Inside the Atom connections to the A level curriculum for England

Based on – AQA AS and A level physics specification December 2015
Edexcel A level physics specification September 2015
OCR Physics A level specification September 2015

Introduction

The teaching of A level physics in England can be enriched and enhanced through connections to particle and nuclear physics. This document highlights the explicit particle and nuclear physics curriculum links for the three main exam boards: AQA, Edexcel and OCR.

This level of education is different to those previously studied as all students doing A level physics have chosen to take this subject. The A level curriculum also contains more opportunities to inspire and involve students in particle and nuclear physics. Many of the stories from these research communities reinforce the aims of the national curriculum for science that pupils should:

- develop essential knowledge and understanding of different areas of the subject and how they relate to each other
- develop and demonstrate a deep appreciation of the skills, knowledge and understanding of scientific methods
- develop competence and confidence in a variety of practical, mathematical and problem solving skills
- develop their interest in and enthusiasm for the subject, including developing an interest in further study and careers associated with the subject
- understand how society makes decisions about scientific issues and how the sciences contribute to the success of the economy and society

Curriculum Connections

Click on the following links to connect to the relevant section of the A level syllabus:

Particles
Constituents of the atom
Stable and unstable nuclei
Particles, antiparticles and photons
Particle interactions
Classification of particles
Quarks and antiquarks
Application of conservation laws

Nuclear Physics
Rutherford scattering
Particle Acceleration
α, β and γ radiation
Radioactive decay
Nuclear instability
Nuclear radius
Mass and energy
Induced fission
Safety aspects

Medical Physics
Magnetic resonance (MR) scanner
X-ray imaging
Radionuclide imaging and therapy
Ultrasound

Particles

Constituents of the atom

- Simple model of the atom, including the proton, neutron and electron. Charge and mass of the proton, neutron and electron in SI units and relative units.
- Relative sizes of atom and nucleus.
- Specific charge of the proton and the electron, and of nuclei and ions.
- Proton number (atomic number) Z, nucleon number (mass number) A, nuclide notation.
- Students should be familiar with the $^{A}_{Z}X$ notation.
- Meaning of isotopes and the use of isotopic data.

Stable and unstable nuclei

- The strong nuclear force; its role in keeping the nucleus stable; short-range attraction up to approximately 3 fm, very-short range repulsion closer than approximately 0.5 fm.
- Unstable nuclei; alpha and beta decay.
- Equations for alpha decay, $\beta-$ decay including the need for the neutrino.
- The existence of the neutrino was hypothesised to account for conservation of energy in beta decay.

Particles, antiparticles and photons

- For every type of particle, there is a corresponding antiparticle.
- Comparison of particle and antiparticle masses, charge and rest energy in MeV.
- Be able to use MeV and GeV (energy) and MeV/c^2, GeV/c^2 (mass) and convert between these and SI units.
- Students should know that the positron, antiproton, antineutron and antineutrino are the antiparticles of the electron, proton, neutron and neutrino respectively.
- Photon model of electromagnetic radiation, the Planck constant: $E = hf = hc/\lambda$.
- Be able to use the equation $\Delta E = c^2\Delta m$ in situations involving the creation and annihilation of matter and antimatter particles.

Particle interactions

- Four fundamental interactions: gravity, electromagnetic, weak nuclear, strong nuclear. (The strong nuclear force may be referred to as the strong interaction.)
- The concept of exchange particles to explain forces between elementary particles.
- Knowledge of the gluon, Z^0 and graviton will not be tested.
- The electromagnetic force; virtual photons as the exchange particle.
- The weak interaction limited to $\beta-$and $\beta+$ decay, electron capture and electron–proton collisions; W+ and W– as the exchange particles.
- Simple diagrams to represent the above reactions or interactions in terms of incoming and outgoing particles and exchange particles.
- Understand how to use laws of conservation of charge, baryon number and lepton number to determine whether a particle interaction is possible.
- Be able to write and interpret particle equations given the relevant particle symbols.

Classification of particles

- Hadrons are subject to the strong interaction.
- The two classes of hadrons: baryons (proton, neutron) and antibaryons (antiproton, antineutron) made from 3 quarks, mesons (pion, kaon) made from a quark and an antiquark.
- Baryon number as a quantum number.
- Conservation of baryon number.
- The proton is the only stable baryon into which other baryons eventually decay.
- The pion as the exchange particle of the strong nuclear force.
- The kaon as a particle that can decay into pions.

- Leptons: electron, muon, neutrino (electron and muon types only) and their antiparticles.
- All leptons are subject to the weak nuclear force.
- Lepton number as a quantum number; conservation of lepton number for muon leptons and for electron leptons.
- The muon as a particle that decays into an electron.
- Strange particles
- Strange particles as particles that are produced through the strong interaction and decay through the weak interaction (e.g. kaons).
- Strangeness (symbol s) as a quantum number to reflect the fact that strange particles are always created in pairs.
- Conservation of strangeness in strong interactions.
- Strangeness can change by 0, +1 or -1 in weak interactions.
- Know that the standard quark-lepton model particles can be classified as: baryons, mesons, leptons, photons, and the symmetry of the model predicted the top quark.
- Appreciation that particle physics relies on the collaborative efforts of large teams of scientists and engineers to validate new knowledge.

Quarks and antiquarks

- Properties of quarks and antiquarks: charge, baryon number and strangeness.
- Combinations of quarks and antiquarks required for baryons (proton and neutron only), antibaryons (antiproton and antineutron only) and mesons (pion and kaon only).
- Only knowledge of up (u), down (d) and strange (s) quarks and their antiquarks will be tested.
- The decay of the neutron should be known.

Application of conservation laws

- Change of quark character in β– and in β+ decay.
  β– decay in terms of a quark model; $d \rightarrow u + {}^{0}_{-1}e + \bar{\nu}$
  β+ decay in terms of a quark model; $u \rightarrow d + {}^{0}_{+1}e + \nu$
- Balancing of quark transformation equations in terms of charge.
- Decay of particles in terms of the quark model.
- Application of the conservation laws for charge, baryon number, lepton number and strangeness to particle interactions. The necessary data will be provided in questions for particles outside those specified.
- Students should recognise that energy and momentum are conserved in interactions.

Nuclear Physics

Rutherford scattering

- Qualitative study of Rutherford scattering: understand how large-angle alpha particle scattering gives evidence for a nuclear model of the atom.
- Appreciation of how knowledge and understanding of the structure of the nucleus has changed over time.

Particle Acceleration

- Understand that electrons are released in the process of thermionic emission and how they can be accelerated by electric and magnetic fields.
- Understand the role of electric and magnetic fields in particle accelerators (linac and cyclotron) and detectors (general principles of ionisation and deflection only).
- Be able to derive and use the equation $r = p/ BQ$ for a charged particle in a magnetic field.
- Be able to apply conservation of charge, energy and momentum to interactions between particles and interpret particle tracks.

- Understand why high energies are required to investigate the structure of nucleons.
- Understand situations in which the relativistic increase in particle lifetime is significant (use of relativistic equations not required).

α, β and γ radiation

- Their properties and experimental identification using simple absorption experiments; applications e.g. to relative hazards of exposure to humans.
- Applications also include thickness measurements of aluminium foil paper and steel.
- Nuclear decay equations for alpha, beta-minus and beta-plus decays; balancing nuclear transformation equations.
- Inverse-square law for γ radiation: $I = k/x^2$.
- Experimental verification of inverse-square law.
- Applications e.g. to safe handling of radioactive sources.
- Background radiation; examples of its origins and experimental elimination from calculations.
- Appreciation of balance between risk and benefits in the uses of radiation in medicine.

Radioactive decay

- Spontaneous and random nature of radioactive decay; constant decay probability of a given nucleus; $\Delta N/\Delta t = -\lambda N$; $N = N_0 e^{-\lambda t}$.
- Use of activity, $A = dN/dt = -\lambda N$.
- Modelling with constant decay probability.
- Questions may be set which require students to use: $A = A_0 e^{-\lambda t}$.
- Questions may also involve use of molar mass or the Avogadro constant.
- Half-life equation: $T_{½} = \ln 2/\lambda$.
- Determination of half-life from graphical decay data including decay curves and log graphs.
- Simulation of radioactive decay using dice.
- Applications e.g. relevance to storage of radioactive waste, radioactive dating etc.

Nuclear instability

- Graph of N against Z for stable nuclei.
- Possible decay modes of unstable nuclei including α, $\beta+$, $\beta-$ and electron capture.
- Changes in N and Z caused by radioactive decay and representation in simple decay equations.
- Questions may use nuclear energy level diagrams.
- Existence of nuclear excited states; γ ray emission; application e.g. use of technetium-99m as a γ source in medical diagnosis.

Nuclear radius

- Estimate of radius from closest approach of alpha particles and determination of radius from electron diffraction.
- Knowledge of typical values for nuclear radius.
- Students will need to be familiar with the Coulomb equation for the closest approach estimate.
- Dependence of radius on nucleon number: $R = R_0 A^{1/3}$ derived from experimental data.
- Interpretation of equation as evidence for constant density of nuclear material.
- Calculation of nuclear density.
- Students should be familiar with the graph of intensity against angle for electron diffraction by a nucleus.

Mass and energy

- Appreciation that $E = mc^2$ applies to all energy changes.
- Understand the concept of nuclear binding energy and be able to use the equation $\Delta E = c^2 \Delta m$ in calculations of nuclear mass (including mass deficit) and energy.

- Atomic mass unit, u to express small masses and convert between this and SI units.
- Conversion of units; 1 u = 931.5 MeV.
- Fission and fusion processes and the need for very high densities of matter and very high temperatures to bring about and maintain nuclear fusion.
- Simple calculations from nuclear masses of energy released in fission and fusion reactions.
- Graph of average binding energy per nucleon against nucleon number.
- Students may be expected to identify, on the plot, the regions where nuclei will release energy when undergoing fission/fusion.
- Appreciation that knowledge of the physics of nuclear energy allows society to use science to inform decision making.

Induced fission

- Fission induced by thermal neutrons; possibility of a chain reaction; critical mass.
- The functions of the moderator, control rods, and coolant in a thermal nuclear reactor.
- Details of particular reactors are not required.
- Students should have studied a simple mechanical model of moderation by elastic collisions.
- Factors affecting the choice of materials for the moderator, control rods and coolant. Examples of materials used for these functions.

Safety aspects

- Fuel used, remote handling of fuel, shielding, emergency shut-down.
- Production, remote handling, and storage of radioactive waste materials.
- Appreciation of balance between risk and benefits in the development of nuclear power.

Medical Physics

Magnetic resonance (MR) scanner

- Cross-section of patient scanned using magnetic fields.
- Protons initially aligned with spins parallel.
- Spinning hydrogen nuclei (protons) precess about the magnetic field lines of a superconducting magnet.
- ‘Gradient’ field coils used to scan cross-section.
- Short radio frequency (RF) pulses cause excitation and change of spin state in successive small regions.
- Protons excited during the scan emit RF signals as they de-excite.
- RF signals detected and the resulting signals are processed by a computer to produce a visual image.
- Students will not be asked about the production of magnetic fields used in an MR scanner, or about de-excitation relaxation times.

X-ray imaging

- Basic structure of an X-ray tube; components – heater (cathode), anode, target metal and high voltage supply.
- Production of X-ray photons from an X-ray tube.
- X-ray attenuation mechanisms; simple scatter, photoelectric effect, Compton effect and pair production.
- Physical principles of the production of X-rays; maximum photon energy, energy spectrum; continuous spectrum and characteristic spectrum.
- Rotating-anode X-ray tube; methods of controlling the beam intensity, the photon energy, the image sharpness and contrast, and the patient dose.
- Flat panel (FTP) detector including X-ray scintillator, photodiode pixels, electronic scanning.
- Advantages of FTP detector compared with photographic detection.
- Contrast enhancement; use of X-ray opaque material as illustrated by the barium meal technique.

- Photographic detection with intensifying screen and fluoroscopic image intensification; reasons for using these.
- Exponential attenuation.
- Linear coefficient μ, mass attenuation coefficient μm, half-value thickness: $I = I_0 e^{-\mu x}$; $\mu_m = \mu/\rho$
- Differential tissue absorption of X-rays excluding details of the absorption processes.
- Basic principles of CT scanner:
  movement of X-ray tube
  narrow, monochromatic X-ray beam
  array of detectors
  computer used to process the signals and produce a visual image.
- Comparisons will be limited to advantages and disadvantages of image resolution, cost and safety issues. Students will not be asked about the construction or operation of the detectors.

Radionuclide imaging and therapy

- Use of a gamma-emitting radioisotope as a tracer; technetium-99m, fluorine-18, iodine-131 and indium-111 and their relevant properties.
- The properties should include the radiation emitted, the half-life, the energy of the gamma radiation, the ability for it to be labelled with a compound with an affinity for a particular organ.
- The Molybdenum-Technetium generator, its basic use and importance.
- Gamma camera; components – collimator, scintillator, photomultiplier tubes, computer and display; formation of image.
- Diagnosis using gamma camera.
- Positron emission tomography (PET) scanner; annihilation of positron–electron pairs; formation of image.
- Diagnosis using PET scanning.
- Physical, biological and effective half-lives; $1/T_E = 1/T_B + 1T_P$; definitions of each term.
- Basic structure and workings of a photomultiplier tube and gamma camera.
- External treatment using high-energy X-rays. Methods used to limit exposure to healthy cells.
- Internal treatment using beta emitting implants.
- Students will be required to make comparisons between imaging techniques. Questions will be limited to consideration of image resolution, convenience and safety issues.

Ultrasound

- Ultrasound; longitudinal wave with frequency greater than 20 kHz.
- Piezoelectric effect; ultrasound transducer as a device that emits and receives ultrasound.
- Ultrasound A-scan and B-scan.
- Acoustic impedance of a medium; $Z = \rho c$.
- Reflection of ultrasound at a boundary; $I^r / I^0 = (Z_2 - Z_1)^2/(Z_2 + Z_1)^2$.
- Impedance (acoustic) matching; special gel used in ultrasound scanning.
- Doppler effect in ultrasound; speed of blood in the patient; $\Delta f/f = 2\nu \cos\theta/c$ for determining the speed ν of blood.