10.1 Understanding the Nucleus of an Atom

10.1.1 Composition of the Nucleus

Based on the above experiment, with the help of his assistants Geiger and Marsden, Rutherford proposed the nuclear model of the atom in 1911.

In this model, the atom has a very small dense core called the nucleus which contains protons and neutrons.

Electrons orbit around the nucleus.

Proton number, \( Z \) is the number of protons in a nucleus. It is also known as the atom number.

Nucleon number, \( A \) is the total number of protons and neutrons in a nucleus. It is also known as the mass number.

<table>
<thead>
<tr>
<th>Subatomic particle</th>
<th>Symbol</th>
<th>Actual mass</th>
<th>Relative mass</th>
<th>Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton, ( p )</td>
<td>(_1^1p)</td>
<td>(1.67 \times 10^{-27} \text{ kg} )</td>
<td>1</td>
<td>(+1.6 \times 10^{-19} \text{ C} )</td>
</tr>
<tr>
<td>Neutron, ( n )</td>
<td>(_0^1n)</td>
<td>(1.67 \times 10^{-27} \text{ kg} )</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Electron, ( e )</td>
<td>(_0^{-1}e)</td>
<td>(9.11 \times 10^{-31} \text{ kg} )</td>
<td>(\frac{1}{1840})</td>
<td>(-1.6 \times 10^{-19} \text{ C} )</td>
</tr>
</tbody>
</table>

10.1.2 Nuclide Notation

10.1.3 Isotopes

Isotopes are atoms of the same element which contain the same number of protons and different number of neutrons/nucleons.

Radioisotopes are unstable nuclei which release radioactive radiation to become more stable (radioactive isotopes).
10.2 Radioactive Decay

10.2.1 Radioactivity

- Radioactivity is the spontaneous disintegration of an unstable nucleus accompanied by the emission of energetic particles of photons.
- There are three types of radioactive rays:
  - Alpha particles (α)
  - Beta particles (β)
  - Gamma rays (γ)
- A radioactive source can transmit more than one type of radioactive ray

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Alpha particle (α-particle)</th>
<th>Beta particle (β-particle)</th>
<th>Gamma ray (γ-ray)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition</td>
<td>Helium nucleus</td>
<td>High speed electron</td>
<td>High frequency electromagnetic wave</td>
</tr>
<tr>
<td>Nuclide notation</td>
<td>$\frac{4}{2}$ He</td>
<td>$\frac{0}{-1}$ e</td>
<td>-</td>
</tr>
<tr>
<td>Relative charge</td>
<td>+2</td>
<td>-1</td>
<td>No charge</td>
</tr>
<tr>
<td>Mass</td>
<td>Large</td>
<td>Very small</td>
<td>No mass</td>
</tr>
<tr>
<td>Velocity</td>
<td>Up to 10% of the speed of light</td>
<td>Up to 99% of the speed of light</td>
<td>Speed of light</td>
</tr>
<tr>
<td>Ionization potential</td>
<td>Greatest</td>
<td>Less than α</td>
<td>Least</td>
</tr>
<tr>
<td>Penetration</td>
<td>Lowest</td>
<td>Greater than α</td>
<td>Largest</td>
</tr>
<tr>
<td>Range in air</td>
<td>Several centimeters</td>
<td>Several meters</td>
<td>Several hundred meters</td>
</tr>
<tr>
<td>Stopped by</td>
<td>Thin paper or human skin</td>
<td>Several millimeters of aluminum</td>
<td>Several centimeters of lead or several meters of concrete</td>
</tr>
<tr>
<td>Electric field</td>
<td>α-particles are attracted to the negative plate and experience a small deflection due to its large mass.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>β-particles are attracted to the positive plate and experience a large deflection due to its small mass.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>γ-rays remain undeflected because they are neutral.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnetic field</td>
<td>The direction of deflection can be determined with Fleming’s Left Hand Rule.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>α-particles and β-particles deflect in the opposite direction due to their opposite charges.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>γ-rays remain undeflected because they are neutral.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
10.2.2 Radioactive Detectors

Geiger-Muller Tube (GM tube)
A Geiger-Muller tube is a very versatile, sensitive radiation detector that is commonly used in the radioactive industry. It is able to provide an immediate reading of the radioactivity, and a siren can be hooked up to emit sound based on the strength of the radioactivity.

Radiation enters the GM tube through the thin mica window and ionises the argon gas particles. A pulse of current is produced and is counted by the scaler or the ratemeter. The scaler gives a reading of the number of counts over a certain period of time, whereas the ratemeter gives a reading of the rate of number of counts (e.g. counts per second, counts per minute).

NOTE: Background Radiation
- When the GM tube and counter is switched on, a random count will still be recorded even without a radioactive source. This is due to background radiation.
- Background radiation comes from natural sources such as rocks, soil, air, building materials, food, and even outer space.
- Background radiation must be taken into account when using the reading taken from the GM tube.

Cloud Chamber
A cloud chamber is used to show the path of ionising radiation. As the radioactive particle ionises the air particles, the alcohol vapour will condense on the ions and form condensation trails which will be visible when observed from the top.

<table>
<thead>
<tr>
<th>Component</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sponge</td>
<td>Presses the solid carbon dioxide so that it touches the black metal plate</td>
</tr>
<tr>
<td>Black metal plate</td>
<td>The metal plate is cooled by solid carbon dioxide and this subsequently cools the air above it. The black color provides a dark background which enables the vapor trails to be seen clearly.</td>
</tr>
<tr>
<td>Felt cloth that is soaked in alcohol and water</td>
<td>Water and alcohol droplets will evaporate</td>
</tr>
<tr>
<td>Perspex lid</td>
<td>After rubbed, the lid will be charged and attract ions in the chamber. In this way the old trails are eliminated and new trails can be observed clearly.</td>
</tr>
</tbody>
</table>

Different radiations will have different trails, based on their ionizing power.
Photographic Film
Photographic film reacts to radiation the same way it reacts to light. The degree of darkening indicates the amount of radiation received.

- **Detects:**
  - Alpha
  - Beta
  - Gamma

Scintillation Counter
When radioactive radiation passes through sodium iodide crystals, energy is absorbed producing visible light. This light results in the emission of electrons from the photo-cathode, which are then detected and multiplied by a photo-multiplier tube which results in an electric signal. The signals will be amplified and counted by an electronic counter.

- **Detects:**
  - Alpha
  - Beta
  - Gamma

Spark Counter
The voltage of a spark counter is increased until sparks are formed, and then decreased a little just until the sparks are not formed anymore. When an ionizing radiation is brought near the wire gauze, the air particles will be ionized and sparks will be seen.

- **Detects:**
  - Alpha
  - Beta
  - Gamma

Gold Leaf Electroscope
The gold leaf electroscope is not considered a radioactive detector, because it is not able to prove the presence of radioactivity; however it responds to ionizing radiation the same way it responds to static charge.

The gold leaf electroscope is charged with positive charge, which will cause the gold leaf to repel. When an ionizing radiation is brought near the disc, it ionizes the air particles near the disc. The negatively-charged ions will be attracted to the disc and neutralizes the gold leaf, and hence the gold leaf will decrease in deflection.

- **Detects:**
  - Alpha
  - Beta
  - Gamma
10.2.3 Radioactive Decay

- Radioactive decay is the process of emission of radioactive radiation from unstable nuclei to achieve a more stable configuration.

<table>
<thead>
<tr>
<th>Alpha decay</th>
<th>Beta decay</th>
<th>Gamma decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha decay happens when a radioactive element decays by emitting alpha particles ($^4_2$He)</td>
<td>Beta decay happens when a radioactive element emits beta particles ($^0_{-1}$e)</td>
<td>Gamma decay happens when a radioactive nucleus releases its excess energy in the form of high frequency electromagnetic waves.</td>
</tr>
<tr>
<td>$^{\pm}<em>{Z}X \rightarrow ^{A+4}</em>{Z+2}Y + ^4_2$He</td>
<td>A neutron will split into one proton and one electron $^0_1n \rightarrow ^1_1p + ^0_{-1}e$</td>
<td>There are no changes in the number of protons and nucleons but the total energy of the radioactive nucleus will decrease.</td>
</tr>
</tbody>
</table>

$$^{A}_{Z}X \rightarrow ^{A+4}_{Z+2}Y + ^4_2He$$

$$^{A}_{Z}X \rightarrow ^{A+4}_{Z+2}Y$$

$$^{A+4}_{Z+2}Y + ^4_2He$$

$$^{A}_{Z}X \rightarrow ^{A+4}_{Z+2}Y + ^0_{-1}e$$

$$^{A+4}_{Z+2}Y + ^0_{-1}e$$

$$^{A}_{Z}X \rightarrow ^{A+4}_{Z+2}Y$$

10.2.4 Decay Series

- Some nuclei are still unstable after one decay; the new nuclei are still radioactive and will continue decay.
- A series of decay will happen until a more stable nucleus is obtained.

E.g.: $^{238}_{92}U \rightarrow ^{234}_{90}Th \beta \rightarrow ^{234}_{91}Pa \beta \rightarrow ^{234}_{92}U \rightarrow ^{230}_{90}Th \alpha \rightarrow ^{226}_{88}Ra \gamma \rightarrow ^{222}_{86}Rn \alpha \rightarrow ^{218}_{84}Po \alpha \rightarrow ^{214}_{82}Pb \beta \gamma \rightarrow ^{210}_{83}Bi \beta \rightarrow ^{214}_{82}Po \rightarrow ^{206}_{82}Pb$

- A decay series can be shown with two different types of graphs, as shown below. Both graphs show the same decay series. However, only alpha and beta decay can be shown in the graph.

For example:

**Graph of A against Z**

**Graph of N against Z**

| A: Number of nucleons | N: Number of neutrons | Z: Number of protons |
10.2.5 Half-Life

The half-life of a radioactive nuclide is the time taken for the number of undecayed nuclei to be reduced to half of its original number.

- It is represented by the symbol $T_{\frac{1}{2}}$
- In the time of one half-life:
  - The activity is halved
  - The number of active atoms is halved
  - The rate of radiation emission is halved

- The half-life of a radioactive nuclide is constant and unique to the radioactive nuclide.

### Examples of the half-lives of common radioisotopes

<table>
<thead>
<tr>
<th>Radioisotope</th>
<th>Symbol</th>
<th>Half-life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radon-220</td>
<td>$^{220}_{86}$Rn</td>
<td>56 seconds</td>
</tr>
<tr>
<td>Technetium-99m</td>
<td>$^{99}_{43}$Tc</td>
<td>6 hours</td>
</tr>
<tr>
<td>Natrium-24</td>
<td>$^{24}_{11}$Na</td>
<td>15 hours</td>
</tr>
<tr>
<td>Iodin-131</td>
<td>$^{131}_{53}$I</td>
<td>8 days</td>
</tr>
<tr>
<td>Phosphorus-32</td>
<td>$^{32}_{15}$P</td>
<td>15 days</td>
</tr>
<tr>
<td>Radium-226</td>
<td>$^{226}_{88}$Ra</td>
<td>1620 years</td>
</tr>
<tr>
<td>Carbon-14</td>
<td>$^{14}_{6}$C</td>
<td>5760 years</td>
</tr>
<tr>
<td>Uranium-238</td>
<td>$^{238}_{92}$U</td>
<td>4500 million years</td>
</tr>
</tbody>
</table>

The decay curve shows how the radioactive element decays over time. It can be plotted as the count rate against time, or mass against time.

- The graph does not touch the x-axis because theoretically, if the value keeps halving, it will not reach zero.
- The time it takes for the activity or mass to be halved each time from its current value is the same.
- Half-life is determined by finding out the time taken for the activity or mass to drop to half its original.
10.3 Uses of Radioisotopes

- Radioisotopes are highly useful in several fields, such as medicine, agriculture, archaeology, and industries.

- Determining the type of radioisotopes for use depends on:
  - **The type of radiation emitted**: alpha / beta / gamma - such as observing the need for ionization power, penetration power, etc.
  - **Half-life of the radioisotope**: Short half-lives are needed for radioisotopes that might be injected into or consumed by a living organism, such as in medicine, fertilization, or water testing. Long half-lives are used when the radioisotopes are used in industries that require as little maintenance as possible.

<table>
<thead>
<tr>
<th>Medicine</th>
<th>Radioisotopes are injected, consumed, or inhaled by a patient and are used as tracers in the body. Imaging of the organs will be used to determine any disorder.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>✓ Technetium-99m: injected in blood stream to detect brain cancer, internal hemorrhage, and blood clots</td>
</tr>
<tr>
<td></td>
<td>✓ Sodium-24: to detect blood clot</td>
</tr>
<tr>
<td></td>
<td>✓ Cobalt-60: kill cancer cells in radiotherapy, sterilization of hospital equipment</td>
</tr>
<tr>
<td></td>
<td>✓ Phosphorus-32: to detect brain tumour</td>
</tr>
<tr>
<td></td>
<td>✓ Iodine-131: to determine thyroid glands</td>
</tr>
<tr>
<td></td>
<td>✓ Iron-59: to trace iron distribution in blood</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Agriculture</th>
<th>The rate and quantity of fertilizer absorption by plants can be determined by mixing radioactive phosphate into the fertilizer. Radioactive radiation from radioisotopes are used to kill pests. Pests can also be multiplied in the lab and exposed to gamma rays, where they will mutate to infertility. Control ripening of fruits.</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Archeology</th>
<th>Carbon dating with carbon-14</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Industries</th>
<th>Gamma rays are used to penetrate deep into weldings to detect faults. Water leaks are determined by dissolving sodium-24 salt into the water and the pipes are checked with a GM tube. Polonium-210 is used to neutralize static charge in photographic plates. Americium-241 is used in smoke detectors. Automatic thickness control of paper, plastic and metal sheets. Automatic check of level of fullness within tins and packages.</th>
</tr>
</thead>
</table>
10.4 Nuclear Energy

10.4.1 Atomic Mass Unit

1 atomic mass unit = \( \frac{1}{12} \) of the mass of a carbon-12 atom.

\[
1 \text{ a.m.u.} = \frac{1}{12} \text{ mass of } ^{12}_6 \text{C}
\]

\[
= \frac{1}{12} \times 1.993 \times 10^{-26} \text{ kg}
\]

\( = 1.66 \times 10^{-27} \text{ kg} \)

10.4.2 Nuclear Fission vs Nuclear Fusion

<table>
<thead>
<tr>
<th>Nuclear Fission</th>
<th>Nuclear Fusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>✶ Splitting of a heavy nucleus into two lighter nuclei&lt;br&gt;( ^{235}<em>{92} \text{U} + ^1_0 n \rightarrow ^{141}</em>{56} \text{Ba} + ^{92}_{36} \text{Kr} + 3 ^1_0 n )</td>
<td>✶ Combining of two lighter nuclei to form a heavier nucleus&lt;br&gt;( ^2_1 \text{H} + ^3_1 \text{H} \rightarrow ^4_2 \text{He} + ^1_0 n + \text{energy} )</td>
</tr>
<tr>
<td>✶ Chain reaction can occur.&lt;br&gt;✶ A chain reaction is a self-sustaining reaction in which the products of a reaction can initiate another similar reaction.&lt;br&gt; ✓ For example, a neutron collides with a U-235 nucleus and splits into two smaller nuclei and produces three neutrons.&lt;br&gt; ✓ Each of these three neutrons will collide with three other U-235 nuclei and split into more nuclei and neutrons.&lt;br&gt; ✓ The minimum mass of uranium needed for a chain reaction is known as the critical mass.</td>
<td>✶ Requires very high temperature for nuclear fusion to occur&lt;br&gt; ✶ Happens on the surface of the sun</td>
</tr>
</tbody>
</table>

10.4.3 Nuclear Energy

✶ When a nuclear reaction or radioactive decay occurs, some of the mass of the reactants are lost. This loss of mass (a.k.a. mass defect) is converted to energy.

Einstein’s law of energy-mass conservation:

\[
E = mc^2
\]

where \( E \) = total energy released [J]  
\( m \) = mass defect [kg]  
\( c \) = speed of light = \( 3 \times 10^8 \text{ m s}^{-2} \)
10.4.4 Nuclear Energy

Nuclear fission generators use uranium to generate electricity.

**Component** | **Description**
--- | ---
Uranium rod (fuel rod) | A long rod that has trace amounts of enriched uranium-235. Nuclear reactions occur within these rods when the uranium nuclei undergo fission due to continuous neutron bombardment.
Boron control rods (sometimes cadmium) | Absorbs excess neutrons so that the rate of chain reactions can be controlled.
Graphite core | Slows down the fission neutrons. Neutrons with low kinetic energy can be easily captured by the uranium nucleus to initiate the fission process.
Gas (coolant) | Transfers the heat generated from the reactor core to the heat exchanger.
Heat exchanger | Transfers the heat from the hot gas to the water in pipes. The water in these pipes boil and become steam. The flow of steam rotates the turbine which then drives the generator to generate electricity.
Radiation shield | A 2 m thick wall of solid concrete, steel, graphite and lead. Ensures the gamma rays and neutrons do not escape from the reactor core.

### Pros and Cons of using Nuclear Fission to Generate Electricity

**PROS**
- Nuclear power stations need less fuel than stations which use fossil fuels.
- Vast reserves of nuclear fuel in the world.
- Safety procedures in the administration of nuclear reactors are very advanced and safe.
- Produces useful radioisotopes as by-products that can be used in industry, medicine, agriculture and research.
- The price of nuclear fuel is more stable than fossil fuels.

**CONS**
- Does not add to the greenhouse effect.
- Does not produce polluting gases like sulphur dioxide and carbon dioxide.
- Produces less waste than fossil fuels.
- Produces useful radioisotopes as by-products that can be used in industry, medicine, agriculture and research.
- The initial cost to design and build a nuclear power station is very high.
- There is always a risk of accidents. If a chain reaction goes out of control, explosion or leakage of large amounts of radioactive substances may happen.

**Electrical energy**

- Used fuel rods are very hot and highly radioactive with very long half-lives.
- Expensive procedures are required to cool down the rods and store them.
- The hot water discharged from the nuclear power stations can cause thermal pollution.
- People who work in the nuclear power station and those living nearby may be exposed to excessive radiation.
10.5 Proper Management of Radioactive Substances

10.5.1 Negative Effects of Radioactive Substances
- Overexposure will cause death of living organisms or mutation of surviving cells.
- The severity of the effects depends on the distance from the radioactive source and the strength of penetration of radiation.
- The effects of exposure to radiation for humans can be categorised as:
  - **Somatic**
    - Damage to the body except reproductive cells
    - Symptoms such as fatigue, nausea, loss of hair and skin lesions
    - Delayed effects such as organ failure, cataracts and leukemia
  - **Genetic**
    - Damage to reproductive cells
    - Dangerous cell mutations and chromosome abnormalities which might be transferred to future generations
    - Birth defects, congenital effects, premature death, cancer later in life

10.5.2 Safety Precautions in the Handling of Radioactive Substances
- Read and follow advice and instructions
- Gloves must be worn when an unsealed source is used or whenever contamination may occur
- Laboratory coats, long pants, and closed-toe footwear must be worn
- Eating, drinking, applying cosmetics or storing of food is prohibited
- All work surfaces and storage areas should be covered with absorbent material to contain radioactive material
- When using radioactive liquids, plastic or metal trays should be utilized to contain potential spills
- Radioactive materials, especially liquids, should be kept in unbreakable containers. If glass is used, a secondary container is necessary
- Before eating or drinking, wash hands and forearms thoroughly
- Radioactive sources should be kept in lead boxes and stored in a secure lead container
- Containers must be marked with the radioactive label

10.5.3 Radioactive Waste Management
- Radioactive wastes are the remnant isotopes after a radioactive reaction or decay
- Radioactive wastes contain radioactive substances that emit radiation which are harmful to humans
- Radioactive wastes usually have long half-lives and strong radiation emissions; therefore efficient management is necessary to minimize exposure and contamination
- Determining how to handle radioactive wastes depends on:
  - The half-lives of the radioisotopes
  - The concentration of the radioactive waste
  - The heat emitted from the radioactive waste

<table>
<thead>
<tr>
<th>Low-grade radioactive waste</th>
<th>Medium-grade radioactive waste</th>
<th>High-grade radioactive waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>Originates from hospitals, industries, and nuclear labs</td>
<td>Mostly originates from nuclear power stations</td>
<td>Consists of spent fuel rods from nuclear reactors which are still radioactive and hot</td>
</tr>
<tr>
<td>Consists of contaminated utensils, clothing, and bandages</td>
<td>Stored in special drums, encased in concrete blocks, and buried underground or in used mines</td>
<td>Stored in pools of water for several years to cool, and then stored in steel containers and buried approx. 500m underground</td>
</tr>
<tr>
<td>Solids are stored in special drums and buried underground</td>
<td></td>
<td>The fuel rods can also be reprocessed and enriched for reuse</td>
</tr>
<tr>
<td>Liquids (coolant fluid from nuclear power stations) are deposited into the sea via long pipes and released 1-2km from coastline</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gases are released into the atmosphere</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**END OF CHAPTER**

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