

CHAPTER 7

Nuclear physics

SYMBOL AND UNIT SUMMARY

Symbol	Quantity	SI units
e	electronic charge	C (coulombs)
q_p	protonic charge	C
m_e	mass of electron	kg
m_p	mass of proton	kg
m_n	mass of neutron	kg
Z	atomic number	-
N	neutron number	-
A	mass number	-
amu or u	atomic mass unit	kg (1 amu = 1.66 \times 10^{-27} kg)
N_A	Avogadro number	-
q/m	charge to mass ratio	C kg ⁻¹
e/m	charge to mass ratio for electrons	C kg ⁻¹

	for electrons	
v	velocity	m s^{-1}
B	magnetic field strength	T
E	electric field strength	NC^{-1}
r	radius	m
KE	kinetic energy	J
E	photon energy	J
T	halflife	s
A	activity	Bq (becquerel)
Δm	mass defect	$\times 10^{-3}$ or amu
BE	binding energy	J or eV
		(1 eV = $1.6 \times 10^{-19} \text{ J}$)
BE/A	binding energy per nucleon	/nucleon or MeV/nucleon
d	nucleon separation	m or fm
c	speed of light	m s^{-1}

Background knowledge on atomic structure

Before starting this unit you should have a knowledge of atomic structure and be able to:

- I. use a current atomic theory to describe atoms:
 - (a) diagrammatically in terms of their charge, mass and the number of electrons, protons and neutrons they contain, as shown in Figure 7.1 for a Lithium atom.

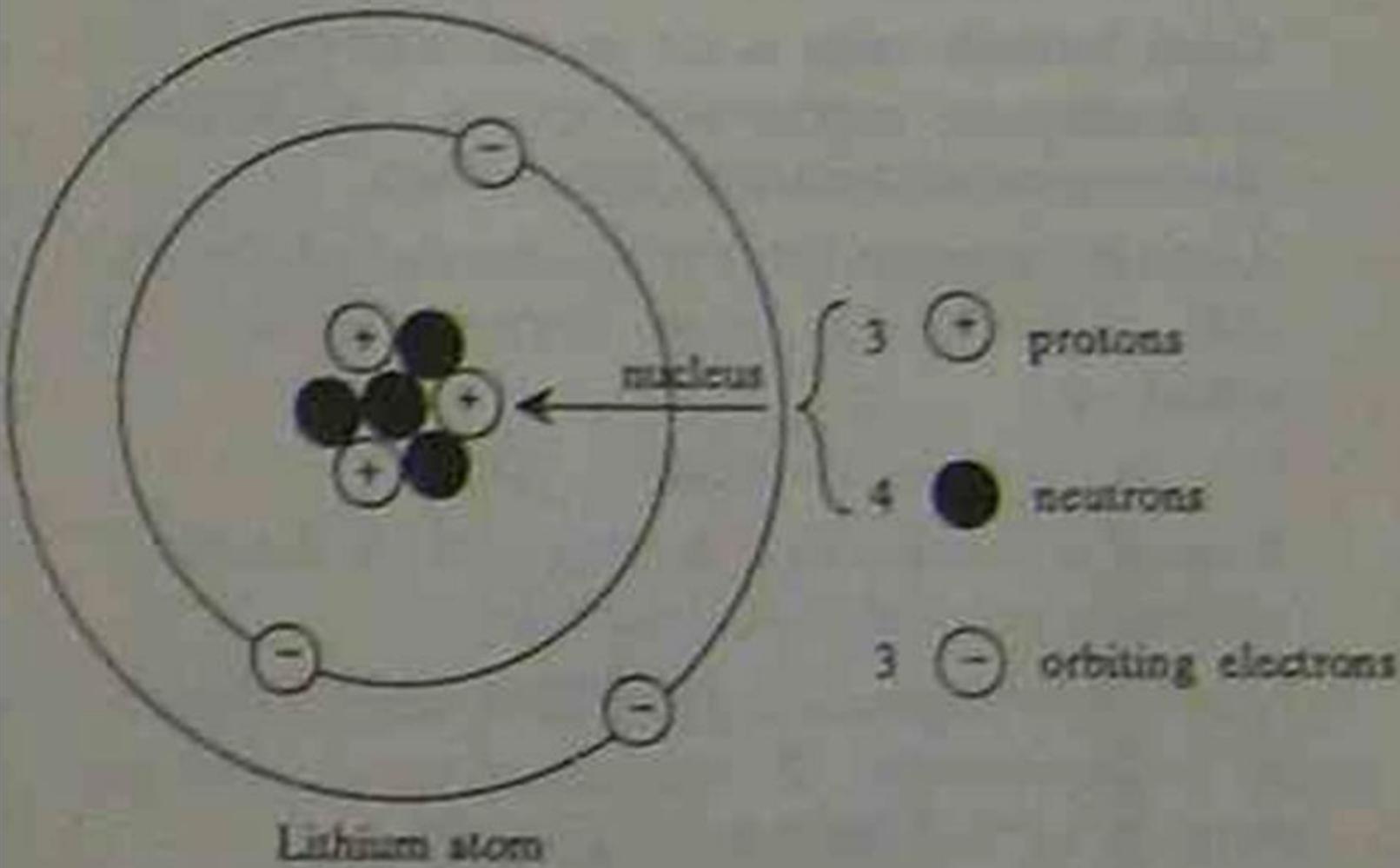


Fig. 7.1

(b) write in chemical shorthand the name (X), mass number (A) and atomic number (Z) of an element as:



e.g. Li⁺

2. recall and define the following atomic terms:

An element is a substance that contains only one type of atom.

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

The neutron number (symbol N) is the number of neutrons in the nucleus.

A nucleon is any particle in the nucleus.

Mass number (symbol A) is the number of protons plus the number of neutrons in the nucleus of the atom:

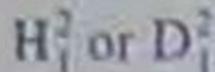
$$A = Z + N$$

An **isotope** is one of several nuclei which occupy the same place in the Periodic Table of elements. Isotopes of a given element have the same atomic number (proton number) but a different neutron number; e.g. the three isotopes of hydrogen are:

hydrogen



deuterium



tritium

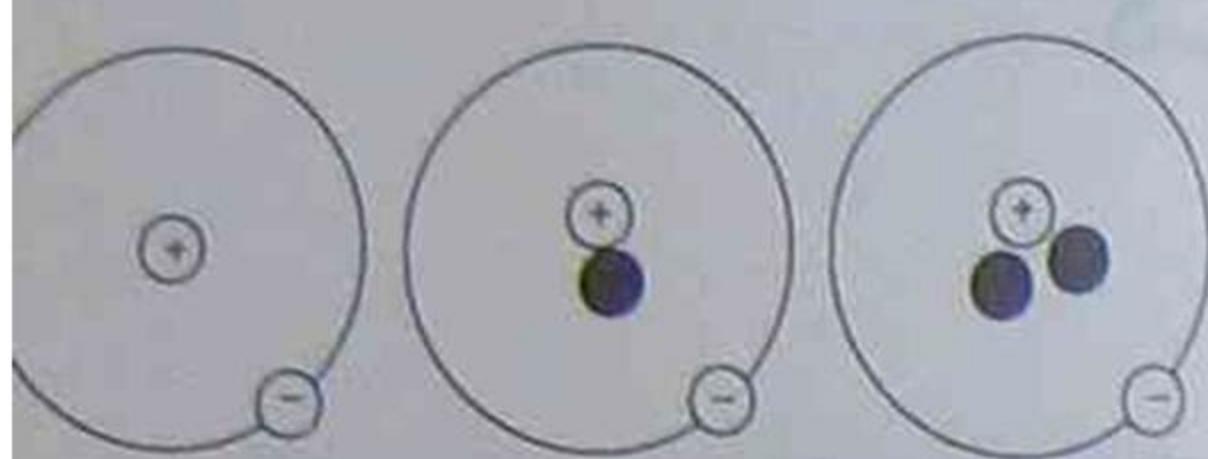
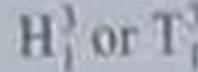


Fig. 7.2

Atomic mass is the mass of an atom compared with the mass of a C atom, which is taken to be 12.000 000 atomic mass units (amu or u).

$$1 \text{ amu} = 1.660\,32 \times 10^{-27} \text{ kg}$$

Gram formula mass is the atomic/molecular mass of a substance expressed in grams, e.g. the gram formula mass of carbon is 12.000 000 g.

Avogadro number (N_A) is the number of particles that make up the gram formula mass of a substance:

$$N_A = 6.022 \times 10^{23}$$

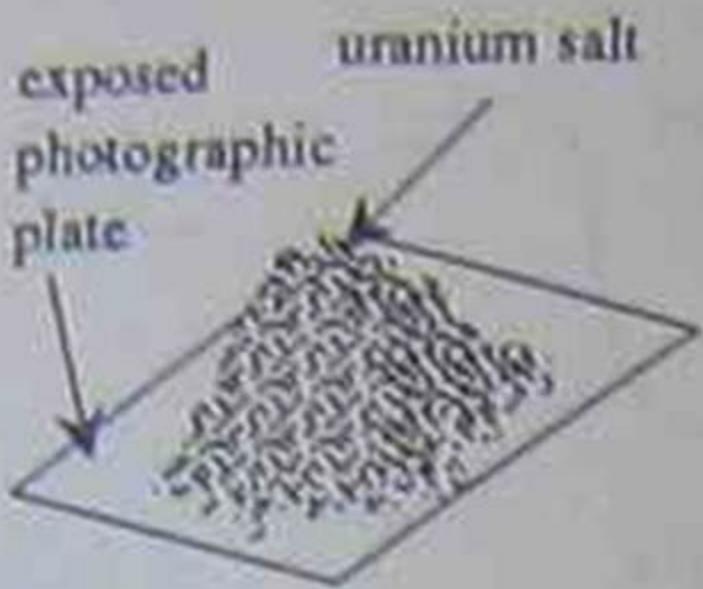
A mole of a substance is composed of Avogadro number of particles of that substance.

A nuclide or nucleide is a particular atom defined by its atomic number Z , mass number A , and the energy of its nucleus; it is written as ${}^A_Z X$.

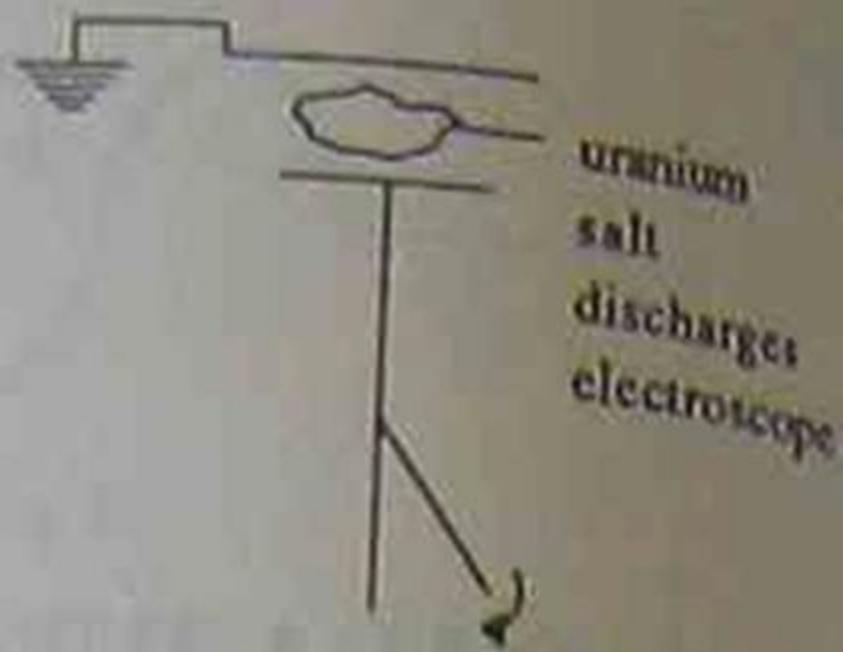
3. recall that in a modern atomic Periodic Table, elements are classified in order of increasing atomic number (see 'Atomic structure' elective, Chapter 19, Table 19.5).

Discovery of radioactivity

In 1896, the French scientist **Henri Becquerel** (1852–1908) found that a uranium salt, placed on a photographic plate and wrapped in light-proof paper, exposed the photographic plate (see Fig. 7.3(a)). The amount of exposure depended on the quantity of uranium on the plate.



(a)



(b)

Fig. 7.3

He also found that radiation discharged an electroscope (see Chapter 5 for description of an electroscope) as shown in Figure 7.3(b). This discharge is due to the radiation transferring electrons between air particles to form positive and negative particles called ions. This ionisation of the air near the vanes of the electroscope also yields free electrons. The ions and free electrons migrate towards, and neutralise the charge on, the vanes of the electroscope. The stronger radiation has a greater ability to ionise air which results in a more rapid discharge of a charged electroscope.

In Paris, Marie (1867–1934) and Pierre (1859–1906) Curie, discovered that thorium and its compounds were radioactive. They also painstakingly treated large quantities of the uranium ore pitchblende and extracted and named two radioactive elements, one in 1898 they called 'polonium', Po, and another in 1902 which they called 'radium', Ra.

Types of radiation

In 1898, working in the Cavendish Laboratory at Cambridge University in England, the New Zealander Ernest Rutherford (1871–1937) identified one type of radiation which could be stopped by paper. He called this radiation alpha (α) rays. He also identified a second, more penetrating, radiation which he named beta (β) rays. Villard, in 1900, showed that a long-range type of radiation existed which could not be deviated. These rays are known as gamma (γ) rays.

Nature of radiation

In 1904, Marie Curie outlined an experiment to show the effect of a magnetic field on α , β and γ rays (see Fig. 7.4). The movement of the radiation in the magnetic field showed that α rays are negative and γ rays are positive, β rays

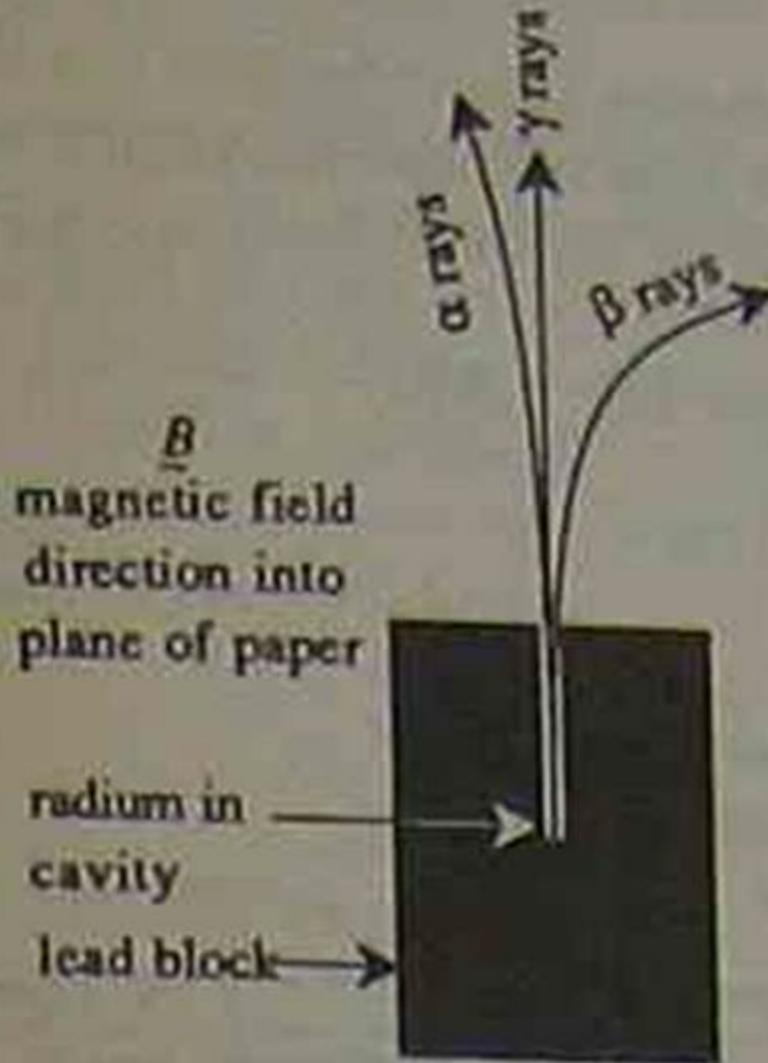


Fig. 7.4

In 1908, Rutherford and Geiger showed that α rays carry two units of positive charge.

In 1909, Rutherford and Royds showed that α rays are helium nuclei, ${}^2_2\text{He}^{2+}$ or He_2^4 , and may have different ranges in air.

Kaufmann (in 1901) and Bucherer (in 1908) showed that β rays are fast electrons, β or e^-_0 . They may have speeds up to 0.98 times the speed of light, i.e. $0.98c$.

Gamma rays are high-frequency electromagnetic radiation in the form of quanta of energy called photons, each with energy $E = hf$, where h is Planck's constant which has a value of 6.63×10^{-34} J s.

EXAMPLE

- (a) When, where, by whom and how was radioactivity first discovered?
- (b) How would you distinguish between α , β and γ rays?
- (c) A gamma ray has a frequency of 10^{20} Hz. What is its energy?

Answer

- (a) 1896, France; H. Becquerel; by chance when he found radiation from a uranium salt exposed a photographic plate in the dark.
- (b) Project the radiation into a magnetic field at right angles as shown in Figure 7.4. The radiation that deflects to the left is +ve (α rays), the radiation passing straight through is the γ radiation, and the radiation deflecting to the right is -ve (β rays).
- (c)
$$E = hf = 6.63 \times 10^{-34} \times 10^{20} \text{ J}$$
$$= 6.63 \times 10^{-14} \text{ J}$$

Properties and detection of nuclear radiation

1. Penetration is the ability of the radiation to pass through paper, aluminium and lead, as shown in Figure 7.5.

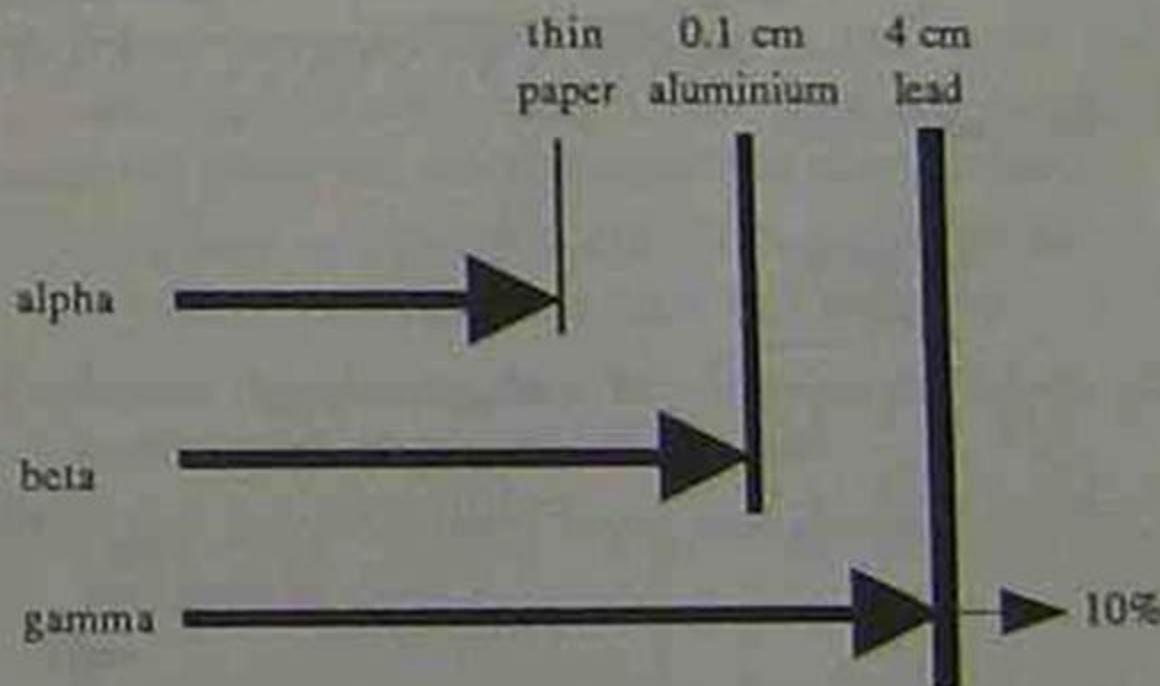


Fig. 7.5

2. Ionisation gives rise to the formation of ion pairs (see Fig. 7.6):

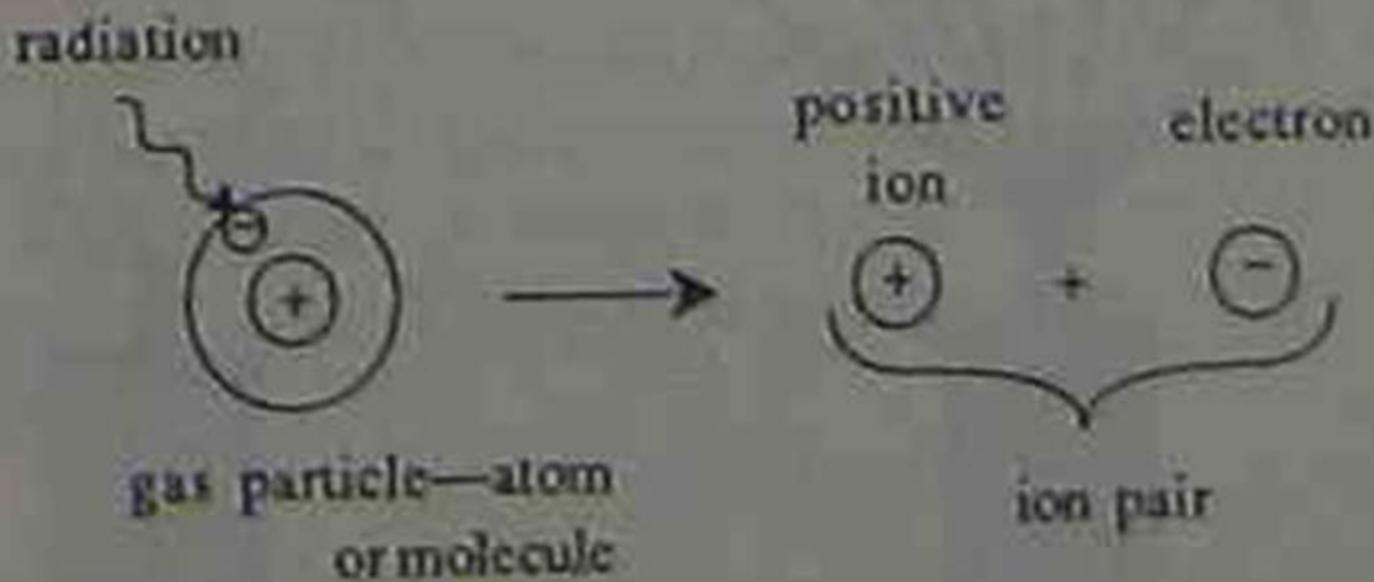
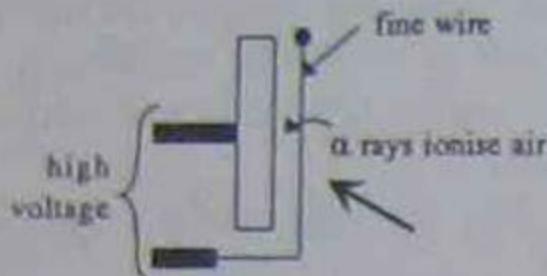


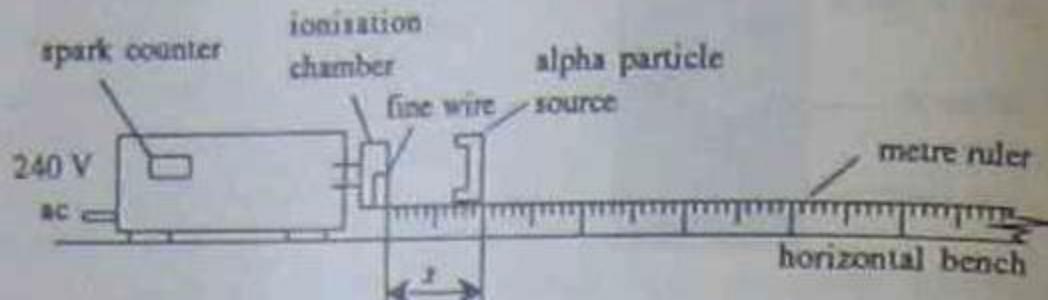
Fig. 7.6

The ability to ionise is measured in the number of ion pairs per centimetre of air (see Table 7.1). Strong ionising radiation rapidly loses energy and therefore has poor penetration. Ionisation gives rise to electrical conductivity in gases. This is the foundation of the detection of radiation by the

(a) Alpha spark counter.



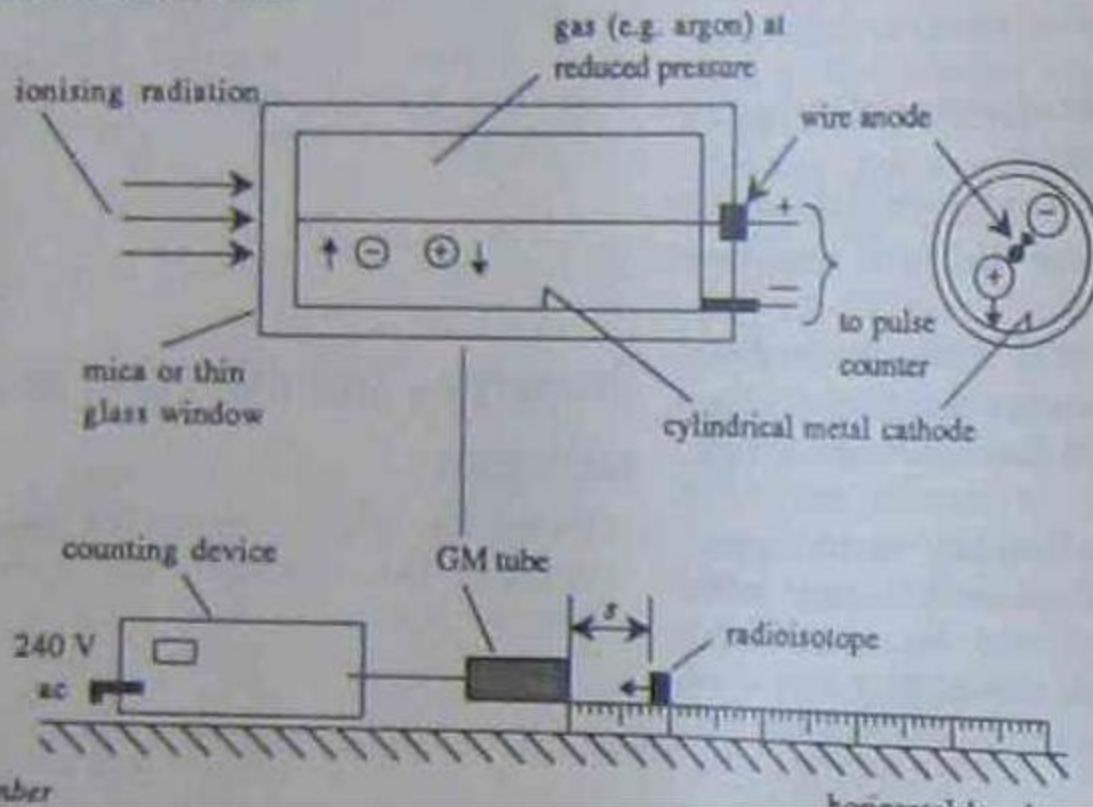
(b) Geiger-Müller tube and counter



following:

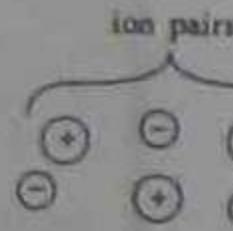
- alpha spark counter (Fig. 7.7(a));
- Geiger-Müller tube with counter (Fig. 7.7(b));
- cloud chamber—vapours form on ion trail (Fig. 7.7(c));
- electroscope (see Fig. 7.3(b)).

(b) Geiger-Müller tube counter

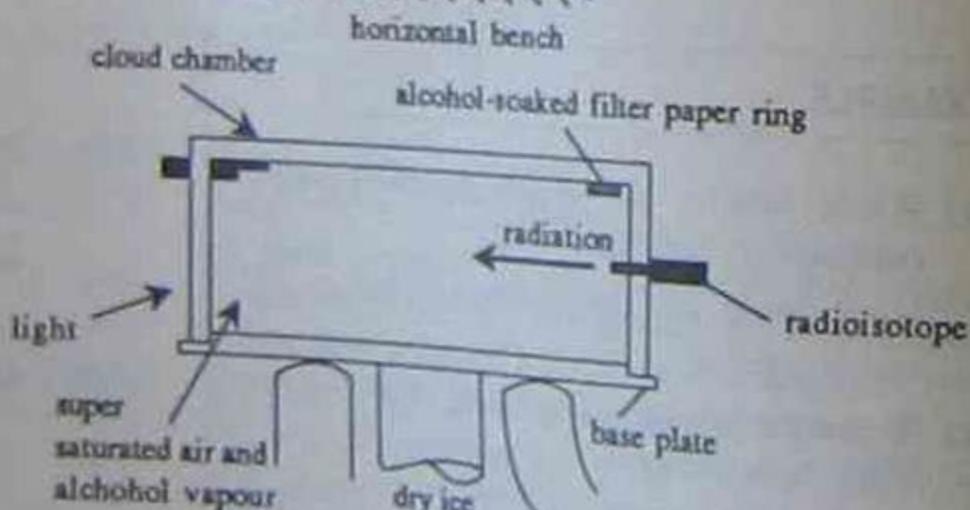


(c) Cloud chamber

(c) Cloud chamber



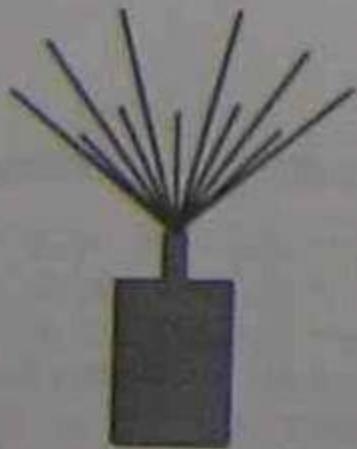
radiation ionises
gas particles by
collision



Cloud chamber tracks

alpha

— thick, straight



beta

— thin, zig-zag



gamma

paths of ejected
electrons
which ionise
gas



Fig. 7.7

3. Energy of rays varies. Values are approximately as shown in Table 7.1.
4. Fluorescence radiation produces light when it falls on certain substances. Sir William Crookes found that a flash of light or scintillation occurred when alpha particles fell on a zinc sulfide screen in a device called a spintharoscope (see Fig. 7.8). The number of flashes per second gives a measure of the intensity of the radiation.

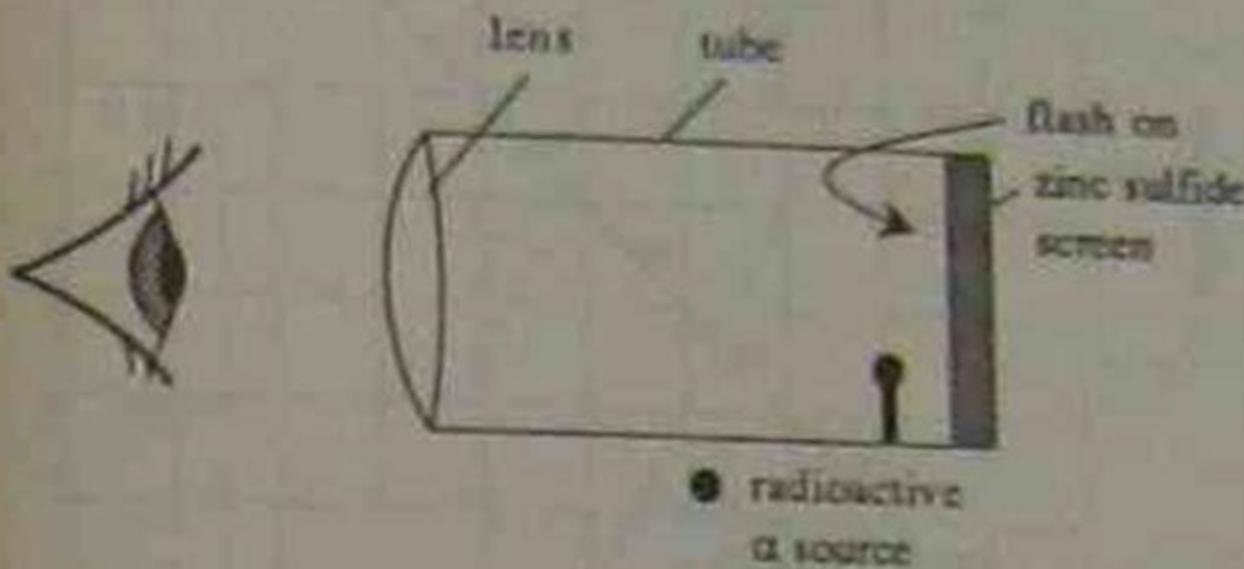


Fig. 7.8 Crookes' spintharoscope

5. Deflection of electric and magnetic fields shows that only alpha and beta rays are deflected in these fields.
6. Exposure of a photographic plate results from all three types of radiation.
7. Biological effects:
 - (a) harmful effects—the radiation may cause mutations, cancer and radiation sickness;
 - (b) useful effects—cancer treatment, sterilisation of surgical instruments and foodstuffs.

Table 7.1 Summary of the properties of alpha, beta and gamma rays

rays

Property	α particle	β particle	γ ray
Nature and symbol	nucleus of helium He^4	high-speed electron e^-	emission radiation γ
Rest mass	4.0015 amu	$= 1/2000$ amu	0
Charge	$+3.2 \times 10^{-19} \text{ C}$	$-1.6 \times 10^{-19} \text{ C}$	0
Energy	$= 6 \text{ MeV}$	$= 1 \text{ MeV}$	$\rightarrow 0.1 \text{ MeV}$
Velocity	$= 0.06c$	up to $0.98c$	c
Ability to ionise (ion pairs per cm of air)	$= 10^2$	$= 10^3$	$= 10^4$
Penetration	$= 5 \text{ mm of air}$	$= 5 \text{ cm of water}$	$= 4 \text{ cm of lead}$

of air) Penetra- tion	=5 cm of air	>500 cm of air =0.1 cm of Al	=4 cm of Pb (drop in intensity of 90%)
Track through matter	straight	straight	straight
Effect on: -emulsions -fluores- cent materials	strong	strong	weak

EXAMPLE

- (a) Assuming all necessary equipment is available in a laboratory, how would you distinguish between two radioactive sources, knowing that one was an alpha emitter and that the other emits beta rays?
- (b) Why does radioactivity discharge an electroscope?

Answer

- (a) Place one of the sources 1 cm from a Geiger-Müller (GM) tube and counter; note five 1 min readings on the counter, then calculate an average activity in counts per minute. Next place a sheet of paper between the source and the GM tube. If there is a large decrease in the average counts per minute reading, then the source is an alpha emitter.
- (b) The radioactivity produces ions in the air; these ions discharge the electroscope.

Representation of radioactive decay and decay series

By emitting radiation, an unstable nucleus can break down or decay to form a more stable nucleus.

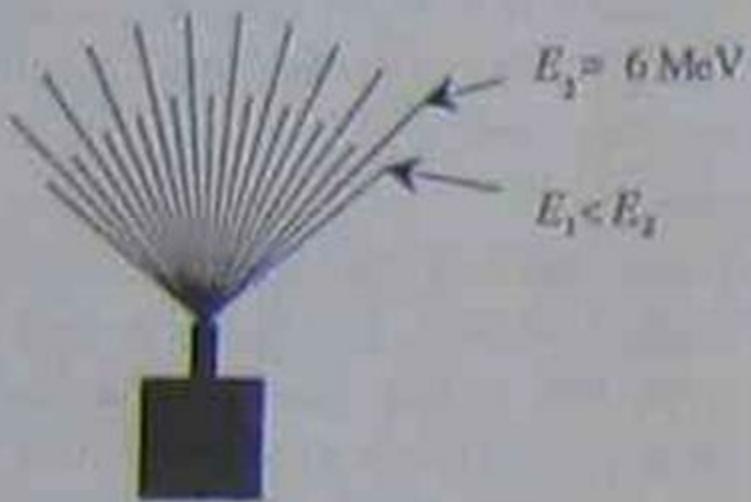
Alpha decay is decay of 'parent' atom X to yield 'daughter' atom Y plus an α particle, He_2^4 , with kinetic energy:



where A = mass number

Z = atomic number.

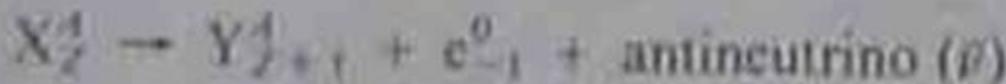
The alpha particle is the nucleus of a helium atom. It is ejected from the nucleus of the parent atom X. These α 's may have a range of energies, E , as shown by cloud chamber tracks in Figures 7.7(c) and 7.9.



alpha particle tracks
Velocity $\approx 0.06 \times$ velocity of light

Fig. 7.9

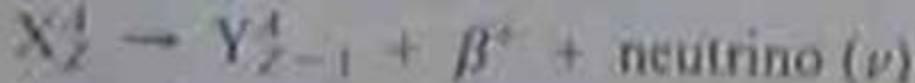
Beta decay is decay of 'parent' atom X to yield 'daughter' atom Y plus a beta particle, e^-_1 , and an antineutrino:



During beta decay, a nuclear neutron decays to form a proton, which stays in the nucleus, and a beta particle and antineutrino. Both the beta particle and antineutrino may have a range of energies. Beta decay can be represented as follows:



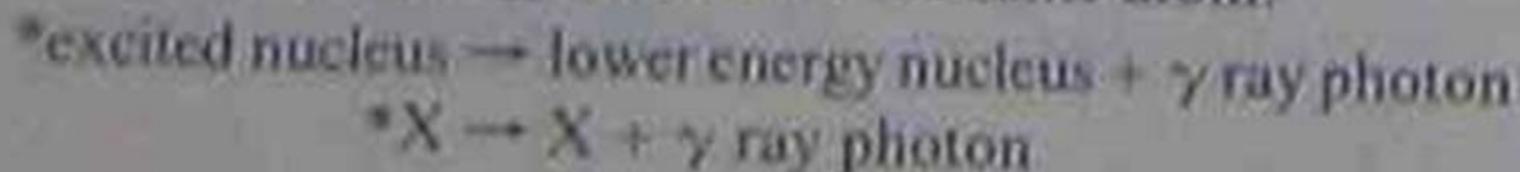
Positron (positive electron) decay (β^+ decay) is decay of 'parent' atom X to yield 'daughter' atom Y, plus a positron (β^+) and a neutrino:



During positron decay, e.g. from a nucleus with excess protons, a proton decays to form a neutron, a positron, and a neutrino:



Gamma decay is the emission of a photon of energy from a high-energy or excited nucleus of an atom to form a lower energy nucleus of the same atom:



In nature and in artificial circumstances it is found that products, called 'daughters', of radioactive decay are often themselves radioactive and so form a **decay series**. The series usually ends with the formation of a stable isotope of lead, Pb. Isotopes in a decay series can be represented graphically (see Fig. 7.10) as a plot of their mass number (vertical axis) versus their atomic number. Also shown for each decay is the type of emitted radiation.

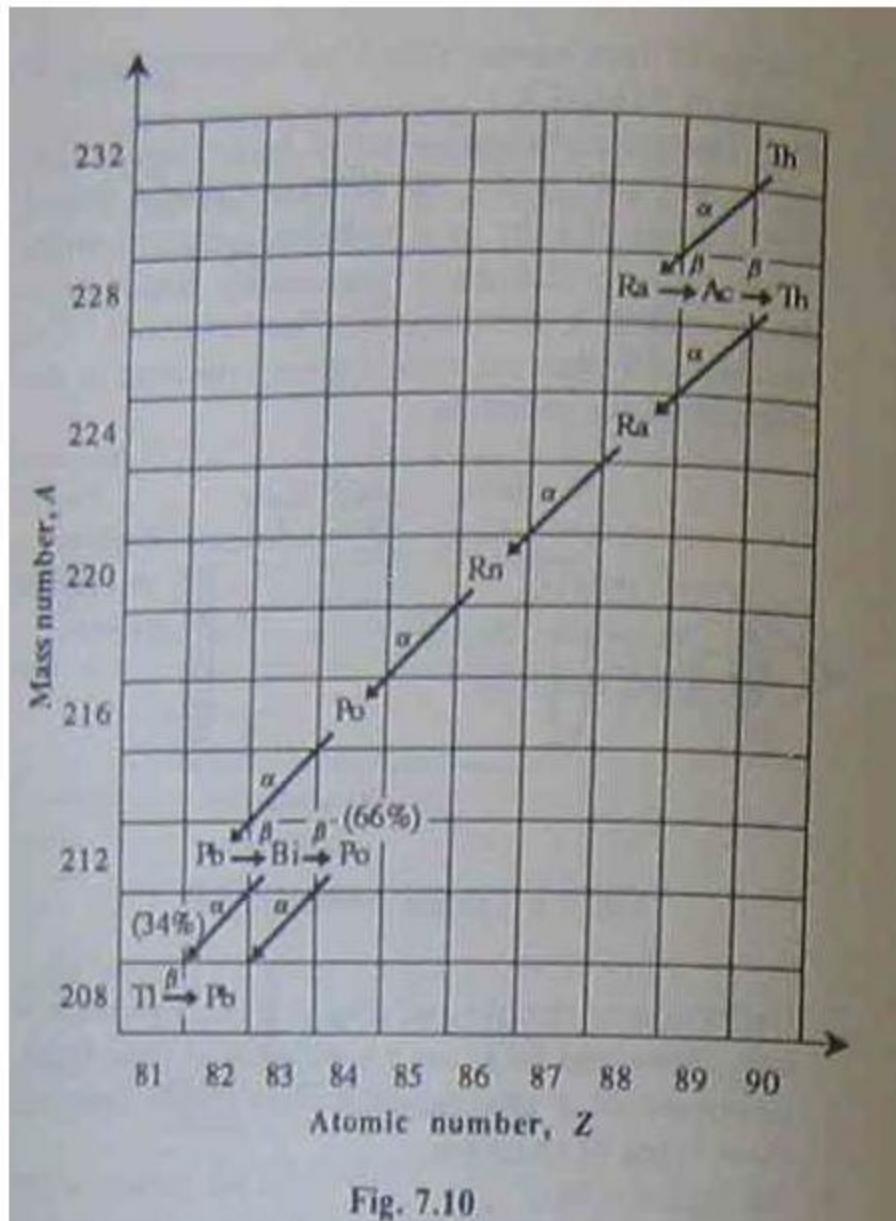


Fig. 7.10

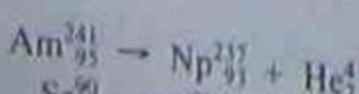
EXAMPLE

- (a) Write equations to represent:
- alpha decay from Am^{241}_{95} ;
 - beta decay from Sr^{90}_{38} ;
 - gamma decay from Co^{60}_{27} .
- (b) Graphically represent the first three decays in the naturally occurring thorium decay series. Use the Periodic Table (Ch. 19, Table 19.5) and the data in the table below.

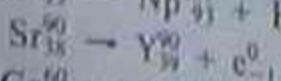
Decay number	Parent isotope	Radiation emitted		
		Type	Half-life	Energy (MeV)
1st	Th^{232}_{90}	α	1.4×10^{10} years	
2nd	Ra^{228}_{88}	β	6.7 years	4.0
3rd	Ac^{228}_{89}	β	1.9 hours	0.05
				2.1

Answer

(a) (i)



(ii)



(iii)

