

A-Level Physics – Nuclear and Thermal

A-Level Physics (Edexcel/AQA/OCR) · Total marks: 38 · Answers on the last page

Practice questions on radioactivity, nuclear binding energy, ideal gases and kinetic theory. Use $u = 1.661 \times 10^{-27}$ kg, $1 \text{ u} = 931.5 \text{ MeV}/c^2$, $k = 1.38 \times 10^{-23} \text{ J K}^{-1}$ and $R = 8.31 \text{ J K}^{-1} \text{ mol}^{-1}$. A calculator is required throughout.

Section A – Radioactivity

- Define what is meant by the half-life of a radioactive isotope.
 - State two features of radioactive decay that show it is a random process. [3]
- A sample of cobalt-60 initially contains 8.0×10^{10} undecayed nuclei. Cobalt-60 has a half-life of 5.27 years. Calculate the number of undecayed nuclei remaining after 15.81 years. [3]
- Calculate the decay constant λ of cobalt-60, in year^{-1} , given its half-life of 5.27 years. [2]
- A sample of iodine-131 (half-life 8.02 days) has an initial activity of 640 Bq. The activity falls to 40 Bq.
 - Calculate the number of half-lives that have elapsed.
 - Calculate the time taken, in days. [4]

Section B – Nuclear Binding Energy

- Explain what is meant by the binding energy of a nucleus, and explain why energy is released when a large nucleus such as uranium-235 undergoes fission. [3]
- A helium-4 nucleus is formed from 2 protons (mass 1.007276 u each) and 2 neutrons (mass 1.008665 u each). The mass of the helium-4 nucleus is 4.001506 u.
 - Calculate the mass defect of the helium-4 nucleus, in u.
 - Calculate the total binding energy of the nucleus, in MeV, using $1 \text{ u} = 931.5 \text{ MeV}/c^2$. [4]
- Using your answer to the previous question, calculate the binding energy per nucleon of helium-4, in MeV, and comment on its size compared with iron-56, which has a binding energy per nucleon of about 8.8 MeV. [3]
- With reference to the graph of binding energy per nucleon against nucleon number, explain why energy is released in both nuclear fusion (of light nuclei) and nuclear fission (of heavy nuclei). [3]

Section C – Thermal Physics and Ideal Gases

- State three assumptions of the kinetic theory of gases used to derive the ideal gas equation for a model (ideal) gas. [3]
- A cylinder contains 0.50 mol of an ideal gas at a temperature of 300 K in a volume of 0.020 m^3 . Calculate the pressure of the gas. [3]
- For an ideal gas at a temperature of 300 K:
 - Calculate the mean translational kinetic energy of a gas molecule.
 - Calculate the root-mean-square speed of a nitrogen molecule of mass $4.65 \times 10^{-26} \text{ kg}$ at this temperature. [4]

12. A fixed mass of ideal gas has an initial pressure of $1.0 \times 10^5 \text{ Pa}$, volume 2.0 dm^3 and temperature 290 K . The gas is compressed to a volume of 1.2 dm^3 and heated to 350 K . Calculate the new pressure of the gas. [3]

Answers

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

- (a) Half-life is the time taken for the number of undecayed nuclei (or the activity) of a radioactive sample to fall to half of its original value.

(b) It is impossible to predict when any individual nucleus will decay; and the decay rate is unaffected by external conditions such as temperature or pressure (any two valid features).
- 15.81 years is 3 half-lives ($15.81/5.27 = 3$). $N = N_0 \left(\frac{1}{2}\right)^3 = \frac{8.0 \times 10^{10}}{8} = 1.0 \times 10^{10}$ nuclei.
- $\lambda = \frac{\ln 2}{T_{1/2}} = \frac{0.693}{5.27} = 0.132 \text{ year}^{-1}$.
- (a) $\frac{640}{40} = 16 = 2^4$, so 4 half-lives have elapsed.

(b) $t = 4 \times 8.02 = 32.1$ days.
- Binding energy is the energy required to completely separate a nucleus into its individual, unbound protons and neutrons (equivalently, the energy equivalent of the mass defect, the difference between the mass of the separate nucleons and the mass of the nucleus). Energy is released in fission because the binding energy per nucleon of the two smaller product nuclei is greater than that of the original uranium-235 nucleus, so the total mass decreases and the mass difference is released as energy.
- (a) $\Delta m = 2(1.007276) + 2(1.008665) - 4.001506 = 0.030376 \text{ u}$.

(b) $E = \Delta m \times 931.5 = 0.030376 \times 931.5 = 28.3 \text{ MeV}$.
- $\frac{28.3}{4} = 7.07 \text{ MeV per nucleon}$. This is noticeably lower than the value for iron-56, consistent with iron-56 being close to the peak of the binding-energy-per-nucleon curve, where nuclei are most stable.
- The binding energy per nucleon is low for both very light nuclei and very heavy nuclei, and reaches a maximum around iron-56. In fusion, light nuclei combine to form a nucleus with a higher binding energy per nucleon (closer to the peak). In fission, a heavy nucleus splits into two nuclei with a higher binding energy per nucleon than the original. In both cases the total binding energy increases, meaning the total mass decreases, and this mass difference is released as energy.
- Any three of: the gas consists of a very large number of identical molecules in random motion; the volume of the molecules is negligible compared with the volume of the container; intermolecular forces are negligible except during collisions; collisions between molecules (and with the container walls) are perfectly elastic; the duration of a collision is negligible compared with the time between collisions.
- Using $pV = nRT$: $p = \frac{nRT}{V} = \frac{0.50 \times 8.31 \times 300}{0.020} = 6.23 \times 10^4 \text{ Pa}$.
- (a) $\overline{E_K} = \frac{3}{2}kT = \frac{3}{2}(1.38 \times 10^{-23})(300) = 6.21 \times 10^{-21} \text{ J}$.

(b) $c_{\text{rms}} = \sqrt{\frac{3kT}{m}} = \sqrt{\frac{3(1.38 \times 10^{-23})(300)}{4.65 \times 10^{-26}}} = 517 \text{ m s}^{-1}$.
- Using $\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2}$: $p_2 = \frac{p_1 V_1 T_2}{T_1 V_2} = \frac{(1.0 \times 10^5)(2.0)(350)}{(290)(1.2)} = 2.0 \times 10^5 \text{ Pa}$.

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