Radioactivity

Composition of an Atom

- An atom is very tiny and typically has a size of **$1 \times 10^{-10} \pu{m}$**.
- It is made up of **subatomic particles** such as protons, neutrons and electrons.
- An atom consists of a positively charged nucleus and negatively charged electrons moving around the nucleus.
- The nucleus of an atom consists of two types of particles - protons and neutrons.
- Strong attractive electrostatic forces between the positively charged nucleus and negatively charged electrons hold the electrons to the atom.

Proton (atomic) Number Z.

- The **proton number *Z*** is the number of protons in an atom.
- The proton number is also known as the **atomic number**.
- In a neutral atom, the number of protons is the same as the number of electrons.
- Each element has a unique proton number.

Nucleon (Mass) Number A

- Proton and neutrons are called **nucleons**.
- The **nucleon number** is the total number of neutrons and protons in the nucleus of an atom.
- The symbol A is used to represent the nucleon number of an element.
- The nucleon number is also known as the **mass number.**
- The mass of an atom depends on the mass of nucleons in the nucleus of the atom as the mass of an electron is very small and thus negligible.
- To find the number of neutrons in an atom,

Number of neutrons

$$= A - Z$$

- Note that in nuclear physics and nuclear chemistry, the various species of atoms whose nuclei contain a particular number of protons and neutrons are called **nuclides.**
- The nucleus of an atom can be represented by the **nuclide notation:**

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

Isotopes

- **Isotopes** are atoms of the same element that have the same number of protons but different numbers of neutrons.
- Isotopes of the same elements have *identical* chemical properties.
- Example: carbon isotopes

Nuclear Decay

- **Nuclear decay** is also known as radioactive decay or radioactivity.
- Nuclear decay is a random process by which an unstable atomic nucleus loses its energy by emission of electromagnetic radiation or particle(s).
- The radiation emitted by a radioactive nucleus is *spontaneous* and *random* in direction.
    - Spontaneous decay means that the decay is not affected by environmental changes (e.g. temperature and pressure.)
    - Random decay means that the decay cannot be predicted which particular nucleus will decay next.
- A material containing unstable nuclei is considered radioactive.
- The instability of the atomic nuclei is because the nuclear forces within the nuclei are not enough to bind the nucleons together.
- Since the direction of the emissions and the time between emissions cannot be predicted, hence it is:
    - not possible to make the radioactive nucleus emit radiation by heating, cooling, chemical means or any other method;

- not possible to predict when a radioactive nucleus will emit radiation; and
- not possible to know the direction in which the emitted radiation will leave a nucleus.

Types of Nuclear Emission

There are three types of nuclear emission: **alpha (α) particles, beta (β) particles and gamma (γ) rays.** Different nuclear emissions have different compositions, ionising effects and penetrating abilities.

Ionisation refers to the ability to eject electrons from atoms to form positively charged cations. Since the atoms lose electrons, the number of protons is greater than the number of electrons. Thus, ions carry a charge. The nuclei of the same isotope will emit the same type of nuclear radiation. During alpha decay or beta decay, the nucleus changes to that of a different element.

Alpha Decay

- When a radioactive nucleus undergoes alpha decay:
  - it emits an alpha particle (identical to helium nucleus $\ce{^4_2He}$)
  - the nucleon number A decreases by 4
  - the proton number Z decreases by 2
- A **nuclide equation** involving nuclide notation can be used to represent the changes in the composition of the nucleus. The arrow in the equation means "reacts to form".

Example: Radium-226 (Ra) nucleus emits an alpha particle and decays to radon-222 (Rn).

$$\ce{^{226}_{88}Ra -> ^{222}_{86}Rn + ^4_2He}$$

Note that in a nuclear reaction, the **mass and charge are conserved.** Hence, before and after the reaction,

- The total number of neutrons and protons remain constant, and
- The total relative charge should also be the same (i.e. sum of proton number before and after decay should be the same.)

Beta Decay

- When a radioactive nucleus undergoes ß-decay:
  - it emits a ß-particle (an electron); and
  - the nucleon number A remains the same
  - the proton number Z increases by 1

Example

$$\ce{^{238}_{92} U -> ^{234}_90 Th + ^4_2He + 2 ^0_0\gamma}$$

Gamma Radiation

- Usually, when radioactive nuclei undergo alpha-decay or beta-decay, gamma radiation is also emitted.
- Example: When uranium-238 (U) emits an alpha particle, it decays to thorium-234 (Th) and two gamma rays of different energies are emitted.

$$\ce{^{238}_{92}U -> ^{234}_90 Th + ^4_2 He + 2 ^0_0 \gamma}$$

Measuring Ionising Nuclear Radiation

A **Geiger-Muller (GM) counter** is an instrument used to measure ionising nuclear radiation.

The SI unit for the amount of radioactivity is the **Becquerel (Bq)**. One becquerel (1 Bq) is equal to 1 disintegration per second. It refers to the amount of ionising radiation released when a radioactive atom (e.g. uranium) spontaneously emits electromagnetic radiation as a result of the radioactive decay.

Alternative unit: count rate: counts per second or minute

Why is ionising radiation still detected even if radioactive sources aren't brought into the environment?

Background radiation from natural or man-made sources is always present. These sources include cosmic radiation from outer space, nautrally occurring radioactive isotopes, man-made radioactive isotopes, radioactive waste from nuclear power stations, and so on.

How would this affect our results when measuring radioactivity from a radioactive substance?

In general, the results collected will not present an accurate account of the radioactivity of the substance being measured, since the radiation detected comes form the radioactive substance being investigated, as well as background radiation.

Suggest what could be done to get a more accurate account of the radioactivity of the substance being investigated.

The background count should be measured and subtracted from the total count.

Background Radiation

Background radiation refers to nuclear radiation in an environment where no radioactive source has been deliberate introduced.

Radiation is all around us. For example, we have learned in Unit 11 Electromagnetic Spectrum that the visible light and infraerd radiation are electromagnetic radiation from the sun. The microwaves and the radio waves are radiation used in communication systems. These are non-ionising radiation, thus they have little biological effect.

Ionising radiation is radiation with high energies that can knock off electrons from atoms to form ions. For example:

- Ionising electromagnetic radiation: Very high frequency ultraviolet rays, X-rays and gamma rays.

- Ionising nuclear radiation: Highly energetic particles from cosmic rays (from outer space) and from naturally occurring radioactive materials

Sources of background radiation that can be artificial (man-made) or natural:

Artificial Sources

- Medical X-rays
- Building materials
- Waste products from nuclear power stations

Natural sources

- Rocks
- Radon gas in the air
- Food and drink (e.g. food high in potassium such as bananas, carrots and salt may contain radioactive potassium-40).

Natural background radiation accounts for about 80% of the radiation that we are exposed to. The amount of background radiation we encounter is usually well below the recommended limit of radiation exposure.

Half-Life

- Since nuclear decay is spontaneous, we will not know exactly when a particular nucleus will decay.
- Every nuclide has a fixed rate of decay. The **half-life** of a radioactive nuclide is the time taken for half the nuclei of that nuclide in any sample to decay.
- Predictions about the decay of a large number of nuclei of a particular nuclide can be made because it has a fixed half-life.

Nuclear Fission and Nuclear Fusion

Nuclear Fission

- **Nuclear fission** is a process in which a **parent nucleus** splits (usually into two **daughter nuclei**) and releases a huge amount of energy.
- The original parent nucleus becomes nucleus of two different elements.
- The daughter nuclei may be stable or may decay further
- There may be several possible fission products and it is important to check that the total number of nucleons and the total relative charge (proton number Z) before and after the reaction are the same.

Nuclear Fusion

- **Nuclear fusion** is a process in which two light atomic nuclei combine to form one heavier atomic nucleus and releases a huge amount of energy.
- Two atoms join to become another bigger atom of a different element.

Energy Changes During Nuclear Processes

- Nuclear fuel is a material used in nuclear power stations.
- Some examples of nuclear fuel are uranium and plutonium. Isotopes such as uranium-233, uranium-235 and plutonium-239 are commonly involved in nuclear fission.
- The nuclear fuels undergo nuclear reactions to release energy
- During **nuclear fission**, energy is transferred form the **nuclear store** of the unstable nucleus to:
    - the **kinetic** and **nuclear stores** of the daughter nuclei and neutrons
    - the **internal store** of the surroundings
- The internal store of the surroundings is used to heat the water so that it changes into steam.
- The neutrons produced in the nuclear fission will go on to split more nuclei.

- This creates a self-sustaining chain reaction taht is controlled in a nuclear reactor.
- The processes involved in mining, refining, purifying, using and disposing of nuclear fuel are collectively known as the nuclear fuel cycle.
- Energy can also be released from **nuclear fusion.**
- During nuclear fusion, energy is transferred from the **nuclear stores of the two nuclei to**:
    - The **kinetic** and **nuclear store** of the bigger nucleus.
    - The **internal store** of the surroundings.
- The internal store of the surroundings can be used in the electical power generation process.
- A lot of work is done to overcome the repusive forces between the positively charged nuclei during nuclear fusion
- Nuclear fusion cannot happen at low temperature and pressure as the two nuclei cannot come into close range of each other due to the repulsive forces.
- Hence, nuclear fusion requires **very high temperatures and pressures** and is currently not used in nuclear power plants.
- Example: Nuclear fusion can take place in the sun where temperature and pressure are high.
- Scientists and engineers are working on reactors where nuclear fusion can take place in a safe and controlled manner.

Uses Related to the Damage of Cells

Medical

Detection of Tumors - Gamma Rays

- Isotope, technetium-99, is used in the detection of tumours
- Small amount of isotope is taken into the body and travels to the internal organs
- A gamma camera is used to detect the gamma-rays emitted from the internal organs due to the technetium-99.
- The images formed will help in the diagnosis of tumours
- The isotope has a short half-life (6 hours) so it does not remain in the body for too long.

Gamma Knife Radiosurgery - Gamma Rays

- Gamma rays from a radioactive source (cobalt-60) are directed at the brain to destroy brain tumours.
- The isotope has a long half-life (5.3 years) so it remains in the body for a long time. Hence, only a small quantity over a long treatment time.

Cancer Treatment - Beta Particles

- Isotope, iodine-131, is used in the treatment of thyroid disorder.
- When small amount is taken into the body, it can destroy the thyroid cells including cancer cells.
- The isotope has a short half-life (8-days) so it does not remain in the body for too long.

Safety

Food Safety - Gamma Rays

- Fodo decays due to the actions of microbes
- Gamma rays can be used to kill the microbes so that the food is safe for consumption and can last longer.
- The isotope has a long half-life (a few years).
- Only a small quantity is needed over a long time.

Sterilisation of Medical Equipment - Gamma Rays

- Medical equipment such as syringes and scapels are kept in sealed packaging and exposed to gamma rays.
- The microbes present on the equipment will be killed and the equipment is sterile.
- Gamma rays can be used to kill the microbes so that the medical equipment is sterile
- The isotope has a long half-life (a few years)

Uses Related to Radioactive Decay and Half-life

Geology

Determine how old an object/material is - Alpha Particles

- The isotopes, uranium-238, is found in most rocks and has a half-life of 4.5 billion years
- The isotope decays to a stable isotope, lead-206.
- y determining the relative amounts of uranium-238 and lead-206 in a sample, the age of the rock can be known.
- The greater amount of lead-206 present, the older the rock.

Uses Related to the Penetrating Abilities and Ionising Effects

Safety

Smoke Detectors - Alpha Particles

- The isotope, Americium-241, is used in smoke detectors.
- When the alpha particles emitted fall on the detector, a current flows in the detector as alpha particles have high ionising ability.
- WHen smoke enters the detector, the smoke absorbs the radiation and disrupts the flow of current in the detector.
- The disruption triggers the detector's alarm.

Industrial

Measure the Thickness of Materials - Beta-particles / Gamma-rays

- Manufacturer needs to ensure that the materials are of uniform thickness.
- Beta particles or gamma rays from a radioactive source are directed at the material.
- A detector measures the amount of radiation passing through.
- If the material is too thick, the amount of radiation is low and vice-versa.
- Beta-particles are more suitable for thinner materials such as papers.
- Gamma rays are more suitable for slightly thicker materials such as metal plates.

Question: Why are alpha-particles not suitable?

Alpha particles have low penetrating power and will be absorbed by the materials most easily.

Hazards of Radioactivity

Protecting Ourselves from Radioactive Materials

Limit Contamination

If we are present at a site where there may have been a radioactive incident, we can take the following precautions.

1. Leave the immediate area quickly to avoid being contaminated with radioactive materials. Follow the directions of officials to the nearest safe building or area.
2. Remove the outer layer of the clothing as the radioactive materials may be on the clothing. Removing the clothing will reduce the risk of contamination.
3. Wash all exposed parts of the body with soap and lukewarm water. This removes radioactive materials that may be present on the body and reduces the risk of contamination.

Reduce Exposure

1. Reduce exposure time
    - Experiments involving radioactive materials should only be carried out in designated locations.
2. Increase distance between radioactive source and living tissue.
    - The intensity of all ionising radiation decreases with distance.
    - Use long tongs or remote-controlled device to increase the distance between radioactive materials and body.
3. Shielding
    - Wear materials that absorb the ionising radiation (e.g. lead-lined gloves)
    - Use thick concrete walls and lead-lined doors for rooms in which ionising radiation is used.
4. Storage
    - Store radioactive mateirals in a selaed container that will absorb hte radiation from the source (e.g. lead box)
    - This prevents the nuclear radiation from penetrating through the container and escaping into the air
    - Label the container with radioactive sign and keep in a secure place that is not accessible by anyone.

Summary

Property	**Alpha**	**Beta**	**Gamma**
Ionising Effect	Highest	Middle	Lowest
Penetrating Effect	Lowest (Paper)	Middle (Aluminium)	Highest (Lead concrete)
Representation	$\ce{^4_2He}$	$\ce{^0_{-1}\beta}$	$\ce{_0^0\gamma}$