Atoms and Relativity

Subtopic 3.2: Wave–particle duality (X-rays only)

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| X-ray photons can be produced when electrons that have been accelerated to high speed interact with a target. This is done in a simple X-ray tube.   * Describe the purpose of the following features of a simple X-ray tube: filament, target, high-voltage supply, evacuated tube, and a means of cooling the target. * Describe the energy changes that occur during the production of X-rays, including the heat produced.   The three main features of the spectrum of the X-rays produced in this way are:   * a continuous range of frequencies (bremsstrahlung) due to the various proximities of the electrons with the nuclei in the target * a maximum frequency given by  where  is the potential difference across the X-ray tube * high-intensity peaks at particular frequencies (known as characteristic X‑rays). |
| * 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. * Explain the effect of manipulating the filament current or potential difference across the X-ray tube on an X-ray spectrum. * Derive the formula for the maximum frequency, . * Solve problems involving the use of . |
| X-rays are attenuated (reduce in intensity) as they pass through matter by scattering and absorption.   * Explain the effect of the filament current on the intensity of X-rays produced by an X-ray tube. * 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. * Relate the minimum exposure time for X-ray photographs of a given hardness to the intensity of the X-rays. |

Subtopic 3.3: Structure of the atom

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| 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 process is known as incandescence. 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. |
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| Atoms can be raised to excited states by heating or by bombardment with light or particles such as electrons.  An atom is in an excited state when a electron has been raised to a higher energy level.  The heated 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. * Explain the production of characteristic X-rays in an X-ray tube. * Solve problems that require comparing spectra of different elements. |
| The presence of discrete frequencies in the spectra of atoms is evidence for the existence of discrete electron energy-levels atoms.  The different electron energy-levels can be represented on an energy-level diagram.  When an electron makes a transition from a higher-electron energy level to a lower-electron energy level 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 the difference in the electron-energy levels of the atom. An atom is in its ground state when its electrons are in their lowest possible electron energy-level in atoms.   * Explain how the presence of discrete frequencies in line emission spectra provides evidence for the existence of states with discrete electron energy-levels in atoms. * Solve problems involving emitted photons and electron energy-levels. * Draw electron energy-level diagrams to represent the energies of different states in an atom. * Draw arrows on an electron energy-level diagram showing transitions between electron energy-levels in atoms. * Given an electron energy-level diagram, calculate the frequencies and wavelengths of lines corresponding to specified transitions. |
| The line emission spectrum of atomic hydrogen consists of several series of lines.   * Draw, on an electron 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 electron energy-level diagram to the region in the electromagnetic spectrum of the emitted photons (ultraviolet, visible, or infrared). |
| The ionisation energy of an atom is the minimum energy required to remove the electron from hydrogen in its ground state.   * Determine the ionisation energy (in either joules or electronvolts) of atoms using an electron energy-level diagram. |
| 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. * On an energy-level diagram, draw 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. |
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| One type of fluorescence is when an electron in an atom absorbs a photon to reach a higher electron energy-level, but then reverts to its previous state by emitting two or more photons with lower energy and longer wavelength.   * Explain, using an electron energy-level diagram, the production of multiple photons via fluorescence.   When an electron in an atom absorbs a photon and reaches a higher electron energy-level the atom is said to be in an excited state. Excited states are generally short-lived and the electron returns spontaneously to its previous electron energy-level often by emitting a series of lower-energy photons. This is known as ‘spontaneous emission’.  When a photon is incident on an electron that has been raised to a higher electron energy-level, and the energy of the photon corresponds to a transition to a lower electron energy-level, then the photon can stimulate a transition to the lower electron energy-level. This results in two identical photons; the original photon and a second photon that results from the transition. This is known as ‘stimulated emission’.   * Compare the process of stimulated emission with that of spontaneous emission. |
| Stimulated emission in gas lasers produces laser light.  The photon emitted in stimulated emission is identical (in energy, direction, and phase) to the incident photon.   * Explain how stimulated emission can produce coherent light in a laser.   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. For practical systems, the higher-energy state must be metastable if a population inversion is to be produced.   * Explain the conditions required for stimulated emission to predominate over absorption when light is incident on a set of atoms.   The energy carried by a laser beam is concentrated in a small area and can travel efficiently over large distances, giving laser radiation a far greater potential to cause injury than light from other sources.   * Describe the useful properties of laser light (i.e. it is coherent and monochromatic, and may be of high intensity). * State the requirements for the safe handling of lasers. |

Subtopic 3.4: Standard Model

This uses the concept of the nucleus developed in Stage 1, Subtopics 6.1: The Nucleus, and 6.2: Radioactive decay.

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| The Standard Model suggests that there are three fundamental types of particles: gauge bosons, leptons, and quarks.  The Standard Model identifies four fundamental forces: electromagnetic, weak nuclear, strong nuclear, and gravitational.  Gauge bosons are particles which mediate the four fundamental forces.  Photons are the gauge bosons for electromagnetic forces; W or Z particles are the gauge bosons for weak nuclear forces; and gluons are the gauge bosons for strong nuclear forces.  The gauge boson for gravitational forces, the graviton, is still to be discovered.   * Describe the electromagnetic, weak nuclear, and strong nuclear forces in terms of gauge bosons. * Solve problems involving the fundamental forces and gauge bosons.   Leptons are particles that are not affected by the strong nuclear force. There are six types of leptons – electron, electron-neutrino, muon, muon-neutrino, tau, and tau-neutrino.  The electron, muon and tau are negatively charged. Neutrinos do not have charge.  Quarks are fractionally charged particles that are affected by all of the fundamental forces.  Quarks combine to form composite particles and are never directly observed or found in isolation. |
| There are six types of quark, with different properties, such as mass and charge. Each quark has a charge of either +2/3*e* or 1/3*e*.   |  |  |  | | --- | --- | --- | | Quark | Symbol | Charge (e) | | Up | u | 2/3 | | Down | d | 1/3 | | Strange | s | 1/3 | | Charm | c | 2/3 | | Top | t | 2/3 | | Bottom | b | 1/3 |   Every particle has an antimatter equivalent. A key difference between a particle and its antimatter equivalent is that their charges are equal magnitude but opposite sign.   * Identify which types of fundamental particles are affected by each type of fundamental force. * Identify the charges of each type of fundamental particle. * Describe the properties of a specified antimatter particle. * Determine the charge of a specified antimatter particle.   All composite matter particles, such as atoms, are thought to be combinations of quarks, antiquarks and leptons.  Baryons are composite particles that consist of a combination of three quarks.  Mesons are composite particles that consist of a combination of one quark and one antiquark.   * Describe how protons, neutrons, and other baryons consist of different combinations of quarks. * Determine the charge of a baryon, given its quark composition. * Describe how pions and other mesons consist of different combinations of quarks and antiquarks. * Determine the charge of a meson, given its quark-antiquark composition.   Each particle is assigned a lepton number and a baryon number.  Lepton numbers can be one of three types:   * electronic lepton number, * muonic lepton number, * tauonic lepton number,   The lepton number, regardless of type, for a lepton is 1. Antileptons have a lepton number of 1. All other particles have a lepton number of 0.  The baryon number of a quark is 1/3. Baryons have a baryon number of 1. Antiquarks have a baryon number of 1/3. Antibaryons have a baryon number of -1.  All other fundamental particles have a baryon number of 0. |
| The laws of the conservation of baryon number, charge, and lepton number determine the types of reactions that can occur between particles.   * Use the conservation laws to determine the baryon number, lepton number, and charge of particles in reactions. * Given a reaction between particles, demonstrate that baryon number, lepton number, and charge are conserved.   When a particle and its antiparticle collide, they annihilate, releasing energy according to the mass–energy equivalence formula:   * Use the mass–energy equivalence relation to determine the energy released when a particle and antiparticle annihilate. |

Subtopic 1.4: Relativity

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| Motion can only be measured relative to an observer; length and time are relative quantities that depend on the observer’s frame of reference.  Some measured quantities of objects travelling at very high speeds cannot be explained by Newtonian physics. Einstein’s Theory of Special Relativity predicts significantly different results to those of Newtonian physics for velocities approaching the speed of light.  The Theory of Special Relativity is based on two postulates. The first postulate is that the laws of physics are the same in all inertial reference frames. The second postulate is that the speed of light in a vacuum is an absolute constant.  In relativistic mechanics, there is no absolute length or time interval.  At relativistic speeds, time intervals in moving frames of reference are dilated when observed from a stationary reference frame according to  where , is the Lorentz factor, is the time interval in the moving frame of reference and *t* is the time interval in the stationary observer’s frame of reference.   * Solve problems using  and the Lorentz factor formula. * Explain the effects of time dilation on objects moving at relativistic speeds. |
| Some subatomic particles exist in the laboratory for very short time periods before decaying. These same particles are detected as part of cosmic ray showers in the atmosphere, travelling at relativistic speeds close to the speed of light.  Time dilation effects allow these particles to travel significant distances without decay.   * Calculate and compare lifetimes and therefore distances travelled by subatomic particles in stationary and moving reference frames. * Solve problems involving subatomic particles moving at relativistic speeds.   An object moving at relativistic speeds is shorter to an observer in a stationary frame of reference, and the length is given by: , where  is the length in the moving object’s frame of reference and *l* is the length in the stationary observer’s frame of reference.   * Solve problems using . * Explain the effects of length contraction on objects moving at relativistic speeds.   The magnitude of the relativistic momentum of a moving object is given by  where is the mass of the object in the frame of reference where the object is stationary and *v* is the speed of the object.   * Solve problems using * Explain why masses moving at relativistic speeds are unable to reach the speed of light. |