

IB Physics – Theme E: Nuclear and Quantum Physics

IB Physics SL & HL (2016 curriculum, questions marked HL for Higher Level only) · Total marks: 39 · Answers on the last page

Covers atomic structure, radioactive decay, nuclear energy, fission/fusion and stellar processes (SL/HL) plus the photoelectric effect, matter waves and the Bohr model (HL). A calculator and the IB Physics data booklet ($h = 6.63 \times 10^{-34} \text{ J s}$, $c = 3.00 \times 10^8 \text{ m s}^{-1}$, $e = 1.60 \times 10^{-19} \text{ C}$, $1 \text{ u} = 931.5 \text{ MeV}/c^2$) are assumed throughout; allow about 55 minutes.

Section A – Atomic structure and radioactivity (SL and HL)

1. State the number of protons, neutrons and electrons in a neutral atom of ${}_{92}^{235}\text{U}$. [2]
2. Nuclide X has 6 protons and 8 neutrons.
 - (a) Write the full nuclide notation for X.
 - (b) State the name of this nuclide and explain why it is an isotope of carbon. [3]
3. A radioactive source emits alpha, beta and gamma radiation.
 - (a) State one property that distinguishes alpha particles from beta particles in terms of penetrating power.
 - (b) Write a nuclear equation for the alpha decay of ${}_{88}^{226}\text{Ra}$. [3]
4. The isotope ${}_{88}^{226}\text{Ra}$ has mass 226.025403 u and decays to ${}_{86}^{222}\text{Rn}$ (mass 222.017576 u) by alpha emission (alpha particle mass 4.002603 u). Calculate the energy released in this decay, in MeV. [3]

Section B – Half-life, fission, fusion and stars (Exam-style, SL and HL)

5. The isotope iodine-131 has a half-life of 8.02 days.
 - (a) Define the term half-life.
 - (b) A hospital sample initially contains 4.0×10^{15} atoms of I-131. Calculate the number of atoms remaining after 24.06 days. [4]
6. Explain, in terms of binding energy per nucleon, why energy is released in both nuclear fission of ${}^{235}\text{U}$ and nuclear fusion of hydrogen isotopes. [3]
7. A fission reaction is ${}_{92}^{235}\text{U} + {}_0^1\text{n} \rightarrow {}_{56}^{141}\text{Ba} + {}_{36}^{92}\text{Kr} + x {}_0^1\text{n}$.
 - (a) Find the value of x .
 - (b) State one condition needed for a self-sustaining chain reaction to occur. [3]
8. Outline, using the Hertzsprung–Russell diagram and stellar evolution, the sequence of stages a star of mass similar to the Sun passes through from the main sequence to its final state. [4]

Section C – Quantum physics (HL) (Higher Level only)

9. The work function of sodium is 2.28 eV. Light of wavelength 400 nm is incident on a sodium surface.
 - (a) Calculate the energy of a photon of this light, in eV.
 - (b) Show that photoelectrons are emitted, and calculate their maximum kinetic energy in eV. [4]
10. (a) State the photoelectric effect evidence that light behaves as a particle (photon) rather than purely as a wave.

(b) Calculate the threshold wavelength for sodium (work function 2.28 eV), above which no photoelectrons are emitted. [3]

11. An electron is accelerated from rest through a potential difference of 150 V.

(a) Calculate the kinetic energy gained by the electron, in J.

(b) Calculate the de Broglie wavelength of the electron. [4]

12. In the Bohr model of the hydrogen atom, electrons occupy discrete energy levels and emission spectra consist of sharp lines rather than a continuum.

(a) Explain, in terms of electron transitions, how a line emission spectrum is produced.

(b) Explain why this observation supports the idea of quantised (discrete) atomic energy levels. [3]

Answers

Check your working against these. If an answer does not match, try the question again before looking for the method.

- Protons = 92, neutrons = $235 - 92 = 143$, electrons = 92.
- (a) ${}^{14}_6\text{C}$.
(b) Carbon-14; it has the same proton (atomic) number as carbon (6) but a different number of neutrons/nucleon number, so it is an isotope of carbon.
- (a) Alpha particles are stopped by a few cm of air or a sheet of paper, while beta particles need a few mm of aluminium to be stopped (alpha is far less penetrating).
(b) ${}^{226}_{88}\text{Ra} \rightarrow {}^{222}_{86}\text{Rn} + {}^4_2\text{He}$.
- Mass defect $\Delta m = 226.025403 - (222.017576 + 4.002603) = 0.005224 \text{ u}$. Energy released = $0.005224 \times 931.5 = 4.87 \text{ MeV}$.
- (a) Half-life is the time taken for the activity (or number of undecayed nuclei) of a radioactive sample to fall to half of its original value.
(b) 24.06 days = 3 half-lives, so fraction remaining = $(1/2)^3 = 0.125$. Atoms remaining = $0.125 \times 4.0 \times 10^{15} = 5.0 \times 10^{14}$.
- Binding energy per nucleon is low for very heavy nuclei (like U) and for very light nuclei (like H), and is greatest for medium-mass nuclei (around iron). Fission splits a heavy nucleus into medium-mass fragments, and fusion joins light nuclei into a medium-mass nucleus; in both cases the products have greater binding energy per nucleon than the reactants, so energy is released.
- (a) Nucleon number balance: $235 + 1 = 141 + 92 + x \Rightarrow x = 3$.
(b) The mass of fissile material must exceed the critical mass, so that on average at least one neutron from each fission goes on to cause a further fission (accept: sufficient concentration/enrichment of ${}^{235}\text{U}$, or neutrons must be moderated/slowed).
- Main sequence star (fusing H to He in core) $\rightarrow$ core H exhausted, core contracts and outer layers expand and cool, star moves to red giant branch $\rightarrow$ He fusion begins in the core (and H fusion in a shell) $\rightarrow$ outer layers are expelled as a planetary nebula $\rightarrow$ the remaining core, no longer able to fuse and supported by electron degeneracy pressure, becomes a white dwarf, which then cools.
- (a) $E = \frac{hc}{\lambda} = \frac{6.63 \times 10^{-34} \times 3.00 \times 10^8}{400 \times 10^{-9}} = 4.97 \times 10^{-19} \text{ J} = 3.11 \text{ eV}$.
(b) Since $3.11 \text{ eV} > 2.28 \text{ eV}$ (the work function), photoelectrons are emitted. $E_{k,\text{max}} = 3.11 - 2.28 = 0.83 \text{ eV}$.
- (a) Emission of electrons is instantaneous (no time delay) and occurs only above a threshold frequency independent of intensity; increasing intensity increases the number of photoelectrons but not their maximum kinetic energy — this cannot be explained by a purely wave model, which predicts energy build-up over time and emission at any frequency given enough intensity.
(b) $\lambda_0 = \frac{hc}{\phi} = \frac{6.63 \times 10^{-34} \times 3.00 \times 10^8}{2.28 \times 1.60 \times 10^{-19}} = 5.45 \times 10^{-7} \text{ m} = 545 \text{ nm}$.
- (a) $E_k = eV = 1.60 \times 10^{-19} \times 150 = 2.40 \times 10^{-17} \text{ J}$.
(b) $v = \sqrt{2E_k/m_e} = 7.26 \times 10^6 \text{ m s}^{-1}$, so $\lambda = \frac{h}{m_e v} = \frac{6.63 \times 10^{-34}}{9.11 \times 10^{-31} \times 7.26 \times 10^6} = 1.00 \times 10^{-10} \text{ m}$ (100 pm).
- (a) An electron in an excited atom falls from a higher energy level to a lower one, emitting a photon whose energy equals the difference between the two energy levels; each possible transition

between levels produces a photon of a specific frequency, seen as one spectral line.

(b) Only certain photon energies (frequencies/wavelengths) are observed, producing a discrete line spectrum rather than a continuous range of frequencies; this can only occur if the electron energies within the atom are restricted to a discrete (quantised) set of allowed values, since a continuum of energy levels would give a continuous spectrum.

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