

Nuclear Physics

Guiding Questions	Learning Objectives
1. What is an atomic nucleus?	(a) infer from the results of the Rutherford α-particle scattering experiment the existence and small size of the atomic nucleus. (b) distinguish between nucleon number (mass number) and proton number (atomic number). (c) show an understanding that an element can exist in various isotopic forms, each with a different number of neutrons in the nucleus, and use the notation A_ZX for the representation of nuclides.
2. How is energy related to mass?	(p) show an understanding of the concept of mass defect. (q) recall and apply the equivalence between energy and mass as represented by $E=mc^2$ to solve problems. (r) show an understanding of the concept of nuclear binding energy and its relation to mass defect. (s) sketch the variation of binding energy per nucleon with nucleon number.
3. How do nuclei react?	(m) represent simple nuclear reactions by nuclear equations of the form ${}^{14}_7N + {}^4_2He \rightarrow {}^{17}_8O + {}^1_1H$ (n) state and apply to problem solving the concept that nucleon number, charge and mass-energy are all conserved in nuclear processes. (t) explain the relevance of binding energy per nucleon to nuclear fusion and to nuclear fission.
4. What is radioactive decay?	(d) show an understanding of the spontaneous and random nature of nuclear decay. (e) infer the random nature of radioactive decay from the fluctuations in count rate. (f) show an understanding of the origin and significance of background radiation. (g) show an understanding of the nature of α, β and γ radiations (knowledge of positron emission is not required). (o) show an understanding of how the conservation laws for energy and momentum in β decay were used to predict the existence of the (anti)neutrino (knowledge of antineutrino and the zoo of particles is not required). (h) define the terms activity and decay constant and recall and solve problems using the equation $A = \lambda N$. (i) infer and sketch the exponential nature of radioactive decay and solve problems using the relationship $x = x_0 \exp(-\lambda t)$ where x could represent activity, number of undecayed particles or received count rate. (j) define and use half-life as the time taken for a quantity x to reduce to half its initial value. (k) solve problems using the relation $\lambda = \frac{\ln 2}{t_{1/2}}$.

5. How does radiation affect us?	(l) discuss qualitatively the applications (e.g. medical and industrial uses) and hazards of radioactivity based on: i. half-life of radioactive materials, ii. penetrating abilities and ionising effects of radioactive emissions.
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What is an atomic nucleus?

1. Atomic Structure and Nuclear Physics Terminology



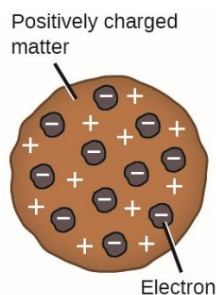
Nature of Science Moment – From Plum Pudding to the Nuclear Atom

At the turn of the 20th century, J. J. Thomson proposed the *plum pudding model* of the atom. Based on his discovery of the electron, he suggested that atoms were positively charged “puddings” with negatively charged electrons embedded within them. Importantly, this model was not a wild guess—it was the best explanation supported by experimental evidence available at the time.

However, science does not stop at accepted ideas. When Ernest Rutherford and his team carried out the alpha-particle scattering experiment with gold foils, they observed results that the plum pudding model could not explain: most alpha particles passed straight through the foil, but a few were deflected at large angles. This led to a radical new conclusion—the atom is mostly empty space with a small, dense, positively charged nucleus at its centre.

This shift from the plum pudding model to Rutherford’s nuclear model highlights a key feature of the Nature of Science: *Scientific models are tentative and change when new evidence emerges.*

Thomson’s model was not “wrong” in a careless sense—it was limited by the evidence and technology of its time. Rutherford’s work did not simply reject earlier ideas; it refined and replaced them using stronger experimental support. This episode reminds us that scientific knowledge grows through questioning, testing, and being open to change when observations demand it.



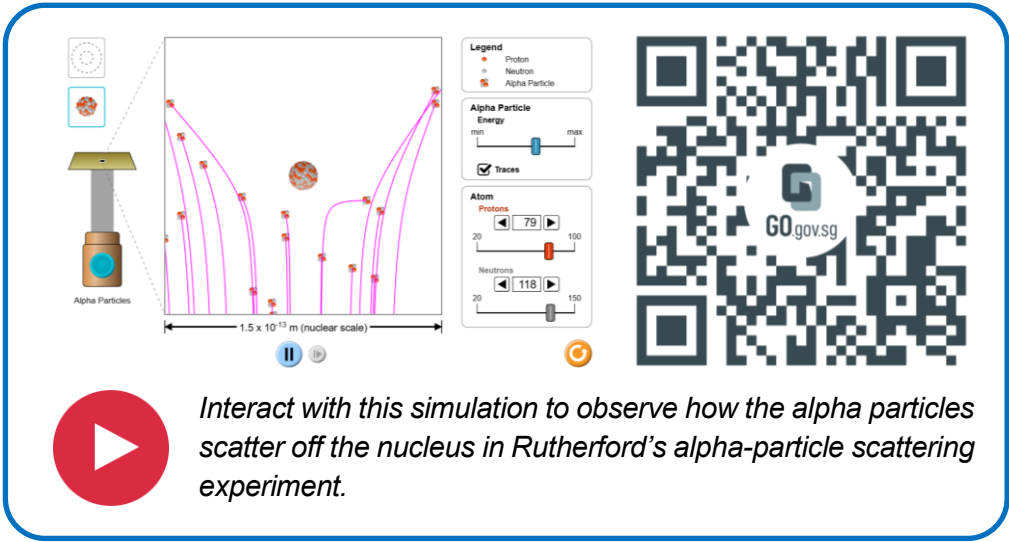
Thomson's Plum Pudding Model



Plum Pudding

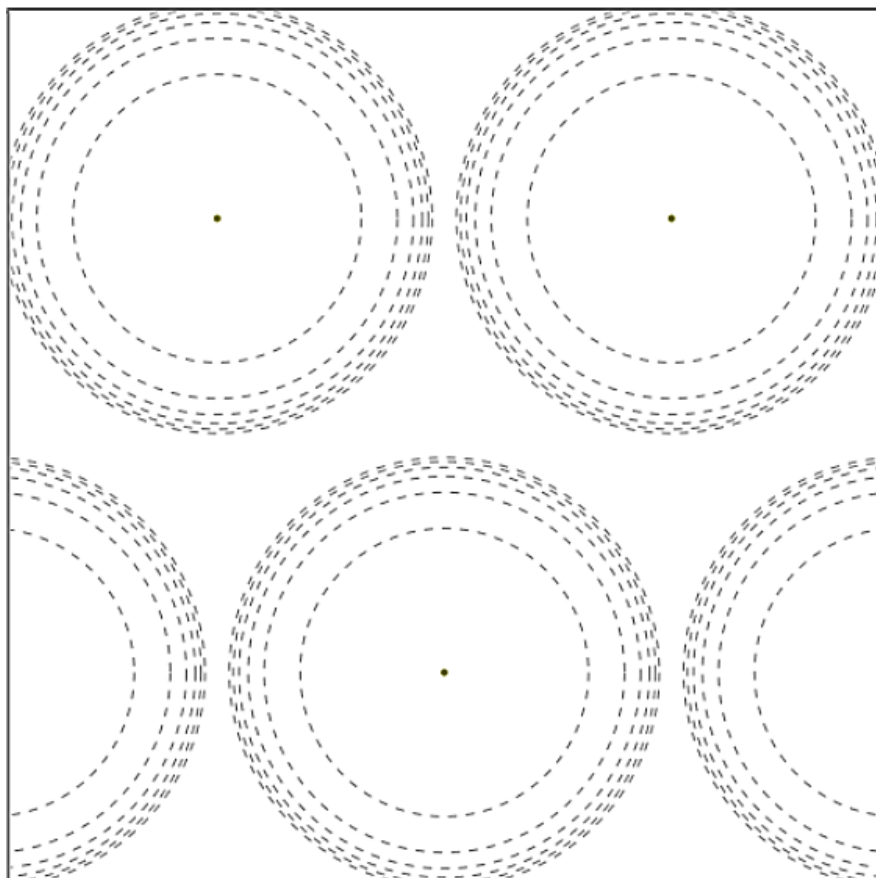
1.1 Rutherford's Alpha-Particle Scattering Experiment

Between 1909-11, Rutherford and two of his students, Hans Geiger and Ernest Marsden investigated the scattering of alpha (α) - particles by a thin film of heavy metal, notably gold $^{197}_{79}\text{Au}$, in a vacuum. The aim was to probe the interior structure of the atom.



Interact with this simulation to observe how the alpha particles scatter off the nucleus in Rutherford's alpha-particle scattering experiment.

Using the simulation above, sketch the paths of ten alpha-particles emitted from a radioactive source (alpha-particle is a helium nucleus which has 2 protons and 2 neutrons) approaching the gold atoms in a thin foil (the nuclei in the atoms are actually smaller than shown).



In the simulation, press the blue button to "turn on" the alpha source.

You may wish to click the "Traces" checkbox to visualise the trails of the alpha particles.

Rough perspective of a nucleus' size: If the nucleus in an atom is the size of a baseball, the diameter of the atom would be the distance from ACJC to City Hall Area.

Legend

- Nucleus
- Electron Energy Level
- ➡ Alpha Particle Trace

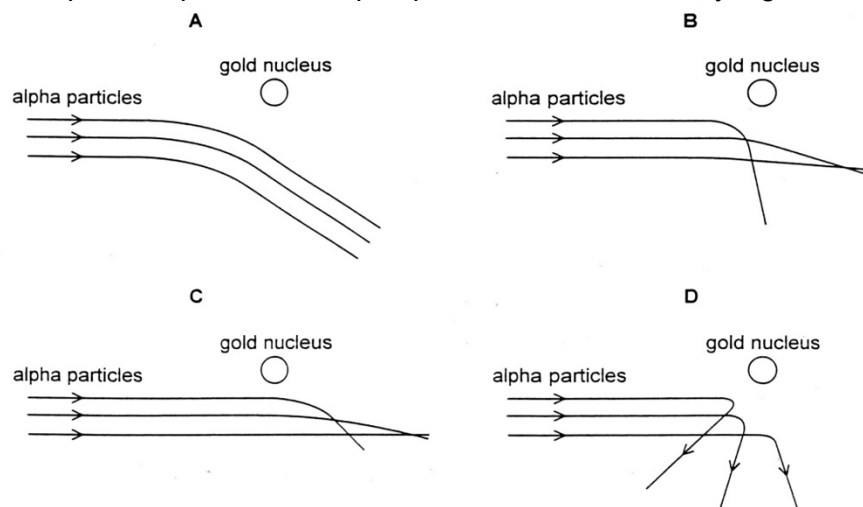
	Observations	Interpretations
(i)	<u>Majority</u> of the alpha-particles pass through the gold foil <u>undeflected</u> .	- Large numbers of high energy alpha-particles (travelling about one tenth of the speed of light) just pass almost straight through this very thin gold layer which was only about a thousandth of a millimetre thick. - This observation suggests that an atom consists of a large amount of empty space.
(ii)	A <u>small number</u> of alpha-particles were deflected through an <u>angle greater than 90°</u> . About <u>1 in 8000</u> alpha-particles was <u>deflected back</u> to where it came from.	- When the positive charges are concentrated in a small volume, some of the alpha-particles could get near it to experience a large electric force to be deflected at larger angles (greater than 90°). - The atom must have all of its positive charges and most of its mass concentrated at its centre; the atom must have a positively charged nucleus that could deflect the alpha-particles through large angles.

Conclusions

1. The nucleus occupies a small volume of the atom.
It is no larger than 10^{-15} m in diameter. An atom has a typical diameter of 10^{-10} m.
2. The nucleus contains a large proportion of the mass of an atom.
It accounts for at least 99.5% of the total mass of the atom.
3. The nucleus is positively charged.

Example 1.1 (Recognising the paths of deflection of alpha-particles)

Which diagram shows possible paths when alpha-particles are deflected by a gold nucleus?

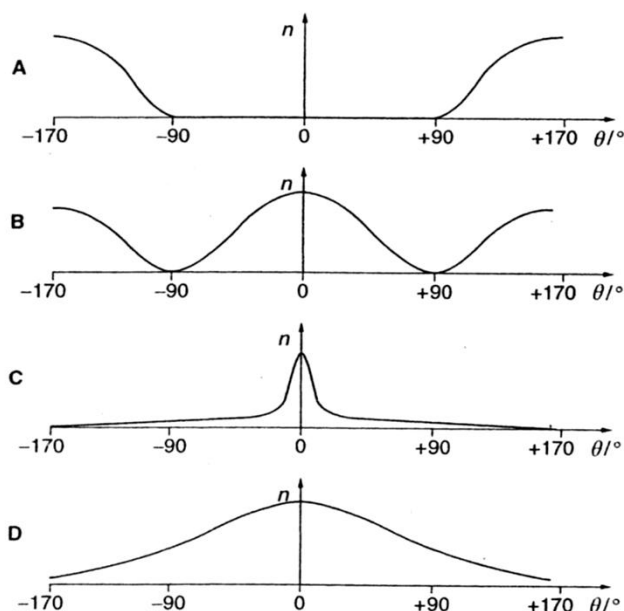
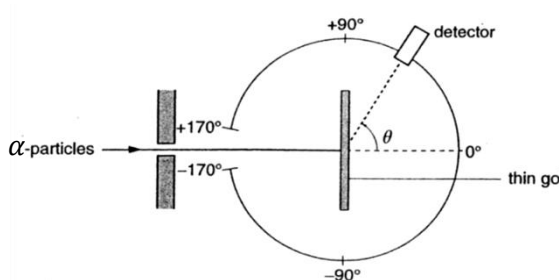


B

Example 1.2 (Identifying the intensity of scattered alpha-particles at various angles)

In an α -particle scattering experiment, a student determined the number n of α -particles incident per unit time on a detector held at various angular positions θ .

Which graph best represents the variation of n with θ ?



C

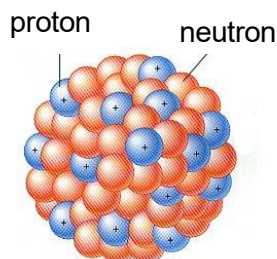
1.2 Commonly Used Terms

- A** An atom consists of a positively charged nucleus which is made up of protons, and neutrons.

The symbol of an atom is given by



where X is the chemical symbol.



A nucleus can be modelled as a cluster of tightly packed spheres, where each sphere is a nucleon.



A is the **nucleon number** (or mass number) which is the number of protons plus number of neutrons (neutrons have no charge). Both protons and neutrons are called nucleons as they are particles in the nucleus.



Z is the **proton number** (or atomic number) which is the number of protons in the nucleus of an atom.

- B** The term *nuclide* is used to specify an atom with a particular proton-neutron combination. This term is useful in sentences like “the helium-3 nuclide and the helium-4 nuclide are isotopes”.

C



Isotopes are atoms of the same element with the same number of protons but with different number of neutrons in their nucleus.

Some examples of isotopes of hydrogen:

	Element	% of isotope	Remarks
${}^1_1\text{H}$	hydrogen	99.985	Stable
${}^2_1\text{H}$	deuterium	0.015	Stable
${}^3_1\text{H}$	tritium	trace	Radioactive Half-life: 12.3 years

Some examples of isotopes of carbon:

	% of isotope	Remarks
${}^{12}_6\text{C}$	98.89%	Stable
${}^{14}_6\text{C}$	Trace	Radioactive Half-life: 5730 years Used for Carbon-Dating

Isotopes have similar chemical properties as they have the same number of protons and electrons. However, the physical properties can differ; one isotope of an element may be radioactive while another is stable. Isotopes that are radioactive (nucleus decay) are called radioisotopes.

- D** For calculations involving nuclei (and other small particles), it is often convenient to use a mass unit that is small. The atomic mass unit u is defined as one-twelfth of the mass of the carbon-12 atom.

From the definition above,

$$\begin{aligned} 1\ u &= \frac{1}{12} \left(\frac{\text{mass of 1 mole of carbon-12}}{\text{avogadro's number}} \right) \\ &= \frac{1}{12} \left(\frac{0.012\ \text{kg}}{6.02 \times 10^{23}} \right) \\ &= 1.661130 \times 10^{-27} \\ &= 1.66 \times 10^{-27}\ \text{kg (data sheet)} \end{aligned}$$

By experiment, $1\ u = 1.660\ 566 \times 10^{-27}\ \text{kg}$

Examples:

Proton: $m_p = 1.007276\ u$ (data sheet: $m_p = 1.67 \times 10^{-27}\ \text{kg}$)

Electron: $m_e = 0.000548799\ u$ (data sheet: $m_e = 9.11 \times 10^{-31}\ \text{kg}$)

You will be given the masses of nuclei in terms of atomic mass unit. The masses can be given to 6 or more sig. fig. as nuclear calculations involve very small differences in mass.

Example 1.3 (Understanding nuclides)

Which two nuclei contain the same number of neutrons?

- A. $^{12}_6\text{C}$ and $^{14}_6\text{C}$
- B. $^{16}_7\text{N}$ and $^{15}_8\text{O}$
- C. $^{23}_{11}\text{Na}$ and $^{24}_{12}\text{Mg}$
- D. $^{32}_{14}\text{Si}$ and $^{32}_{15}\text{P}$

C

How is energy related to mass?

2. Mass–Energy Equivalence and Nuclear Stability

2.1 Energy and Mass

2.1.1 Einstein's Mass-Energy Equation

In 1905, Einstein showed from his Special Theory of Relativity that mass m and energy E can be changed from one to the other, i.e. energy and mass are equivalent. This relationship is given by:

$$E = mc^2$$

where

c : speed of light in vacuum, $c = 3.00 \times 10^8 \text{ m s}^{-1}$

Given the rest mass of a particle (its mass when it is stationary), we can use this equation to calculate the rest mass energy.

Generally, we are concerned with the changes in mass owing to changes in energy hence the equation becomes

$$\Delta E = \Delta mc^2$$

1. When energy is supplied to a system, its mass increases.
2. When energy is released from a system, its mass decreases.

Everyday examples of energy gain are much too small to produce detectable change in mass. The mass is therefore assumed to be constant.

In nuclear processes involving subatomic particles, quantities of energy released are of the order of megaelectronvolts (MeV), producing significant changes in masses of the particles.

Example 2.1 (Converting mass to energy)

Show that 1 u has an energy of 934 MeV.

Solution

From the data sheet, 1 $u = 1.66 \times 10^{-27}$ kg

1 eV corresponds to the kinetic energy gained by a particle of charge e when accelerated by a potential difference of 1 V.

$$1 \text{ eV} = (1.60 \times 10^{-19} \text{ C}) (1 \text{ V}) = 1.60 \times 10^{-19} \text{ J}$$

Use $E = mc^2$ to convert 1 u to energy and express in terms of electron-volt.

$$\begin{aligned} E &= mc^2 \\ &= (1.66 \times 10^{-27}) (3.00 \times 10^8)^2 = 1.494 \times 10^{-10} \text{ J} \end{aligned}$$

$$\begin{aligned} \text{Since } 1.60 \times 10^{-19} \text{ J} &= 1 \text{ eV,} \\ 1.494 \times 10^{-10} \text{ J} &= (1.494 \times 10^{-10}) / (1.60 \times 10^{-19}) \\ &= 933.8 \times 10^6 \text{ eV} \\ &= 934 \text{ MeV (3 sf)} \end{aligned}$$

Note: 1 u of mass is very small but the amount of energy generated is very large. In nuclear physics, because the amount of energy that can be generated from a very small mass is so great, we need to specify the masses of the nuclei involved in nuclear reactions to great precision.

2.2 Mass Defect and Binding Energy

2.2.1 The Nuclear Force

The force that keeps electrons in an atom within the space surrounding the nucleus is the electrostatic (Coulomb) force of attraction between positively charged nucleus and the negatively charged electron.

The force that binds protons and neutrons together in the nucleus, despite of the electrostatic force of repulsion of the protons, is known as the strong nuclear force.

Here are some of its characteristics:

1. It does not depend on charge; neutrons as well as protons are bound, and the forces associated with the proton-proton, proton-neutron and neutron-neutron interactions are the same.
2. It is a very short range attractive force, of the order of nuclear dimensions, that is 10^{-15} m. If not, the nucleus would grow by pulling in additional protons and neutrons. But within its range, the nuclear force is much stronger than electric forces. Otherwise, the nucleus could never be stable.

2.2.2 Mass Defect

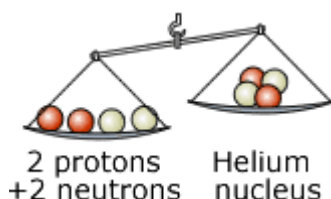
The nucleons in a nucleus are bounded together by the strong nuclear force. To break apart the nucleus, a minimum amount of energy is required to separate the nucleus into its individual nucleons.

(nucleus) + minimum amount of energy to separate nucleus $\rightarrow$ (individual nucleons)

Since energy is added to the nucleus to break it apart, the mass of the individual nucleons is more than the mass of the nucleus. The difference in these two masses is known as the mass defect.



Mass defect is the difference between the sum of the mass individual nucleons that makes up the nucleus and mass of the nucleus itself.



Mass defect = mass of nucleons – mass of nucleus

$$\Delta m = Z(m_p) + N(m_n) - (m_{\text{nucleus}})$$

where Z = proton number and N = neutron number

2.2.3 Binding Energy



Binding energy is the minimum external energy required to completely separate all the neutrons and protons of a nucleus to infinity.

The binding energy is also the energy that is released when the nucleons bind together to form the nucleus.

We can calculate the binding energy using

$$\text{binding energy} = (\text{mass defect}) c^2$$

Note: Data tables in books sometimes give atomic masses rather than nuclear masses, and it is useful to distinguish the mass defect of an atom as:

mass defect of an **atom** = mass of nucleons and electrons – mass of **atom** (i.e. atomic mass)

This contrasts with the mass defect of a nucleus as shared previously and shown below:

mass defect of a **nucleus** = mass of nucleons – mass of **nucleus** (i.e. nuclear mass)

Example 2.2 (Calculating mass defect)

Calculate the mass defect of a ${}^{40}_{20}\text{Ca}$ nucleus of mass 39.95159 u .
[mass of a proton = 1.00728 u ; mass of a neutron = 1.00867 u]

Solution

The nucleus has 20 protons and 20 neutrons.

$$\begin{aligned} \text{Mass defect} &= \text{mass of nucleons} - \text{mass of nucleus} \\ &= Z(m_p) + N(m_n) - (m_{\text{nucleus}}) \end{aligned}$$

$$\begin{aligned} \text{Mass defect} &= (20 \times 1.00728 \text{ u}) + (20 \times 1.00867 \text{ u}) - 39.95159 \text{ u} \\ &= 0.36741 \text{ u} \end{aligned}$$

Example 2.3 (Understanding binding energy)

The mass of a nucleus is X . The total mass of its constituent protons and neutrons is Y .

What is the binding energy of the nucleus?

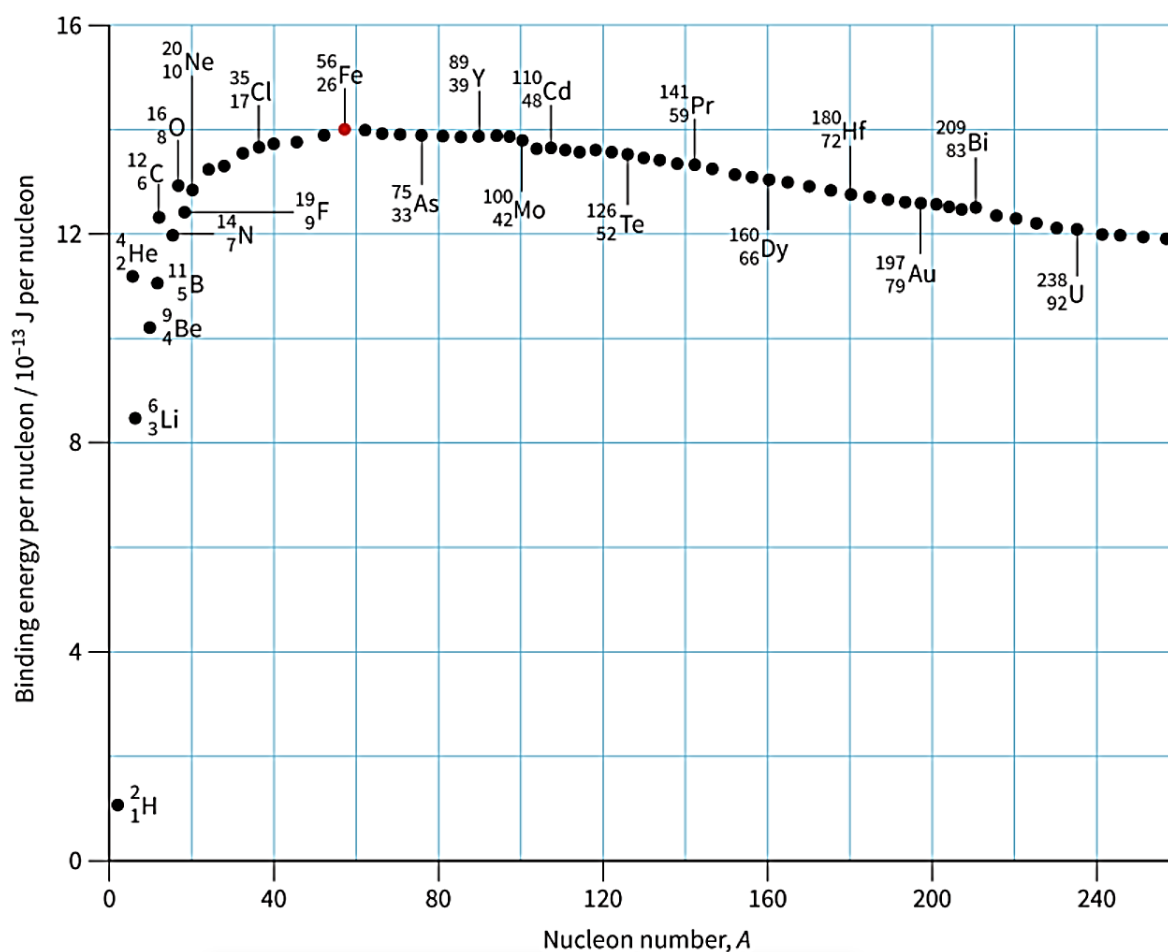
- A. $X - Y$ B. $Y - X$ C. $(X - Y) c^2$ D. $(Y - X) c^2$

D

2.2.4 Binding Energy per Nucleon and Stability of a Nucleus

A useful measure of the stability of a nucleus is its binding energy per nucleon, since this represents the minimum average energy which needs to be supplied to remove a nucleon.

The graph below shows the energy per nucleon plotted against mass number, for all the different isotopes of all the elements. The higher the value of the binding energy per nucleon, the more energy per nucleon would be needed to split the nucleus into its separate constituent nucleons. Therefore, the nucleus is said to be more stable.



The general trend is for light nuclei to have low binding energies per nucleon. Note, however, that helium has a much higher binding energy per nucleon than its place in the periodic table suggests. This means it is very stable.

The nuclides of intermediate mass numbers have the largest values of binding energy per nucleon. The binding energy to remove a nucleon for nuclei above mass number 40 does not vary as much.

The greatest value of binding energy per nucleon is found for $^{56}_{26}\text{Fe}$. This isotope of iron requires the most energy per nucleon to separate into its nucleons. It is the most stable isotope in nature.

There is a very delicate balance between the strong forces that act between adjacent nucleons and the electrostatic forces that act between the protons and this determines how stable a particular nucleus is. There are about 260 stable nuclei; hundreds of others have been observed, but are unstable.

Example 2.4 (Understanding binding energy per nucleon)

The mass of tritium ${}^3_1\text{H}$, an isotope of hydrogen is 3.0160 u .
($m_n = 1.00867\text{ u}$, $m_p = 1.00728\text{ u}$, $m_e = 0.00054880\text{ u}$)

- (a) Calculate the binding energy of this atom.
(b) Hence find the binding energy per nucleon of this atom.

Solution

Binding Energy of atom = $[Z(m_p) + N(m_n) + Z(m_e) - (m_{\text{atom}})] \times c^2$

$$\begin{aligned} \text{(a) } BE &= [1(1.00728) + 2(1.00867) + 1(0.00054880) - (3.0160)](1.66 \times 10^{-27})(3.00 \times 10^8)^2 \\ &= 1.37 \times 10^{-12} \text{ J} \end{aligned}$$

$$\begin{aligned} \text{(b) } BE \text{ per nucleon} &= BE / \text{no. of nucleons} \\ &= 1.37 \times 10^{-12} / 3 \\ &= 4.6 \times 10^{-13} \text{ J} \end{aligned}$$

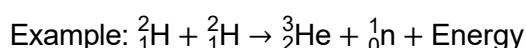
How do nuclei react?

3. Energy from Nuclear Processes

3.1 Nuclear Reactions

3.1.1 Simple Nuclear Reactions

Nuclear reactions can be represented by the following example:



3.1.2 Conservation Laws in Nuclear Processes

(a) Conservation of proton number

Sum of the atomic numbers of the nuclides after reaction is equal to the sum of the atomic numbers of nuclides before reaction.

$$\sum Z_f = \sum Z_i$$

(b) Conservation of nucleon number

Sum of the mass numbers of the nuclides after reaction is equal to the sum of the mass numbers of the nuclides before reaction.

$$\sum A_f = \sum A_i$$

(c) Conservation of mass-energy

For an isolated system, the total mass-energy of the system remains constant.

For example, in the reaction: ${}^2_1\text{H} + {}^2_1\text{H} \rightarrow {}^3_2\text{He} + {}^1_0\text{n} + \text{Energy}$

Expressing the masses in terms of its energy equivalence,

$$(\text{Mass of } {}^2_1\text{H} + \text{Mass of } {}^2_1\text{H}) c^2 = (\text{Mass of } {}^3_2\text{He} + \text{Mass of } {}^1_0\text{n}) c^2 + \text{Energy}$$

$$\text{Energy} = [(\text{Mass of } {}^2_1\text{H} + \text{Mass of } {}^2_1\text{H}) - (\text{Mass of } {}^3_2\text{He} + \text{Mass of } {}^1_0\text{n})] c^2$$

Points to note:

- (i) For a nuclear reaction to take place spontaneously, the total mass of the products must be smaller than the total mass of the reactants. The difference in mass will result in energy being given off as kinetic energy of products and/or other forms.
- (ii) If the total mass of the products is greater than the total mass of the reactants, then energy must be supplied for the reaction to occur.

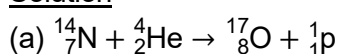
Example 3.1 (Applying conservation of mass-energy - mass gain)

A nitrogen nucleus ${}^{14}_7\text{N}$, bombarded with an α -particle of a certain energy, transmutes to an oxygen nucleus ${}^{17}_8\text{O}$ and a proton.

- (a) Write an equation for this nuclear reaction, showing the mass numbers and the atomic numbers of the particles involved.
- (b) Find the minimum energy of the α -particle to make this reaction occur.

$$[\text{mass of } {}^{14}_7\text{N} = 2.32530 \times 10^{-26} \text{ kg, mass of } {}^{17}_8\text{O} = 2.82282 \times 10^{-26} \text{ kg, } m_{\text{proton}} = 0.16735 \times 10^{-26} \text{ kg, } m_{\alpha} = 0.66466 \times 10^{-26} \text{ kg}]$$

Solution



(b) $(\text{mass of } {}^{14}_7\text{N} + \text{mass of } {}^4_2\text{He}) c^2 + \text{Energy of } \alpha\text{-particle} = (\text{mass of } {}^{17}_8\text{O} + \text{mass of } {}^1_1\text{p}) c^2$

$$\begin{aligned} \text{Energy of } \alpha\text{-particle} &= [(\text{mass of } {}^{17}_8\text{O} + \text{mass of } {}^1_1\text{p}) - (\text{mass of } {}^{14}_7\text{N} + \text{mass of } {}^4_2\text{He})] \times c^2 \\ &= [(2.82282 \times 10^{-26} + 0.16735 \times 10^{-26}) - (2.32530 \times 10^{-26} + 0.66466 \times 10^{-26})] \\ &\quad \times (3.00 \times 10^8)^2 \\ &= 1.89 \times 10^{-13} \text{ J} \end{aligned}$$

Note that the actual minimum amount of energy required for the reaction to occur must be slightly greater than this. This is to ensure that the law of conservation of linear momentum is obeyed. The products (oxygen or/and proton) would have some kinetic energy.

Example 3.2 (Applying conservation of mass-energy – mass loss)

Consider the following nuclear reaction: ${}^2_1\text{H} + {}^{14}_7\text{N} \rightarrow {}^{12}_6\text{C} + {}^4_2\text{He}$
 [mass of ${}^2_1\text{H} = 2.014102 \text{ u}$; mass of ${}^{14}_7\text{N} = 14.003074 \text{ u}$; mass of ${}^{12}_6\text{C} = 12.000000 \text{ u}$;
 mass of ${}^4_2\text{He} = 4.002602 \text{ u}$]

- (a) What is the energy lost by the system in MeV?
- (b) What is this energy lost manifested as?

Solution

(a) $(\text{mass of } {}^2_1\text{H} + \text{mass of } {}^{14}_7\text{N}) c^2 = (\text{mass of } {}^{12}_6\text{C} + \text{mass of } {}^4_2\text{He}) c^2 + \text{Energy}$

$$\begin{aligned} \text{Energy} &= [(\text{mass of } {}^2_1\text{H} + \text{mass of } {}^{14}_7\text{N}) - (\text{mass of } {}^{12}_6\text{C} + \text{mass of } {}^4_2\text{He})] \times c^2 \\ &= [(2.014102 + 14.003074) - (12.000000 + 4.002602)] \times 1.66 \times 10^{-27} \times (3.00 \times 10^8)^2 \\ &= 2.18 \times 10^{-12} \text{ J} \\ &= 13.6 \text{ MeV} \end{aligned}$$

- (b) Kinetic energy of the carbon and helium nuclei.

3.2 Nuclear Fission and Fusion

3.2.1 Nuclear Fission



Nuclear Fission is the disintegration of a massive nucleus into smaller fragments of comparable masses with the release of a large amount of energy as the total mass of the daughter products is lower than the parent nuclei.

Example: ${}_{92}^{235}\text{U} + {}_0^1\text{n} \rightarrow {}_{92}^{236}\text{U} \rightarrow {}_{57}^{148}\text{La} + {}_{35}^{85}\text{Br} + 3 {}_0^1\text{n} + \text{energy}$

There are few important points to note in problem solving:

Point 1:

The total masses of the products are lower than the total mass of the reactants. This loss in mass results in a release of energy in the form of kinetic energy of the products.

$$\text{Energy released} = (\text{mass of reactants}) c^2 - (\text{mass of products}) c^2$$

Point 2:

Referring to the binding energy per nucleon graph, fission of any heavy nuclei (mass number more than 60) to form nuclei that have smaller mass number is likely to release energy.

In any fission reaction, the reactants are on the right side of graph and the products formed are in the region towards the peak of the graph. The products have a greater total binding energy per nucleon which means they are more stable.

The energy released can also be calculated using

$$\text{Energy released} = \text{Binding energies of products} - \text{Binding energies of reactants}$$

We can think of it as energy absorbed when the reactants break apart is less than the energy released when the products are formed.

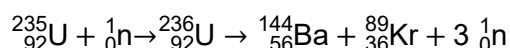
Note: Products such as neutrons do not have binding energies.

Case Study: Fission of Uranium

Both the common isotope (99.3%) $^{238}_{92}\text{U}$ and the uncommon isotope (0.7%) $^{235}_{92}\text{U}$ (as well as several other nuclides) can be easily split by neutron bombardment: of $^{235}_{92}\text{U}$ by slow neutrons but $^{238}_{92}\text{U}$ only by neutrons with a minimum of about 1 MeV of energy. Fission resulting from neutron absorption is called *induced fission*. Some nuclides can also undergo *spontaneous fission* without initial neutron absorption, but this is quite rare.

When $^{235}_{92}\text{U}$ absorbs a neutron, the resulting nuclide $^{236}_{92}\text{U}$ is in a highly excited state and splits into two fragments almost instantaneously. Strictly speaking, it is $^{236}_{92}\text{U}$, not $^{235}_{92}\text{U}$ that undergoes fission, but it is usual to speak of the fission of $^{235}_{92}\text{U}$.

A typical fission reaction:



Example 3.3 (Energy released in nuclear fission)

Bombardment of $^{235}_{92}\text{U}$ by slow neutrons can result in the capture of a neutron and formation of $^{236}_{92}\text{U}$ which is unstable and undergoes fission.

Many different pairs of nuclei can be produced by the fission of $^{236}_{92}\text{U}$, but over 95% of the cases, mass number of the heavier fragment is between 130 and 149.

One possible reaction is : $^{235}_{92}\text{U} + {}^1_0\text{n} \rightarrow ^{236}_{92}\text{U} \rightarrow ^{148}_{57}\text{La} + ^{85}_{35}\text{Br} + 3 {}^1_0\text{n} + \text{energy}$

Given the following data,

rest mass of $^{235}_{92}\text{U}$ is 235.1 u , rest mass of ${}^1_0\text{n}$ is 1.009 u

rest mass of $^{148}_{57}\text{La}$ is 148.0 u , rest mass of $^{85}_{35}\text{Br}$ is 84.9 u

(a) Calculate the energy released per atom of uranium fissioned in MeV.

(b) Calculate the total energy released when 1 kg of uranium is used.

Solution

(a) Energy released per reaction

$$\begin{aligned} &= [(\text{mass of } ^{235}_{92}\text{U} + \text{mass of } {}^1_0\text{n}) - (\text{mass of } ^{148}_{57}\text{La} + \text{mass of } ^{85}_{35}\text{Br} + \text{mass of } 3 {}^1_0\text{n})] \times c^2 \\ &= \{[235.1 + 1.009] - [148.0 + 84.9 + 3(1.009)]\} \times (1.66 \times 10^{-27}) \times (3.00 \times 10^8)^2 \\ &= 2.72 \times 10^{-11} \text{ J} \\ &= 169.94 \text{ MeV} \end{aligned}$$

$$\begin{aligned} \text{(b) Total energy released} &= (1000/235) \times 6.02 \times 10^{23} \times 169.94 \\ &= 4.35 \times 10^{26} \text{ MeV} \end{aligned}$$

Alternate method (Using binding energy)

Energy released

$$= [(\text{BE per nucleon of } ^{148}_{57}\text{La} \times 148) + (\text{BE per nucleon of } ^{85}_{35}\text{Br} \times 85)] - (\text{BE per nucleon of } ^{235}_{92}\text{U} \times 235)$$

[Note: We do not associate binding energy for the neutron. The value of BE per nucleon would have to be given in the question.]



Nature of Science Moment – From Nuclear Reactions to National Decisions

You have learned how nuclear fission releases a tremendous amount of energy from the nucleus of an atom. This video places that same physics in a real-world context by exploring whether nuclear energy — including newer technologies such as small modular reactors — could one day play a role in Singapore's energy mix.

As you watch, pay attention to how scientific understanding is applied. Notice how knowledge of fission is considered alongside safety studies, technological constraints, and long-term planning. This reflects an important feature of the nature of science: scientific ideas inform decisions, but they are interpreted within broader practical and societal contexts.

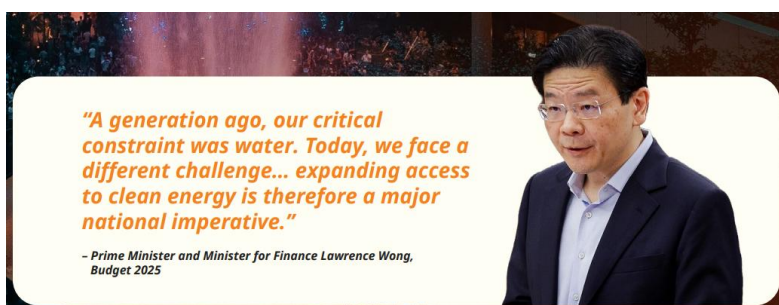
As you reflect, consider:

- What kinds of evidence would be needed to assess the feasibility of small modular reactors in Singapore?
- How do uncertainty and risk shape scientific advice?
- How do scientific findings interact with economic, social, and policy considerations?

This video invites you to see science not only as content to master, but as a way of thinking that helps societies make informed choices about the future.



Watch this video to discover how nuclear energy enters real-world decision-making in Singapore.



Refer to this 16-page Nuclear Energy Background Paper published in October 2025 if you wish to find out more.

[Building Singapore's Capabilities to Assess Nuclear Energy](#)

3.2.2 Nuclear Fusion



Nuclear Fusion is the combining or fusing of two light nuclei to produce a heavier nucleus with the release of a large amount of energy as the nucleus formed has a lower total mass than that of the parent nuclei.

Point 1:

The total masses of the products are lower than the total mass of the reactants. This loss in mass results in a release of energy in the form of kinetic energy of the products.

$$\text{Energy released} = (\text{mass of reactants}) c^2 - (\text{mass of products}) c^2$$

Point 2:

Referring to the binding energy per nucleon graph, fusion of any two light nuclei that have mass number up to 60 is likely to release energy.

In any fusion reaction, the product nuclei that are formed are in the region towards the peak of the graph. The nuclei produced from fusion have a greater total binding energy per nucleon. The reactants are on the left side of graph.

The energy released can also be calculated using

$$\text{Energy released} = \text{Binding energies of products} - \text{Binding energies of reactants}$$

Note: Products such as neutrons do not have binding energies.

Example 3.4 (Energy released in nuclear fusion)

Fusion of two nuclei of deuterium, ${}^2_1\text{H}$ results in a helium nucleus ${}^3_2\text{He}$.

Equation: ${}^2_1\text{H} + {}^2_1\text{H} \rightarrow {}^3_2\text{He} + {}^1_0\text{n}$

Given: mass of deuterium = 2.015 u, mass of helium nucleus = 3.017 u and mass of neutron = 1.009 u

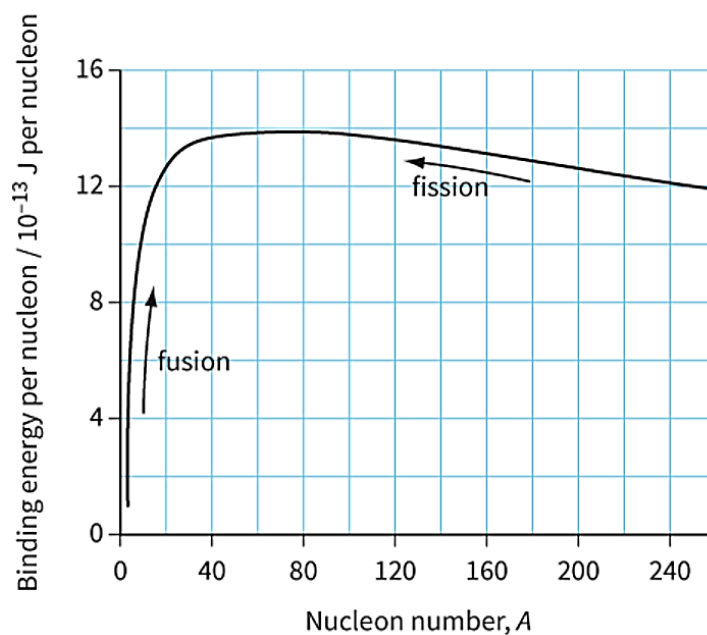
Find the energy released by fusion of 1 kg of deuterium.

Solution

$$(\text{mass of } {}^2_1\text{H} + \text{mass of } {}^2_1\text{H}) c^2 = (\text{mass of } {}^3_2\text{He} + \text{mass of } {}^1_0\text{n}) c^2 + \text{Energy}$$

$$\begin{aligned} \text{Energy released per reaction} &= [(\text{mass of } {}^2_1\text{H} + \text{mass of } {}^2_1\text{H}) - (\text{mass of } {}^3_2\text{He} + \text{mass of } {}^1_0\text{n})] \times c^2 \\ &= [(2.015 + 2.015) - (3.017 + 1.009)] \times 1.66 \times 10^{-27} \times (3.00 \times 10^8)^2 \\ &= 5.976 \times 10^{-13} \text{ J} \end{aligned}$$

$$\begin{aligned} \text{Total energy released} &= (500 / 2) (6.02 \times 10^{23}) (5.976 \times 10^{-13}) \\ &= 9.0 \times 10^{13} \text{ J} \end{aligned}$$



From the figure above, very small nuclei and very large nuclei are both less stable than nuclei of intermediate sizes.

For nuclear fusion:

- a) Reactant nuclei have smaller mass number (mass number smaller than where the peak occurs).
- b) Product nuclei have mass number approaching the value where the peak occurs (from left side of peak).

For nuclear fission:

- a) Reactant nuclei have larger mass number (mass number larger than where the peak occurs).
- b) Product nuclei have mass number approaching the value where the peak occurs (from right side of peak).



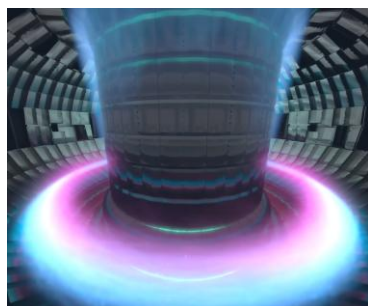
Nature of Science Moment – Controlling a Star in a Doughnut

The video takes you inside **ITER**, the world's most ambitious nuclear fusion project, where scientists aim to reproduce on Earth the process that powers the Sun. At its core is a **doughnut-shaped tokamak**, which uses powerful magnetic fields to confine an extremely hot **plasma**. This plasma is the fusion fuel itself — fast-moving hydrogen nuclei and free electrons — heated to temperatures high enough for nuclei to fuse and release energy.

Fusion is not just a theoretical idea. The challenge lies in **controlling this energetic plasma** without letting it touch the reactor walls, requiring extraordinary engineering precision. Massive superconducting magnets, complex control systems and carefully designed structures must work together to shape, heat and stabilise the plasma long enough for fusion to occur.

ITER's scale shows how modern science often depends on **global collaboration**. Seven major members — the European Union, China, India, Japan, South Korea, Russia and the United States — coordinate construction and share expertise, and in total **dozens more countries contribute through systems, components and research**, making ITER a truly worldwide effort.

As you reflect on the video, consider how scientific ideas are transformed into real experiments, how uncertainty and ingenuity drive innovation, and why some scientific challenges can only be tackled through global cooperation.



Watch this video to discover how ITER is trying to harness nuclear fusion — the power of the Sun — here on Earth. Consider why achieving this takes decades of science, engineering, and global collaboration.

What is radioactive decay?

4. Radioactivity and Background Radiation

4.1 Radioactive Decay



Nature of Science Moment – From Unexpected Observation to Nuclear Theory

In the late 19th century, the belief that atoms were stable was challenged when **Antoine Henri Becquerel** discovered that uranium compounds emitted invisible radiation capable of exposing photographic plates without any external energy source. Building on this unexpected result, **Marie Curie** and **Pierre Curie** showed that radioactivity was independent of chemical or physical changes, implying that it originates from within the atom. Subsequent experiments by **Ernest Rutherford** and others identified three distinct types of nuclear radiation—alpha, beta and gamma rays—illustrating how scientific understanding develops through observation, experimentation and refinement of ideas.

Radioactive decay is a naturally occurring process in which the nucleus of an unstable atom will spontaneously change into a different nuclear configuration by the emission of combinations of alpha particles, beta particles and gamma radiation.

Alpha particles, beta particles and gamma radiation are termed nuclear radiations as they originate in the nucleus of an unstable atom. Nuclear radiation ionises matter as they pass through.

Radioactive decay is a process which is:

(i) Spontaneous



Radioactive decay is **spontaneous** because it is not affected by

- the presence of other nuclei
- chemical reactions or external factors such as temperature and pressure

(ii) Random

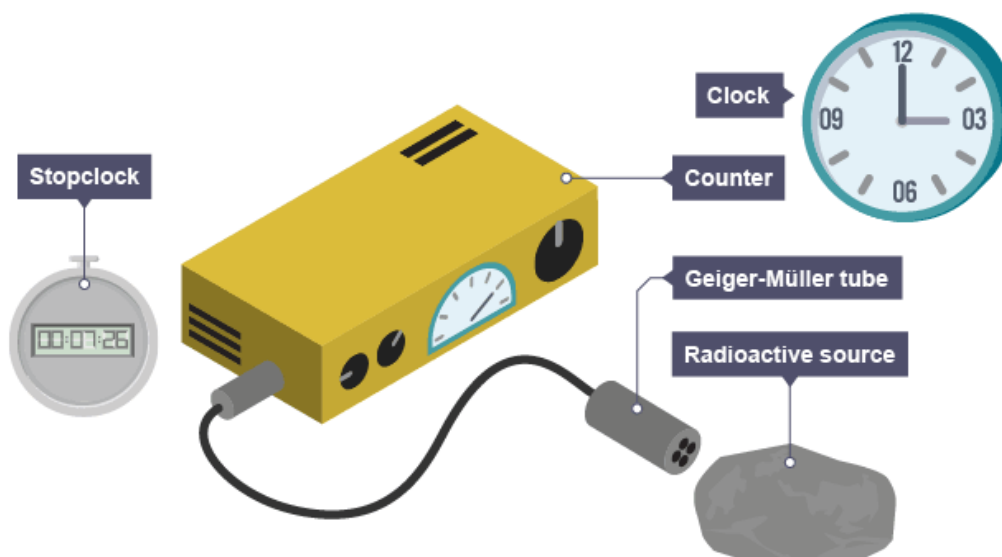


Radioactive decay is **random** because

- it is impossible to predict when a particular nucleus in a sample is going to decay
- each nucleus in a sample has the same chance of decaying per unit time

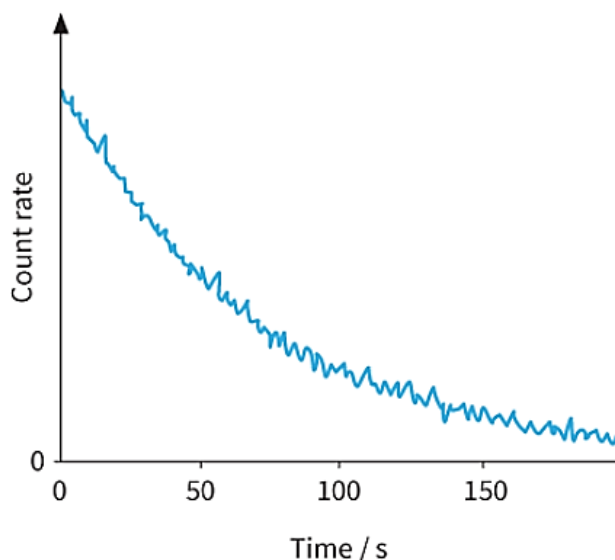
Given a large sample of nuclei, it is probable that in a given time duration, a predictable number of nuclei will decay even if we do not know exactly which particular ones. We say that the nuclide has a constant probability of decay (section 4.1.5) and the sample has a half-life (section 4.1.4).

The instrument to measure radioactivity is the Geiger-Müller (GM) tube. A counter connected to a GM tube measures count rate from a radioactive source.



Each count represents the detection of a single alpha-particle or a beta-particle or a gamma ray photon. The individual counts do not come regularly but clicks in a random irregular manner. We say that radioactive decay is a random and irregular phenomenon. If you try to predict when the next clicks will come, you are unlikely to be right.

The graph below shows count rate against time; the count rate decreases with time as the number of radioactive nuclei that are left decreases. The fluctuations either side of the graph are caused by the randomness of the decay.



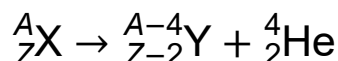
The GM tube cannot detect all of the radiation emitted from the decay of a radioactive sample because some will escape past the GM tube or some may be absorbed within the sample itself. Therefore, a GM tube placed in front a radioactive source only detects a fraction of the activity (section 4.1.7). Furthermore, the count rate is smaller when the GM tube is further from the source. Lastly, count rate due to background radiation must be subtracted from the measured count rate to give the corrected count rate.

4.1.1 Nuclear Radiation (Ionising Radiation from the Nucleus)

A Alpha (α) Decay

When a nucleus emits an α -particle, it is clear that the remaining nucleus will be different from the original.

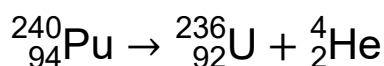
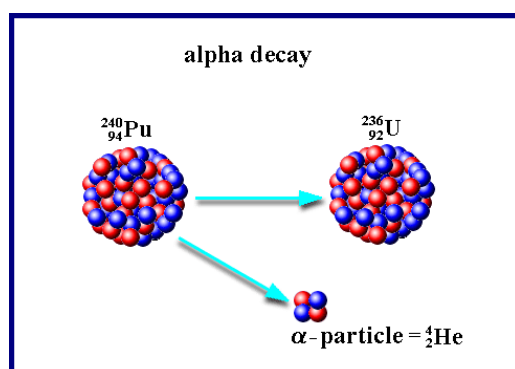
It loses 2 protons and 2 neutrons.



As seen above, the alpha particle is the helium nucleus and it is positively charged. X is known as the parent nucleus and Y is known as the daughter nucleus.

Alpha decay occurs because the strong nuclear force is unable to hold the very large nuclei together. The nucleus has too many protons (ratio of neutrons to protons is low) which cause excessive repulsion. So the atoms attain greater stability by emitting alpha particles.

The alpha radiation is the slowest travelling nuclear radiation among the three types of radiation and highly charged; hence it is not able to travel far in matter as it loses its energy quickly due to its interaction (ionisation) with matter.



An example of α decay¹

B Beta (β) Decay

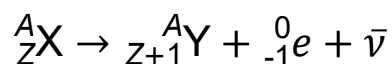
Beta decay is a type of radioactive decay in which a β -particle is emitted. A β -particle can be:

- An electron, referred to as β^- , or
- A positron, referred to as β^+ .

(Note: In the A-Level exam, positron emission is not required. Hence, the term ' β -particle' will be used to refer to the electron and we will study only beta decays involving electrons.)

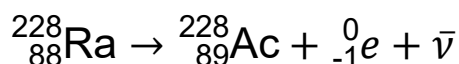
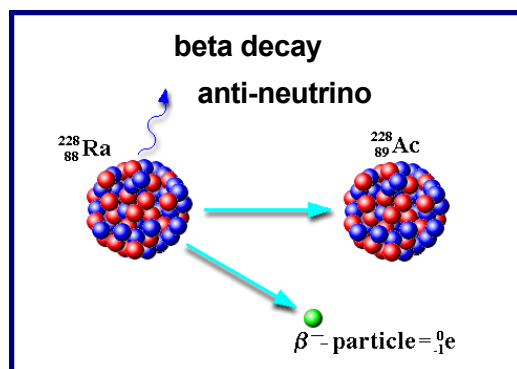
In beta decay, an unstable nucleus decays, converting a neutron into a proton, an electron and an antineutrino. The electron and the antineutrino are emitted. The electron is ejected from the nucleus as a β particle. The antineutrino has no proton or nucleon number.

¹ <http://www.nuceng.ca/igna/radioactivity.htm>



The decay occurs for those nuclei with too high a neutron-proton ratio for stability.

Note that the electron emitted is created within the nucleus and NOT an orbital electron (This process is not the same as ionisation, where an orbital electron is freed from an atom).

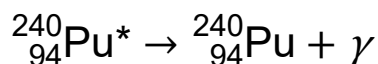
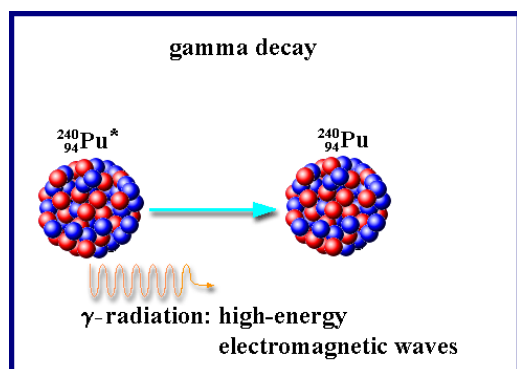
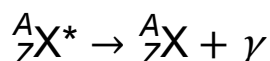


An example of β decay

C Gamma (γ) Ray Emission

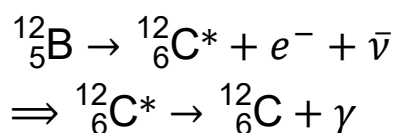
The gamma ray is a high-energy electromagnetic wave that is emitted from the nucleus.

A gamma ray emission can happen after an alpha decay or a beta decay because the daughter nucleus is left in an excited state which is unstable. It stabilises by emitting gamma photon(s) thus losing its excess energy. The excited nucleus is denoted by an asterisk *.



An example of γ emission

The following example shows a sequence of events of a typical gamma emission process:

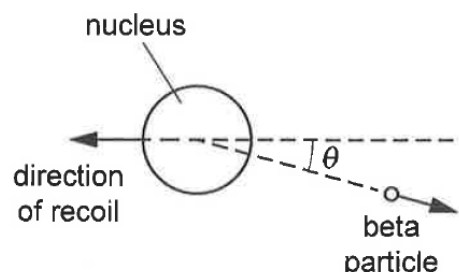


4.1.2 Neutrino (Italian word for “little, neutral one”)

Momentum Argument

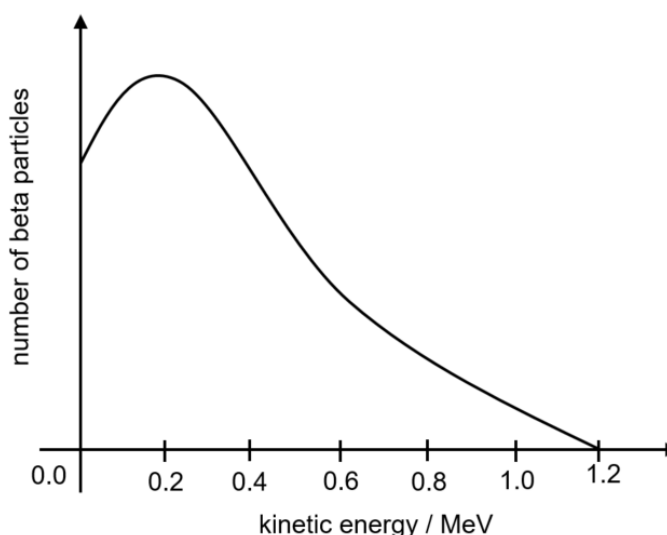
We can always study the beta decay in the frame of reference of the parent nuclide thus we can take it that the parent nuclide is stationary initially. Before the decay, the total momentum of the system is zero as the nucleus is stationary.

After the decay, the total momentum of the daughter nucleus and the beta particle should be zero to conserve total linear momentum. However, it was observed that the beta particle is emitted at an angle from the horizontal and there is a net linear momentum in the vertical direction. Hence, there must be another particle emitted with a vertical component of momentum in the opposite direction to conserve linear momentum.



Energy Argument

In the study of beta decay, when a parent nuclide decays into its daughter nucleus and the beta particle, we can determine the energy of the beta particle produced using the conservation of mass-energy. Since the calculation of the beta particle's energy depends only on the masses of the particles involved and the masses of the nuclei and beta particle are constant, the kinetic energy and hence speed of the beta particle produced should be the same each time we conduct the same beta decay experiment. However, this was not what was observed experimentally as shown in the figure on the right.



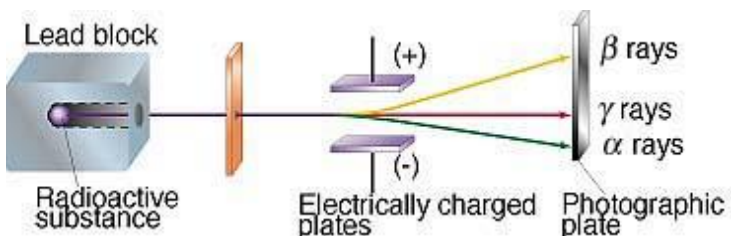
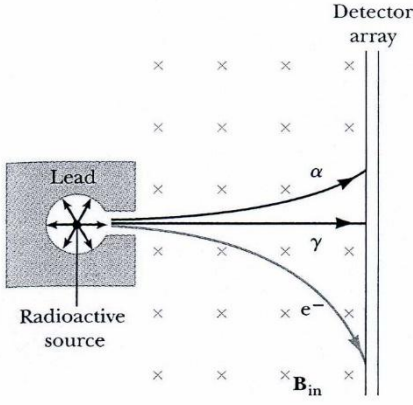
In this decay of bismuth-210 into polonium-210, the kinetic energy of the beta particles is theoretically calculated to be 1.2 MeV only. However, the beta particles are emitted with a continuous spectrum (range) of energies. The speeds of beta particles range up to 90% of the speed of light. For a range of kinetic energies to be possible, the particles from the nuclear decay cannot be just the beta-particle and the recoiling daughter nucleus. There must be a third particle involved and it must be taking away a proportion of the energy that would have gone to the beta particle. And this particle must be neutral since the presence of the beta particle already balances the charge in the nuclear equation.

This third particle is an antineutrino, the antiparticle of a neutrino (Symbol: $\bar{\nu}$). Both the neutrino and the antineutrino have zero charge and very small mass and therefore produce very little observable effect due to its weak interaction when passing through matter. (See Review Question 1 for more details.)

Fact: Each second, more than 100 trillion neutrinos pass through your body. Almost all of these neutrinos were formed by nuclear reactions in the core of the Sun.

4.1.3 Summary of Nature & Properties of Nuclear Radiation

(Values given are rough figures)

Property	Alpha (α)	Beta (β)	Gamma (γ)
Nature	${}^4_2\text{He}$ nucleus mass $4.0015\,u$	${}^0_{-1}\text{e}$ (electron) $1/1860\,u$	EM waves/Photon $\lambda \approx 10^{-11}\,\text{m}$
Charge	$+2e$	$-e$	0
Speed	$0.1\,c$	$0.3 - 0.9\,c$	c
Ionisation power (ion-pairs per mm of air)	Intense (producing 10^4 ions per mm of air)	Less intense (producing 10^2 ions per mm of air)	Weak (usually secondary ionisation)
Penetrating power	Easily stopped by - 0.1 mm paper - 0.01 mm Al foil - Skin	Stopped by a few mm of Al plate. Penetrates about 1 cm into the body.	Intensity reduced by lead block. Penetrates right through the body.
Range in air	About 5 cm	About 30 – 50 cm	Great distance
Energy	4 to 10 MeV depending on element. For a given element, it is mono-energetic.	Continuous energy spectrum (range of energies) 0.025 to 3.2 MeV	Gamma rays are photons, each photon with energy of 10 keV to a few MeV.
Deflection by an Electric Field			
Deflection by a Magnetic Field			



Watch this video to compare the penetrating power of α , β and γ radiation.

Example 4.1 (Properties of radioactive radiation)

A student conducts an experiment using an α -particle source.

When considering safety precautions, what can be assumed to be the maximum range of α -particles in air?

- A. between 0 and 5 mm
- B. between 5 mm and 200 mm
- C. between 200 mm and 500 mm
- D. between 500 mm and 1000 mm

B

Example 4.2 (Changes to nucleus in terms of mass and atomic number after decay)

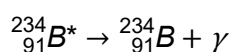
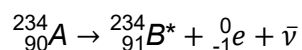
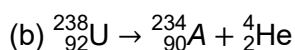
- (a) Give a summary of the changes that occur within the nucleus when they emit (i) α -particle, (ii) β particle and (iii) γ -radiation.
- (b) The uranium nucleus ${}^{238}_{92}\text{U}$ undergoes successive decays, emitting respectively an α -particle, a β -particle and a γ -photon. Determine the atomic number and mass number of the resulting nucleus.

Solution

(a) (i) 2 neutrons and 2 protons form a helium nucleus and is emitted.

(ii) Assuming β^- decay, 1 neutron forms 1 proton, 1 electron and 1 anti-neutrino. The electron and anti-neutrino is emitted.

(iii) Nucleus goes from an excited nuclear state to a stable nuclear state.



4.1.4 Half-life



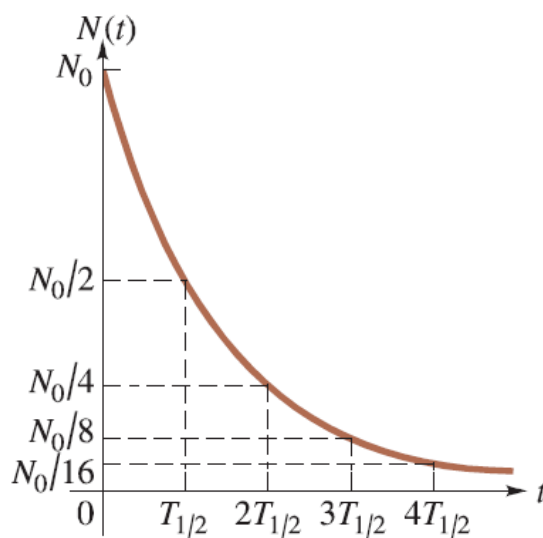
The **half-life**, $t_{1/2}$, of a radioactive nuclide is the mean time taken for a quantity x to reduce to half its initial value where x represents either the activity, number of undecayed particles or received count rate.

Consider a radioactive sample with half-life, $t_{1/2} = 10$ years

Time, t	Number of radioactive nuclei present, N , equals to	Equation
0	N_0	$N = \frac{N_0}{2^0}$
10 yrs (1 half-life)	$\frac{N_0}{2}$	$N = \frac{N_0}{2^1}$
20 yrs (2 half-life)	$\frac{N_0}{4}$	$N = \frac{N_0}{2^2}$
30 yrs (3 half-life)	$\frac{N_0}{8}$	$N = \frac{N_0}{2^3}$

Therefore, we see that after n number of half-lives, the number of radioactive nuclei present, N , in the sample is equal to $\frac{N_0}{2^n}$.

The variation with time of the number of radioactive nuclei left (or parent nuclei) can be represented by a decay curve.



4.1.5 Decay Law

Radioactivity is due to disintegrating nuclei of atoms. The disintegrations obey the statistical law of chance. Thus, although we cannot tell which particular atom is likely to disintegrate next, the number of atoms disintegrating per second, dN/dt , is directly proportional to the number of atoms, N , present at that instant.

For a large number of nuclei of a radioactive element, the decay law states that the rate of decay is proportional to the number of undecayed parent nuclei present.

If there are N parent nuclei (parent nuclei) present at time t ,

$$\frac{dN}{dt} \propto N$$

$$\frac{dN}{dt} = -\lambda N$$

where $\frac{dN}{dt}$ is the rate at which the number of parent nuclei in the sample is changing.



The **decay constant** λ represents the probability per unit time that a nucleus will undergo decay.

SI Unit of λ : s^{-1}

Note: $\frac{dN}{dt}$ is a negative value as it is the gradient of the graph in Section 4.1.4.

If there are N_0 active nuclei at time $t = 0$, and after a time t , the number of active nuclei decreases to N .

$$\int \frac{1}{N} dN = \int -\lambda dt$$

$$\ln N = -\lambda t + C$$

Since $N = N_0$ at $t = 0$,

$$\ln N_0 = -\lambda(0) + C$$

$$C = \ln N_0$$

Hence,

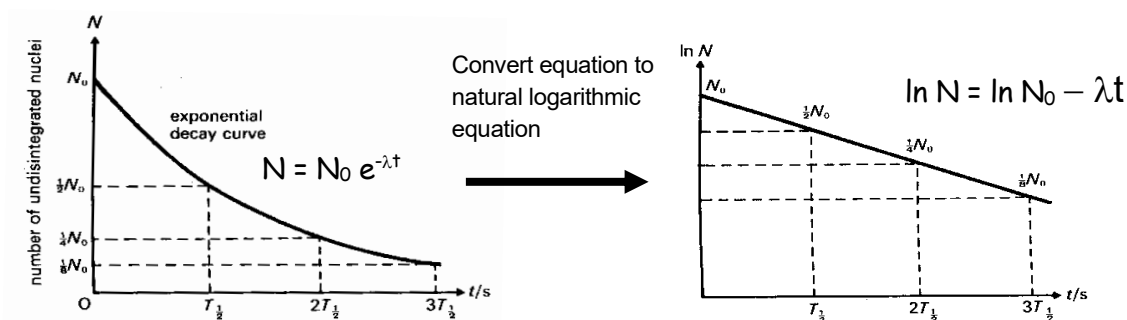
$$\ln N = -\lambda t + \ln N_0$$

$$\ln \left(\frac{N}{N_0} \right) = -\lambda t$$

$$N = N_0 e^{-\lambda t}$$

The number of parent nuclei (N) remaining decreases with time exponentially.

Graphical Representation of the Decay Law



4.1.6 Decay Constant and Half-life

Since t is represented by $t_{1/2}$ when $N = N_0/2$, using the exponential equation,

$$\frac{N_0}{2} = N_0 e^{-\lambda t_{1/2}}$$

$$t_{1/2} = \frac{\ln 2}{\lambda} \text{ or } \lambda = \frac{\ln 2}{t_{1/2}}$$

4.1.7 Activity and Count Rate



The **activity** A of a radioactive source is the number of decays (or disintegrations) per unit time.

$$A = -\frac{dN}{dt}$$

From the decay law,

$$A = \lambda N$$

SI Unit of activity, A : becquerel (Bq), $1 \text{ Bq} \equiv 1 \text{ decay s}^{-1}$

This implies that $A_0 = \lambda N_0$ where A_0 represents the initial rate of decay and N_0 the original number of parent nuclei.

Additionally, from $N = N_0 e^{-\lambda t}$,

$$A = A_0 e^{-\lambda t}$$

Example 4.3 (Calculating decay constant and activity)

The radioactive isotope ^{57}Co is a β^- emitter with a half-life of 272 days.

- (a) Find the decay constant.
 - (b) If you have a radiation source containing ^{57}Co , with an activity of $1.00\ \mu\text{Ci}$, how many radioactive nuclei does it contain?
 - (c) What will be the activity of your source after one year?
- [$1\ \text{Ci} = 3.7 \times 10^{10}\ \text{Bq}$]

Solution

(a) Decay constant = $\ln 2 / (272 \times 24 \times 60 \times 60)$
 $= 2.95 \times 10^{-8}\ \text{s}^{-1}$

(b) $N = A / \lambda$
 $= 3.7 \times 10^4 / 2.95 \times 10^{-8}$
 $= 1.25 \times 10^{12}\ \text{atoms}$

(c) $A = (3.7 \times 10^4) e^{-(2.95 \times 10^{-8})(365 \times 24 \times 60 \times 60)}$
 $= 14600\ \text{Bq}\ (3\ \text{s.f.})$

Count Rate

The Geiger-Muller tube is a device for measuring the count rate of a radioactive source. But it only captures a proportion of the radioactive emissions from a sample of radioactive nuclide.

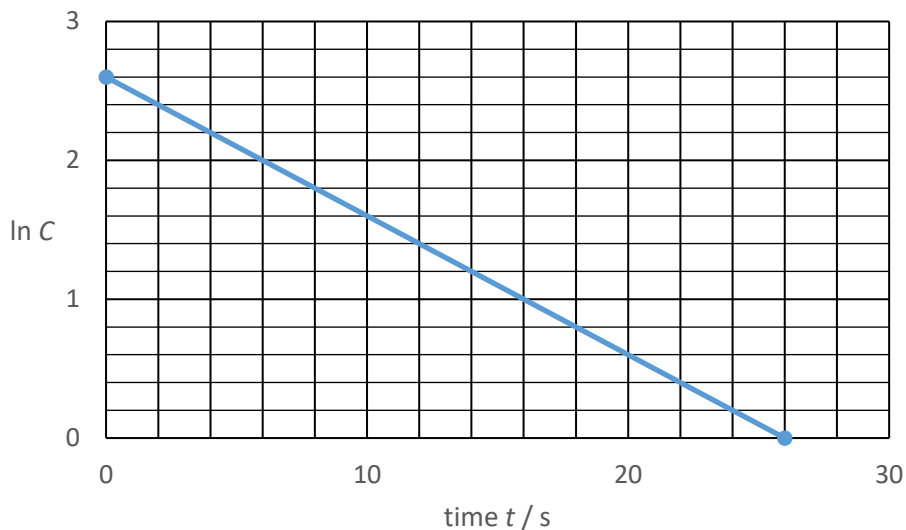
The count rate is a fraction of the activity, i.e. $C \propto A$,

Hence,

$$C = C_0 e^{-\lambda t}$$

Example 4.4

The graph below shows how the count-rate C of a radioactive source as measured by a Geiger counter varies with time t .



What is the relationship between C and t ?

Solution

$$\ln C = m t + c$$

$$m = \text{Gradient} = (0.2 - 2.6) / (24 - 0) = -0.1$$

$$c = 2.6$$

$$\ln C = -0.1 t + 2.6$$

$$C = e^{-0.1t + 2.6} = 13.46374 e^{-0.1t} = 13.5 e^{-0.1t}$$

$$\text{Compare to } C = C_0 e^{-\lambda t}$$

4.1.8 Factors Affecting Count Rate

A Random Nature of Decay

Radioactive decay is random in nature because there is no way to predict which particular nucleus in a radioactive sample will decay next.

In measurements with a counter, we must always make sure that we count a sufficiently large number of particles to allow for the *random fluctuations* in the emission rates.

These differences are not caused by errors, but are a genuine record of the fluctuations in the number of particles received.

B The Background Count

Even without any special radioactive source in the neighbourhood, some background radiation is recorded by any radiation detector.

The background radiation is caused partly by radioactive impurities inevitably present in the apparatus and its surroundings, and partly by cosmic radiation entering the earth's atmosphere from outer space.

Before doing any experiment with a radiation detector, the background radiation level should be measured over a suitable period of time, say 10 minutes. Randomness of the background count rate is expected. Repeat the experiment to obtain the average count rate. This background count rate must be deducted from later measurements made with a radioactive source.

4.2 Background Radiation

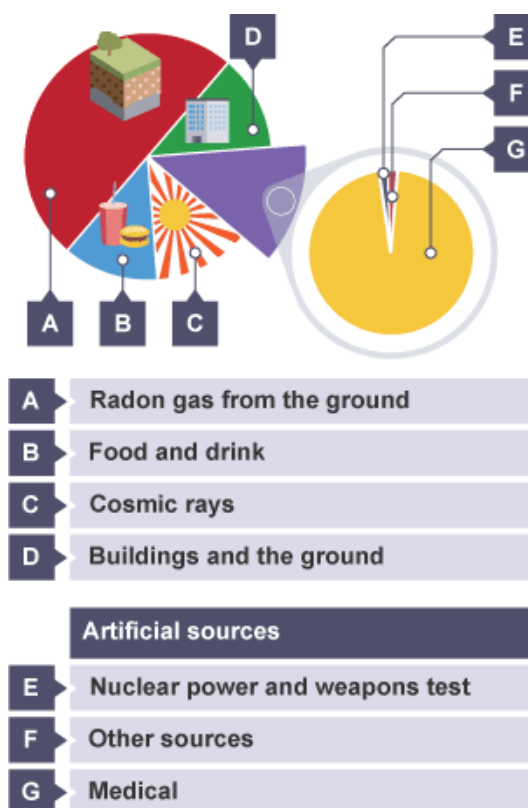
Background radiation is the ionising radiation that is constantly present in the environment.

Sources of background radiation can be natural or artificial.

The pie-chart shows the contribution of various sources of radiation that the average person is exposed to.

Naturally sources account for about 85% of the average background radiation dose. Most of it is from indoor radon gas from the ground.

Artificial sources account for about 15% of the average background radiation dose.



Natural Sources

Cosmic Radiation: radiation that reaches the Earth from space.

Rocks and Soil: some rocks are radioactive and give off radioactive Radon gas.

Radon (^{222}Rn) is an inert colourless, odourless radioactive gas that poses serious health hazard in some areas as it accumulates in houses. Its half-life is 3.82 days. But it is continuously being produced by the decay of ^{226}Ra , which is found in minute quantities in rocks and soil on which some houses are built. The reason ^{222}Rn is hazardous is that it is a gas. It can migrate from the soil into your house through openings in any ground contact floor or wall. If a ^{222}Rn nucleus decays in your lungs, it emits a damaging α -particle and its daughter nucleus ^{218}Po which is chemically inert and is likely to stay in your lungs until it decays, emits another damaging α -particle and so on. Radon is the second leading cause of lung cancer in the U.S., with only smoking causing more lung cancer deaths.

Living Things: plants absorb radioactive materials from the soil and these pass up the food chain.

For most people, natural sources contribute the most to their background radiation dose.

Artificial Sources

Human activity has added to background radiation by creating and using artificial sources of radiation. These include radioactive waste from nuclear power stations, radioactive fallout from nuclear weapon testing and medical x-rays. Nearly all artificial background radiation comes from medical procedures such as receiving x-rays for x-ray photographs.

How does radiation affect us?

5. Applications and Hazards of Radioactivity

Nuclear physics applications are extremely widespread in manufacturing, medicine, and biology. Conversely, radiation can also cause severe damage as they pass through matter by losing energy, breaking molecular bonds and creating ions – hence the term *ionising radiation*. Excessive exposure to radiation can destroy tissues. The degree of damage or extent of application depend on several factors such as the half-life, the penetrating abilities and ionising effects of radioactive emissions. For example, alpha particles cause extensive damage, but penetrate only to a shallow depth in a material due to the strong interaction with other charged particles. Gamma rays are high-energy photons that can cause severe damage, but often pass through matter without interaction.

5.1 Applications of Ionising Radiation

Medical Studies and Imaging

Radioactive iodine is used in thyroid studies since nearly all the iodine ingested is either eliminated or stored in the thyroid. When a small quantity of the unstable isotope $^{131}_{53}\text{I}$ is injected into the patient, the speed with which it becomes concentrated in the thyroid provides a measure of thyroid function. The half-life is 8.02 days, so there are no long-lasting radiation hazards. By using more sophisticated scanning detectors, an image of the thyroid showing enlargement or other abnormalities can also be obtained. If it discovers cancerous thyroid nodules, they can be further destroyed by larger quantities of $^{131}_{53}\text{I}$ as a form of medical therapy.

Technetium-99 ($^{99}_{43}\text{Tc}$) is formed in an excited state by the β decay of molybdenum ($^{99}_{42}\text{Mo}$). The technetium then decays to its ground state by emitting a γ -ray photon with energy 143 keV. The half-life is 6.01 hours. Technetium can be readily attached to organic molecules that are taken up by various organs in the body. A small quantity of such technetium-bearing molecules is injected into a patient and a machine detects the γ -rays emitted from the parts of the body that take up these molecules producing an image of these parts of the patient's body. In this technique $^{99}_{43}\text{Tc}$ acts as a *radioactive tracer* and helps in locating cancers.

Radiation Therapy

Since radiation can cause damage to rapidly dividing cells, it is useful in cancer treatment. Narrow beams of radiation from a radioactive source can deliver radiation doses to specific parts of the patient's body in the hospital. An example of such a radioactive source is the $^{60}_{27}\text{Co}$ isotope with a half-life of 5.3 years as it emits gamma rays with photon energies higher than 1 MeV.

Radiation can also be delivered directly to the cancerous tumour in a technique called *brachytherapy*. Thin radioactive needles are implanted in cancerous tissue. This reduces the exposure of surrounding tissue to radiation damage. This technique is commonly used for prostate cancer where the active isotopes are $^{125}_{53}\text{I}$ and $^{103}_{46}\text{Pd}$.

Materials Analysis

When a material is irradiated with neutrons, nuclei in the material absorb the neutrons and are changed to different isotopes, most of which are radioactive. For example, $^{65}_{29}\text{Cu}$ absorbs a neutron to become $^{66}_{29}\text{Cu}$, which undergoes beta decay. $^{66}_{29}\text{Cu}$ has a half-life of 5.1 mins and by examining the radiation emitted by a sample after it has been exposed to neutron irradiation, one can detect extremely small amounts of copper in that sample. This is known as neutron activation analysis, and it is also used to check airline luggage for hidden explosives. Art historians also use neutron activation analysis to detect forgeries. The pigments used in paints have changed throughout history, and old and new pigments react differently to neutron activation.

Food Preservation

Exposure to high levels of radiation can destroy or incapacitate bacteria and mold spores. Exposing foods to ionising radiation allows them to be placed in a sealed container and stored for long periods of time. Chicken and beef are commonly sterilised this way, thus reducing the threat of E.Coli contamination.

Smoke Detectors

There are smoke detectors that use a weak radioactive source (Americium) to ionise the air to create charged particles. A voltage is maintained between the plates, and the charged particles set up a small current in the circuit. The alarm is deactivated as long as the current is maintained. When smoke drifts into the detectors, the charged air particles are then attached to the smoke particles. These heavier smoke particles do not drift as readily as the charged air particles, causing a decrease in current which then sets off the alarm.

Radioactive Dating

The dating of archaeological and geological specimens by measuring the concentration of radioactive isotopes is another application of radioactivity. For example, in carbon dating, the unstable isotope $^{14}_6\text{C}$ is present in the CO_2 in the atmosphere in small proportions. Plants that obtain their carbon from this source contains the same proportion of $^{14}_6\text{C}$ in the atmosphere. When a plant dies, it stops taking in carbon and its $^{14}_6\text{C}$ β decays to $^{14}_7\text{N}$ with a half-life of 5730 years. By measuring the proportion of $^{14}_6\text{C}$ in the remains, we can determine how long ago the organism died.

5.2 Hazards of Ionising Radiation

Direct Effect: Damage to Living Cells

If radiation interacts with the atoms of the DNA molecule, or some other cellular component critical to the survival of the cell, it is referred to as a direct effect. Such an interaction may affect the ability of the cell to reproduce and, thus, survive. If enough atoms are affected such that the chromosomes do not replicate properly, or if there is significant alteration in the information carried by the DNA molecule, then the cell may be destroyed by “direct” interference with its life-sustaining system.

Indirect Effect: Creating Free Radicals

If a cell is exposed to radiation, the probability of the radiation interacting with the DNA molecule is very small since these critical components make up such a small part of the cell. Therefore, there is a much higher probability of radiation interacting with the water that makes up most of the cell's volume. When radiation interacts with water, it may break the bonds that hold the water molecule together, producing fragments such as hydrogen (H) and hydroxyls (OH). These fragments may combine to form toxic substances, such as hydrogen peroxide (H_2O_2), which can contribute to the destruction of the cell.



Watch this video to learn more about ionising and non-ionising radiation as well as their applications.

6. Review Questions

- 1 Fig. 1.1 below shows the decay series of Uranium-238. Uranium undergoes a series of alpha and beta decays to become a stable isotope of Lead-206 after a long period of time.

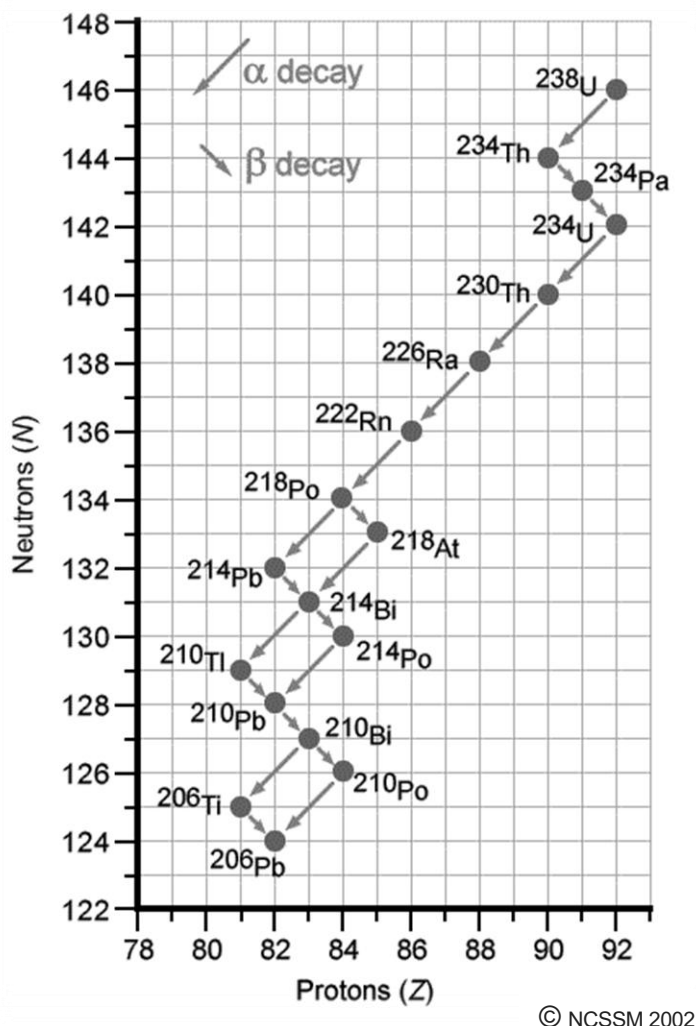


Fig. 1.1

- (a) Suggest why stable nuclei tend to have a greater proportion of neutrons to protons in their nucleus.
- (b) It can be seen that all the daughter nuclei that result from the decay of Uranium-238 have a multiple four nucleons lesser than that of Uranium.
Explain why this is so.
- (c) State the Principle of Conservation of Linear Momentum.

- (d) A stationary Radon (^{222}Rn) nucleus decays spontaneously into a Polonium (^{218}Po) nucleus via an α decay. It may be assumed that no γ -ray is emitted during this decay.

The rest masses of the nuclei involved are given as shown:

$$\begin{aligned}\text{Rn: } & 222.0176 \, u, \\ \text{Po: } & 218.0090 \, u, \\ \alpha: & 4.0026 \, u\end{aligned}$$

- (i) Write down the nuclear equation which describes this decay.
- (ii) Show that the net energy released during this reaction is about $8.96 \times 10^{-13} \, \text{J}$.
- (iii) Using (c), show that $\frac{\text{kinetic energy of } \alpha \text{ particle}}{\text{kinetic energy of Po nucleus}} = \frac{218}{4}$
- (iv) Hence, calculate the speed of the α particle.
- (e) The Polonium (Po) nucleus subsequently decays spontaneously into an Astatine (At) nucleus via a β decay. It may be assumed that no γ -ray is emitted during this decay. Fig. 1.2 shows the variation with kinetic energy of β particles produced during the decay of the number of β particles emitted.

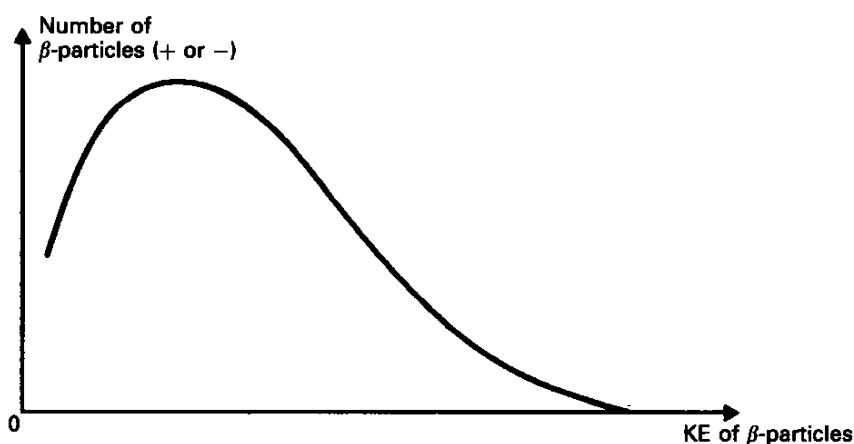


Fig. 1.2

- (i) Explain how Fig 1.2 provided evidence for the discovery of the neutrino, which was emitted during a β decay.
- (ii) A student suggests that the Astatine nucleus and β particle would be moving in opposite directions after the decay.

Comment on the validity of this statement.

Solution

1(a)	A high ratio of protons to neutrons would make the nucleus unstable due to the repulsive nature of the electrostatic force between protons.
(b)	Alpha decay causes a loss of 4 nucleons while beta decay has no effect on the number of nucleons.
(c)	Total initial momentum = total final momentum of a system provided there is no net external force acting on the system.
(d)(i)	${}_{86}^{222}\text{Rn} \rightarrow {}_{84}^{218}\text{Po} + {}_2^4\text{He} + \text{energy}$ Correct balanced equation Energy added to equation
(d)(ii)	Energy released = $(m_{\text{Rn}} - (m_{\text{Po}} + m_{\text{He}}))c^2$ = $(222.1706 - (218.0090 + 4.0026)) \times 1.66 \times 10^{-27} \times (3.00 \times 10^8)^2$ = $8.964 \times 10^{-13} \text{ J}$
(d)(iii)	By COM, total p initial = total p final $m_{\text{Rn}}(0) = m_{\text{Po}} v_{\text{Po}} + m_{\text{He}} v_{\text{He}}$ $m_{\text{Po}} v_{\text{Po}} = - m_{\text{He}} v_{\text{He}}$ $KE = \frac{1}{2} m v^2 = \frac{p^2}{2 m}$ $\frac{\text{KE of } \alpha \text{ particle}}{\text{KE of Po nucleus}} = \frac{\frac{p_{\alpha}^2}{2m_{\alpha}}}{\frac{p_{\text{Po}}^2}{2m_{\text{Po}}}} = \frac{m_{\text{Po}}}{m_{\alpha}} = \frac{218}{4}$
(d)(iv)	KE of α particle = $(218 / (218 + 4)) \times 8.964 \times 10^{-13}$ $\frac{1}{2} (4 \times 1.66 \times 10^{-27}) v^2 = (218 / 222) \times 8.964 \times 10^{-13}$ $v = 1.63 (1.62830) \times 10^7 \text{ m s}^{-1}$
(e)(i)	Range of KE of β particles produced. For energy to be conserved, there must be another particle / wave (neutrino) that accounts for the remaining energy produced.
(e)(ii)	Student is correct if anti-neutrino is emitted along the same axis as the At nucleus and β particle so that linear momentum can be conserved in <u>all directions</u>. OR Student is wrong as there should be an angle between the paths of the At nucleus and β particle because the anti-neutrino is also emitted so that linear momentum can be conserved in <u>all directions</u>.

- 2 (a) Distinguish between a nucleon, a nucleus and a nuclide.
- (b) A nuclear power plant is capable of generating up to 4.7 gigawatts of power through neutron-induced fission of Uranium-235.

Fig 2.1 illustrates a typical nuclear fission reaction where a neutron is captured by a Uranium-235 nucleus.

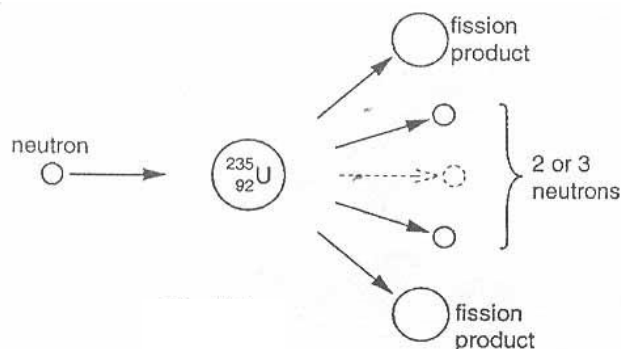


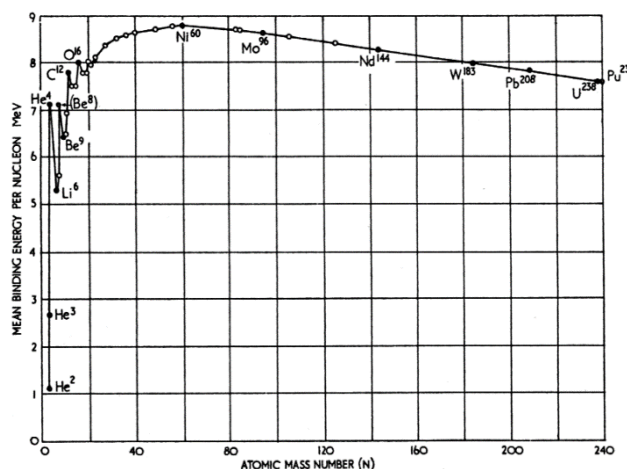
Fig. 2.1

On average, 2.5 neutrons are emitted in fission reactions and large amounts of energy are released. When conditions are suitable, a chain reaction can occur and if it is controlled, a source of continuous power may be created.

- (i) Explain what is meant by *nuclear fission*.
- (ii) Two possible fission products that can be formed from the fission of Uranium--235 are Barium-141 ($^{141}_{56}\text{Ba}$) and Krypton-92 ($^{92}_{36}\text{Kr}$).

Write down the nuclear equation for this nuclear reaction.

- (c) Fig. 2.2 shows how the binding energy per nucleon of a nucleus varies with mass number.



Source: <https://nige.wordpress.com/2011/03/>

Fig. 2.2

- (i) State what is meant by the *binding energy per nucleon* of a nucleus.
- (ii) Explain why fission of nuclei having low mass numbers ($N < 60$) is not associated with a release of energy.
- (iii) Using data from Fig. 2.2 and (b)(ii), show that the energy released in one fission reaction is about 185 MeV.
- (iv) Suggest one form of energy in which the energy released in (c)(ii) is transformed to.
- (v) A typical nuclear reactor has about 100 tonnes (1 ton = 1000 kg) of Uranium spread throughout the fuel assemblies to act as fuel to generate electrical energy.
If a nuclear reactor is 30% efficient, estimate, in years, how long can a nuclear reactor supply electricity to the households in Singapore given that the total annual household electricity consumption is 6500 GWh.

Solution

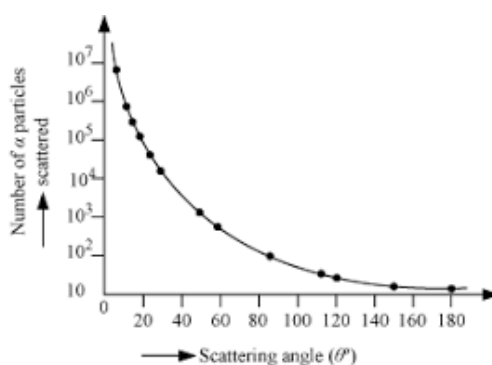
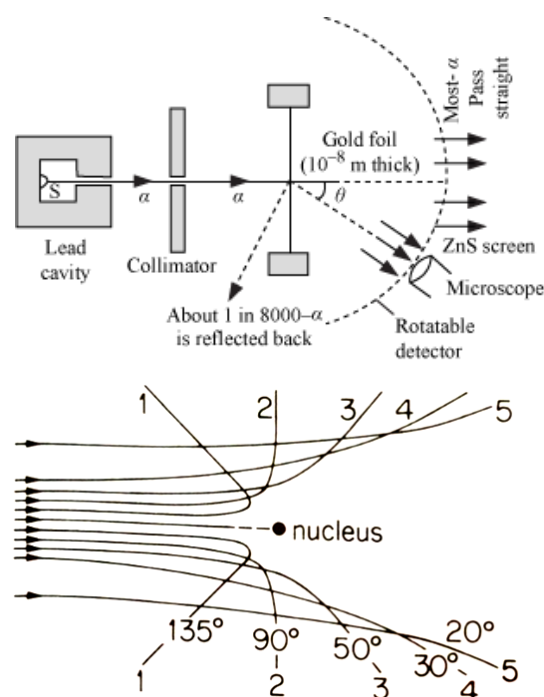
2(a)	Nucleon: constituent of a nucleus, can be either a proton or neutron Nucleus: positively charged centre of an atom, made up of protons and neutrons Nuclide: an atom with a particular proton-neutron combination (nuclear structure)
	Note: Isotopes are nuclides having the same number of protons but different number of neutrons
(b)(i)	Disintegration of a massive nucleus into smaller fragments of comparable masses with the release of a large amount of energy
	as the total mass of the daughter products is lower than the parent nuclei
(b)(ii)	${}_{92}^{235}\text{U} + {}_0^1\text{n} \rightarrow {}_{56}^{141}\text{Ba} + {}_{36}^{92}\text{Kr} + 3{}_0^1\text{n} + \text{energy}$ Correct balanced equation Inclusion of energy
(c)(i)	Minimum external energy required to completely separate all the neutrons and protons of a nucleus to infinity divided by total number of nucleons.
(c)(ii)	Daughter nuclei has lower binding energy per nucleon than parent nuclei (as can be seen from the BE/nucleon graph).
	and the total mass of the daughter nuclei formed is more than the parent nucleus which means that energy has to be supplied for the fission process to occur.
(c)(iii)	Energy released = Total <i>BE</i> of <i>Ba</i> and <i>Kr</i> - Total <i>BE</i> of <i>U</i>
	= $[141(8.3) + 92(8.7)] - [235(7.6)]$
	= 184.7 MeV = 185 MeV
(c)(iv)	<i>KE</i> of daughter nuclei / <i>KE</i> of neutrons / γ rays

(c)(v)	Number of nuclear reactions $= (100 \times 10^3 / 0.235)(6.02 \times 10^{23}) = 2.56 \times 10^{29}$
	$185 \text{ MeV} = (185 \times 10^6)(1.6 \times 10^{-19}) = 2.96 \times 10^{-11} \text{ J}$
	Time = $(0.30) (100 \times 10^3 / 0.235) (6.02 \times 10^{23}) (185 \times 10^6)$ $(1.6 \times 10^{-19}) / (6500 \times 10^9 \times 60 \times 60)$
	$= 97.2 = 97 \text{ yrs (2 s.f.)}$

Annex A Alpha-Particle Scattering Experiment

Experimental Setup²:

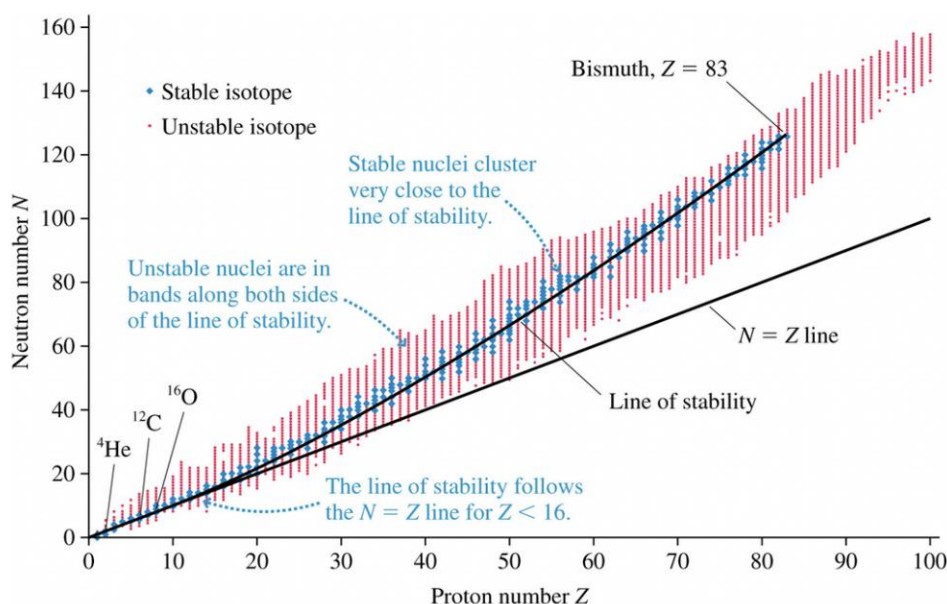
- Naturally radioactive element that produces α -particles (speed in the order of 10^7 m s^{-1}).
- A collimator (to focus beam of the positively charged α -particles).
- Direct at very thin sheet of gold foil (to reduce likelihood of multiple collisions).
- The vacuum prevents collision of the α -particles with air molecules.
- Angular deflection, θ of the particles was measured with a microscope that can be rotated and had a glass screen coated with zinc sulphide.
- On impact with the screen, the α -particle produces a tiny flash (scintillation).
- The number of scintillation N for a given fixed time was obtained for each angular deflection, θ .



Graph showing the results of α -particle scattering experiment

² <http://cbse12phy.syncacademy.com/2012/04/physics-ch-12-1-alpha-particle.html>

Annex B Stability of a Nucleus



The graph shows the number of neutrons plotted against the number of protons for all the stable nuclei. Note how the neutron/proton ratio increases for the heavier elements.

Why is it that certain combinations of nucleons are stable in a nucleus while others are not? A complete answer to this question cannot yet be given, largely because the exact nature of the forces holding the nucleons together is still only partially understood. We can, however, point to several factors which affect nuclear stability. The most obvious is the neutron/ proton ratio. If this is too high or too low, it makes for an unstable nucleus.

If we plot the number of neutrons against the number of protons for all known stable (i.e., non-radioactive) nuclei, we obtain the result shown in the figure. All the stable nuclei lie within a definite area called the zone of stability (in red). For low atomic numbers most stable nuclei have a neutron/proton ratio which is very close to 1. As the atomic number increases, the zone of stability corresponds to a gradually increasing neutron/proton ratio. In the case of the heaviest stable isotope, ${}^{209}_{83}\text{Bi}$ for instance, the neutron/proton ratio is 1.518. If an unstable isotope lies to the left of the zone of stability in the fig., it is neutron rich and decays by β emission. If it lies to the right of the zone, it is proton rich and decays by positron emission or electron capture.

Another factor affecting the stability of a nucleus is whether the number of protons and neutrons is even or odd. Among the 354 known stable isotopes, 157 (almost half) have an even number of protons and an even number of neutrons. Only five have an odd number of both kinds of nucleons. In the universe as a whole (with the exception of hydrogen) we find that the even-numbered elements are almost always much more abundant than the odd-numbered elements close to them in the periodic table. Finally, there is a particular stability associated with nuclei in which either the number of protons or the number of neutrons is equal to one of the so-called "magic" numbers 2, 8, 20, 28, 50, 82, and 126. These numbers correspond to the filling of shells in the structure of the nucleus. These shells are similar in principle but different in detail to those found in electronic structure. Of particular stability, and also of high abundance in the universe, are nuclei in which both the-number of protons and the number of neutrons correspond to magic numbers. Examples are ${}^4_2\text{He}$, ${}^{16}_8\text{O}$, ${}^{40}_{20}\text{Ca}$, and ${}^{208}_{82}\text{Pb}$.