1938, the German scientists Otto Hahn and Fritz Strassmann made an amazing discovery. Following up on Fermi's work, they found that uranium bombarded by neutrons sometimes produced smaller nuclei that were roughly half the size of the original uranium nucleus. Lise Meitner and Otto Frisch quickly realized what had happened: the uranium nucleus, after absorbing a neutron, actually had split into two roughly equal pieces. This was startling, for until then the known nuclear reactions involved knocking out only a tiny fragment (for example, n, p, or α) from a nucleus.

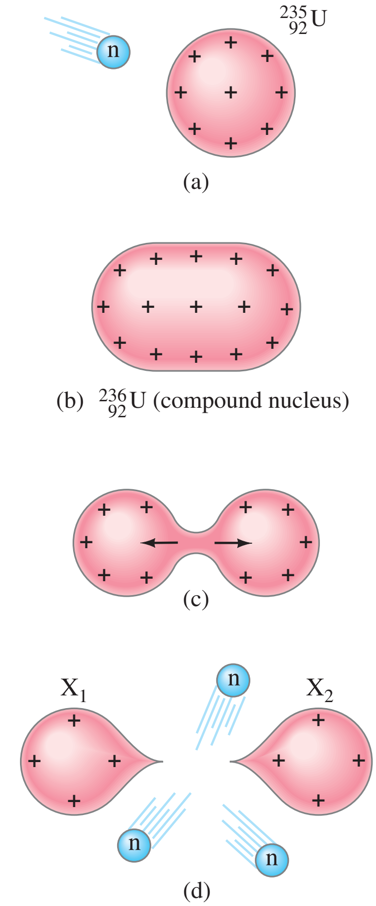


FIGURE 31–3 Fission of a $^{235}_{92}$U nucleus after capture of a neutron, according to the liquid-drop model.

Nuclear Fission and Chain Reactions

This new phenomenon was named **nuclear fission** because of its resemblance to biological fission (cell division). It occurs much more readily for $^{235}_{92}$U than for the more common $^{238}_{92}$U. The process can be visualized by imagining the uranium nucleus to be like a liquid drop. According to this **liquid-drop model**, the neutron absorbed by the $^{235}_{92}$U nucleus (Fig. 31–3a) gives the nucleus extra internal energy (like heating a drop of water). This intermediate state, or **compound nucleus**, is $^{236}_{92}$U (because of the absorbed neutron), Fig. 31–3b. The extra energy of this nucleus—it is in an excited state—appears as increased motion of the individual nucleons inside, which causes the nucleus to take on abnormal elongated shapes. When the nucleus elongates (in this model) into the shape shown in Fig. 31–3c, the attraction of the two ends via the short-range nuclear force is greatly weakened by the increased separation distance. Then the electric repulsive force becomes dominant, and the nucleus splits in two (Fig. 31–3d). The two resulting nuclei, X_1 and X_2, are called **fission fragments**, and in the process a number of neutrons (typically two or three) are also given off. The reaction can be written

$$\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow {}^{236}_{92}\mathrm{U} \rightarrow X_1 + X_2 + \text{neutrons}. \quad \textbf{(31–3)}$$

The compound nucleus, $^{236}_{92}$U, exists for less than 10^{-12} s, so the process occurs very quickly. The two fission fragments, X_1 and X_2, rarely split the original uranium mass precisely half and half, but more often as about 40%–60%. A typical fission reaction is

$$\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow {}^{141}_{56}\mathrm{Ba} + {}^{92}_{36}\mathrm{Kr} + 3\mathrm{n}, \quad \textbf{(31–4)}$$

although many others also occur.

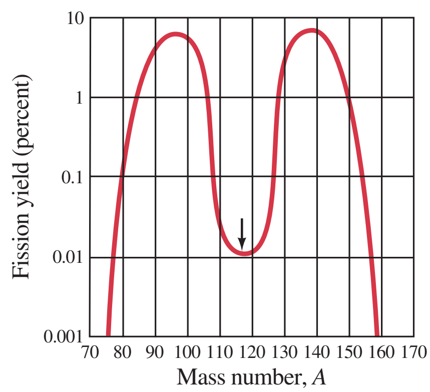
CONCEPTUAL EXAMPLE 31–4 **Counting nucleons.** Identify the element X in the fission reaction $\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow {}^{A}_{Z}\mathrm{X} + {}^{93}_{38}\mathrm{Sr} + 2\mathrm{n}$.

RESPONSE The number of nucleons is conserved (Section 30–7). The uranium nucleus with 235 nucleons plus the incoming neutron make $235 + 1 = 236$ nucleons. So there must be 236 nucleons after the reaction. The Sr has 93 nucleons, and the two neutrons make 95 nucleons, so X has $A = 236 - 95 = 141$. Electric charge is also conserved: before the reaction, the total charge is $92e$. After the reaction the total charge is $(Z + 38)e$ and must equal $92e$. Thus $Z = 92 - 38 = 54$. The element with $Z = 54$ is xenon (see Appendix B or the Periodic Table inside the back cover), so the isotope is $^{141}_{54}$Xe.

EXERCISE B In the fission reaction $\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow {}^{137}_{53}\mathrm{I} + {}^{96}_{39}\mathrm{Y} +$ neutrons, how many neutrons are produced?

Figure 31–4 shows the measured distribution of $^{235}_{92}$U fission fragments according to mass. Only rarely (about 1 in 10^4) does a fission result in equal mass fragments (arrow in Fig. 31–4).

FIGURE 31–4 Mass distribution of fission fragments from $^{235}_{92}\mathrm{U} + \mathrm{n}$. The small arrow indicates equal mass fragments ($\frac{1}{2} \times (236 - 2) = 117$, assuming 2 neutrons are liberated). Note that the vertical scale is logarithmic.



A tremendous amount of energy is released in a fission reaction because the mass of ${}^{235}_{92}U$ is considerably greater than the total mass of the fission fragments plus released neutrons. This can be seen from the binding-energy-per-nucleon curve of Fig. 30–1; the binding energy per nucleon for uranium is about 7.6 MeV/nucleon, but for fission fragments that have intermediate mass (in the center portion of the graph, $A \approx 100$), the average binding energy per nucleon is about 8.5 MeV/nucleon. Since the fission fragments are more tightly bound, the sum of their masses is less than the mass of the uranium. The difference in mass, or energy, between the original uranium nucleus and the fission fragments is about $8.5 - 7.6 = 0.9\,\text{MeV}$ per nucleon. Because there are 236 nucleons involved in each fission, the total energy released per fission is

$$(0.9\,\text{MeV/nucleon})(236\,\text{nucleons}) \approx 200\,\text{MeV}. \qquad \textbf{(31–5)}$$

This is an enormous amount of energy for one single nuclear event. At a practical level, the energy from one fission is tiny. But if many such fissions could occur in a short time, an enormous amount of energy at the macroscopic level would be available. A number of physicists, including Fermi, recognized that the neutrons released in each fission (Eqs. 31–3 and 31–4) could be used to create a **chain reaction**. That is, one neutron initially causes one fission of a uranium nucleus; the two or three neutrons released can go on to cause additional fissions, so the process multiplies as shown schematically in Fig. 31–5.

If a **self-sustaining chain reaction** was actually possible in practice, the enormous energy available in fission could be released on a larger scale. Fermi and his co-workers (at the University of Chicago) showed it was possible by constructing the first **nuclear reactor** in 1942 (Fig. 31–6).

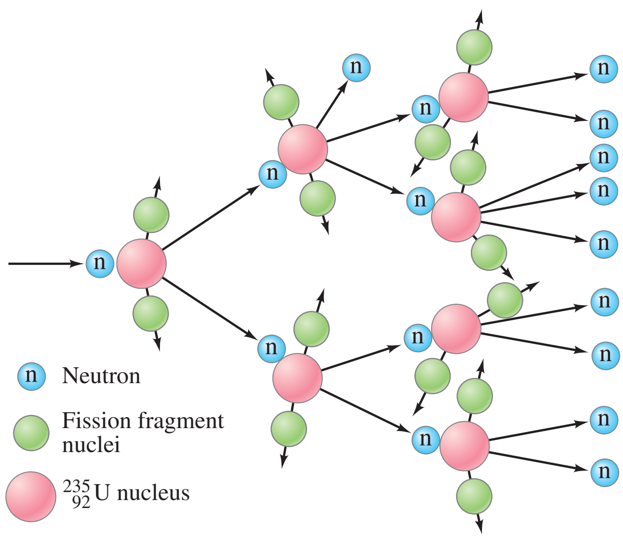


FIGURE 31–5 Chain reaction.

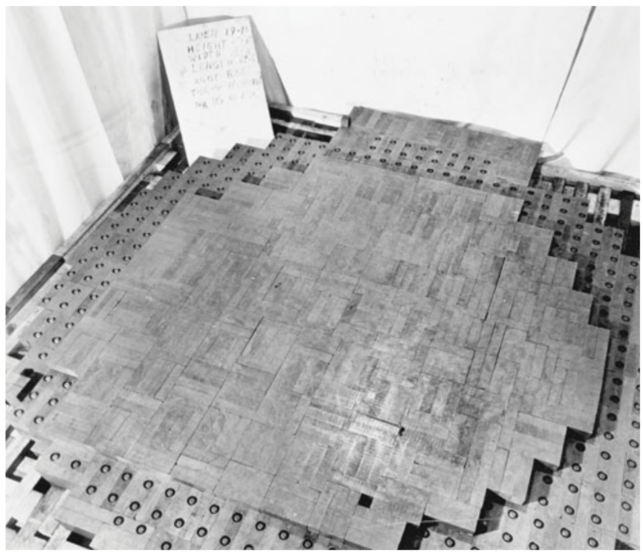


FIGURE 31–6 This is the only photograph of the first nuclear reactor, built by Fermi under the grandstand of Stagg Field at the University of Chicago. It is shown here under construction as a layer of graphite (used as moderator) was being placed over a layer of natural uranium. On December 2, 1942, Fermi slowly withdrew the cadmium control rods and the reactor went critical. This first self-sustaining chain reaction was announced to Washington, via telephone, by Arthur Compton who witnessed the event and reported: "The Italian navigator has just landed in the new world."

Nuclear Reactors

Several problems have to be overcome to make any nuclear reactor function. First, the probability that a $^{235}_{92}U$ nucleus will absorb a neutron is large only for slow neutrons, but the neutrons emitted during a fission (which are needed to sustain a chain reaction) are moving very fast. A substance known as a **moderator** must be used to slow down the neutrons. The most effective moderator will consist of atoms whose mass is as close as possible to that of the neutrons. (To see why this is true, recall from Chapter 7 that a billiard ball striking an equal mass ball at rest can itself be stopped in one collision; but a billiard ball striking a heavy object bounces off with nearly unchanged speed.) The best moderator would thus contain $^{1}_{1}H$ atoms. Unfortunately, $^{1}_{1}H$ tends to absorb neutrons. But the isotope of hydrogen called *deuterium*, $^{2}_{1}H$, does not absorb many neutrons and is thus an almost ideal moderator. Either $^{1}_{1}H$ or $^{2}_{1}H$ can be used in the form of water. In the latter case, it is **heavy water**, in which the hydrogen atoms have been replaced by deuterium. Another common moderator is *graphite*, which consists of $^{12}_{6}C$ atoms.

A second problem is that the neutrons produced in one fission may be absorbed and produce other nuclear reactions with other nuclei in the reactor, rather than produce further fissions. In a "light-water" reactor, the $^{1}_{1}H$ nuclei absorb neutrons, as does $^{238}_{92}U$ to form $^{239}_{92}U$ in the reaction $n + {}^{238}_{92}U \rightarrow {}^{239}_{92}U + \gamma$. Naturally occurring uranium† contains 99.3% $^{238}_{92}U$ and only 0.7% fissionable $^{235}_{92}U$. To increase the probability of fission of $^{235}_{92}U$ nuclei, natural uranium can be **enriched** to increase the percentage of $^{235}_{92}U$ by using processes such as diffusion or centrifugation. Enrichment is not usually necessary for reactors using heavy water as moderator because heavy water doesn't absorb neutrons.

The third problem is that some neutrons will escape through the surface of the reactor core before they can cause further fissions (Fig. 31–7). Thus the mass of fuel must be sufficiently large for a self-sustaining chain reaction to take place. The minimum mass of uranium needed is called the **critical mass**. The value of the critical mass depends on the moderator, the fuel ($^{239}_{94}Pu$ may be used instead of $^{235}_{92}U$), and how much the fuel is enriched, if at all. Typical values are on the order of a few kilograms (that is, neither grams nor thousands of kilograms). Critical mass depends also on the average number of neutrons released per fission: 2.5 for $^{235}_{92}U$, 2.9 for $^{239}_{94}Pu$ so the critical mass for $^{239}_{94}Pu$ is smaller.

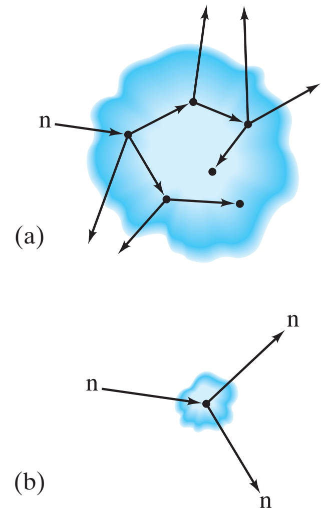


FIGURE 31–7 If the amount of uranium exceeds the critical mass, as in (a), a sustained chain reaction is possible. If the mass is less than critical, as in (b), too many neutrons escape before additional fissions occur, and the chain reaction is not sustained.

To have a self-sustaining chain reaction, on average at least one neutron produced in each fission must go on to produce another fission. The average number of neutrons per fission that do go on to produce further fissions is called the **neutron multiplication factor**, f. For a self-sustaining chain reaction, we must have $f \geq 1$. If $f < 1$, the reactor is "subcritical." If $f > 1$, it is "supercritical" (and could become dangerously explosive). Reactors are equipped with movable **control rods** (good neutron absorbers like cadmium or boron), whose function is to absorb neutrons and maintain the reactor at just barely "critical," $f = 1$.

The release of neutrons and subsequent fissions occur so quickly that manipulation of the control rods to maintain $f = 1$ would not be possible if it weren't for the small percentage ($\approx 1\%$) of so-called **delayed neutrons**. They come from the decay of neutron-rich fission fragments (or their daughters) having lifetimes on the order of seconds—sufficient to allow enough reaction time to operate the control rods and maintain $f = 1$.

Nuclear reactors have been built for use in research and to produce electric power. Fission produces many neutrons and a "research reactor" is basically an intense source of neutrons. These neutrons can be used as projectiles in nuclear reactions to produce nuclides not found in nature, including isotopes used as tracers and for therapy. A "power reactor" is used to produce electric power.

†$^{238}_{92}U$ will fission, but only with fast neutrons ($^{238}_{92}U$ is more stable than $^{235}_{92}U$). The probability of absorbing a fast neutron and producing a fission is too low to produce a self-sustaining chain reaction.

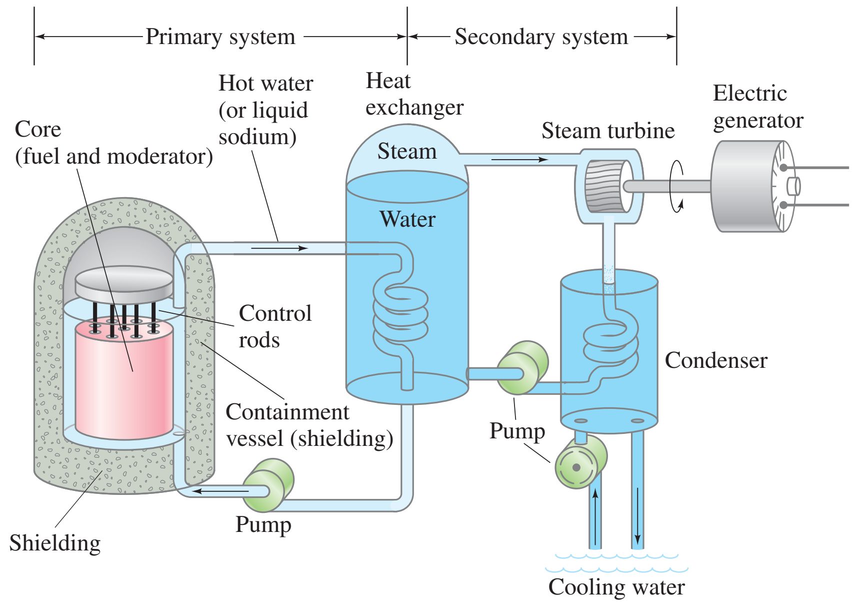


FIGURE 31–8 A nuclear reactor. The heat generated by the fission process in the fuel rods is carried off by hot water or liquid sodium and is used to boil water to steam in the heat exchanger. The steam drives a turbine to generate electricity and is then cooled in the condenser (to reduce pressure on the back side of the turbine blades).

The energy released in the fission process appears as heat, which is used to boil water and produce steam to drive a turbine connected to an electric generator (Fig. 31–8). The **core** of a nuclear reactor consists of the fuel and a moderator (water in most U.S. commercial reactors). The fuel is usually uranium enriched so that it contains 2 to 4 percent $^{235}_{92}\mathrm{U}$. Water at high pressure or other liquid (such as liquid sodium) is allowed to flow through the core. The thermal energy it absorbs is used to produce steam in the heat exchanger, so the fissionable fuel acts as the heat input for a heat engine (Chapter 15).

There are problems associated with nuclear power plants. Besides the usual thermal pollution associated with any heat engine (Section 15–11), there is the serious problem of disposal of the radioactive fission fragments produced in the reactor, plus radioactive nuclides produced by neutrons interacting with the structural parts of the reactor. Fission fragments, like their uranium or plutonium parents, have about 50% more neutrons than protons. Nuclei with atomic number in the typical range for fission fragments $(Z \approx 30 \text{ to } 60)$ are stable only if they have more nearly equal numbers of protons and neutrons (see Fig. 30–2). Hence the highly neutron-rich fission fragments are very unstable and decay radioactively. The accidental release of highly radioactive fission fragments into the atmosphere poses a serious threat to human health (Section 31–4), as does possible leakage of the radioactive wastes when they are disposed of. The accidents at Three Mile Island, Pennsylvania (1979), at Chernobyl, Russia (1986), and at Fukushima, Japan (2011), have illustrated some of the dangers and have shown that nuclear plants must be located, constructed, maintained, and operated with great care and precision (Fig. 31–9).

FIGURE 31–9 Smoke rising from Fukushima, Japan, after the nuclear power plant meltdown in 2011.

Finally, the lifetime of nuclear power plants is limited to 30-some years, due to buildup of radioactivity and the fact that the structural materials themselves are weakened by the intense conditions inside. The cost of "decommissioning" a power plant is very great.

So-called **breeder reactors** were proposed as a solution to the problem of limited supplies of fissionable uranium, $^{235}_{92}\mathrm{U}$. A breeder reactor is one in which some of the neutrons produced in the fission of $^{235}_{92}\mathrm{U}$ are absorbed by $^{238}_{92}\mathrm{U}$, and $^{239}_{94}\mathrm{Pu}$ is produced via the set of reactions shown in Fig. 31–1. $^{239}_{94}\mathrm{Pu}$ is fissionable with slow neutrons, so after separation it can be used as a fuel in a nuclear reactor. Thus a breeder reactor "breeds" new fuel† $\left(^{239}_{94}\mathrm{Pu}\right)$ from otherwise useless $^{238}_{92}\mathrm{U}$. Natural uranium is 99.3 percent $^{238}_{92}\mathrm{U}$, which in a breeder becomes useful fissionable $^{239}_{94}\mathrm{Pu}$, thus increasing the supply of fissionable fuel by more than a factor of 100. But breeder reactors have the same problems as other reactors, plus other serious problems. Not only is plutonium a serious health hazard in itself (radioactive with a half-life of 24,000 years), but plutonium produced in a reactor can readily be used in a bomb, increasing the danger of nuclear proliferation and theft of fuel to produce a bomb.

†A breeder reactor does *not* produce more fuel than it uses.

Nuclear power presents risks. Other large-scale energy-conversion methods, such as conventional oil and coal-burning steam plants, also present health and environmental hazards; some of them were discussed in Section 15–11, and include air pollution, oil spills, and the release of CO_2 gas which can trap heat as in a greenhouse to raise the Earth's temperature. The solution to the world's needs for energy is not only technological, but also economic and political. A major factor surely is to "conserve"—to minimize our energy use. "Reduce, reuse, recycle."

EXAMPLE 31–5 **Uranium fuel amount.** Estimate the minimum amount of $^{235}_{92}U$ that needs to undergo fission in order to run a 1000-MW power reactor per year of continuous operation. Assume an efficiency (Chapter 15) of about 33%.

APPROACH At 33% efficiency, we need $3 \times 1000\text{ MW} = 3000 \times 10^6\text{ J/s}$ input. Each fission releases about 200 MeV (Eq. 31–5), so we divide the energy for a year by 200 MeV to get the number of fissions needed per year. Then we multiply by the mass of one uranium atom.

SOLUTION For 1000 MW output, the total power generation needs to be 3000 MW, of which 2000 MW is dumped as "waste" heat. Thus the total energy release in 1 yr $(3 \times 10^7\text{ s})$ from fission needs to be about

$$(3 \times 10^9\text{ J/s})(3 \times 10^7\text{ s}) \approx 10^{17}\text{ J}.$$

If each fission releases 200 MeV of energy, the number of fissions required for a year is

$$\frac{(10^{17}\text{ J})}{(2 \times 10^8\text{ eV/fission})(1.6 \times 10^{-19}\text{ J/eV})} \approx 3 \times 10^{27}\text{ fissions}.$$

The mass of a single uranium atom is about $(235\text{ u})(1.66 \times 10^{-27}\text{ kg/u}) \approx 4 \times 10^{-25}\text{ kg}$, so the total uranium mass needed is

$$(4 \times 10^{-25}\text{ kg/fission})(3 \times 10^{27}\text{ fissions}) \approx 1000\text{ kg},$$

or about a ton of $^{235}_{92}U$.

NOTE Because $^{235}_{92}U$ makes up only 0.7% of natural uranium, the yearly requirement for uranium is on the order of a hundred tons. This is orders of magnitude less than coal, both in mass and volume. Coal releases $2.8 \times 10^7\text{ J/kg}$, whereas $^{235}_{92}U$ can release 10^{17} J per ton, as we just calculated, or $10^{17}\text{ J}/10^3\text{ kg} = 10^{14}\text{ J/kg}$. For natural uranium, the figure is 100 times less, 10^{12} J/kg.

EXERCISE C A nuclear-powered submarine needs 6000-kW input power. How many $^{235}_{92}U$ fissions is this per second?

Atom Bomb

The first use of fission, however, was not to produce electric power. Instead, it was first used as a fission bomb (called the "atomic bomb"). In early 1940, with Europe already at war, Germany's leader, Adolf Hitler, banned the sale of uranium from the Czech mines he had recently taken over. Research into the fission process suddenly was enshrouded in secrecy. Physicists in the United States were alarmed. A group of them approached Einstein—a man whose name was a household word—to send a letter to President Franklin Roosevelt about the possibilities of using nuclear fission for a bomb far more powerful than any previously known, and inform him that Germany might already have begun development of such a bomb. Roosevelt responded by authorizing the program known as the Manhattan Project, to see if a bomb could be built. Work began in earnest after Fermi's demonstration in 1942 that a sustained chain reaction was possible. A new secret laboratory was developed on an isolated mesa in New Mexico known as Los Alamos. Under the direction of J. Robert Oppenheimer (1904–1967; Fig. 31–10), it became the home of famous scientists from all over Europe and the United States.

FIGURE 31–10 J. Robert Oppenheimer, on the left, with General Leslie Groves, who was the administrative head of Los Alamos during World War II. The photograph was taken at the Trinity site in the New Mexico desert, where the first atomic bomb was exploded.

FIGURE 31–11 Photo taken a month after the bomb was dropped on Nagasaki. The shacks were constructed afterwards from debris in the ruins. The bombs dropped on Hiroshima and Nagasaki were each equivalent to about 20,000 tons of the common explosive TNT ($\sim 10^{14}$ J).

To build a bomb that was subcritical during transport but that could be made supercritical (to produce a chain reaction) at just the right moment, two pieces of uranium were used, each less than the critical mass but together greater than the critical mass. The two masses, kept separate until the moment of detonation, were then forced together quickly by a kind of gun, and a chain reaction of explosive proportions occurred. An alternate bomb detonated conventional explosives (TNT) surrounding a plutonium sphere to compress it by implosion to double its density, making it more than critical and causing a nuclear explosion. The first fission bomb was tested in the New Mexico desert in July 1945. It was successful. In early August, a fission bomb using uranium was dropped on Hiroshima and a second, using plutonium, was dropped on Nagasaki (Fig. 31–11), both in Japan. World War II ended shortly thereafter.

Besides its destructive power, a fission bomb produces many highly radioactive fission fragments, as does a nuclear reactor. When a fission bomb explodes, these radioactive isotopes are released into the atmosphere as **radioactive fallout**.

Testing of nuclear bombs in the atmosphere after World War II was a cause of concern, because the movement of air masses spread the fallout all over the globe. Radioactive fallout eventually settles to the Earth, particularly in rainfall, and is absorbed by plants and grasses and enters the food chain. This is a far more serious problem than the same radioactivity on the exterior of our bodies, because α and β particles are largely absorbed by clothing and the outer (dead) layer of skin. But inside our bodies as food, the isotopes are in contact with living cells. One particularly dangerous radioactive isotope is ${}^{90}_{38}\mathrm{Sr}$, which is chemically much like calcium and becomes concentrated in bone, where it causes bone cancer and destroys bone marrow. The 1963 treaty signed by over 100 nations that bans nuclear weapons testing in the atmosphere was motivated because of the hazards of fallout.

31–3 Nuclear Fusion

The mass of every stable nucleus is less than the sum of the masses of its constituent protons and neutrons. For example, the mass of the helium isotope ${}^{4}_{2}\mathrm{He}$ is less than the mass of two protons plus two neutrons, Example 30–3. If two protons and two neutrons were to come together to form a helium nucleus, there would be a loss of mass. This mass loss is manifested in the release of energy.

Nuclear Fusion; Stars

The process of building up nuclei by bringing together individual protons and neutrons, or building larger nuclei by combining small nuclei, is called **nuclear fusion**. In Fig. 31–12 (same as Fig. 30–1), we can see why small nuclei can combine to form larger ones with the release of energy: it is because the binding energy per nucleon is less for light nuclei than it is for heavier nuclei (up to about $A \approx 60$).

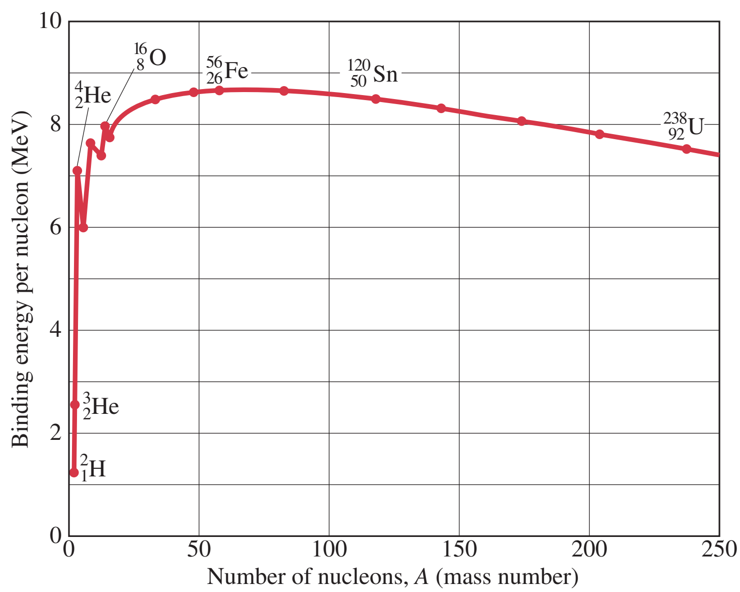


FIGURE 31–12 Average binding energy per nucleon as a function of mass number A for stable nuclei. Same as Fig. 30–1.

For two positively charged nuclei to get close enough to fuse, they must have very high kinetic energy to overcome the electric repulsion. It is believed that many of the elements in the universe were originally formed through the process of fusion in stars (see Chapter 33) where the temperature is extremely high, corresponding to high KE (Eq. 13–8). Today fusion is still producing the prodigious amounts of light energy (EM waves) stars emit, including our Sun.

EXAMPLE 31–6 **Fusion energy release.** One of the simplest fusion reactions involves the production of deuterium, ^2_1H, from a neutron and a proton: $^1_1\text{H} + \text{n} \rightarrow {^2_1\text{H}} + \gamma$. How much energy is released in this reaction?

APPROACH The energy released equals the difference in mass (times c^2) between the initial and final masses.

SOLUTION From Appendix B, the initial mass is

$$1.007825\text{ u} + 1.008665\text{ u} = 2.016490\text{ u},$$

and after the reaction the mass is that of the ^2_1H, namely 2.014102 u (the γ is massless). The mass difference is

$$2.016490\text{ u} - 2.014102\text{ u} = 0.002388\text{ u},$$

so the energy released is

$$(\Delta m)c^2 = (0.002388\text{ u})(931.5\text{ MeV/u}) = 2.22\text{ MeV},$$

and it is carried off by the ^2_1H nucleus and the γ ray.

The energy output of our Sun is believed to be due principally to the following sequence of fusion reactions:

Proton–proton chain

$$^1_1\text{H} + {^1_1\text{H}} \rightarrow {^2_1\text{H}} + \text{e}^+ + \nu \qquad (0.42\text{ MeV}) \qquad \textbf{(31–6a)}$$

$$^1_1\text{H} + {^2_1\text{H}} \rightarrow {^3_2\text{He}} + \gamma \qquad (5.49\text{ MeV}) \qquad \textbf{(31–6b)}$$

$$^3_2\text{He} + {^3_2\text{He}} \rightarrow {^4_2\text{He}} + {^1_1\text{H}} + {^1_1\text{H}}. \qquad (12.86\text{ MeV}) \qquad \textbf{(31–6c)}$$

where the energy released (Q-value) for each reaction is given in parentheses. These reactions are between nuclei (without electrons at these very high temperatures); the first reaction can be written as

$$\text{p} + \text{p} \rightarrow \text{d} + \text{e}^+ + \nu$$

where p = proton and d = deuteron. The net effect of this sequence, which is called the **proton–proton chain**, is for four protons to combine to form one ^4_2He nucleus plus two positrons, two neutrinos, and two gamma rays:

$$4\,{^1_1\text{H}} \rightarrow {^4_2\text{He}} + 2\text{e}^+ + 2\nu + 2\gamma. \qquad \textbf{(31–7)}$$

Note that it takes two of each of the first two reactions (Eqs. 31–6a and b) to produce the two ^3_2He for the third reaction. So the total energy release for the net reaction, Eq. 31–7, is $(2 \times 0.42\text{ MeV} + 2 \times 5.49\text{ MeV} + 12.86\text{ MeV}) = 24.7\text{ MeV}$. In addition, each of the two e^+ (Eq. 31–6a) quickly annihilates with an electron to produce 2 γ rays (Section 27–6) with total energy $2m_e c^2 = 1.02\text{ MeV}$; so the total energy released is $(24.7\text{ MeV} + 2 \times 1.02\text{ MeV}) = 26.7\text{ MeV}$. The first reaction, the formation of deuterium from two protons (Eq. 31–6a), has a very low probability, and so limits the rate at which the Sun produces energy. (Thank goodness! This is why the Sun is still shining brightly.)

EXERCISE D Return to the Chapter-Opening Question, page 885, and answer it again now. Try to explain why you may have answered it differently the first time.

EXAMPLE 31–7 ESTIMATE **Estimating fusion energy.** Estimate the energy released if the following reaction occurred:

$$^2_1\text{H} + {^2_1\text{H}} \rightarrow {^4_2\text{He}}.$$

APPROACH We use Fig. 31–12 for a quick estimate.

SOLUTION We see in Fig. 31–12 that each ^2_1H has a binding energy of about $1\frac{1}{4}$ MeV/nucleon, which for 2 nuclei of mass 2 is $4 \times \left(1\frac{1}{4}\right) \approx 5\text{ MeV}$. The ^4_2He has a binding energy per nucleon (Fig. 31–12) of about 7 MeV for a total of $4 \times 7\text{ MeV} \approx 28\text{ MeV}$. Hence the energy release is about $28\text{ MeV} - 5\text{ MeV} \approx 23\text{ MeV}$.

In stars hotter than the Sun, it is more likely that the energy output comes principally from the **carbon** (or **CNO**) **cycle**, which comprises the following sequence of reactions:

Carbon cycle

$$
\begin{aligned}
{}^{12}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{H} &\rightarrow {}^{13}_{7}\mathrm{N} + \gamma \\
{}^{13}_{7}\mathrm{N} &\rightarrow {}^{13}_{6}\mathrm{C} + \mathrm{e}^{+} + \nu \\
{}^{13}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{H} &\rightarrow {}^{14}_{7}\mathrm{N} + \gamma \\
{}^{14}_{7}\mathrm{N} + {}^{1}_{1}\mathrm{H} &\rightarrow {}^{15}_{8}\mathrm{O} + \gamma \\
{}^{15}_{8}\mathrm{O} &\rightarrow {}^{15}_{7}\mathrm{N} + \mathrm{e}^{+} + \nu \\
{}^{15}_{7}\mathrm{N} + {}^{1}_{1}\mathrm{H} &\rightarrow {}^{12}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He}.
\end{aligned}
$$

No net carbon is consumed in this cycle and the net effect is the same as the proton–proton chain, Eq. 31–7 (plus one extra γ). The theory of the proton–proton chain and of the carbon cycle as the source of energy for the Sun and stars was first worked out by Hans Bethe (1906–2005) in 1939.

CONCEPTUAL EXAMPLE 31–8 **Stellar fusion.** What is the heaviest element likely to be produced in fusion processes in stars?

RESPONSE Fusion is possible if the final products have more binding energy (less mass) than the reactants, because then there is a net release of energy. Since the binding energy curve in Fig. 31–12 (or Fig. 30–1) peaks near $A \approx 56$ to 58 which corresponds to iron or nickel, it would not be energetically favorable to produce elements heavier than that. Nevertheless, in the center of massive stars or in supernova explosions, there is enough initial kinetic energy available to drive endothermic reactions that produce heavier elements as well.

EXERCISE E If the Sun is generating a constant amount of energy via fusion, the mass of the Sun must be (*a*) increasing, (*b*) decreasing, (*c*) constant, (*d*) irregular.

Possible Fusion Reactors

PHYSICS APPLIED
Fusion energy reactors

The possibility of utilizing the energy released in fusion to make a power reactor is very attractive. The fusion reactions most likely to succeed in a reactor involve the isotopes of hydrogen, ${}^{2}_{1}\mathrm{H}$ (deuterium) and ${}^{3}_{1}\mathrm{H}$ (tritium), and are as follows, with the energy released given in parentheses:

$$ {}^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{3}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \qquad (4.03\ \mathrm{MeV}) \qquad \textbf{(31–8a)} $$

$$ {}^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + \mathrm{n} \qquad (3.27\ \mathrm{MeV}) \qquad \textbf{(31–8b)} $$

$$ {}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + \mathrm{n}. \qquad (17.59\ \mathrm{MeV}) \qquad \textbf{(31–8c)} $$

Comparing these energy yields with that for the fission of ${}^{235}_{92}\mathrm{U}$, we can see that the energy released in fusion reactions can be greater for a given mass of fuel than in fission. Furthermore, as fuel, a fusion reactor could use deuterium, which is very plentiful in the water of the oceans (the natural abundance of ${}^{2}_{1}\mathrm{H}$ is 0.0115% on average, or about 1 g of deuterium per 80 L of water). The simple proton–proton reaction of Eq. 31–6a, which could use a much more plentiful source of fuel, ${}^{1}_{1}\mathrm{H}$, has such a small probability of occurring that it cannot be considered a possibility on Earth.

Although a useful fusion reactor has not yet been achieved, considerable progress has been made in overcoming the inherent difficulties. The problems are associated with the fact that all nuclei have a positive charge and repel each other. However, if they can be brought close enough together so that the short-range attractive strong nuclear force can come into play, it can pull the nuclei together and fusion can occur. For the nuclei to get close enough together, they must have large kinetic energy to overcome the electric repulsion. High kinetic energies are readily attainable with particle accelerators (Chapter 32), but the number of particles involved is too small. To produce realistic amounts of energy, we must deal with matter in bulk, for which high kinetic energy means higher temperatures.

Indeed, very high temperatures are required for sustained fusion to occur, and fusion devices are often referred to as **thermonuclear devices**. The interiors of the Sun and other stars are very hot, many millions of degrees, so the nuclei are moving fast enough for fusion to take place, and the energy released keeps the temperature high so that further fusion reactions can occur. The Sun and the stars represent huge self-sustaining thermonuclear reactors that stay together because of their great gravitational mass. But on Earth, containment of the fast-moving nuclei at the high temperatures and densities required has proven difficult.

It was realized after World War II that the temperature produced within a fission (or "atomic") bomb was close to 10^8 K. This suggested that a fission bomb could be used to ignite a fusion bomb (popularly known as a thermonuclear or hydrogen bomb) to release the vast energy of fusion. The uncontrollable release of fusion energy in an H-bomb (in 1952) was relatively easy to obtain. But to realize usable energy from fusion at a slow and controlled rate has turned out to be a serious challenge.

EXAMPLE 31–9 ESTIMATE Temperature needed for d–t fusion. Estimate the temperature required for deuterium–tritium fusion (d–t) to occur.

APPROACH We assume the nuclei approach head-on, each with kinetic energy KE, and that the nuclear force comes into play when the distance between their centers equals the sum of their nuclear radii. The electrostatic potential energy (Chapter 17) of the two particles at this distance equals the minimum total kinetic energy of the two particles when far apart. The average kinetic energy is related to Kelvin temperature by Eq. 13–8.

SOLUTION The radii of the two nuclei ($A_d = 2$ and $A_t = 3$) are given by Eq. 30–1: $r_d \approx 1.5\,\mathrm{fm}$, $r_t \approx 1.7\,\mathrm{fm}$, so $r_d + r_t = 3.2 \times 10^{-15}\,\mathrm{m}$. We equate the kinetic energy of the two initial particles to the potential energy when at this distance:

$$2\mathrm{KE} \approx \frac{1}{4\pi\epsilon_0}\frac{e^2}{(r_d + r_t)}$$

$$\approx \left(9.0 \times 10^9\,\frac{\mathrm{N\cdot m^2}}{\mathrm{C^2}}\right)\frac{(1.6 \times 10^{-19}\,\mathrm{C})^2}{(3.2 \times 10^{-15}\,\mathrm{m})(1.6 \times 10^{-19}\,\mathrm{J/eV})} \approx 0.45\,\mathrm{MeV}.$$

Thus, $\mathrm{KE} \approx 0.22\,\mathrm{MeV}$, and if we ask that the average kinetic energy be this high, then from Eq. 13–8, $\frac{3}{2}kT = \overline{\mathrm{KE}}$, we have a temperature of

$$T = \frac{2\overline{\mathrm{KE}}}{3k} = \frac{2(0.22\,\mathrm{MeV})(1.6 \times 10^{-13}\,\mathrm{J/MeV})}{3(1.38 \times 10^{-23}\,\mathrm{J/K})} \approx 2 \times 10^9\,\mathrm{K}.$$

NOTE More careful calculations show that the temperature required for fusion is actually about an order of magnitude less than this rough estimate, partly because it is not necessary that the *average* kinetic energy be 0.22 MeV—a small percentage of nuclei with this much energy (in the high-energy tail of the Maxwell distribution, Fig. 13–20) would be sufficient. Reasonable estimates for a usable fusion reactor are in the range $T \gtrsim 1$ to 4×10^8 K.

A high temperature is required for a fusion reactor. But there must also be a high density of nuclei to ensure a sufficiently high collision rate. A real difficulty with controlled fusion is to contain nuclei long enough and at a high enough density for sufficient reactions to occur so that a usable amount of energy is obtained. At the temperatures needed for fusion, the atoms are ionized, and the resulting collection of nuclei and electrons is referred to as a **plasma**. Ordinary materials vaporize at a few thousand degrees at most, and hence cannot be used to contain a high-temperature plasma. Two major containment techniques are *magnetic confinement* and *inertial confinement*.

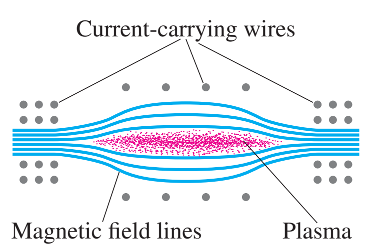


FIGURE 31–13 "Magnetic bottle" used to confine a plasma.

In **magnetic confinement**, magnetic fields are used to try to contain the hot plasma. A simple approach is the "magnetic bottle" shown in Fig. 31–13. The paths of the charged particles in the plasma are bent by the magnetic field; where magnetic field lines are close together, the force on the particles reflects them

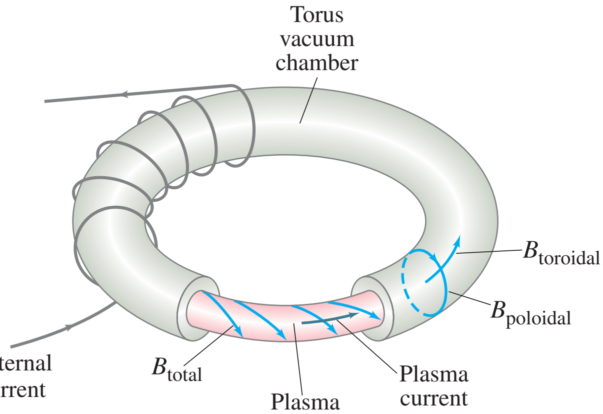


FIGURE 31–14 Tokamak configuration, showing the total $\vec{\mathbf{B}}$ field due to external current plus current in the plasma itself.

back toward the center. Unfortunately, magnetic bottles develop "leaks" and the charged particles slip out before sufficient fusion takes place. The most promising design today is the **tokamak**, first developed in Russia. A tokamak (Fig. 31–14) is toroid-shaped (a torus, which is like a donut) and involves complicated magnetic fields: current-carrying conductors produce a magnetic field directed along the axis of the toroid ("toroidal" field); an additional field is produced by currents within the plasma itself ("poloidal" field). The combination produces a helical field as shown in Fig. 31–14, confining the plasma, at least briefly, so it doesn't touch the vacuum chamber's metal walls (Fig. 31–15a).

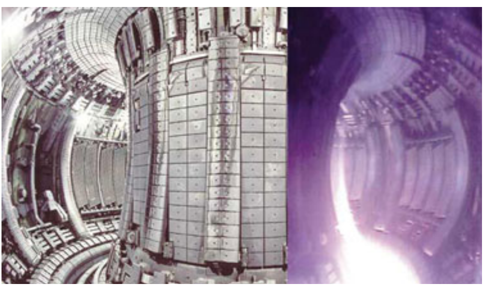
In 1957, J. D. Lawson showed that the product of ion density n ($=$ ions/m^3) and confinement time τ must exceed a minimum value of approximately

$$n\tau \gtrsim 3 \times 10^{20}\,\mathrm{s/m^3}.$$

This **Lawson criterion** must be reached to produce **ignition**, meaning fusion that continues after all external heating is turned off. Practically, it is expected to be achieved with $n \approx 1$ to $3 \times 10^{20}\,\mathrm{m^{-3}}$ and $\tau \approx 1$ to 3 s. To reach **break-even**, the point at which the energy output due to fusion is equal to the energy input to heat the plasma, requires an $n\tau$ about an order of magnitude less. The break-even point was very closely approached in the 1990s at the Tokamak Fusion Test Reactor (TFTR) at Princeton, and the very high temperature needed for ignition $(4 \times 10^8\,\mathrm{K})$ was exceeded—although not both of these at the same time.

Magnetic confinement fusion research continues throughout the world. This research will help us in developing the huge multinational test device (European Union, India, Japan, South Korea, Russia, China, and the U.S.), called ITER (International Thermonuclear Experimental Reactor). It is hoped that ITER will be finished and running by 2020, in France, with an expected power output of about 500 MW, 10 times the input energy. ITER is planned to be the final research step before building a working reactor.

The second method for containing the fuel for fusion is **inertial confinement fusion** (ICF): a small pellet or capsule of deuterium and tritium (Fig. 31–15b) is struck simultaneously from hundreds of directions by very intense laser beams. The intense influx of energy heats and ionizes the pellet into a plasma, compressing it and heating it to temperatures at which fusion can occur $(>10^8\,\mathrm{K})$. The confinement time is on the order of 10^{-11} to 10^{-9} s, during which time the ions do not move appreciably because of their own inertia, and fusion can take place.


(a)

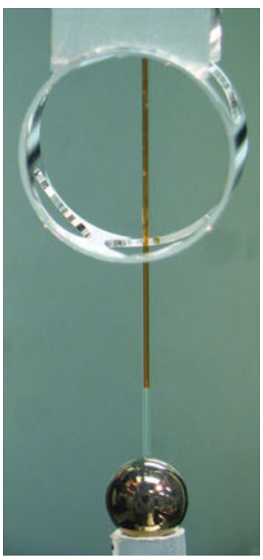

(b)

FIGURE 31–15 (a) Tokamak: split image view of the Joint European Torus (JET) located near Oxford, England. Interior, on the left, and an actual plasma in there ($T \approx 1 \times 10^8$ K) on the right. (b) A 2-mm-diameter round d–t (deuterium–tritium) inertial target, being filled through a thin glass tube from above, at the National Ignition Facility (NIF), Lawrence Livermore National Laboratory, California.

31–4 Passage of Radiation Through Matter; Biological Damage

When we speak of *radiation*, we include α, β, γ, and X-rays, as well as protons, neutrons, and other particles such as pions (see Chapter 32). Because charged particles can ionize the atoms or molecules of any material they pass through, they are referred to as **ionizing radiation**. And because radiation produces ionization, it can cause considerable damage to materials, particularly to biological tissue.

Charged particles, such as α and β rays and protons, cause ionization because of electric forces. That is, when they pass through a material, they can attract or repel electrons strongly enough to remove them from the atoms of the material. Since the α and β rays emitted by radioactive substances have energies on the order of 1 MeV (10^4 to 10^7 eV), whereas ionization of atoms and molecules requires on the order of 10 eV (Chapter 27), we see that a single α or β particle can cause thousands of ionizations.

Neutral particles also give rise to ionization when they pass through materials. For example, X-ray and γ-ray photons can ionize atoms by knocking out electrons by means of the photoelectric and Compton effects (Chapter 27). Furthermore, if a γ ray has sufficient energy (greater than 1.02 MeV), it can undergo pair production: an electron and a positron are produced (Section 27–6). The charged particles produced in all of these processes can themselves go on to produce further ionization. Neutrons, on the other hand, interact with matter mainly by collisions with nuclei, with which they interact strongly. Often the nucleus is broken apart by such a collision, altering the molecule of which it was a part. The fragments produced can in turn cause ionization.

Radiation passing through matter can do considerable damage. Metals and other structural materials become brittle and their strength can be weakened if the radiation is very intense, as in nuclear reactor power plants and for space vehicles that must pass through areas of intense cosmic radiation.

Biological Damage

PHYSICS APPLIED
Biological radiation damage

The radiation damage produced in biological organisms is due primarily to ionization produced in cells. Several related processes can occur. Ions or radicals are produced that are highly reactive and take part in chemical reactions that interfere with the normal operation of the cell. All forms of radiation can ionize atoms by knocking out electrons. If these are bonding electrons, the molecule may break apart, or its structure may be altered so that it does not perform its normal function or may perform a harmful function. In the case of proteins, the loss of one molecule is not serious if there are other copies of the protein in the cell and additional copies can be made from the gene that codes for it. However, large doses of radiation may damage so many molecules that new copies cannot be made quickly enough, and the cell dies.

Damage to the DNA is more serious, since a cell may have only one copy. Each alteration in the DNA can affect a gene and alter the molecule that gene codes for (Section 29–3), so that needed proteins or other molecules may not be made at all. Again the cell may die. The death of a single cell is not normally a problem, since the body can replace it with a new one. (There are exceptions, such as neurons, which are mostly not replaceable, so their loss is serious.) But if many cells die, the organism may not be able to recover. On the other hand, a cell may survive but be defective. It may go on dividing and produce many more defective cells, to the detriment of the whole organism. Thus radiation can cause cancer—the rapid uncontrolled production of cells.

The possible damage done by the medical use of X-rays and other radiation must be balanced against the medical benefits and prolongation of life as a result of their diagnostic use.

31–5 Measurement of Radiation—Dosimetry

Although the passage of ionizing radiation through the human body can cause considerable damage, radiation can also be used to treat certain diseases, particularly cancer, often by using very narrow beams directed at a cancerous tumor in order to destroy it (Section 31–6). It is therefore important to be able to quantify the amount, or **dose**, of radiation. This is the subject of **dosimetry**.

PHYSICS APPLIED
Dosimetry

The strength of a source can be specified at a given time by stating the **source activity**: how many nuclear decays (or disintegrations) occur per second. The traditional unit is the **curie** (Ci), defined as

$$1\ \text{Ci} = 3.70 \times 10^{10}\ \text{decays per second.}$$

(This number comes from the original definition as the activity of exactly one gram of radium.) Although the curie is still in common use, the SI unit for source activity is the **becquerel** (Bq), defined as

$$1\ \text{Bq} = 1\ \text{decay/s.}$$

CAUTION
In the lab, activity will be less than written on the bottle—note the date

Commercial suppliers of **radionuclides** (radioactive nuclides) used as tracers specify the activity at a given time. Because the activity decreases over time, more so for short-lived isotopes, it is important to take this decrease into account.

The magnitude of the source activity, $\Delta N/\Delta t$, is related to the number of radioactive nuclei present, N, and to the half-life, $T_{\frac{1}{2}}$, by (see Section 30–8):

$$\frac{\Delta N}{\Delta t} = \lambda N = \frac{0.693}{T_{\frac{1}{2}}} N.$$

EXAMPLE 31–10 Radioactivity taken up by cells. In a certain experiment, 0.016 μCi of $^{32}_{15}\text{P}$ is injected into a medium containing a culture of bacteria. After 1.0 h the cells are washed and a 70% efficient detector (counts 70% of emitted β rays) records 720 counts per minute from the cells. What percentage of the original $^{32}_{15}\text{P}$ was taken up by the cells?

APPROACH The half-life of $^{32}_{15}\text{P}$ is about 14 days (Appendix B), so we can ignore any loss of activity over 1 hour. From the given activity, we find how many β rays are emitted. We can compare 70% of this to the $(720/\text{min})/(60\ \text{s/min}) = 12$ per second detected.

SOLUTION The total number of decays per second originally was $(0.016 \times 10^{-6})(3.7 \times 10^{10}) = 590$. The counter could be expected to count 70% of this, or 410 per second. Since it counted $720/60 = 12$ per second, then $12/410 = 0.029$ or 2.9% was incorporated into the cells.

Another type of measurement is the exposure or **absorbed dose**—that is, the *effect* the radiation has on the absorbing material. The earliest unit of dosage was the **roentgen** (R), defined in terms of the amount of ionization produced by the radiation ($1\ \text{R} = 1.6 \times 10^{12}$ ion pairs per gram of dry air at standard conditions). Today, 1 R is defined as the amount of X-ray or γ radiation that deposits 0.878×10^{-2} J of energy per kilogram of air. The roentgen was largely superseded by another unit of absorbed dose applicable to any type of radiation, the **rad**: *1 rad is that amount of radiation which deposits energy per unit mass of 1.00×10^{-2} J/kg in any absorbing material.* (This is quite close to the roentgen for X- and γ rays.) The proper SI unit for absorbed dose is the **gray** (Gy):

$$1\ \text{Gy} = 1\ \text{J/kg} = 100\ \text{rad}. \tag{31–9}$$

The absorbed dose depends not only on the energy per particle and on the strength of a given source or of a radiation beam (number of particles per second), but also on the type of material that is absorbing the radiation. Bone, for example, absorbs more of X-ray or γ radiation normally used than does flesh, so the same beam passing through a human body deposits a greater dose (in rads or grays) in bone than in flesh.

The gray and the rad are physical units of dose—the energy deposited per unit mass of material. They are, however, not the most meaningful units for measuring the biological damage produced by radiation because equal doses of different types of radiation cause differing amounts of damage. For example, 1 rad of α radiation does 10 to 20 times the amount of damage as 1 rad of β or γ rays. This difference arises largely because α rays (and other heavy particles such as protons and neutrons) move much more slowly than β and γ rays of equal energy due to their greater mass. Hence, ionizing collisions occur closer together, so more irreparable damage can be done. The **relative biological effectiveness** (RBE) of a given type of radiation is defined as the number of rads of X-ray or γ radiation that produces the same biological damage as 1 rad of the given radiation. For example, 1 rad of slow neutrons does the same damage as 5 rads of X-rays. Table 31–1 gives the RBE for several types of radiation. The numbers are approximate because they depend somewhat on the energy of the particles and on the type of damage that is used as the criterion.

TABLE 31–1 Relative Biological Effectiveness (RBE)

Type	RBE
X- and γ rays	1
β (electrons)	1
Protons	2
Slow neutrons	5
Fast neutrons	≈ 10
α particles and heavy ions	≈ 20

The **effective dose** can be given as the product of the dose in rads and the RBE, and this unit is known as the **rem** (which stands for *rad equivalent man*):

$$\text{effective dose (in rem)} = \text{dose (in rad)} \times \text{RBE}. \qquad \textbf{(31–10a)}$$

This unit is being replaced by the SI unit for "effective dose," the **sievert** (Sv):

$$\text{effective dose (Sv)} = \text{dose (Gy)} \times \text{RBE} \qquad \textbf{(31–10b)}$$

so

$$1\,\text{Sv} = 100\,\text{rem} \qquad \text{or} \qquad 1\,\text{rem} = 10\,\text{mSv}.$$

By these definitions, 1 rem (or 1 Sv) of any type of radiation does approximately the same amount of biological damage. For example, 50 rem of fast neutrons does the same damage as 50 rem of γ rays. But note that 50 rem of fast neutrons is only 5 rads, whereas 50 rem of γ rays is 50 rads.

Human Exposure to Radiation

PHYSICS APPLIED
Radon

We are constantly exposed to low-level radiation from natural sources: cosmic rays, natural radioactivity in rocks and soil, and naturally occurring radioactive isotopes in our food, such as $^{40}_{19}$K. **Radon**, $^{222}_{86}$Rn, is of considerable concern today. It is the product of radium decay and is an intermediate in the decay series from uranium (see Fig. 30–11). Most intermediates remain in the rocks where formed, but radon is a gas that can escape from rock (and from building material like concrete) to enter the air we breathe, and damage the interior of the lung.

PHYSICS APPLIED
Human radiation exposure

The **natural radioactive background** averages about 0.30 rem (300 mrem) per year per person in the U.S., although there are large variations. From medical X-rays and scans, the average person receives about 50 to 60 mrem per year, giving an average total dose of about 360 mrem (3.6 mSv) per person. U.S. government regulators suggest an upper limit of allowed radiation for an individual in the general populace at about 100 mrem (1 mSv) per year in addition to natural background. It is believed that even low doses of radiation increase the chances of cancer or genetic defects; there is *no safe level* or threshold of radiation exposure.

PHYSICS APPLIED
Radiation worker exposure
Film badge

The upper limit for people who work around radiation—in hospitals, in power plants, in research—has been set higher, a maximum of 20 mSv (2 rem) whole-body dose, averaged over some years (a maximum of 50 mSv (5 rem/yr) in any one year). To monitor exposure, those people who work around radiation generally carry some type of dosimeter, one common type being a **radiation film badge** which is a piece of film wrapped in light-tight material. The passage of ionizing radiation through the film changes it so that the film is darkened upon development, and thus indicates the received dose. Newer types include the *thermoluminescent dosimeter* (TLD). Dosimeters and badges do not protect the worker, but high levels detected suggest reassignment or modified work practices to reduce radiation exposure to acceptable levels.

PHYSICS APPLIED
Radiation sickness

Large doses of radiation can cause unpleasant symptoms such as nausea, fatigue, and loss of body hair, because of cellular damage. Such effects are sometimes referred to as **radiation sickness**. Very large doses can be fatal, although the time span of the dose is important. A brief dose of 10 Sv (1000 rem) is nearly always fatal. A 3-Sv (300-rem) dose in a short period of time is fatal in about 50% of patients within a month. However, the body possesses remarkable repair processes, so that a 3-Sv dose spread over several weeks is usually not fatal. It will, nonetheless, cause considerable damage to the body.

The effects of low doses over a long time are difficult to determine and are not well known as yet.

CONCEPTUAL EXAMPLE 31–11 **Limiting the dose.** A worker in an environment with a radioactive source is warned that she is accumulating a dose too quickly and will have to lower her exposure by a factor of ten to continue working for the rest of the year. If the worker is able to work farther away from the source, how much farther away is necessary?

RESPONSE If the energy is radiated uniformly in all directions, then the intensity (dose/area) should decrease as the distance squared, just as it does for sound and light. If she can work four times farther away, the exposure lowers by a factor of sixteen, enough to make her safe.

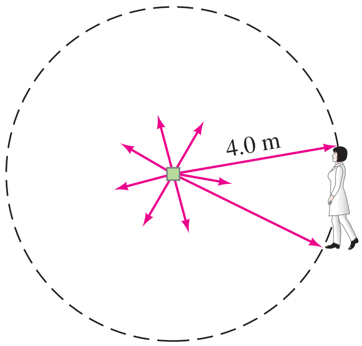


FIGURE 31–16 Radiation spreads out in all directions. A person 4.0 m away intercepts only a fraction: her cross-sectional area divided by the area of a sphere of radius 4.0 m. Example 31–12.

EXAMPLE 31–12 **Whole-body dose.** What whole-body dose is received by a 70-kg laboratory worker exposed to a 40-mCi $^{60}_{27}\mathrm{Co}$ source, assuming the person's body has cross-sectional area $1.5\ \mathrm{m^2}$ and is normally about 4.0 m from the source for 4.0 h per day? $^{60}_{27}\mathrm{Co}$ emits γ rays of energy 1.33 MeV and 1.17 MeV in quick succession. Approximately 50% of the γ rays interact in the body and deposit all their energy. (The rest pass through.)

APPROACH Of the given energy emitted, only a fraction passes through the worker, equal to *her* area divided by the total area (or $4\pi r^2$) over a full sphere of radius $r = 4.0$ m (Fig. 31–16).

SOLUTION The total γ-ray energy per decay is $(1.33 + 1.17)\ \mathrm{MeV} = 2.50\ \mathrm{MeV}$, so the total energy emitted by the source per second is

$$(0.040\ \mathrm{Ci})(3.7 \times 10^{10}\ \mathrm{decays/Ci\cdot s})(2.50\ \mathrm{MeV}) = 3.7 \times 10^{9}\ \mathrm{MeV/s}.$$

The proportion of this energy intercepted by the body is its $1.5\text{-}\mathrm{m^2}$ area divided by the area of a sphere of radius 4.0 m (Fig. 31–16):

$$\frac{1.5\ \mathrm{m^2}}{4\pi r^2} = \frac{1.5\ \mathrm{m^2}}{4\pi(4.0\ \mathrm{m})^2} = 7.5 \times 10^{-3}.$$

So the rate energy is deposited in the body (remembering that only 50% of the γ rays interact in the body) is

$$E = \left(\tfrac{1}{2}\right)(7.5 \times 10^{-3})(3.7 \times 10^{9}\ \mathrm{MeV/s})(1.6 \times 10^{-13}\ \mathrm{J/MeV}) = 2.2 \times 10^{-6}\ \mathrm{J/s}.$$

Since $1\ \mathrm{Gy} = 1\ \mathrm{J/kg}$, the whole-body dose rate for this 70-kg person is $(2.2 \times 10^{-6}\ \mathrm{J/s})/(70\ \mathrm{kg}) = 3.1 \times 10^{-8}\ \mathrm{Gy/s}$. In 4.0 h, this amounts to a dose of

$$(4.0\ \mathrm{h})(3600\ \mathrm{s/h})(3.1 \times 10^{-8}\ \mathrm{Gy/s}) = 4.5 \times 10^{-4}\ \mathrm{Gy}.$$

$\mathrm{RBE} \approx 1$ for gammas, so the effective dose is 450 μSv (Eqs. 31–10b and 31–9) or:

$$(100\ \mathrm{rad/Gy})(4.5 \times 10^{-4}\ \mathrm{Gy})(1\ \mathrm{rem/rad}) = 45\ \mathrm{mrem} = 0.45\ \mathrm{mSv}.$$

NOTE This 45-mrem effective dose is almost 50% of the normal allowed dose for a whole year (100 mrem/yr), or 1% of the maximum one-year allowance for radiation workers. This worker should not receive such a large dose every day and should seek ways to reduce it (shield the source, vary the work, work farther from the source, work less time this close to source, etc.).

We have assumed that the intensity of radiation decreases as the square of the distance. It actually falls off faster than $1/r^2$ because of absorption in the air, so our answers are a slight overestimate of dose received.

PHYSICS APPLIED
Radon exposure

EXAMPLE 31–13 **Radon exposure.** In the U.S., yearly deaths from radon exposure (the second leading cause of lung cancer) are estimated to exceed the yearly deaths from drunk driving. The Environmental Protection Agency recommends taking action to reduce the radon concentration in living areas if it exceeds 4 pCi/L of air. In some areas 50% of houses exceed this level from naturally occurring radon in the soil. Estimate (*a*) the number of decays/s in $1\ \mathrm{m^3}$ of air and (*b*) the mass of radon that emits 4.0 pCi of $^{222}_{86}\mathrm{Rn}$ radiation.

APPROACH We can use the definition of the curie to determine how many decays per second correspond to 4 pCi, then Eq. 30–3b to determine how many nuclei of radon it takes to have this activity $\Delta N/\Delta t$.

SOLUTION (*a*) We saw at the start of this Section that $1\text{ Ci} = 3.70 \times 10^{10}$ decays/s. Thus

$$\frac{\Delta N}{\Delta t} = 4.0\text{ pCi} = (4.0 \times 10^{-12}\text{ Ci})(3.70 \times 10^{10}\text{ decays/s/Ci})$$
$$= 0.148\text{ s}^{-1}$$

per liter of air. In 1 m^3 of air $(1\text{ m}^3 = 10^6\text{ cm}^3 = 10^3\text{ L})$ there would be $(0.148\text{ s}^{-1})(1000) = 150$ decays/s.

(*b*) From Eqs. 30–3b and 30–6

$$\frac{\Delta N}{\Delta t} = \lambda N = \frac{0.693}{T_{\frac{1}{2}}}N.$$

Appendix B tells us $T_{\frac{1}{2}} = 3.8235$ days for radon, so

$$N = \left(\frac{\Delta N}{\Delta t}\right)\frac{T_{\frac{1}{2}}}{0.693}$$
$$= (0.148\text{ s}^{-1})\frac{(3.8235\text{ days})(8.64 \times 10^4\text{ s/day})}{0.693}$$
$$= 7.06 \times 10^4 \text{ atoms of radon-222.}$$

The molar mass (222 u) and Avogadro's number are used to find the mass:

$$m = \frac{(7.06 \times 10^4\text{ atoms})(222\text{ g/mol})}{6.02 \times 10^{23}\text{ atoms/mol}} = 2.6 \times 10^{-17}\text{ g}$$

or 26 attograms in 1 L of air at the limit of 4 pCi/L. This 2.6×10^{-17} g/L is 2.6×10^{-14} grams of radon per m^3 of air.

NOTE Each radon atom emits 4 α particles and 4 β particles, each one capable of causing many harmful ionizations, before the sequence of decays reaches a stable element.

*31–6 Radiation Therapy

The medical application of radioactivity and radiation to human beings involves two basic aspects: (1) **radiation therapy**—the treatment of disease (mainly cancer)—which we discuss in this Section; and (2) the *diagnosis* of disease, which we discuss in the following Sections of this Chapter.

PHYSICS APPLIED
Radiation therapy

Radiation can cause cancer. It can also be used to treat it. Rapidly growing cancer cells are especially susceptible to destruction by radiation. Nonetheless, large doses are needed to kill the cancer cells, and some of the surrounding normal cells are inevitably killed as well. It is for this reason that cancer patients receiving radiation therapy often suffer side effects characteristic of radiation sickness. To minimize the destruction of normal cells, a narrow beam of γ or X-rays is often used when a cancerous tumor is well localized. The beam is directed at the tumor, and the source (or body) is rotated so that the beam passes through various parts of the body to keep the dose at any one place as low as possible—except at the tumor and its immediate surroundings, where the beam passes at all times (Fig. 31–17). The radiation may be from a radioactive source such as ${}^{60}_{27}\text{Co}$, or it may be from an X-ray machine that produces photons in the range 200 keV to 5 MeV. Protons, neutrons, electrons, and pions, which are produced in particle accelerators (Section 32–1), are also being used in cancer therapy.

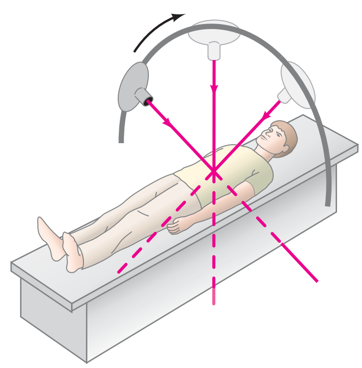


FIGURE 31–17 Radiation source rotates so that the beam always passes through the diseased tissue, but minimizes the dose in the rest of the body.

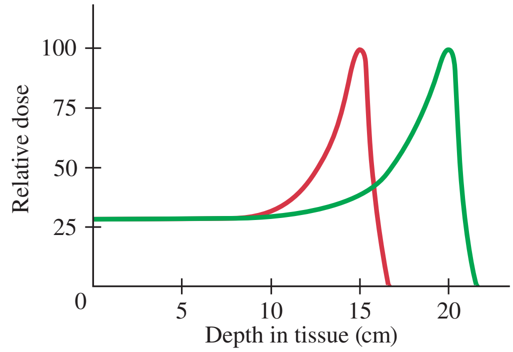


FIGURE 31–18 Energy deposited in tissue as a function of depth for 170-MeV protons (red curve) and 190-MeV protons (green). The peak of each curve is often called the Bragg peak.

PHYSICS APPLIED
Proton therapy

Protons used to kill tumors have a special property that makes them particularly useful. As shown in Fig. 31–18, when protons enter tissue, most of their energy is deposited at the end of their path. The protons' initial kinetic energy can be chosen so that most of the energy is deposited at the depth of the tumor itself, to destroy it. The incoming protons deposit only a small amount of energy in the tissue in front of the tumor, and none at all behind the tumor, thus having less negative effect on healthy tissue than X- or γ rays. Because tumors have physical size, even several centimeters in diameter, a range of proton energies is often used. Heavier ions, such as α particles or carbon ions, are similarly useful. This **proton therapy** technique is more than a half century old, but the necessity of having a large accelerator has meant that few hospitals have used the technique until now. Many such "proton centers" are now being built.

Another form of treatment is to insert a tiny radioactive source directly inside a tumor, which will eventually kill the majority of the cells. A similar technique is used to treat cancer of the thyroid with the radioactive isotope $^{131}_{53}I$. The thyroid gland concentrates iodine present in the bloodstream, particularly in any area where abnormal growth is taking place. Its intense radioactivity can destroy the defective cells.

Another application of radiation is for sterilizing bandages, surgical equipment, and even packaged foods such as ground beef, chicken, and produce, because bacteria and viruses can be killed or deactivated by large doses of radiation.

*31–7 Tracers in Research and Medicine

Radioactive isotopes are used in biological and medical research as **tracers**. A given compound is artificially synthesized incorporating a radioactive isotope such as $^{14}_{6}C$ or $^{3}_{1}H$. Such "tagged" molecules can then be traced as they move through an organism or as they undergo chemical reactions. The presence of these tagged molecules (or parts of them, if they undergo chemical change) can be detected by a Geiger or scintillation counter, which detects emitted radiation (see Section 30–13). How food molecules are digested, and to what parts of the body they are diverted, can be traced in this way.

Radioactive tracers have been used to determine how amino acids and other essential compounds are synthesized by organisms. The permeability of cell walls to various molecules and ions can be determined using radioactive tracers: the tagged molecule or ion is injected into the extracellular fluid, and the radioactivity present inside and outside the cells is measured as a function of time.

In a technique known as **autoradiography**, the position of the radioactive isotopes is detected on film. For example, the distribution of carbohydrates produced in the leaves of plants from absorbed CO_2 can be observed by keeping the plant in an atmosphere where the carbon atom in the CO_2 is $^{14}_{6}C$. After a time, a leaf is placed firmly on a photographic plate and the emitted radiation darkens the film most strongly where the isotope is most strongly concentrated (Fig. 31–19a). Autoradiography using labeled nucleotides (components of DNA) has revealed much about the details of DNA replication (Fig. 31–19b). Today gamma cameras are used in a similar way—see next page.

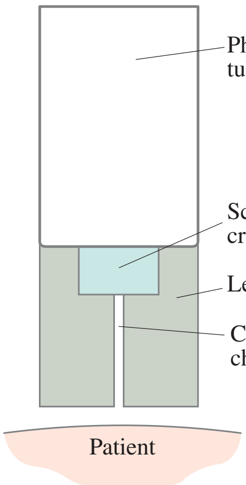
(a)

(b)

FIGURE 31–19 (a) Autoradiograph of a leaf exposed for 30 s to $^{14}CO_2$. Only the tissue where the CO_2 has been taken up, to be used in photosynthesis (Example 27–7), has become radioactive. The non-metabolizing tissue of the veins is free of $^{14}_{6}C$ and does not blacken the X-ray sheet. (b) Autoradiograph of chromosomal DNA. The dashed arrays of film grains show the Y-shaped growing point of replicating DNA.

For medical diagnosis, the radionuclide commonly used today is ${}^{99m}_{43}Tc$, a long-lived excited state of technetium-99 (the "m" in the symbol stands for "metastable" state). It is formed when ${}^{99}_{42}Mo$ decays. The great usefulness of ${}^{99m}_{43}Tc$ derives from its convenient half-life of 6 h (short, but not too short) and the fact that it can combine with a large variety of compounds. The compound to be labeled with the radionuclide is so chosen because it concentrates in the organ or region of the anatomy to be studied. Detectors outside the body then record, or image, the distribution of the radioactively labeled compound. The detection could be done by a single detector (Fig. 31–20a) which is moved across the body, measuring the intensity of radioactivity at a large number of points. The image represents the relative intensity of radioactivity at each point. The relative radioactivity is a diagnostic tool. For example, high or low radioactivity may represent overactivity or underactivity of an organ or part of an organ, or in another case may represent a lesion or tumor. More complex **gamma cameras** make use of many detectors which simultaneously record the radioactivity at many points. The measured intensities can be displayed on a TV or computer monitor. The image is sometimes called a scintigram (after scintillator), Fig. 31–20b. Gamma cameras are relatively inexpensive, but their resolution is limited—by non-perfect collimation†. Yet they allow "dynamic" studies: images that change in time, like a movie.

PHYSICS APPLIED
Medical diagnosis



(a)

(b)

FIGURE 31–20 (a) Collimated gamma-ray detector for scanning (moving) over a patient. The collimator selects γ rays that come in a (nearly) straight line from the patient. Without the collimator, γ rays from all parts of the body could strike the scintillator, producing a poor image. Detectors today usually have many collimator tubes and are called *gamma cameras*. (b) Gamma camera image (scintigram), of both legs of a patient with shin splints, detecting γs from ${}^{99m}_{43}Tc$.

*31–8 Emission Tomography: PET and SPECT

The images formed using the standard techniques of nuclear medicine, as briefly discussed in the previous Section, are produced from radioactive tracer sources within the *volume* of the body. It is also possible to image the radioactive emissions from a single plane or slice through the body using the computed tomography techniques discussed in Section 25–12. A gamma camera measures the radioactive intensity from the tracer at many points and angles around the patient. The data are processed in much the same way as for X-ray CT scans (Section 25–12). This technique is referred to as **single photon emission computed tomography** (SPECT), or simply SPET (single photon emission tomography).

PHYSICS APPLIED
Medical imaging

PHYSICS APPLIED
Emission tomography (SPECT, PET)

Another important technique is **positron emission tomography** (PET), which makes use of positron emitters such as ${}^{11}_{6}C$, ${}^{13}_{7}N$, ${}^{15}_{8}O$, and ${}^{18}_{9}F$ whose half-lives are short. These isotopes are incorporated into molecules that, when inhaled or injected, accumulate in the organ or region of the body to be studied.

†To "collimate" means to "make parallel," usually by blocking non-parallel rays with a narrow tube inside lead, as in Fig. 31–20a.

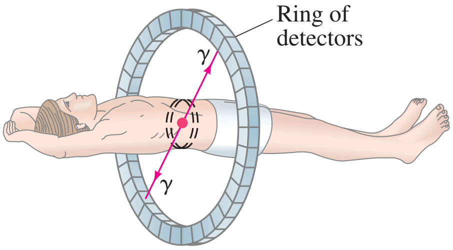


FIGURE 31–21 Positron emission tomography (PET) system showing a ring of detectors to detect the two annihilation γ rays $(e^+ + e^- \rightarrow 2\gamma)$ emitted at 180° to each other.

When such a nuclide undergoes β^+ decays, the emitted positron travels at most a few millimeters before it collides with a normal electron. In this collision, the positron and electron are annihilated, producing two γ rays $(e^+ + e^- \rightarrow 2\gamma)$, each having an energy of 511 keV $(= m_e c^2)$. The two γ rays fly off in opposite directions (180° ± 0.25°) since they must have almost exactly equal and opposite momenta to conserve momentum (the momenta of the initial e^+ and e^- are essentially zero compared to the momenta afterward of the γ rays). Because the photons travel along the same line in opposite directions, their detection in coincidence by rings of detectors surrounding the patient (Fig. 31–21) readily establishes the line along which the emission took place. If the difference in time of arrival of the two photons could be determined accurately, the actual position of the emitting nuclide along that line could be calculated. Present-day electronics can measure times to at best ±300 ps, so at the γ ray's speed $(c = 3 \times 10^8\,\mathrm{m/s})$, the actual position could be determined to an accuracy on the order of about $d = vt \approx (3 \times 10^8\,\mathrm{m/s})(300 \times 10^{-12}\,\mathrm{s}) \approx 10\,\mathrm{cm}$, which is not very useful. Although there may be future potential for *time-of-flight* measurements to determine position, today computed tomography techniques are used instead, similar to those for X-ray CT, which can reconstruct PET images with a resolution on the order of 2–5 mm. One big advantage of PET is that no collimators are needed (as for detection of a single photon—see Fig. 31–20a). Thus, fewer photons are "wasted" and lower doses can be administered to the patient with PET.

Both PET and SPECT systems can give images that relate to biochemistry, metabolism, and function. This is to be compared to X-ray CT scans, whose images reflect shape and structure—that is, the anatomy of the imaged region.

Figure 31–22 shows PET scans of the same person's brain (a) when using a cell phone near the ear and (b) with the cell phone off. The bright red spots in (a) indicate a higher rate of glucose metabolism, suggesting excitability of brain tissue (the glucose was tagged with a radioactive tracer). Emfs from the cell phone antenna thus seem to affect metabolism and may be harmful to us!

The colors shown here are faked (only visible light has colors). The original images are various shades of gray, representing intensity (or counts).

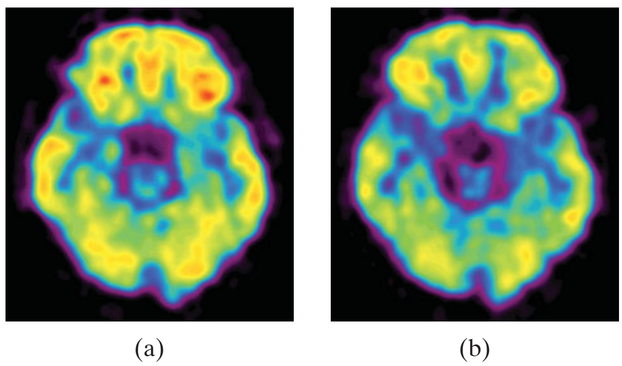


FIGURE 31–22 False-color PET scans of a horizontal section through a brain showing glucose metabolism rates (red is high) by a person (a) using a cell phone near the ear, and (b) with the cell phone off.

31–9 Nuclear Magnetic Resonance (NMR) and Magnetic Resonance Imaging (MRI)

Nuclear magnetic resonance (NMR) is a phenomenon which soon after its discovery in 1946 became a powerful research tool in a variety of fields from physics to chemistry and biochemistry. It is also an important medical imaging technique. We first briefly discuss the phenomenon, and then look at its applications.

* Nuclear Magnetic Resonance (NMR)

We saw in Chapter 28 (Section 28–6) that when atoms are placed in a magnetic field, atomic energy levels split into several closely spaced levels (see Fig. 28–8). Nuclei, too, exhibit these magnetic properties. We examine only the simplest, the hydrogen (H) nucleus, since it is the one most used, even for medical imaging.

The $^1_1$H nucleus consists of a single proton. Its spin angular momentum (and its magnetic moment), like that of the electron, can take on only two values when placed in a magnetic field: we call these "spin up" (parallel to the field) and "spin down" (antiparallel to the field), as suggested in Fig. 31–23. When a magnetic field is present, the energy of the nucleus splits into two levels as shown in Fig. 31–24, with the spin up (parallel to field) having the lower energy. (This is like the Zeeman effect for atomic levels, Fig. 28–8.) The difference in energy ΔE between these two levels is proportional to the total magnetic field B_T at the nucleus:

$$\Delta E = kB_T,$$

where k is a proportionality constant that is different for different nuclides.

In a standard **nuclear magnetic resonance** (NMR) setup, the sample to be examined is placed in a static magnetic field. A radiofrequency (RF) pulse of electromagnetic radiation (that is, photons) is applied to the sample. If the frequency, f, of this pulse corresponds precisely to the energy difference between the two energy levels (Fig. 31–24), so that

$$hf = \Delta E = kB_T, \tag{31–11}$$

then the photons of the RF beam will be absorbed, exciting many of the nuclei from the lower state to the upper state. This is a resonance phenomenon because there is significant absorption only if f is very near $f = kB_T/h$. Hence the name "nuclear magnetic resonance." For free $^1_1$H nuclei, the frequency is 42.58 MHz for a magnetic field $B_T = 1.0\,\text{T}$. If the H atoms are bound in a molecule the total magnetic field B_T at the H nuclei will be the sum of the external applied field (B_{ext}) plus the local magnetic field (B_{local}) due to electrons and nuclei of neighboring atoms. Since f is proportional to B_T, the value of f for a given external field will be slightly different for bound H atoms than for free atoms:

$$hf = k(B_{ext} + B_{local}).$$

This small change in frequency can be measured, and is called the "chemical shift." A great deal has been learned about the structure of molecules and bonds using this NMR technique.

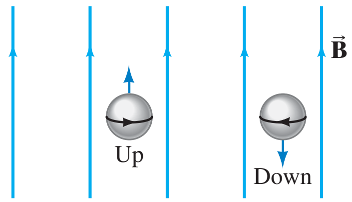
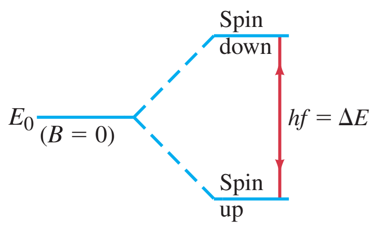


FIGURE 31–23 Schematic picture of a proton in a magnetic field $\vec{B}$ (pointing upward) with the two possible states of proton spin, up and down.

FIGURE 31–24 Energy E_0 in the absence of a magnetic field splits into two levels in the presence of a magnetic field.



* Magnetic Resonance Imaging (MRI)

PHYSICS APPLIED
NMR imaging (MRI)

For producing medically useful NMR images—now commonly called MRI, or **magnetic resonance imaging**—the element most used is hydrogen since it is the commonest element in the human body and gives the strongest NMR signals. The experimental apparatus is shown in Fig. 31–25. The large coils set up the static magnetic field, and the RF coils produce the RF pulse of electromagnetic waves (photons) that cause the nuclei to jump from the lower state to the upper one (Fig. 31–24). These same coils (or another coil) can detect the absorption of energy or the emitted radiation (also of frequency $f = \Delta E/h$, Eq. 31–11) when the nuclei jump back down to the lower state.

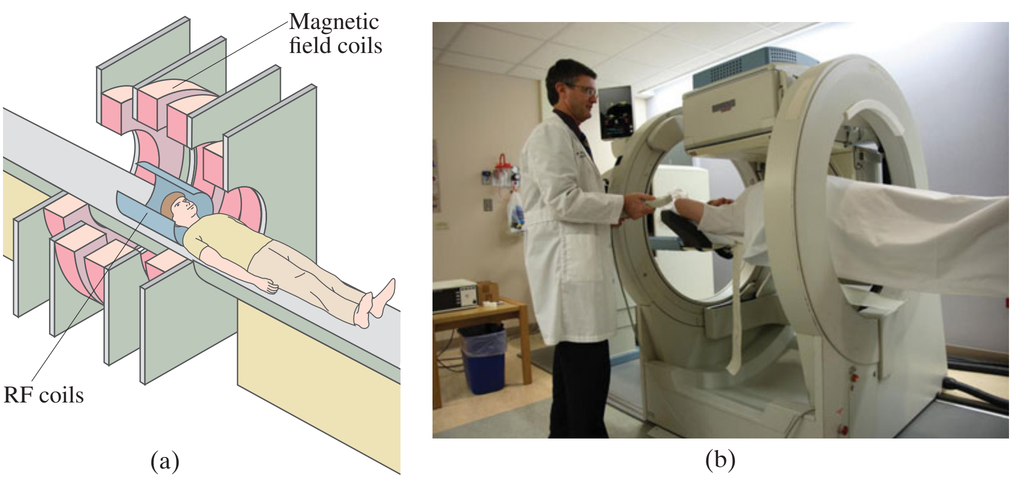


FIGURE 31–25 NMR imaging setup: (a) diagram; (b) photograph.

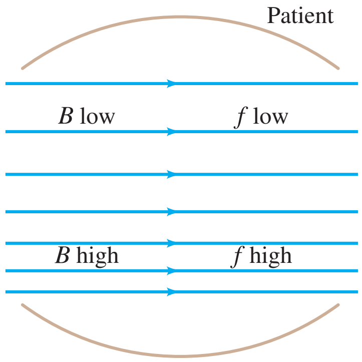
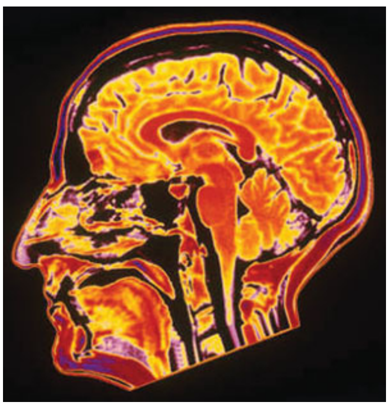


FIGURE 31–26 A static field that is stronger at the bottom than at the top. The frequency of absorbed or emitted radiation is proportional to B in NMR.

The formation of a two-dimensional or three-dimensional image can be done using techniques similar to those for computed tomography (Section 25–12). The simplest thing to measure for creating an image is the intensity of absorbed and/or reemitted radiation from many different points of the body, and this would be a measure of the density of H atoms at each point. But how do we determine from what part of the body a given photon comes? One technique is to give the static magnetic field a gradient; that is, instead of applying a uniform magnetic field, B_T, the field is made to vary with position across the width of the sample (or patient), Fig. 31–26. Because the frequency absorbed by the H nuclei is proportional to B_T (Eq. 31–11), only one plane within the body will have the proper value of B_T to absorb photons of a particular frequency f. By varying f, absorption by different planes can be measured. Alternately, if the field gradient is applied *after* the RF pulse, the frequency of the emitted photons will be a measure of where they were emitted. If a magnetic field gradient in one direction is applied during excitation (absorption of photons) and photons of a single frequency are transmitted, only H nuclei in one thin slice will be excited. By applying a gradient during reemission in a direction perpendicular to the first, the frequency f of the reemitted radiation will represent depth in that slice. Other ways of varying the magnetic field throughout the volume of the body can be used in order to correlate NMR frequency with position.

A reconstructed image based on the density of H atoms (that is, the intensity of absorbed or emitted radiation) is not very interesting. More useful are images based on the rate at which the nuclei decay back to the ground state, and such images can produce resolution of 1 mm or better. This NMR technique (sometimes called **spin-echo**) produces images of great diagnostic value, both in the delineation of structure (anatomy) and in the study of metabolic processes. An NMR image is shown in Fig. 31–27.

FIGURE 31–27 False-color NMR image (MRI) through the head showing structures in the brain.



NMR imaging is considered to be noninvasive. We can calculate the energy of the photons involved: as mentioned above, in a 1.0-T magnetic field, $f = 42.58\,\text{MHz}$ for ${}^1_1\text{H}$. This corresponds to an energy of $hf = (6.6 \times 10^{-34}\,\text{J}\cdot\text{s})(43 \times 10^6\,\text{Hz}) \approx 3 \times 10^{-26}\,\text{J}$ or about $10^{-7}\,\text{eV}$. Since molecular bonds are on the order of 1 eV, the RF photons can cause little cellular disruption. This should be compared to X- or γ rays, whose energies are 10^4 to 10^6 eV and thus can cause significant damage. The static magnetic fields, though often large (as high as 1.0 to 1.5 T), are believed to be harmless (except for people who wear heart pacemakers).

TABLE 31–2 Medical Imaging Techniques

Technique	Where Discussed in This Book	Optimal Resolution
Conventional X-ray	Section 25–12	$\frac{1}{2}$ mm
CT scan, X-ray	Section 25–12	$\frac{1}{2}$ mm
Nuclear medicine (tracers)	Section 31–7	1 cm
SPECT (single photon emission)	Section 31–8	1 cm
PET (positron emission)	Section 31–8	2–5 mm
MRI (NMR)	Section 31–9	$\frac{1}{2}$–1 mm
Ultrasound	Section 12–9	0.3–2 mm

Table 31–2 lists the major techniques we have discussed for imaging the interior of the human body, along with the optimum resolution attainable today. Resolution is only one factor that must be considered, because the different imaging techniques provide different types of information that are useful for different types of diagnosis.

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

$$Q = (M_a + M_X - M_b - M_Y)c^2 \qquad \textbf{(31–2a)}$$
$$= \text{KE}_b + \text{KE}_Y - \text{KE}_a - \text{KE}_X. \qquad \textbf{(31–2b)}$$

In **fission**, a heavy nucleus such as uranium splits into two intermediate-sized nuclei after being struck by a neutron. ${}^{235}_{92}\text{U}$ is fissionable by slow neutrons, whereas some fissionable nuclei require fast neutrons. Much energy is released in fission ($\approx 200\,\text{MeV}$ 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 ${}^{4}_{2}\text{He}$ 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 ($\approx 10^8$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: $1\text{ Ci} = 3.70 \times 10^{10}$ decays per second, whereas $1\text{ Bq} = 1\text{ decay/s}$. 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} 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 × 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**: $1\text{ Sv} = 100\text{ rem}$.

[*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*) $n + {}^{232}_{90}\text{Th} \rightarrow\ ? + \gamma$;
(*b*) $n + {}^{137}_{56}\text{Ba} \rightarrow {}^{137}_{55}\text{Cs} +\ ?$;
(*c*) $d + {}^{2}_{1}\text{H} \rightarrow {}^{4}_{2}\text{He} +\ ?$;
(*d*) $\alpha + {}^{197}_{79}\text{Au} \rightarrow\ ? + d$
where d stands for deuterium.

2. When ${}^{22}_{11}\text{Na}$ is bombarded by deuterons $({}^{2}_{1}\text{H})$, 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 ${}^{235}_{92}\text{U}$ 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, ${}^{2}_{1}H$, each of mass m_H, fuse together and form a helium nucleus of mass m_{He},
   (*a*) $m_{He} < 2m_H$.
   (*b*) $m_{He} = 2m_H$.
   (*c*) $m_{He} > 2m_H$.
   (*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. ${}^{235}_{92}U$ releases an average of 2.5 neutrons per fission compared to 2.9 for ${}^{239}_{94}Pu$. Which has the smaller critical mass?
   (*a*) ${}^{235}_{92}U$.
   (*b*) ${}^{239}_{94}Pu$.
   (*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_1H.) (*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 KE = 41.4 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_2He 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 $^{235}_{92}U$ in fission, and give its ratio to each reaction in (*a*).

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

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) If $^{6}_{3}Li$ is struck by a slow neutron, it can form $^{4}_{2}He$ and another nucleus. (*a*) What is the second nucleus? (This is a method of generating this isotope.) (*b*) How much energy is released in the process?

35. (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.

36. (III) Show that the energies carried off by the $^{4}_{2}He$ 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?

37. (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.

38. (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

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

40. (I) A dose of 4.0 Sv of γ rays in a short period would be lethal to about half the people subjected to it. How many grays is this?

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

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

43. (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.

44. (II) A 0.035-μCi sample of $^{32}_{15}P$ 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?

45. (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.

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

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

48. (II) $^{57}_{27}Co$ emits 122-keV γ rays. If a 65-kg person swallowed 1.55 μCi of $^{57}_{27}Co$, 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.]

49. (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?

50. (III) Huge amounts of radioactive $^{131}_{53}I$ 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, $^{131}_{53}I$ absorption can cause damage to the thyroid. (*a*) Write down the reaction for the decay of $^{131}_{53}I$. (*b*) Its half-life is 8.0 d; how long would it take for ingested $^{131}_{53}I$ to become 5.0% of the initial value? (*c*) Absorbing 1 mCi of $^{131}_{53}I$ can be harmful; what mass of iodine is this?

51. (III) Assume a liter of milk typically has an activity of 2000 pCi due to $^{40}_{19}K$. 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.

52. (III) Radon gas, $^{222}_{86}Rn$, 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 $^{222}_{86}Rn$ 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

53. (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

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

55. J. Chadwick discovered the neutron by bombarding $^{9}_{4}Be$ 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?

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

57. 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 $^{235}_{92}U$ and $^{238}_{92}U$, on which this process depends.

58. (*a*) What mass of $^{235}_{92}U$ 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?

59. 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?

60. 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.)

61. Radon gas, $^{222}_{86}Rn$, 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. 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.

63. 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 62. [*Hint*: Use $1/r^2$ law.]

64. 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 62 and 63.]

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

66. Some stars, in a later stage of evolution, may begin to fuse two $^{12}_{6}C$ nuclei into one $^{24}_{12}Mg$ 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?

67. An average adult body contains about 0.10 μCi of $^{40}_{19}K$, 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?

68. 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.)

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

70. A 1.2-μCi $^{137}_{55}Cs$ source is used for 1.4 hours by a 62-kg worker. Radioactive $^{137}_{55}Cs$ 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?

71. Suppose a future fusion reactor would be able to put out 1000 MW of electrical power continuously. Assume the reactor will produce energy solely through the reaction given in Eq. 31–8a and will convert this energy to electrical energy with an efficiency of 33%. Estimate the minimum amount of deuterium needed to run this facility per year.

72. 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?

73. Consider the fission reaction

$$n + ^{235}_{92}U \rightarrow ^{92}_{38}Sr + X + 3n.$$

(*a*) What is X? (*b*) If this were part of a chain reaction in a fission power reactor running at "barely critical," what would happen on average to the three produced neutrons? (*c*) (optional) What is the Q-value of this reaction? [*Hint*: Mass values can be found at www.nist.gov/pml/data/comp.cfm.]

74. 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.

75. 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?

76. A 55-kg patient is to be given a medical test involving the ingestion of $^{99m}_{43}\mathrm{Tc}$ (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 31–2, (*a*) state three problems that must be overcome to make a functioning fission nuclear reactor; (*b*) state three environmental problems or dangers that do or could result from the operation of a nuclear fission reactor; (*c*) describe an additional problem or danger associated with a breeder reactor.

2. 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?

3. 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.

4. 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 $(\approx 2 \times 10^7\,\mathrm{K})$ than the proton–proton chain $(\approx 1.5 \times 10^7\,\mathrm{K})$?

5. Consider the effort by humans to harness nuclear fusion as a viable energy source. (*a*) What are some advantages of using nuclear fusion rather than nuclear fission? (*b*) What is the major technological problem with using controlled nuclear fusion as a source of energy? (*c*) Discuss two different approaches to solving this problem. (*d*) What fuel is necessary in a nuclear fusion reaction? (*e*) Write a nuclear reaction using two nuclei of the fuel in part (*d*) to create a third nucleus. (*f*) Calculate the Q-value of the reaction in part (*e*).

6. (*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*).