21.1 Fission and Fusion

SECTION OUTCOMES

- Compare and contrast fission and fusion.
- Apply quantitatively the law of conservation of mass and energy using Einstein's mass-energy equivalence.

KEY TERMS

- nuclear fission
- nuclear fusion

What is nuclear fission? How does it produce so much energy? You learned in Chapter 20 that many nuclei can absorb a neutron and become a different isotope. When certain very large nuclei absorb a neutron, something entirely different happens.

Nuclear Fission

One of the most important reactions that is stimulated by absorbing a neutron is **nuclear fission**, the reaction in which a very large nucleus splits into two large nuclei plus two or more neutrons. The two most common isotopes that can undergo fission are $^{235}_{92}U$ and $^{239}_{94}Pu$. When a nucleus fissions, or splits, a tremendous amount of energy is released in the form of kinetic energy of the neutrons and the fission products — the resulting smaller nuclei. Since the kinetic energy of atoms and molecules is thermal energy, the temperature of the material rises dramatically. You can understand why such large amounts of energy are released by examining the graph of binding energy per nucleon in Figure 21.1.

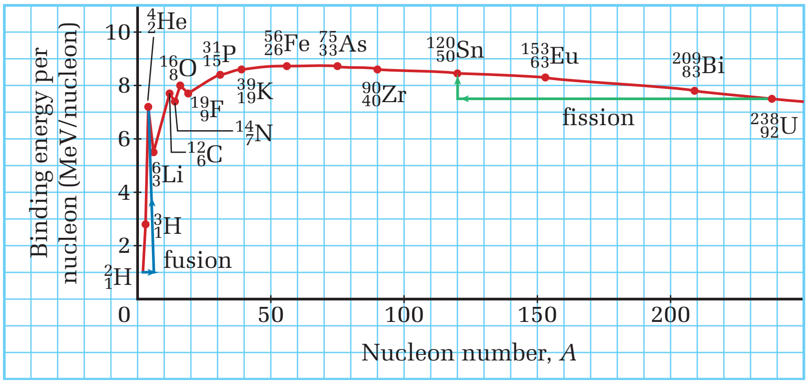

Figure 21.1 The binding energy of mid-range nuclei is greater than that of either very large or very small nuclei.

As you can see in Figure 21.1, when a large nucleus fissions, the smaller nuclei have much larger binding energies than the original nucleus had. Consequently, the sum of the masses of the fission products is much smaller than the mass of the original nucleus. This large mass defect yields the large amount of energy.

You cannot write one equation to describe nuclear fission because many different fission reactions are possible. The most probable reactions are those for which the fission products have atomic numbers roughly between 30 and 60. The sum of the atomic numbers of the products must equal the atomic number of the nucleus that fissions. One common example is the following in which an atom of barium-141 and an atom of krypton-92 are produced by the fission of uranium-235.

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

Nuclear Fusion

At first glance, nuclear fusion would appear to be the opposite of fission. Fusion means to combine and **nuclear fusion** means that two nuclei combine to form one nucleus. If the fission or splitting of a nucleus releases energy you might expect that fusion would require energy. However, the opposite is true. The fusion or combining of two very small nuclei results in the release of a tremendous amount of energy. Figure 21.1 shows you why fusion releases energy. The nuclides with very low nucleon numbers have less binding energy than those that are slightly larger. When, for example, hydrogen nuclei fuse to form helium, the products have a much larger binding energy than the reactants. The large mass defect results in the release of large amounts of energy.

Causing small nuclei to fuse is much more difficult than causing large nuclei to fission. In order to fuse, two nuclei must be close enough together for the strong nuclear force to draw them closer and keep them together. However, as you know, the Coulomb repulsion force is much greater than the attractive nuclear force when the positive nuclei are approaching each other. Therefore, in order to fuse, the small nuclei must be highly energetic so they can continue to approach each other and overcome the Coulomb repulsion force. Highly energetic atoms means high temperatures. It is difficult to artificially generate temperatures high enough to cause atoms to fuse while also containing the atoms.

Such temperatures are found on the Sun and other stars. In fact, fusion is the source of solar and stellar energy. Once the process begins, the heat produced provides the energy to cause more fusion. Some of the reactions that occur on the Sun are the following.

$${}^{1}_{1}\text{H} + {}^{1}_{1}\text{H} \rightarrow {}^{2}_{1}\text{H} + \text{e}^{+} + v_{\text{e}}$$

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

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

The following Model and Practice Problems will show you the amount of energy that is released during fission and fusion.

MODEL PROBLEM

Energy from Nuclear Reactions

Determine the mass defect in the fission reaction $^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{141}_{56}\text{Ba} + {}^{92}_{36}\text{Kr} + 3{}^{1}_{0}\text{n}$ and energy released due to each fission.

Data

Particle	Nuclear mass (u)	Particle	Nuclear mass (u)
$^{235}_{92}\text{U}$	234.993	$^{141}_{56}\text{Ba}$	140.883
$^{1}_{0}\text{n}$	1.008 665	$^{92}_{36}\text{Kr}$	91.905

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Frame the Problem

- *Mass defect* is the *difference* between the total *mass* of the *reactants* and the total *mass* of the *fission products*.
- The *energy* released is the *energy equivalent* of the *mass defect*.

Identify the Goal

The mass defect, Δm, and the energy, E, released during each fission reaction

Variables and Constants

Known	Implied	Unknown
Identity of reactants and products	$c = 2.998 \times 10^8 \ \frac{\text{m}}{\text{s}}$	Δm
	$m_\text{n} = 1.008\ 665\ \text{u}$	E
	$m\left({}^{235}_{92}\text{U}\right) = 234.993\ \text{u}$	
	$m\left({}^{141}_{56}\text{Ba}\right) = 140.883\ \text{u}$	
	$m\left({}^{92}_{36}\text{Kr}\right) = 91.905\ \text{u}$	

Strategy / Calculations

Find the total mass of reactants.

$$m_\text{reactants} = m_\text{n} + m\left({}^{235}_{92}\text{U}\right)$$
$$m_\text{reactants} = 1.008\ 665\ \text{u} + 234.993\ \text{u}$$
$$m_\text{reactants} = 236.002\ \text{u}$$

Find the total mass of the products.

$$m_\text{products} = m\left({}^{141}_{56}\text{Ba}\right) + m\left({}^{92}_{36}\text{Kr}\right) + 3m_\text{n}$$
$$m_\text{products} = 140.883\ \text{u} + 91.905\ \text{u} + 3(1.008665\ \text{u})$$
$$m_\text{products} = 235.814\ \text{u}$$

Find the mass defect by subtraction.

$$\Delta m = 236.002\ \text{u} - 235.814\ \text{u}$$

Convert the mass defect into kilograms.

$$\Delta m = (0.188\ \cancel{\text{u}})\left(1.6605 \times 10^{-27}\ \frac{\text{kg}}{\cancel{\text{u}}}\right)$$
$$\Delta m = 3.12 \times 10^{-28}\ \text{kg}$$

Convert the mass into energy, using $\Delta E = \Delta mc^2$.

$$\Delta E = \Delta mc^2$$
$$\Delta E = (3.12 \times 10^{-28}\ \text{kg})\left(2.998 \times 10^8\ \frac{\text{m}}{\text{s}}\right)^2$$
$$\Delta E = 2.80 \times 10^{-11}\ \text{J}$$

The mass defect is 0.188 u or 3.12×10^{-28} kg. This is equivalent to an energy of 2.80×10^{-11} J.

Validate

The mass defect is positive, indicating an energy release.

PRACTICE PROBLEMS

1. Another possible fission reaction involving uranium-235 would proceed as follows.

$${}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{90}_{38}Sr + {}^{135}_{54}Xe + 11{}^{1}_{0}n$$

Determine the mass loss and the energy released in this reaction.

Particle	Mass (u)
${}^{1}_{0}n$	1.008 665
${}^{235}_{92}U$	234.993
${}^{90}_{38}Sr$	89.886
${}^{135}_{54}Xe$	134.879

2. Determine the energy that would be released by the fusion of the nuclei of deuterium and tritium as indicated by the equation below.
${}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n$

Particle	Mass (u)
${}^{2}_{1}H$	2.013 553
${}^{3}_{1}H$	3.015 500
${}^{4}_{2}He$	4.001 506
${}^{1}_{0}n$	1.008 665

3. In the Sun, four hydrogen nuclei are combined into a single helium nucleus by a series of reactions. The overall effect is given by the following equation.

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

(a) Calculate the mass defect for the reaction and the energy produced by this fusion.

(b) If 4.00 g of helium contain 6.02×10^{23} nuclei, determine how much energy is released by the production of 1.00 g of helium.

Particle	Mass (u)
${}^{1}_{1}H$	1.007 276
${}^{4}_{2}He$	4.001 506
${}^{0}_{1}e$	0.000 549

21.1 Section Review

1. K/U What is the source of the kinetic energy of the neutrons and fission products that are produced when a uranium or plutonium atom fissions?
2. K/U Why can only very large nuclei fission?
3. C Fission is a process in which a nucleus splits into two parts that are roughly half the size of the original nucleus. In fusion, two nuclei fuse, or combine, to form one nucleus. These reactions seem to be opposite to each other, yet they both release large amounts of energy. Explain why this is not really a contradiction. Use the graph of binding energy per nucleon versus atomic mass number in your explanation.
4. K/U Why is fusion difficult to generate artificially?