Skills

The ways in which investigation and mathematical skills in physics are expressed are set out in the following table of intended student learning.

| Key Ideas  Students should know and understand the following: | Intended Student Learning  Students should provide evidence that they are able to do the following: |
| --- | --- |
| Purposes of Investigations |  |
| Investigations and experiments have a clearly defined purpose. | State the purpose of the investigation or experiment. |
| Investigations and experiments are based on existing information or issues.  Before searching for information it is necessary to have a clear idea of the information required, the level of detail needed, and the appropriate facilities for extracting the information. | For a given topic, state the key ideas or issues relevant to the information required, and identify the type of resource that might provide the information. |
| Before undertaking an information search it is necessary to be familiar with search techniques, the way in which the information is structured, and the means of retrieving the information. | Identify key search words and phrases for a given topic.  Use an information source (e.g. library catalogue, CD-ROM, or the Internet) to obtain information about a topic. |
| Questions and Hypotheses |  |
| Investigable questions guide investigations based on issues in physics. | Formulate a question for investigation based on an issue or phenomenon in physics. |
| Investigations are often designed to explore questions and to develop possible solutions to those questions. | Suggest possible investigations to test the question. |
| Experiments may be used to test hypotheses. | State a testable hypothesis, where appropriate. |
| Designing Investigations and Experiments |  |
| Design |  |
| Scientific inquiry involves designing procedures, including practical investigations based on the scientific method or observations made in the field, to investigate questions. Designing an investigation involves identifying:   * what needs to be observed * the measurements that need to be taken * the techniques that need to be used * the apparatus or measuring instruments needed. | Design procedures to investigate posed questions or hypotheses.  Design and carry out investigations to explore an issue or phenomenon in physics.  Design and carry out experiments, using scientific procedures.  Record and analyse observations. |
| Every step in a practical or issues investigation serves a purpose. | Describe the steps of an investigation.  Draw or interpret diagrams of the apparatus used in an experiment. |
| Variables |  |
| Many practical investigations involve deliberately changing one quantity and determining the effect on another quantity. These quantities are referred to as ‘variables’. | Identify the variables in a practical investigation. |
| The quantity being deliberately changed is called the ‘independent variable’. The quantity that changes as a result, and is measured, is called the ‘dependent variable’. | Classify appropriate variables in a practical investigation as independent or dependent. |
| Other variables are held constant, if possible, throughout a practical investigation. | Identify any variables that are deliberately held constant throughout a practical investigation. |
| Conducting Investigations |  |
| Procedures |  |
| Practical investigations require a particular set of actions to be carried out in a well-defined order. | Follow instructions accurately and safely. |
| Safety and Ethics |  |
| Ethical practices must be followed when conducting investigations. | Maintain confidentiality, report accurately, and acknowledge the work of other people. |
| Safety must be considered when conducting investigations. | Recognise hazards and work safely during an investigation. |
| Many investigations involve the collaborative efforts of a team of people. | Negotiate procedures with the other members of the team. Define the role of each member. |
| Work as a member of a team. | Perform the role of a member of a team. |
| Errors in Measurements |  |
| Measurements are affected by random and/or systematic errors. | Identify sources of errors and uncertainty that may occur in a practical investigation. |
| Random errors are present when there is scatter in the measured values. Systematic errors are present when measured values differ consistently from the true value. | Distinguish between random and systematic errors. |
| Where applicable, increasing the number of samples or repeating a practical investigation minimises the effects of random errors and improves the reliability of the data. | Explain the importance of increasing the number of samples in a practical investigation. |
| Systematic errors can be identified and results verified by repeating a practical investigation using an alternative source of equipment and materials. | Explain the importance of repeating a practical investigation where feasible. |
| Reliability, Precision, and Accuracy |  |
| The reliability/precision of data collection is related to the reproducibility of the measurements. | Where possible, collect data using measurements that can be reproduced consistently. |
| Measurements are more reliable when there is less scatter in the results. | Determine which of two or more measuring instruments or sets of measurements is most reliable/precise. |
| Reliability/precision depends on the extent to which random errors are minimised. | Use averages or graphing as a means of detecting or minimising the effects of random errors. |
| The accuracy of an experimental value indicates how close the result is to the true value and depends on the extent to which systematic errors are minimised. | State which result of two or more experiments is most accurate, given the true value. |
| The resolution of a measuring instrument is the smallest increment measurable by the measuring instrument. | Select an instrument of appropriate resolution for a measurement. |
| The number of significant figures for a measurement is determined by the reproducibility of the measurement and the resolution of the measuring instrument. | Record and use measurements to an appropriate number of significant figures. |
| Information and Data |  |
| Valid conclusions depend on the gathering of appropriate evidence. | Make and record careful and honest observations and measurements in an investigation. |
| Data can be easily interpreted if presented in a well-structured table. | Present data in an appropriate tabular form. Include a title, column headings showing the quantities measured or observations made and the units used, and the values recorded to an appropriate number of significant figures. |
| Graphs are a useful way of displaying some forms of data. When a graph is plotted, the independent variable (or a quantity derived from it) is plotted horizontally and the dependent variable (or a quantity derived from it) is plotted vertically. | Plot a graph of a dependent variable versus an independent variable. Include a title, labelled axes, and appropriate scales and units. |
| A line of best fit can show relationships between variables in an experiment. | Draw a line of best fit through a series of points on a graph such that the plotted points are scattered evenly above and below the line of best fit. |
| Understanding of a topic, issue, or question is enhanced by the use of information from different sources. | Obtain information from different sources. |
| Information obtained must be critically examined for accuracy and for its suitability for the purpose for which it was sought. | Evaluate for bias, credibility, accuracy, and suitability the information obtained from a source. |
| The source of information used must be recorded so that the information is accessible to others. | List the sources of the information, using an appropriate format. |
| Interpretation and Evaluation |  |
| Careful observation in a practical investigation is essential for analysis and for comparison with other investigations. | Describe a pattern observed in the results of an investigation. |
| The scatter of data points above and below the line of best fit is probably due to random errors. | Using the scatter in the graphs of data from similar investigations, compare the random errors. |
| The slope of the line of best fit represents the ratio of the change in the dependent variable to the change in the independent variable, and may have physical significance. | Given a straight-line graph of two quantities, determine the slope of the line of best fit and state its units.  Using the line of best fit on a graph and the measured slope of the graph, write an equation between the variables in the form |
| The intercept(s) of the line of best fit may also have physical significance and may indicate the existence of a systematic error. | Given a straight-line graph of two quantities, determine the intercept(s) of the line of best fit, and state any physical significance of the intercept(s). |
| If a straight line of best fit passes through the origin of the graph and is a good representation of the data, the plotted quantities are directly proportional to each other. | Using a graph that has a straight line of best fit through the origin, describe the relationship between the two plotted variables.  Distinguish between proportionality and linear dependence. |
| Variables resulting in curved graphs may be interpreted by plotting one of the variables in the form | Use a graph of  to investigate the relationship between the two variables.  Interpret a straight line through the origin of  as an inverse relationship, and  as an inverse square relationship. |
| Subsequent investigations can be improved by the evaluation of the procedure and results. | Analyse and evaluate information from a series of observations or an investigation and suggest improvements or the additional information needed. |
| A conclusion should be written at the end of each investigation. | Write a conclusion that is based on the results of an investigation and is related to the question posed and the purpose of, or the hypothesis for, the investigation. |
| Alternative Views |  |
| The evidence collected through investigations may be interpreted in a variety of ways. | Describe a range of alternative interpretations based on evidence, and state reasons for the selection of the preferred interpretation. |
| Different sources can be used to present arguments for and against an issue. | Construct for-and-against arguments on an issue based on information gathered from different credible sources. |
| Personal views must be substantiated by the evidence collected in an investigation. | Present a justification of, or evidence for, a personal view. |
| Communication |  |
| Specific terminology, conventions, and symbols are used for communicating in physics. | Use the terminology, conventions, and symbols of physics that are appropriate to the purpose of the communication. |
| Communication for different audiences requires the use of a format suitable for the purpose. | Choose the format that is appropriate to the audience. |
| All communication needs to be well structured, well organised, and clearly presented. | Present communications (oral, written, and multimedia) clearly and logically, using the concepts of physics that are appropriate to the audience. |
| Written reports should state what was done and why, the results, the analysis and interpretation of the results, and the conclusions drawn from the results. Sufficient information should be included to enable the procedure to be repeated by others. | Write a report of an investigation that includes a description of its purpose and experimental procedure, results, and analysis, discussing alternative explanations and presenting conclusions. |
| Multimedia presentations use minimal words and a variety of graphics to present information. | Use concise language and graphics to present information. |
| Mathematical Skills |  |
| The International System of Units (SI System) |  |
| The fundamental units in the SI system include kilogram, metre, second, and ampere. | State units of quantities in SI units.  Convert between units for quantities such as mass, distance, time, speed, energy, and wavelength. |
| Values in physics are commonly expressed in scientific notation. | State values in scientific notation with appropriate prefixes. |
| Scientific prefixes are commonly used in physics. | Use the prefixes pico (10−12), nano (10−9), micro (10−6), milli (10−3), centi (10−2), kilo (103), mega (106), giga (109), and tera (1012) in calculations. |
| Significant Figures |  |
| The number of significant figures in the result of a calculation is determined using the following simple rules:  1. For multiplication and division, round the result of the calculation to the number of significant figures equal to the smallest number of significant figures in the given data.  2. For addition and subtraction:   * write all numbers to the same power of ten * identify the number in the given data with the smallest number of decimal places * round the result of the final calculation to the number of decimal places you have identified. | Express final numerical answers to the appropriate number of significant figures by using simple rules. |
| Mathematical Relationships |  |
| Many basic mathematical relationships and skills are used in physics in order to understand relationships between variables. | Rearrange algebraic equations.  Use Pythagoras’ theorem to find the length of unknown sides of a right-angled triangle.  Use sine, cosine, and tangent in right-angled triangles to find unknown side-lengths and angles.  Solve simple quadratic equations.  Use the relationship between the circumference and the radius of a circle.  Perform simple geometric calculations with equilateral and isosceles triangles.  Use complementary angles to find unknown angles. |
| Vectors |  |
| Vectors and their components are useful tools for simplifying complex motions and interactions. | Identify and distinguish between scalar quantities and vector quantities.  Draw a representation of a vector quantity to scale.  Separate a vector quantity into perpendicular components.  Add and subtract vectors and vector components. |

Content

Stage 2 Physics is a 20-credit subject that is organised into four sections, as shown in the table below. Each section is divided into four topics. Each topic includes one application, which is an integral part of the subject outline. The sections and topics are presented in suggested teaching order. Physics investigation skills should be integrated throughout the teaching and learning program.

| Section 1: Motion in Two Dimensions | Section 2: Electricity and Magnetism | Section 3: Light and Matter | Section 4: Atoms and Nuclei |
| --- | --- | --- | --- |
| Topic 1: Projectile Motion  Application: Projectiles in Sport | Topic 1: Electric Fields  Application: Photocopiers and Laser Printers | Topic 1: Electromagnetic Waves  Application: Laser Airborne Depth Sounder (LADS) | Topic 1: The Structure of the Atom  Application: Lasers |
| Topic 2: Uniform Circular Motion  Application: The Banking of Road Curves | Topic 2: The Motion of Charged Particles in Electric Fields  Application: The Use of Electric Fields in Cyclotrons | Topic 2: The Interference of Light  Application: Compact Discs and DVDs | Topic 2: The Structure of the Nucleus  Application: The Production of Medical Radioisotopes |
| Topic 3: Gravitation and Satellites  Application: Weather and Communication Satellites | Topic 3: Magnetic Fields  Application: The Moving-coil Loudspeaker | Topic 3: Photons  Application: The Use of X-rays in Medicine | Topic 3: Radioactivity  Application: Positron Emission Tomography (PET) |
| Topic 4: Momentum in Two Dimensions  Application: Spacecraft Propulsion | Topic 4: The Motion of Charged Particles in Magnetic Fields  Application: The Use of Magnetic Fields in Cyclotrons | Topic 4: Wave Behaviour of Particles  Application: Electron Microscopes | Topic 4: Nuclear Fission and Fusion  Application: Fission Nuclear Power |

Section 1: Motion in Two Dimensions

Two types of motion in two dimensions are studied: projectile motion and uniform circular motion. These topics prepare students for an understanding of the vector form of Newton’s second law of motion. In projectile motion, in the absence of air resistance, acceleration is constant in magnitude and direction, whereas in uniform circular motion acceleration is constant in magnitude but not in direction. In each case, acceleration is in the direction of the net force causing it.

Newton’s law of universal gravitation is introduced, and used to describe the motion of satellites in circular orbits.

The directional relationship between acceleration and net force leads to a vector statement of Newton’s second law of motion for situations involving motion in more than one dimension. The law is expressed in terms of momentum and is used in conjunction with Newton’s third law to obtain a vector expression for the law of conservation of momentum for two interacting particles. The fact that the law of conservation of momentum is a fundamental conservation law that applies to any number of particles is presented without proof.

Topic 1: Projectile Motion

In the absence of air resistance, and moving under the action of a constant gravitational force, a projectile has a constant acceleration in the direction of the force. The horizontal component of velocity of such a projectile is constant, and the vertical component changes at a constant rate. The time of flight and the range of the projectile are calculated, and the effect of air resistance on the motion is treated qualitatively. These key ideas are applied to projectiles in sport (e.g. a shot put).

| Key Ideas  Students should know and understand the following: | Intended Student Learning  Students should be able to do the following: |
| --- | --- |
| Vertical and Horizontal Components of Velocity |  |
| For a projectile, in the absence of air resistance, the:   * horizontal component of velocity is constant * acceleration is in the vertical direction and is the same as that of a vertically free-falling object. | Given a multi-image photograph of a projectile, demonstrate that the:   * horizontal component of velocity is constant * acceleration is in the vertical direction and is the same as that of a vertically free-falling object. |
| The horizontal motion and the vertical motion are independent of each other: the constant vertical acceleration is independent of the horizontal speed. | Draw a vector diagram in which the horizontal and vertical components of velocity are added, giving the resultant velocity vector at any instant. |
| The acceleration of a projectile, in the absence of air resistance, is in the direction of the gravitational force. | Using trigonometric calculations or a scale diagram, calculate, from its horizontal and vertical components, the magnitude and direction of a velocity vector at any instant. |
|  | On a diagram showing the path of a projectile, draw vectors to represent the velocity and acceleration of the projectile at any instant. |
| Determination of the Vertical Component of Velocity |  |
| The equations for constant acceleration in one dimension can be used to calculate the vertical component of velocity of a projectile at any instant. | Given the initial velocity of a projectile, calculate the vertical component of velocity at any instant. |
| Resolution of Velocity into Components |  |
| Velocity can be resolved into its horizontal and vertical components at any instant. | Using trigonometric calculations or a scale diagram, resolve a velocity vector into its horizontal and vertical components. |
| Time of Flight |  |
| The time of flight of a projectile is determined by the change in vertical component of velocity and the acceleration. | Calculate the time of flight of a projectile in cases where the final height is the same as the initial height. |
| Range |  |
| The range of a projectile is calculated by multiplying the horizontal component of velocity and the time of flight. | Using the horizontal component of velocity and the time of flight, calculate the range of a projectile.  For a projectile launched from ground height, find, by using sample calculations or otherwise, the:   * launch angle that results in the maximum range * relation between the launch angles that result in the same range. |
| Maximum Height |  |
| The maximum height of a projectile can be calculated from the vertical component of the initial velocity and the acceleration or the time of flight and the acceleration. | Using the vertical component of the initial velocity and the acceleration, calculate the maximum height of a projectile.  Using the time of flight and the acceleration, calculate the maximum height of a projectile. |
| Effect of Air Resistance |  |
| Air resistance acts in the opposite direction to the velocity of a projectile at any instant. | Describe how air resistance affects both the horizontal component and the vertical component of velocity and hence the time of flight and range of a projectile. |
| The magnitude of the force of air resistance on an object depends on the object’s shape, size, speed, and surface texture and the density of the air. | Compare qualitatively the force of air resistance acting on different objects. |
| Application: Projectiles in Sport |  |
|  | Describe and explain the effect of the launch height of a projectile (e.g. a shot put launched from shoulder height) on the maximum range, and the effect of the launch angle for a given height.  Investigate the extent to which air resistance affects various projectiles in sport. |

Topic 2: Uniform Circular Motion

In projectile motion (the example of motion in two dimensions introduced in Topic 1), force and acceleration in the absence of air resistance are constant in both magnitude and direction. This second example of motion in two dimensions involves an object moving with constant speed in a circle (referred to as ‘uniform circular motion’). In uniform circular motion the force and acceleration continually change direction and are always directed towards the centre of the circle. The force is always perpendicular to the velocity. The resulting acceleration produces a continual change in the direction of the velocity without changing the magnitude of the velocity. The theory is applied to the banking of road curves.

| Key Ideas  Students should know and understand the following: | Intended Student Learning  Students should be able to do the following: |
| --- | --- |
| Centripetal Acceleration |  |
| The velocity of an object moving with uniform circular motion continually changes direction, and hence the object accelerates.  Average acceleration  for motion in more than one dimension is defined as  where  The acceleration  at any instant is obtained by allowing the time interval  to become very small.  The acceleration of an object moving with uniform circular motion is directed towards the centre of the circle and is called ‘centripetal acceleration’.  The magnitude of the centripetal acceleration is constant for a given speed and radius and given by | Using a vector subtraction, show that the change in the velocity  and hence the acceleration, of an object over a very small time interval is directed towards the centre of the circle.  Using the relationship  relate the speed  to the period  for a fixed radius.  Solve problems involving the use of the equations |
| Force Causing the Centripetal Acceleration |  |
| A net force directed towards the centre of the circle is necessary to produce the centripetal acceleration. | Describe situations in which the centripetal acceleration is caused by a tension force, a frictional force, a gravitational force, or a normal force. |
| Application: The Banking of Road Curves |  |
|  | Identify the vertical and horizontal forces on a vehicle moving with constant velocity on a flat horizontal road. |
|  | Explain that when a vehicle travels round a banked curve at the correct speed for the banking angle, the horizontal component of the normal force on the vehicle (not the frictional force on the tyres) causes the centripetal acceleration.  Derive the equation  relating the banking angle  to the speed  of the vehicle and the radius of curvature  Solve problems involving the use of the equation |

Topic 3: Gravitation and Satellites

The characteristics of gravitational force are examined in this topic. Newton’s law of universal gravitation is introduced and used to extend the study of uniform circular motion to the centripetal acceleration caused by the gravitational force on a satellite. These key ideas are applied to weather and communication satellites.

| Key Ideas  Students should know and understand the following: | Intended Student Learning  Students should be able to do the following: |
| --- | --- |
| Newton’s Law of Universal Gravitation |  |
| Any two particles experience mutually attractive gravitational forces along the line joining them.  The magnitude of these forces is directly proportional to the product of the two masses and inversely proportional to the square of the distance between them.  Spherically symmetric objects interact gravitationally as if their masses were located at their centres. | Solve problems involving the use of  where  is the magnitude of the gravitational forces,  are the masses of the particles,  is the distance between them, and  is the constant of universal gravitation.  Using proportionality, discuss changes in the magnitude of the gravitational force on each of the masses as a result of a change in one or both of the masses and/or a change in the distance between them.  Explain that the gravitational forces are consistent with Newton’s third law.  Using Newton’s law of universal gravitation and second law of motion, calculate the value of the acceleration due to gravity  at a planet or moon. |
| Satellites in Circular Orbits |  |
| The gravitational force causes the centripetal acceleration when a satellite moves in a circular orbit.  For a particular radius of circular orbit there is only one possible speed for a stable satellite orbit. | Demonstrate an understanding that the speed, and hence the period, of a satellite moving in a circular orbit depends only on the radius of the orbit and not on the mass of the satellite.  Derive the formula  for the speed  of a satellite moving in a circular orbit of radius  about a spherically symmetric mass  given that its gravitational effects are the same as if all its mass were located at its centre.  Solve problems involving the use of the equations |
| Application: Weather and Communication Satellites |  |
|  | Explain why the centres of the circular orbits of Earth satellites must coincide with the centre of the Earth.  Explain why a geostationary satellite must move in a particular orbit of relatively large radius in the Earth’s equatorial plane and in the same direction as that in which the Earth rotates.  Explain the advantages of launching low-altitude equatorial-orbit satellites in a west-to-east direction.  Explain why low-altitude polar orbits are used in meteorology and surveillance.  Perform calculations involving orbital periods, radii, altitudes above the surface, and speeds of satellites, including examples that involve the orbits of geostationary satellites. |

Topic 4: Momentum in Two Dimensions

A comparison of the directions of the acceleration and of the net force in projectile motion and uniform circular motion suggests the vector form of Newton’s second law of motion.

The key implication is that the force on an object determines only the change in its velocity. The new velocity depends on this change, and on the original velocity. The net force on an object therefore changes the speed and/or direction of motion of the object according to a simple vector formula, 

Newton’s second law of motion is restated in terms of momentum. The resulting relation is used, with Newton’s third law, to introduce the general law of conservation of momentum for systems of any number of particles. An implication of the law of conservation of momentum is that the total momentum after a collision, if no external forces are applied to the system, is equal to the total momentum before the collision. This is useful because the equality holds independently of the details of the (possibly unknown or complicated) collision process.

The theory is applied to spacecraft propulsion.

| Key Ideas  Students should know and understand the following: | Intended Student Learning  Students should be able to do the following: |
| --- | --- |
| Vector Form of Newton’s Second Law of Motion |  |
| The acceleration  of an object is in the direction of the net force  acting on it.  Newton’s second law of motion can therefore be expressed as a vector relation, | Given the initial velocity of a particle bouncing off a surface without a change of speed, and the duration of the collision, calculate the average acceleration of the particle.  Using  calculate the average force applied to the particle by the surface.  Using Newton’s third law, deduce the average force applied to the surface by the particle. |
| Newton’s Second Law of Motion in Terms of Momentum |  |
| Newton’s second law of motion can be expressed as a vector relation,  where  is the momentum of the object. | Derive  by substituting the defining expression for acceleration () into Newton’s second law of motion  for particles of fixed mass. (The net force  and hence the acceleration  are assumed to be constant. Otherwise, average or instantaneous quantities apply.)  Draw a vector diagram in which the initial momentum is subtracted from the final momentum, giving the change in momentum |
|  | Solve problems involving the use of the vector relation |
| Law of Conservation of Momentum |  |
| Newton’s third law of motion,  in conjunction with the second law expressed in terms of momentum, implies that the total momentum of a system of two interacting particles, subject only to the force of each one on the other, is conserved.  This can be extended to the law of conservation of momentum, which states that the total momentum of any number of objects remains unchanged in the absence of external forces. | Derive an equation expressing the conservation of momentum for two interacting particles by substituting  Compare the magnitudes and directions of the total momentum vectors before and after a  two-puck air-table collision recorded using a multi-image photograph, in order to show that momentum is conserved. Consider only examples in which the mass of one puck is an integral multiple of the mass of the other puck. Ignore the scale of the photograph, the flash rate, and the actual masses of the pucks.  Using trigonometric relations or scale diagrams, perform calculations in one or two dimensions, applying the law of conservation of momentum to two objects or to one object that explodes into two or three fragments. |
| Application: Spacecraft Propulsion |  |
|  | Explain qualitatively, in terms of the law of conservation of momentum, the change in motion (in a straight line) of a spacecraft as a result of the emission of discrete particles  (e.g. ions emitted by an ion thruster on a satellite).  Explain qualitatively, in terms of the law of conservation of momentum, how the reflection of light particles (photons) can be used to accelerate a solar sail.  Use vector diagrams to compare the acceleration of a spacecraft using a solar sail where photons are reflected with the acceleration of a spacecraft using a solar sail where photons are absorbed. |

Section 2: Electricity and Magnetism

This section introduces the concept of fields as used in physics. The conventions adopted to represent fields pictorially show the magnitude and direction of the relevant field vectors at points within the field. Forces between stationary charges are discussed and the motion of charged particles in uniform electric fields is analysed quantitatively, in one and two dimensions. Comparisons are made with projectile motion, as described in Section 1.

Moving charges are also examined, first in electric currents and then in a vacuum. A magnetic field is shown to exist in each case. This magnetic field can exert a force on another electric current or a charge moving in a vacuum. In the latter case the force can cause the charge to move uniformly in a circle. The quantitative analysis of this motion involves the ideas on uniform circular motion developed in Section 1.

Topic 1: Electric Fields

The two fundamental postulates of electrostatics are introduced: Coulomb’s law, and the principle of superposition. Several important electric field distributions are discussed.

The electric field at a point in space is defined and used, with Coulomb’s law, to derive an expression for the electric field at a distance from a point charge. In this topic the charges are assumed to be in a vacuum (or, for practical purposes, air).

The principle of superposition is used to explain the fact that a near-uniform electric field can be produced by two charged parallel conducting plates. The absence of an electric field in hollow conductors is discussed. The presence of strong electric fields in the vicinity of sharp points on charged conductors is identified and applied to corona discharges in relation to photocopiers and laser printers.

| Key Ideas  Students should know and understand the following: | Intended Student Learning  Students should be able to do the following: |
| --- | --- |
| Coulomb’s Law |  |
| Any two stationary point charges experience mutual forces along the line joining them.  These forces are attractive if the charges are unlike and repulsive if they are alike.  The magnitude of these forces is directly proportional to the product of the two charges and inversely proportional to the square of the distance between them. | Solve problems involving the use of  where is the magnitude of the electric forces,  and  are the charges,  is the distance between them, and  is the proportionality constant.  Using proportionality, discuss changes in the magnitude of the force on each of the charges as a result of a change in one or both of the charges and/or a change in the distance between them.  Explain that the electric forces are consistent with Newton’s third law. |
| Principle of Superposition |  |
| When more than two point charges are present, the force on any one of them is equal to the vector sum of the forces due to each of the other point charges. | Using vector addition, calculate the magnitude and direction of the force on a point charge due to two other point charges. |
| Electric Field |  |
| Electric charges establish an electric field  in the surrounding space. The electric field at any point produces a force on an electric charge placed at that point.  The electric field at a point is defined as the electric force  per unit charge on a small positive test charge  placed at that point, provided that all charges remain undisturbed:  The direction of the electric force on a charge is parallel to the electric field if the charge is positive and antiparallel if the charge is negative. | Describe how the concept of the electric field replaces the concept of action at a distance (inherent in Coulomb’s law) with the localised action of the field of one charge on the other charge.  Solve problems involving the use of  Determine the direction of the electric field at any point due to a point charge.  Using Coulomb’s law, derive the expression  for the magnitude of the electric field at a distance  from a point charge  Solve problems involving the use of |
| Pictorial Representation of Electric Fields |  |
| An electric field can be represented by field lines such that the direction of the field is at a tangent to each line, and the magnitude of the field at any point is represented by the number of lines crossing a unit area perpendicular to the field in the vicinity of the point. | Sketch the electric field lines for an isolated positive or negative point charge. |
| Superposition of Electric Fields |  |
| The principle of superposition applies also to electric fields, as the electric field is the force per unit charge. | Calculate the magnitude and direction of the electric field at a point due to two charges with the same or opposite sign.  Sketch the electric field lines for two point charges of equal magnitude with the same or opposite sign. |
| Electric Field Due to One or Two Charged Plates |  |
| The electric field due to an infinite charged conducting plate is uniform.  The electric field between two infinite parallel conducting plates with equal and opposite charges per unit area is uniform between the plates and zero elsewhere.  The electric field near and beyond the edges of two finite plates is non-uniform. | Describe and draw the electric field due to an infinite conducting plate of positive or negative charge.  Using the principle of superposition, draw the electric field due to two infinite parallel conducting plates with equal and opposite charges per unit area.  Sketch the electric field between and near the edges of two finite oppositely charged parallel plates. |
| Electric Fields and Conductors |  |
| For any conductor, whether charged or uncharged:   * electric fields always meet the conducting surface at right angles * there is no electric field inside the conducting material. | In terms of the motion of the charges in the conductor, explain why:   * the component of the electric field parallel to the conducting surface must be zero * there is no electric field inside the conducting material. |
| An uncharged conductor in an external electric field will experience charge polarisation. | Sketch the electric field that results when a solid uncharged conducting sphere is placed in the region between two oppositely charged parallel plates. |
| Electric Field Inside a Hollow Conductor |  |
| There is no electric field inside a hollow conductor of any shape, whether or not the conductor is charged, provided that there is no charge in the cavity. | Sketch the electric field produced by a hollow spherical charged conductor. |
| Electric Fields Near Sharp Points |  |
| Electric fields are strongest near sharp points on conductors.  These fields may be large enough to ionise the air in the vicinity of the sharp points, resulting in charge movement away from the conductor. This is called a ‘corona discharge’. | Sketch the electric field produced by a charged pear-shaped conductor.  Describe how the large electric field in the vicinity of sharp points may ionise the air. |
| Application: Photocopiers and Laser Printers |  |
|  | Describe the action of a corona wire in charging the photoconductive surface of a photocopier or laser printer. |
|  | Describe the action of the corona wire in:   * charging the paper so as to transfer the toner from the photoconductive surface to the paper * discharging the paper so that it does not cling to the photoconductive surface. |

Topic 2: The Motion of Charged Particles in Electric Fields

The concept of work done by an electric field on a charged particle is introduced. The potential difference between two points in an electric field is defined and used to determine the work, and hence energy changes, of charged particles moving in uniform electric fields in a vacuum.

The potential difference between a pair of parallel plates is used to determine the electric field between the plates. From the field, the force, and hence the acceleration, of a charged particle can be found and its motion determined. These ideas are applied to the motion of ions in a cyclotron.

| Key Ideas  Students should know and understand the following: | Intended Student Learning  Students should be able to do the following: |
| --- | --- |
| Electric Potential Difference |  |
| The electric potential difference  between two points is the work  done per unit charge  on a small positive test charge moved between the points, provided that all other charges remain undisturbed:  The unit of potential difference, the volt (V), is equal to a joule per coulomb (J ).  The electronvolt (eV) is the work done when a charge of one electron moves through a potential difference of 1 V. | Solve problems involving the use of  Convert energy from joules into electronvolts and vice versa.  Derive the expression  for the magnitude of the electric field (away from the edges) between two oppositely charged parallel plates a distance  apart, where  is the potential difference between the plates.  Solve problems involving the use of |
| Acceleration in a Constant Electric Field |  |
| The force on a charged particle moving in a uniform electric field is constant in magnitude and direction, thus producing a constant acceleration. | Describe the motion of a charged particle in a uniform electric field.  Perform calculations involving the movement of charged particles parallel or antiparallel to a uniform electric field. |
| Motion of a Charged Particle in a Constant Electric Field |  |
| When a charged particle moves across a uniform electric field the component of the velocity perpendicular to the field remains constant. | Compare the motion of a projectile in the absence of air resistance with the motion of a charged particle in a uniform electric field.  Calculate the time of flight and deflection of a charged particle that enters a uniform electric field at right angles to the field. |
| Application: The Use of Electric Fields in Cyclotrons |  |
|  | Describe how hydrogen atoms are given a negative charge or a positive charge in an ion source of a cyclotron. |
|  | Describe the following parts of a cyclotron:   * semicircular metal containers (‘dees’) * evacuated outer container.   Explain why there is no electric field inside the dees.  Describe how an electric field between the dees can transfer energy to an ion passing between them.  Describe how ions could be accelerated to high energies if they could be made to move in a circular path inside the dees so that they repeatedly moved across the electric field, the direction of which was reversing every  half-revolution.  Calculate the energy transferred to an ion each time it passes between the dees.  Explain why the cyclotron must be evacuated. |

Topic 3: Magnetic Fields

Whenever a charge is moving, it produces a magnetic field in addition to its electric field. Magnetic fields may exert forces on other moving charges and hence on current-carrying conductors. The interaction between magnetic fields and electric currents is described and used to define the strength of the magnetic field in terms of the force on current-carrying conductors. The theory is applied to the moving-coil loudspeaker.

| Key Ideas  Students should know and understand the following: | Intended Student Learning  Students should be able to do the following: |
| --- | --- |
| Magnetic Fields and Their Pictorial Representation |  |
| Moving electric charges, and hence electric currents, produce magnetic fields.  The magnetic field is in addition to the electric field produced by the charges.  A magnetic field can be represented by field lines such that the direction of the field is at a tangent to each line, and the magnitude of the field at any point is represented by the number of lines crossing a unit area perpendicular to the field in the vicinity of the point.  The direction of the magnetic field is the direction in which the north pole of a small compass needle points. | Sketch the magnetic field lines produced by an electric current flowing in a straight conductor, a loop, and a solenoid. |
| Magnetic Force on a Current-carrying Conductor |  |
| When placed in a magnetic field, a current-carrying conductor experiences a force due to the movement of charge in the conductor.  The magnitude  of a magnetic field is the force per unit current element placed at right angles to the field, where a current element is the product of the current  and its length  (i.e. ).  Hence  The direction of the magnetic force is perpendicular to the plane defined by  andand is given by a right-hand rule, where the direction of is that of the conventional current.  The force on a current element that is parallel to a magnetic field is zero. | Using a right-hand rule, relate the directions of the force, magnetic field, and conventional current.  Use the unit for  tesla (T), equivalent to  Solve problems involving the use of |
| The magnitude of the force on a current element that is at any angle  to a uniform magnetic field is given by  where is the component of the current element perpendicular to the field. |  |
| Application: The Moving-coil Loudspeaker |  |
|  | Describe the following components of a moving-coil loudspeaker: a cone, a magnet structure, a voice coil, and a supporting frame.  Explain the action of a moving-coil loudspeaker. |

Topic 4: The Motion of Charged Particles in Magnetic Fields

The interaction of current-carrying conductors and magnetic fields is extended to the interaction of moving charged particles and uniform magnetic fields. The magnetic force on a moving charged particle is velocity-dependent, whereas electric forces are not.

The circular path of charged particles moving at right angles to a uniform magnetic field is discussed and applied to the deflection of ions in a cyclotron.

| Key Ideas  Students should know and understand the following: | Intended Student Learning  Students should be able to do the following: |
| --- | --- |
| Force on a Charged Particle in a Magnetic Field |  |
| There is no magnetic force on either a stationary charged particle in a uniform magnetic field or a charged particle moving with velocity parallel to a uniform magnetic field.  When a charged particle is moving at any angle  to a uniform magnetic field, the magnitude of the force on the particle is given by  where  is the component of the velocity of the particle perpendicular to the field.  The magnetic force is velocity-dependent.  The direction of the magnetic force is at right angles to the plane defined by  and is given by a right-hand rule. | Demonstrate an understanding that the magnetic force depends on both the magnitude and the direction of the velocity of the particle.  Solve problems involving the use of  Determine the direction of the force on a charged particle moving at any angle  to a uniform magnetic field. |
| Motion of a Charged Particle at Right Angles to a Magnetic Field |  |
| A charged particle moving at right angles to a uniform magnetic field experiences a force of constant magnitude at right angles to the velocity, and hence moves with uniform circular motion. | Explain how the velocity-dependence of the magnetic force on a charged particle causes the particle to move with uniform circular motion when it enters a uniform magnetic field at right angles.  Derive  for the radius  of the circular path of an ion of charge  and mass  that is moving with speed  at right angles to a uniform magnetic field of magnitude  Solve problems involving the use of |
| Application: The Use of Magnetic Fields in Cyclotrons |  |
|  | Describe the nature and direction of the magnetic field needed to deflect ions into a circular path in the dees of a cyclotron. |
|  | Derive the expression  for the period  of the circular motion of an ion, and hence show that the period is independent of the speed of the ion.  Using the relationships  and  derive the expression  for the kinetic energy  of the ions emerging at radius  from a cyclotron. Use this expression to show that  is independent of the potential difference across the dees and, for given ions, depends only on the magnetic field and the radius of the cyclotron.  Solve problems involving the use of |

Section 3: Light and Matter

The study of charges at rest and charges moving with uniform velocity is extended to accelerating charges, which radiate electromagnetic waves. When the acceleration is in the form of a continuous oscillation, the frequency of the electromagnetic waves is equal to the frequency of oscillation of the charges. The behaviour of these waves is described, and interference patterns are explained, using the principle of superposition.

The behaviour of light at relatively low intensity is used to introduce photons. The photoelectric effect and X-ray production are explained in terms of photons.

The interference of electrons reflected by crystal lattices is used to introduce matter waves.

Topic 1: Electromagnetic Waves

Accelerating electric charges radiate electromagnetic waves, which propagate at the speed of light. The link between electromagnetism and light is discussed. Orders of magnitude of the wavelengths of waves in the various sections of the electromagnetic spectrum are considered.

The frequency of television and radio waves is related to the frequency of oscillation of the electrons in an antenna.

These key ideas are applied to the laser airborne depth sounder.

| Key Ideas  Students should know and understand the following: | Intended Student Learning  Students should be able to do the following: |
| --- | --- |
| Characteristics of Electromagnetic Waves |  |
| Accelerating charged particles radiate electromagnetic waves.  Electromagnetic waves exist because the accelerating charges produce changing electric and magnetic fields.  An electromagnetic wave in a vacuum consists of oscillating mutually perpendicular electric and magnetic fields.  The electric and magnetic fields oscillate at right angles to the direction of travel of the electromagnetic wave. The wave is therefore transverse.  The plane of polarisation of an electromagnetic wave is the plane defined by the direction of travel and the oscillating electric field.  The frequency of the radiated electromagnetic waves is the same as the frequency of oscillation of the source charges. | Describe the relation between the oscillating electric and magnetic fields and the direction of travel of an electromagnetic wave.  Relate the frequency of radio or television waves to the frequency of oscillation of the electrons in the transmitting antenna.  Relate the orientation of the receiving antenna to the plane of polarisation of radio or television waves.  Explain why transmissions from some country television channels are polarised at right angles to city channels. |
| Speed, Frequency, and Wavelength |  |
| Electromagnetic waves in a vacuum travel at a constant speed  which is the speed of light.  Electromagnetic waves in a transparent medium travel at a speed  less than  The speed of a wave  is related to its frequency  and its wavelength  by | Solve problems involving the use of |
| Application: Laser Airborne Depth Sounder (LADS) |  |
|  | Explain how the depth of a body of water can be determined by the detection of reflections of laser light from the surface and the bottom of the water.  Calculate the depth of water from given reflection times at normal incidence and the given speed of the light in water.  Justify the use of powerful lasers because of light losses due to factors such as scattering by suspended sediment and absorption. |

Topic 2: The Interference of Light

Interference and diffraction are two phenomena most easily understood in terms of the propagation of light as a wave. Interference of light occurs when two or more light sources are superimposed. Diffraction of light occurs when part of its wave-front is obstructed (e.g. by a narrow slit). Diffraction is treated qualitatively as a precursor to a more extended quantitative treatment of the interference of light from two slits. This is extended to the transmission diffraction grating.

The topic ends with an overview of some aspects of the optical systems of compact disc players as an application.

| Key Ideas  Students should know and understand the following: | Intended Student Learning  Students should be able to do the following: |
| --- | --- |
| Coherent Wave Sources |  |
| ‘Coherent’ wave sources are wave sources that maintain a constant phase relationship with each other. They must therefore have the same frequency.  ‘Monochromatic’ light is light composed of a single frequency. | Describe what is meant by two wave sources being in phase or out of phase.  Give a qualitative explanation of why light from an incandescent source is neither coherent nor monochromatic. |
| Interference |  |
| In the region where two or more electromagnetic waves overlap, the resultant electric and magnetic fields at a point are the vector sums of their separate fields. This is an example of the principle of superposition.  When the waves at a point are in phase, the resultant amplitude is the sum of the individual amplitudes. This is referred to as ‘constructive interference’.  When the waves at a point are out of phase, the resultant amplitude is the difference between the individual amplitudes. This is referred to as ‘destructive interference’. | Describe constructive and destructive interference in terms of the principle of superposition. |
| Two-source Interference |  |
| For two monochromatic sources in phase, the waves at a point some distance away in a vacuum:   * constructively interfere when the path difference from the sources to the point is * destructively interfere when the path difference from the sources to the point is   where  is an integer and  is the wavelength. | Perform a geometrical construction to identify the locations in two dimensions of the lines of maximum and minimum amplitude due to the interference of light from two wave sources of the same frequency.  Explain the maximum and minimum amplitudes in terms of constructive and destructive interference.  Identify the path difference associated with each line of maximum and minimum amplitude. |
| Diffraction |  |
| The spreading out of plane waves as they pass through an opening is an example of diffraction. This is most noticeable when the opening is comparable in size with the wavelength of the waves. | Describe without detailed explanation the main feature of the diffraction of light by a narrow slit, where the width of the slit is about the same size as the wavelength. |
| Two-slit Interference |  |
| Interference between light diffracted by two narrow slits can be produced by illuminating the slits with light from a laser or by passing light from a monochromatic source through a single slit before illuminating the double slits. | Explain why a single slit is used before a double slit for two-slit interference when the light source used is not coherent.  Describe how two-slit interference is produced in the laboratory.  Describe how diffraction of the light by the slits in a two-slit interference apparatus allows the light to overlap and hence interfere.  Sketch a graph of the intensity distribution for two-slit interference of monochromatic light.  (Consider only cases where the slit separation is much greater than the width of the slits.)  Explain the bright fringes of a two-slit interference pattern in terms of constructive interference, and the dark fringes in terms of destructive interference.  Derive  for two-slit interference, where  is the distance between the slits and  is the angular position of the  maximum.  Solve problems involving the use of  and   is the distance between adjacent minima or maxima on the screen and  is the slit-to-screen distance.  Determine the wavelength of monochromatic light from measurements of the two-slit interference pattern. |
| Transmission Diffraction Gratings |  |
| A transmission diffraction grating consists of many very thin, equally spaced parallel slits.  The interference of light from a grating results in a pattern consisting of very narrow intensity maxima separated by regions of negligible intensity. | Describe how diffraction by the very thin slits in a grating allows the light from the slits to overlap and hence interfere to produce significant intensity maxima at large angles.  Derive  for the intensity maxima in the pattern produced by a transmission diffraction grating, where  is the distance between the slits in the grating and  is the angular position of the  maximum ( specifies the order of the maximum).  Solve problems involving the use of  where  for a grating with  slits per metre.  Sketch a graph of the intensity distribution of the maxima produced by a grating, for monochromatic light.  Determine, from the distance between the slits in the grating, the maximum number of orders possible for a given grating and wavelength.  Give a qualitative explanation of the negligible intensity between the maxima.  Describe how a grating can be used to measure the wavelength of light from a monochromatic source.  Describe and explain the white-light pattern produced by a grating.  Identify the properties of a grating which make it useful in spectroscopy. |
| Speckle |  |
| Speckle is produced whenever a laser beam is reflected by a rough surface.  Speckle is due to the interference between light reflected in different directions by the rough surface. | Explain the speckle effect in terms of interference. |
| Application: Compact Discs and DVDs |  |
|  | Explain how the interference of light can be used to read the information stored on a compact disc or a DVD.  Explain how a diffraction grating is used in the three-beam method to keep the laser on the correct track of a compact disc or a DVD. |

Topic 3: Photons

Although the propagation of light can most simply be described in terms of waves, when light interacts with matter it does so in a manner characteristic of particles. Some of the properties of photons are introduced. Two phenomena — the photoelectric effect and  
X-rays — are then examined and explained in terms of photons.

The key ideas are applied to the use of X-rays in medicine.

| Key Ideas  Students should know and understand the following: | Intended Student Learning  Students should be able to do the following: |
| --- | --- |
| Photons |  |
| In interacting with matter, light behaves like particles (called ‘photons’), with energy given by  and momentum given by  where  is Planck’s constant,  is the frequency of the light, and  is its wavelength. | Describe how microscopic observations of the building up of an image produced by light of very low intensity demonstrate the arrival of localised bundles of energy and momentum called ‘photons’.  Calculate the energy and momentum of the photons in various regions of the electromagnetic spectrum.  Describe how two-slit interference patterns build up over time when light of very low intensity is used. |
| The Photoelectric Effect |  |
| When light of sufficiently high frequency is incident on matter, it may be absorbed by the matter, from which electrons are then emitted. This is called the ‘photoelectric effect’.  The intensity of the incident light affects the number, but not the energy, of emitted electrons.  The minimum frequency  at which electrons are emitted varies with the type of material and is called the ‘threshold frequency’.  The work function  of a surface is the minimum energy required to remove an electron from it.  The work function  is related to the threshold frequency by | Describe an experimental method for investigating the relation between the maximum kinetic energy of the emitted electrons (calculated from the measured stopping voltage) and the frequency of the light incident on a metal surface.  Describe how Einstein used the concept of photons and the conservation of energy to explain the photoelectric effect.  Deduce the equation  where  is the maximum kinetic energy of the emitted electrons.  Plot experimental values of maximum kinetic energy versus frequency, and relate the slope and horizontal and vertical intercepts to the equation  Using graphical and algebraic methods, solve problems that require the use of |
| X-rays |  |
| X-ray photons can be produced when electrons that have been accelerated to high speed collide with a target.  The three main features of the spectrum of the X-rays produced in this way are:   * a continuous range of frequencies (bremsstrahlung) * a maximum frequency * high-intensity peaks at particular frequencies.   The intensity of X-rays is decreased (i.e. attenuated) as they pass through matter by scattering and absorption. | Describe the following features of a simple  X-ray tube: filament, target, high voltage supply, evacuated tube, and a means of cooling the target.  Explain how the electrons are accelerated in an X-ray tube, the choice of target material, and why the target needs to be cooled.  Sketch a graph of the spectrum from an  X-ray tube, showing the three main features of the spectrum.  Explain the continuous range of frequencies and the maximum frequency in the spectrum of the X-rays.  Derive the equation for the maximum frequency,  where  is the potential difference across the X-ray tube.  Solve problems involving the use of |
| Application: The Use of X-rays in Medicine |  |
|  | Relate the attenuation of X-rays to the types of tissue through which they pass (e.g. soft tissue or bone).  Relate the penetrating power (hardness) of  X-rays required to pass through a particular type of tissue to the energy and frequency of the  X-rays, and hence to the potential difference across the X-ray tube.  Relate the minimum exposure time for X-ray photographs of a given hardness to the intensity of the X-rays, and hence to the tube current, which is determined by the filament current. |

Topic 4: Wave Behaviour of Particles

In some circumstances (associated with its propagation), light exhibits the behaviour of waves, and in other circumstances (associated with its interaction with matter) it exhibits the behaviour of particles, prompting the question that forms the subject of this topic: do electrons and other particles exhibit wave behaviour in similar circumstances?

A classic experiment in which the interference effects of electrons were observed is examined.

The use of electrons as an alternative to light in microscopy is discussed as an application.

| Key Ideas  Students should know and understand the following: | Intended Student Learning  Students should be able to do the following: |
| --- | --- |
| Wave Behaviour of Particles |  |
| Particles exhibit wave behaviour with a wavelength determined by the equation   (de Broglie relation), where  is Planck’s constant and  is the momentum of the particles. | Solve problems involving the use of the equation  for electrons and other particles. |
| Experimental Evidence for Wave Behaviour of Particles |  |
| The spacing of the atoms in crystals is such that interference effects are observed when low-energy electrons are used. | Describe the Davisson–Germer experiment, in which the diffraction of electrons by the surface layers of a crystal lattice was observed.  Using the grating equation  and the measured angle  of the first-order maximum from the Davisson–Germer experiment, calculate the wavelength of the electrons used in the experiment.  Calculate the momentum of the electrons used in the Davisson–Germer experiment, and hence verify that |
| Application: Electron Microscopes |  |
|  | Explain how the very short wavelength of electrons and the ability to use electric or magnetic fields to focus them allow electron microscopes to achieve very high resolution. |

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  Students should know and understand the following: | Intended Student Learning  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  is the energy difference of the atom,  is the energy of the photon, and  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  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. |
| 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, depend 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. |
| 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’. | Draw, on an energy-level diagram of hydrogen, the process of 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. | 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. |
| Application: Lasers |  |
|  | 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  Students should know and understand the following: | Intended Student Learning  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  of an atom is the number of protons in the nucleus of the atom and hence the charge of the nucleus in units of  the charge of an electron.  The mass number  of an atom is the number of nucleons in the nucleus of an atom.  where  is the number of neutrons. | Specify a nucleus in the form  where  represents the chemical symbol for the element.  Given the specification for any nucleus in the form  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. |
| Isotopes of a given element are chemically identical but have different masses. |  |
| Mass Defect and Binding Energy |  |
| Mass  and energy  are related according to  where  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  is calculated from the mass defect  using | 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. |
| Application: The Production of Medical Radioisotopes |  |
|  | 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    how the medical radioisotope phosphorus-32 may be produced using neutrons emitted from a nuclear fission reactor.  Identify one use of  (e.g. the treatment of excess red blood cells).  Explain, using the equations    and    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: | Intended Student Learning  Students should be able to do 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. | 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. |
| 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 () decay, in which helium nuclei (alpha particles) are emitted * beta minus () decay, in which electrons () are emitted * beta plus () decay, in which positrons () are emitted * spontaneous fission, in which a nucleus splits into two.   These types of decay correspond predominantly to three regions on the  versus  graph:   * Alpha decay occurs for nuclei with * 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 | Indicate, on an  versus  graph, the regions corresponding to alpha decay, beta minus decay, beta plus decay, and spontaneous fission.  Using an  versus  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. |
| 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 | 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 |  |
| 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    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    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. | 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. |
| Gamma Decay |  |
| After alpha or beta decay, a nucleus is sometimes left in one of a small number of possible excited states:  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    where  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. |
| 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. | 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  water as a tracer for blood flow).  State one use of the radioisotope fluorine-18 in PET (e.g. the use of  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  Students should know and understand the following: | Intended Student Learning  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  where  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.  (and ) 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  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 |
| The fraction of  in naturally occurring uranium is small. It is therefore necessary to increase the fraction of  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 |  |
|  | 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. |
| 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  where  is the mass of the reactants minus the mass of the products. | 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. |