11.2 Nuclear Reactions: Fission

Following Fermi's work in 1938, Otto Hahn, Lise Meitner, and Fritz Strassmann discovered that when neutrons bombarded uranium atoms, the reaction produced smaller nuclei that were about half the size of a uranium nucleus. Later, Meitner and Otto Frisch realized that after the uranium nucleus had absorbed a neutron, it split into two smaller nuclei. Until then, the only known nuclear processes involved a nucleus emitting a small fragment such as an alpha particle or a beta particle. This process of splitting a large nucleus into two smaller nuclei is called **nuclear fission**. Meitner and Frisch used the term because of the similarity to the process of cellular fission in biology.

Meitner and Frisch realized that, although the positively charged protons could exist side by side inside the nucleus, when the nucleus divided, there would be two positively charged nuclei very close to each other. These two nuclei would exert a very large electrostatic force of repulsion on each other and, therefore, would be driven apart with great speed. This means that the nuclei would have a great amount of kinetic energy. They concluded that a nuclear fission reaction would produce very large amounts of energy.

On Earth, uranium naturally occurs as three isotopes: 99.275 % is uranium-238, 0.720 % is uranium-235, and 0.005 % is uranium-234. Although all three isotopes are radioactive, they have very long half-lives and this type of decay is not significant for nuclear energy. Uranium-234 and uranium-238 do not undergo fission readily. However, if an atom of uranium-235 absorbs a neutron, it becomes uranium-236. The nuclear equation for this reaction is

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{236}_{92}\mathrm{U}$$

The uranium-236 nucleus is unstable and exists very briefly—for about a millionth of a millionth of a second—and then splits into two smaller nuclei (N_1 and N_2). The reaction releases a tremendous amount of energy. In addition, this process usually produces two or three neutrons. The nuclear fission reaction of uranium-235 can be written as

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{236}_{92}\mathrm{U} \rightarrow N_1 + N_2 + \text{neutrons}$$

Several models have been proposed to describe how the nucleus splits into two parts. The liquid drop model treats the nucleus as if it were composed of a liquid. The protons and neutrons are like the molecules in a drop of water. The liquid nucleus is held together by cohesive forces that compete with repulsive electrostatic forces. The liquid drop model not only provides an

Did You KNOW?

Cheated out of a Nobel Prize?

Should Lise Meitner have been awarded the Nobel Prize? Meitner and Hahn worked together for 30 years in Germany. In 1917, they discovered the element protactinium. After she fled Nazi Germany at the end of 1938, Hahn and Strassmann analyzed the products formed when uranium was bombarded with neutrons and found that the elements were lighter than uranium. Hahn turned to Meitner to come up with the explanation. Within days, she and Otto Frisch had worked out a theoretical model of nuclear fission. Meanwhile, Hahn published his evidence of fission without listing Meitner as a contributor. Hahn won the 1944 Nobel Prize in Chemistry. Element 109 was named meitnerium after Meitner in 1994.

explanation of the splitting of a nucleus, but also provides a means of visualizing the process, as shown in Figure 1.

Note that the smaller nuclei (N_1 and N_2) are roughly half the original mass, but they are not equal in size. However, the total mass is about the same as the mass of the uranium-236 nucleus. Although there are many different possible nuclei produced, one possible nuclear fission equation is

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

There are three neutrons produced in this fission reaction. The reaction follows the two rules for nuclear equations. First, the conservation of electric charge (atomic number) is obeyed since the total before (92 + 0) is the same as the total after (56 + 36 + 0). Second, the conservation of the total number of protons and neutrons (mass number) is obeyed since the total before (235 + 1) is the same as the total after (141 + 92 + 3(1)). Although the mass number is the same before and after, the mass is not. The mass of the products is slightly less since the fission reaction has converted a tiny amount of mass into energy. GO

To learn more about nuclear fission, go to
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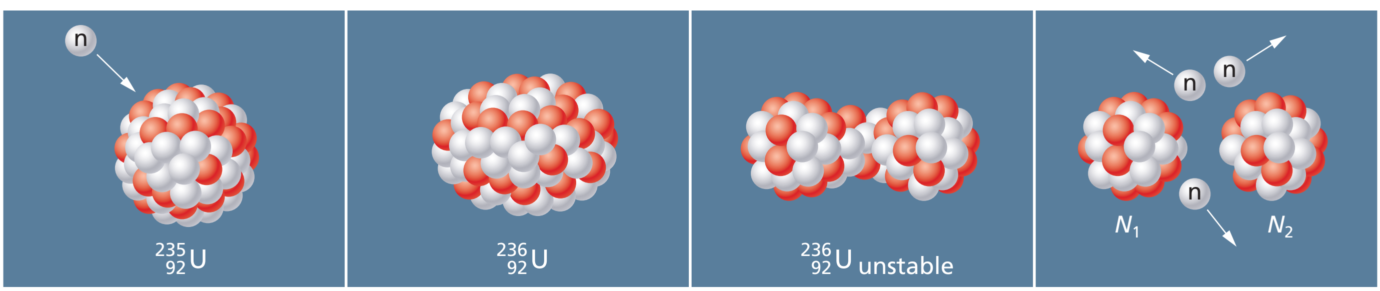

(a) **(b)** **(c)** **(d)**

Figure 1 (a) The neutron penetrates the nucleus and transforms the uranium-235 into uranium-236. (b) The neutron changes the isotope and excites the nucleus. This causes the nucleus to become elongated. Since the two ends of the nucleus are both positively charged, they repel each other. (c) Because the force of repulsion is so strong, it causes the nucleus to split apart. (d) The fission of the nucleus is accompanied by the release of energy and three neutrons.

STUDY TIP

To help you recognize and solve similar problems on an exam, make a two-column chart of sample problems and methods of solution. In one column of the chart, write the problem. In the other column, write the steps to the solution. Reread the chart and try to picture the solution in your head.

SAMPLE PROBLEM

Determine the Missing Fragment

Consider the following nuclear equation:

$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{140}_{54}\text{Xe} + ? + 2^{1}_{0}\text{n}$$

(a) How many neutrons are produced by the reaction?

(b) Complete the nuclear equation.

Solution

(a) The large number 2 in front of the neutron indicates that there are 2 neutrons produced.

(b) Since the total of the atomic numbers on each side of the equation must be equal, the missing atomic number is 92 − 54 = 38. This means that the missing element is strontium. Since the total mass number on each side of the equation must be equal, the mass of the strontium must be (235 + 1) − (140 + 2(1)) = 94. Therefore, the missing isotope of the missing fragment is strontium-94 and the completed equation is

$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{140}_{54}\text{Xe} + ^{94}_{38}\text{Sr} + 2^{1}_{0}\text{n}$$

Practice

Consider the following nuclear equation:

$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ? + ^{89}_{36}\text{Kr} + 3^{1}_{0}\text{n}$$

(a) How many neutrons are produced by the reaction?

(b) Complete the nuclear equation.

Both uranium-235 and uranium-238 occur in natural ores containing uranium. Since the isotopes of uranium are chemically very similar, they must be separated from each other using physical properties. Uranium-238 is slightly heavier (by one percent) than uranium-235. This difference in mass can be used to separate the isotopes. However, since the difference is very small, the separation is both difficult and costly.

Energy in Nuclear Fission Reactions

A tremendous amount of energy is produced in a nuclear fission reaction. Since the sum of the mass numbers before and after a nuclear fission is the same, how is it possible to get energy from nuclear fission? The answer is that a tiny amount of mass is converted to energy. We know this because there is a difference between the sum of the atomic masses before and after the reaction. To see exactly how much mass is converted into energy, we must convert the masses from accurate atomic mass units (u) into kilograms (kg). For example, let's look at the reaction

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

Tables 1 and 2 show the calculations for the masses of uranium-235 and neutrons before nuclear fission, and the isotopes and the neutrons produced after nuclear fission.

LEARNING TIP

Check your understanding of nuclear fission. Discuss the following analogy with a partner: Nuclear fission is to physics as cellular fission is to biology.

Table 1 Before Nuclear Fission

Isotope	Atomic mass unit (u)	Mass (kg)
uranium-235	235.04392	3.902999×10^{-25}
neutron	1.008665	1.674929×10^{-27}
total	236.05259	3.91975×10^{-25}

Table 2 After Nuclear Fission

Isotope	Atomic mass unit (u)	Mass (kg)
barium-141	140.91436	2.339940×10^{-25}
krypton-92	91.92627	1.526473×10^{-25}
neutrons (3)	3.025995	5.024786×10^{-27}
total	235.86663	3.916660×10^{-25}

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

$$m = 3.91975 \times 10^{-25}\ \text{kg} - 3.916660 \times 10^{-25}\ \text{kg} = 3.09000 \times 10^{-28}\ \text{kg}$$

We can calculate the amount of energy produced using Einstein's equation (with a slightly more accurate number for the speed of light):

$$E = mc^2 = (3.09000 \times 10^{-28}\ \text{kg})(2.997925 \times 10^{8}\ \text{m/s})^2$$
$$E = 2.77715 \times 10^{-11}\ \text{J}$$

While this may seem like a tiny amount of energy, it is an enormous amount for a single atom to produce. By comparison, this is more than a million times more energy than a single molecule of carbon in a lump of coal releases when it reacts chemically. However, to produce a useful amount of energy using nuclear fission, a nuclear fission reactor is needed.

STUDY TIP

Reduce chapter test anxiety—start to study for a chapter test early. You cannot hope to cram three or four weeks of learning into a couple of days of studying!

Nuclear Fission Weapons

Once scientists understood that a fission reaction could produce great quantities of energy, their focus turned to creating nuclear weapons. A fission bomb, which is also called an atomic bomb, uses uranium or plutonium stored at a mass that is less than the critical mass. Critical mass is the mass of radioactive material required to sustain the reaction. When the material starts to undergo a reaction, the reaction proceeds at an increasing rate until all of the material is used. The nuclear material must be stored safely until needed, and then the goal is to use up all of the nuclear material before the bomb destroys itself. The simplest way to keep the mass less than critical mass is to keep the material in two sections and then force the pieces together. This is known as the "gun method." The bomb that was dropped on Hiroshima in Japan was a gun-type bomb.

Another way to detonate a nuclear weapon uses the "implosion" method. In this case, a chemical explosion compresses a single subcritical piece of nuclear material so that the nuclear material exceeds the critical mass. The bomb detonated over Nagasaki in Japan was an implosion-type bomb (Figure 2). GO

Did You KNOW?

The Manhattan Project

Established just before the start of World War II in 1939, the Manhattan Project was the code name for the U.S. government's secret program to develop the first nuclear fission bomb. Enrico Fermi's successful production of a controlled nuclear fission reaction, in 1942, quickly led to the development of the first nuclear fission bombs. The first bomb was exploded at Los Alamos, New Mexico, on July 6, 1945. One month later, two nuclear weapons were exploded over Japan, at Hiroshima and Nagasaki. The Manhattan Project had taken fission from the laboratory to the battlefield.

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

Figure 2 The detonation of a nuclear fission bomb in Nagasaki caused immense damage from the intense heat of the explosion, the pressure of the shock wave from the blast, and radioactive fallout.

11.2 CHECK YOUR Understanding

1. Write a definition of nuclear fission in your own words.
2. How is nuclear fission in physics similar to cellular fission in biology?
3. Nuclear fission produces two daughter nuclei that are driven apart with great speed. What causes the nuclei to be driven apart?
4. Compare radioactive decay and nuclear fission.
5. Describe the liquid drop model of nuclear fission in your own words.
6. Uranium-238 is the most common isotope of uranium on Earth. Would a 10 kg sample of uranium-238 be dangerous?
7. Uranium-236 is used in fission reactions to produce energy.
   (a) Why does uranium-236 not exist naturally on Earth?
   (b) How is uranium-236 produced for fission reactions?
8. When writing nuclear equations, you must follow two rules. Describe each rule.
9. Complete the following nuclear equations:
   (a) ${}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{139}_{56}\text{Ba} + \textbf{?} + 3\,{}^{1}_{0}\text{n}$
   (b) ${}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{132}_{50}\text{Sn} + \textbf{?} + 3\,{}^{1}_{0}\text{n}$
   (c) ${}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow \textbf{?} + {}^{101}_{41}\text{Nb} + 3\,{}^{1}_{0}\text{n}$
   (d) ${}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{141}_{56}\text{Ba} + \textbf{?} + 3\,{}^{1}_{0}\text{n}$
   (e) ${}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{90}_{37}\text{Rb} + {}^{144}_{55}\text{Cs} + \textbf{?}$
10. One possible outcome of the fission reaction of uranium is the production of strontium-90 and xenon-143 along with three neutrons and energy (Figure 3). Write the nuclear equation for this reaction beginning with the addition of a neutron to a uranium-235 nucleus.

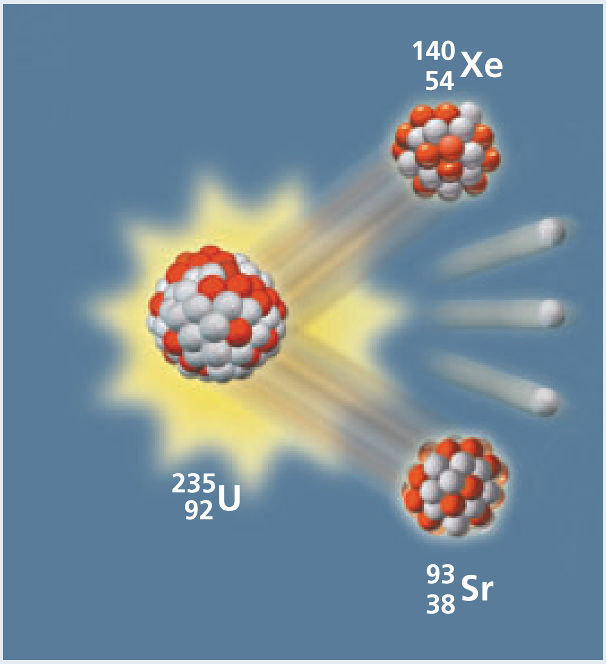

Figure 3

11. How does the total mass of the uranium-235 atom plus the neutron compare with the total mass of the products? Explain your answer.
12. If the mass of an electron ($9.10938188 \times 10^{-31}$ kg) were converted to energy, how much energy would it produce?
13. Uranium-235 is separated from the other two naturally occurring isotopes of uranium by physical means. Why is it not possible to use chemical means?
14. When an atom undergoes nuclear fission, it releases a relatively large amount of energy. Where does the energy come from?
15. What is meant by the term “critical mass”?