4.4 Atomic structure

Ionising radiation is hazardous but can be very useful. Although radioactivity was discovered over a century ago, it took many nuclear physicists several decades to understand the structure of atoms, nuclear forces and stability. Early researchers suffered from their exposure to ionising radiation. Rules for radiological protection were first introduced in the 1930s and subsequently improved. Today radioactive materials are widely used in medicine, industry, agriculture and electrical power generation.

4.4.1 Atoms and isotopes

4.4.1.1 The structure of an atom

Atoms are very small, having a radius of about 1×10^{-10} metres.

The basic structure of an atom is a positively charged nucleus composed of both protons and neutrons surrounded by negatively charged electrons.

The radius of a nucleus is less than 1/10 000 of the radius of an atom. Most of the mass of an atom is concentrated in the nucleus.

The electrons are arranged at different distances from the nucleus (different energy levels). The electron arrangements may change with the absorption of electromagnetic radiation (move further from the nucleus; a higher energy level) or by the emission of electromagnetic radiation (move closer to the nucleus; a lower energy level).

4.4.1.2 Mass number, atomic number and isotopes

In an atom the number of electrons is equal to the number of protons in the nucleus. Atoms have no overall electrical charge.

All atoms of a particular element have the same number of protons. The number of protons in an atom of an element is called its atomic number.

The total number of protons and neutrons in an atom is called its mass number.

Atoms can be represented as shown in this example:

(Mass number)
(Atomic number) $^{23}_{11}\text{Na}$

Atoms of the same element can have different numbers of neutrons; these atoms are called isotopes of that element.

Atoms turn into positive ions if they lose one or more outer electron(s).

Students should be able to relate differences between isotopes to differences in conventional representations of their identities, charges and masses.

4.4.1.3 The development of the model of the atom (common content with chemistry)

New experimental evidence may lead to a scientific model being changed or replaced.

Before the discovery of the electron, atoms were thought to be tiny spheres that could not be divided.

The discovery of the electron led to the plum pudding model of the atom. The plum pudding model suggested that the atom is a ball of positive charge with negative electrons embedded in it.

The results from the alpha particle scattering experiment led to the conclusion that the mass of an atom was concentrated at the centre (nucleus) and that the nucleus was charged. This nuclear model replaced the plum pudding model.

Niels Bohr adapted the nuclear model by suggesting that electrons orbit the nucleus at specific distances. The theoretical calculations of Bohr agreed with experimental observations.

Later experiments led to the idea that the positive charge of any nucleus could be subdivided into a whole number of smaller particles, each particle having the same amount of positive charge. The name proton was given to these particles.

The experimental work of James Chadwick provided the evidence to show the existence of neutrons within the nucleus. This was about 20 years after the nucleus became an accepted scientific idea.

Students should be able to describe:

- why the new evidence from the scattering experiment led to a change in the atomic model
- the difference between the plum pudding model of the atom and the nuclear model of the atom.

Details of experimental work supporting the Bohr model are not required.

Details of Chadwick's experimental work are not required.

4.4.2 Atoms and nuclear radiation

4.4.2.1 Radioactive decay and nuclear radiation

Some atomic nuclei are unstable. The nucleus gives out radiation as it changes to become more stable. This is a random process called radioactive decay.

Activity is the rate at which a source of unstable nuclei decays.

Activity is measured in becquerel (Bq)

Count-rate is the number of decays recorded each second by a detector (eg Geiger-Muller tube).

The nuclear radiation emitted may be:

• an alpha particle (α) – this consists of two neutrons and two protons, it is the same as a helium nucleus

• a beta particle (β) – a high speed electron ejected from the nucleus as a neutron turns into a proton

• a gamma ray (γ) – electromagnetic radiation from the nucleus

• a neutron (n).

Required knowledge of the properties of alpha particles, beta particles and gamma rays is limited to their penetration through materials, their range in air and ionising power.

Students should be able to apply their knowledge to the uses of radiation and evaluate the best sources of radiation to use in a given situation.

4.4.2.2 Nuclear equations

Nuclear equations are used to represent radioactive decay.

In a nuclear equation an alpha particle may be represented by the symbol:

$$^{4}_{2}\text{He}$$

and a beta particle by the symbol:

$$^{0}_{-1}\text{e}$$

The emission of the different types of nuclear radiation may cause a change in the mass and /or the charge of the nucleus. For example:

$$^{219}_{86}\text{radon} \longrightarrow {}^{215}_{84}\text{polonium} + {}^{4}_{2}\text{He}$$

So alpha decay causes both the mass and charge of the nucleus to decrease.

$$^{14}_{6}\text{carbon} \longrightarrow {}^{14}_{7}\text{nitrogen} + {}^{0}_{-1}\text{e}$$

So beta decay does not cause the mass of the nucleus to change but does cause the charge of the nucleus to increase.

Students are not required to recall these two examples.

Students should be able to use the names and symbols of common nuclei and particles to write balanced equations that show single alpha (α) and beta (β) decay. This is limited to balancing the atomic numbers and mass numbers. The identification of daughter elements from such decays is not required.

The emission of a gamma ray does not cause the mass or the charge of the nucleus to change.

4.4.2.3 Half-lives and the random nature of radioactive decay

Radioactive decay is random.

The half-life of a radioactive isotope is the time it takes for the number of nuclei of the isotope in a sample to halve, or the time it takes for the count rate (or activity) from a sample containing the isotope to fall to half its initial level.

Students should be able to explain the concept of half-life and how it is related to the random nature of radioactive decay.

Students should be able to determine the half-life of a radioactive isotope from given information.

(HT only) Students should be able to calculate the net decline, expressed as a ratio, in a radioactive emission after a given number of half-lives.

4.4.2.4 Radioactive contamination

Radioactive contamination is the unwanted presence of materials containing radioactive atoms on other materials. The hazard from contamination is due to the decay of the contaminating atoms. The type of radiation emitted affects the level of hazard.

Irradiation is the process of exposing an object to nuclear radiation. The irradiated object does not become radioactive.

Students should be able to compare the hazards associated with contamination and irradiation.

Suitable precautions must be taken to protect against any hazard that the radioactive source used in the process of irradiation may present.

Students should understand that it is important for the findings of studies into the effects of radiation on humans to be published and shared with other scientists so that the findings can be checked by peer review.

4.4.3 Hazards and uses of radioactive emissions and of background radiation (physics only)

4.4.3.1 Background radiation

Background radiation is around us all of the time. It comes from:

- *natural sources such as rocks and cosmic rays from space*
- *man-made sources such as the fallout from nuclear weapons testing and nuclear accidents.*

The level of background radiation and radiation dose may be affected by occupation and/or location.

Radiation dose is measured in sieverts (Sv)

1000 millisieverts (mSv) = 1 sievert (Sv)

Students will not need to recall the unit of radiation dose.

4.4.3.2 Different half-lives of radioactive isotopes

Radioactive isotopes have a very wide range of half-life values.

Students should be able to explain why the hazards associated with radioactive material differ according to the half-life involved.

4.4.3.3 Uses of nuclear radiation

Nuclear radiations are used in medicine for the:

- *exploration of internal organs*
- *control or destruction of unwanted tissue.*

Students should be able to:

- *describe and evaluate the uses of nuclear radiations for exploration of internal organs, and for control or destruction of unwanted tissue*
- *evaluate the perceived risks of using nuclear radiations in relation to given data and consequences.*

4.4.4 Nuclear fission and fusion (physics only)

4.4.4.1 Nuclear fission

Nuclear fission is the splitting of a large and unstable nucleus (eg uranium or plutonium).

Spontaneous fission is rare. Usually, for fission to occur the unstable nucleus must first absorb a neutron.

The nucleus undergoing fission splits into two smaller nuclei, roughly equal in size, and emits two or three neutrons plus gamma rays. Energy is released by the fission reaction.

All of the fission products have kinetic energy.

The neutrons may go on to start a chain reaction.

The chain reaction is controlled in a nuclear reactor to control the energy released. The explosion caused by a nuclear weapon is caused by an uncontrolled chain reaction.

Students should be able to draw/interpret diagrams representing nuclear fission and how a chain reaction may occur.

4.4.4.2 Nuclear fusion

Nuclear fusion is the joining of two light nuclei to form a heavier nucleus. In this process some of the mass may be converted into the energy of radiation.