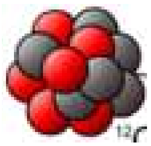
Nuclear Physics

Content

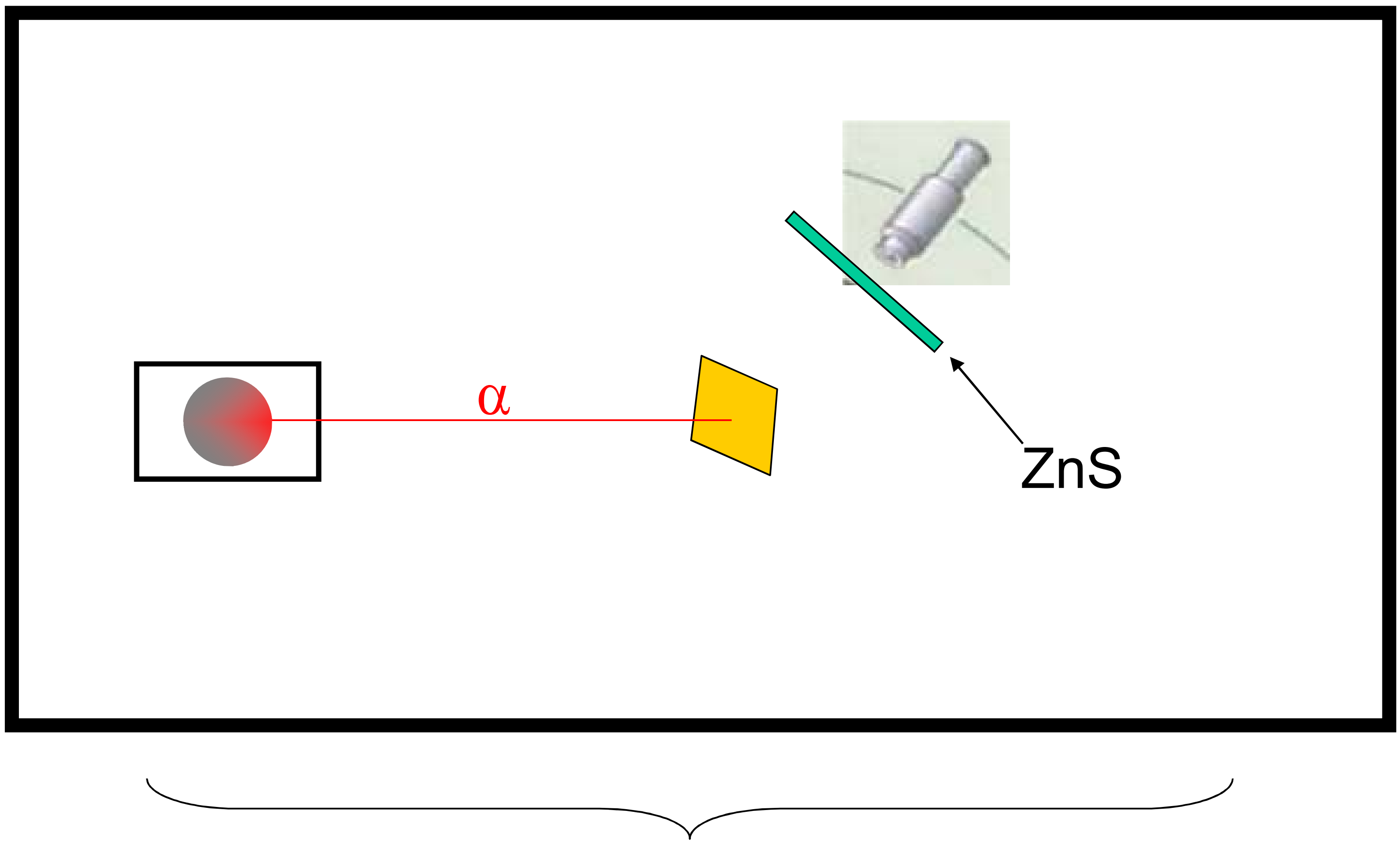
- **27.1 The nucleus**
- **27.2 Isotopes**
- **27.3 Nuclear processes**

Background~~

- The Greek philosophers : Matter cannot be subdivided infinitely.
- John Dalton's postulate : Matter made up of tiny indivisible particle known as atom (1803)
- J.J Thomson : discovers sub particle known as electron and proposed the pudding model of atom (1897)
- Rutherford : proposed the structure of atom as mostly space with a tiny nucleus at the center and surrounded by electrons. His model was based on the famous experiment done by his two students. (1911)
- Geiger and Marsden: **alpha particle scattering experiment**

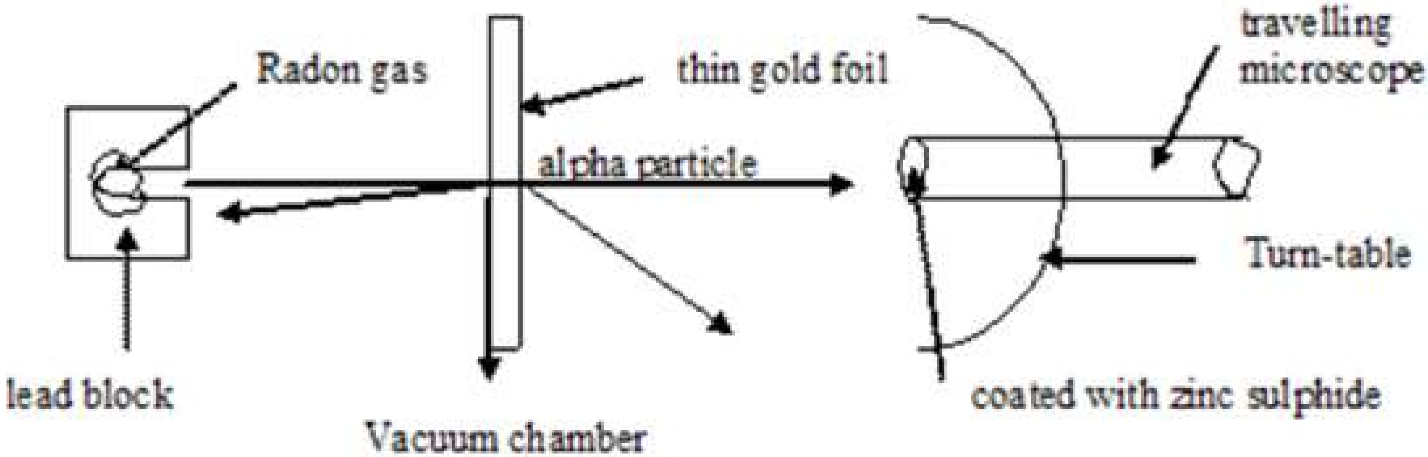


- Radioactive Source
- Thin Gold Foil
- Fluorescent screen + Movable Microscope



- Vacuum Chamber

Rutherford's alpha-particle scattering experiment.



- Rutherford uses the principle of electrostatic repulsion between positive charge of atom and the energetic incident alpha particle which can penetrate into the atom.
- Experiment conducted in a dark room and the chamber in which the alpha particle travels is vacuumed.

Rutherford's alpha-particle scattering experiment.

- A narrow beam of alpha particles are aimed at a film of gold foil about 1 μm thick.

- The angular deflections of alpha particles are measured by means of the microscope, which is used to observe the scintillations (tiny flashed of light) that occur whenever an alpha particle strikes the zinc sulphide screen.

- The screen and microscope can be rotated around the fixed source and metal foil.

Observations:

1st Observation:

Majority of the alpha particles passed through the foil with very little or no deviation from their original path. Most α particles pass through un-deflected. Many scintillations are observed in the direction of source (0˚)

2nd Observation:

A small number of particles were deviated through an angle of more than 10 degrees. An extremely small number of particles were deflected through an angle greater than 90 degrees; in fact, going right back at the source.

Conclusions:

1st Conclusion (based on 1st Observation):

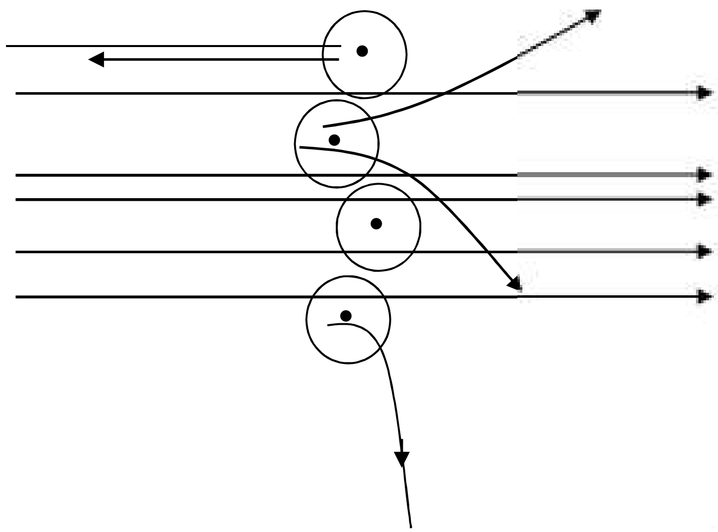
Most α particles are un-deflected because the **atom is mostly empty space.**

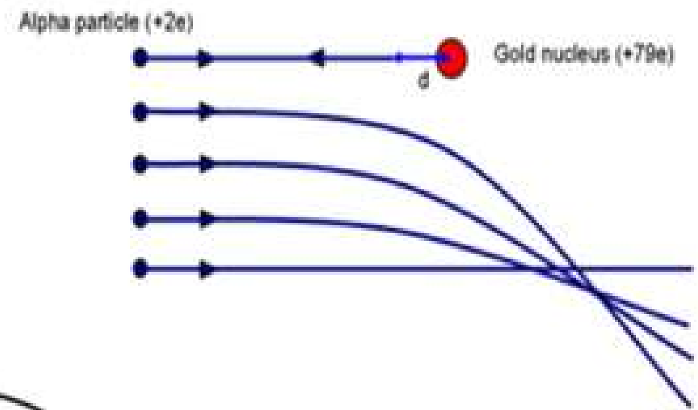
2nd Conclusion (based on 2nd Observation):

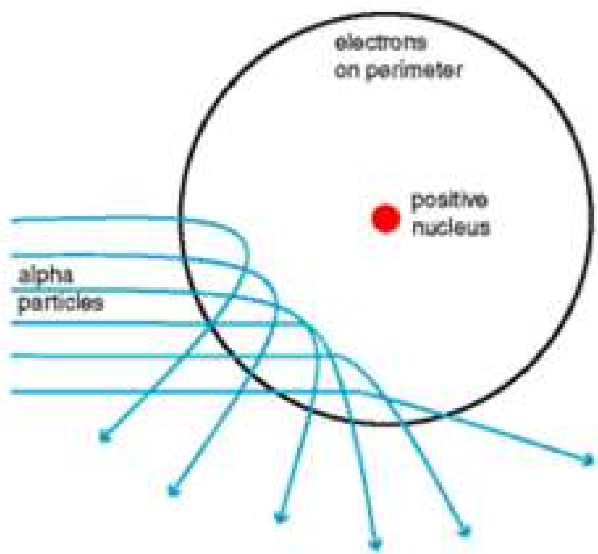
Few α particles are deflected because of the **strong electrostatic repulsion between the nucleus and the α particles.**

Rutherford’s alpha-particle scattering experiment.

- This experiment thus proposed that atom is mainly empty space, which is made up of a very small size nucleus that is very dense and positively charged.







Example 1:

- In an experiment to investigate the nature of the atom, a very thin gold film was bombarded with α-particles. What pattern of deflection of the α-particles was observed?

  A A few α-particles were deflected through angles greater than a right angle.

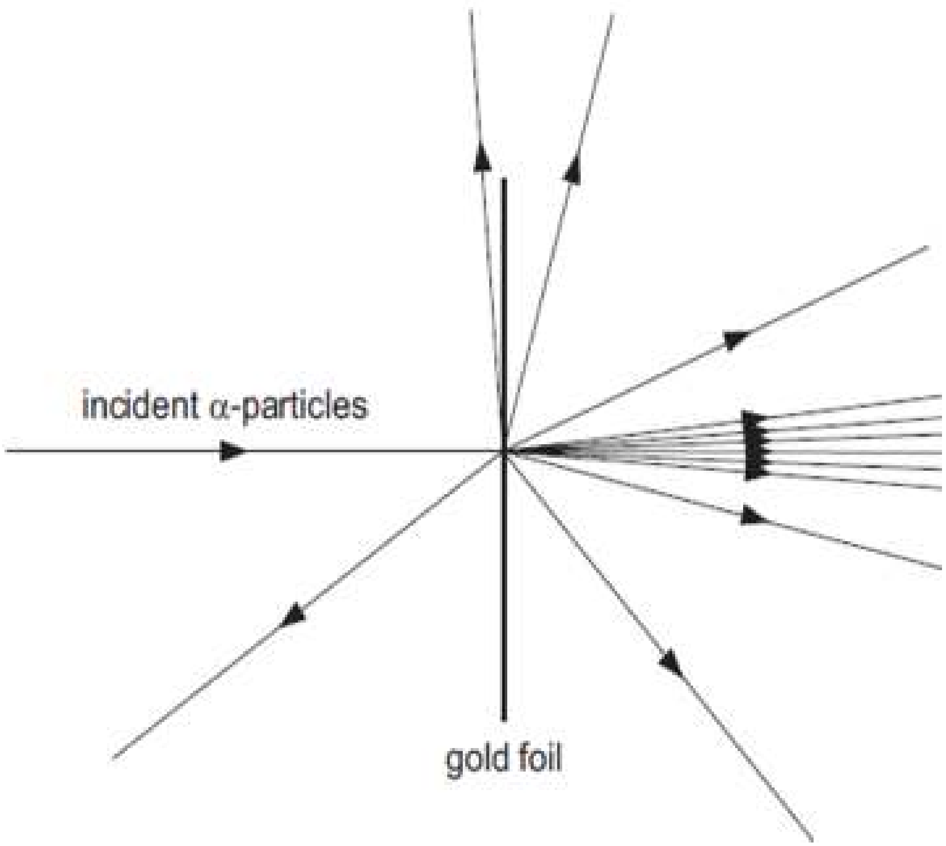
  B All α-particles were deflected from their original path.

  C Most α-particles were deflected through angles greater than a right angle.

  D No α-particle was deflected through an angle greater than a right angle.

Example 2

- A thin gold foil is bombarded with α-particles as shown.



The results of this experiment provide information about the

A binding energy of a gold nucleus.

B energy levels of electrons in gold atoms.

C size of a gold nucleus.

D structure of a gold nucleus

Example 3

- Which conclusion can be drawn from the results of the experiment showing the scattering of α-particles by gold foil?

  A Electrons orbit the atomic nucleus in well-defined paths.

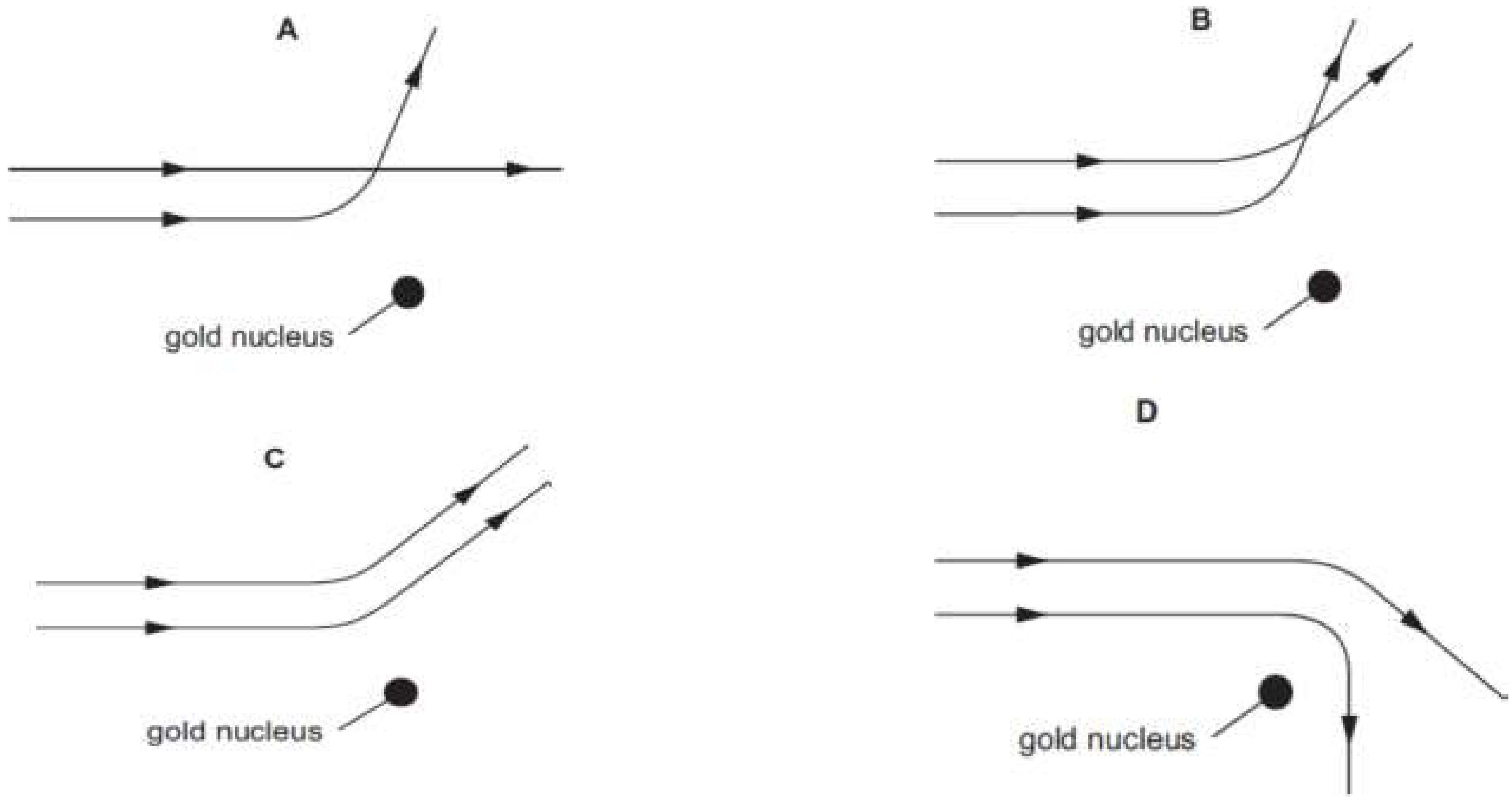
  B Nuclei of different isotopes contain different numbers of neutrons.

  C The atomic nucleus contains protons and neutrons.

  D The nucleus is very small compared with the size of the atom

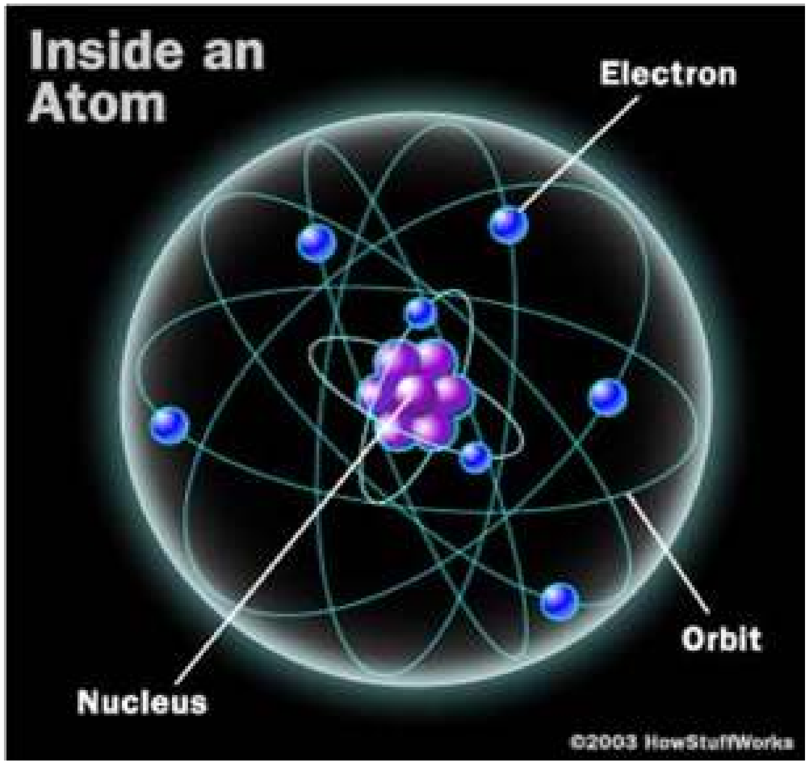
Example 4

- Two α-particles with equal energies are fired towards the nucleus of a gold atom. Which diagram best represents their paths?



A simple model of the nuclear atom

- Up till today, this is the model of the atom as far as the study of science is concern. In this model, the ***nucleus is orbited by electrons, which are in different energy levels.***
- This model assumes that atom possesses a nucleus which is made up of positively charged particles called protons, together with particles of neutral charge, called neutrons.
- The nucleus therefore, is on the whole, positive. To make the atom electrically neutral, negatively charged particles called electrons circulate in orbits around the nucleus, such that there are as many protons as there are electrons in the atom.



- Size of the nucleus is about 10^{-15} m
- Size of the atom is about 10^{-10} m

Atomic particle properties

Particle	Charge	Mass / kg	(in term of unified atomic mass constant, u)	Value of relative charge / C
proton $^{1}_{1}p$	positive	1.67×10^{-27}	1.007276 u	1.6×10^{-19} C
neutron $^{1}_{0}n$	neutral	1.67×10^{-27}	1.008665 u	0
electron $^{0}_{-1}e$	Negative	9.11×10^{-31}	1/1840 u	-1.6×10^{-19} C

***where 1 u = 1.66×10^{-27} kg**

Example 5

- What is a correct order of magnitude estimate for the diameter of a typical atomic nucleus?

A 10^{-14}m

B 10^{-18}m

C 10^{-22}m

D 10^{-26}m

Example 6

- Where are electrons, neutrons and protons found in an atom?

	electrons	neutrons	protons
A	in the nucleus	in the nucleus	orbiting the nucleus
B	in the nucleus	orbiting the nucleus	in the nucleus
C	orbiting the nucleus	in the nucleus	orbiting the nucleus
D	orbiting the nucleus	in the nucleus	in the nucleus

Nucleus, Nuclides, Nucleons and Isotopes

- Nucleus – center of atom which is extremely dense, contains protons and neutrons
- Nuclei – more than one nucleus
- Nuclide – a particular species of atoms with a specified number of protons and neutrons
- Nucleons – sub-particles within the nucleus – namely proton and neutron

Representation of Nuclides

- A nuclide is represented by the symbol below

$$^{A}_{Z}X$$

- X – element
- A – nucleon number : number of nucleons in the nucleus
- Z – proton number : number of protons in the nucleus
- N – neutron number : number of neutron in the nucleus

  (N = A – Z)

- Eg : $^{4}_{2}He$ - 2 protons, 2 neutrons, 4 nucleons

Example 7

An oxygen nucleus is represented by $^{16}_{8}O$

Such information can be drawn:

1. The nucleus has a proton number of ___ and a nucleon number of ____
2. Thus, its nucleus contains ___ protons and ___ neutrons.
3. For an oxygen atom, there are ___ electrons (equal to the number of protons) orbiting the nucleus.
4. The atom is electrically __________

Example 8

- Which two nuclei contain the same number of neutrons?

A $^{12}_{6}C$ and $^{14}_{6}C$

B $^{16}_{7}N$ and $^{15}_{8}O$

C $^{23}_{11}Na$ and $^{24}_{12}Mg$

D $^{32}_{14}Si$ and $^{32}_{15}P$

Isotopes

- Isotope – nuclei of the **same element** that contains the **<u>same number of protons</u>** but **<u>different number of neutrons</u>**.
- **Or same proton number but different nucleon number.**
- Isotopes of an element have the same chemical properties but different physical properties. (Eg: atomic mass is different)
- Eg: three isotopes of oxygen
- 8 proton, 8 neutron $^{16}_{8}O$
- 8 proton, 9 neutron $^{17}_{8}O$
- 8 proton, 10 neutron $^{18}_{8}O$

Example 9

- The nucleus of one of the isotopes of nickel is represented by $^{60}_{28}Ni$ .Which line in the table correctly describes a neutral atom of this isotope?

	number of protons	number of neutrons	number of orbital electrons
A	28	32	28
B	28	60	28
C	60	28	28
D	60	32	32

Example 10

- A certain nuclide, Uranium-235, has nucleon number 235, proton number 92 and neutron number143. Data on four other nuclides are given below. Which is an isotope of Uranium-235?

	nucleon number	proton number	neutron number
A	235	91	144
B	236	92	144
C	237	94	143
D	238	95	143

Example 11

In what way do the atoms of the isotopes ${}^{12}_{6}C$, ${}^{13}_{6}C$ and ${}^{14}_{6}C$ differ?

A different charge

B different numbers of electrons

C different numbers of neutrons

D different numbers of protons

Isotopes of a given element all have the same

A charge / mass ratio.
B neutron number.
C nucleon number.
D proton number.

Nuclear reaction and equation

- Nuclear reaction refers to the process that happens within the nucleus
- During nuclear reaction, there are few laws which are conserved.

1.) Proton number is conserved. Thus proton numbers of nuclides must add up to the same total before the reaction as after the reaction.

2.) Nucleon number is conserved. Thus the sum of nucleon numbers of nuclides before reaction is the same as after reaction.

3.) Mass-Energy is conserved.

4.) Momentum is conserved.

5.) Charge is conserved.

Nuclear reaction and equation

- Examples of nuclear reactions.

1.) $^{14}_{7}N + ^{4}_{2}He \rightarrow ^{17}_{8}O + ^{1}_{1}H$

2.) $^{9}_{4}Be + ^{4}_{2}He \rightarrow ^{12}_{6}C + ^{1}_{0}n$

3.) $^{7}_{3}Li + ^{1}_{1}H \rightarrow ^{4}_{2}He + ^{4}_{2}He$

4.) $^{14}_{7}N + ^{1}_{0}n \rightarrow ^{14}_{6}C + ^{1}_{1}H$

Radioactivity

- Some elements have ***nuclei which are unstable***, and ***in order to become more stable, the nucleus emits particles and/or electromagnetic radiation***. This emission or decay is called ***radioactivity.***
- Radioactivity is the process by which unstable nucleus becomes more stable with the emission of particles, or energy, or both from the nucleus.
- First discovered by Becquerel in 1896.
- Nuclides that are actively emitting radiation are known as **radioactive** nuclides.
- Activity refers to the rate of disintegration or rate of decay.

Radioactivity

- Radioactivity is a **random** and **spontaneous** process.

Random decay

1. Each nucleus in a sample has the same chance / constant probability of decaying per unit time.

2. Cannot predict which particular nucleus will decay next

Spontaneous decay

1. Decay unaffected by chemical reaction or environmental changes such as temperature, pressure, etc.

2. Decay of particular nucleus is not affected by the presence of other nuclei.

Radioactive Emissions

- ***Radioactive nuclei will emits particles and/or electromagnetic radiation in order to achieve stability.***
- ***Radioactive emissions result in changes in the number of protons and neutrons in the nuclei***
- However, in all radioactive equations, the nucleon number and the proton number are conserved.
- Examination shows 3 types of radioactive emissions
  - ***alpha particles, α***, $Z = 2$, $A = 4$ (2 protons + 2 neutrons)
  - ***beta particles, β***, electron
  - ***gamma rays, γ***, no charge, no mass

Characteristics of α-particles and α-decay

- It is a Helium nucleus.
- Contains 2 protons and 2 neutrons, hence carries a charge of +2 e
- In α–decay, the proton number of the nucleus decreases by 2, and the nucleon number decreases by 4.
- Travels at about 5~10% of the speed of light.
- Least penetrating of the 3 types of emissions.
- Can pass through thin paper but not thin cardboard.
- Affects photographic film.
- Range in air is a few cm.
- Since it is charged, thus can be deflected by electric and magnetic fields.
- ***As α–particles have relatively large mass and charge, they interact with nearby atoms causing them to lose one or more electrons hence ionising them***. The ionised atom and the dislodged electron are called an ***ion pair.***
- This requires energy thus they lose energy relatively quickly and have low penetrating power

Characteristics of β-particles and β-decay

- Are fast moving electrons.
- ***They come from a neutron which consists of a proton and an electron, <u>and not from the orbiting electron outside the nucleus.</u>***
- The proton number of the 'daughter' nuclide is increased by 1 compared to the 'parent' nuclide but with the same nucleon number.
- Have speeds in excess of 90~99% of the speed of light.
- Have very much less mass and only half the charge compared to α-particles hence much less efficient than α-particles in producing ion pairs but far more penetrating.
- Can travel up to about 1 metre in air, can penetrate card and sheets of aluminium up to a few mm thick.
- Affects photographic film.
- Are affected by electric and magnetic fields since they are charged particles and are deflected in the ***opposite direction*** to α-particles.
- Since their mass is also much less, will experience ***a much greater deflection*** when moving at the same speed as α-particles.

Characteristics of γ-radiation

- γ-radiation (gamma radiation) is part of the electromagnetic spectrum.
- It is emission of excess energy due to an excited state.
- Has no charge, no mass, hence ionising power is much less than that of the other 2 emissions.
- Penetrates almost unlimited thicknesses of air, several meters of concrete or several cm of lead (Pb).
- Since no charge is not deflected by electric or magnetic fields.
- Affects photographic film.
- ***No particles are emitted and hence no change to proton number or nucleon number.***

The characteristics of these radiations are summarized in the table below:

Characteristics	**Alpha particle** $^{4}_{2}He$	**Beta particle** $^{0}_{-1}e$	**Gamma radiation** γ
Nature	Heavy. Identified as Helium nuclei (2p + 2n).	Light. Identified as high energy electrons.	Electromagnetic radiation of short wavelength.
Charge	+2e = (2)(1.6×10^{-19} C)	-1e = -1.6×10^{-19} C	0
Mass (*1u = 1.67×10^{-27}kg)	4 u	(1 / 1840) u	0
Speed (*c = 3×10^{-8} ms^{-1})	0.1 c	0.9 c	c

The characteristics of these radiations are summarized in the table below:

Characteristics	Alpha particle	Beta particle	Gamma radiation
Effect on magnetic-field & electric-field	Deflected slightly in the same direction as +ve charge.	Strong deflection in opposite direction to +ve charge / α particle	No effect.
Penetrating power	5~6cm of air. Thin sheets of paper. Thin layers of mica.	Many cm (~100cm) of air. Few mm (~4mm) of light metal (AL)	Almost unlimited thickness of air. Several metres of concrete. Few cm (4~8cm) of lead (Pb)
Ionising power	Cause intense ionisation. 10 000 ion pairs per mm of air.	Less intense than α. 100 ion pairs per mm of air.	Weak interaction with matter. 1 ion pair per mm of air.

Example 12

When a nucleus of $^{238}_{92}U$ absorbs a slow neutron it subsequently emits two β-particles.

What is the resulting nucleus?

A $^{240}_{93}Np$ B $^{240}_{91}Pa$ C $^{239}_{94}Pu$ D $^{239}_{90}Th$

Example 13

Strontium- 90 ($^{90}_{38}Sr$) is radioactive and emits β-particles.

Which equation could represent this nuclear decay?

A $^{90}_{38}Sr \rightarrow {}^{90}_{39}Sr + {}^{0}_{-1}\beta$

B $^{90}_{38}Sr \rightarrow {}^{90}_{39}Y + {}^{0}_{-1}\beta$

C $^{90}_{38}Sr \rightarrow {}^{90}_{37}Rb + {}^{0}_{1}\beta$

D $^{90}_{38}Sr \rightarrow {}^{90}_{37}Sr + {}^{0}_{1}\beta$

Example 14

A nucleus of the nuclide $^{241}_{94}Pu$ decays by emission of a β-particle followed by the emission of an α-particle.

Which of the nuclides shown is formed?

A $^{239}_{93}Np$ **B** $^{239}_{91}Pa$ **C** $^{237}_{93}Np$ **D** $^{237}_{92}U$

Example 15

The symbol $^{77}_{32}Ge$ represents a nuclide of germanium that decays to a nuclide of arsenic (As) by emitting a β-particle.

What is the symbol of this arsenic nuclide?

A $^{76}_{32}As$ **B** $^{78}_{32}As$ **C** $^{78}_{31}As$ **D** $^{77}_{33}As$

Some Facts: Dangers of Radioactivity

ALPHA PARTICLES

- Alpha particles are slow, have a short range in air, and can be stopped by a sheet of paper. You might therefore assume that alpha particles are the least dangerous of the three types of radiation.
- Wrong! Whilst they cannot penetrate your skin, you could easily eat or drink something contaminated with an source. This would put a source of alpha particles inside your body, wreaking havoc by ionising atoms in nearby cells.
- If this happens to part of the DNA in one of your cells, then that cell's instructions about how to live and grow have been scrambled. The cell is then likely to do something very different to what it's supposed to do, for example, it may turn cancerous and start multiplying uncontrollably.
- Thus alpha particles, whilst they have a low penetrating power, can be the most dangerous because they ionise so strongly.

Some Facts: Dangers of Radioactivity

BETA PARTICLES

- Beta particles have a longer range than alphas, but ionise much less strongly, with the result that they do around 1/20th of the damage done by the same dose of alpha particles.
- However, they do have more penetrating power, which means that they can get through your skin and affect cells inside you.

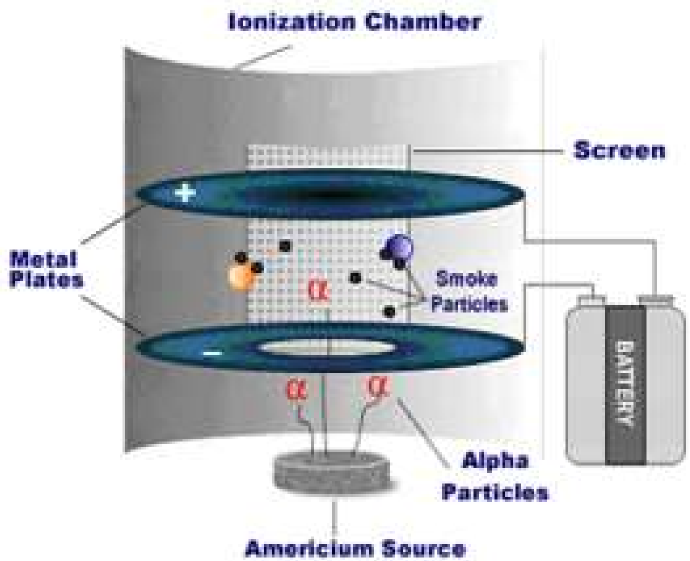
GAMMA RAYS

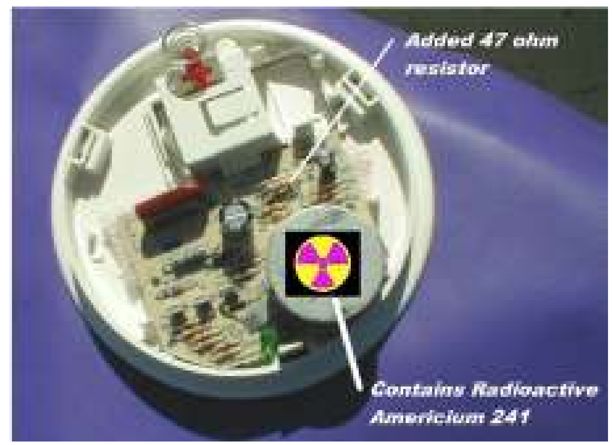
- Gamma rays hardly ionise atoms at all, so they do not cause damage directly in this way. However, they do have more penetrating power, which means that they can get through your skin and affect cells inside you.
- However, gamma rays are very difficult to stop, you require lead or concrete shielding to keep you safe from them. When they are absorbed by an atom, that atom gains quite a bit of energy, and may then emit other particles. If that atom is in one of your cells, this is not good!

Some Facts: Uses of Radioactivity

SMOKE DETECTORS

- Smoke alarms contain a weak source made of Americium-241. Alpha particles are emitted from here, which ionise the air, so that the air conducts electricity and a small current flows.
- If smoke enters the alarm, this absorbs the a particles, the current reduces, and the alarm sounds. Am-241 has a half-life of 460 years.

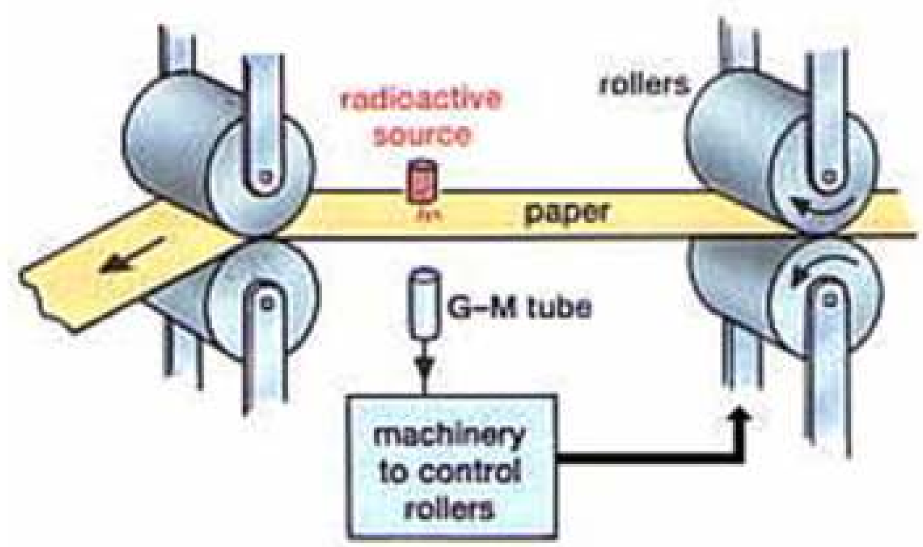




Some Facts: Uses of Radioactivity

<u>THICKNESS CONTROL</u>

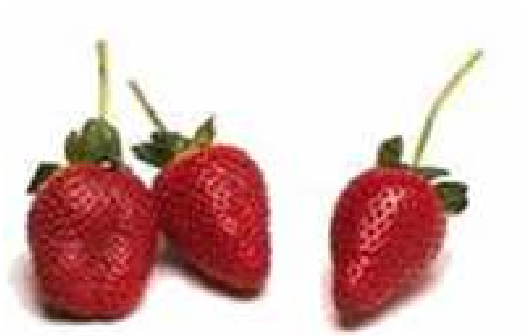
- In paper mills, the thickness of the paper can be controlled by measuring how much beta radiation passes through the paper to a Geiger counter.
- The counter controls the pressure of the rollers to give the correct thickness. With very thin paper, or plastic, or aluminium foil, alpha rays are used, because as it will not go through the paper.
- We choose a source with a long half-life so that it does not need to be replenished often.



Some Facts: Uses of Radioactivity

STERILISATION

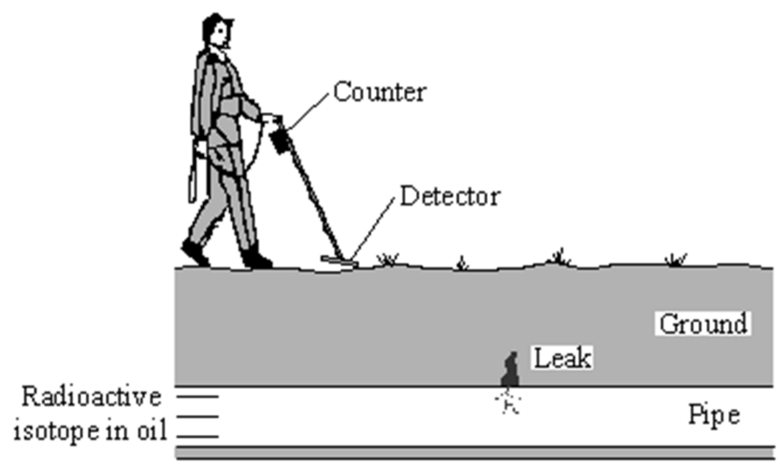
- Even after it has been packaged, gamma rays can be used to kill bacteria, mould and insects in food. This process prolongs the shelf-life of the food, but sometimes changes the taste.
- Gamma rays are also used to sterilise hospital equipment, especially plastic syringes that would be damaged if heated.



Some Facts: Uses of Radioactivity

<u>RADIOACTIVE TRACERS</u>

- The most common tracer is called Technetium-99 and is very safe because it only emits gamma rays which doesn't cause much ionisation.
- It is a chemical compound in which one or more atoms have been replaced by a radioisotope. (isotope which is unstable)
- Radioisotopes can be used for medical purposes, such as checking for a blocked kidney. To do this a small amount of Iodine-123 is injected into the patient, after 5 minutes 2 Geiger counters are placed over the kidneys.
- Also radioisotopes are used in industry, to detect leaking pipes. To do this, a small amount is injected into the pipe. It is then detected with a GM counter above ground.



Some Facts: Uses of Radioactivity

CANCER TREATMENT

- Because Gamma rays can kill living cells, they are used to kill cancer cells without having to resort to difficult surgery. This is called "**Radiotherapy**", and works because cancer cells can't repair themselves when damaged by gamma rays, as healthy cells can.
- It's vital to get the dose correct - too much and you'll damage too many healthy cells, too little and you won't stop the cancer from spreading in time.
- Some cancers are easier to treat with radiotherapy than others - it's not too difficult to aim gamma rays at a breast tumour, but for lung cancer it's much harder to avoid damaging healthy cells. Also, lungs are more easily damaged by gamma rays, therefore other treatments may be used.