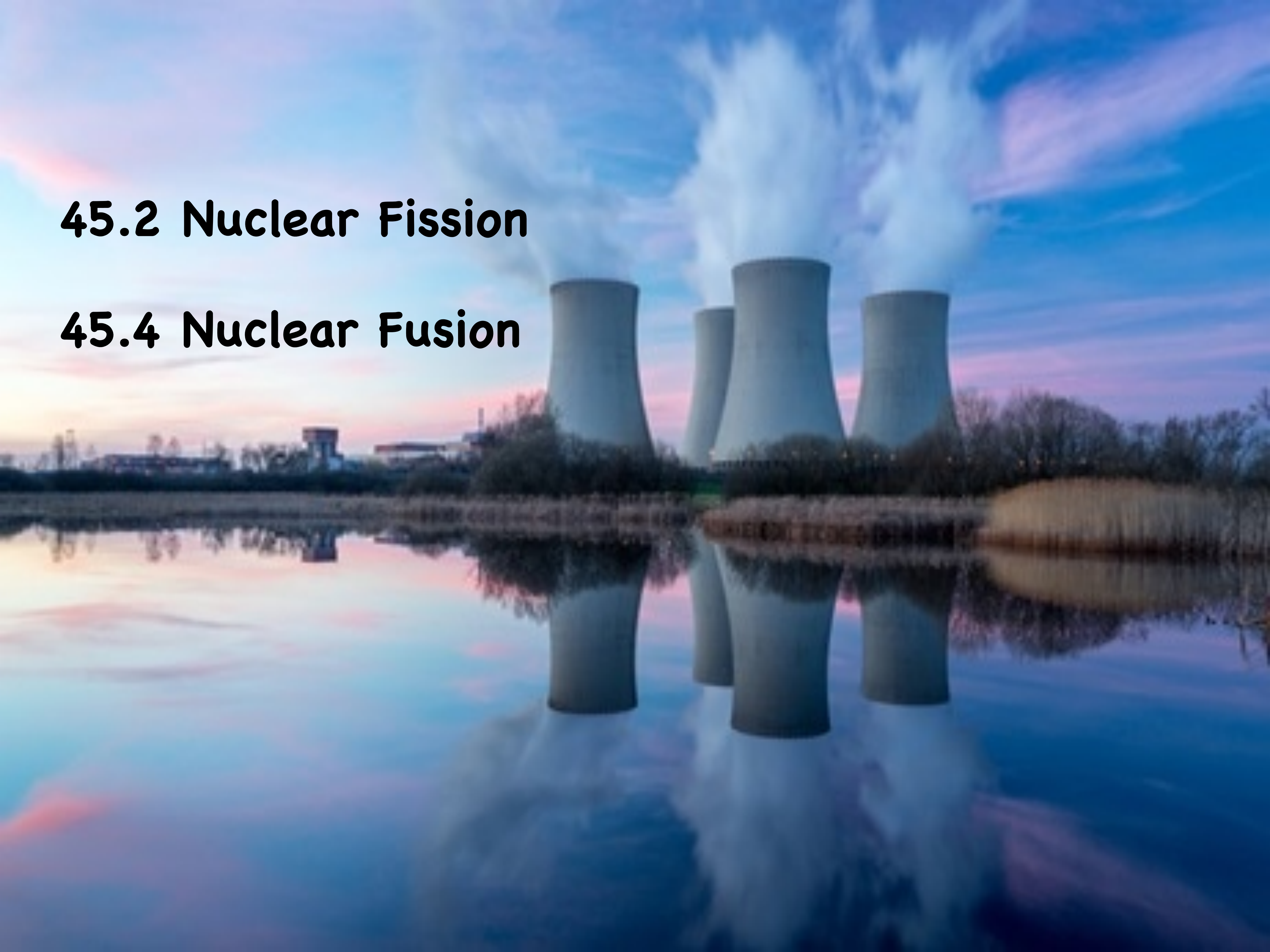
# Ch.45: Applications of Nuclear Physics

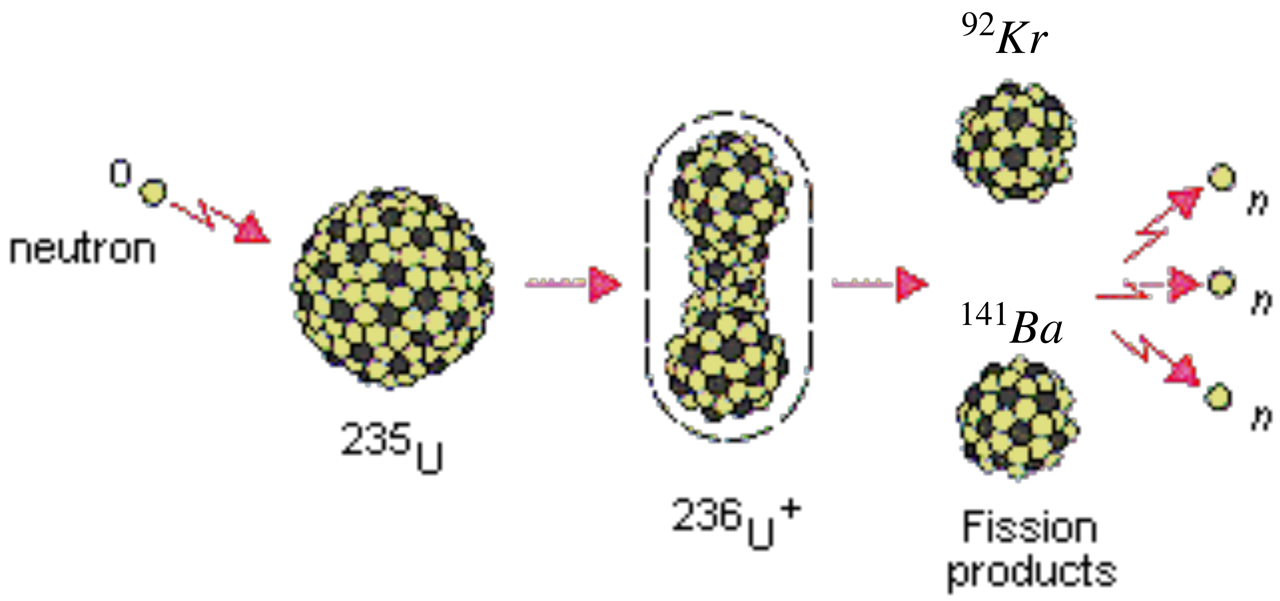
## 45.2 Nuclear Fission

## 45.4 Nuclear Fusion



# 45.2 Nuclear Fission

- What does "Nuclear Fission" mean?
- When Does it happen?



# 45.2 Nuclear Fission

- **Nuclear fission** occurs when a heavy nucleus, such as $^{235}U$ splits into two smaller nuclei.
- Fission can be initiated when a heavy nucleus captures a thermal neutron (free neutron with high energy ~ several MeV).
- The absorption of the neutron creates a nucleus that is unstable.
- The mass of daughter nuclei is less than the parent nuclei, the difference in masses is called the **mass defect**.

Neutron capture:

$$^{1}_{0}\text{n} + ^{235}_{92}\text{U} \rightarrow ^{236}_{92}\text{U}^* \rightarrow \text{X} + \text{Y} + \text{neutrons}$$

$$^{1}_{0}\text{n} + ^{235}_{92}\text{U} \rightarrow ^{141}_{56}\text{Ba} + ^{92}_{36}\text{Kr} + 3(^{1}_{0}\text{n})$$

Fission fragments

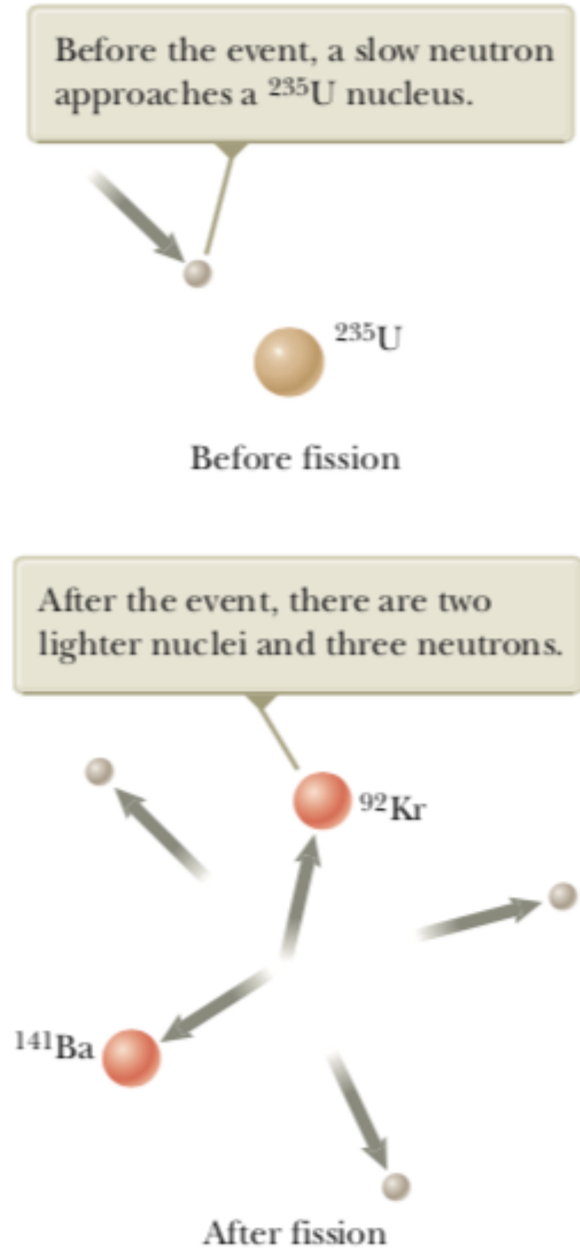



**Figure 45.1** A nuclear fission event.

## 45.2 Nuclear Fission

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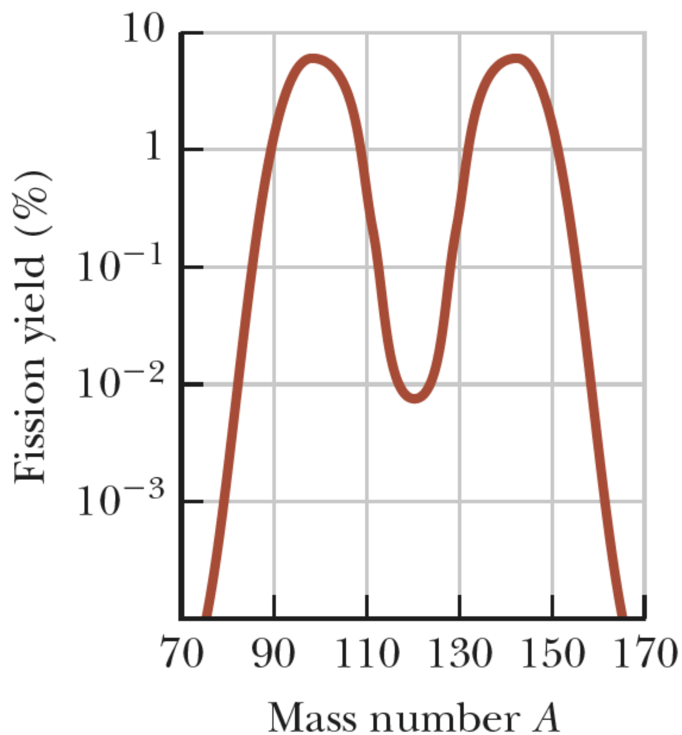


**Figure 45.2** Distribution of fission products versus mass number for the fission of $^{235}$U bombarded with thermal neutrons. Notice that the vertical axis is logarithmic.

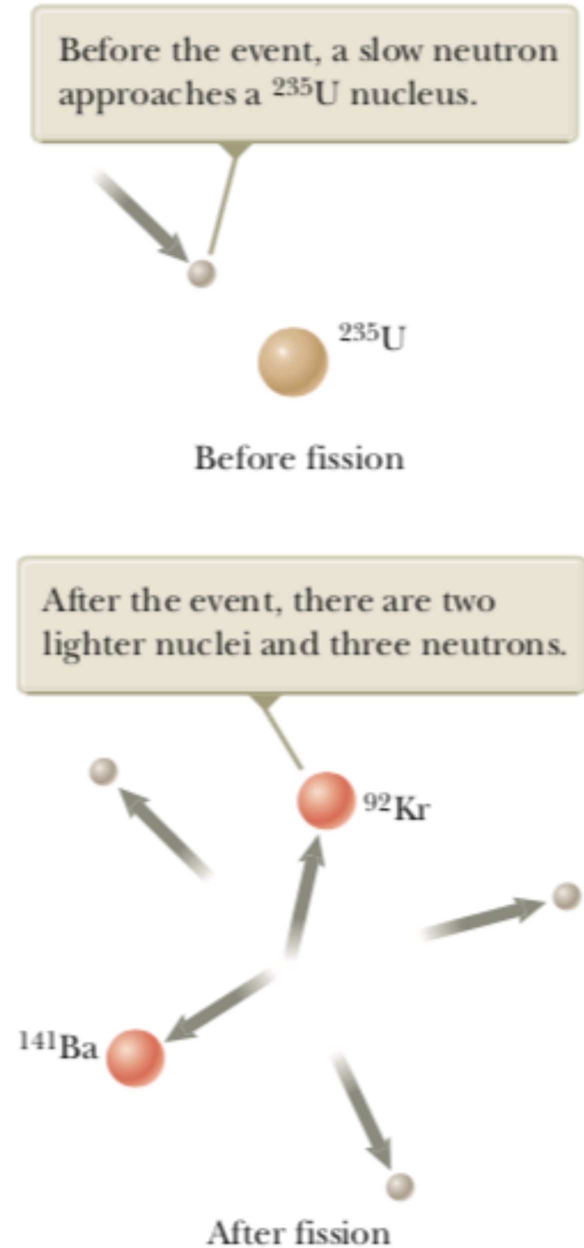


**Figure 45.1** A nuclear fission event.

## Example 45.1 The Energy Released in the Fission of $^{235}U$

Calculate the energy released when 1.00 kg of $^{235}U$ fissions, taking the disintegration energy per event to be $Q$ = 208 MeV.

## Nuclear reactors

In 235U fissions, one incoming neutron results in an average of 2.5 neutrons emitted per event. These neutrons can trigger other nuclei to fission. Because more neutrons are produced by the event than are absorbed, there is the possibility of an ever-building chain reaction

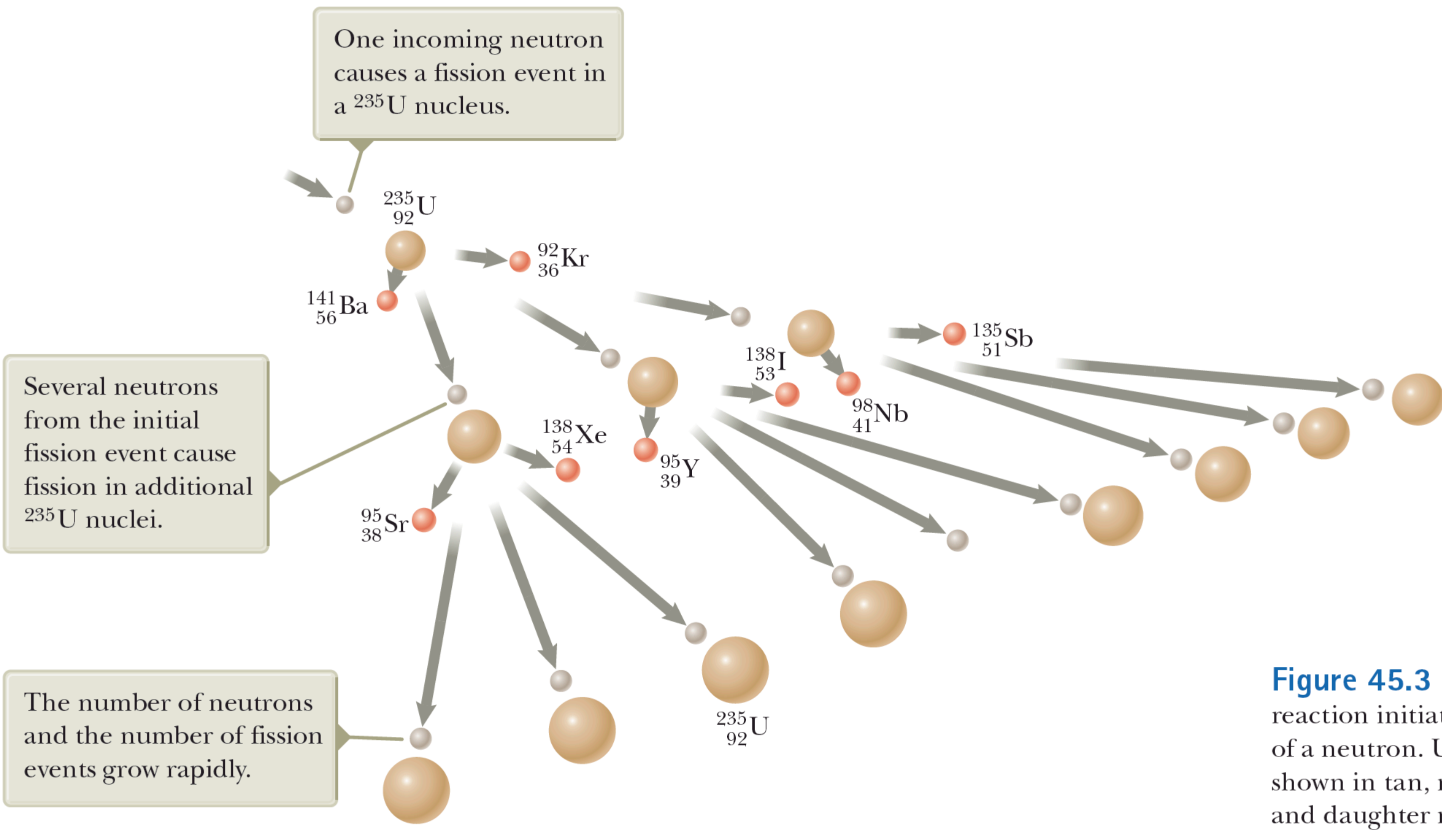


**Figure 45.3** A nuclear chain reaction initiated by the capture of a neutron. Uranium nuclei are shown in tan, neutrons in gray, and daughter nuclei in orange.

## Nuclear reactors

- If the chain reaction is not controlled (that is, if it does not proceed slowly), it can result in a violent explosion, with the sudden release of an enormous amount of energy. When the reaction is controlled, however, the energy released can be put to constructive use.
- A nuclear reactor is a system designed to maintain what is called a self-sustained chain reaction.
- Commercial reactors achieve safety through careful design and rigid operating protocol, and only when these variables are compromised do reactors pose a danger. Radiation exposure and the potential health risks associated with such exposure are controlled by three layers of containment.

## 45.4 Nuclear Fusion

- **Nuclear fusion** occurs when two light nuclei combine to form a heaver nucleus. For example:

$$ {}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{2}_{1}\mathrm{H} + e^{+} + \nu $$

$$ {}^{1}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + \gamma $$

# 45.4 Nuclear Fusion

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$$^{1}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{2}He + \gamma$$

$$^{1}_{1}H + ^{3}_{2}He \rightarrow ^{4}_{2}He + e^{+} + \nu$$

$$^{3}_{2}He + ^{3}_{2}He \rightarrow ^{4}_{2}He + ^{1}_{1}H + ^{1}_{1}H$$

- These fusion reactions are the basic reactions in the **proton-proton cycle** and are believed to be one of the basic cycles by which the energy is generated in the sun and other stars.
- Reactions in proton-proton cycle are *exothermic*.
- These reactions require high temperature, therefore they are called **thermonuclear fusion reactions**.

## Example 45.2 Energy Released in Fusion

Find the total energy released in the fusion reactions in the proton–proton cycle.

The atomic masses are: $M({}^{1}_{1}H) = 1.007825$ u, $M({}^{4}_{2}He) = 4.002603$ u

- **Terrestrial Fusion Reactions**

The enormous amount of energy released in fusion reactions suggests the possibility of harnessing this energy for useful purposes. A great deal of effort is currently under way to develop a sustained and controllable thermonuclear reactor, a fusion power reactor. Controlled fusion is often called the ultimate energy source because of the availability of its fuel source: water. For example, if deuterium were used as the fuel, 0.12 g of it could be extracted from 1 gal of water at a cost of about four cents. This amount of deuterium would release approximately $10^{10}$ J if all nuclei underwent fusion. By comparison, 1 gal of gasoline releases approximately $10^{8}$ J upon burning and costs far more than four cents.

An additional advantage of fusion reactors is that comparatively few radioactive by-products are formed. For the proton–proton cycle, for instance, the end product is safe, nonradioactive helium. Unfortunately, a thermonuclear reactor that can deliver a net power output spread over a reasonable time interval is not yet a reality, and many difficulties must be resolved before a successful device is constructed.

The Sun's energy is based in part on a set of reactions in which hydrogen is converted to helium. The proton–proton interaction is not suitable for use in a fusion reactor, however, because the event requires very high temperatures and densities. The process works in the Sun only because of the extremely high density of protons in the Sun's interior.

The reactions that appear most promising for a fusion power reactor involve deuterium ($^2_1$H) and tritium ($^3_1$H):

$$\begin{aligned} {}^2_1\text{H} + {}^2_1\text{H} &\rightarrow {}^3_2\text{He} + {}^1_0\text{n} \quad Q = 3.27\ \text{MeV} \\ {}^2_1\text{H} + {}^2_1\text{H} &\rightarrow {}^3_1\text{H} + {}^1_1\text{H} \quad Q = 4.03\ \text{MeV} \\ {}^2_1\text{H} + {}^3_1\text{H} &\rightarrow {}^4_2\text{He} + {}^1_0\text{n} \quad Q = 17.59\ \text{MeV} \end{aligned} \tag{45.4}$$

As noted earlier, deuterium is available in almost unlimited quantities from our lakes and oceans and is very inexpensive to extract. Tritium, however, is radioactive ($T_{1/2} = 12.3$ yr) and undergoes beta decay to $^3$He. For this reason, tritium does not occur naturally to any great extent and must be artificially produced.

One major problem in obtaining energy from nuclear fusion is that the Coulomb repulsive force between two nuclei, which carry positive charges, must be overcome before they can fuse. Figure 45.7 is a graph of potential energy as a function of the separation distance between two deuterons (deuterium nuclei, each having charge $+e$). The potential energy is positive in the region $r > R$, where the Coulomb repulsive force dominates ($R \approx 1$ fm), and negative in the region $r < R$, where the nuclear force dominates. The fundamental problem then is to give the two nuclei enough kinetic energy to overcome this repulsive force. This requirement can be accomplished by raising the fuel to extremely high temperatures (to approximately $10^8$ K). At these high temperatures, the atoms are ionized and the system consists of a collection of electrons and nuclei, commonly referred to as a *plasma*.

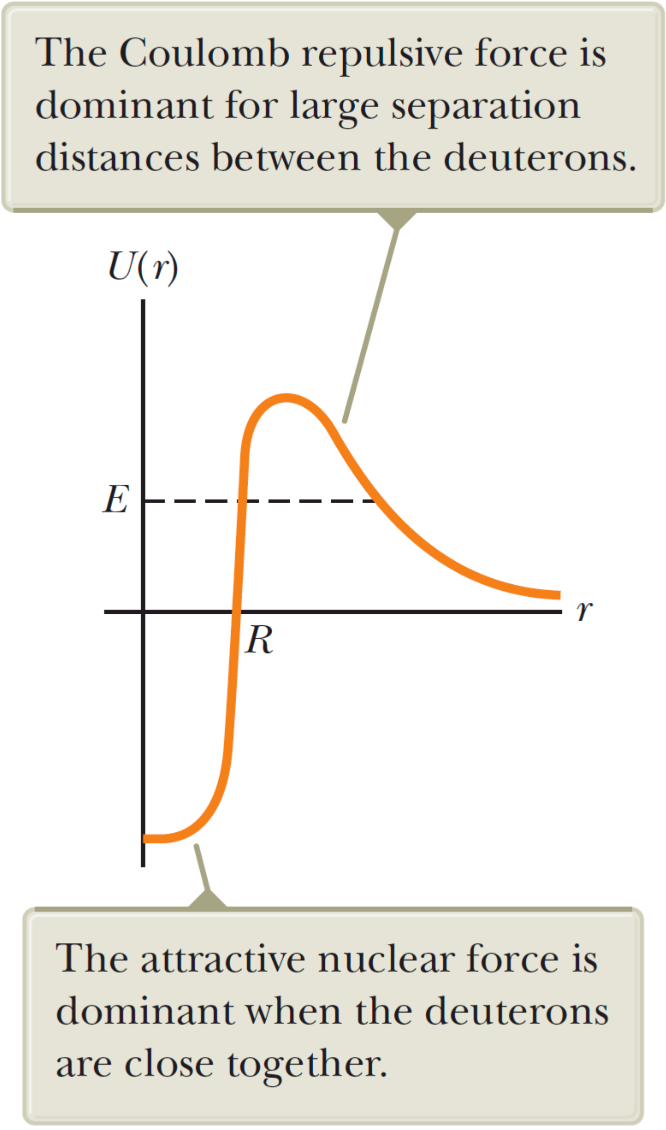
The Coulomb repulsive force is dominant for large separation distances between the deuterons.
U(r)
E
R
r
The attractive nuclear force is dominant when the deuterons are close together.

Figure 45.7

## Example 45.3 The Fusion of Two Deuterons

For the nuclear force to overcome the repulsive Coulomb force, the separation distance between two deuterons must be approximately $1.0 \times 10^{-14}$ m.

**(A)** Calculate the height of the potential barrier due to the repulsive force.

**(B)** Estimate the temperature required for a deuteron to overcome the potential barrier, assuming an energy of $\frac{3}{2}k_B T$ per deuteron (where $k_B$ is Boltzmann's constant).

Boltzmann's constant: $k_B = 1.38 \times 10^{-23}$ J/K

**(C)** Find the energy released in the deuterium–deuterium reaction

$$^{2}_{1}\mathrm{H} + ^{2}_{1}\mathrm{H} \rightarrow ^{3}_{1}\mathrm{H} + ^{1}_{1}\mathrm{H}$$

The atomic masses are: M($^{1}_{1}H$) = 1.007825 u, M($^{2}_{1}H$) = 2.014102 u, M($^{3}_{1}H$) = 3.016049 u

## Advantages and Problems of Fusion

If fusion power can ever be harnessed, it will offer several advantages over fission-generated power: (1) low cost and abundance of fuel (deuterium), (2) impossibility of runaway accidents, and (3) decreased radiation hazard. Some of the anticipated problems and disadvantages include (1) scarcity of lithium, (2) limited supply of helium, which is needed for cooling the superconducting magnets used to produce strong confining fields, and (3) structural damage and induced radioactivity caused by neutron bombardment. If such problems and the engineering design factors can be resolved, nuclear fusion may become a feasible source of energy in the twenty-first century.