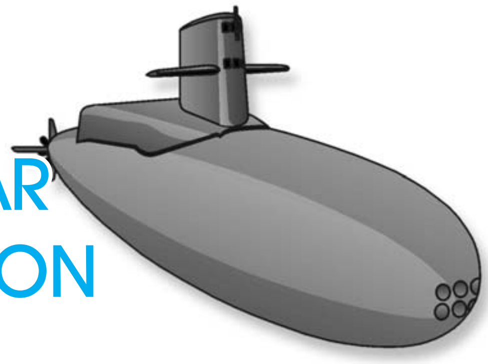
9.2 NUCLEAR RADIATION



Objectives

- Explain the difference between isotopes of the same element.
- Describe the force that holds nucleons together.
- Explain the relationship between mass and energy according to Einstein's theory of relativity.
- Given the atomic masses of the constituent particles, calculate nuclear binding energy and energy released in nuclear reactions.
- Describe alpha, beta, and gamma radiation. Predict the resulting isotope of a given alpha, beta, or gamma decay.
- Explain why it is possible to have a self-sustaining nuclear fission chain reaction.
- Explain why it is necessary to heat deuterium and tritium to millions of degrees to achieve nuclear fusion.

INTERNET *connection*

To find out more about nuclear radiation, follow the links at **www.learningincontext.com.**

An atom consists of a nucleus surrounded by electrons. The electrons are negatively charged, and they are held to the atom by the electric force of attraction to a positive charge in the nucleus. All the mechanical, fluid, electrical (and electromagnetic), and thermal properties discussed so far are results of interactions among atomic electrons. We have not yet discussed nuclear interactions.

However, the nucleus is extremely important. The nucleus can hold multiple positive charges, and this creates the difference between elements. In addition, nearly all the energy in the universe was created by nuclear reactions.

The Nucleus

The nucleus contains two types of particles: protons and neutrons. A proton has a charge equal and opposite to the charge of an electron. Remember, the elementary charge is 1.6022×10^{-19} C. We use the symbol e to represent this charge. A single electron has a charge of $-e$ and a proton has a charge of $+e$. Neutrons have no charge—they are neutral.

The vast majority of an atom's mass is in the nucleus. The mass of a proton is 1836 times that of an electron. Neutrons have a mass slightly larger than that of a proton. Atomic and nuclear masses are extremely small, and are conveniently expressed in terms of the **atomic mass unit**, abbreviated u. The value of the atomic mass unit is

$$1 \text{ u} = 1.660438 \times 10^{-27} \text{ kg}$$

The charges and masses of the three fundamental atomic particles are summarized in Table 9.1. Notice the number of significant figures listed for mass. You need to use approximately this many figures in nuclear calculations.

Table 9.1
Charge and Mass of the Fundamental Atomic Particles

Particle	Charge	Mass
Electron	$-e$	0.0005486 u
Proton	e	1.007277 u
Neutron	o	1.008665 u

Isotopes

The a**tomic number** of an atom is the number of protons in the nucleus of the atom. We use Z to represent atomic number. The **mass number** is the number of protons plus the number of neutrons in the nucleus. We use A to represent mass number. Sometimes we refer to protons and neutrons jointly as *nucleons*. Thus, A is the number of nucleons in the nucleus of an atom. Notice that Z and A are always integers.

Elements are specified by atomic number. For example, oxygen is atomic number 8—there are eight protons in the nucleus of an atom of oxygen.

An oxygen atom is neutral (uncharged) if it also has eight electrons. Figure 9.13 illustrates the atomic composition of the four lightest elements.

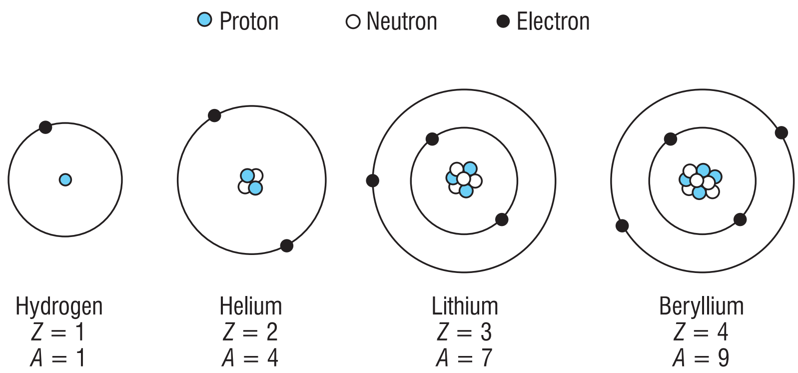


Figure 9.13
Electrons and nucleons of the four lightest elements
(The relative size of each nucleus is greatly enlarged to show the composition.)

An element has a given number of protons, Z. But it is possible for an element to have various values of mass number, A. The differing atoms of the same element are called **isotopes**. Oxygen has three isotopes, with mass numbers 16, 17, and 18. The number of protons and neutrons in the nucleus of each isotope is shown in Table 9.2.

Table 9.2

Atomic Number	Element	Mass Number (A)	Number of Protons (Z)	Number of Neutrons
8	Oxygen	16	8	8
		17	8	9
		18	8	10
9	Fluorine	19	9	10

We use the following symbolic notation to specify the nuclei of isotopes, or *nuclides*. Write the element symbol with the value of Z as a subscript to the left and the value of A as a superscript to the left. The atomic numbers of all the elements are listed in Appendix B.

$$^{A}_{Z}\text{element}$$

For example, the three nuclides of oxygen are written as follows:

$$^{16}_{8}\text{O} \qquad ^{17}_{8}\text{O} \qquad ^{18}_{8}\text{O}$$

It is redundant to write both Z and the element symbol. But we write the value of Z because, as you will see, it helps balance nuclear equations.

Example 9.6 Calculating the Number of Neutrons in a Nuclide

How many neutrons are in $^{64}_{29}\text{Cu}$?

Solution: From Appendix B, this is an isotope of copper. Since $Z = 29$, there are 29 protons in the nucleus. Since $A = 64$, there are 64 nucleons. The number of neutrons is the difference:

$$\text{Number of neutrons} = \text{number of nucleons} - \text{number of protons}$$

$$= 64 - 29 = 35$$

There are 35 neutrons in $^{64}_{29}\text{Cu}$.

The Strong Nuclear Force

The diameter of the nucleus is approximately 10^{-14} m. This is less than 1/10,000 of the diameter of the atom. Thus, the distance d between adjacent nucleons is very small. Remember, the electrical force of repulsion between two like charges increases as the distance between the charges decreases. (The force varies as $1/d^2$.) This force is extremely large for values of d found in the nucleus. Without another, greater force of *attraction* the nucleus will fly apart. The force of attraction between nucleons is an entirely different kind of force, called the **strong force**. The strong force is important only when particles such as protons and neutrons are as close together as they are in the nucleus of an atom.

The strong force holds the nucleons together. To remove a nucleon from the nucleus, this force must be overcome. Therefore, work is required to remove a proton or neutron from a nucleus. The amount of work required is called the *binding energy* of the nucleon. The total amount of work required to separate all nucleons from a nucleus is called the **binding energy** of the nucleus. Stated another way, this is the total amount of energy that holds the nucleus together.

The binding energy of a nucleon is the energy required to remove the nucleon from the nucleus.

The binding energy of a nucleus is the energy required to separate all the nucleons.

Figure 9.14
Binding energy

Nuclear Binding Energy

Deuterium is an isotope of hydrogen, written as ${}^{2}_{1}H$. It contains one proton and one neutron. What would you predict for the mass of the deuterium nucleus? The mass should be the sum of the masses of a proton m_p and a neutron m_n. From Table 9.1:

$$m_p + m_n = 1.007277 \text{ u} + 1.008665 \text{ u} = 2.015942 \text{ u}$$

However, the mass of the deuterium nucleus has been measured very accurately, and it is actually 2.013554 u. The difference in nuclear masses for deuterium is an example of a general observation:

> *The mass of a stable nucleus is always less than the combined masses of the constituent nucleons.*

The difference in the masses is called the **mass defect**. What happened to the missing mass?

$$m_p + m_n = 2.015942 \text{ u} \qquad m_D = 2.013554 \text{ u}$$

$$\text{Mass defect} = 2.015942 \text{ u} - 2.013554 \text{ u}$$
$$= 0.002388 \text{ u}$$

Figure 9.15
The mass of a deuterium nucleus is less than the sum of the masses of the constituents. The difference is the mass defect.

In 1905, Albert Einstein published his theory of relativity. Relativity links electricity and magnetism, time and space, and *mass and energy*. Einstein concluded that mass and energy are the same. The mass defect is not really "missing." It has been converted into energy—the binding energy of the nucleus. The amount of energy E can be calculated by Einstein's equation

$$E = mc^2$$

where m is the mass converted into energy and c is the speed of light. To five significant figures, $c = 2.9979 \times 10^8$ m/s.

When making nuclear calculations, it is convenient to use a new unit for energy—the **electron volt**, abbreviated eV. This is defined as the amount of energy gained by an electron when accelerated through a potential difference of one volt. You learned in Section 1.3 that this amount of energy is the product of the charge and voltage:

$$1 \text{ eV} = (1.6022 \times 10^{-19} \text{ C})(1 \text{ V}) = 1.6022 \times 10^{-19} \text{ J} \qquad [\text{J} = \text{C} \cdot \text{V}]$$

Example 9.7 Binding Energy of Deuterium

Calculate the binding energy of ${}^{2}_{1}H$ in joules and in electron volts.

Solution: Let m represent the mass defect. As shown in Figure 9.15, $m = 0.002388$ u. Convert to kilograms.

$$m = (0.002388 \text{ u})(1.6604 \times 10^{-27} \text{ kg/u}) = 3.9650 \times 10^{-30} \text{ kg}$$

$$E = mc^2 = (3.9650 \times 10^{-30} \text{ kg})(2.9979 \times 10^{8} \text{ m/s})^2$$

$$E = 3.5635 \times 10^{-13} \text{ J} \qquad \left[\text{kg} \cdot \text{m}^2/\text{s}^2 = \text{J}\right]$$

Convert to eV:

$$E = (3.5635 \times 10^{-13} \text{ J})\left(\frac{1 \text{ eV}}{1.6022 \times 10^{-19} \text{ J}}\right) = 2.224 \times 10^{6} \text{ eV}$$

To three significant figures, the binding energy of the deuterium nucleus is 3.56×10^{-13} J or 2.22×10^{6} eV. You can also write the binding energy as 2.22 MeV, where MeV = 10^{6} eV.

Converting mass to energy is a common calculation in nuclear physics. It is convenient to use a mass-energy conversion factor. You will work with mass in atomic mass units and energy in electron volts. What is the energy equivalent of 1 u? (1 u = 1.6604×10^{-27} kg)

$$E = mc^2 = (1.6604 \times 10^{-27} \text{ kg})(2.9979 \times 10^{8} \text{ m/s})^2$$

$$= 1.4923 \times 10^{-10} \text{ J}$$

Convert to eV:

$$E = (1.4923 \times 10^{-10} \text{ J})\left(\frac{1 \text{ eV}}{1.6022 \times 10^{-19} \text{ J}}\right) \approx 9.315 \times 10^{8} \text{ eV}$$

$$= 931.5 \text{ MeV} \qquad \left[\text{MeV} = 10^{6} \text{ eV}\right]$$

Rounded to four significant figures,

a mass of 1 u is equivalent to an energy of 931.5 MeV.

Most of the time in nuclear calculations, masses are given as *atomic*, not nuclear masses. The atomic mass of an element or isotope includes the mass of the electrons. This mass should be removed from the calculation of nuclear binding energy. But, instead of subtracting the electron masses, you can use the *atomic* mass of ${}^{1}_{1}H$ instead of the mass of a proton. Then the electron masses cancel.

In the example below, helium (atomic number 2) has two neutrons, two protons, and two electrons. In the mass-defect calculation, the mass of two $^{1}_{1}H$ atoms is used instead of two protons. Thus, the two electron masses cancel in the subtraction.

Example 9.8 Binding Energy of Helium

The atomic mass of $^{4}_{2}He$ is 4.002603 u. The atomic mass of $^{1}_{1}H$ is 1.007825 u. What is the binding energy of the nucleus?

Solution: Calculate the mass of the constituents. There are two protons and two neutrons. Use the atomic mass of $^{1}_{1}H$ instead of a proton to include the electron mass.

$$2m_H + 2m_n = 2(1.007825 \text{ u}) + 2(1.008665 \text{ u}) = 4.032980 \text{ u}$$

Calculate the mass defect m. The electron masses cancel.

$$m = 4.032980 \text{ u} - 4.002603 \text{ u} = 0.030377 \text{ u}$$

The binding energy E is the energy equivalent of the mass defect.

$$E = (0.030377 \text{ u})(931.5 \text{ MeV/u})$$
$$= 28.30 \text{ MeV}$$

The binding energy of $^{4}_{2}He$ is 28.30 million electron volts.

Radioactivity

Refer to Appendix F for a career link to this concept.

In 1896, the French physicist Henri Becquerel accidentally discovered that a uranium compound would expose a covered photographic plate. The exposure resulted in an effect on the plate similar to that produced by light. But the plate was covered, and no light was emitted by the compound. Becquerel concluded that the uranium compound must be emitting a different kind of radiation. This radiation is not visible and it passes through a cover to expose the photographic plate underneath.

Several years later, the English scientist Ernest Rutherford described the properties of the radiation emitted by uranium. He discovered three different kinds of radiation, and he named them *alpha*, *beta*, and *gamma* radiation. In addition, Rutherford discovered the existence of the nucleus in 1911. This helped form our current understanding of the atom. It also explained the origin of alpha, beta, and gamma radiation. The nuclei of uranium and many other isotopes are unstable. This means they spontaneously transform themselves into other nuclides. When they do, they emit radiation. These unstable nuclides are said to be **radioactive**.

Alpha radiation consists of particles. Rutherford determined that alpha particles are the same as the nuclei of helium atoms, ${}^{4}_{2}\mathrm{He}$. When an unstable nucleus emits an alpha particle, it is said to undergo **alpha decay**. Since the mass number of an alpha particle is 4 and the atomic number is 2, the nucleus undergoing alpha decay loses 4 nucleons, including 2 protons. Therefore, its mass number decreases by 4 and its atomic number decreases by 2.

For example, ${}^{238}_{92}\mathrm{U}$ is radioactive and emits an alpha particle. The following equation descibes the alpha decay. This is called a **nuclear equation**.

$$ {}^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He} $$

In words, the equation says that uranium-238 yields thorium-234 plus an alpha particle.

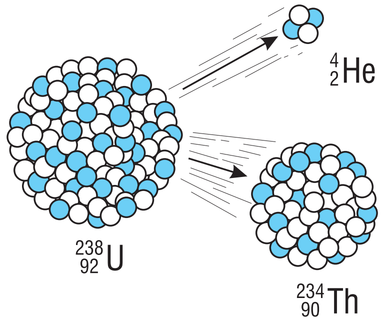


Figure 9.16
Alpha decay

Notice that *the total number of nucleons is conserved*. Uranium-238 has 238 nucleons, and thorium-234 plus the alpha has 234 + 4 = 238 nucleons. In other words, the sum of the superscripts on the right must equal the sum of the superscripts on the left. Notice also that *the total charge is conserved*. Uranium-238 has 92 protons, and thorium-234 plus the alpha has 90 + 2 = 92 protons. In other words, the sum of the subscripts on the right must equal the sum of the subscripts on the left. These two conditions must be satisfied for all nuclear equations.

Example 9.9 Alpha Decay

Plutonium-238 is radioactive, and it emits an alpha particle when it decays. What is the resultant nuclide?

Solution: From Appendix B, plutonium is atomic number 94. Write the nuclear equation with A, Z, and X representing the unknown atomic mass, atomic number, and element.

$$ {}^{238}_{94}\mathrm{Pu} \rightarrow {}^{A}_{Z}X + {}^{4}_{2}\mathrm{He} $$

To conserve nucleons, $238 = A + 4$. So $A = 234$.

To conserve charge, $94 = Z + 2$. So $Z = 92$.

From Appendix B, the element with atomic number 92 is uranium.

The resultant nuclide is ${}^{234}_{92}\mathrm{U}$.

Beta radiation also consists of particles. Beta particles are the same as electrons, but they can have charge of either sign. A positively charged electron is called a **positron**. Except for sign, it is identical to a negatively charged electron. A positron is an example of an *antiparticle*, a particle of *antimatter*.

Some unstable nuclei undergo beta decay by electron emission and some undergo positron emission. But how does a nucleus emit an electron when there are no electrons in the nucleus? In electron emission, a neutron in the nucleus is transformed into a proton. This transformation conserves charge. The neutron charge (0) equals the sum of the proton charge (+1) and the electron charge (–1). Since the mass number of an electron is 0 and the charge is –1, the nucleus undergoing electron emission loses no nucleons and its atomic number increases by 1.

Similarly, in positron emission a proton in the nucleus is transformed into a neutron. This transformation also conserves charge.

As examples, ${}^{234}_{90}\text{Th}$ is radioactive and emits an electron, while ${}^{13}_{7}\text{N}$ emits a positron. The following nuclear equations descibe these beta-decay reactions.

$$ {}^{234}_{90}\text{Th} \rightarrow {}^{234}_{91}\text{Pa} + {}^{0}_{-1}e $$

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

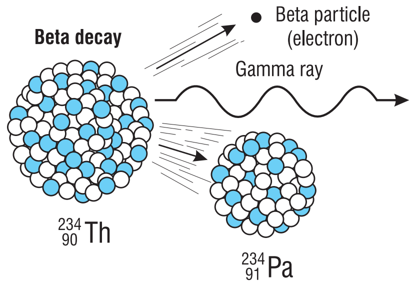


Figure 9.17
Beta decay

Notice that nucleons and charge are conserved in each equation.

Example 9.10 Beta Decay

Strontium-90 is radioactive, and it emits an electron when it decays. What is the resultant nuclide?

Solution: From Appendix B, strontium is atomic number 38. Write the nuclear equation with A, Z, and X representing the unknown atomic mass, atomic number, and element.

$$ {}^{90}_{38}\text{Sr} \rightarrow {}^{A}_{Z}X + {}^{0}_{-1}e $$

To conserve nucleons, $90 = A + 0$. So $A = 90$.

To conserve charge, $38 = Z - 1$. So $Z = 39$.

From Appendix B, the element with atomic number 39 is yttrium.

The resultant nuclide is ${}^{90}_{39}\text{Y}$.

Gamma radiation consists of high-energy photons. (See Figure 9.5, the electromagnetic spectrum, in the last section.) Photons have no mass or charge. If an unstable nucleus emits only a gamma ray, neither the atomic mass nor the atomic number of the nucleus changes. Gamma rays are often emitted with alpha and beta decay. (See Figure 9.17.)

Nuclear Fission

In the late 1930s, scientists discovered that neutrons can cause uranium to split into smaller nuclides. This process is called **fission**. The process begins when a nuclide such as uranium-235 absorbs a neutron. (The neutron must be supplied by some source.) The uranium-235 plus the neutron becomes uranium-236, which is so unstable that it breaks apart into two smaller nuclides, called *fission fragments*. Neutrons are also emitted during fission. These neutrons can be used to cause other uranium nuclei to fission. Thus the process can be continued in a *chain reaction*.

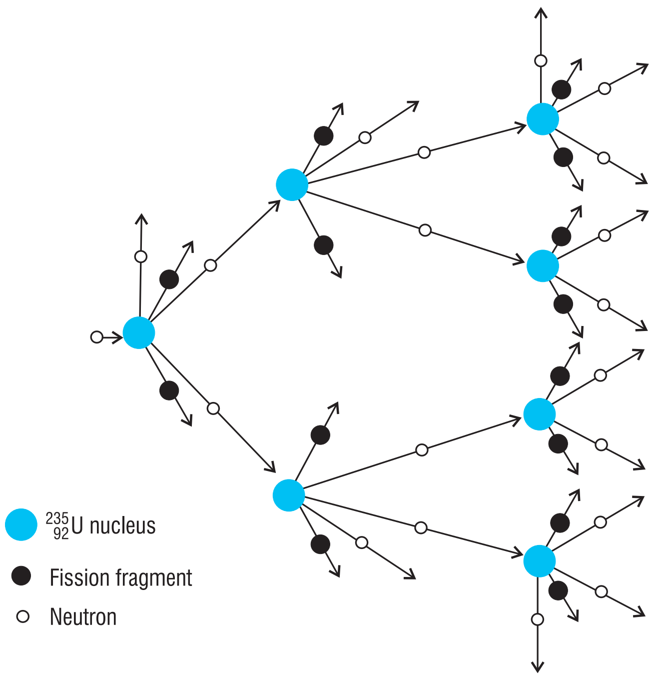


Figure 9.18
In a chain reaction, some of the neutrons produced by fission cause further fissions.

Once it begins, the chain reaction is self-sustaining. No additional neutrons from a source are needed to continue the reactions. The ability to create a self-sustained chain reaction enabled the development of nuclear reactors and nuclear bombs. In a reactor, energy released in nuclear fission provides power for electrical generating plants and submarines. Nuclear reactors can produce energy and power for years without refueling.

During a fission nuclear reaction, mass is converted into energy. This energy is carried away in gamma rays, kinetic energy of the fission fragments, and kinetic energy of the neutrons.

Example 9.11 Energy Release in a Fission Reaction

Calculate the energy released in the following fission reaction.

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{140}_{55}Cs + ^{93}_{37}Rb + 3\left(^{1}_{0}n\right)$$

The atomic masses are listed in the table below.

Particle or Nuclide	Atomic Mass
Neutron	1.0087 u
U-235	235.0439 u
Cs-140	139.9173 u
Rb-93	92.9220 u

Solution: Calculate the mass defect *m*.

Mass before fission

1 neutron	=	1.0087 u
U-235	=	235.0439 u
Total		236.0526 u

Mass after fission

3 neutrons	=	3.0261 u
Cs-140	=	139.9173 u
Rb-93	=	92.9220 u
Total		235.8654 u

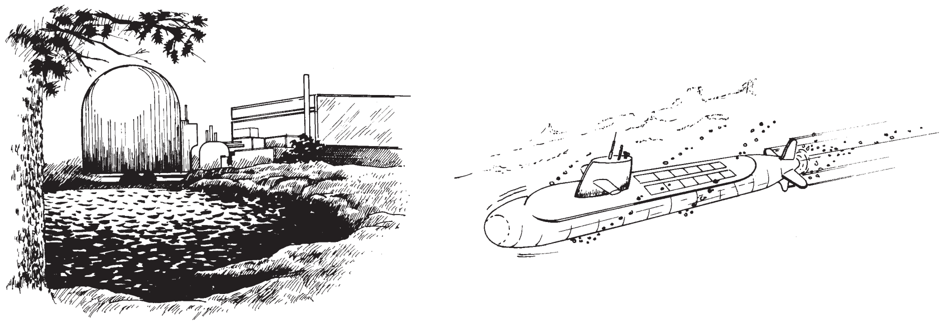
$$m = 236.0526 \text{ u} - 235.8654 \text{ u} = 0.1872 \text{ u}$$

This is the mass converted into energy during the fission reaction. Use the conversion factor 1 u = 931.5 MeV.

$$E = (0.1872 \text{ u})(931.5 \text{ MeV/u}) = 174 \text{ MeV}$$

The energy released is 174 million electron volts.

Example 9.11 shows two possible fission fragments, cesium-140 and rubidium-93. Hundreds of other combinations are possible, in fact any combination that conserves nucleons and charge. Almost all fission fragments are radioactive. The fission fragments are the source of highly radioactive waste from nuclear reactors and radioactive fallout from nuclear explosions.



(a) Nuclear reactor for electric power (b) Nuclear reactor for submarine propulsion

Figure 9.19
In a nuclear reactor, energy released in fission provides power for generating electricity and propelling submarines.

Nuclear Fusion

In nuclear fission, a single large nucleus splits into two smaller nuclei. In **nuclear fusion**, two small nuclei combine to form a single larger nucleus. In both fission and fusion, the mass of the particles after the reaction is less than the mass before the reaction. Mass is converted into energy.

Figure 9.20
The fusion of two protons produces a deuterium nucleus plus an electron.

Nuclear fusion is the source of energy in the stars. For example, in the sun most energy is produced by fusion reactions in a *proton-proton cycle*.

$$^1_1H + ^1_1H \rightarrow ^2_1H + ^0_{+1}e$$

$$^1_1H + ^2_1H \rightarrow ^3_2He$$

$$^3_2He + ^3_2He \rightarrow ^4_2He + 2\left(^1_1H\right)$$

The first two reactions must occur twice to produce the two nuclei for the last reaction. The net outcome of the cycle is that four protons produce one helium nucleus and two positrons.

Two nuclei must travel at very high speeds to overcome the electrical force of repulsion and get close enough together for the strong force to cause fusion. Thus, the nuclei must have very high thermal energies. This is why fusion is often called a *thermonuclear reaction*. On a star such as the sun, the thermal energy comes from a conversion of gravitational potential energy into kinetic energy of the reacting particles.

On Earth, scientists and engineers are trying to develop a reactor that uses fusion as a means of producing energy to generate electrical power. The most likely reaction will use two isotopes of hydrogen, deuterium ${}^{2}_{1}\text{H}$ and tritium ${}^{3}_{1}\text{H}$, as fuels. This is called a D-T fusion reaction.

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

Deuterium can be extracted from seawater. Tritium can be produced in a fusion reactor using the neutrons produced by D-T fusion in a reaction with lithium.

$${}^{6}_{3}\text{Li} + {}^{1}_{0}\text{n} \rightarrow {}^{3}_{1}\text{H} + {}^{4}_{2}\text{He}$$

To achieve D-T fusion, the deuterium and tritium must be heated to millions of degrees. At these temperatures, the materials will be in the plasma state. The plasma must be confined long enough to achieve fusion without being in contact with another material. (The plasma will be cooled if it touches another material.) There are two strategies for achieving these conditions. One uses a magnetic field to heat and confine the plasma. This method is called *magnetic confinement fusion*. The other uses laser beams to deposit energy on the surface of small spheres containing deuterium and tritium. The pressure created on the surface of the sphere forces the sphere to implode, compressing the D-T fuel and raising its temperature. This method is called *inertial confinement fusion*.

Using either method, a reactor for generating electricity is practical only if the power output from D-T fusion is greater than the power input to generate the magnetic field or the laser beams. The practicality has not yet been demonstrated.

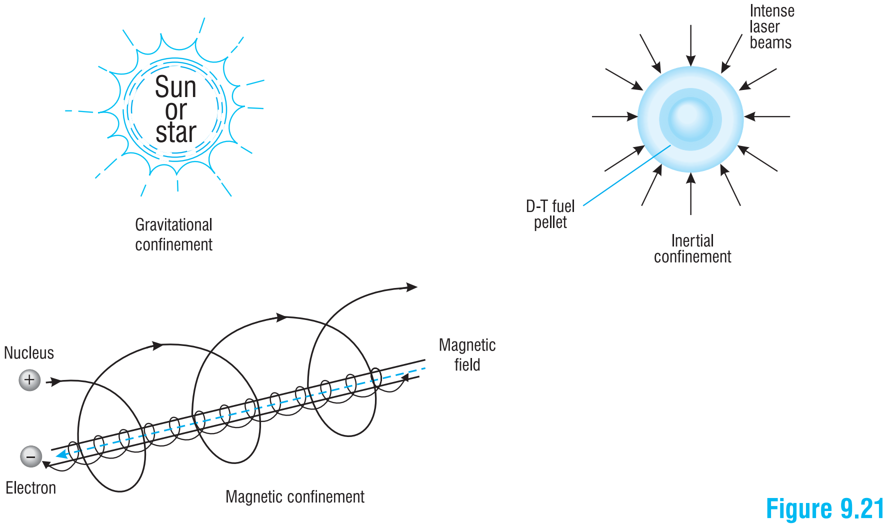


Figure 9.21
Three ways to achieve nuclear fusion

Example 9.12 Energy Released in D-T Fusion

Calculate the energy released in the D-T fusion reaction. The atomic masses are listed in the table below.

Particle or Nuclide		Atomic Mass
neutron	$^{1}_{0}n$	1.008665 u
hydrogen	$^{1}_{1}H$	1.007825 u
deuterium	$^{2}_{1}H$	2.01410 u
tritium	$^{3}_{1}H$	3.01605 u
helium-3	$^{3}_{2}He$	3.01603 u
helium-4	$^{4}_{2}He$	4.00260 u

Solution: Calculate the mass defect *m*.

Mass before fusion		Mass after fusion	
$^{2}_{1}H$ =	2.01410 u	$^{4}_{2}He$ =	4.00260 u
$^{3}_{1}H$ =	3.01605 u	$^{1}_{0}n$ =	1.00867 u
Total	5.03015 u	**Total**	5.01127 u

$$m = 5.03015 \text{ u} - 5.01127 \text{ u} = 0.01888 \text{ u}$$

Use the conversion factor 1 u = 931.5 MeV.

$$E = (0.01888 \text{ u})(931.5 \text{ MeV/u}) = 17.6 \text{ MeV}$$

The energy released is 17.6 million electron volts.

Summary

- Two isotopes of an element have the same atomic number (number of protons) but different mass numbers (number of nucleons).
- The strong force holds nucleons together. In a stable nucleus, the strong force is much greater than the electrical force of repulsion between protons.
- According to Einstein's theory of relativity, mass and energy are equivalent. The relationship is expressed mathematically as $E = mc^2$.
- The nucleus of an atom has less mass than the sum of its constituents. The difference in the two masses, called the mass defect, has been converted into nuclear binding energy.
- In a nuclear reaction, charge is conserved and nucleons are conserved. The total mass after the reaction is less than the total mass before the reaction. The difference in the two masses is converted into energy.
- Three forms of radioactive decay are alpha decay, beta decay, and gamma decay. Alpha particles are identical to helium nuclei. Beta particles are electrons or positrons. Gamma rays are electromagnetic radiation.
- Nuclear fission occurs when a nucleus such as $^{235}_{92}U$ absorbs a neutron, becomes highly unstable, and splits into two smaller nuclei. Other particles, such as neutrons, can also be emitted during fission.
- Nuclear fusion occurs when two high-speed nuclei collide, and come close enough together that the strong force of attraction overcomes the electrical force of repulsion.

Exercises

Note: You will need to use the atomic masses listed in the table in Example 9.12 for some exercises.

1. An atom contains 11 electrons, 11 protons, and 12 neutrons. What is the atomic number of the atom? What is the mass number?
2. How many protons are in the nucleus of each of the following isotopes? How many neutrons?

   (a) $^{50}_{26}Fe$ (b) $^{29}_{14}Si$ (c) $^{198}_{79}Au$ (d) $^{197}_{79}Au$
3. The mass of a $^{12}_{6}C$ nucleus is 0.0989 u less than the sum of the masses of six protons and six neutrons. What is the binding energy of the nucleus of $^{12}_{6}C$.

4. Calculate the binding energy of the tritium nucleus.

5. The atomic mass of ${}^{10}_{5}B$ is 10.01294 u. What is the binding energy of the nucleus?

6. The binding energy of ${}^{7}_{3}Li$ is 39.2 MeV. What is the atomic mass of ${}^{7}_{3}Li$?

7. Match the nuclear radiation with its common name on the right.

(a) ___ alpha particle	1.	proton
(b) ___ beta particle	2.	electron
(c) ___ gamma radiation	3.	neutron
	4.	photon
	5.	helium nucleus
	6.	deuterium nucleus

8. What happens to the atomic number when a radioactive nucleus emits an alpha particle? What happens to the mass number?

9. What happens to the atomic number when a radioactive nucleus emits an electron? What happens to the mass number?

10. What happens to the atomic number when a radioactive nucleus emits a positron? What happens to the mass number?

11. The isotope ${}^{226}_{88}Ra$ is radioactive, and it decays by emitting an alpha particle. Write the nuclear equation. What nuclide is produced by the alpha decay?

12. The isotope ${}^{131}_{53}I$ is radioactive, and it decays by emitting an electron. Write the nuclear equation. What nuclide is produced by the beta decay?

13. The isotope ${}^{22}_{11}Na$ is radioactive, and it decays by emitting a positron. Write the nuclear equation. What nuclide is produced by the beta decay?

14. Complete the following nuclear reactions.

    (a) ${}^{7}_{3}Li + {}^{1}_{0}n \rightarrow ? + {}^{4}_{2}He + {}^{1}_{0}n$

    (b) ${}^{24}_{12}Mg + ? \rightarrow {}^{28}_{14}Si$

    (c) ${}^{63}_{29}Cu + ? \rightarrow {}^{61}_{28}Ni + {}^{4}_{2}He$

15. In a nuclear reactor, a ${}^{238}_{92}U$ (mass 238.05078 u) nucleus absorbs a neutron, fissions, and produces two neutrons and two fission fragments. The fragments are ${}^{96}_{39}Y$ (mass 95.91590 u) and ${}^{141}_{534}I$ (mass 140.93483 u).

    (a) Write the nuclear equation for the fission reaction.

    (b) Calculate the mass defect.

    (c) How much energy is released by this reaction?

16. The radioactive isotope $^{238}_{94}Pu$ is used to provide power for space probes. How much energy is released when $^{238}_{94}Pu$ (mass 238.04955 u) alpha decays to $^{234}_{92}U$ (mass 234.04095 u)?

17. When $^{239}_{94}Pu$ (mass 239.05216 u) absorbs a neutron, it fissions. The fission results in three neutrons and two fission fragments: $^{96}_{42}Mo$ (mass 95.90468 u) and $^{141}_{52}Te$ (mass 140.94439 u).

    (a) Write the nuclear equation for the fission reaction.

    (b) Calculate the mass defect.

    (c) How much energy is released by this reaction?

18. A D-D fusion reaction has more than one possible result. Complete each of the following.

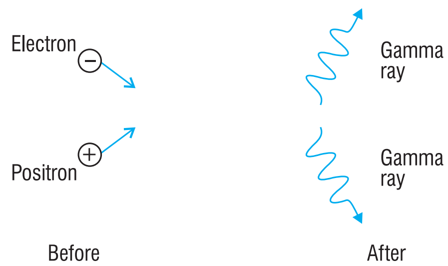
    (a) $^{2}_{1}H + ^{2}_{1}H \rightarrow ?$

    (b) $^{2}_{1}H + ^{2}_{1}H \rightarrow ? + ^{1}_{0}n$

    (c) $^{2}_{1}H + ^{2}_{1}H \rightarrow ? + ^{1}_{1}H$

19. Calculate the energy released by each of the reactions in exercise 18.

20. Since an electron and a positron have opposite charge, they are attracted to each other. When the force of attraction causes a collision, they can annihilate each other. An **annihilation reaction** converts all the mass of the two particles into energy in the form of gamma rays. The mass of an electron is 9.11×10^{-31} kg. The mass of a positron is the same. Calculate the energies of the gamma rays emitted in an electron-positron annihilation reaction.



21. A nuclear reactor using $^{235}_{92}U$ as fuel operates at a power level of 950 MW (9.5×10^{8} watts).

    (a) $^{235}_{92}U$ releases an average of 200 MeV per fission. How many fissions per second occur to yield 950 MW of power?

    (b) In one year of continuous operation, how much of the fuel's mass is lost?