7.5 Nuclear Fusion

Figure 1 The Sun is a natural fusion reactor.

nuclear fusion a nuclear reaction in which the nuclei of two atoms fuse together to form a larger nucleus

What powers the stars, such as our Sun (**Figure 1**)? A particular type of nuclear reaction powers the stars, and knowledge of these reactions can help us understand how stellar objects are formed and how they die. These reactions can also potentially provide society with a clean, renewable source of power. Unlike fossil fuel reactors, nuclear fission reactors are very clean in that they emit very small quantities of pollutants into the atmosphere. However, fission reactors have some negative environmental effects. The radioactive waste products are potentially harmful if not disposed of properly. This has led scientists to seek a cleaner source of power in the form of nuclear fusion. **Nuclear fusion** is a nuclear reaction in which the nuclei of two atoms fuse to form another element. Nuclear fusion is the opposite process of nuclear fission.

In order for nuclear fusion to occur, the fusing nuclei must have enough kinetic energy to overcome the repulsive electrostatic force between them. This allows the nuclei to get close enough to each other for the strong nuclear force to take effect. This is not an easy task to achieve in the laboratory, much less in a power reactor.

Nuclear Stability

Under what conditions are nuclear fission and nuclear fusion most likely to occur? To understand this, we need to consider the relative stability of heavy and light isotopes. **Figure 2** shows the binding energy per nucleon of all stable elements. The higher the binding energy value, the more stable is the nucleus.

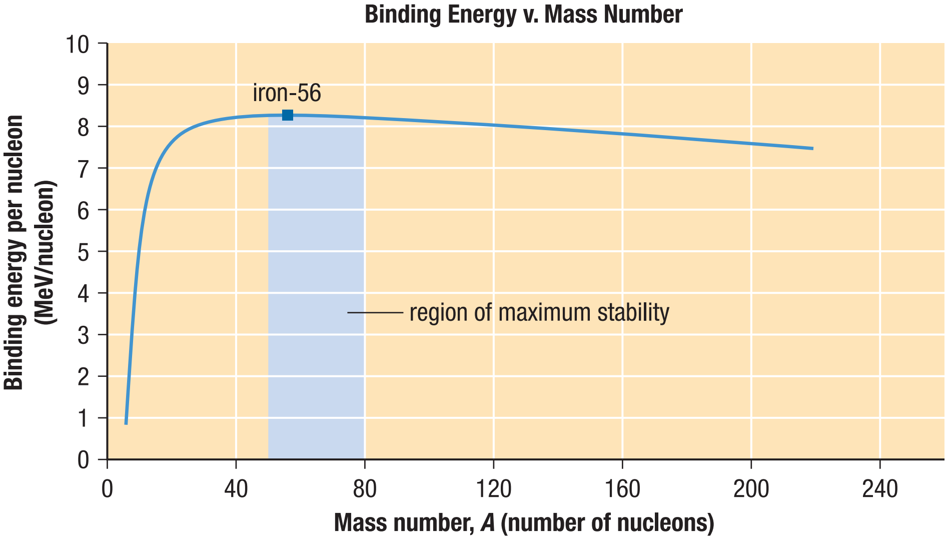

Figure 2 Binding energy as a function of mass number

Notice that this binding energy graph rises sharply, reaching a maximum at $A = 56$, before gradually decreasing. This suggests that iron-56 is the most stable of all nuclei, with the most tightly bound nucleus.

Consider the right side of the graph: the heavier nuclei. When a heavy nucleus undergoes nuclear fission, the nuclei of the daughter atoms typically have mass numbers that average around 118, which is closer to the region of maximum stability. The binding energy of the daughters of a fission reaction is therefore greater than that of the parent. The products are more stable than the reactant.

Consider the left side of the graph: the lighter nuclei. When these atoms fuse together to form a heavier nucleus, the binding energy increases sharply, with the reaction again producing a product that is closer to the region of maximum stability. The product is more stable than the reactants.

Nuclear fission is more likely to occur with very heavy nuclei, while nuclear fusion is more likely to occur with very light nuclei. In both situations, the total binding energy increases during the reaction. This implies that the mass defect has increased, which corresponds to a release of energy. Both fission and fusion reactions are highly exothermic.

By calculating the energy released in each type of reaction, you can accurately compare the relative energy output of a nuclear fusion reaction with that of a nuclear fission reaction. It is important to consider the energy equivalent of one atomic unit of mass, measured in MeV:

$$\begin{aligned} E &= mc^2 \\ &= (1.66 \times 10^{-27}\ \text{kg})(3.0 \times 10^{8}\ \text{m/s})^2 \times \frac{1\ \text{MeV}}{1.602 \times 10^{-13}\ \text{J}} \\ &= 930\ \text{MeV} \end{aligned}$$

Since this is the energy of 1 atomic mass unit (1 u), we can use

$mc^2 = (1\ \text{u})c^2 = 930\ \text{MeV}$ or $(1\ \text{u})c^2 = 930\ \text{MeV}$

Dividing both sides by 1 u gives another way to represent c^2:

$c^2 = 930\ \text{MeV/u}$

In the following Tutorial, you will determine the mass defect and use it to calculate the energy produced during a fusion reaction and a fission reaction.

LEARNING **TIP**

Unit Analysis
Use unit analysis to simplify the units in this equation: 1 $\text{kg}\cdot\text{m}^2/\text{s}^2$ is equal to 1 J. The joules will divide out, leaving MeV as the unit of energy.

Tutorial 1 Using the Mass Defect to Compare the Energy Output of Fusion and Fission Reactions

Sample Problem 1

Determine the energy released when a deuterium atom (D) fuses with a tritium atom (T) to form helium, according to the nuclear reaction equation below. Use the given masses.

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

$m_D = 2.014\ 10\ \text{u}$

$m_T = 3.016\ 05\ \text{u}$

$m_{He} = 4.002\ 60\ \text{u}$

$m_n = 1.008\ 67\ \text{u}$

$c^2 = 930\ \text{MeV/u}$

Given: $m_D = 2.014\ 10\ \text{u}$; $m_T = 3.016\ 05\ \text{u}$; $m_{He} = 4.002\ 60\ \text{u}$; $m_n = 1.008\ 67\ \text{u}$; $c^2 = 930\ \text{MeV/u}$

Required: E

Analysis: $E = \Delta mc^2$

Solution: In this problem, the masses of the parent and daughter atoms of a fusion reaction are given. Since the mass defect is related to the binding energy, use $E = \Delta mc^2$ to calculate the energy released. First, calculate the mass defect, Δm.

$$\begin{aligned} \Delta m &= (m_D + m_T) - (m_{He} + m_n) \\ &= (2.014\ 10\ \text{u} + 3.016\ 05\ \text{u}) - (4.002\ 60\ \text{u} + 1.008\ 67\ \text{u}) \\ &= 5.030\ 15\ \text{u} - 5.011\ 27\ \text{u} \\ \Delta m &= 0.018\ 88\ \text{u} \end{aligned}$$

Substitute 0.018 88 u into $E = \Delta mc^2$ to determine the binding energy.

$$\begin{aligned} E &= \Delta mc^2 \\ &= (0.018\ 88\ \text{u})(930\ \text{MeV/u}) \\ E &= 17.6\ \text{MeV} \end{aligned}$$

Statement: 17.6 MeV of energy is released when a deuterium atom fuses with a tritium atom to form helium.

Sample Problem 2

Determine the energy released when uranium-235 produces tellurium-140 and zirconium-94, according to the nuclear fission reaction equation below. Use the given masses.

$$^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{140}_{52}\text{Te} + {}^{94}_{40}\text{Zr} + 2({}^{1}_{0}\text{n}) + \text{energy}$$

$$\begin{aligned} m_{\text{U-235}} &= 235.043\ 9\ \text{u} \\ m_{\text{Te-140}} &= 139.938\ 9\ \text{u} \\ m_{\text{Zr-94}} &= 93.906\ 3\ \text{u} \\ m_{\text{n}} &= 1.008\ 67\ \text{u} \\ \text{c}^2 &= 930.0\ \text{MeV/u} \end{aligned}$$

Given: $m_{\text{U-235}} = 235.0439$ u; $m_{\text{Te-140}} = 139.938\ 9$ u; $m_{\text{Zr-94}} = 93.906\,3$ u; $m_{\text{n}} = 1.008\ 67$ u; $c^2 = 930.0$ MeV/u

Required: E

Analysis: $E = \Delta mc^2$

Solution: In this problem, the masses of the parent and daughter atoms of a fission reaction are given. Since the mass defect is related to the binding energy, use $E = \Delta mc^2$ to calculate the energy released. Calculate the mass defect. Notice that one neutron can be cancelled on either side of the reaction equation.

$$^{235}_{92}\text{U} + {}^{1}_{0}\cancel{\text{n}} \rightarrow {}^{140}_{52}\text{Te} + {}^{94}_{40}\text{Zr} + \cancel{2}({}^{1}_{0}\text{n}) + \text{energy}$$

$$^{235}_{92}\text{U} \rightarrow {}^{140}_{52}\text{Te} + {}^{94}_{40}\text{Zr} + {}^{1}_{0}\text{n} + \text{energy}$$

$$\begin{aligned} \Delta m &= m_{\text{U-235}} - (m_{\text{Te-140}} + m_{\text{Zr-94}} + m_{\text{n}}) \\ &= 235.043\ 9\ \text{u} - (139.938\ 9\ \text{u} + 93.906\ 3\ \text{u} + 1.008\ 67\ \text{u}) \\ \Delta m &= 0.190\ 030\ \text{u} \end{aligned}$$

Substitute 0.190 030 u into $E = \Delta mc^2$ to determine the binding energy.

$$\begin{aligned} E &= \Delta mc^2 \\ &= (0.190\ 030\ \text{u})(930.0\ \text{MeV/u}) \\ E &= 176.7\ \text{MeV} \end{aligned}$$

Statement: 176.7 MeV of energy is released when U-235 undergoes fission to produce Te-140 and Zr-94.

Practice

1. One type of stellar fusion reaction is the burning of helium to form carbon. The reaction equation for this process is

$$^{4}_{2}\text{He} + {}^{4}_{2}\text{He} + {}^{4}_{2}\text{He} \rightarrow {}^{12}_{6}\text{C} + \text{energy}$$

The masses of the parent and daughter atoms are $m_{\text{He}} = 4.002\ 60$ u and $m_{\text{C}} = 12.000\ 00$ u. T/I C

(a) Calculate the mass defect for this reaction. [ans: 0.007 80 u]

(b) Determine the energy released in this reaction. [ans: 7.25 MeV]

(c) What is the energy released per nucleon? [ans: 0.60 MeV/nucleon]

The calculations in Tutorial 1 suggest that fission produces more energy than fusion. Note, however, that the uranium-235 in the fission reaction has about 50 times more mass than the reactants in the fusion reaction. So, on a per mass basis, fusion typically yields more energy than fission.

The Quest for Controlled Nuclear Fusion

Achieving nuclear fusion in a laboratory is very difficult. The only natural conditions that allow for nuclear fusion to occur are in the cores of stars, where the pressure, temperature, and density of nuclei are tremendous. Even under such conditions, the probability of a nuclear fusion reaction occurring is low. Successful fusion reactions occur only because of the huge number of interactions.

Stellar Fusion

In the cores of stars, temperatures and pressures can build to the high levels necessary for fusion. Two of the processes in which stellar fusion occurs are described below.

PROTON-PROTON CHAIN

Fusion occurs in stars the size of the Sun and smaller through a process called the proton-proton chain. In this series of reactions, four protons eventually fuse to form one helium-4 atom. The net reaction in a proton-proton chain can be described by the following equation:

$$4({}^{1}_{1}\mathrm{H}) \rightarrow {}^{4}_{2}\mathrm{He} + 2({}^{0}_{+1}\mathrm{e}) + \text{energy}$$

Notice that two of the four protons each becomes a neutron and a positron. Conversion of hydrogen to helium in the core of a star is just the first step in the production of all of the naturally occurring elements listed in the periodic table. In this sense, stars can be thought of as the factories of all matter. The process of forming larger elements from smaller ones via nuclear fusion is known as nucleosynthesis.

CARBON-NITROGEN-OXYGEN CYCLE

Another process occurs in stars that are significantly larger, and hotter, than the Sun. The carbon-nitrogen-oxygen cycle activates the fusion of hydrogen into helium. In this cycle, a carbon-12 nucleus undergoes a number of nuclear reactions involving fusion and decay. A summary of these is shown below. Notice that this cycle begins and ends with a carbon-12 atom.

$${}^{12}_{6}\mathrm{C} \rightarrow {}^{13}_{7}\mathrm{N} \rightarrow {}^{13}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} \rightarrow {}^{15}_{8}\mathrm{O} \rightarrow {}^{15}_{7}\mathrm{N} \rightarrow {}^{12}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He}$$

This series of nuclear reactions produces large quantities of energy. The high energy yield of the carbon-nitrogen-oxygen cycle has motivated scientists to develop technologies for producing controlled nuclear fusion. However, another important factor makes nuclear fusion better than fission from an environmental standpoint. Nuclear fission reactors produce radioactive waste that is potentially harmful to humans and the environment. During the process of nuclear fusion, far less radioactive waste is produced. Theoretically, nuclear fusion is our cleanest potential source of energy.

Modern Advances in Nuclear Fusion

MAGNETIC CONFINEMENT FUSION

One of the most promising methods for controlling nuclear fusion is based on the principle of magnetic confinement. Deuterium and tritium are placed in the core of the reactor and heated to an extremely high temperature, comparable to that of the Sun's core. When this happens, the materials change to the fourth state of matter, called plasma. Plasma is the fluid state of matter in which all atoms are ionized. These are the required conditions for nuclear fusion to occur.

The challenge, however, is how to confine matter that is in such a high thermal energy state. In the Sun, the enormous attractive gravitational forces due to its immense mass are sufficient to confine the plasma. This is not practical, however, for the masses of fuels suited to a laboratory or reactor.

LEARNING **TIP**

Superconducting Electromagnets

A superconductor is a material with little to no electrical resistance. A superconducting electromagnet produces powerful magnetic fields when current is applied. You will learn more about electromagnets in Chapter 13.

To achieve plasma confinement under laboratory conditions, a superconducting electromagnet is placed around the core in the shape of a toroid (donut shape) as shown in **Figure 3**. When a high current is passed through the coil, a very powerful magnetic field is produced, which confines the plasma.

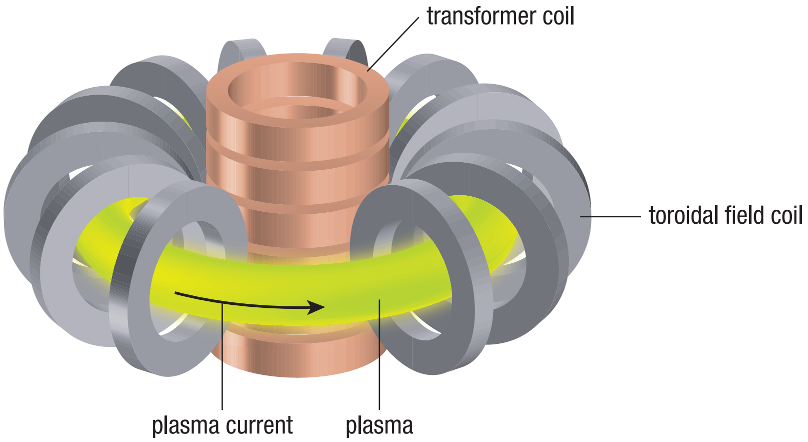

Figure 3 Magnetic confinement fusion reactor design

Theory suggests that with the plasma state achieved, and the fuel magnetically confined, fusion can occur, resulting in the release of energy. While there have been some reports of successful trials of controlled nuclear fusion in laboratory conditions, none have yet been achieved that can sustain a chain reaction. This is the ultimate goal that must be achieved if we are to use nuclear fusion as a practical energy source.

THE ITER PROJECT

The ITER project is an international joint effort aimed at developing a functional nuclear fusion reactor for research purposes. (Iter means ″the way″ in Latin.) The ITER reactor in Cadarache, France, is a type of magnetic confinement fusion reactor called a Tokamak (**Figure 4**). This very expensive project has provoked controversy from skeptics who feel that too much money will be wasted with little return on investment. Canada, originally a participant, has withdrawn due to lack of funding. Critics of the project also voice objections to the experimental nature of the facility.

WEB **LINK**

To learn more about the ITER Tokamak reactor,

GO TO NELSON SCIENCE

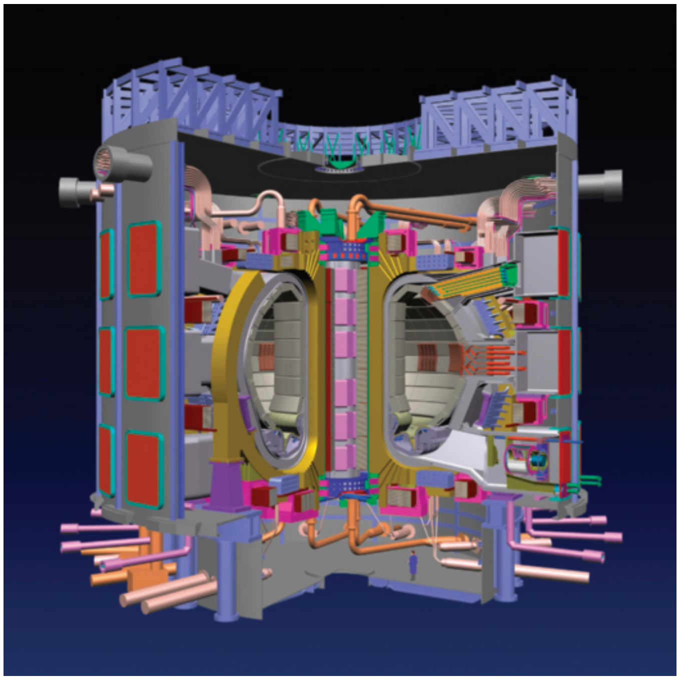

Figure 4 ITER Tokamak reactor design

7.5 Summary

- Nuclear fusion is the process by which lighter atoms fuse together to form heavier atoms.
- Nuclear fusion reactions are exothermic and produce significantly more energy per mass of fuel than fission reactions.
- Nuclear fusion is a potential source of clean energy, producing little pollution or waste.
- Magnetic confinement fusion is a method in which electromagnetic forces are used to confine fusion fuel that is in a very high-temperature, plasma state.
- Controlled nuclear fusion has been achieved, but not in a sustainable way.
- The ITER project is the first significant international attempt to create a functioning nuclear fusion research reactor.

Investigation 7.5.1

Nuclear Energy: Benefit or Hazard? (p. 350) Now that you have learned about nuclear fission and nuclear fusion, you can perform Investigation 7.5.1. You will explore public opinion on the issue of nuclear energy. You will conduct research, analyze data, and present your findings.

7.5 Questions

1. Compare and contrast nuclear fission and nuclear fusion. How are these reactions alike? How are they different? K/U C
2. (a) Explain why nuclear fusion is more difficult to achieve than nuclear fission.
   (b) Why is nuclear fusion more desirable than nuclear fission for power generation? K/U C
3. Use the following values to answer (a) and (b): T/I C

   $m_{\text{H-1}} = 1.007\ 825\ \text{u}$

   $m_{\text{C-12}} = 12.000\ 00\ \text{u}$

   $m_{\text{C-13}} = 13.003\ 35\ \text{u}$

   $m_{\text{N-14}} = 14.003\ 07\ \text{u}$

   (a) Determine the amount of energy released in the third stage of the carbon-nitrogen-oxygen cycle:

   $${}^{13}_{6}\text{C} + {}^{1}_{1}\text{H} \rightarrow {}^{14}_{7}\text{N} + \text{energy}$$

   (b) In the first stage of the carbon-nitrogen-oxygen cycle, 1.95 MeV is produced per reaction:

   $${}^{12}_{6}\text{C} + {}^{1}_{1}\text{H} \rightarrow {}^{13}_{7}\text{N} + \text{energy}$$

   Use this information to determine the mass of nitrogen-13. T/I
4. Refer to Tutorial 1 on page 343.
   (a) Determine the energy released per nucleon for the fission and fusion reactions in Sample Problems 1 and 2.
   (b) What is illustrated by comparing these energy values? K/U T/I C
5. Deuterium can be extracted from normal water, and tritium is a waste product of CANDU reactors. What does this suggest about the fuel availability for nuclear fusion reactors? A
6. Consider the carbon-nitrogen-oxygen cycle:

   $${}^{12}_{6}\text{C} \rightarrow {}^{13}_{7}\text{N} \rightarrow {}^{13}_{6}\text{C} \rightarrow {}^{14}_{7}\text{N} \rightarrow {}^{15}_{8}\text{O} \rightarrow {}^{15}_{7}\text{N} \rightarrow {}^{12}_{6}\text{C} + {}^{4}_{2}\text{He}$$

   The first two reaction equations of this cycle are

   $${}^{12}_{6}\text{C} + {}^{1}_{1}\text{H} \rightarrow {}^{13}_{7}\text{N} + \text{energy}$$

   $${}^{13}_{7}\text{N} \rightarrow {}^{13}_{6}\text{C} + {}^{0}_{+1}\text{e} + \text{energy}$$

   (a) Which of these is a fusion reaction? Explain.
   (b) Which of these is a beta decay reaction? What type of beta decay is it? Explain how you know.
   (c) Write the remaining reaction equations for this cycle and classify each by type of nuclear reaction. Assume that the beta decay reactions are of the same type as the one given above. K/U T/I C
7. Perform some research on nuclear fusion techniques. What are some alternative methods for controlling nuclear fusion that have not been discussed in this section? Write a sentence or two to describe how each of these works. Include diagrams to support your explanations. T/I C
8. Conduct research on the ITER project. What advances have been made since the publication of this text? T/I

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