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GCSE Physics AQA: Topic 4

4 Atomic Structure

4.1 Atoms and Isotopes

4.1.1 The Structure of an Atom

- **Atom Size:**
  - Atoms have a radius of approximately 1×10^-10 metres (0.1 nanometers).
  - The nucleus is much smaller, with a radius less than 1/10,000 of the atom’s radius.
- **Basic Structure:**
  - **Nucleus:** Contains positively charged protons and neutral neutrons. Most of the atom's mass is concentrated here.
  - **Electrons:** Negatively charged particles orbit the nucleus in energy levels or shells.
- **Mass Concentration:**
  - The nucleus contains almost all of the atom’s mass due to the high mass of protons and neutrons compared to electrons.
- **Electron Arrangement:**
  - Electrons are arranged in discrete energy levels. The arrangement determines the atom's chemical properties and its position in the periodic table.

4.1.2 Mass Number, Atomic Number, and Isotopes

- **Atomic Number (Z):**
  - The number of protons in the nucleus of an atom, defining the element.
- **Mass Number (A):**
  - The total number of protons and neutrons in the nucleus.
  - Calculated as Mass Number=Number of Protons+Number of Neutrons

- ○ **Isotopes:**
  - Atoms of the same element with different numbers of neutrons, leading to different mass numbers.
  - **Example:** Carbon-12 and Carbon-14 are isotopes of carbon with 6 protons but different numbers of neutrons.
- **Ions:**
  - Atoms can gain or lose electrons to become ions. Positive ions are formed by losing electrons.

Atomic Model

Dalton's Model (Early 1800s)

John Dalton proposed the **first scientific atomic model**, based on experiments and measurements of chemical reactions.

Dalton's Key Ideas:

- Atoms are **tiny, solid spheres** that cannot be broken down further.
- Each element is made up of **identical atoms**.

4.3 Thomson's "Plum Pudding" Model (1897)

J. J. Thomson discovered the **electron** using the **cathode ray tube experiment**.

Discovery of the Electron:

- He found that atoms contained **tiny, negatively charged particles** (electrons) much smaller than atoms.
- This showed atoms were **not indivisible** after all.

Thomson's Model:

- The atom was imagined as a **positive sphere** with **negative electrons** embedded within it — like **plums in a pudding**.

- The positive charge of the "pudding" balanced the negative charge of the electrons, making the atom neutral overall.

Rutherford's Nuclear Model (1909)

Ernest Rutherford, with **Geiger** and **Marsden**, carried out the **alpha particle scattering experiment** (gold foil experiment).

The Experiment:

- A thin sheet of **gold foil** was bombarded with **alpha particles** (positively charged helium nuclei).
- Observations:
  1. **Most particles passed straight through** the foil.
  2. **A few were deflected** slightly.
  3. **A very small number bounced straight back.**

Rutherford's Conclusions:

- Most of the atom is **empty space** (since most alpha particles passed through).
- The **positive charge** (and most of the atom's mass) is concentrated in a tiny central **nucleus**.
- **Electrons orbit** this nucleus, like planets orbiting the sun.
- The atom as a whole is **neutral**, since negative electrons balance the positive nucleus.

Result:

The "plum pudding" model was **rejected**, and the **nuclear model** replaced it.

Bohr's Model (1913)

Niels Bohr refined Rutherford's model.

Problems with Rutherford's Model:

- According to classical physics, orbiting electrons should **lose energy** and **spiral into the nucleus**, making atoms unstable.

- But atoms clearly are stable.

Bohr's Proposal:

- Electrons orbit the nucleus at **specific, fixed distances** called **energy levels** or **shells**.

4.2 Atoms and Nuclear Radiation

4.2.1 Radioactive Decay and Nuclear Radiation

- **Radioactive Decay:**
  - **Definition:** Unstable atomic nuclei lose energy by emitting radiation, becoming more stable over time.
  - **Activity:** The rate at which decay occurs, measured in Becquerels (Bq), where 1 Bq equals one decay per second.
  - **Count Rate:** Number of decays detected per second by a detector.
- **Types of Radiation:**
  - **Alpha Particles (α):**
    - Consist of 2 protons and 2 neutrons (helium nucleus).
    - **Effect on Nucleus:** Reduces mass number by 4 and atomic number by 2.
    - **Penetration:** Low; stopped by paper or skin.
  - **Beta Particles (β):**
    - **Beta-minus Decay:** A neutron decays into a proton, emitting an electron and an antineutrino.
    - **Effect on Nucleus:** Increases atomic number by 1, mass number remains unchanged.
    - **Penetration:** Moderate; stopped by aluminium.
  - **Gamma Rays (γ):**
    - High-energy electromagnetic radiation.
    - **Effect on Nucleus:** No change in mass or atomic number.

- **Penetration:** High; requires lead or thick concrete to block.
- **Neutrons (n):**
  - Emitted during some decay processes or fission.
  - **Effect:** Neutral particles that do not affect the charge of the nucleus but can induce further reactions.

4.2.2 Nuclear Equations

- **Representation:**
  - **Alpha Decay:** $X^{Z}_{A} \rightarrow X^{Z-4}_{A-2} + \alpha^{4}_{2}$
  - **Beta Decay:** $X^{Z}_{A} \rightarrow X^{Z}_{A+1} + \beta^{0}_{-1}$
- **Balancing Equations:**
  - Ensure that both sides of the equation have the same total mass number and atomic number.

4.2.3 Half-lives and the Random Nature of Radioactive Decay

- **Half-life:**
  - The time it takes for half of the radioactive nuclei in a sample to decay.
- **Randomness:**
  - Radioactive decay is a random process. Although it is impossible to predict exactly when an individual nucleus will decay, statistical patterns allow predictions for large numbers of nuclei.

Short Half-Life

Definition:
A short half-life means the isotope **decays quickly** — it loses activity in a short time.

Features:

- Emits a **large amount of radiation** in a short period.
- **Activity falls rapidly** because most unstable nuclei decay quickly.
- After a few half-lives, it becomes **almost completely stable**.

Uses:

- **Medical tracers** (e.g. technetium-99m) — gives quick results and becomes safe soon after use.
- **Smoke alarms** (e.g. americium-241, though its half-life is moderate).

Risk:

- **High initial radiation dose**, so it must be handled carefully.

Long Half-Life

Definition:
A long half-life means the isotope **decays slowly** — it stays radioactive for a long time.

Features:

- Emits **low levels of radiation** over a long period.
- **Activity decreases slowly**, taking thousands or millions of years to halve.
- Remains **hazardous for a very long time**.

Uses:

- **Archaeological or geological dating** (e.g. carbon-14 or uranium-238).
- Sometimes used in **industrial gauges** where a constant source is needed.

Risk:

- Causes **long-term contamination** — difficult and costly to store safely.

4.2.4 Radioactive Contamination

- **Contamination:**
  - The unwanted presence of radioactive substances on or within other materials.
  - **Hazards:** Depends on the type of radiation and the amount of contamination.
- **Irradiation:**
  - The process of exposing an object to radiation without making it radioactive.

4.3 Background Radiation

4.3.1 Background Radiation

- **Sources:**
    - **Natural Sources:** Cosmic rays from space, radon gas from the ground, and radiation from rocks and soil.
    - **Man-made Sources:** Fallout from nuclear weapons tests, nuclear power stations, and medical procedures such as X-rays.
- **Variation:**
    - Background radiation levels can vary based on geographic location and occupation. For example, areas with high natural radon levels or higher altitudes may have higher background radiation.

4.3.2 Uses of Nuclear Radiation

- **Medical Applications:**
    - **Imaging:** Techniques such as X-rays, CT scans, and PET scans use radioactive tracers to visualise internal organs.
    - **Treatment:** Radiation therapy targets and destroys cancer cells. It uses high doses of radiation to kill or damage cancer cells.

4.4 Nuclear Fission and Fusion

4.4.1 Nuclear Fission

- **Definition:**
    - The process of splitting a large and unstable nucleus into two smaller nuclei, releasing energy and additional neutrons.
    - **Initiation:** Typically occurs when the nucleus absorbs a neutron.
- **Process:**
    - **Splitting:** The nucleus breaks into two smaller nuclei and releases additional neutrons and gamma rays.
    - **Energy Release:** Energy is released as kinetic energy of the fission fragments and radiation.
- **Chain Reaction:**
    - **Controlled Chain Reaction:** Used in nuclear reactors to produce a steady flow of energy by controlling the rate of fission.
    - **Uncontrolled Chain Reaction:** In nuclear weapons, an uncontrolled chain reaction leads to an explosion.

4.4.2 Nuclear Fusion

- **Definition:**
    - The process of combining two light atomic nuclei to form a heavier nucleus, releasing energy in the process.
- **Process:**
    - **Conditions Required:** Extremely high temperatures and pressures to overcome electrostatic repulsion between the positively charged nuclei.

    - **Fusion Reaction:** Common reactions involve isotopes of hydrogen, such as Deuterium and Tritium, combining to form Helium and releasing energy.
- **Challenges:**
    - **Containment:** Achieving and maintaining the required conditions for fusion is challenging. Techniques like magnetic confinement (tokamaks) and inertial confinement are under investigation.
    - **Energy Output:** Currently, fusion reactions require more energy to initiate and sustain than they produce. Research aims to achieve net positive energy production.