CAIE Physics IGCSE

Topic 5: Nuclear Physics

Summary Notes

Definitions in ***bold*** *are for extended students only*

5.1 The nuclear model of the atom

5.1.1 The atom

The nuclear model of an atom consists of:

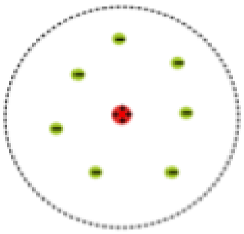
- A positively charged nucleus.
- Surrounded by negatively charged electrons which orbit the nucleus.

When atoms form an ion, electrons are lost or gained so that the atom has an overall charge:

- Positive ions are formed by the loss of electrons (the loss of a negative makes something more positive).
    - Metals usually form positive ions.
- Negative ions are formed by the gain of electrons (the gain of a negative makes something more negative).
    - Non-metals usually form negative ions.

This nuclear model of an atom is supported by an experiment by Rutherford: 'Alpha particle scattering'

- **A beam of alpha particles was aimed at a thin gold foil and he concluded that:**
    - **The atom was composed primarily of empty space because most alpha particles passed straight through, so the nucleus must be very small.**
    - **It had a nucleus which contained most of the mass of the atom because it deflected some alpha particles straight back.**
    - **The nucleus was positively charged because it repelled the positively charged alpha particles.**



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5.1.2 The nucleus

The positively charged nucleus is made of:

- Positive protons
- Neutral neutrons

Atoms of the same element have the same number of protons and are represented by a nuclide notation:

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

- X is the symbol of the element.
- Z is the proton number (number of protons, also known as atomic number).
    - **As bigger proton number means the nucleus has a larger charge.**
- A is the nucleon number (number of neutrons and protons, also known as mass number).
    - **A bigger nucleon number means the nucleus has a larger mass.**

Protons, neutrons, and electrons have different properties:

Particle	Relative Mass	Relative Charge
Proton	1	+1
Neutron	1	0
Electron	0.0005	-1

- Neutral atoms of an element have the same number of protons as electrons so the electron's and proton's charges cancel one another out.
- Ions of an element have more/less electrons, so have an overall charge.
- Isotopes of an atom have same number of protons but a different number of neutrons, so have different nucleon numbers (mass).
    - The number of neutrons in a nucleus can be calculated from nucleon number:

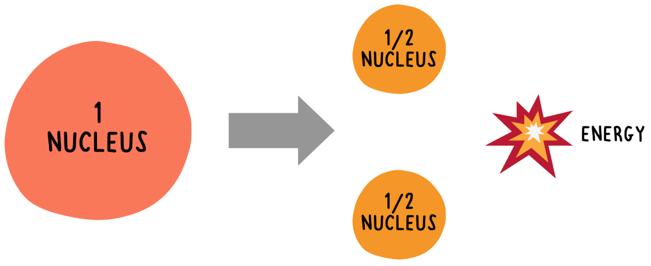
$$number\ of\ neutrons\ =\ nucleon\ number\ -\ proton\ number$$

    - An element may have more than one isotope.

In some isotopes, the imbalance between protons and neutrons means that their nuclei are unstable, and have excess energy which is given off in nuclear fission reactions.

The process of splitting a nucleus is called nuclear fission:

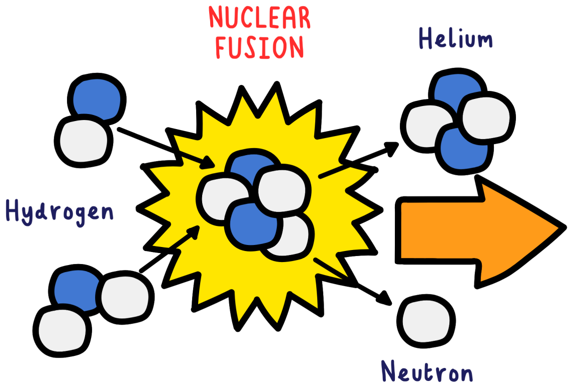
- **A neutron collides with a large unstable nucleus.**
    - **Some isotopes that have unstable nuclei are Uranium-235 and Plutonium-239.**
- **The nucleus is split into two smaller nuclei and 2 or 3 neutrons are released.**
- **The products have less mass than the original nucleus because some mass is converted to energy, which is released.**
    - **Therefore, isotopes are used as fuels by fission in nuclear reactors.**
- **The neutrons released then induce further fission events in a chain reaction.**



NUCLEAR FISSION

The process of joining two nuclei to form a larger nucleus is called nuclear fusion:

- **Energy is also released during this process.**
    - **The mass of the product is less than the mass of the two original nuclei because some of the mass is converted to energy.**
- **Nuclear fusion is how the sun and other stars release energy.**



Nuclide equations can be used to represent fission or fusion reactions:

- **Reactants and products are given in nuclide notation.**
- **The sum of the nucleon numbers on the left-hand side must be equal to the the sum of the nucleon numbers on the right-hand side.**
- **The sum of the proton numbers on the left-hand side must be equal to the the sum of the proton numbers on the right-hand side.**

Fission Example)

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{92}_{36}\mathrm{Kr} + {}^{141}_{56}\mathrm{Ba} + 3\,{}^{1}_{0}\mathrm{n} + \text{energy}$$

5.2 Radioactivity

5.2.1 Detection of radioactivity

Background radiation is weak ionising radiation that is released from naturally occurring radioactive materials or man-made sources:

- Radon gas in the air
    - Emitted from radioactive uranium
- Radiation from rocks and buildings
    - Radioactive uranium and thorium are in the rock used to make buildings.
- Cosmic rays
    - Radiation in the form of a subatomic particle created as the sun's protons enter our atmosphere.
- Food and drink
    - Radioactive potassium-40 is found in bananas and other foods come into contact with radioactive isotopes in rocks as they grow.

Background radiation can be measured using a detector connected to a counter:

- When radiation enters the detector (a Geiger-Muller tube), a counter clicks.
- The count is displayed on a screen.
- Count rate = the number of counts per second (units = Bq) or per minute.
    - Count rate decreases with distance from the detector, as the radiation spreads out.

The release of ionising radiation occurs randomly, so an average should be taken over a longer time frame (e.g. 20 minutes) and a mean calculated.

- The background count rate is around 18 counts per minute.

A corrected count rate gives the count produced solely from the source being investigated.

- **It is calculated by taking measurements with and without the sources of background radiation present, and subtracting the two:**

$$corrected\ count\ =\ count\ with\ source\ being\ investigated\ -\ count\ without source\ being\ investigated$$

5.2.2 The three types of nuclear emission

The emission of radiation from a nucleus is spontaneous (random in time) and random in direction.

There are three types of subatomic particle emitted as ionising radiation from the nucleus of unstable isotopes: Alpha (α), Beta (β), and Gamma (γ).

Alpha particles are ‘packages’ of two protons and two neutrons.

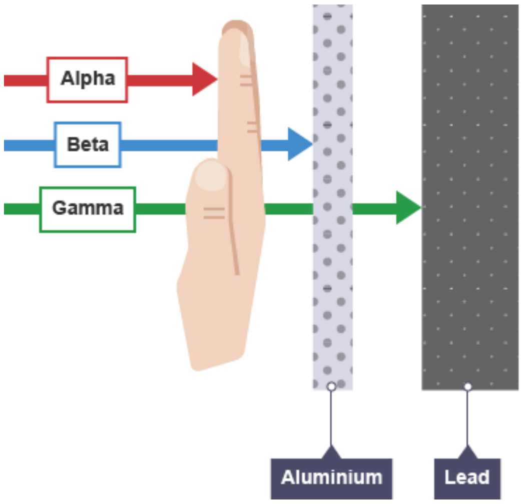
- They are large, heavy, slow, and have a positive charge.
- They are highly ionising (produce ions from atoms).
- They are weakly penetrating (stopped by a sheet of paper).
- **They are slightly deflected by electric and magnetic fields.**

Beta particles are fast-moving electrons emitted when extra neutrons in unstable nuclei split into an electron and a proton.

- They are small, light, fast, and have a negative charge.
- They are moderately ionising.
- They are moderately penetrating (stopped by a thin sheet of aluminium).
- **They are greatly deflected by electric and magnetic fields.**

Gamma rays are a high-energy electromagnetic wave emitted alongside beta and alpha particles.

- They have a short wavelength, high energy, no mass, and no charge.
- They are lowly ionising.
- They are highly penetrating (stopped by many centimetres of lead).
- **They are not deflected by electric and magnetic fields.**



The ionising effect of each type of radiation depends on its kinetic energy and charge.

- **The greater the charge of the radiation, the more ionising it is.**
- **The greater the kinetic energy of the radiation, the more ionising it is.**
- **The more ionising it is, the less penetrating it is.**

5.2.3 Radioactive decay

Radioactive isotopes are so unstable due to their excess neutrons and heavy nucleus, that they have excess energy, which is given off as as radiation, leaving them more stable.

Radioactive decay is the name for the spontaneous, random change of an isotope's nucleus by the release of radiation (α-particles or β-particles and/or γ-radiation).

- The decay is named after the type of particle emitted (α-decay or β-decay)
    - Whether γ-decay occurs is additional.

α-decay or β-decay both change the isotope into a different element:

- Alpha:
    - **α-decay leaves the nucleus in an excited state, with nucleon and atomic number altered due to proton and neutron loss.**
    - The nucleus changes to that of a different element **according to the following equation:** ${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha$
- Beta:
    - **β-decay leaves the nucleus in an excited state, with only the proton number altered due to electron loss and neutron transformation to a proton.**
    - The nucleus changes to that of a different element **according to the following equation:** ${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e^{-}$
- Gamma:
    - After a previous α-decay or β-decay, the nuclei with excess energy emit gamma rays, which leave leaves mass number and atomic number unchanged:

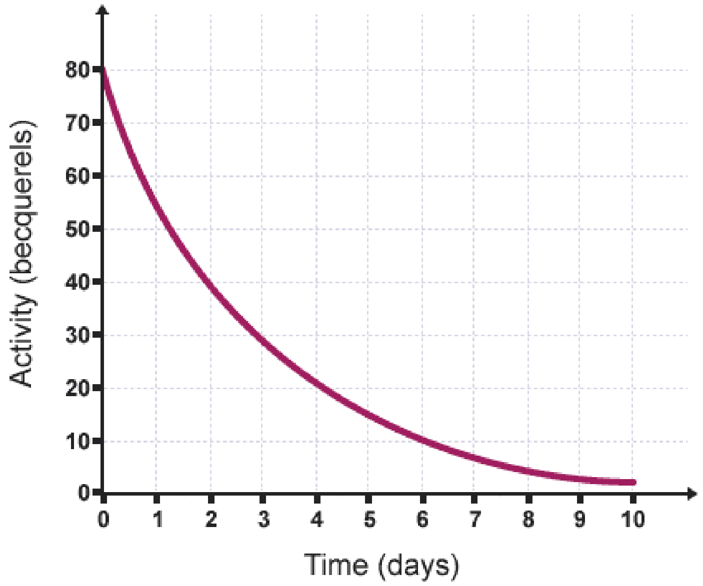
$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z}Y + {}^{0}_{0}y $$

5.2.4 Half-life

The half-life of a particular isotope is the time taken for half the nuclei of that isotope to decay.

Half-life can be found by investigating the count rate:

- Half-life is the time taken for the count rate to halve in value.
    - If it takes 2 days to go from 80 to 40 counts, its half-life is 2 days.



- Background radiation has to be subtracted before attempting to perform half-life calculations.

The type of radiation emitted and the half-life of an isotope can be used to determine which isotope is suitable for different everyday applications:

- Household fire (smoke) alarms
    - Long half-life alpha emitters are used in smoke detectors.
    - Alpha particles are used as they are charged so cause a current in the alarm and they are the most weaky penetrating so are absorbed by smoke.
    - When smoke enters the detector, some of the alpha particles are absorbed and the current drops, triggering the alarm.
- Irradiating food and sterilisation of equipment
    - Gamma emitters are used to kill bacteria or parasites by breaking their DNA, so it is safe for consumption or for equipment use in the medical field.
    - Gamma particles are chosen as they are the most penetrating so can reach the equipment or food without removing packaging.
- Measuring and controlling the thicknesses of materials
    - Long half-life beta emitters can be used for thickness monitoring of metal sheets because they have a moderate penetration.
    - A source and receiver are placed on either side of the sheet during its production.
    - If there is a drop or rise in the number of beta particles detected, then the thickness of the sheet has changed, as more/ less beta particles can penetrate the material.
- Diagnosis and treatment of cancer using gamma rays
    - Short half-life gamma emitters such as technetium-99m are used as tracers in medicine as they concentrate in certain parts of the body.
    - The half-life must be long enough for diagnostic procedures to be performed, but short enough to not remain radioactive for too long.
    - Other gamma emitters such as cobalt-60 can be used to destroy tumours with a high dose of radiation.

5.2.5 Safety precautions

Radiation exposure can destroy living cell membranes by ionisation, causing the cells to die, or damaging DNA, which causes mutations that could lead to cancer.

Therefore, radioactive materials must be moved, used and stored in a safe way that keeps exposure to a minimum:

Safety measures include:

- Safe movement and use involves **keeping as big a distance between the radioactive source and living tissue as possible** and **minimising the time of exposure to radiation:**
    - Handle using tongs.
    - Hold far away from living material.
    - Use materials with a short half-life when possible, so radiation doesn't remain an issue for a long time after disposal.
- Safe storage involves keeping radioactive sources in a lead-lined box and **using shielding to absorb radiation, such as the concrete shielding around a nuclear reactor.**