IB DP PHYSICS

Theme E · Atomic, Nuclear and Particle Physics

MARK SCHEME

E.1 Structure of the Atom · E.2 Quantum Physics (HL) · E.3 Radioactive Decay
E.4 Fission · E.5 Fusion and Stars

Standard and Higher Level · Syllabus 2025

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Original exam-style questions written for the IB Diploma Programme Physics course (first assessment 2025)

Section A — Multiple Choice: Answer Key (15 marks)

1. Answer: **B** — $E = hf = 6.63\times10^{-34}\cdot5.0\times10^{14} = 3.32\times10^{-19}$ J.

2. Answer: **A** — Because electron energy levels in an atom are quantized, photons are only emitted with energies equal to the discrete differences between allowed energy levels, producing sharp spectral lines.

3. Answer: **B** — $\Delta E = E_2 - E_1 = -3.40 - (-13.6) = 10.2$ eV.

4. Answer: **B** — $hf = 4.14\times10^{-15}\cdot8.0\times10^{14} = 3.31$ eV; $KE_{max} = hf - \Phi = 3.31 - 2.30 = 1.01$ eV.

5. Answer: **B** — Classical wave theory predicts that sufficiently intense light of any frequency should eventually eject electrons; the existence of a sharp threshold frequency, independent of intensity, can only be explained by the photon (quantum) model.

6. Answer: **C** — $\lambda = h/p = 6.63\times10^{-34}/2.0\times10^{-24} = 3.32\times10^{-10}$ m.

7. Answer: **C** — $\lambda = \ln2/T_{½} = 0.693/(5.0\times86400) = 1.60\times10^{-6}\ s^{-1}$; $A = \lambda N = 1.60\times10^{-6}\cdot2.0\times10^{10} \approx 3.2\times10^{4}$ Bq.

8. Answer: **C** — Gamma rays (high-energy photons) are the most penetrating; alpha particles are stopped by paper or a few cm of air, and beta particles by a few mm of aluminium.

9. Answer: **C** — 15 years = 3 half-lives, so the remaining fraction is $(1/2)^3 = 1/8$.

10. Answer: **B** — $E = \Delta mc^2 = 2.0\times10^{-28}\cdot(3.0\times10^{8})^2 = 1.8\times10^{-11}$ J.

11. Answer: **B** — Each fission event releases (typically 2−3) additional neutrons, which can go on to induce fission in further nuclei, allowing a self-sustaining chain reaction.

12. Answer: **B** — Binding energy is the energy released when separate nucleons come together to form a nucleus (mass defect × c^2), equal to the energy that would be required to completely separate the nucleus into its individual nucleons.

13. Answer: **B** — $E = \Delta mc^2 = 3.0\times10^{-29}\cdot(3.0\times10^{8})^2 = 2.7\times10^{-12}$ J.

14. Answer: **B** — The Sun's core temperature and pressure are so high that nuclei have enough kinetic energy (with a further boost from quantum tunnelling) to approach closely enough to fuse, despite mutual electrostatic repulsion.

15. Answer: **C** — $L \in R^2T^4$. With $R \to 2R$ and $T \to T/2$: factor = $2^2\cdot(1/2)^4 = 4\cdot1/16 = 1/4$, so luminosity decreases to 1/4 of its original value.

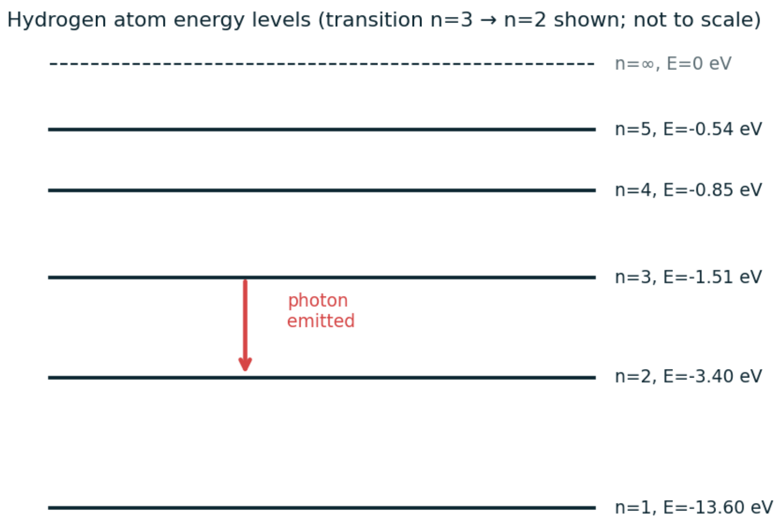
Section B — Structured Questions: Worked Solutions (67 marks)

Mark-scheme notation: M = method mark, A = accuracy mark (dependent on the preceding M mark), R = reasoning mark.

E.1 Structure of the Atom

Question 1 [7 marks]

The diagram shows some of the energy levels of the hydrogen atom. An electron makes a transition from the n = 3 level to the n = 2 level, emitting a photon.



Energy level diagram for hydrogen (energy values are given data).

(a) Calculate the energy of the emitted photon, in eV and in joules. **[2]**

$\Delta E = |E_3 - E_2| = |-1.51 - (-3.40)|$ = **1.89 eV** = $1.89 \cdot 1.6\times10^{-19}$ = **3.024×10^{-19} J**. **M1 A1**

(b) Calculate the frequency of the emitted photon. **[2]**

$f = \Delta E/h = 3.024\times10^{-19}/6.63\times10^{-34}$ = **4.5611×10^{14} Hz**. **M1 A1**

(c) Calculate the wavelength of the emitted photon, and state whether it lies within the visible spectrum (≈400–700 nm). **[3]**

$\lambda = c/f = 3.0\times10^{8}/4.5611\times10^{14}$ = **657.7 nm**. This lies **within** the visible spectrum (it is the red Hα line). **M1 A1 A1**

Question 2 [6 marks]

The ionization energy of a hydrogen atom in its ground state is 13.6 eV.

(a) Express the ionization energy in joules. **[2]**

$E = 13.6 \cdot 1.6\times10^{-19}$ = **2.176×10^{-18} J**. **M1 A1**

(b) Calculate the minimum frequency of a photon that could ionize a ground-state hydrogen atom. **[2]**

$f = E/h = 2.176\times10^{-18}/6.63\times10^{-34}$ = **3.282×10^{15} Hz**. **M1 A1**

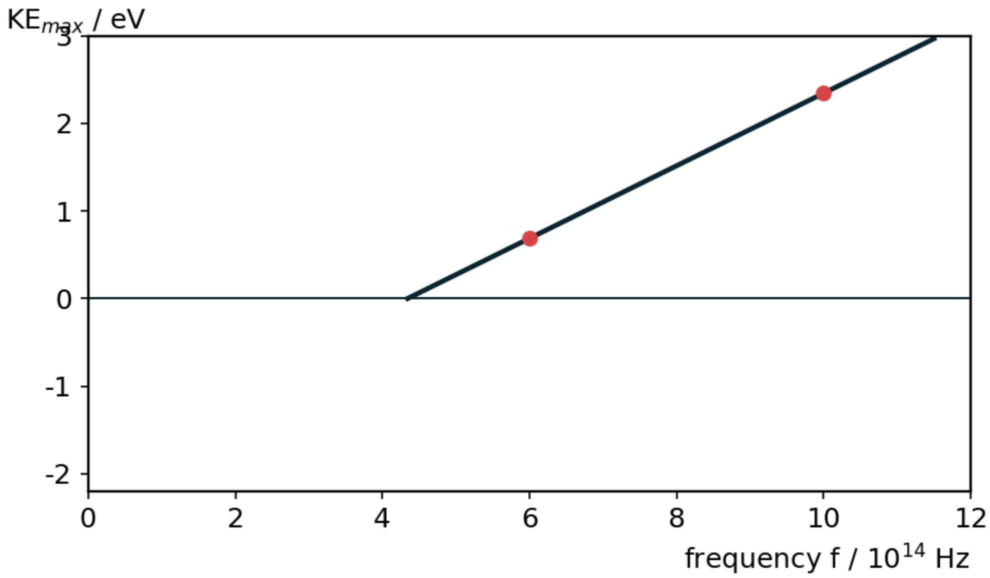
(c) State what happens if a photon whose energy is less than 13.6 eV, but exactly equal to the difference between two of the atom's energy levels, is absorbed. **[2]**

The electron is **excited** to the higher of the two energy levels (rather than being removed from the atom altogether); the atom is not ionized. **A1 A1**

E.2 Quantum Physics (HL)

Question 3 [7 marks]

In a photoelectric effect experiment, the maximum kinetic energy of emitted photoelectrons, KE_{max}, is measured for light of different frequencies incident on the same metal surface. The graph shows the results.



Maximum photoelectron kinetic energy against frequency of incident light (two data points shown; the given work function is 1.80 eV).

(a) Using the two labelled data points, calculate the gradient of the graph in SI units, and explain why this gradient is expected to equal the Planck constant. **[3]**

Gradient = $\Delta KE_{max}/\Delta f = (1.657\text{eV}\cdot 1.6\times10^{-19})/(10.0\times10^{14} - 6.0\times10^{14})$ = $\mathbf{6.630\times10^{-34}}$ **J s**. **M1 A1 R1**
By Einstein's photoelectric equation $KE_{max} = hf - \Phi$, the gradient of a KE_{max} against f graph equals the Planck constant h – consistent with the accepted value.

(b) Use one of the data points to calculate the work function of the metal, in eV. **[2]**

$\Phi = hf_1 - KE_{max,1}$ = **1.80 eV** (as given/confirmed by the data). **M1 A1**

(c) Calculate the threshold frequency of the metal. **[2]**

$f_0 = \Phi/h$ = $\mathbf{4.344\times10^{14}}$ **Hz** (the x-intercept of the graph). **M1 A1**

Question 4 [6 marks]

An electron, initially at rest, is accelerated through a potential difference of 150 V.

(a) Calculate the kinetic energy gained by the electron. **[2]**

$KE = eV = 1.6\times10^{-19}\cdot 150$ = $\mathbf{2.40\times10^{-17}}$ **J**. **M1 A1**

(b) Calculate the speed of the electron. **[2]**

$v = \sqrt{(2KE/m_e)} = \sqrt{(2\cdot 2.40\times10^{-17}/9.11\times10^{-31})}$ = $\mathbf{7.259\times10^{6}\ m\ s^{-1}}$. **M1 A1**

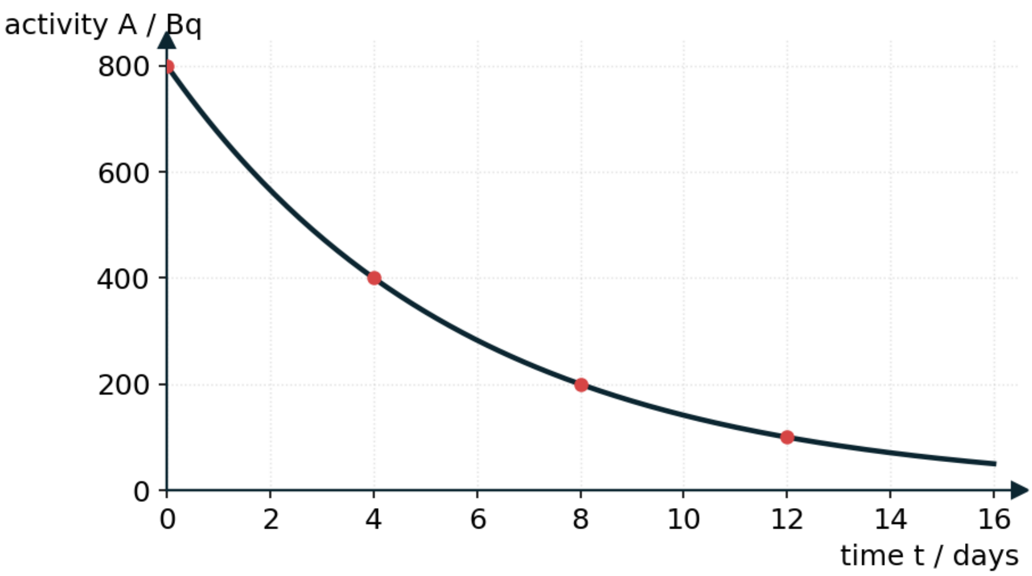
(c) Calculate the de Broglie wavelength associated with the electron. **[2]**

$\lambda = h/(m_e v) = 6.63\times10^{-34}/(9.11\times10^{-31}\cdot 7.259\times10^{6})$ = $\mathbf{1.003\times10^{-10}\ m}$ ($\approx$ 100.3 pm). **M1 A1**

E.3 Radioactive Decay

Question 5 [7 marks]

A radioactive source has an initial activity of 800 Bq. The graph shows how its activity varies with time; the half-life can be read from the graph as 4.0 days.



Activity–time decay curve (initial activity and half-life are given data).

(a) Use the half-life read from the graph to calculate the decay constant of the source. **[2]**

$\lambda = \ln 2/T_{½} = 0.693/4.0$ = $\mathbf{0.1733\ day^{-1}}$ (= $2.006\times10^{-6}\ s^{-1}$). **M1 A1**

(b) Calculate the activity of the source after 10 days. **[2]**

$A = A_0 e^{-\lambda t} = 800\cdot e^{-0.1733\cdot 10}$ = **141.4 Bq**. **M1 A1**

(c) Using $A = \lambda N$, calculate the number of radioactive nuclei present at t = 0. **[3]**

$N_0 = A_0/\lambda = 800/2.006\times10^{-6}$ = $\mathbf{3.989\times10^{8}}$ nuclei. **M1 M1 A1**

Question 6 [6 marks]

A sample initially contains 5.0×10^{12} radioactive nuclei of an isotope with a half-life of 6.0 hours.

(a) Calculate the decay constant of the isotope. **[2]**

$\lambda = \ln 2/T_{½} = 0.693/6.0$ = $\mathbf{0.1155\ hour^{-1}}$ (= $3.209\times10^{-5}\ s^{-1}$). **M1 A1**

(b) Calculate the initial activity of the sample, in Bq. **[2]**

$A_0 = \lambda N_0 = 3.209\times10^{-5}\cdot 5.0\times10^{12}$ = $\mathbf{1.605\times10^{8}\ Bq}$. **M1 A1**

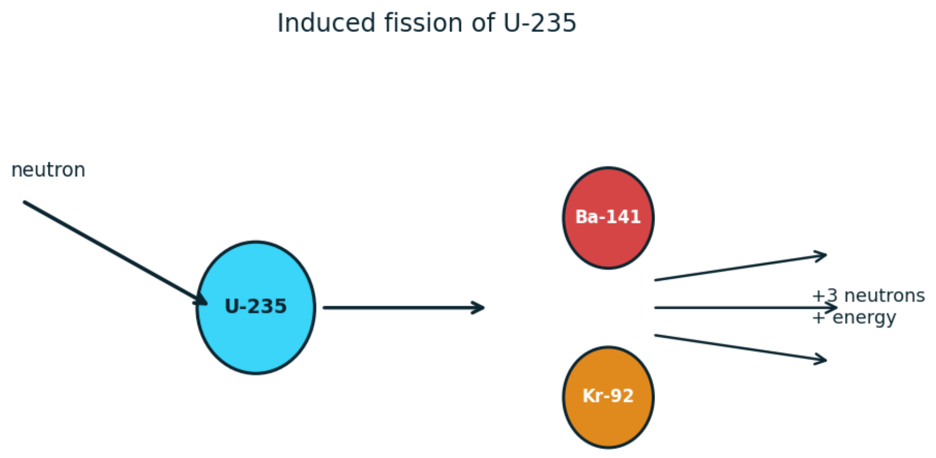
(c) Calculate the number of nuclei remaining after 18 hours. **[2]**

18 hours = 3 half-lives: $N = N_0(1/2)^3 = 5.0\times10^{12}/8 = \mathbf{6.250\times10^{11}}$ nuclei. **M1 A1**

E.4 Fission

Question 7 [8 marks]

A neutron is absorbed by a U-235 nucleus, inducing fission into barium-141 and krypton-92, releasing 3 neutrons, as shown. (1 u = 1.66×10^{-27} kg; masses: U-235 = 235.0439 u, neutron = 1.0087 u, Ba-141 = 140.9144 u, Kr-92 = 91.9262 u.)



Induced fission of U-235 following neutron capture.

(a) Calculate the mass defect of this reaction, in u and in kg. **[3]**

m_{before} = 235.0439 + 1.0087 = 236.0526 u. **M1 M1 A1**
m_{after} = 140.9144 + 91.9262 + 3·1.0087 = 235.8667 u.
$\Delta m = m_{before} - m_{after}$ = **0.1859 u** = $0.1859\cdot1.66\times10^{-27}$ = $\mathbf{3.086\times10^{-28}}$ **kg**.

(b) Calculate the energy released in this single fission event, in joules and in MeV. **[3]**

$E = \Delta mc^2 = 3.086\times10^{-28}\cdot(3.0\times10^8)^2 = \mathbf{2.777\times10^{-11}}$ **J** = **173.6 MeV**. **M1 M1 A1**

(c) State the additional role played by the 3 emitted neutrons in a nuclear reactor or bomb. **[2]**

Each emitted neutron can go on to be absorbed by another U-235 nucleus, inducing further fission events and enabling a self-sustaining **chain reaction**. **A1 A1**

Question 8 [6 marks]

A nuclear reactor generates 1.5 GW of thermal power. Each fission of U-235 releases approximately 200 MeV of usable energy.

(a) Express the energy released per fission event in joules. **[2]**

$E = 200\times10^6\cdot1.6\times10^{-19} = \mathbf{3.200\times10^{-11}}$ **J**. **M1 A1**

(b) Calculate the number of fission events needed per second to sustain this power output. **[2]**

N = P/E = $1.5\times10^{9}/3.200\times10^{-11}$ = **4.688×10^{19}** fissions per second. **M1 A1**

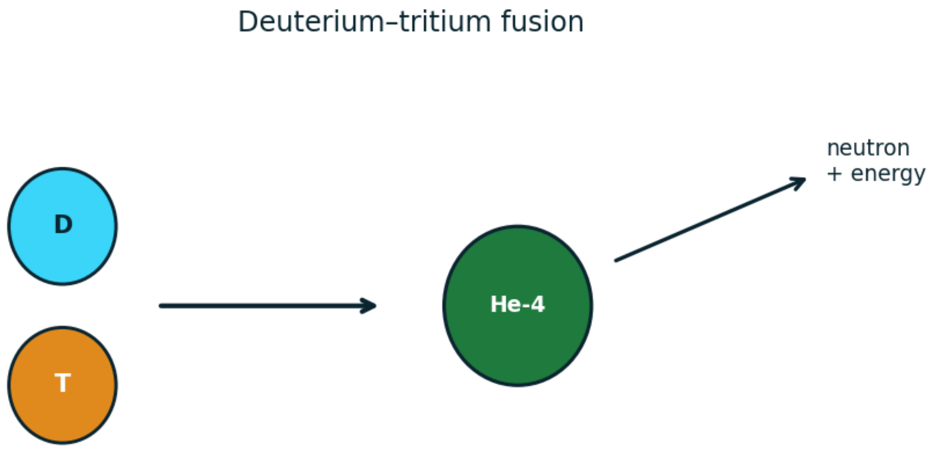
(c) Estimate the mass of U-235 consumed per second (mass of one U-235 nucleus ≈ 235 u = 3.90×10^{-25} kg). **[2]**

mass rate = N·(mass per nucleus) = $4.688\times10^{19}\cdot3.90\times10^{-25}$ = **1.829×10^{-5} kg s^{-1}** (≈ 0.02 mg s^{-1}). **M1 A1**

E.5 Fusion and Stars

Question 9 [8 marks]

A deuterium nucleus (D) fuses with a tritium nucleus (T) to form helium-4 and a neutron, as shown. (Masses: D = 2.0141 u, T = 3.0160 u, He-4 = 4.0026 u, neutron = 1.0087 u; 1 u = 1.66×10^{-27} kg.)



Deuterium–tritium (D–T) fusion.

(a) Calculate the mass defect of this fusion reaction, in u and in kg. **[3]**

m_{before} = 2.0141 + 3.0160 = 5.0301 u. **M1 M1 A1**
m_{after} = 4.0026 + 1.0087 = 5.0113 u.
Δm = **0.0188 u** = $0.0188\cdot1.66\times10^{-27}$ = **3.121×10^{-29} kg**.

(b) Calculate the energy released in this fusion reaction, in joules and in MeV. **[3]**

$E = \Delta mc^2 = 3.121\times10^{-29}\cdot(3.0\times10^{8})^2$ = **2.809×10^{-12} J** = **17.6 MeV**. **M1 M1 A1**

(c) Explain, in terms of binding energy per nucleon, why energy is released in this fusion reaction. **[2]**

Helium-4 has a substantially higher binding energy per nucleon than deuterium or tritium (it is one of the most tightly bound light nuclei), so it is more stable. Energy is released because the products (He-4 + n) are in a lower-energy, more tightly bound configuration than the reactants (D + T). **R1 R1**

Question 10 [6 marks]

The Sun has a surface temperature of 5800 K and a radius of 6.96×10^{8} m. (Stefan–Boltzmann constant σ = 5.67×10^{-8} W m^{-2} K^{-4}.)

(a) Calculate the luminosity of the Sun, using $L = 4\pi R^2\sigma T^4$. **[2]**

$L = 4\pi(6.96\times10^{8})^{2}\cdot5.67\times10^{-8}\cdot5800^{4}$ = **3.906×10^{26} W**. **M1 A1**

(b) A second star has the same surface temperature as the Sun but twice its radius. Calculate its luminosity as a multiple of the Sun's luminosity. **[2]**

Since $L \in R^{2}$ at fixed T: doubling R increases L by a factor of 2^{2} = **4**× the Sun's luminosity. **M1 A1**

(c) State how the Sun's luminosity would change if its surface temperature doubled, with its radius unchanged. **[2]**

Since $L \in T^{4}$, doubling T alone increases the luminosity by a factor of 2^{4} = **16**×. **A1 A1**