CAIE Physics A-level

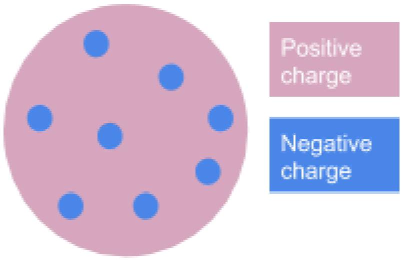
Topic 11: Particle Physics

Notes

11 - Particle Physics

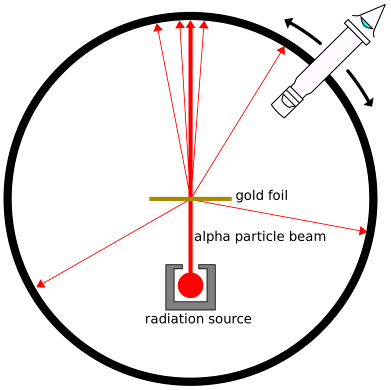
11.1 - Atoms, Nuclei, and Radiation

Rutherford scattering demonstrated the existence of a nucleus. Before this experiment, scientists believed in **Thomson's plum pudding model**, which stated that the atom was made up of a sphere of positive charge, with small areas of negative charge evenly distributed throughout, like fruit in a plum pudding. Rutherford scattering led to the production of a new model for the atom, known as the **nuclear model,** because the plum pudding model had been disproved.



Plum pudding model

Rutherford's apparatus included an **alpha source and gold foil in an evacuated chamber which was covered in a fluorescent coating** so that you could see where the alpha particles hit the inside of the chamber. To observe the paths of the alpha particles, there was a **microscope** which could be moved around the outside of the chamber.



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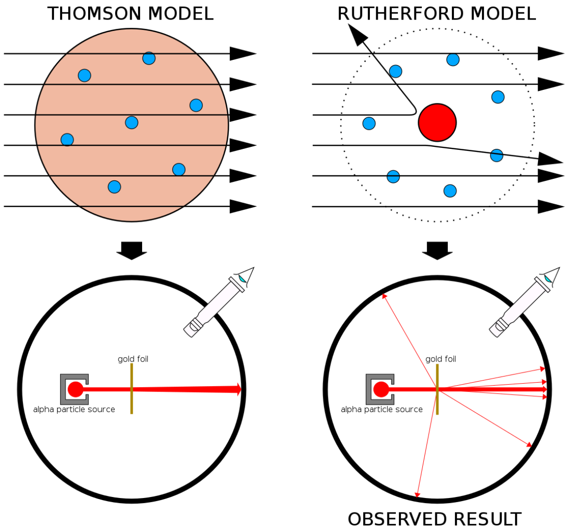
If the plum pudding model was true, the expected results would be that the positively charged alpha particles would be deflected by a very small amount when passing through the foil, however this was not what was observed:

- **Most alpha particles passed straight through the foil with no deflection** - this suggested that the **atom is mostly empty space** (and did not have a uniform density, as suggested by the plum pudding model).

- **A small amount of particles were deflected by a large angle** - this suggested that the **centre of the atom is positively charged**, because positively charged alpha particles were repelled from the centre and deflected.
- **Very few particles were deflected back by more than 90°** - this suggested that the **centre of the atom was very dense** because it could deflect fast moving alpha particles, but also that it was **very small** because a very small amount of particles were deflected by large angles.

From the above results, it was concluded that the atom has a small, dense, positively charged **nucleus** at its centre.



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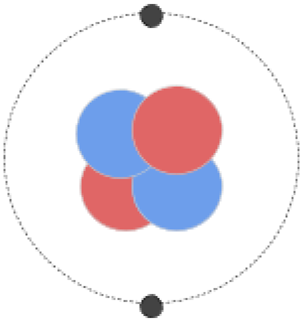
An atom is formed of 3 constituents: **protons, neutrons and electrons**. At the centre of an atom is a nucleus consisting of protons and neutrons (known as nucleons), whereas electrons orbit the nucleus in shells.

These particles have properties which can be described in two ways, in SI units and relative units, as shown below:

Particle	Charge (C)	Relative Charge	Mass (kg)	Relative Mass	Specific Charge (Ckg^{-1})
Proton	$+1.6 \times 10^{-19}$	+1	1.67×10^{-27}	1	9.58×10^{7}
Neutron	0	0	1.67×10^{-27}	1	0
Electron	-1.6×10^{-19}	-1	9.11×10^{-31}	0.0005	1.76×10^{11}

The **specific charge** of a particle is the charge-mass ratio, and is calculated by dividing a particle's charge by its mass.

$$Specific\ charge = \frac{Charge}{Mass}$$



For example,

A proton has a charge of $+1.6 \times 10^{-19} C$, and a mass of 1.67×10^{-27} kg

so its specific charge $= \frac{1.6 \times 10^{-19}}{1.67 \times 10^{-27}} = 9.58 \times 10^{7} Ckg^{-1}$

The proton number is the number of protons in an atom and is denoted by Z, while the nucleon number is the number of protons and neutrons, denoted by A. These will often be shown in the form (where 'X' is the symbol for the element).

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

In all nuclear processes, the **total charge**, no. of **nucleons (protons+neutrons)**, and **lepton (electrons+neutrinos) number** of the system are conserved.

Isotopes are atoms with the same number of protons but different numbers of neutrons. For example, carbon-14 is a radioactive isotope of carbon, which can be used to find the approximate age of an object containing organic material. This is done through **carbon dating**, which involves calculating the percentage of carbon-14 remaining in the object, and using the known starting value of carbon-14 (which is the same for all living things) and its half-life to calculate an approximate age.

Radiation is where an unstable nucleus emits energy in the form of EM waves or subatomic particles in order to become more stable. There are three types of radiation, all of which have different properties which are summarised in the table on the next page. The **unified atomic mass unit** - denoted by **u** - is equivalent to the mass of one nucleon (a proton or a neutron). This equates to 1.6×10^{-27} kg. The **elementary charge** (e) is the magnitude of charge carried by one electron or one proton. Electrons have charge of -e and protons have a charge of +e. One elementary charge equates to 1.6×10^{-19} C.

An **antiparticle** is the opposite of a particle. It has the same mass but the opposite charge and quantum numbers to its corresponding particle. For example, the **positron** is the antiparticle of the **electron**.

The composition, mass, and charge of each type of radiation are shown below:

Type of Radiation	Composition	Mass	Charge
Alpha (α)	An α particle (two protons, two neutrons)	$6.6 \times 10^{-27} kg$ 4u	$+2e$
Beta-plus (β+)	A positron / anti-electron (e^+) and a neutrino	$9.1\times 10^{-31}\ kg$ 1/2000 u	$+e$
Beta-minus (β−)	An electron (e^-) and an antineutrino	$9.1\times 10^{-31}\ kg$ 1/2000 u	$-e$
Gamma (γ)	A photon	Massless	None

During **alpha radiation**, an **alpha particle** consisting of **two neutrons and two protons** is emitted from an atomic nucleus. This usually occurs when a nucleus has **too many nucleons** and so must eject some to become stable. The equation for such a reaction can be written as:

$$^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}\alpha$$

From this, it's clear that the nucleon number decreases by 4, while the proton number decreases by 2.

The emitted alpha particle will have a discrete energy equal to the energy difference between the original nucleus and the remaining product after decay. Because all this 'excess' energy is removed from the nucleus via the alpha particle alone, the energy it carries will be well defined.

There are two forms of beta radiation. Beta-minus decay occurs when the nucleus has **too many neutrons compared to protons**. It involves the decay of one **neutron** into a **proton**, a **β− particle** (an electron), and an **antineutrino**. This increases the proton number of the nucleus while keeping the nucleon number the same.

Beta-plus decay occurs when the nucleus has **too many protons** compared to neutrons. It involves the decay of one **proton** into a **neutron**, a **β+ particle** (a positron), and a **neutrino**. This reduces the proton number but keeps the nucleon number the same.

Nuclear decay equations are shown for both of these below:

$$^{228}_{88}\mathrm{Ra} \rightarrow {}^{228}_{89}\mathrm{Ac} + {}^{0}_{-1}\beta$$ Beta Minus Decay

$$^{11}_{6}\mathrm{C} \rightarrow {}^{11}_{5}\mathrm{B} + {}^{0}_{+1}\beta$$ Beta Plus Decay

Image source: http://slideplayer.com/slide/15503069/

Since beta decay involves the emission of two particles - the electron/positron and the anti-neutrino/neutrino - the energy difference from the decay is shared between the two. This means that the beta particles themselves have a continuous range of possible energies, dependent on the energy of the neutrino.

11.2 - Fundamental Particles

Quarks are a type of **fundamental** particle which combine to form **hadrons** such as protons and neutrons. There are six **flavours (types)** of quark: up, down, top, bottom, strange, and charm. The symbols and charges of each quark flavour are given in the table below:

Flavour	Charge (e)
Up (u)	$+\frac{2}{3}$
Down (d)	$-\frac{1}{3}$
Top (t)	$+\frac{2}{3}$
Bottom (b)	$-\frac{1}{3}$
Charm (c)	$+\frac{2}{3}$
Strange (s)	$-\frac{1}{3}$

Each quark has a respective **antiquark** which has the opposite charge. An antiquark is denoted the same way as other antiparticles, with a bar over the letter. E.g. an anti-up quark is written as $\overline{u}$.

Protons and neutrons are not fundamental particles since they are each composed of three quarks. A proton is composed of two up quarks and one down quark (uud), giving an overall charge of +1e. A neutron is composed of two down quarks and one up quark (udd), giving an overall charge of 0. As they are made of three quarks, protons and neutrons are classified as a type of hadron called **baryons**.

Another type of hadron is the **meson**. Mesons are particles composed of one quark and one antiquark. The antiquark does not have to be of the same flavour as the quark, for example the π^+ meson is composed of $u\bar{d}$.

During beta decay the quark composition of the decaying nucleon changes. In beta-minus decay where a neutron decays into a proton- a down quark changes into an up quark. The opposite occurs in beta-plus decay.