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Physics
Xavier International College

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Chapter- Radioactivity

Key Points

1. Looking inside the atom
2. Alpha particles scattering and the nucleus
3. A simple model of the atom
4. Nucleons and electrons
5. Forces in the nucleus
6. Fundamental particles
7. Families of particles
8. Discovering radioactivity
9. Radiation from radioactive substances
10. Discovering neutrinos
11. Fundamental families
12. Fundamental forces
13. Properties of ionizing radiation

Introduction

- The idea that matter is composed of very small particles called atoms was first suggested by the Greeks some 2000 years ago.
- The English scientist J.J Thomson suggested that the atom is a neutral particle of a positive charge with lumps of negative charges electrons.
- Experiments show that the electron has a mass of approximately 9.11×10^{-31} kg and charge of -1.60×10^{-19} C.
- The phenomenon of spontaneous emission of highly penetrating radiation (α, β and ɣ rays) form nucleus of heavy elements to give stable lighter nuclei is called Radioactivity.
- For example : Uranium, Radium Neptunium etc.

Radioactivity is two types

1. Natural radioactivity
2. Artificial radioactivity

Rutherford scattering

- Evidence for the structure of the atom was discovered by Ernest Rutherford in the beginning of the 20th century from the study of **α-particle scattering**
- The experimental setup consists of alpha particles fired at thin gold foil and a detector on the other side to detect how many particles deflected at different angles.
- One reason for choosing gold was that it can be made into a very thin sheet or foil. Rutherford's foil was only a few hundreds of atoms thick.
- Air in the apparatus was pumped out to leave a vacuum, α- radiation is absorbed by a few cm of air

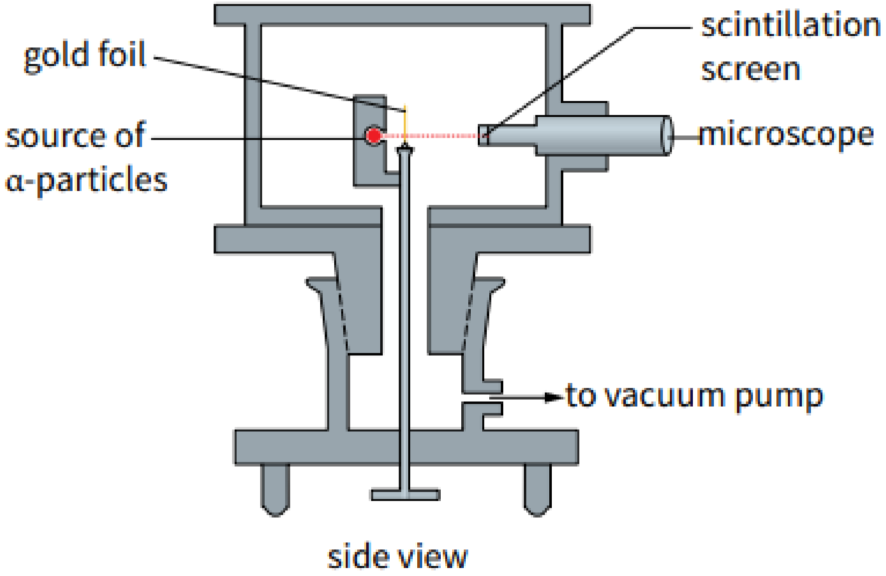
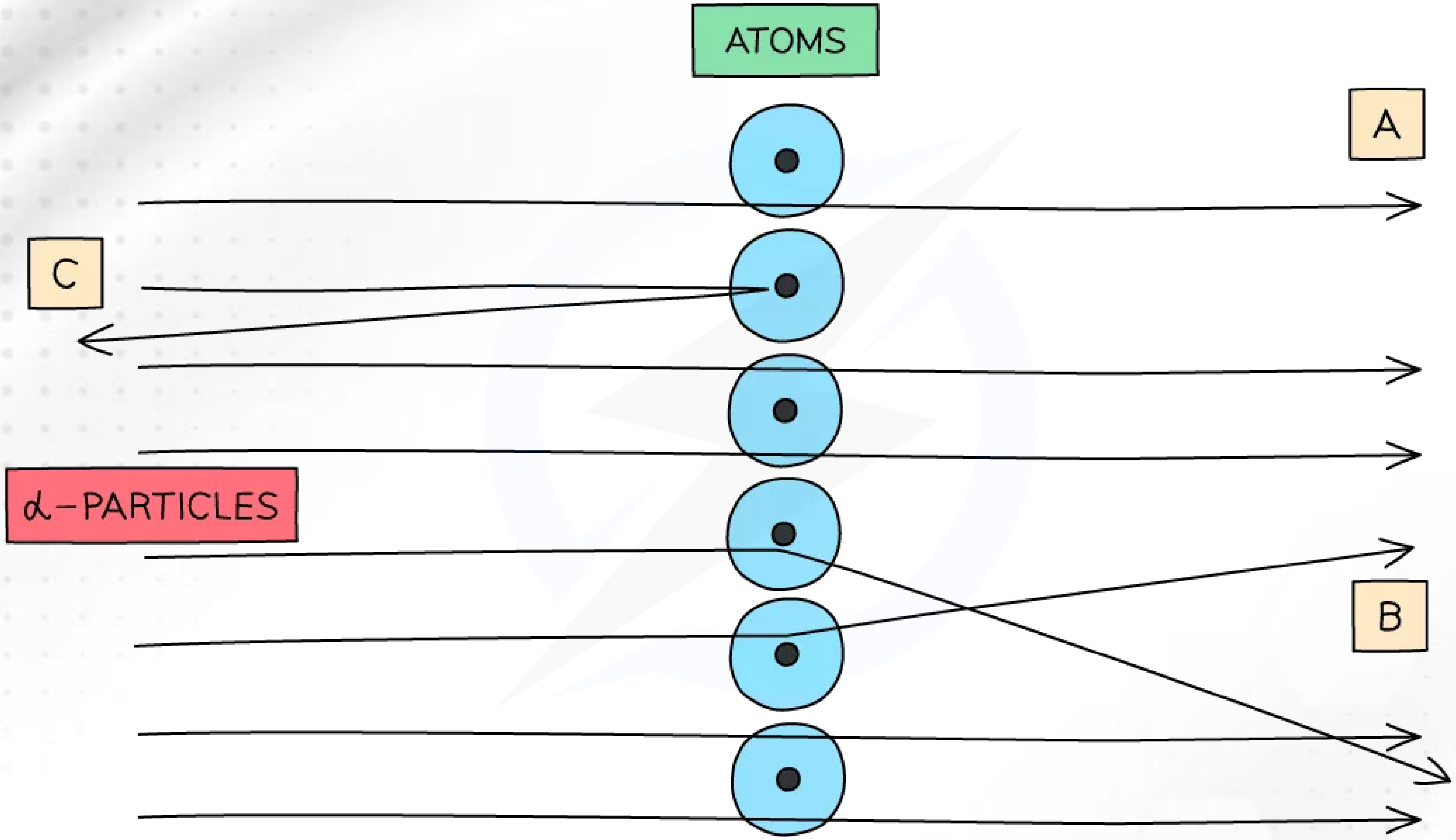


Figure 16.3 The apparatus used for the α-scattering experiment. The microscope can be moved round to detect scattered radiation at different angles.

- The α-particles were detected when they struck a solid ‘scintillating’ material. Each α-particle gave a tiny flash of light and these were counted by the experimenters (Geiger and Marsden).
- The detector could be moved round to detect α-particles scattered through different angles.

- α-particles are the nucleus of a helium atom having two protons and two neutron and are positively charged.
- α-particles are more massive than electrons.
- They are deflected by electric and magnetic fields.
- Their speed is much less than that of light.
- They have less penetrating power.

${}^{4}_{2}\alpha$ OR ${}^{4}_{2}\mathrm{He}$



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When α particles are fired at thin gold foil, most of them go straight through but a small number bounce straight back.

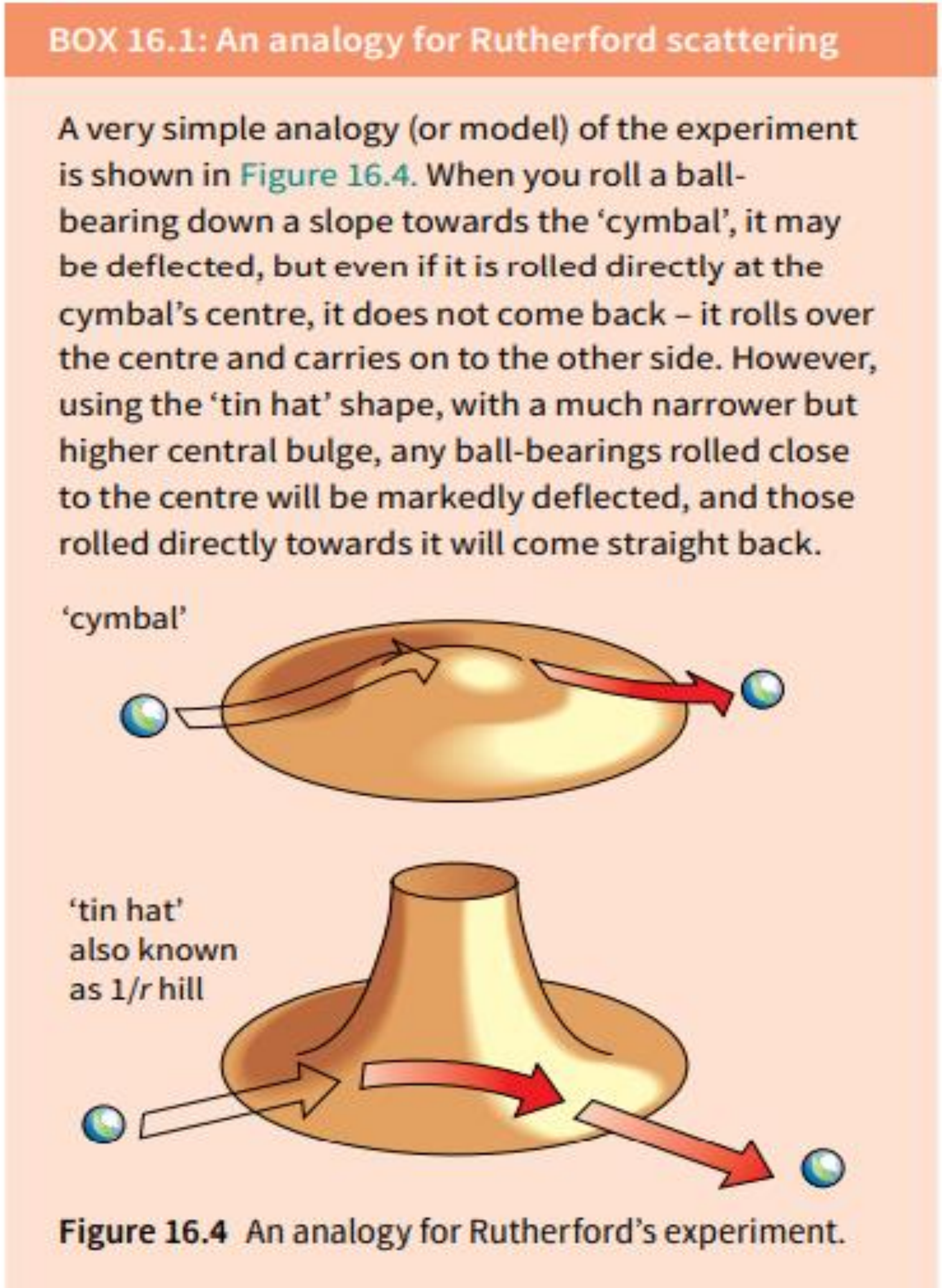
- From this experiment, Rutherford results were:
- **The majority of α-particles went straight through (A)**

  This suggested the atom is mainly empty space
- **Some α-particles deflected through small angles of $< 10^{o}$**

  This suggested there is a positive nucleus at the centre (since two positive charges would repel)
- .Only a small number of **α-** particles deflected straight back at angles of **$> 90^{o}$**.

  \- This suggested the nucleus is extremely small and this is where the mass and charge of the atom is concentrated.

  \- It was therefore concluded that atoms consist of small dense positively charged nuclei, surrounded by negatively charged electrons.
- Large number of **α-** particles deflected due to the electrostatic repulsion between the positive charge of the **α-** particle and +vely charge nucleus.



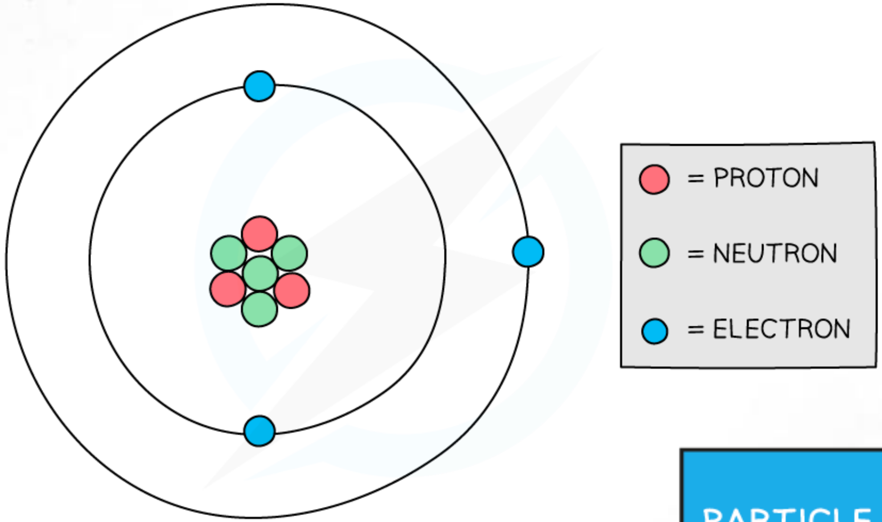
BOX 16.1: An analogy for Rutherford scattering

A very simple analogy (or model) of the experiment is shown in Figure 16.4. When you roll a ball-bearing down a slope towards the 'cymbal', it may be deflected, but even if it is rolled directly at the cymbal's centre, it does not come back – it rolls over the centre and carries on to the other side. However, using the 'tin hat' shape, with a much narrower but higher central bulge, any ball-bearings rolled close to the centre will be markedly deflected, and those rolled directly towards it will come straight back.

Figure 16.4 An analogy for Rutherford's experiment.

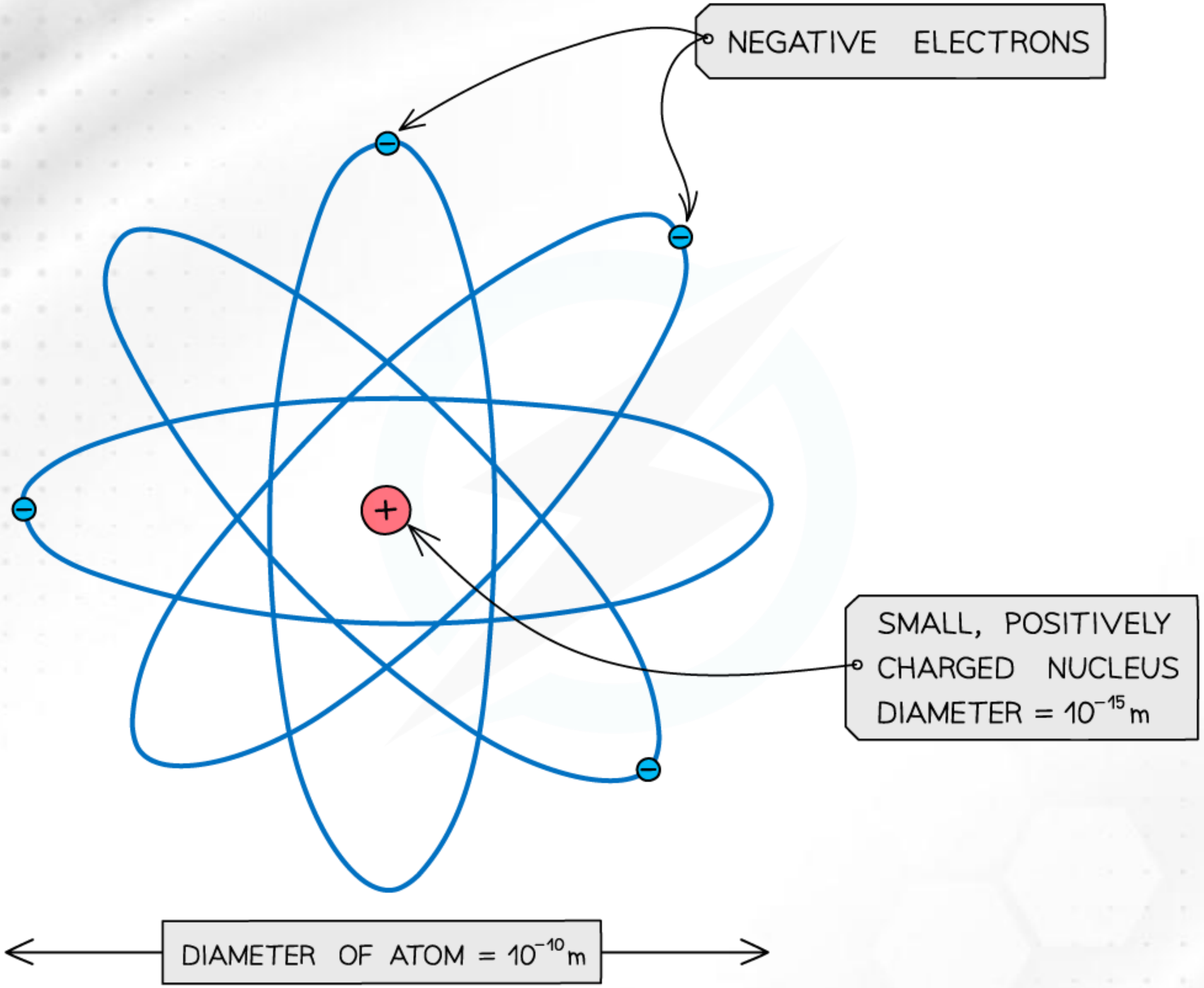
Atomic Structure

- The atoms of all elements are made up of three types of particles: protons, neutrons and electrons.



- The atoms of all elements are made up of three types of particles: protons, neutrons and electrons.
- The properties of each particle are shown in the table below:

PARTICLE	RELATIVE CHARGE	RELATIVE MASS
PROTON	+1	1
NEUTRON	0	1
ELECTRON	−1	1/2000 (NEGLIGIBLE)



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- An atom: a small

- A stable atom is **neutral** (it has no charge)
- Since protons and electrons have the same charge, but opposite signs, a stable atom has an equal number of both for the overall charge to remain neutral
- Protons and neutrons make up the nucleus of the atom.
- The electrons move around the nucleus in a cloud, some closer to and some further from the centre of the nucleus
- 99% of the atom is empty.

The scale of things

- It is useful to have an idea of the approximate sizes of typical particles:
- radius of proton ~ radius of neutron ~ 10^{-15}m
- radius of nucleus ~ 10^{-15}m to 10^{-14}m
- radius of atom ~ 10^{-10}m
- size of molecule ~ 10^{-10}m to 10^{-6}m
- (Some molecules, such as large protein molecules, are very large indeed – compared to an atom!) The radii of nuclear particles are often quoted in femtometres (fm), where 1 fm = 10^{-15}m .

Nuclear Density

- A proton is a small and positively charged sphere.

  mass of proton m_p= 1.67 $\times 10^{-27}$ kg

  Radius of proton r = 0.80fm = 0.80 $\times 10^{-15}$ m

  volume of proton = 4/ 3 πr^3

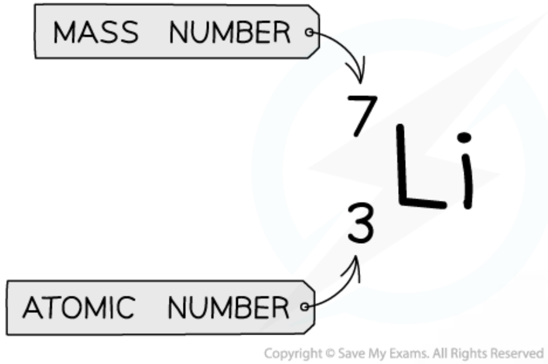
  $$= 4/3\ \pi \times (0.80 \times 10^{-15})^3$$

  $$= 2.14 \times 10^{-45} m^3 \approx 2.1 \times 10^{-45}\ m^3$$

- Density = $\frac{mass}{volumn}$
- Density = $\frac{1.67 \times 10^{-27}}{2.1 \times 10^{-45}} \approx\ 7.8 \times 10^{17}\ m^{-3}$
- This is also the density of a neutron, and of an atomic nucleus.

Nucleon and Proton Number

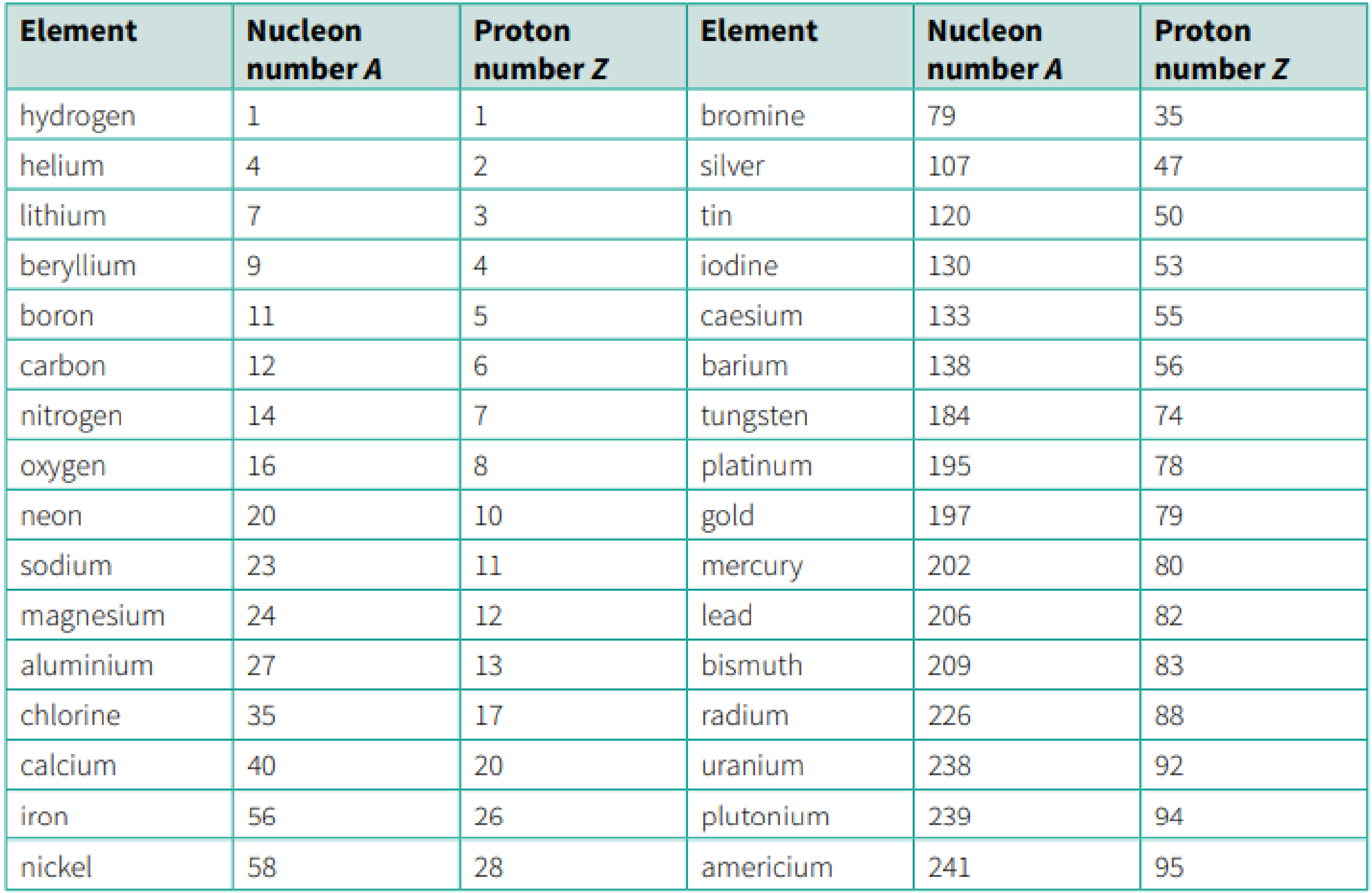
- The atomic symbol of an element is used to describe the constituents of the nuclei
- An example of this notation for Lithium is:



- When given an atomic symbol, you can figure out the number of protons, neutrons and electrons in the atom:
  - **Protons**: The atomic number
  - **Electrons**: Atoms are neutrals, so the number of negative electrons is equal to the number of positive protons. Therefore, this is also the atomic number
  - **Neutrons**: Subtract the proton number from the mass number

- Protons and neutrons in a nucleus are collectively called nucleons. For example, in a nucleus of gold, there are 79 protons and 118 neutrons, giving a total of 197 nucleons altogether.
- The nucleon number is equal to the sum of the number of neutrons in the nucleus, the neutron number N, and the number of protons, the proton number (or atomic number) Z,

  i.e. $A = N+Z$
- For lighter atoms number of protons are equal to number of neutrons while for heavy atoms number of neutrons are always greater than number of protons.



Element	Nucleon number *A*	Proton number *Z*	Element	Nucleon number *A*	Proton number *Z*
hydrogen	1	1	bromine	79	35
helium	4	2	silver	107	47
lithium	7	3	tin	120	50
beryllium	9	4	iodine	130	53
boron	11	5	caesium	133	55
carbon	12	6	barium	138	56
nitrogen	14	7	tungsten	184	74
oxygen	16	8	platinum	195	78
neon	20	10	gold	197	79
sodium	23	11	mercury	202	80
magnesium	24	12	lead	206	82
aluminium	27	13	bismuth	209	83
chlorine	35	17	radium	226	88
calcium	40	20	uranium	238	92
iron	56	26	plutonium	239	94
nickel	58	28	americium	241	95

- For the lithium atom, these numbers would be:

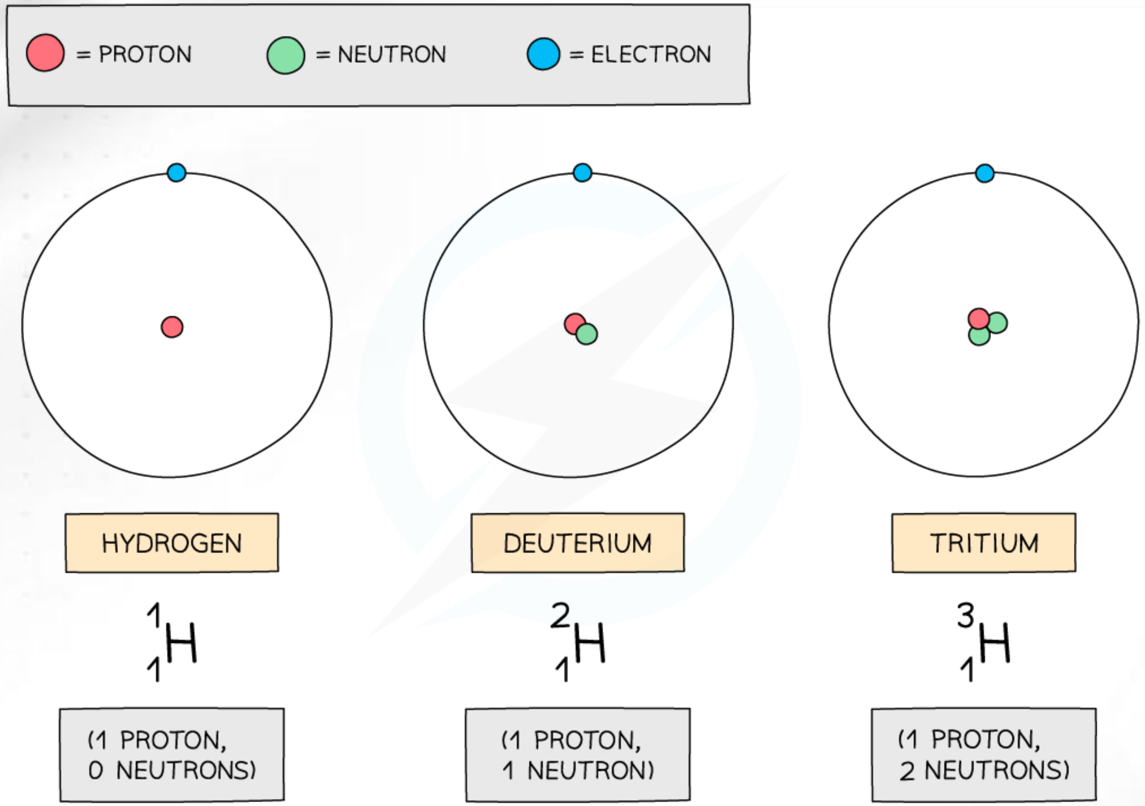
  Protons: 3

  Electrons: 3

  Neutrons: 7 − 3 = 4
- The term **nucleon** is the used to mean a particle in the nucleus – i.e. a proton or neutron
- The term **nuclide** is used to refer to a nucleus with a specific combination of protons and neutrons

Isotopes

- Although all atoms of the same element always have the same number of protons (and hence electrons), the number of neutrons can vary
- **An isotope is an atom (of the same element) that has an equal number of protons but different number of neutrons**
- The isotopes of hydrogen are deuterium and tritium:



- Remember, the neutron number of an atom is found by subtracting the proton number from the nucleon number
- Since nucleon number includes the number of neutrons, an isotope of an element will also have a **different nucleon/mass number**
- Since isotopes have an imbalance of neutrons and protons, they are **unstable**. This means they constantly decay and emit radiation to achieve a more stable form
- This can happen from anywhere between a few nanoseconds to 100,000 years

The atom ${}^{133}_{55}Cs$ is a neutral atom

How many protons, neutrons and electrons are in this atom?

	protons	neutrons	electrons
A	133	55	133
B	55	78	55
C	78	55	78
D	55	133	55

One of the rows in the table shows a pair of nuclei that are isotopes of one another.

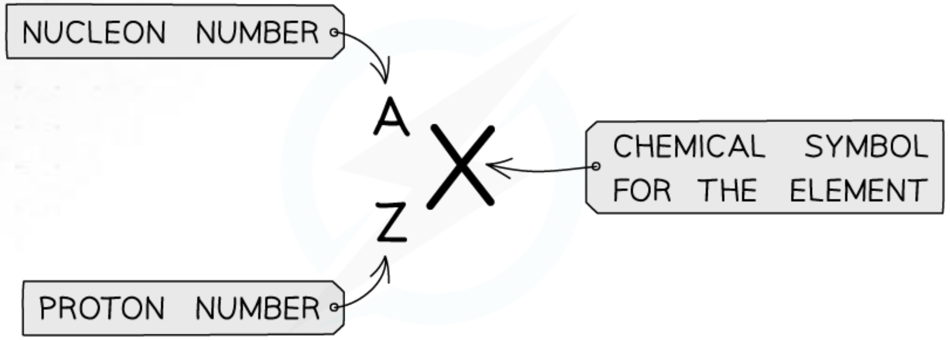
Which row is it?

	nucleon number	number of neutrons
A	186 180	112 118
B	184 187	110 110
C	186 182	112 108
D	186 186	110 112

- Any atom is electrically neutral so, the number of electrons surrounding the nucleus must equal the number of protons in the nucleus of the atom.
- If an atom gains or loses an electron, it is called ion.
- Generally, for an atom, the number of electrons determines the chemical properties while number of protons and neutrons determine the nuclear properties.
- The different number of neutrons in the isotopes of an element means that the isotopes have different relative atomic masses, and also differences in physical properties such as density and boiling point.

AZX Notation

- Atomic symbols are written in a specific notation called **AZX notation.**



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- The top number A represents the **nucleon** number or the **mass** number
  Nucleon number (A) = total number of **protons and neutrons** in the nucleus
- The lower number Z represents the **proton** or **atomic** number
  Proton number (Z) = total number of **protons** in the nucleus

- Note: In Chemistry the nucleon number is referred to as the mass number and the proton number as the atomic number. The periodic table is ordered by atomic number

Force in the nucleus

- In the nucleus, there are two kinds of particles : protons and neutrons. Protons are positively charged while neutrons are charge less.
- In the nucleus, the electrostatic repulsions form all those positively charged protons. But there is attraction force between nucleons called strong nuclear force.
- Strong force acts over short distances (10^{-14}m) and it holds the nucleus together.
- In a large nucleus the nucleons are not held together so tightly and this can make the nucleus unstable. The more protons in the nucleus, the greater the electric forces between them and we need a few extra neutrons to help keep the protons apart.
- The instability of nucleus depends upon the number of protons and neutrons,

Conservation of Nucleon Number and Charge

- Nuclear processes such as fission and fusion are represented using nuclear equations (similar to chemical reactions in chemistry)
- The number of protons and neutrons in atom is known as its **constituents**
- For example:

$$^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{90}_{38}Sr + {}^{144}_{54}Xe + 2\,{}^{1}_{0}n$$

- The above equation represents a fission reaction in which a Uranium nucleus is hit with a neutron and splits into two smaller nuclei – a Strontium nucleus and Xenon nucleus, releasing two neutrons in the process
- In nuclear equations, the nucleon number and charge are always **conserved**
- This means that the sum of the nucleons and charge on the left hand side must equal the sum of the number of nucleons and charge on the right hand side

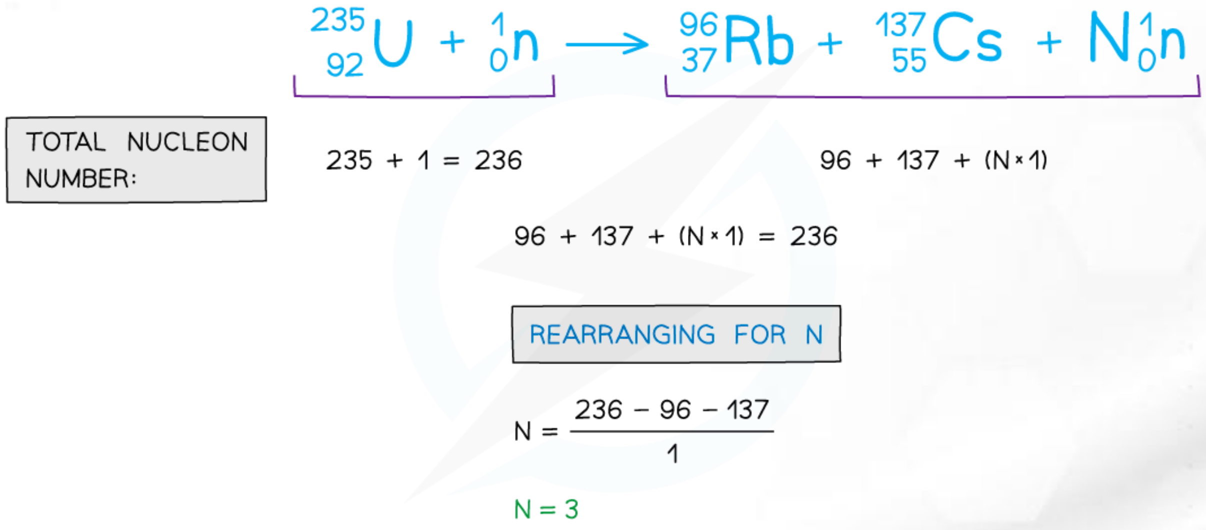
- In the above equation, the sum of the nucleon (top) numbers on both sides are equal

$$235 + 1 = 236 = 90 + 144 + 2 \times 1$$

- The same is true for the proton (bottom) numbers

$$92 + 0 = 92 = 38 + 54 + 2 \times 0$$

- By balancing equations in this way, you can determine the nucleon, proton number or the number of missing elements



$$\underbrace{{}^{235}_{92}U + {}^{1}_{0}n}_{235 + 1 = 236} \longrightarrow \underbrace{{}^{96}_{37}Rb + {}^{137}_{55}Cs + N\,{}^{1}_{0}n}_{96 + 137 + (N \times 1)}$$

TOTAL NUCLEON NUMBER:

$$96 + 137 + (N \times 1) = 236$$

REARRANGING FOR N

$$N = \frac{236 - 96 - 137}{1}$$

$$N = 3$$

Fundamental Particles

- There are differences types of particles other than proton, electron and neutron.
- These new particles were found in two ways:
- by looking at cosmic rays, which are particles that arrive at the Earth from outer space
- by looking at the particles produced by high-energy collisions in particle accelerators

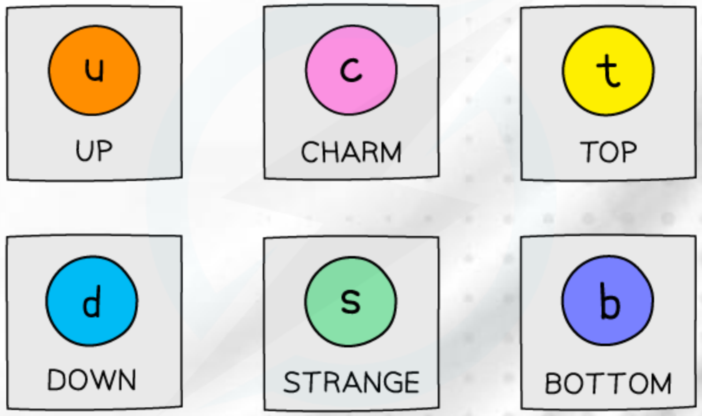
Figure 16.10 Particle accelerators have become bigger and bigger as scientists have sought to look further and further into the fundamental nature of matter. This is one of the particle detectors of the Large Hadron Collider (LHC), as it was about to be installed. The entire collider is 27 km in circumference.

Families of particles

- Today, sub atomic particles are divided into two families:
- Hadrons such as protons and neutrons. These are all particles that are affected by the strong nuclear force.
- Leptons such as electrons. These are particles that are unaffected by the strong nuclear force.
- The word ‘hadron’ comes from a Greek word meaning ‘bulky’, while ‘lepton’ means ‘light’ (in mass). It is certainly true that protons and neutrons are bulky compared to electrons.
- There are large numbers of experimenting with hadrons in Large Hadron Collider at the CERN laboratory in Geneva.
- Higgs boson is a particle discovered in 2013, which is required to explain why matter has mass.

Fundamental Particles: Quarks

- Murray Gell Mann in 1964 proposed a new model that hadrons were made up of a few different particles called quarks.
- Quarks are **fundamental particles** that make up other subatomic particles such as **protons and neutrons**
- Protons and neutrons are in a category of particles called **hadrons**
  - Hadrons are defined as any particle made up of quarks
- **Fundamental** means that quarks are not made up of any other particles. Another example is electrons
- Quarks have never been observed on their own, they're either in pairs or groups of three
- There are six flavors (types) of quarks that exist:



Which of the following statements is what the Rutherford scattering experiment has led to?

A the quark model of hadrons

B the discovery of the electron

C evidence for wave–particle duality

D the discovery of the nucleus

Rutherford used the scattering of α particles to provide evidence for the structure of the atom. The apparatus includes an α particle source fired at a gold foil inside a vacuum chamber.

a) Explain why is it essential for there to be a vacuum in the chamber.

Antimatter is a particle that is an antiparticle to the corresponding particle. A positron is th
antiparticle of an electron.

What is the difference between a positron and an electron?

A mass

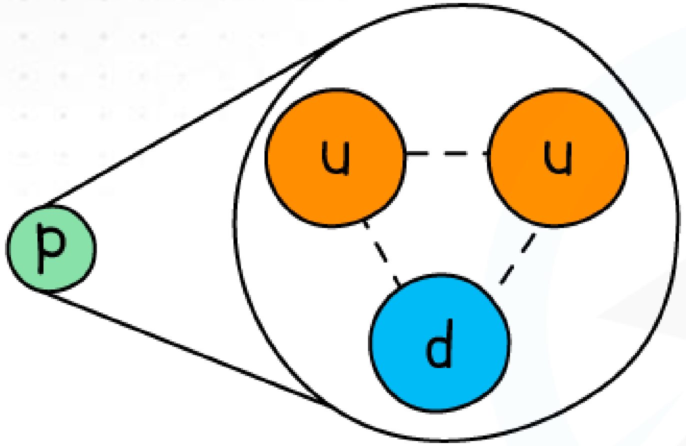
B magnitude of charge

C charge

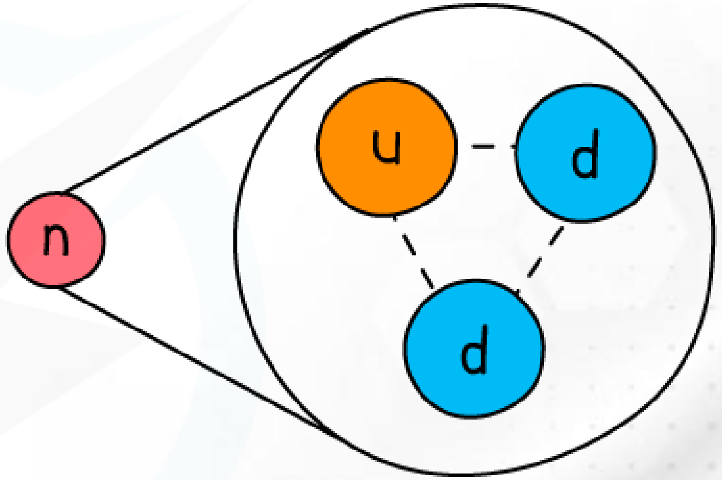
D spin

Quark Composition: Protons and Neutrons

- Protons and neutrons are **not** fundamental particles. They are each made up of three quarks
- **Protons** are made up of **two up quarks and a down quark**
- **Neutrons** are made up of **two down quarks and an up quark**



PROTON: uud



NEUTRON: udd

- A pi+ meson is made up of an up quark and a down antiquark; pi+ meson = (u$\bar{d}$).
- A pi meson is made up of a strange quark and an antistrange quark; phi meson = (s$\bar{s}$)
- Antiquarks are shown with a ‘bar’ on top of the letter for the quark.
- Antiquarks are needed to account for the existence of antimatter.
- When particles and antiparticles of same types meets they annihilate each other leaving only photons of energy.

Discovering Radioactivity

- The French physicist Henri Becquerel first introduced radioactivity in 1896. He was looking at the properties of uranium compounds.
- The process by which an unstable nucleus becomes stable or less unstable by emitting radiations like alpha (α), beta (β)and gamma (ɣ) is called radioactivity.
- Normally, the nuclei having more number of protons than the number of neutrons are unstable i.e. if the electrostatic repulsive force is greater than attractive strong force in the nucleus, nucleus is unstable.

Radiation from radioactive substances

- There are three types of radiation which emitted by radioactive substances : alpha (α), beta (β)and gamma (ɣ) radiations come from the unstable nuclei of atoms.
- If the number of protons and neutrons in an atom are not balanced than the nucleus may emits α and β radiations while gamma radiation is usually emitted after α and β decay.

Alpha, Beta and Gamma Particles

- Some elements have nuclei that are unstable
  - This tends to be when the number of nucleons does not balance
- In order to become more stable, they emit particles and/or electromagnetic radiation
  - These nuclei are said to be **radioactive**
- There are three different types of radioactive emission:
- **Alpha (α) particles** are high energy particles made up of **2 protons and 2 neutrons** (the same as a helium nucleus)
- They are usually emitted from nuclei that are too large

$${}^{4}_{2}\alpha \quad \text{OR} \quad {}^{4}_{2}\mathrm{He}$$

- **Beta (β^-) particles are high energy electrons** emitted from the nucleus
- **Beta (β^+) particles are high energy positrons** (antimatter of electrons) also emitted from the nucleus
  - β^- particles are emitted by nuclei that have too many **neutrons**
  - β^+ particles are emitted by nuclei that have too many **protons**

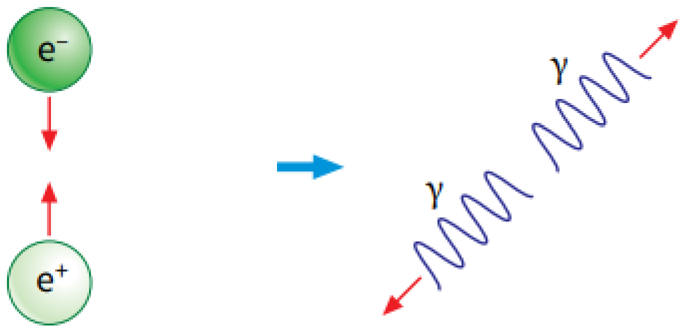
$${}^{0}_{-1}\beta \qquad {}^{0}_{+1}\beta$$

BETA MINUS

BETA PLUS

- **Gamma (γ) rays are high energy electromagnetic waves**
- They are emitted by nuclei that need to lose some energy

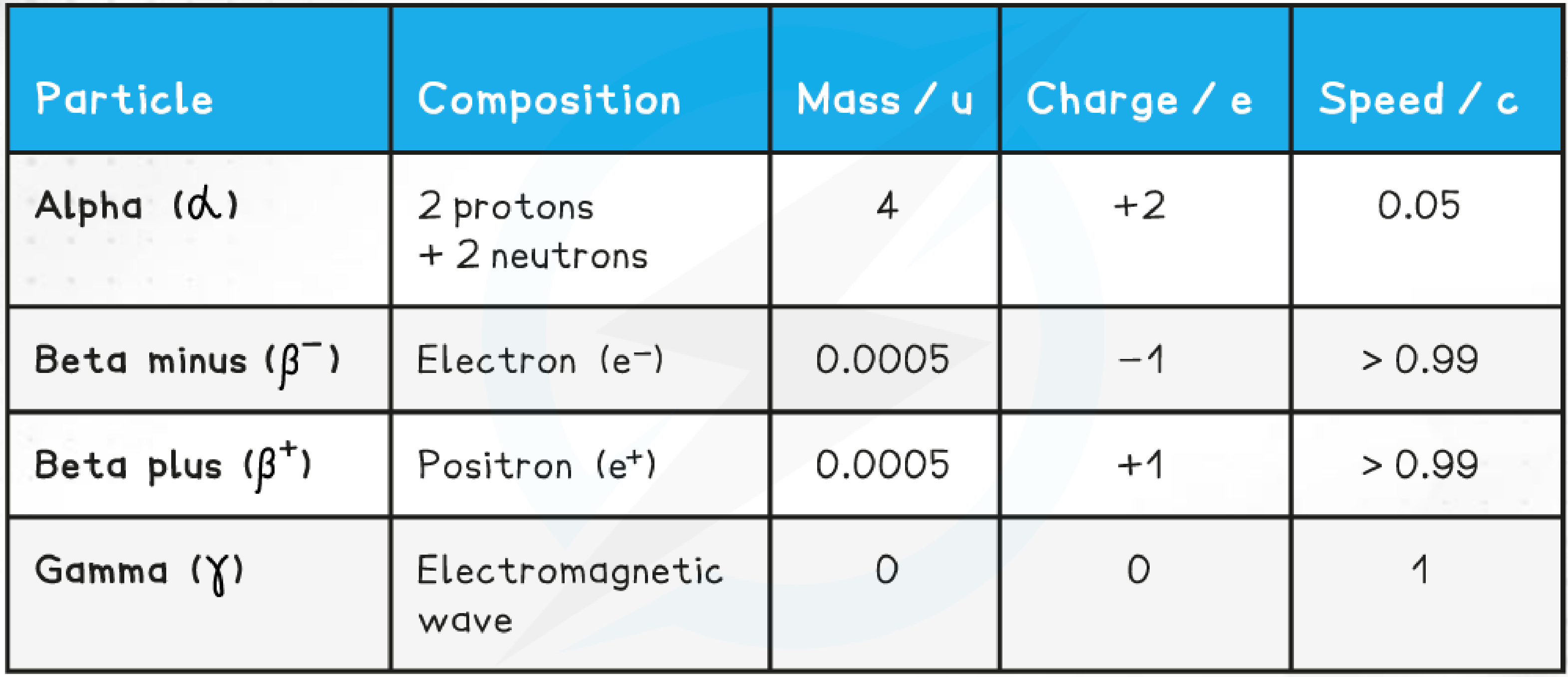
$${}^{0}_{0}\gamma$$



$$\underset{\text{electron}}{e^-} + \underset{\text{positron}}{e^+} \longrightarrow \underset{\text{gamma-ray photons}}{\gamma + \gamma}$$

Figure 16.13 Energy is released in the annihilation of matter and antimatter.

- The properties of the different types of radiation are summarised in the table below

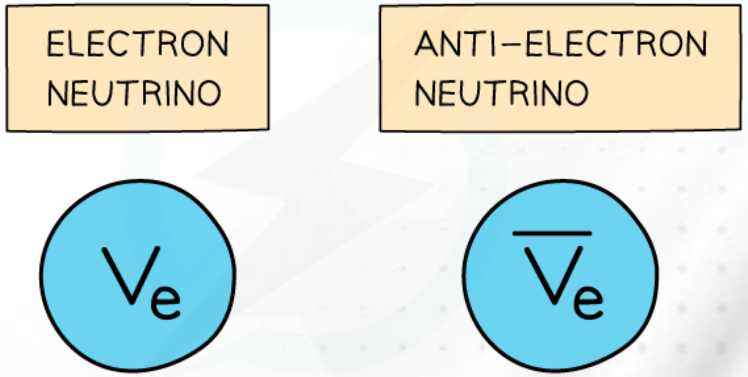


Particle	Composition	Mass / u	Charge / e	Speed / c
Alpha (α)	2 protons + 2 neutrons	4	+2	0.05
Beta minus (β^-)	Electron (e^-)	0.0005	−1	> 0.99
Beta plus (β^+)	Positron (e^+)	0.0005	+1	> 0.99
Gamma (γ)	Electromagnetic wave	0	0	1

u is the atomic mass unit (see “Atomic Mass Unit (u)”)
e is the charge of the electron: 1.60×10^{-19} C
c is the speed of light: 3×10^{8} m s^{-1}

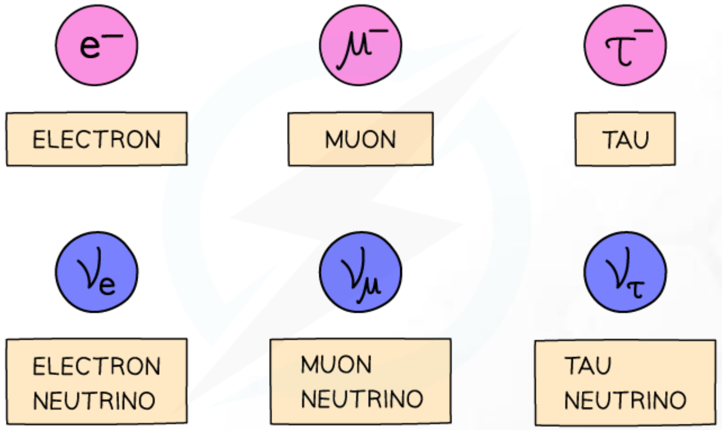
Neutrino Emission

- An electron neutrino is a type of subatomic particle with no charge and negligible mass which is also emitted from the nucleus
- The anti-neutrino is the antiparticle of a neutrino
  - Electron anti-neutrinos are produced during β– decay
  - Electron neutrinos are produced during β+ decay



Fundamental Particles: Leptons

- **Leptons** are a group of **fundamental** (elementary) particles
- This means they are not made up of any other particles (no quarks)
- Electrons and neutrinos both belongs to the Leptons families.
- There are six leptons altogether:



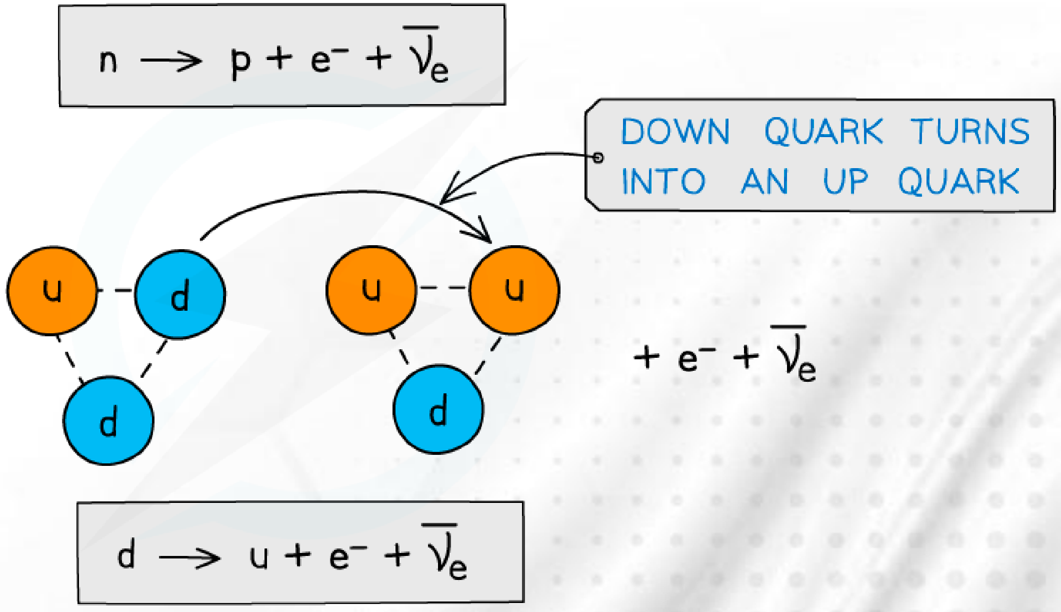
- The muon and tau particle are very similar to the electron but with slightly larger mass
- Electrons, muon and tau particles **all** have a charge of -1e and a mass of 0.0005u

- There are three **flavours** (types) of neutrinos **(electron, muon, tau)**
- Neutrinos are the most abundant leptons in the universe
  - They have **no charge** and **negligible** mass (almost 0)

- Leptons interact with the weak interaction, electromagnetic and gravitational forces
- However, they do **not** interact with the strong force
- Although quarks are fundamental particles too, they are not classed as leptons
- Leptons do **not** interact with the strong force, whilst quarks do

Quark Composition: β– & β+ decay

- Beta decay happens via the **weak interaction**
  - This is one of the four fundamental forces and it's responsible for radioactive decays
- **Quark Composition: β⁻ decay**
- Recall that **β⁻ decay is when a neutron turns into a proton emitting an electron and anti-electron neutrino**
- More specifically, a neutron turns into a proton because a **down quark turning into an up quark**



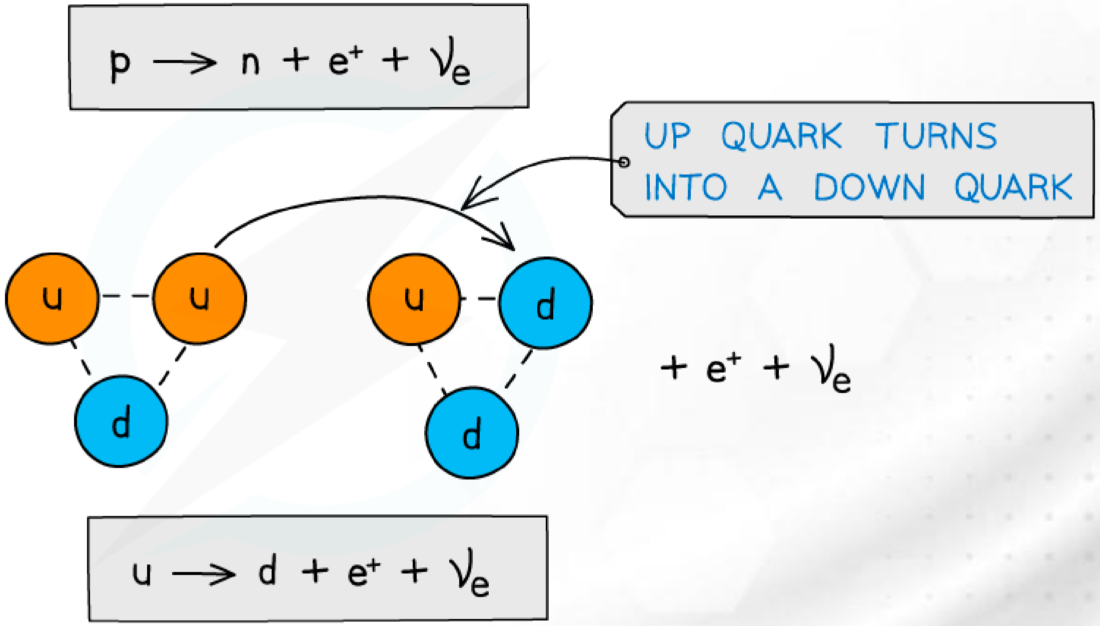
$n \longrightarrow p + e^- + \bar{\nu}_e$

DOWN QUARK TURNS INTO AN UP QUARK

$+ e^- + \bar{\nu}_e$

$d \longrightarrow u + e^- + \bar{\nu}_e$

- **Quark Composition: β$^+$ decay**
- Recall that **β$^+$ decay is when a proton turns into a neutron emitting an positron and an electron neutrino**
- More specifically, a proton turns into a neutron because an **up quark turns into a down quark**



$p \rightarrow n + e^+ + \nu_e$

UP QUARK TURNS INTO A DOWN QUARK

$+ e^+ + \nu_e$

$u \rightarrow d + e^+ + \nu_e$

The Weak Interaction

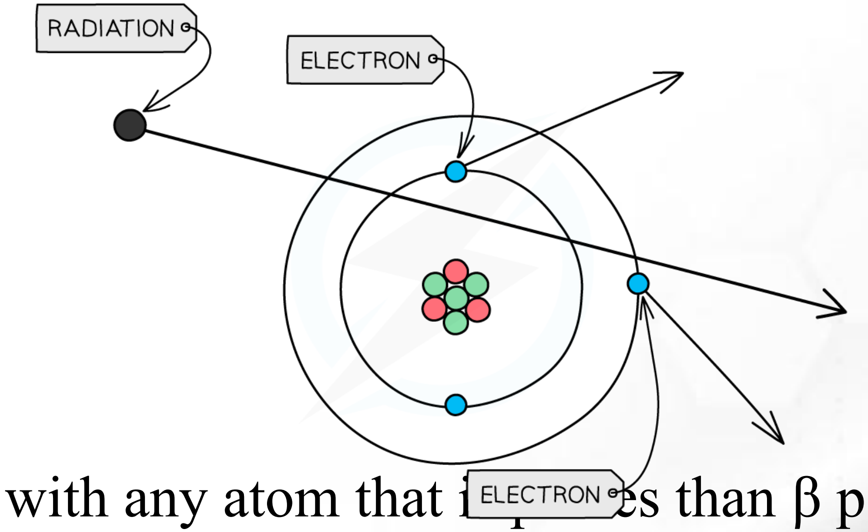
- The weak interaction is one of the four fundamental forces of nature
  - It is responsible for the radioactive decay of atoms
- **This is a force that acts on both quarks and leptons.**
- **β decay occurs because of the weak interaction between quarks**
- β minus and plus decay are examples of the weak interaction in action
  - In beta minus decay, a neutron turns into a proton emitting an electron and an electron antineutrino
  - In beta plus decay, a proton turns into a neutron emitting a positron and an electron neutrino
- At the quark level, a down quark turns into an up quark (or vice versa)

$$d \xrightarrow{W^-} u + e^- + \overline{\nu}_e$$

- The carrier particles that mediate the weak interaction are the: **W^+, W^- or Z^0 bosons**
  - Bosons are a group of particles that mediate the fundamental forces
- The W^- boson ‘carries away’ the negative charge of the down quark and transforms it into an up quark
- **Note:** you will only need to specify that the weak interaction that gives rise to beta decay, you will **not** need to remember the details about bosons

Properties of ionizing radiation

- If α- and β-particles hit other atoms, they can knock out electrons away from the atoms called **ionizing the atom or ionization.**
- In the process, the radiation loses some ot its kinetic energy and no longer has any ionizing effect.
- This can cause chemical changes in materials and can damage or kill living cells



- A- particles interacts more strongly with any atom that i p es than β particle because beta particles are much lighter and faster and so their effect is smaller..
- Gamma radiation also causes ionization but not as strongly as α and β particles.

Behavior of radiations in electric and magnetic fields

- α-, β–- and γ-radiations have different charges, or no charge, they behave differently in electric and magnetic fields.
- Since α- and β–-particles are charged, they are attracted to the plate that has the opposite charge to their own.
- β–-particles are deflected more than α-particles, since their mass is so much less.
- Gamma-rays are undeflected since they are uncharged

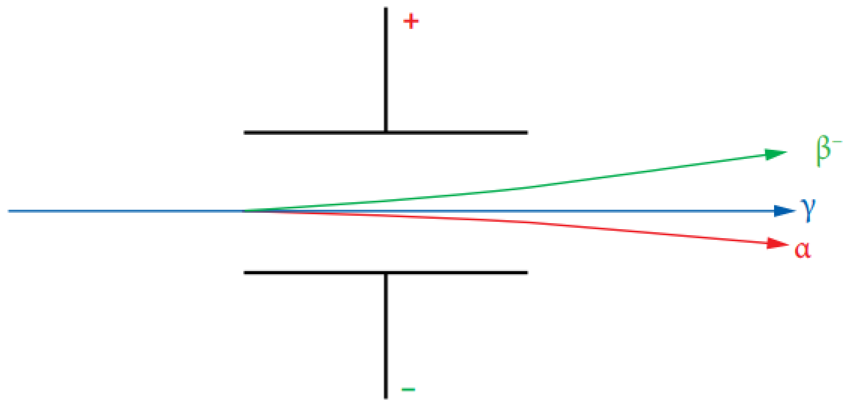


Figure 16.15 An electric field can be used to separate α-, β⁻- and γ- radiations. (The deflection of the α-radiation has been greatly exaggerated here.)

In magnetic field

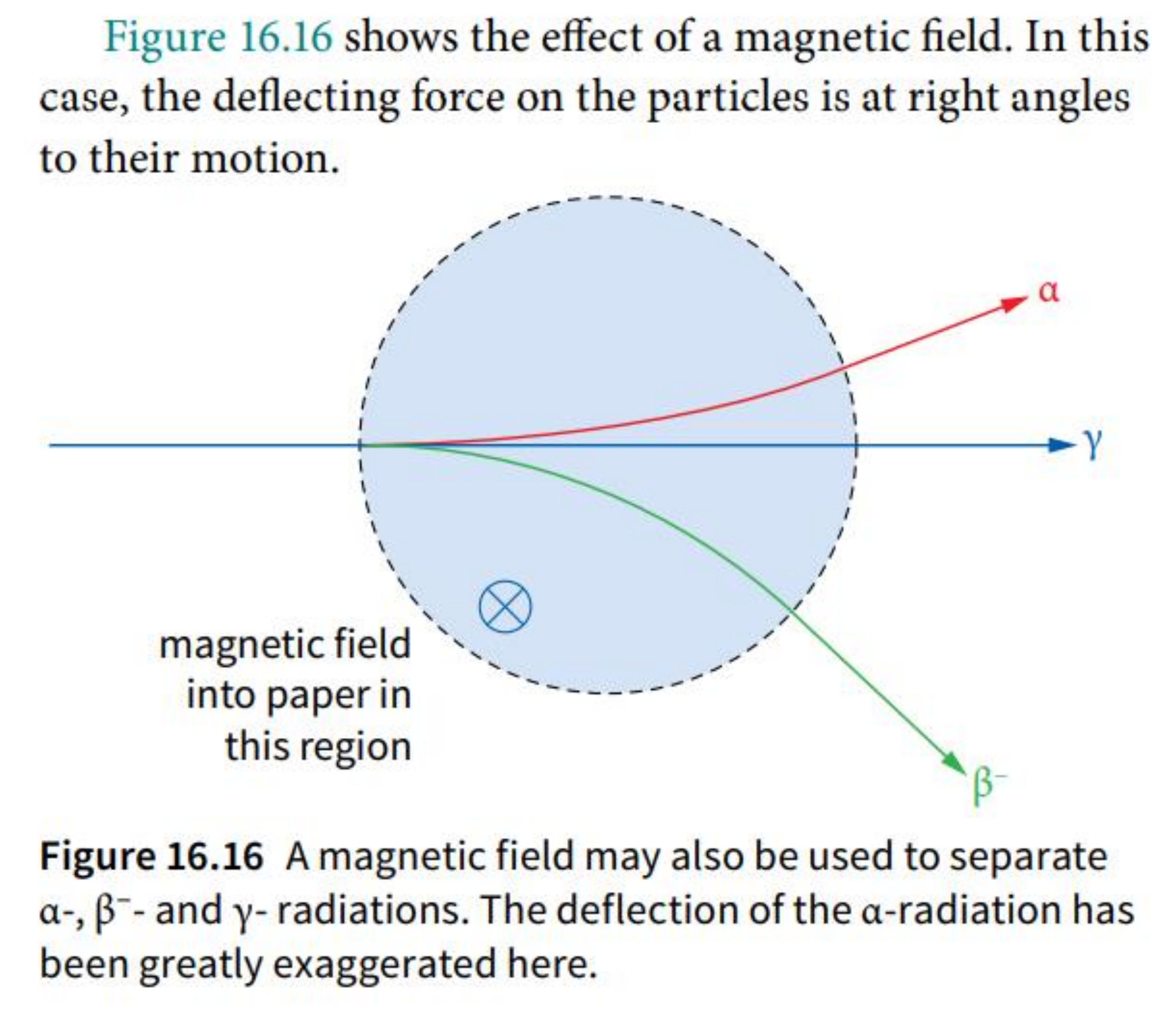


Figure 16.16 shows the effect of a magnetic field. In this case, the deflecting force on the particles is at right angles to their motion.

Figure 16.16 A magnetic field may also be used to separate α-, β^-- and γ- radiations. The deflection of the α-radiation has been greatly exaggerated here.

Alpha Radiation

- The α particles are the helium nuclei.
- The α particles carries positive charge whose magnitude is twice that of an electron.
- The mass of an α particle is 6.6×10^{-27} kg which is about four times that of a proton.
- They are deflected by electric and magnetic fields.
- They have very less penetrating power.
- They have high ionizing power.
- They show photographic effect.
- Their speed is much lesser than that of light.
- α particle is absorbed by a thin sheet of paper or a few centimeters of air.

Beta Radiation

- The β particles are the fast moving electrons.
- The β particles carries negative charge equal to that of an electron 1.6×10^{-19} c.
- The mass of an α particle is 9.1×10^{-31} kg which is equal to that of a electron.
- They are deflected by electric and magnetic fields.
- The penetrating power is 100 times that of the α particle .
- The ionizing power is 100 times less than that of an α particles .
- They show photographic effect.
- Their speed is less than that of light.
- β particle is absorbed by a few millimeters of metal.

Gamma Radiation

- The γ particles are electromagnetic waves of short wavelength.
- The γ particles are chargeless and massless radiations.
- They are not deflected by electric and magnetic fields.
- The penetrating power is 100 times that of the β particle .
- The ionizing power is 100 times less than that of an β particles .
- They show photographic effect.
- Their speed is equal to that of light.
- γ particle is never completely absorbed but a few centimeters of lead or several meters of concrete greatly reduces the intensity.

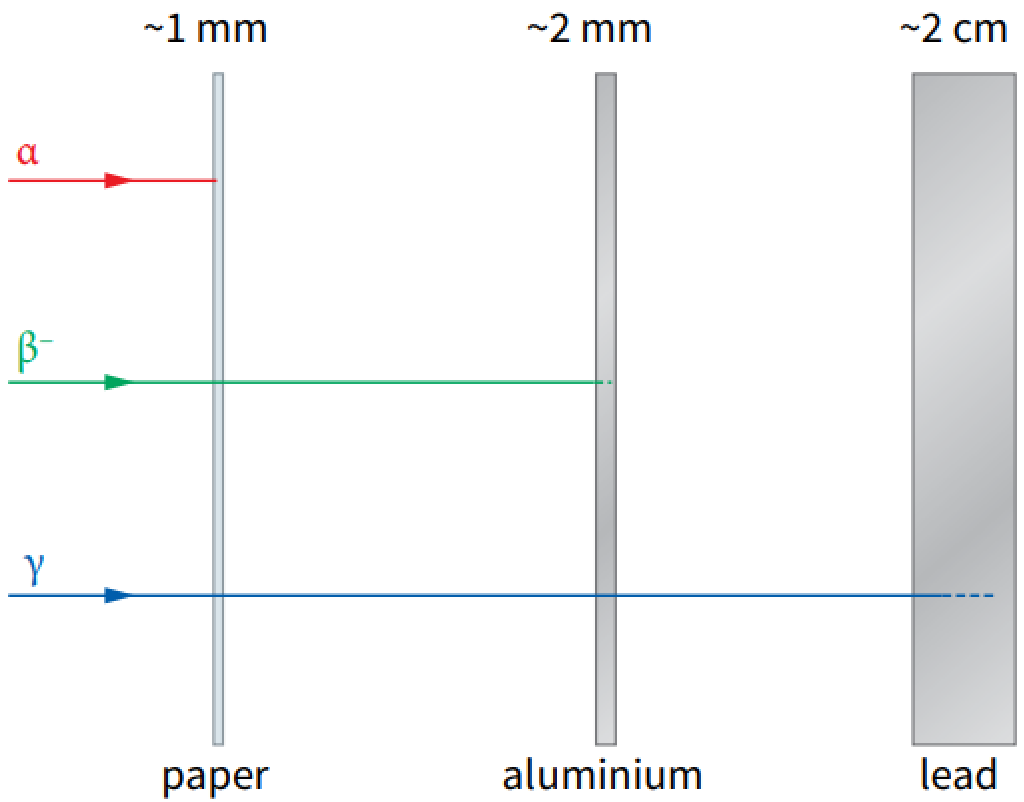


Figure 16.19 A summary of the penetrating powers of α-, β^-- and γ-radiations. The approximate thickness of the absorbing material is also shown.

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Thank you!