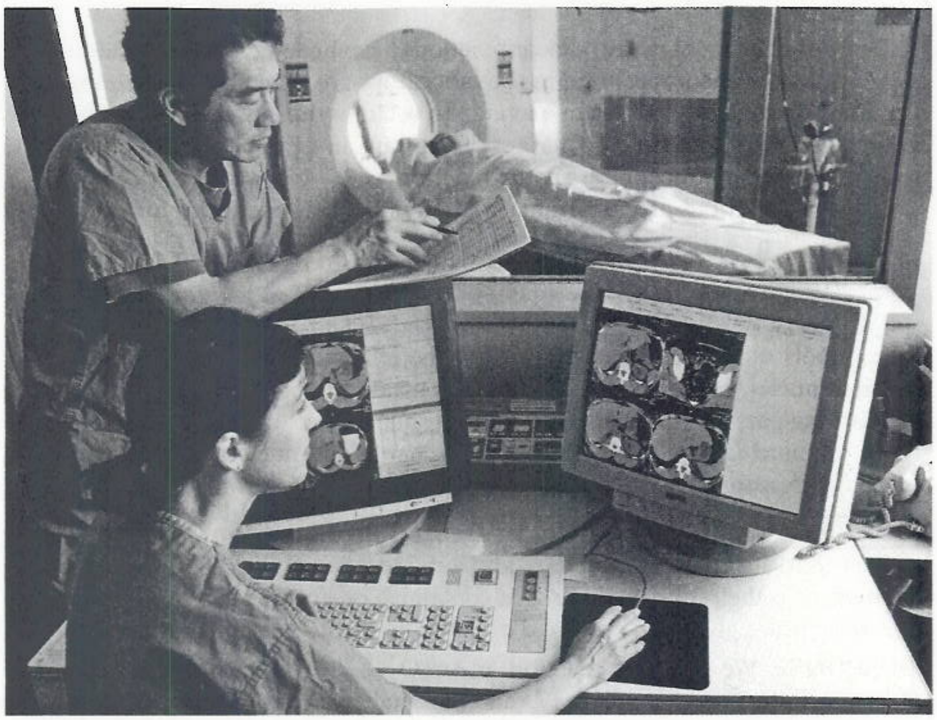

Technicians are looking at an MRI image of sections through a patient's body. MRI is one of several powerful types of medical imaging based on physics used by doctors to diagnose illnesses.

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 $^{4}_{2}$He is an α particle, and $^{1}_{1}$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: ${}^{14}_{6}\mathrm{C}$ is continually being made in the atmosphere via the reaction $\mathrm{n} + {}^{14}_{7}\mathrm{N} \rightarrow {}^{14}_{6}\mathrm{C} + \mathrm{p}$.

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

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

can be written

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

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 ${}^{16}_{8}\mathrm{O}$ nucleus, and a deuteron is given off. (A **deuteron**, or **deuterium**, is the isotope of hydrogen containing one proton and one neutron, ${}^{2}_{1}\mathrm{H}$; it is sometimes given the symbol d or D.) What is the nucleus that results?

RESPONSE We have the reaction $\mathrm{n} + {}^{16}_{8}\mathrm{O} \rightarrow ? + {}^{2}_{1}\mathrm{H}$. 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 ${}^{15}_{7}\mathrm{N}$.

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

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

$$\mathrm{a} + \mathrm{X} \rightarrow \mathrm{Y} + \mathrm{b}, \tag{31–1}$$

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

$$Q = (M_{\mathrm{a}} + M_{\mathrm{X}} - M_{\mathrm{b}} - M_{\mathrm{Y}})c^2. \tag{31–2a}$$

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):

$$Q = \mathrm{KE}_{\mathrm{b}} + \mathrm{KE}_{\mathrm{Y}} - \mathrm{KE}_{\mathrm{a}} - \mathrm{KE}_{\mathrm{X}}. \tag{31–2b}$$

If X is a target nucleus at rest (or nearly so) struck by incoming particle a, then $\mathrm{KE}_{\mathrm{X}} = 0$. 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

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

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

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

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 $v_{He} = 9.30 \times 10^6\,\mathrm{m/s}$ is not close to the speed of light c. And v_{Li} will be even less because $M_{Li} > M_{He}$. Thus we can write the KE of the lithium, using the momentum equation just above, as

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

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

$$\mathrm{KE}_{Li} = \frac{(4.0026\,\mathrm{u})^2(1.66 \times 10^{-27}\,\mathrm{kg/u})^2(9.30 \times 10^6\,\mathrm{m/s})^2}{2(7.0160\,\mathrm{u})(1.66 \times 10^{-27}\,\mathrm{kg/u})}$$
$$= 1.64 \times 10^{-13}\,\mathrm{J} = 1.02\,\mathrm{MeV}.$$

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

$$\mathrm{KE}_{He} = \tfrac{1}{2}M_{He}v_{He}^2 = \tfrac{1}{2}(4.0026\,\mathrm{u})(1.66 \times 10^{-27}\,\mathrm{kg/u})(9.30 \times 10^6\,\mathrm{m/s})^2$$
$$= 2.87 \times 10^{-13}\,\mathrm{J} = 1.80\,\mathrm{MeV}.$$

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

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

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

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

(We must use the mass of the ${}^{1}_{1}\mathrm{H}$ atom rather than that of the bare proton because the masses of ${}^{13}_{6}\mathrm{C}$ and ${}^{13}_{7}\mathrm{N}$ 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

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

Thus $Q = -3.00\,\mathrm{MeV}$, 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 ${}^{13}_{7}\mathrm{N}$ 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.