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

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

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

Deuterium

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 ${}^{15}_{7}\mathrm{N}$.

Energy and momentum are also conserved in nuclear reactions, and can be used to determine whether a given reaction can occur or not. For example, if the total mass of the 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 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

$$\mathrm{a} + \mathrm{X} \rightarrow \mathrm{Y} + \mathrm{b},$$

where a is a 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-value

$$Q = \left(M_{\mathrm{a}} + M_{\mathrm{X}} - M_{\mathrm{b}} - M_{\mathrm{Y}}\right)c^2. \tag{31–1}$$

These are all rest masses; $M = 0$ for a γ ray. Since energy is conserved, Q is equal to the change in kinetic energy (final minus initial):

Energy conservation

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

In many reactions, $\mathrm{KE}_{\mathrm{X}} = 0$ since X is the target nucleus at rest (or nearly so) struck by an incoming particle a. For $Q > 0$, the reaction is said to be *exothermic* or *exoergic*; energy is released in the reaction, so the total KE is greater after the reaction than before. If Q is negative ($Q < 0$), the reaction is said to be *endothermic* or *endoergic*. In this case the final total KE is less than the initial KE, and 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 a boron atom 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 $\left(M_{\mathrm{Li}} = 7.0160\,\mathrm{u}\right)$, and (*b*) the Q-value of the reaction.

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

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

is 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).