11.5 Nuclear Reactions: Fusion

Nuclear fusion reactions occur in the Sun and supply the energy needed to sustain life on Earth (Figure 1). **Nuclear fusion** is the fusing or joining of two small nuclei to make one larger nucleus. When two nuclei join together, the mass of the product nucleus is less than the sum of the masses of the original nuclei. The loss of mass is converted into energy and released. GO

To learn more about nuclear fusion, go to
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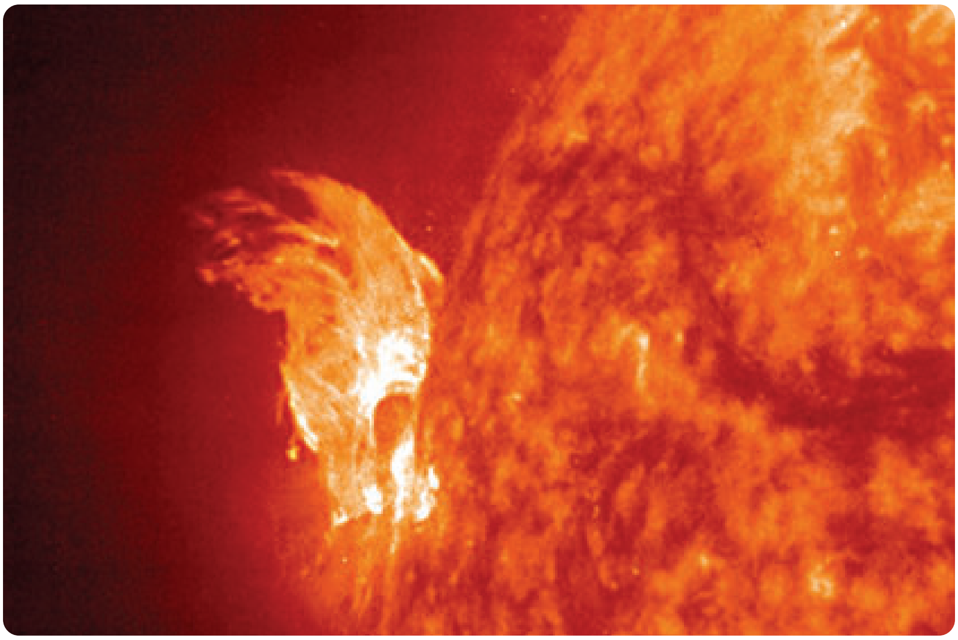

Figure 1 Nuclear fusion reactions take place in the Sun.

LEARNING TIP

Skim (read quickly) to get a general sense of Section 11.5. Examine the headings and figures, and scan for words in bold. Ask yourself, "What information is important here?"

For two nuclei to join together, their natural electrostatic repulsion needs to be overcome. To do this, the nuclei must collide at very high speeds. These high speeds can only occur at very high temperatures, such as in the Sun and other stars.

The simplest nuclear fusion is between two hydrogen nuclei (protons). This type of fusion reaction takes place in the Sun. This can be written as the nuclear equation

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

As with other nuclear equations, the total of the atomic numbers and masses are the same before and after the fusion reaction. Because the $^{2}_{2}\mathrm{He}$ is unstable, it decays immediately to a deuterium nucleus ($^{2}_{1}\mathrm{H}$) by radioactive emission of a positron and a neutrino. A positron is identical to an electron except that it has a positive charge whereas an electron has a negative charge. A positron can be written as $^{0}_{+1}\mathrm{e}$. A neutrino is a particle that has energy, but no mass or charge. The nuclear equation for the reaction is

$$^{2}_{2}\mathrm{He} \rightarrow ^{2}_{1}\mathrm{H} + ^{0}_{+1}\mathrm{e} + \text{a neutrino}$$

Did You KNOW?

Antiparticles

For every type of particle in nature there is a corresponding antiparticle. For example, the antiparticle of a proton is an antiproton and the antiparticle of an electron is a positron. An antiproton is identical to a proton except that it has a negative charge. Similarly, the positron is identical to the electron except that it has a positive charge. When a particle collides with its matching antiparticle, they annihilate or destroy each other and release energy. The mystery is why the universe is populated with particles and not antiparticles.

That means that the fusion of two hydrogen nuclei (protons) results in the formation of a deuterium nucleus. This is followed by the fusion of deuterium with another hydrogen nucleus (proton) to produce helium-3:

$$^{2}_{1}\mathrm{H} + ^{1}_{1}\mathrm{H} \rightarrow ^{3}_{2}\mathrm{He} + ^{0}_{0}\gamma$$

LEARNING TIP
When reading about nuclear equations, slow down your reading pace. Look back and forth between the equations and the related information in the text to help you understand the equations.

Note that a gamma ray (γ), which is electromagnetic radiation that has energy, but no mass or charge, is produced. The product of this reaction is then used to produce helium-4:

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

This series of nuclear reactions produces one helium-4 atom from six hydrogen nuclei. In addition to producing helium, a vast amount of energy is also produced from nuclear reactions in the Sun.

Today, scientists are working to duplicate what is happening in the Sun in a controlled manner and to use it to create energy for use by society. Deuterium is readily available. Normal water contains two hydrogen atoms, and about 0.015 % of them are deuterium. Although this may seem like a small percentage, there is a vast amount of water available on Earth! The fusion of two deuterium atoms produces the following:

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

Energy in Nuclear Fusion Reactions

The energy from fusion reactions comes from the conversion of mass, as with nuclear fission. Tables 1 and 2 show the calculations for the masses of deuterium before and after a fusion reaction.

Table 1 Before Nuclear Fission

Isotope	Atomic mass unit (u)	Mass (kg)
deuterium	2.014	3.344×10^{-27}
deuterium	2.014	3.344×10^{-27}
total	4.028	6.689×10^{-27}

Table 2 After Nuclear Fission

Isotope	Atomic mass unit (u)	Mass (kg)
hydrogen	1.008	1.674×10^{-27}
tritium	3.016	5.008×10^{-27}
total	4.024	6.682×10^{-27}

Using Tables 1 and 2, we can see that the total mass converted as a result of the nuclear fusion is

$$m = 6.689 \times 10^{-27}\ \mathrm{kg} - 6.682 \times 10^{-27}\ \mathrm{kg} = 7.000 \times 10^{-30}\ \mathrm{kg}$$

We can calculate the amount of energy produced using Einstein's equation:

$$\begin{aligned} E &= mc^2 \\ &= (7.000 \times 10^{-30}\ \mathrm{kg})(3.0 \times 10^{8}\ \mathrm{m/s})^2 \\ E &= 6.3 \times 10^{-13}\ \mathrm{J} \end{aligned}$$

While this may seem like a tiny amount of energy, it is an enormous amount for a single atom to produce—even by comparison with nuclear fission.

The goal of designing and building a nuclear fusion reactor has not yet been achieved. One of the advantages of using fusion to produce energy is that the process does not produce harmful waste products in the form of long-lived radioactive isotopes. The major difficulty is the very high temperatures needed to give the particles the high speeds they need to overcome their electrostatic repulsion. The high temperatures make it impossible to hold the material in any container. Nuclear scientists are experimenting with using magnetic fields to hold the material in place long enough for fusion to occur. Although experimental reactors have been made, not one is in commercial use at this time. The present reactors still require more energy than they are able to produce.

Nuclear Fusion Weapons

In the 1940s, scientists realized that the temperatures achieved in the explosion of a nuclear fission bomb were similar to the temperature of the Sun's core. This meant that a fission bomb using plutonium or enriched uranium could be used to start a fusion bomb, which is also called a thermonuclear or hydrogen bomb. The fusion bomb would be many times more powerful than a fission bomb. GO

Although some scientists thought that a fusion bomb would be so powerful that it should not be developed, on November 1, 1952, the United States detonated the first fusion bomb (Figure 2). The resulting mushroom cloud was 150 km wide and 40 km high. The area was obliterated and the surrounding area was littered with radioactive debris. The bomb weighed about 65 tonnes and was an experimental device, not a weapon.

To learn more about nuclear fusion weapons, go to **www.science.nelson.com** GO

Figure 2 The first hydrogen bomb was detonated by the United States in 1952 on the Enewetak Atoll in the Marshall Islands in the Central Pacific Ocean.

In 1954, a second hydrogen bomb was exploded on Bikini Atoll, a ring of 23 islands in the Pacific Ocean. One island was completely vaporized and the radioactive fallout contaminated the surrounding area. Today, the people of Bikini live scattered around the Marshall Islands waiting for a complete radiological cleanup of the atoll.

In a hydrogen bomb, tritium ($^{3}_{1}H$) is used with deuterium. This produces more than four times the energy of using only deuterium. The fusion reaction is

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n$$

Tritium is radioactive with a half-life of 12 years, which means that it is not very plentiful on Earth, whereas deuterium is plentiful.

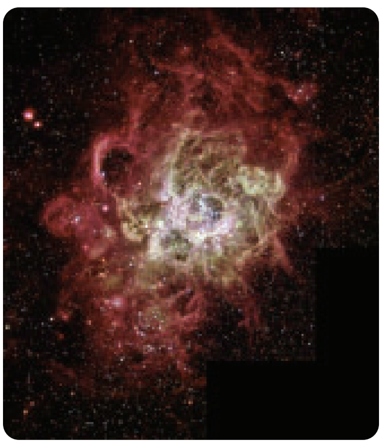

Figure 3 Nebula NGC 604 is one of the largest known star-forming regions. The nebula contains more than 200 stars in a cloud that is nearly 1300 light years across.

Nuclear Processes in Stars

The nuclear processes that occur in stars (Figure 3) follow the stages in the life of the star and allow for different combinations. For example, in addition to the previously mentioned method of the formation of helium-4 from six hydrogen nuclei that takes place in our Sun, other routes are possible. For example, helium isotopes can produce beryllium, which is transmuted into lithium and turned back into two helium-4 nuclei. The stages involved in the process are

$$^{3}_{2}He + ^{4}_{2}He \rightarrow ^{7}_{4}Be + ^{0}_{0}\gamma$$
$$^{7}_{4}Be + ^{0}_{-1}e \rightarrow ^{7}_{3}Li \text{ and a neutrino}$$
$$^{7}_{3}Li + ^{1}_{1}H \rightarrow ^{4}_{2}He + ^{4}_{2}He$$

The nuclear process starts with one helium-4 nucleus and ends with the two helium-4 nuclei. The fusion reactions also release tremendous amounts of energy. The helium-4 nuclei are very important for the production of other elements. When all of the hydrogen is converted into helium-4, the temperature of the star rises, and then helium-4 begins to produce heavier elements. The production of carbon occurs in two steps:

$$^{4}_{2}He + ^{4}_{2}He \rightarrow ^{8}_{4}Be + ^{0}_{0}\gamma$$
$$^{4}_{2}He + ^{8}_{4}Be \rightarrow ^{12}_{6}C + ^{0}_{0}\gamma$$

Since the helium-4 nucleus is also called an alpha particle, this process is known as the triple-alpha process. Adding another alpha particle to the carbon-12 creates oxygen-16. Repeating the process with the oxygen-16 creates neon-20 and then magnesium-24. Each nuclear fusion reaction releases large amounts of energy. Different masses of stars follow different paths and produce different elements. Stars are the factories of the universe that make up all of the elements of the Periodic Table. Many heavy isotopes however, are only produced in the nuclear reactions in supernova explosions at the end of the life of some heavy stars.

STUDY TIP

A concept map can be used to map the stages involved in the nuclear processes that occur in stars. At the top of a study card, write "Stages of Nuclear Processes in Stars." Add words that are connected with lines or arrows. Write on the lines or arrows to explain the connections to the stages.

11.5 CHECK YOUR Understanding

1. Write a definition of nuclear fusion in your own words.
2. Why must two nuclei be moving at high speeds for nuclear fusion to occur?
3. Compare nuclear fission and fusion.
4. When two nuclei combine in fusion, does this reaction obey the law of conservation of mass? Explain your answer.
5. What is a neutrino? How is a neutrino produced?
6. Why is it not possible to use heavy elements, such as uranium, for nuclear fusion?
7. Jupiter is largely made of hydrogen in the same proportions as the Sun. Why do nuclear fusion reactions occur in the Sun, but not in Jupiter?
8. What is deuterium and why would it be a good fuel for a nuclear fusion reactor?
9. Compete the following nuclear fusion reactions:
   (a) ${}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{2}He + \textbf{?}$
   (b) ${}^{3}_{2}He + {}^{3}_{2}He \rightarrow \textbf{?} + 2{}^{1}_{1}H$
   (c) ${}^{3}_{2}He + {}^{3}_{2}He \rightarrow \textbf{?} + {}^{1}_{1}H + {}^{1}_{1}H$
   (d) ${}^{2}_{1}H + \textbf{?} \rightarrow {}^{3}_{1}H + {}^{1}_{1}H$
10. What are the major obstacles facing the development of a commercially successful nuclear fusion power plant?
11. What are the waste products produced by nuclear fusion? Are these products dangerous?
12. Why is tritium not plentiful on Earth?
13. Hydrogen bombs that have been exploded on Earth have radioactive waste products. How did the bomb produce these?
14. Why does a hydrogen bomb require a nuclear fission bomb?
15. What is the advantage of using tritium with deuterium in a hydrogen bomb?
16. Is it possible to store tritium for later use in a bomb? Explain your answer.
17. In the first part of a star's life, hydrogen is converted into helium-4. What happens to the star so that it converts helium-4 into other elements?
18. What elements can be made in stars using helium-4 building blocks?
19. Explain how stars produce carbon-12.
20. Stars produce the elements of the Periodic Table (Figure 4). Will our Sun produce all the elements on the Periodic Table at the end of its life?

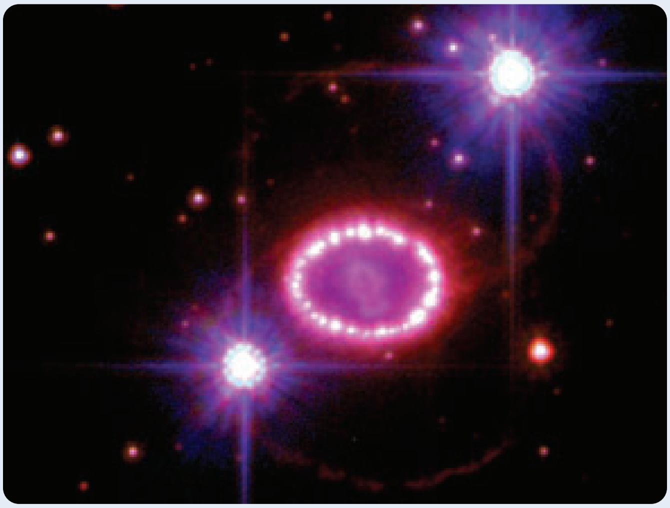

Figure 4