CHAPTER 6

Nuclear Physics

What is radioactive decay?

What is half-life?

How can the uranium decay series be used to determine the age of rocks and Earth?

What is meant by nuclear fission and nuclear fusion?

What is the relationship between nuclear energy and mass defect?

Is it feasible to build a nuclear power plant in Malaysia?

You will learn about:

List of Learning Standards and Formulae in Chapter 6

Information Portal

Hydrogen nuclei fusions occur naturally in the core of the Sun at about 15.6 million Kelvin and 250 billion times the Earth's atmospheric pressure. Over 560 million tons of hydrogen fuse to become helium in an instant. The nuclear energy released in the fusion reaction is the source of light and heat energy for the Sun and stars in the outer space.

Nowadays, scientists have succeeded in designing small-sized Tokamak fusion reactors in the laboratory. The heat produced by the nuclear reaction (nuclear fusion) is used to generate electrical power. If such technology can be commercialised, the dependence on the consumption of fuel sources like petroleum and coal to generate electrical power can be overcome in the future.

http://bit.ly/2FKLFpR

Importance of the Chapter

Knowledge of nuclear physics allows engineers and scientists to design safer nuclear power plants to generate electrical energy. This knowledge can also be applied to manage the nuclear plant waste carefully and efficiently to prevent environmental pollution and to ensure the well-being of the ecosystem of the earth. Such advancements will bring about the sustainability of energy resources and improve the productivity of our country.

Futuristic Lens

Research on the construction of nuclear fusion reactors to meet the increasing demand for electrical power generation may be achieved in the future. Energy from nuclear fusion is an alternative energy that is capable of reducing the consumption of petroleum and coal. This alternative energy is more efficient, has zero carbon footprint and has minimal impact on our earth's ecosystem if it is well coordinated.

http://bit.ly/2EfUt6H

6.1 Radioactive Decay

Radioactive decay is a process in which an unstable nucleus becomes more stable by emitting radioactive radiation. This process is random and spontaneous. There are three types of radioactive radiation, namely alpha particle (α), beta particle (β) and gamma ray (γ).

Info GALLERY

A radioactive decay is random and spontaneous because it is not influenced by temperature, pressure and other physical factors.

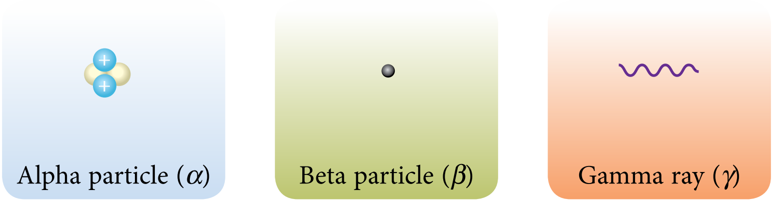


Figure 6.1 *Three types of radioactive radiation*

LET'S RECALL

Radioactivity

http://bit.ly/3ghCObR

Activity 6.1 ISS ICS

Aim: To discuss radioactive decay equations

Instructions:

1. Carry out this activity in groups.
2. Gather information from various reading resources or websites on the changes in a nucleus after a radioactive decay.
3. Discuss:
   (a) examples of decay equations for α-decay, β-decay and γ-decay
   (b) the changes in the composition of the nucleus after each type of radioactive decay
4. Present your findings.

Equation for Alpha (α) Decay

Alpha particle is a helium nucleus which consist of two protons and two neutrons. During alpha decay, an unstable nucleus releases an alpha particle to become a more stable nucleus of a new element. Figure 6.2 shows the process of alpha decay.

The general equation for an α-decay is as follows:

$$ {}^{A}_{Z}\mathrm{X} \rightarrow {}^{A-4}_{Z-2}\mathrm{Y} + \underbrace{{}^{4}_{2}\mathrm{He}}_{\alpha\text{-particle}} $$

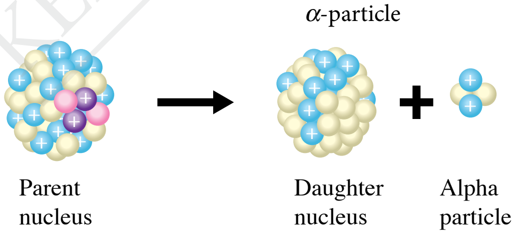


Figure 6.2 *Alpha decay*

Parent nucleus has proton number, Z and nucleon number, A. After α-decay, the daughter nucleus has proton number, $Z - 2$ and nucleon number, $A - 4$.

Example of an α-decay:

$$ {}^{210}_{84}\mathrm{Po} \rightarrow {}^{206}_{82}\mathrm{Pb} + {}^{4}_{2}\mathrm{He} $$

Equation for Beta (β) Decay

Beta particle is a fast-moving electron. During beta decay, a neutron in an unstable nucleus decomposes into one proton and one electron as shown below:

$$ {}^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e $$

The resulting proton remains in the nucleus while the electron is emitted with high kinetic energy as β-particle as shown in Figure 6.3.

The general equation for β-decay is as follows:

$$ {}^{A}_{Z}\mathbf{X} \rightarrow {}^{A}_{Z+1}\mathbf{Y} + \underbrace{{}^{0}_{-1}e}_{\beta\text{-particle}} $$

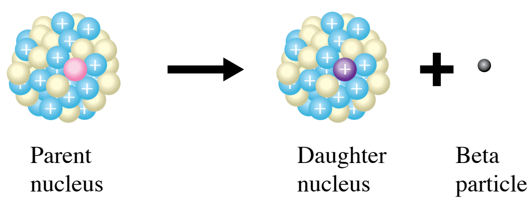


Figure 6.3 *Beta decay*

After β-decay, the proton number for the daughter nucleus becomes $Z + 1$ but the nucleon number, A does not change.

Example of a β-decay:

$$ {}^{24}_{11}\text{Na} \rightarrow {}^{24}_{12}\text{Mg} + {}^{0}_{-1}e $$

Equation for Gamma (γ) Decay

Gamma rays are high-frequency electromagnetic wave. During gamma decay, an unstable nucleus releases its excess energy to become more stable, as shown in Figure 6.4. Gamma rays have no mass and are neutral (not charged).

The general equation for γ-decay is as follows:

$$ {}^{A}_{Z}\mathbf{X} \rightarrow {}^{A}_{Z}\mathbf{X} + \underbrace{\gamma}_{\gamma\text{-ray}} $$

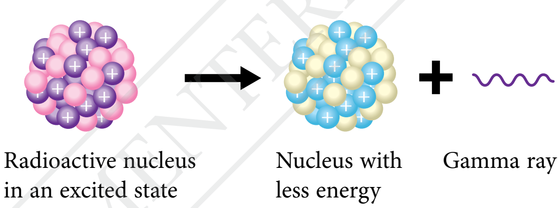


Figure 6.4 *Gamma decay*

After γ-decay, there are no changes in the proton number and nucleon number for the nucleus. The nucleus is less energetic after gamma decay.

Example of a γ-decay:

$$ {}^{60}_{27}\text{Co} \rightarrow {}^{60}_{27}\text{Co} + \gamma $$

During a radioactive decay, some nuclei can emit more than one radiation. For example, during the disintegration of uranium-234, its nucleus emits α-particle and γ-ray. Examples of its decay equation and a simpler decay equation are as follows:

Decay equation:

$$ {}^{234}_{92}\text{U} \rightarrow {}^{230}_{90}\text{Th} + {}^{4}_{2}\text{He} + \gamma $$

Simpler decay equation:

$$ {}^{234}_{92}\text{U} \xrightarrow{\alpha,\,\gamma} {}^{230}_{90}\text{Th} $$

Half-life

When a sample of radioactive material decays, the number of parent nuclei which has not decayed decreases with time while the number of daughter nuclei increases. Let us do the following activities to get an idea about half-life.

Activity 6.2

ISS ICS

Aim: Watch the animated video to get an idea about the half-life and discuss the decay series of a radioactive source

SCAN ME
Video of half-life
http://bit.ly/2CPwomw

Instructions:

1. Carry out this activity in pairs.
2. Scan the QR code to watch the video on half-life and browse the Internet for more information on half-life.
3. Based on the video and the information obtained from the website, discuss:
   (a) What is half-life?
   (b) What is radioactive decay series?
   (c) State the types of radiation emitted, the elements produced and the time taken for the uranium-238 decay series.
   (d) Explain the importance of the uranium-238 decay series in determining the age of rocks and the age of the Earth.
4. Prepare a short multimedia presentation and present it in class.

The half-life, $T_{\frac{1}{2}}$ is **the time taken for a sample of radioactive nuclei to decay to half of its initial number**. After one half-life, the number of nuclei that are not decayed will be half of its initial value.

When an unstable radioactive nucleus decays, the new nucleus that is formed may also be unstable. The new nucleus will experience a series of continuous decay until a stable nucleus is formed. Figure 6.5 shows a complete decay series from uranium-238 to lead-206 and their respective half-life.

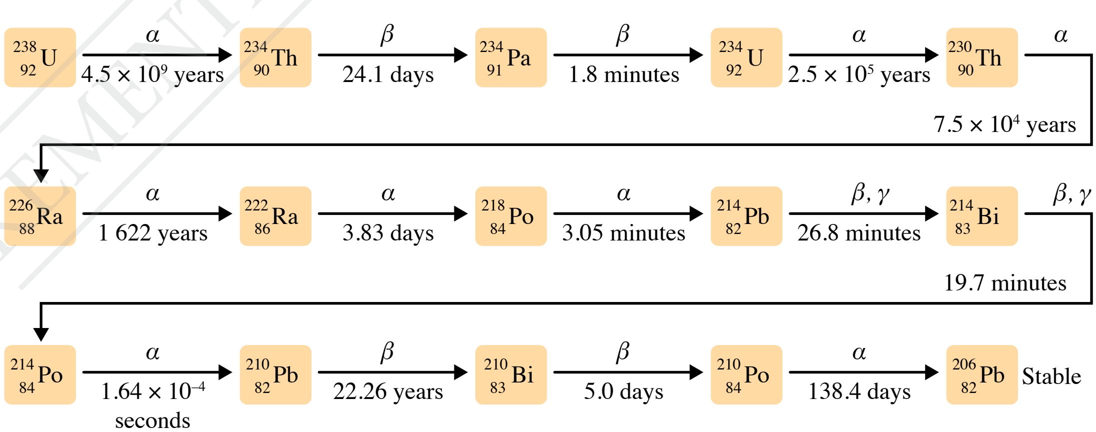


***Figure 6.5** Uranium-238 decay series*

LS 6.1.2

Uranium-238 is a radioactive element with a long half-life, that is, about 5 000 million years. This element is trapped during the formation of rocks. The trapped uranium-238 will decay and eventually form a stable lead-206 as shown in Figure 6.6. This decay process takes a long time because the decay rate is low. By determining the ratio of lead-206 to uranium-238 in a rock sample, the age of the rock can be estimated. The higher the ratio, the older the rock. This geological method of measurement can also estimate the age of our Earth. Do you know the age of our Earth?

Info GALLERY

Radioactive material is usually stored in a thick sealed container made of lead for safety purposes.

Info GALLERY

Radioisotopes are isotopes with unstable nuclei that can emit radioactive radiation.

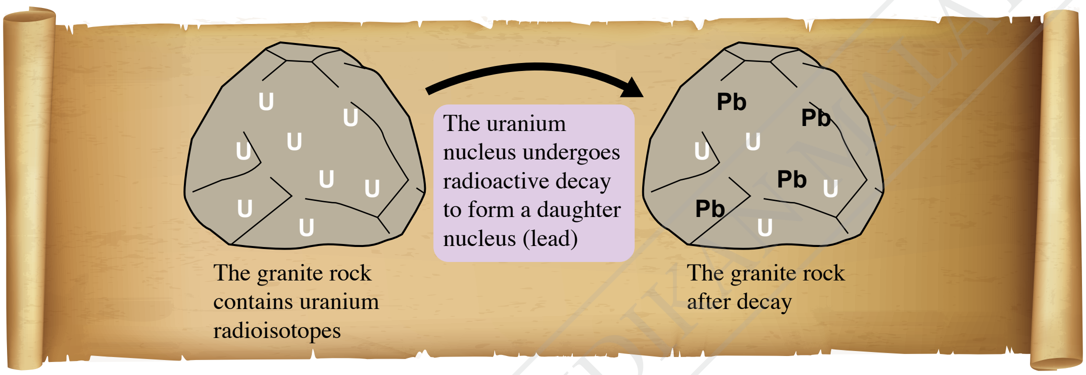


Figure 6.6 *Determining the age of granite rock*

To Determine the Half-life of a Radioactive Substance from its Decay Curve

Radioactive substance will experience random and spontaneous radioactive decay. The number of nuclei which has not disintegrated decreases with time. Different radioactive substances decay at different rates. A decay rate can be determined from a decay curve. Let us carry out a radioactive decay simulation to draw a decay curve.

Career Booth

Geologists use radioactive dating techniques to determine the age of rocks.

Activity 6.3

Aim: To draw a decay curve

Apparatus: 10 plastic bags containing 60 dice per bag

Material: Graph paper

Instructions:

1. Divide the class into 10 groups. Each group is provided with a plastic bag containing 60 pieces of dice each.
2. Throw the 60 dice on top of the table.
3. Remove all dice which display the number “3”. Record the number of dice left.
4. Throw the remaining dice again on the table and remove the dice which display the number “3”. Record the number of dice left.

LS 6.1.2 6.1.3

5. Repeat step 4 for 20 times.
6. Scan the QR code and print Table 6.1.
7. Record the results of all the 10 groups in Table 6.1.

SCAN ME
Worksheet (Table 6.1)
http://bit.ly/3j098S5

Results:

Table 6.1

Number of throws	Number of dice left, N										
	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	Average
0											
1											
2											
3											

G1= Group 1

Data analysis:
Plot the graph of the number of dice left against the number of throws.

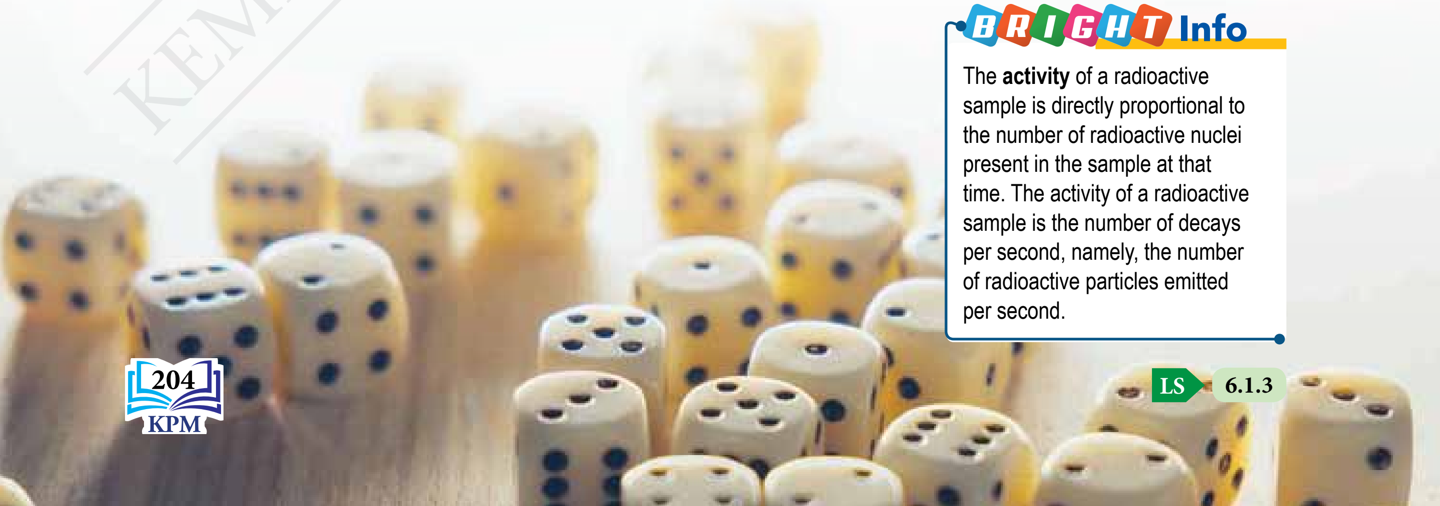
Discussion:
1. From your graph, determine the following:
   (a) the number of throws when the number of dice left becomes 30, 15 and 7.5
   (b) the average time interval, for the number of dice left to be halved if each throw represents a time of one minute
2. Will the results of your class change if this activity is repeated with the dice displaying number “1” for each throw?
3. What are the characteristics of the radioactive decay in this activity?

In Activity 6.3, each dice represents one radioactive nucleus. The dice displaying the number “3” represents a decayed nucleus. The remaining dice are considered as nuclei that have not decayed. The number of dice that displays the number “3” represents the **activity** of the radioactive sample. Your class results will not change if the activity is repeated with a dice displaying the number “1” for a throw because the probability for all numbers is the same.

SCAN ME
Graphical simulation of radioactive decay in Activity 6.3
http://bit.ly/2EdQzLp

BRIGHT Info

The **activity** of a radioactive sample is directly proportional to the number of radioactive nuclei present in the sample at that time. The activity of a radioactive sample is the number of decays per second, namely, the number of radioactive particles emitted per second.



LS 6.1.3

The concept of half-life can also be expressed in the form of a decay series as follow:

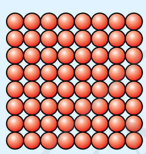
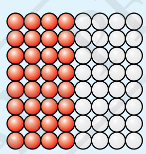
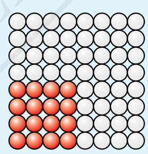
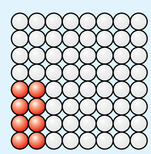
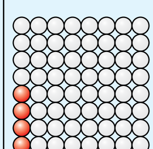
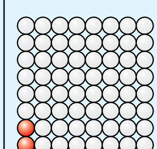
$$N_0 \xrightarrow[T_{\frac{1}{2}}]{} \left(\frac{N_0}{2}\right) \xrightarrow[T_{\frac{1}{2}}]{} \left(\frac{N_0}{4}\right) \xrightarrow[T_{\frac{1}{2}}]{} \left(\frac{N_0}{8}\right) \xrightarrow[T_{\frac{1}{2}}]{} \cdots \xrightarrow[T_{\frac{1}{2}}]{} \left(\frac{1}{2}\right)^n N_0$$

Number of radioactive nuclei that has not decayed, $N = \left(\frac{1}{2}\right)^n N_0$

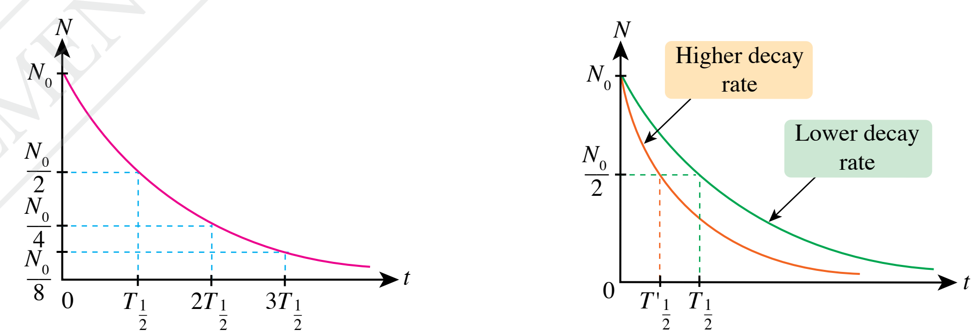
where N_0 = the initial number of radioactive nuclei
n = number of half-life (limited to positive integers)
$T_{\frac{1}{2}}$ = half-life of radioactive substances

Table 6.2 shows the change in the number of radioactive nuclei in five half-life.

***Table 6.2** The change in the number of radioactive nuclei in five half-life*

Half-life	**Initial condition**	$T_{\frac{1}{2}}$	$2T_{\frac{1}{2}}$	$3T_{\frac{1}{2}}$	$4T_{\frac{1}{2}}$	$5T_{\frac{1}{2}}$
Number of radioactive nuclei has not decayed	N_0	$\frac{1}{2}N_0$	$\left(\frac{1}{2}\right)^2 N_0$ $= \frac{1}{4}N_0$	$\left(\frac{1}{2}\right)^3 N_0$ $= \frac{1}{8}N_0$	$\left(\frac{1}{2}\right)^4 N_0$ $= \frac{1}{16}N_0$	$\left(\frac{1}{2}\right)^5 N_0$ $= \frac{1}{32}N_0$
Number of decayed radioactive nuclei	$N_0 - N_0 = 0$	$N_0 - \frac{1}{2}N_0$ $= \frac{1}{2}N_0$	$N_0 - \frac{1}{4}N_0$ $= \frac{3}{4}N_0$	$N_0 - \frac{1}{8}N_0$ $= \frac{7}{8}N_0$	$N_0 - \frac{1}{16}N_0$ $= \frac{15}{16}N_0$	$N_0 - \frac{1}{32}N_0$ $= \frac{31}{32}N_0$
● Radioactive nuclei that has not decayed ○ Decayed radioactive nuclei						

The curved graph for a radioactive decay is as shown in Figure 6.7(a). The shorter the half-life of a radioactive sample ($T'_{\frac{1}{2}} < T_{\frac{1}{2}}$), the higher the rate of decay as shown in Figure 6.7(b).



(a) (b)

***Figure 6.7** Curved graph for a radioactive decay*

Solving Problems Involving Half-Life

Example 1

A sample of radioactive material stored in the laboratory has an initial activity of 480 s^{-1}. If its half-life is 6 minutes, how much is its activity after 30 minutes?

LET'S ANSWER

http://bit.ly/32b5cqV

Solution

Step 1: Identify the problem

Step 2: Identify the information given

Step 3: Identify the formula that can be used

Step 4: Solve the problem numerically

1. Activity of radioactive material, t = 30 minutes

2. Initial activity of radioactive material, $A_0 = 480\ s^{-1}$
   Half-life, $T_{\frac{1}{2}} = 6$ min

3. Final activity, $A = \left(\frac{1}{2}\right)^n A_0$

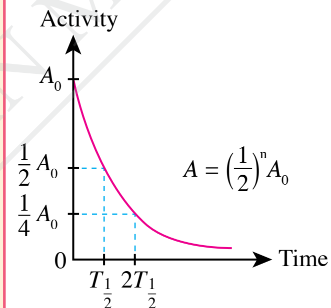
4. Number of half-life in 30 min,

$$n = \frac{t}{T_{\frac{1}{2}}} = \frac{30 \text{ min}}{6 \text{ min}} = 5 \text{ half-life}$$

Sample activity after 30 minutes

$$A = \left(\frac{1}{2}\right)^5 \times 480\ s^{-1} = 15\ s^{-1}$$

Info GALLERY



Example 2

A radioactive material stored in the laboratory has a half-life of 10 days. Calculate the number of days taken for the activity of a sample of radioactive material to reduce to 25% of its initial activity.

Solution

$$100\% \xrightarrow[\text{10 days}]{T_{\frac{1}{2}}} 50\% \xrightarrow[\text{10 days}]{T_{\frac{1}{2}}} 25\%$$

Number of days taken = 2 × 10
= 20 days

Therefore, after 20 days, the activity of the remaining radioactive material is 25% of its initial activity.

Example 3

The ratio of nuclei of argon-40 to potassium-40 in a sample of volcanic rocks is 3 : 1. In the early formation of the rocks, there was no argon element trapped in it. If potassium-40 decays to argon-40 with a half-life of 1 250 million years, estimate the age of the rocks.

Solution

Table 6.3

Half-life	Initial condition	$T_{\frac{1}{2}}$	$2T_{\frac{1}{2}}$
Number of potassium-40 nuclei that has not decayed	N_0	$\frac{1}{2}N_0$	$\frac{1}{2}\left(\frac{1}{2}N_0\right) = \frac{1}{4}N_0$
Number of argon-40 nuclei formed	0	$N_0 - \frac{1}{2}N_0 = \frac{1}{2}N_0$	$N_0 - \frac{1}{4}N_0 = \frac{3}{4}N_0$
Ratio of Argon-40 : potassium-40	–	1 : 1	3 : 1

Table 6.3 shows the method of estimating the age of rocks. The ratio of nuclei of argon-40 to potassium-40 in the rock sample is 3 : 1 after two half-lives.

Thus, the age of the rock = 2 × 1 250 million years
= 2 500 million years

Formative Practice 6.1

1. Complete the radioactive decay equation. Identify A, B and C.

   (a) ${}^{228}_{88}\text{Ra} \rightarrow \boxed{A} + {}^{0}_{-1}e$ (b) ${}^{209}_{84}\text{Po} \rightarrow {}^{205}_{82}\text{Pb} + \boxed{B}$ (c) $\boxed{C} \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e$

2. The decay series of a radioactive source is ${}^{238}_{92}\text{U} \rightarrow \ldots \rightarrow {}^{206}_{82}\text{Pb}$. Determine the number of α-particles and β-particles that are emitted.

3. Table 6.4 shows the record of the activity of a radioactive sample stored in the laboratory.

Table 6.4

Date	10 January 2020	20 January 2020	30 January 2020
Activity / s^{-1}	1 520	380	95

   (a) Determine the half-life of the radioactive sample.

   (b) Sketch a radioactive decay curve for the sample.

6.2 Nuclear Energy

The sun provides light and heat energy to Earth since millions of years ago. Hydrogen nuclear fusion occurs in the core of the Sun under very high pressure. In this nuclear reaction, two hydrogen nuclei fuse to form a helium nucleus and release nuclear energy. This energy is radiated to the surface of the Sun in the form of light and heat energy as shown in Photograph 6.1.

Nuclear energy is known as **atomic energy, released during nuclear reactions such as radioactive decay, nuclear fission and nuclear fusion**.

Photograph 6.1 *Light and heat energy radiated to the surface of Sun*

My Glorious Malaysia

The history of nuclear energy in Malaysia started with the establishment of the Tun Ismail Atomic Research Centre (PUSPATI) under the Ministry of Science, Technology and Environment on 19 September, 1972. Now, the centre is known as the Malaysian Nuclear Agency (ANM).

Activity 6.4

ISS ICS

Aim: To compare nuclear fission and nuclear fusion

Instructions:

1. Carry out a Table Talkers activity.
2. Study the keywords in the cards given.
3. Scan the QR code to watch the videos on nuclear fission and nuclear fusion.
4. Each group needs to:
   (a) explain the keywords in the cards with reference to the videos
   (b) compare the two reactions

Discussion:

Create a mind map comparing the two reactions.

SCAN ME
Video of nuclear fission
http://bit.ly/2rADgP6

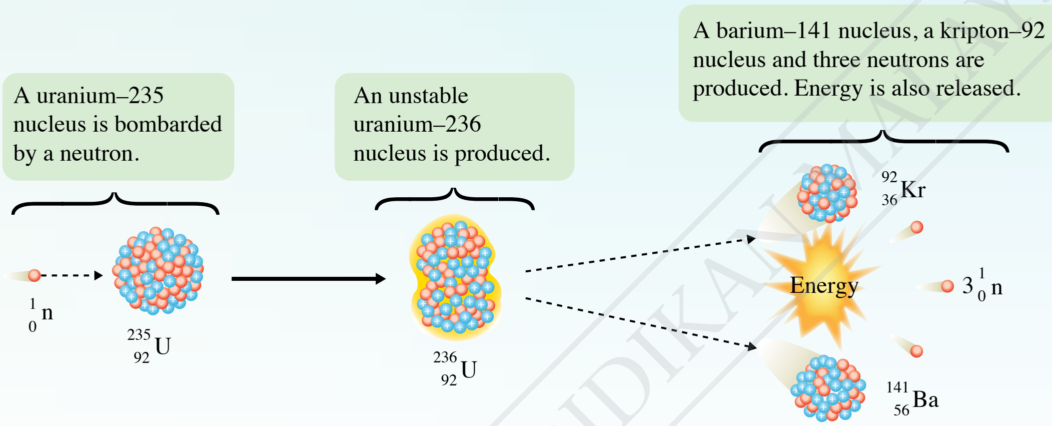
SCAN ME
Video of nuclear fusion
http://bit.ly/3kYY3mh

Nuclear fission and nuclear fusion are two nuclear reactions that produce nuclear energy. There is a loss of mass (mass defect) occurs during these nuclear reactions. Figure 6.8 shows a nuclear fission while Figure 6.9 shows a nuclear fusion.

Nuclear fission

Nuclear fission is a **nuclear reaction when a heavy nucleus splits into two or more lighter nuclei while releasing a large amount of energy.**

Example:



$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{236}_{92}U \longrightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n + \text{energy}$$

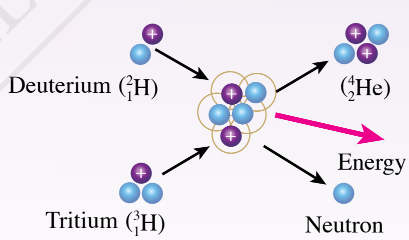
Figure 6.8 *Nuclear fission involving uranium–235 bombarded by a single neutron*

Nuclear fusion

Nuclear fusion is a **nuclear reaction in which small and light nuclei fuse to form a heavier nucleus while releasing a large amount of energy. This nuclear reaction happens under extremely high temperature and pressure**.

Example:

Nuclear fusion between deuterium and tritium occurs to form a heavier helium nucleus. Energy and one neutron is also released.



SCAN ME
Eduweb TV: Nuclear energy
http://bit.ly/2Ync0R7

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

Figure 6.9 *Nuclear fusion between deuterium and tritium*

LS 6.2.1

The Relationship between Energy Released During Nuclear Reaction and Mass Defect

Atomic mass unit (amu) is a measurement of the mass of an atom. The mass of an atom is too small and difficult to measure using units such as grams or kilograms. Therefore, a relative comparison between the mass of an atom with the mass of one carbon-12 atom is used. Isotope carbon-12 is used as a reference because carbon can be found in many compounds found on Earth. Carry out Activity 6.5 to discuss amu by using the mass of one carbon-12 atom and the Avogadro number.

Activity 6.5

CPS

Aim: Discuss the atomic mass unit (amu) using the mass of one carbon-12 atom and the Avogadro number

SCAN ME
Worksheet
(Figure 6.10)
http://bit.ly/31fBn9g

Instructions:

1. Carry out this activity in pairs.
2. Scan the QR code and print Figure 6.10.
3. Discuss with your partner and complete Figure 6.10

The Avogadro number is the number of atoms found in 1 mole of carbon-12, that is,
N_A = ________________ atom

↓

The mass of one carbon-12 atom is 12 amu.

↓

1 amu is defined as a mass equal to ________________ that of the mass of a carbon-12 atom.

↓

Mass of one mole of carbon-12 = ________________ kg

↓ Therefore,

The mass of one carbon-12 atom is ______________________.

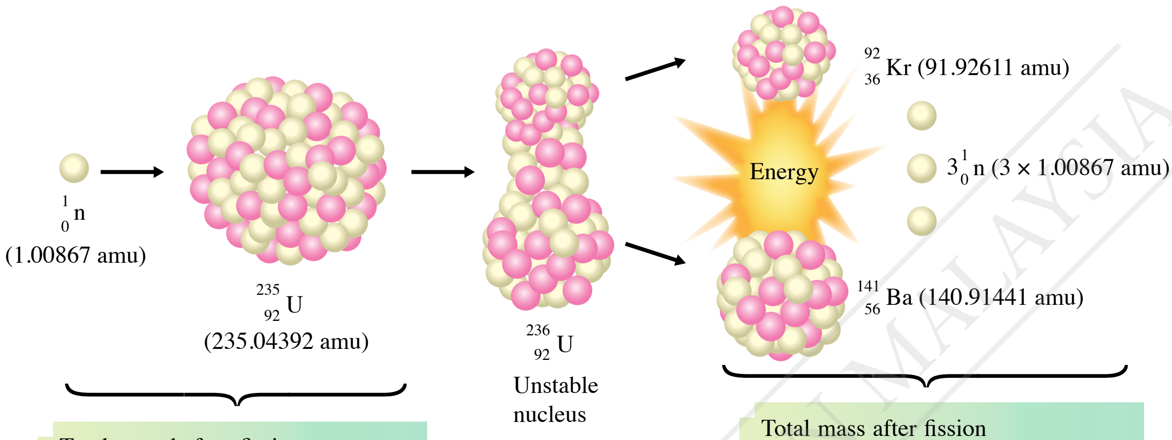
↓ From the definition of atomic mass unit (amu):

$$1 \text{ amu} = \frac{\boxed{}}{\boxed{}} \times \frac{\boxed{}}{\boxed{}}$$

= ________________________ kg

Figure 6.10 *Definition of atomic mass unit (amu)*

In a nuclear reaction or radioactive decay, the total mass of the decay products is always less than the total mass of the radioactive nucleus. This loss of mass is known as **mass defect**, *m*. Figure 6.11 shows an example of a change in total before decay mass before and after a nuclear fission.



Total mass before fission
= 1.00867 + 235.04392
= 236.05259 amu

Total mass after fission
= 91.92611 + 3(1.00867) + 140.91441
= 235.86653 amu

Mass defect, m = 236.05259 – 235.86653
= 0.18606 amu

***Figure 6.11** Example of mass defect in nuclear fission*

The relationship between the energy released during nuclear reaction and the mass defect can be summarised by the following equation:

$$E = mc^2$$

where E = total energy released
m = mass defect
c = the speed of light in vacuum

1 amu = 1.66×10^{-27} kg

Based on knowledge of amu and the equation $E = mc^2$, we can calculate the nuclear energy produced from radioactive decay processes and nuclear reactions.

EAL History

Albert Einstein stated that mass and energy are interchangeable. The relationship between the two quantities is expressed in the equation $E = mc^2$.

Info GALLERY

Nuclear energy can be expressed in the unit of megaelectronvolts, MeV.

1 MeV = 1.6×10^{-13} J

Solving problems involving Nuclear Energy due to Radioactive Decay and Nuclear Reactions

Example 1

The equation below shows radium-226 decaying into radon-222 by emitting alpha particle.

$$^{226}_{88}\text{Ra} \longrightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\text{He}$$

Given that the mass of $^{226}_{88}$Ra is 226.54 amu, $^{222}_{86}$Rn is 222.018 amu and $^{4}_{2}$He is 4.003 amu, calculate the nuclear energy released.
[1 amu = 1.66×10^{-27} kg and speed of light in vacuum, $c = 3.00 \times 10^{8}$ m s^{-1}]

LET'S ANSWER

http://bit.ly/2Q9FTQs

Solution

Step 1: Identify the problem

Step 2: Identify the information given

Step 3: Identify the formula that can be used

Step 4: Solve the problem numerically

1. Nuclear energy that is released

2. Mass $^{226}_{88}$Ra = 226.54 amu
   Mass $^{222}_{86}$Rn = 222.018 amu
   Mass $^{4}_{2}$He = 4.003 amu
   Speed of light in vacuum,
   $c = 3.00 \times 10^{8}$ m s^{-1}
   1 amu = 1.66×10^{-27} kg

3. Nuclear energy released, $E = mc^2$

4. Mass defect, m = 226.54 – (222.018 + 4.003)
   = 0.519 amu
   Mass defect, m (in kg) = $0.519 \times 1.66 \times 10^{-27}$
   = 8.6154×10^{-28} kg
   $E = mc^2$
   $= 8.6154 \times 10^{-28} \times (3.00 \times 10^{8})^2$
   $= 7.75 \times 10^{-11}$ J

Example 2

The Sun is the source of energy to the Earth. This energy is produced by the nuclear fusion in the core of the Sun as shown in the following equation:

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

Calculate the nuclear energy released in joules.
[Mass of $^{2}_{1}$H = 2.014 amu, mass of $^{3}_{1}$H = 3.016 amu, mass of $^{4}_{2}$He = 4.003 amu, mass of $^{1}_{0}$n = 1.009 amu, 1 amu = 1.66×10^{-27} kg and the speed of light in a vacuum, $c = 3.0 \times 10^{8}$ m s^{-1}]

Solution

Mass defect, m
= (2.014 + 3.016) – (4.003 + 1.009)
= 5.030– 5.012
= 0.018 amu

Thus, $m = 0.018 \times 1.66 \times 10^{-27}$ kg
$m = 2.988 \times 10^{-29}$ kg
$E = mc^2$
$= 2.988 \times 10^{-29} \times (3.0 \times 10^{8})^2$
$= 2.69 \times 10^{-12}$ J

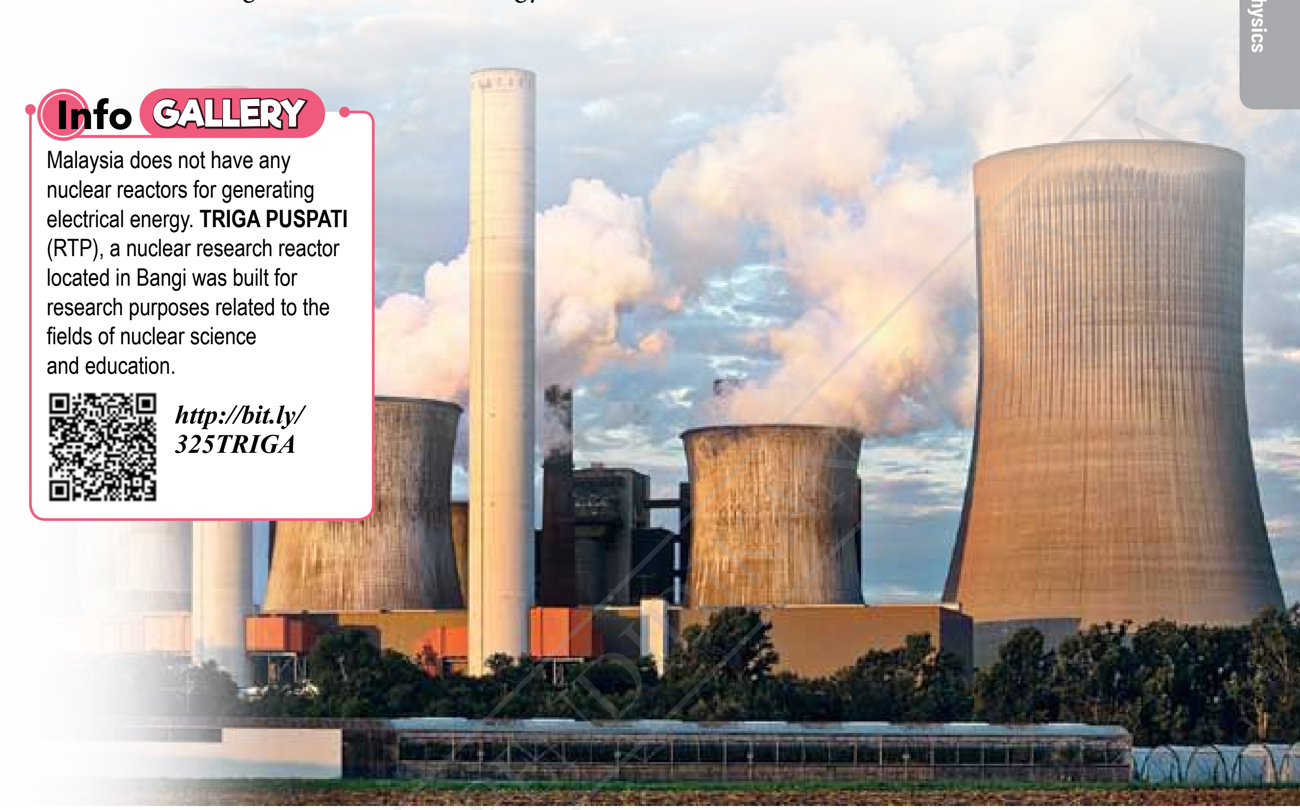
Generation of Electrical Energy in a Nuclear Reactor

Photograph 6.2 shows a nuclear reactor. What is the nuclear reaction that takes place in the nuclear reactor to generate electrical energy?

Info GALLERY

Malaysia does not have any nuclear reactors for generating electrical energy. **TRIGA PUSPATI** (RTP), a nuclear research reactor located in Bangi was built for research purposes related to the fields of nuclear science and education.

http://bit.ly/325TRIGA



Photograph 6.2 *A nuclear reactor*

Activity 6.6

ISS ICS

Aim: To find information on the generation of electrical energy in a nuclear reactor

Instructions:

1. Conduct an Envoys activity.
2. Scan the QR code given or refer to any reference materials on the generation of electrical energy in a nuclear reactor.
3. Discuss the following:
   (a) What nuclear reaction is taking place in the nuclear reactor?
   (b) What is the energy change in the nuclear reactor?
   (c) Why is nuclear fusion not currently used in the electrical energy generation industry?
4. Present your findings.

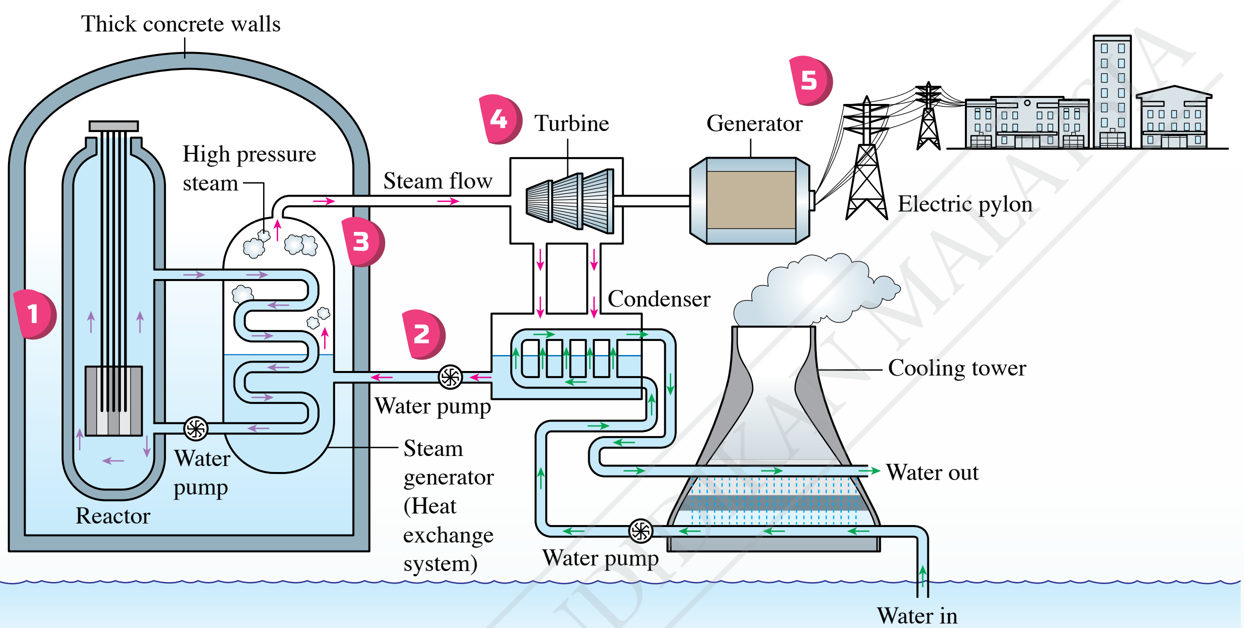
SCAN ME

Video of working principles of a nuclear reactor

http://bit.ly/2FGK9F3

Figure 6.12 shows the structure of a nuclear reactor and the process of electrical energy generation at a nuclear power station.

SCAN ME
Video of function of each section in a nuclear reactor
http://bit.ly/3ghpyUv



1 Nuclear fission of uranium-235 and its chain reaction produce heat energy.

2 Water is pumped into the reactor core to absorb the heat energy that is produced by the nuclear fission.

3 The boiling of water produces high pressure steam. This steam will be channelled to the turbine.

4 The turbine is rotated by the high pressure steam which in turn rotates the magnet or coil in the generator. The steam will condense into water.

5 The electrical energy generated is sent consumers via a power supply transmission system.

Figure 6.12 *The structure of a nuclear reactor and the process of generating electrical energy*

In a nuclear reactor, the fission of uranium-235 nucleus produces two daughter nuclei, three fast moving neutrons and releases a large amount of energy. These neutrons will bombard other uranium nuclei and release more neutrons through continuous nuclear fission. These continuous reactions is known as a **chain reaction**. Figure 6.13 shows the chain reaction of uranium-235.

SCAN ME
Video of a chain reaction in the core of a nuclear reactor
http://bit.ly/ChaRea8

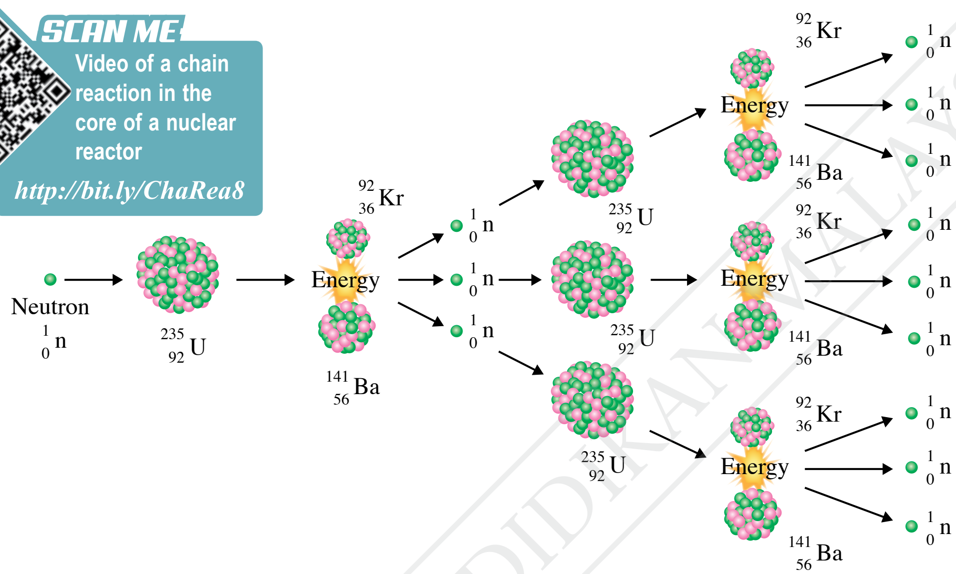


Figure 6.13 *Chain reaction of uranium-235*

The chain reaction that takes place in the reactor core needs to be controlled. The reactor needs to have a structure which can prevent the leakage of radioactive radiation to the surroundings. How can we control the energy produced during the chain reaction and ensure that a nuclear reactor is safe for electricity generation?

Activity 6.7

ISS ICS

Aim: To discuss a chain reaction and ways to control the energy produced in a nuclear reactor

Instructions:

1. Carry out a Talk Partners activity.
2. Scan the QR code given or refer to the reading resources to obtain information on chain reactions and ways of controlling energy produced in a nuclear reactor core.
3. Based on the information obtained:
   (a) write the equation for the fission of a uranium-235 nucleus when it is bombarded by a neutron
   (b) discuss ways of controlling the energy produced during a chain reaction in a nuclear reactor.
4. Present your findings.

SCAN ME
Video on ways of controlling energy in a nuclear reactor
http://bit.ly/3Vid215

Figure 6.14 shows the control of rate of nuclear reaction and safety features in a nuclear reactor.

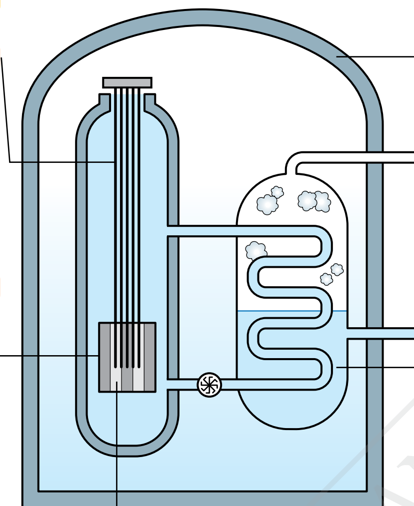
Control of rate of nuclear reaction:

Control rod

- Controls the reaction rate by absorbing excess neutrons.
- Made of boron or cadmium.

Moderator

- Slows down the fast moving neutrons released so that nuclear fission can occur.
- Made from materials such as graphite or water.



Safety features:

Thick concrete walls

Prevent radioactive radiations from leaking into the surroundings.

Water as a cooling agent

Absorbs heat energy from the chain reactions to generate steam. This can control the reactor temperature.

Uranium rods

Used as fuels for producing nuclear energy through nuclear fission reaction.

Figure 6.14 *Control of rate of nuclear reaction and safety features in a nuclear reactor*

The Use of Nuclear Energy as an Alternative Source to Generate Electrical Energy

In Malaysia, electricity is generated using sources like coal, natural gas and water. The hydro dam in Bakun, Sarawak as shown in Photograph 6.3 is the second largest dam in Asia that is used to generate electrical energy. However, countries like the United States, Japan, France, India and China have been using nuclear energy to generate electrical energy. Let us carry out the following activity to compare the electrical energy generation from a power plant using coal, hydropower and nuclear energy.

Photograph 6.3 *Hydro dam in Bakun, Sarawak*

Activity 6.8

Logical Reasoning | ISS | ICS

Aim: To find information to compare the generation of electrical energy from power plants that use coal, hydropower and nuclear energy

Instructions:

1. Carry out this activity in groups.
2. Obtain information on electrical energy generation from power plants that use coal, hydropower and nuclear energy.
3. The aspects that need to be considered when searching for information are as follows:
   (a) costs of construction, operation and maintenance
   (b) location of power plant
   (c) impact on ecosystems and carbon footprint
   (d) safety and health issues
   (e) technology and expertise
   (f) waste management issues
4. Based on the information obtained, hold a forum to discuss the feasibility of building a nuclear power plant in Malaysia.

SCAN ME
Video of electricity generation
http://bit.ly/37ElecWbJ

Nuclear energy is now the alternative source to generate electrical energy to meet the growing energy demand and to replace the reliance on fossil fuel.

However, the use of this energy is still a highly debatable issue. In your opinion, should nuclear energy be used as an alternative source to generate electrical energy in Malaysia?

Formative Practice 6.2

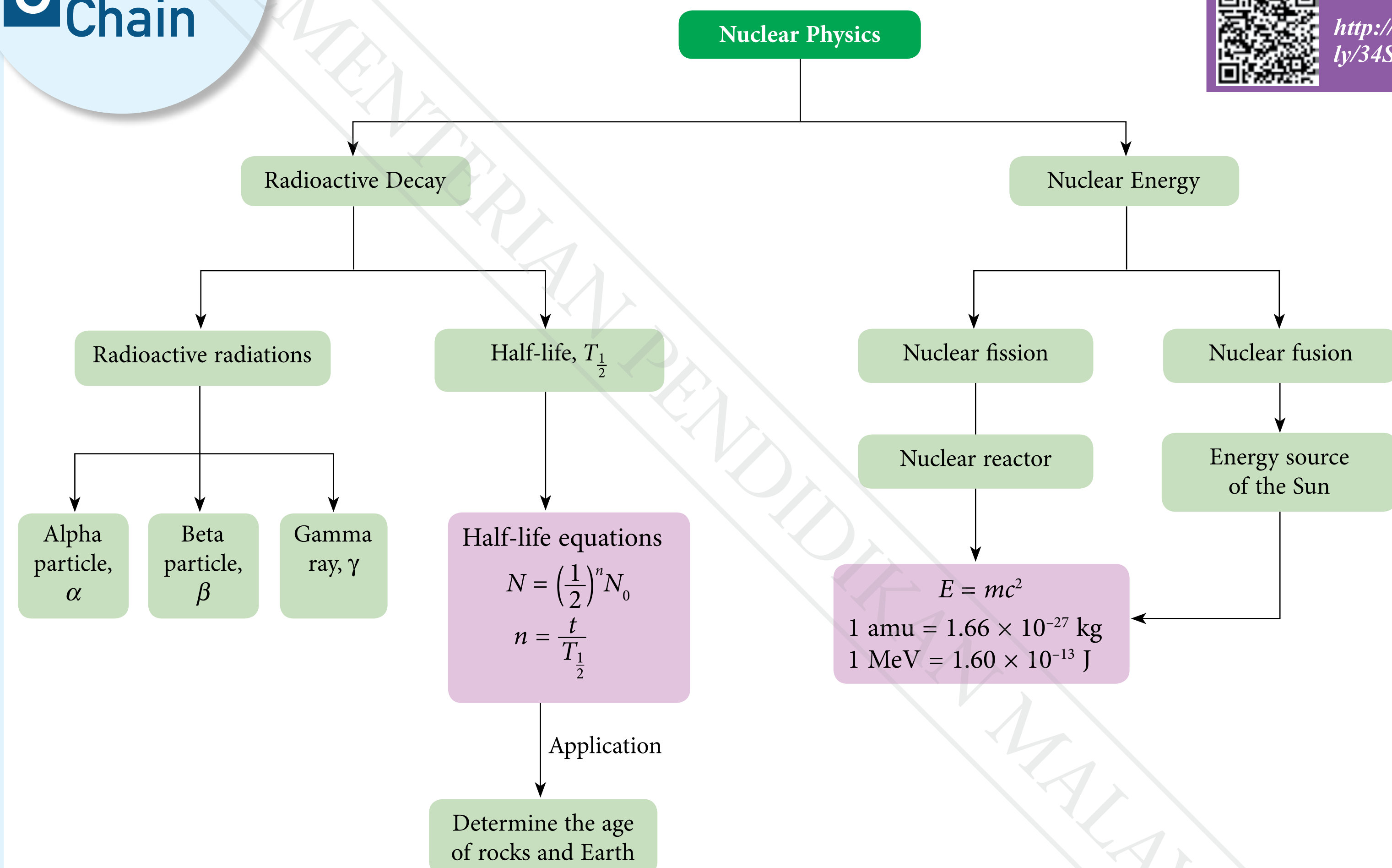
1. What is meant by nuclear fission and nuclear fusion?
2. Describe the chain reaction that occurs in a nuclear reactor.
3. Explain how a nuclear reactor generates electrical energy.
4. A nuclear reaction is represented by the following equation:

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{141}_{55}Cs + ^{93}_{37}Rb + 2^{1}_{0}n + \text{energy}$$

The mass defect is 0.19585 amu. Calculate the energy that is released by the reaction.

Concept Chain

Interactive Games
http://bit.ly/34SRhM



Self-Reflection

SCAN ME
Download and print Self-Reflection
http://bit.ly/3gi5xC

1. New things that I have learnt from the chapter 'Nuclear Physics' are ____________.
2. The most interesting thing that I have learnt in this chapter is ____________.
3. The things I still do not fully understand are ____________.
4. My performance in this chapter.

   Poor | 1 | 2 | 3 | 4 | 5 | Very good

5. I need to ____________ to improve my performance in this chapter.

Summative Practice

QUIZ PORTAL
http://bit.ly/2D3VKVT

1. What is meant by:
   (a) radioactive decay
   (b) half-life
   (c) nuclear energy
2. The following shows the equation for a radioactive decay:

$$^{226}_{88}\text{Ra} \longrightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\text{X} + \text{Y}$$

   (a) Identify X and Y in the decay equation.
   (b) How many α and β-particles will be released when $^{222}_{86}\text{Rn}$ decays to $^{210}_{82}\text{Pb}$?
3. (a) Astatine-218 has a half-life of 1.6 s. How long will it take for 99% of the nucleus in one sample of astatine-218 to disintegrate?
   (b) Radium-226 has a half-life of 1 600 years. What percentage of the sample of radium-226 will be left after 8 000 years?

4. During the formation of rocks, radioisotope uranium-238 is trapped. The decay rate of uranium-238 is low and the end result of the decay series is lead-206. Table 1 shows the composition of samples of rock *A* and rock *B*.

Table 1

	Sample *A*	Sample *B*
Ratio of uranium-238 to lead-206	5 : 1	7 : 1

(a) Between the samples of rock *A* and rock *B*, which one is older? Justify your answer.

(b) The composition of the lead nucleus is unlikely to be greater than the uranium nucleus in the rocks sample. Explain your answer.

5. Carbon-14 has a half-life of 5 730 years.

(a) What is the fraction of undecayed carbon in a fossil sample at the end of 1.719×10^4 years?

(b) Based on your answer to 5(a), sketch a graph of the decay curve for carbon-14 in the fossil sample.

6. In a nuclear reaction as shown in Figure 1, the total mass of the particles that are produced is less than the initial mass of the particles. The nuclear reaction experiences a mass defect. The lost mass is converted into energy.

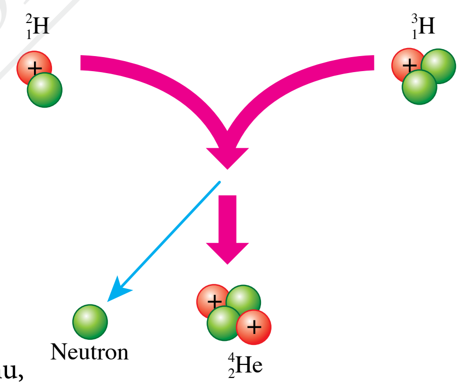


Figure 1

(a) Name the nuclear reaction and write the equation involved.

(b) Calculate the mass defect and the nuclear energy that is released.
[Mass $^{2}_{1}H$ = 2.01410 amu, mass $^{3}_{1}H$ = 3.01605 amu, mass $^{4}_{2}He$ = 4.00260 amu, mass $^{1}_{0}n$ = 1.00866 amu, 1 amu = 1.66×10^{-27} kg and speed of light in vacuum, $c = 3.00 \times 10^{8}$ ms^{-1}]

7. A radioactive decay series of a source of uranium-235 is

$$^{235}_{92}U \rightarrow \cdots \rightarrow ^{207}_{82}Pb$$

(a) What is the number of α-particles and β-particles emitted?

(b) Draw a graph of the nucleon number against atomic number that is possible for the decay series.

8. Figure 2 shows the conversion of energy that occurs from nuclear energy to electrical energy in a nuclear reactor.

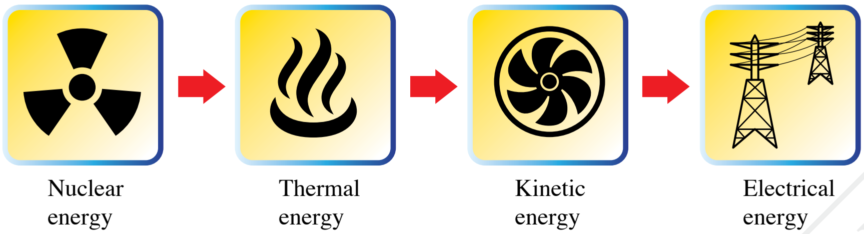


Figure 2

(a) How is nuclear energy produced in a reactor?

(b) How is heat energy converted to kinetic energy in the rotation of a turbine? Explain your answer.

(c) The kinetic energy from the turbine rotation can produce electrical energy. How does this process happen? Explain.

(d) Usually, high cooling towers are built at nuclear power stations. Explain the reason.

21st Century Challenge

9. A nuclear agency plans to build a nuclear power plant in our country to meet the growing demand for energy. However, nuclear fission requires very expensive uranium or plutonium fuels. Furthermore, the issue of radioactive waste management and the threat of environmental pollution is worrying the public.

Imagine that you are a nuclear scientist assigned to construct the nuclear power station. Discuss the considerations that need to be made based on the following aspects:

- location of the nuclear power plant
- walls for the reactor core
- walls for the reactor building
- cooling agents
- energy control methods
- radioactive waste management
- safety measures

Justify each of your suggestions.