Section 4: Atoms and Nuclei

Some aspects of atomic and nuclear physics are introduced. A study of spectra provides the link to Section 3 and establishes the experimental basis for inferences about atomic states with discrete energies.

Most of the section is devoted to the atomic nucleus: the composition of stable nuclei, the behaviour of unstable nuclei, and the important nuclear reactions of fission and fusion.

Also in this section, issues related to nuclear power — its present form and possibilities for the future — are examined.

Topic 1: The Structure of the Atom

The existence of line emission spectra from atomic gases is used to infer a structure of an atom in terms of states with discrete energies. The structure of an atom as a positive nucleus surrounded by one or more electrons is assumed.

The visible continuous spectra emitted by hot objects are introduced and atomic absorption spectra are explained.

The phenomena of population inversion and stimulated emission are used to introduce a simple explanation of the operation of a laser.

Key Ideas	Intended Student Learning
Students should know and understand the following:	*Students should be able to do the following:*
Line Emission Spectrum	
A hot vapour of a pure element emits light of discrete frequencies, resulting in a line emission spectrum when the light is viewed with a spectrometer.	Describe the general characteristics of the line emission spectra of elements. Explain how the uniqueness of the spectra of elements can be used to identify the presence of an element.
Energy Levels in Atoms	
The presence of discrete frequencies in the spectra of atoms is evidence for the existence of different states in atoms. The states have their own specific energies. The different energies can be represented on an energy-level diagram. When an electron makes a transition from a higher-energy state to a lower-energy state in an atom, the energy of the atom decreases and can be released as a photon. The energy of the emitted photon is given by $E_n - E_m = hf$, where $E_n - E_m$ is the energy difference of the atom, hf is the energy of the photon, and f is the frequency of the emitted light.	Explain how the presence of discrete frequencies in line emission spectra provides evidence for the existence of states with discrete energies in atoms. Solve problems involving the use of $E_n - E_m = hf$. Draw energy-level diagrams to represent the energies of different states in an atom. Given an energy-level diagram, calculate the frequencies and wavelengths of lines corresponding to specified transitions.

Key Ideas	Intended Student Learning
Students should know and understand the following:	*Students should be able to do the following:*
An atom is in its ground state when its electrons have their lowest energy. If an electron is in any of the higher-energy states, the atom is said to be in an excited state.	
Spectrum of Atomic Hydrogen	
The line emission spectrum of atomic hydrogen consists of several series of lines, each of which converges to a series limit.	Draw, on an energy-level diagram of hydrogen, transitions corresponding to each of the series terminating at the three lowest-energy levels. Relate the magnitude of the transitions on an energy-level diagram to the region in the electromagnetic spectrum of the emitted photons (ultraviolet, visible, or infrared). Draw, on an energy-level diagram, the transition corresponding to the series limit for a given spectral series of hydrogen.
Ionisation Energy	
The ionisation energy of an atom is the minimum energy required to remove a single electron from the atom in its ground state.	Using an energy-level diagram, determine the ionisation energy of an atom. Express this energy in either joules or electronvolts.
Continuous Spectrum	
A continuous spectrum contains a continuous range of frequencies. Solid, liquid, or dense gaseous objects radiate a continuous spectrum, which may extend into or beyond the visible region. The frequency distribution, and hence the dominant colour, depends on the temperature of the object.	Describe the changes in the spectrum of a filament globe as the temperature of the filament increases.
Line Absorption Spectrum	
When light with a continuous spectrum is incident on a gas of an element, discrete frequencies of light are absorbed, resulting in a line absorption spectrum. The frequencies of the absorption lines are a subset of those in the line emission spectrum of the same element.	Describe the line absorption spectrum of atomic hydrogen. Draw, on an energy-level diagram, transitions corresponding to the line absorption spectrum of hydrogen. Explain why there are no absorption lines in the visible region for hydrogen at room temperature. Account for the presence of absorption lines (Fraunhofer lines) in the Sun's spectrum.

Key Ideas

Students should know and understand the following:

Fluorescence

When an atom absorbs a photon, it is elevated to an ‘excited state’, which has a higher energy. Excited states are generally short-lived and the atom quickly returns to its ground state, often by emitting a series of lower-energy photons. This process of converting high-energy photons into a larger number of lower-energy photons is called ‘fluorescence’.

Stimulated Emission

When a photon with energy corresponding to a transition from a higher-energy state to a lower-energy state is incident on an atom in the lower state, it can be absorbed by the atom.

When a photon with energy corresponding to a transition from a higher-energy state to a lower-energy state is incident on an atom in the higher state, it can stimulate a transition to the lower state.

The photon emitted in stimulated emission is identical (in energy, direction, and phase) to the incident photon.

A population inversion is produced in a set of atoms whenever there are more atoms in a higher-energy state than in a lower-energy state.

If photons with energy corresponding to the transition from the higher-energy state to the lower-energy state are incident on a set of atoms in which there is a population inversion, there will be more stimulated emissions than absorptions.

Some excited states last for a relatively long time before the atom undergoes a transition to a lower-energy state by spontaneously emitting a photon. These states are called ‘metastable’ states.

For practical systems, the higher-energy state must be metastable if a population inversion is to be produced.

Intended Student Learning

Students should be able to do the following:

Draw, on an energy-level diagram of hydrogen, the process of fluorescence.

Compare the process of stimulated emission with that of ordinary (or spontaneous) emission.

Describe the conditions required for stimulated emission to predominate over absorption when light is incident on a set of atoms.

Key Ideas

Students should know and understand the following:

Application: Lasers

Intended Student Learning

Students should be able to do the following:

Describe the structure and purpose of the main components of a helium–neon gas laser:

- pump (electrodes)
- gain medium
- laser cavity.

Describe the useful properties of laser light (i.e. it is coherent and monochromatic, and may be of high intensity).

Discuss the requirements for the safe handling of lasers.

Identify some uses of lasers.

Topic 2: The Structure of the Nucleus

The composition of the nucleus is described in terms of protons and neutrons. An attractive force, which balances the repulsive electrostatic force between the positively charged protons, is identified. The terminology and notation used to describe nuclei are introduced. Some of the fundamental conservation laws are used to discuss nuclear reactions.

The key ideas are applied to the production of medical radioisotopes.

Key Ideas	Intended Student Learning
Students should know and understand the following:	*Students should be able to do the following:*
Composition of Nuclei	
The nucleus of an atom consists of protons and neutrons, which have approximately the same mass. The proton has a positive charge equal in magnitude to that of an electron. The neutron is uncharged. The term 'nucleon' refers to either a proton or a neutron. The atomic number Z of an atom is the number of protons in the nucleus of the atom and hence the charge of the nucleus in units of e, the charge of an electron. The mass number A of an atom is the number of nucleons in the nucleus of an atom. $A = Z + N$, where N is the number of neutrons.	Specify a nucleus in the form ${}^{A}_{Z}\mathrm{X}$, where X represents the chemical symbol for the element. Given the specification for any nucleus in the form ${}^{A}_{Z}\mathrm{X}$, determine the number of protons, neutrons, and nucleons it contains.
The Force between Nucleons	
At short distances nucleons exert strong attractive forces on each other. These forces become negligible at separations of more than a few nucleon diameters, and become repulsive at extremely short distances. These forces are independent of the nature of the nucleons.	Explain how it is possible to have stable nuclei despite the strong repulsive electrostatic force between the protons.
Isotopes	
Nuclei of a given element all have the same number of protons. In neutral atoms this is also the number of electrons. Nuclei of a given element may have different numbers of neutrons. These nuclei are the isotopes of the element.	Explain why the isotopes of a given element are chemically identical.

Key Ideas

Students should know and understand the following:

Isotopes of a given element are chemically identical but have different masses.

Intended Student Learning

Students should be able to do the following:

Mass Defect and Binding Energy

Mass m and energy E are related according to $E = mc^2$, where c is the speed of light.

Accurate measurements show that the mass of a nucleus is less than that of its individual nucleons. The difference is called the 'mass defect'. When a nucleus is formed from its constituents, an amount of energy corresponding to the mass defect is released.

When a nucleus is separated into its constituent nucleons, energy must be supplied and the mass increases.

The minimum energy necessary to separate a nucleus into its constituent nucleons is called the 'binding energy' of the nucleus.

The binding energy E_b is calculated from the mass defect Δm, using $E = \Delta m c^2$.

Given the masses (in kg) of a nucleus and its constituent nucleons, calculate the mass defect and binding energy (in J and MeV) of the nucleus.

Conservation Laws in Nuclear Reactions

In a nuclear reaction the total charge and the total number of nucleons are conserved.

In a nuclear reaction the total mass of the reactants is different from the total mass of the products.

In a nuclear reaction the total energy (including the energy associated with the mass) is conserved. Hence the energy absorbed or released in a reaction can be calculated from the difference in the masses of the products and the reactants.

In a nuclear reaction momentum is conserved.

Complete simple nuclear equations for reactions between two nuclei or nucleons.

In given nuclear reactions, calculate the differences in masses, and hence determine whether energy is absorbed or released.

Explain, using the law of conservation of momentum, why a particle of relatively small mass that is emitted by a nucleus acquires most of the kinetic energy released in the reaction.

Key Ideas

Students should know and understand the following:

Application: The Production of Medical Radioisotopes

Intended Student Learning

Students should be able to do the following:

Describe how a nucleus may be changed into a nucleus of a different element by the absorption of particles such as neutrons, protons, and deuterons.

Explain, using the equation

$$ {}^{1}_{0}\mathrm{n} + {}^{32}_{16}\mathrm{S} \longrightarrow {}^{32}_{15}\mathrm{P} + {}^{1}_{1}\mathrm{H}, $$

how the medical radioisotope phosphorus-32 may be produced using neutrons emitted from a nuclear fission reactor.

Identify one use of ${}^{32}_{15}\mathrm{P}$ (e.g. the treatment of excess red blood cells).

Explain, using the equations

$$ {}^{1}_{1}\mathrm{H} + {}^{18}_{8}\mathrm{O} \longrightarrow {}^{18}_{9}\mathrm{F} + {}^{1}_{0}\mathrm{n} $$

and

$$ {}^{2}_{1}\mathrm{H} + {}^{14}_{7}\mathrm{N} \longrightarrow {}^{15}_{8}\mathrm{O} + {}^{1}_{0}\mathrm{n}, $$

how the medical radioisotopes fluorine-18 and oxygen-15 (commonly used in positron emission tomography scans) may be produced in hospitals, using cyclotrons.

Topic 3: Radioactivity

Radioactivity is the spontaneous disintegration of certain nuclei. It is a random process in which particles and/or high-energy photons are emitted. These radiations differ in their behaviour in electric and magnetic fields and in their reaction with matter, although to varying degrees they all ionise matter through which they pass. The concept of radioactive half-life is introduced using graphical methods, and the effects of radiation on living matter are described. The theory is applied to positron emission tomography (PET).

Key Ideas

Students should know and understand the following:

Stable and Unstable Nuclei

Not all atoms have stable nuclei.

Stable nuclei of low mass have approximately equal numbers of neutrons and protons.

Stable nuclei of high mass have more neutrons than protons.

Types of Decay of Unstable Nuclei

Unstable nuclei undergo a process of decay by the emission of radiation.

The following are four types of decay:

- alpha (α) decay, in which helium nuclei (alpha particles) are emitted
- beta minus (β^-) decay, in which electrons (e^-) are emitted
- beta plus (β^+) decay, in which positrons (e^+) are emitted
- spontaneous fission, in which a nucleus splits into two.

These types of decay correspond predominantly to three regions on the N versus Z graph:

- Alpha decay occurs for nuclei with $Z > 83$.
- Beta minus decay occurs above the graph of stable nuclei.
- Beta plus decay occurs below the graph of stable nuclei.
- Spontaneous fission occurs for some nuclei with $Z > 83$.

Intended Student Learning

Students should be able to do the following:

Using the properties of the attractive nuclear force and the repulsive electrostatic force between protons, discuss the reasons for the increase in the neutron-to-proton ratio of stable nuclei as the atomic number increases.

Indicate, on an N versus Z graph, the regions corresponding to alpha decay, beta minus decay, beta plus decay, and spontaneous fission.

Using an N versus Z graph, predict the likely type(s) of decay (if any) for a specified nucleus.

State what characterises the region on the graph that corresponds to each type of decay.

Key Ideas

Students should know and understand the following:

Alpha Decay

Like atoms, nuclei have states with discrete energies. The spacing of these energies is much larger than that of the energies of atoms, and is in the MeV range.

A helium nucleus is particularly tightly bound. If a heavy nucleus is unstable owing to an excess of nucleons it may decay by emitting a helium nucleus (alpha particle). Because the initial and final nuclei have discrete energies, the emitted alpha particle also has a discrete energy.

The general equation for an alpha decay is given by

$$ {}_{Z}^{A}\mathrm{X} \longrightarrow {}_{Z-2}^{A-4}Y + \alpha. $$

Beta Decay

Beta minus decay occurs when a nucleus has an excess of neutrons, and involves the conversion of a neutron into a proton. This is accompanied by the emission of an electron and an antineutrino.

The general equation for beta minus decay is given by

$$ {}_{Z}^{A}\mathrm{X} \longrightarrow {}_{Z+1}^{A}Y + e^{-} + \overline{v}. $$

Beta plus decay occurs when a nucleus has an excess of protons, and involves the conversion of a proton into a neutron. This is accompanied by the emission of a positron and a neutrino.

The general equation for beta plus decay is given by

$$ {}_{Z}^{A}\mathrm{X} \longrightarrow {}_{Z-1}^{A}Y + e^{+} + v. $$

The emitted electrons and positrons from these decays are observed to have a range of energies and momenta, up to some maxima.

A positron and an electron can annihilate each other, producing two gamma rays.

Intended Student Learning

Students should be able to do the following:

Alpha Decay

State the charge, mass, and nature of alpha and gamma emissions.

Write and/or balance nuclear equations for a decay.

Explain why the emitted alpha particles have discrete energies.

Beta Decay

State the charge, mass, and nature of the emissions in beta minus and beta plus decays.

Justify appropriate charge and mass number values for an electron, a positron, a neutrino, and an antineutrino.

Write and/or balance nuclear equations for beta minus and beta plus decays.

Write a nuclear equation for the conversion of a neutron into a proton in beta minus decay.

Write a nuclear equation for the conversion of a proton into a neutron in beta plus decay.

Using the laws of conservation of momentum and energy, justify the emission of an antineutrino in beta minus decay, and a neutrino in beta plus decay.

Key Ideas	Intended Student Learning
Students should know and understand the following:	*Students should be able to do the following:*

Gamma Decay

After alpha or beta decay, a nucleus is sometimes left in one of a small number of possible excited states: ${}^{A}_{Z}\mathrm{X}^{*}$. Such a nucleus decays to the ground state by emitting one or more high-energy photons (gamma rays).

The general equation for a gamma decay is given by

$${}^{A}_{Z}\mathrm{X}^{*} \longrightarrow {}^{A}_{Z}\mathrm{X} + n\gamma$$

where n is the number of high-energy photons emitted.

Explain why alpha or beta decay is often accompanied by the emission of gamma rays with discrete energies.

State the charge, mass, and nature of the emissions in gamma decay.

Justify the appropriate charge and mass number values for a gamma ray.

Write and/or balance nuclear equations for gamma decay.

Some Properties of Radioactive Emissions

Alpha, beta, and gamma radiations all produce ionisation in material through which they pass.

The penetration through matter of radioactive emissions of comparable energy increases in the order alpha, beta, gamma.

Because of their charge, alpha and beta particles are deflected by electric and magnetic fields, whereas gamma radiation is not deflected.

Compare the penetration through matter in various materials (including air) of alpha, beta, and gamma radiations.

Determine the sign of the charge of the radiation from the deflections of alpha, beta, and gamma radiations in electric or magnetic fields.

Sketch diagrams showing the deflections of alpha, beta, and gamma radiations in electric or magnetic fields.

The Effects of Ionising Radiation on Living Matter

In addition to alpha, beta, and gamma, other radiations, including X-rays, neutrons, and protons, cause ionisation in matter. They are collectively called ‘ionising radiation’.

Ionising radiation can break chemical bonds in living matter, and this can kill cells. It can also change the genetic material in cells.

Give some examples of ionising radiations and their sources.

Explain how ionising radiation can damage living matter.

Give some examples of how radiation dosages can be minimised by:

- increasing the distance from the source
- limiting the time of exposure
- using adequate shielding.

Half-life Activity

The number of radioactive nuclei in a sample of a given isotope decreases exponentially with time.

Using a graph of number of radioactive nuclei or activity versus time, determine the half-life of a sample of radioactive material.

Key Ideas

Students should know and understand the following:

Half-life is the time required for half of the radioactive nuclei in a sample to decay.

Radioactivity is a random process with constant probability and hence constant half-life.

Half-life is independent of both the physical state and the chemical state of the material.

The activity of a radioactive substance is the number of radioactive nuclei that decay per unit time.

Activity is proportional to the number of radioactive nuclei present, and hence decreases exponentially with time.

For a given nucleus, the half-life for the activity is the same as the half-life for the number of radioactive nuclei.

Intended Student Learning

Students should be able to do the following:

Given the half-life of a sample of radioactive material, sketch a graph of number of radioactive nuclei or activity versus time.

Use the unit of activity, becquerel (Bq), equal to the number of decays per second.

Perform calculations of the number of radioactive nuclei that remain after a whole number of half-lives.

Perform calculations of the activity of a radioactive sample after a whole number of half-lives.

Application: Positron Emission Tomography (PET)

State the fact that some radioisotopes used in PET can become concentrated in certain body tissues.

Describe how the beta plus decay of a radioisotope can result in the production of photons through positron–electron annihilation.

Use the law of conservation of momentum to explain why two photons travelling in opposite directions are produced in positron–electron annihilation.

Calculate the energy of the photons produced in positron–electron annihilation.

Describe how a ring of photon detectors allows the location of a tracer radioisotope in a human body to be determined.

State one use of the radioisotope oxygen-15 in PET (e.g. the use of $^{15}\mathrm{O}$-labelled water as a tracer for blood flow).

State one use of the radioisotope fluorine-18 in PET (e.g. the use of $^{18}\mathrm{F}$-labelled glucose to measure the metabolism of glucose in the heart).

Explain why PET facilities need to be located near particle accelerators.

Topic 4: Nuclear Fission and Fusion

The characteristics of nuclear fission reactions are discussed and applied to the example of a nuclear reactor used for the generation of electrical power. Energy can also be produced by nuclear fusion. Reference is made to the fusion reactions in stars, and some advantages and disadvantages of fusion as a future source of power are considered.

Key Ideas	Intended Student Learning
Students should know and understand the following:	*Students should be able to do the following:*
Spontaneous and Induced Nuclear Fission	
Nuclear fission is the process in which a very heavy nucleus splits into two lighter nuclei. Some heavy nuclei undergo nuclear fission spontaneously. Fission can also be induced in some heavy nuclei by the capture of a neutron. In either case the nucleus splits into two nuclei and several neutrons, with accompanying emission of gamma rays. The total mass of the reactants in a fission reaction is greater than that of the products, releasing energy given by $E = \Delta m c^2$, where Δm is the mass of the reactants minus the mass of the products. This energy is released in the form of the kinetic energy of the product particles and the energy of the gamma ray photons.	Given all relevant masses (in kg), calculate the energy (in J and MeV) released per fission reaction. Compare the amount of energy released in a fission reaction with the (given) energy released in a chemical reaction. Give a simple explanation of fission in terms of short-range nuclear-attractive forces and long-range coulomb-repulsive forces.
Chain Reaction	
On average more than one neutron is emitted in nuclear fission. This leads to the possibility that these neutrons will induce further fissions, resulting in a chain reaction. The neutrons emitted as a result of nuclear fission have high speeds, corresponding to energies of 1 to 2 MeV. ^{235}U (and ^{233}U) undergoes fission with slow neutrons of energy of about 10 eV or less. Hence to induce fission in these nuclei the neutrons must be slowed down. This is achieved by collisions with particles of similar mass in a moderator. Many neutrons are absorbed by surrounding nuclei, or escape and cause no further fissions.	Explain why neutrons have to be slowed down in order to produce fission in ^{235}U. Explain why the most effective moderators have atoms of low mass and low absorption of neutrons. Explain why the nuclei produced by fission reactions are likely to have an excess of neutrons, and identify the type of radioactive decay they undergo. Explain why the fission products are hazardous and difficult to process. Explain why it is generally not possible to attain a continuous chain reaction using naturally occurring uranium unless it is enriched with ^{235}U.

Key Ideas

Students should know and understand the following:

The fraction of $^{235}\mathrm{U}$ in naturally occurring uranium is small. It is therefore necessary to increase the fraction of $^{235}\mathrm{U}$ in order to achieve a chain reaction. The process is called 'enrichment'.

About 1% of the neutrons produced in nuclear fission are emitted after a delay of 10 seconds or more.

There is no unique fission for any given nucleus. The many possible reactions result in the production of a range of fission products.

The nuclei produced by fission reactions are likely to have an excess of neutrons, and hence are likely to be radioactive.

Application: Fission Nuclear Power

Intended Student Learning

Students should be able to do the following:

Given a diagram of a reactor, describe and discuss the function of the principal components of a water-moderated fission power reactor (core, fuel rods, moderator, control rods, heat exchanger, safety rods, and shielding).

Explain why the uranium fuel needs to be enriched.

Relate the starting, normal operation, and stopping of a nuclear reactor to the nature of the chain reaction.

Explain briefly why the delayed emission of neutrons allows the chain reaction in a nuclear power reactor to be controlled.

Discuss some of the advantages and disadvantages of nuclear fission over fossil fuel power stations.

Key Ideas

Students should know and understand the following:

Nuclear Fusion

Nuclear fusion is the process in which two nuclei combine into a single nucleus.

For fusion to occur, high kinetic energies are needed to overcome the repulsive electrostatic force between the nuclei and to allow the nuclei to approach within the very short range of the nuclear-attractive forces.

The total mass of the reactants in a fusion reaction is greater than that of the products, releasing energy given by $E = \Delta m c^2$, where Δm is the mass of the reactants minus the mass of the products.

Intended Student Learning

Students should be able to do the following:

Given all relevant masses (in kg), calculate the energy (in J and MeV) released per fusion reaction.

Compare the amount of energy released in a fusion reaction with the (given) energy released in a chemical reaction.

Describe how the conditions in the interiors of the Sun and other stars allow nuclear fusion to take place, and hence how nuclear fusion is their main energy conversion process.

Discuss the advantages and disadvantages of nuclear fusion over nuclear fission as a future source of power.