7.4 Nuclear Fission and Nuclear Power Generation

When Ernest Rutherford split the atom for the first time in 1919, few would have predicted how profoundly our world would change. The footprint of the nuclear revolution of the twentieth century can be found in areas ranging from medical advances that save lives, to nuclear power, to devastating weaponry.

Figure 1 CANDU reactor facility

Nuclear power generation is controversial. Nuclear power reactors emit virtually no pollutants into the atmosphere, yet they produce harmful radioactive waste that must be safely contained and stored for long periods of time. Opponents of nuclear power cite the dangers of reactor meltdowns. However, Canada's reactors have impressive safety records. Nuclear energy is a critical part of our power supply. Over 50 % of Ontario's electric power is generated from Canadian Deuterium Uranium reactors, or CANDU reactors, as they are commonly called (**Figure 1**).

The process by which a nuclear reactor operates is based on the work of Albert Einstein, whose theory of relativity consists of a number of abstract ideas. One of these is that mass and energy are actually different aspects of the same phenomenon.

Mass–Energy Equivalence

In the early twentieth century, Einstein proposed what is arguably the most famous equation in science:

$$E = mc^2$$

This equation challenged the foundations of physics by suggesting that energy and mass are equivalent. The equation states that the energy, E, of an object at rest is equal to its mass, m, multiplied by the speed of light, c, squared. The speed of light is 3.0×10^8 m/s.

As Einstein's theory became widely accepted, the notions of conservation of mass and conservation of energy were replaced by the more general law of conservation of mass–energy.

Law of Conservation of Mass–Energy

Mass can transform into energy, and energy into mass, such that the total mass–energy in an isolated system remains constant.

An isolated system is a system that is free from outside influences. No energy flows into or out of the system, and no mass is added or removed from the system. It is this relationship between mass and energy that can help explain the vast amount of energy that is released during a nuclear reaction, as you will see in Tutorial 1.

The atomic mass unit is commonly used in chemistry and physics as a more convenient unit of mass than the kilogram. One **atomic mass unit (u)** is equal to the mass of one-twelfth of a carbon-12 atom, or 1.66×10^{-27} kg. **Table 1** lists the masses of subatomic particles in kilograms and in atomic mass units.

atomic mass unit (u) a unit of mass equal to 1.66×10^{-27} kg

Table 1 Masses of Subatomic Particles

Particle	Mass (kg)	Mass (u)
proton	$1.672\,614 \times 10^{-27}$	1.007 276
neutron	$1.674\,920 \times 10^{-27}$	1.008 665
electron	$9.109\,56 \times 10^{-31}$	0.000 549

Einstein's equation allows for a deeper understanding of the nucleus. A chart of the nuclides is a chart that lists the atomic number and mass number for every known isotope. If you compare the mass number of an atom on the nuclide chart to the calculated mass of all the atom's nucleons and electrons, you will notice a **mass defect**. The sum of the masses of the nucleons and electrons of an atom is always slightly greater than the actual atomic mass. The "missing mass" exists in the form of energy, which is used to hold the nucleus together. This **binding energy** is the amount of energy that would be needed to separate all of the nucleons of an atom's nucleus.

mass defect the difference between the calculated mass of an atom, based on the nucleons and electrons present, and the actual atomic mass

binding energy the energy used to hold a nucleus together

WEB **LINK**

To learn more about Einstein's work,

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In nuclear physics, the joule is not a very convenient unit of measure to use for energy. Instead, a much smaller unit, called the mega-electron volt (MeV), is more useful. An electron-volt (eV) is defined as the amount of energy given to an electron when it is accelerated through a potential difference of 1 V. One electron-volt is equal to 1.602×10^{-19} J. The **mega-electron volt** is one million times this value:

mega-electron volt (MeV) the energy required to accelerate an electron through a potential difference of 1 million volts

$$1 \text{ MeV} = 1.602 \times 10^{-13} \text{ J}$$

In the following Tutorial, you will determine the mass defect of a parent atom in a nuclear fission reaction and then use Einstein's equation to calculate the energy released during the reaction.

Tutorial 1 Calculating the Mass Defect and Binding Energy

We can calculate the mass defect of a nucleus by comparing the total mass of its nucleons and electrons to the actual atomic mass. Note that we will use Δm to represent the *difference* in mass. Once the mass defect is known, we can use Einstein's equation to calculate the corresponding binding energy. We will use this strategy in the following Sample Problem.

Sample Problem 1

Determine the mass defect and binding energy of a lithium-7 nucleus, given that its actual atomic mass is 7.016 00 u. Use Table 1 on the previous page.

Given: $m = 7.016\ 00$ u

Required: mass defect; E

Analysis: $E = \Delta mc^2$

Solution: First use Table 1 to calculate the combined mass of the individual protons, neutrons, and electrons. The actual atomic mass is given. The difference between these quantities is the mass defect. Since the mass defect is related to the binding energy, use $E = \Delta mc^2$ to calculate the binding energy, Δm. A lithium-7 atom has three protons, four neutrons, and three electrons. Calculate the total mass of these subatomic particles.

$$\begin{aligned} 3m_p + 4m_n + 3m_e &= 3(1.007\ 276 \text{ u}) + 4(1.008\ 665 \text{ u}) + 3(0.000\ 549 \text{ u}) \\ &= 7.058\ 135 \text{ u} \end{aligned}$$

Subtract the actual atomic mass of Li-7 to calculate the mass defect, Δm.

$$\Delta m = 7.058\ 135 \text{ u} - 7.016\ 00 \text{ u}$$
$$\Delta m = 0.042\ 135 \text{ u}$$

Therefore, the mass defect of lithium-7 is 0.042 135 u.

Multiply the mass defect by 1.66×10^{-27} kg/u to convert atomic mass units to kilograms.

$$\begin{aligned} \Delta m &= (0.042\ 135 \cancel{\text{u}})\left(1.66 \times 10^{-27} \frac{\text{kg}}{\cancel{\text{u}}}\right) \\ &= 6.994\ 4 \times 10^{-29} \text{ kg (two extra digits carried)} \end{aligned}$$

Substitute 6.9944×10^{-29} kg and the speed of light (3.0×10^8 m/s) into $E = \Delta mc^2$.

$$E = (6.9944 \times 10^{-29}\ \text{kg})(3.0 \times 10^8\ \text{m/s})^2$$
$$= 6.2950 \times 10^{-12}\ \text{kg·m}^2/\text{s}^2 \text{ (three extra digits carried)}$$
$$= 6.2950 \times 10^{-12}\ \text{J}$$

The binding energy of a lithium-7 nucleus is 6.2950×10^{-12} J.

We can convert this to MeV by dividing by the number of joules in a mega-electron volt:

$$E = \frac{6.2950 \times 10^{-12}\ \cancel{\text{J}}}{1.602 \times 10^{-13}\ \frac{\cancel{\text{J}}}{\text{MeV}}}$$

$$E = 39\ \text{MeV}$$

Statement: The mass defect of Li-7 is 0.042 135 u. The binding energy of the nucleus is 39 MeV.

Practice

1. The mass of a helium-4 atom is 4.002 603 u. T/I C
   (a) Determine the mass defect of a helium-4 atom. [ans: 0.030 378 u]
   (b) Determine the binding energy of a helium-4 atom. Give your final answer in MeV. [ans: 28 MeV]

Nuclear Fuel

Nuclear fuel is the radioactive material that is used to power a nuclear reactor. When nuclear fission occurs, the binding energy of a nucleus is released and is converted into a useful form of energy. Some radioactive isotopes with very large mass numbers undergo nuclear fission when struck by a neutron. For example, uranium-235 can be split into krypton-92 and barium-141, as shown in **Figure 2**.

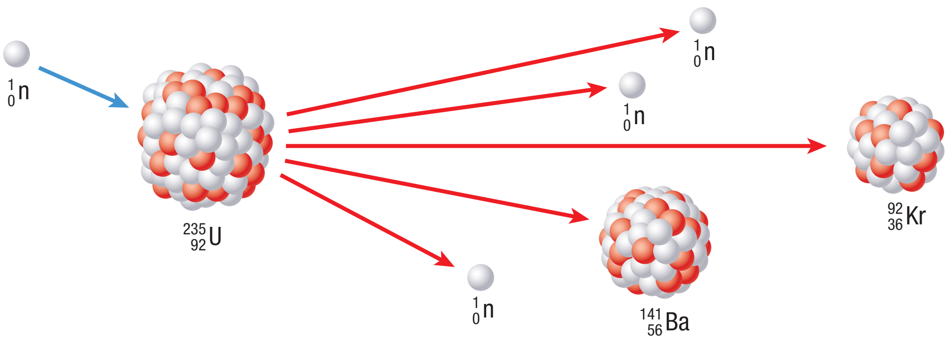

Figure 2 Nuclear fission of uranium-235

The equation for this nuclear reaction is

$$^{235}_{92}\text{U} + ^1_0\text{n} \rightarrow ^{92}_{36}\text{Kr} + ^{141}_{56}\text{Ba} + 3(^1_0\text{n}) + \text{energy}$$

Parent isotopes such as U-235 that can undergo nuclear fission are said to be fissionable. Some other examples of fissionable isotopes are thorium-232, uranium-233, and plutonium-239. Fissionable isotopes are the nuclear fuel used in nuclear fission reactors.

The large quantity of energy produced during each nuclear reaction makes nuclear fission desirable for power generation. In comparison, the amount of energy produced in a nuclear fission reaction is about seven million times as great as the energy released when the same mass of dynamite explodes.

WEB LINK

To see a simulation of this nuclear fission reaction,

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Chain Reactions

The products of the nuclear fission reaction shown in Figure 2 on the previous page include three neutrons and energy. Not only is a very large quantity of energy released, but some of the neutrons produced in the reaction are used to generate further reactions. If enough fuel is present, a chain reaction can occur. A **chain reaction** is a series of reactions that can repeat over several cycles (**Figure 3**). These reactions occur without requiring any material being added to the system. The products of one reaction produce subsequent reactions. The amount of nuclear fuel required to cause a chain reaction is called the critical mass.

chain reaction the repeated series of reactions in which the products of one reaction generate subsequent reactions

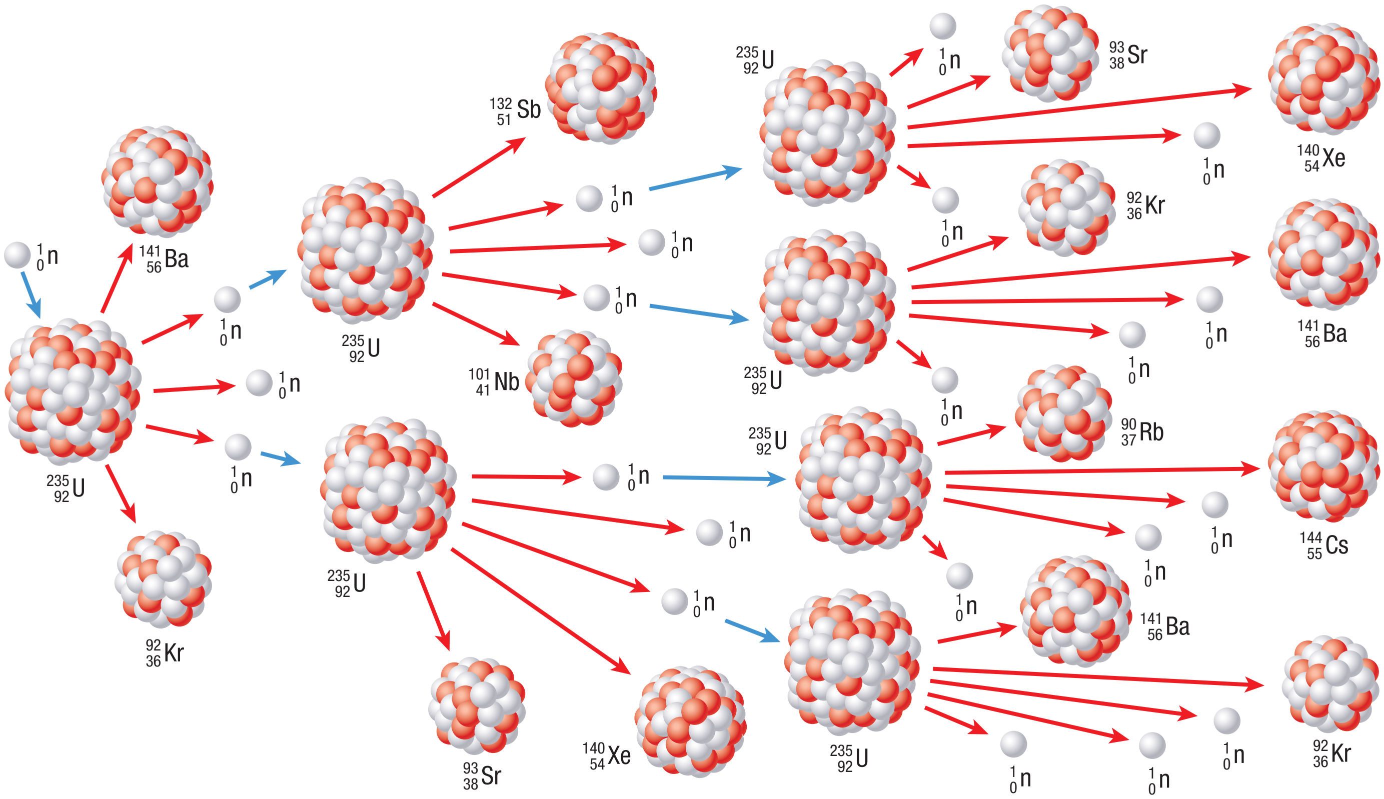

Figure 3 Chain reaction induced by the fission of U-235

Neutron Moderation

The neutrons that are released from the fission of U-235 are initially too high in energy to be absorbed by another U-235 nucleus. They must be slowed down, or moderated. In a CANDU reactor, neutrons are moderated by surrounding the fuel elements with heavy water, which is water that contains a high level of deuterium. Heavy water also reduces neutron leakage from a reactor core. Heavy water is about 11 % denser than normal water.

Neutrons that have been slowed down using heavy water are called thermal neutrons because their kinetic energy is at about the same level as the other materials around them. Once a high-energy neutron has been moderated, it can be absorbed by another U-235 nucleus, eventually establishing a chain reaction. Examples of fissionable materials that can sustain a chain reaction are uranium-235 and plutonium-239. In the following Tutorial, you will calculate the energy released during a nuclear fission reaction.

WEB LINK

CANDU reactors are used in many parts of the world. They are considered one of the safest fission reactors. To learn more about CANDU reactors,

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Tutorial 2 Calculating Energy Yield in a Fission Reaction

We can calculate the energy released in a fission reaction by calculating the mass defect between the reactant and the products and then converting this to its energy equivalent using Einstein's equation $E = mc^2$.

Sample Problem 1

What is the energy yield of the following fission reaction? Use the given masses below.

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

mass of U (m_U) = 235.044 u
mass of Cs (m_{Cs}) = 139.909 u
mass of Rb (m_{Rb}) = 92.922 u
mass of neutron (m_n) = 1.009 u

Given: $m_{\text{U-235}} = 235.044$ u; $m_{\text{Cs-140}} = 139.909$ u; $m_{\text{Rb-93}} = 92.922$ u; $m_n = 1.009$ u

Required: energy released

Analysis: $E = \Delta mc^2$

Solution: The energy released is equal to the binding energy. So first use the given masses to calculate the difference in mass between the reactant and the products. The difference is the mass defect. Then substitute the mass defect into the equation $E = \Delta mc^2$ to calculate the binding energy. Note that the reaction equation can be simplified by subtracting one neutron from each side:

$$^{235}_{92}\text{U} + \cancel{{}^{1}_{0}\text{n}} \rightarrow {}^{140}_{55}\text{Cs} + {}^{93}_{37}\text{Rb} + \overset{2}{\cancel{3}}({}^{1}_{0}\text{n})$$

$$^{235}_{92}\text{U} \rightarrow {}^{140}_{55}\text{Cs} + {}^{93}_{37}\text{Rb} + 2({}^{1}_{0}\text{n})$$

Calculate the mass defect.

$$\begin{aligned}\Delta m &= m_{\text{U-235}} - (m_{\text{Cs-140}} + m_{\text{Rb-93}} + 2m_n)\\ &= 235.044 \text{ u} - [139.909 \text{ u} + 92.922 \text{ u} + 2(1.009 \text{ u})]\\ &= 235.044 \text{ u} - 234.849 \text{ u}\\ \Delta m &= 0.1950 \text{ u}\end{aligned}$$

Convert the mass defect to kilograms.

$$\begin{aligned}0.1950 \text{ u} &= 0.1950 \cancel{\text{u}}\left(1.66 \times 10^{-27} \frac{\text{kg}}{\cancel{\text{u}}}\right)\\ &= 3.237 \times 10^{-28} \text{ kg}\end{aligned}$$

Now determine the binding energy.

$$\begin{aligned}E &= \Delta mc^2\\ &= (3.237 \times 10^{-28} \text{ kg})(3.0 \times 10^8 \text{ m/s})^2\\ &= 2.91 \times 10^{-11} \text{ kg·m}^2/\text{s}^2\\ E &= 2.91 \times 10^{-11} \text{ J}\end{aligned}$$

Statement: The nuclear fission reaction releases 2.91×10^{-11} J of energy per reaction.

Practice

1. Determine the energy yield of the following fission reaction. Use the given masses below.

$$^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{94}_{40}\text{Zr} + {}^{139}_{52}\text{Te} + 3({}^{1}_{0}\text{n})$$

$m_{\text{Zr-94}} = 93.906$ u

$m_{\text{Te-139}} = 138.935$ u

T/I C [ans: 2.8×10^{-11} J]

CANDU Reactors

A simplified schematic of a CANDU reactor is shown below in **Figure 4**. The calandria, or core, of the reactor is where the fission process occurs. As neutrons and thermal energy are produced, heavy water both moderates neutrons and absorbs thermal energy. As the heavy water flows through the primary loop, thermal energy is transferred to the steam generator. This transfer of energy cools the heavy water, which then flows back into the core to repeat the cycle.

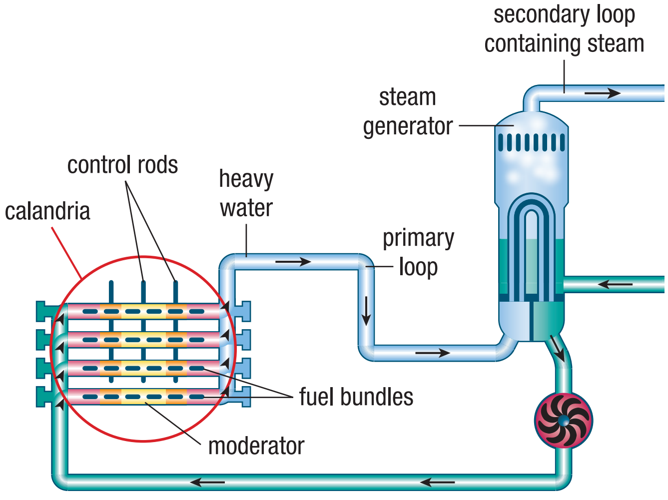

Figure 4 Schematic of a CANDU reactor

calandria core of the reactor, consisting of fuel bundles, control rods, and moderator

fuel bundles fuel elements consisting of uranium pellets

control rods adjustable cadmium rods used to control nuclear reaction rates

moderator heavy water used to slow neutrons and absorb thermal energy

steam generator absorbs thermal energy from the heavy water in the primary loop, producing steam

primary loop closed loop through which heavy water flows

secondary loop closed loop through which normal water, which becomes steam, flows

The steam generator uses the absorbed thermal energy to heat normal water in the secondary loop, producing steam. The steam is sent to a steam turbine, where its high pressure causes the turbine to turn. An electrical energy generator is then used to convert this mechanical energy into electrical energy, which can then be delivered to the electrical power network.

The fission reaction within a CANDU reactor core can be controlled in two ways: coarsely and finely. Cadmium adjuster rods are used for coarse control. The coarse control of the fission reaction is determined by how far the cadmium rods are inserted within the core. To slow the reaction, the rods are inserted farther in. This allows the cadmium to absorb more neutrons. To accelerate the reaction, the rods are moved out of the core to reduce the absorption of neutrons. Liquid zone control compartments are used for fine control.

CANDU Reactor Fuel

CANDU reactors use only natural uranium as fuel. Natural uranium consists of 99.27 % of U-238 and only 0.72 % of U-235, a radioactive isotope. The core consists of a number of fuel bundles, as shown in **Figure 5**. Each fuel bundle consists of several hundred natural uranium pellets. These fuel bundles are responsible for driving the chain reaction within the reactor core.

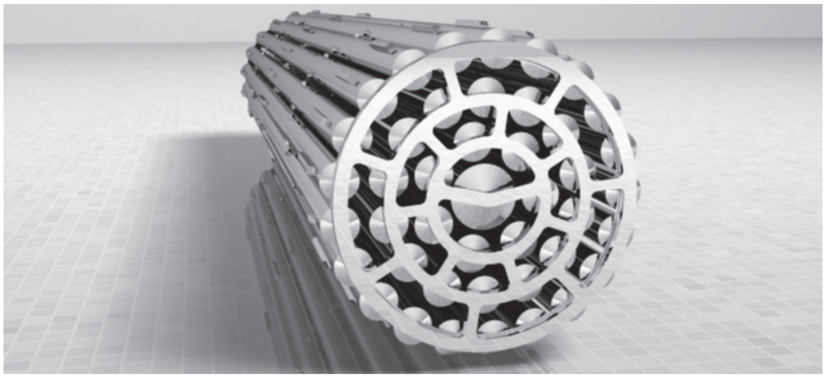

Figure 5 Fuel bundle

CAREER LINK

A nuclear engineer is focused on the safe development and application of nuclear energy. To learn more about careers in the Canadian nuclear industry,

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Safety Considerations

Safety is always a concern when dealing with radioactive materials. In a nuclear reactor facility, it is important to ensure that workers are protected from the harmful effects of radiation. Nuclear reactor design engineers must take this into account when choosing materials to shield the reactor core.

Despite all precautions, it is inevitable that workers in a nuclear reactor facility will be exposed to some level of radiation. Tiny levels of radiation exposure are not dangerous. In fact, we are all exposed to background levels of radiation every day. But it is important in a nuclear facility to closely monitor exposure levels and ensure that they are kept within safe limits. For this reason, all workers in a nuclear facility wear badges that indicate their level of radiation exposure. Each badge contains photographic film that becomes exposed when subjected to radiation.

CANDU fission reactors are known worldwide for their safety record. One key design feature is the way that the cadmium shut-off rods are arranged. The rods are inserted into the core vertically from above, suspended by electrically controlled magnets. The rods are dropped into the core to reduce reaction rates, and lifted to increase them. If there is any disruption in electrical power to the reactor, the magnets automatically turn off, causing the rods to drop completely into the core. This immediately stops the chain reaction, ensuring a safe reactor shutdown.

WEB LINK

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Waste Disposal

Nuclear reactors emit very small quantities of pollutants into the atmosphere. In addition, radioactive waste must be dealt with. Radioactive waste consists of radioactive by-products of nuclear power generation that are generally not useful for other purposes. These materials must be safely stored in appropriately shielded containers, in some cases for hundreds of years.

Research This

Breeder Reactors

Skills: Researching, Analyzing

One way to obtain rare, but useful, isotopes to use as nuclear fuel is to produce them in a breeder reactor.

1. Research breeder reactors on the Internet or in the library. Write a brief report of your findings or design a poster that includes answers to the following questions.

A. What is a breeding chain? T/I C

B. Provide an example of a breeding chain. Identify the isotope that occurs at each reaction stage. T/I C

C. Write reaction equations for each stage of the breeding chain you provided in B. Identify the type of decay that occurs at each stage. Which of these reactions are transmutations? Explain. T/I C

D. Which isotopes are commonly produced in breeder reactors? T/I C

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7.4 Summary

- Albert Einstein was the first person to propose that mass and energy are equivalent and related by $E = mc^2$.
- The law of conservation of mass–energy states that the total of mass–energy in any reaction remains constant.
- Very large amounts of energy are released during a nuclear fission reaction; the amount of released energy is equivalent to the mass defect.
- CANDU fission reactors use only natural uranium as a fuel and heavy water as a moderator.
- Heavy water in a nuclear reactor is used to slow neutrons and absorb thermal energy from the core.
- Nuclear waste disposal is a complex issue whose long-term solution is still under development.

7.4 Questions

1. Determine the energy equivalent, in joules, of
   (a) an electron
   (b) a proton T/I C
2. A small sample of coal, when completely converted to energy, releases 4.5×10^{14} J. Determine the original mass of the coal. Assume that the final mass is zero. T/I C
3. Calculate the energy released in the following nuclear reaction, given the masses indicated: T/I C

   $^{236}_{92}\text{U} \rightarrow {}^{232}_{90}\text{Th} + {}^{4}_{2}\text{He}$

   $m_{\text{U-236}} = 236.045\ 562$ u

   $m_{\text{Th-232}} = 232.038\ 051$ u

   $m_{\text{He-4}} = 4.003\ 603$ u
4. Calculate the energy released in the following reaction, given the masses indicated: T/I C

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

   $m_{\text{U-235}} = 235.044$ u

   $m_{\text{Sr-90}} = 89.908$ u

   $m_{\text{Xe-135}} = 134.879$ u
5. The following shows the products of a uranium-238 decay series: K/U C

   $^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} \rightarrow {}^{234}_{91}\text{Pa} \rightarrow {}^{234}_{92}\text{U} \rightarrow {}^{230}_{90}\text{Th} \rightarrow {}^{226}_{88}\text{Ra}$

   (a) Write a nuclear reaction equation for each stage of this series. Assume that beta decay reactions are beta-negative.
   (b) Identify each reaction by type of decay. Explain your answers.
6. Refer to Question 5. This series of reactions is part of a longer one known as the uranium-lead series. K/U T/I
   (a) Research this series and identify the other reactions involved.
   (b) What is the final stable isotope?
7. Summarize the safety issues related to nuclear fission reactors. K/U C
8. Explain how CANDU reactors are designed to minimize danger due to electrical power loss. K/U C
9. The following illustrates the breeding chain used to produce plutonium-239 from uranium-238 in a breeder reactor. The process is initiated by bombarding U-238 with high-energy neutrons:

   $^{238}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{239}_{92}\text{U} \rightarrow {}^{239}_{93}\text{Np} \rightarrow {}^{239}_{94}\text{Pu}$

   Classify the nuclear reactions occurring at each stage of this breeding cycle as alpha decay, beta decay, or electron capture. Then write a reaction equation for each stage. Assume that beta decay reactions are beta-negative. T/I C
10. Another breeding chain involves the transmutation of thorium-233 to uranium-233. This occurs in three stages: first a neutron is absorbed by a Th-233 nucleus, and then the daughter isotope undergoes beta-negative decay twice. Write the series of nuclear reaction equations for this breeding chain. Identify parent and daughter isotopes and their mass numbers and atomic numbers for each stage. T/I C