Mass defect and binding energy

Checking the reports from a nuclear-mass laboratory

35–40 minutes independent work + 15–20 minutes review

OCR A H556 | A-level physics | Module 6 | 37 marks

Specification points covered

6.4.4(d): mass defect and binding energy.

6.4.4(f): binding-energy calculations using supplied nuclear masses and $E = \Delta mc^2$.

6.4.4(b): energy released or absorbed in simple nuclear reactions. Supporting: 6.4.4(a), (k).

Use $m_p = 1.00728$ u, $m_n = 1.00866$ u; 1 u $c^2 = 931.5$ MeV; 1 MeV $= 1.602 \times 10^{-13}$ J. For kg calculations use 1 u $= 1.66054 \times 10^{-27}$ kg and $c = 2.998 \times 10^8$ m s^{-1}. Small conversion differences reflect rounded constants. All stated nuclear masses exclude electrons.

Use a calculator and your OCR A data booklet. Show working, units and directions where relevant.

1 Say precisely what binding energy means

A research team checks mass measurements before using nuclear reactions in an instrument energy standard. Supplied masses are rounded data; keep guard digits until the final answer.

Figure 1 compares the same numbers of protons and neutrons before and after binding. It does not compare two different nuclides.

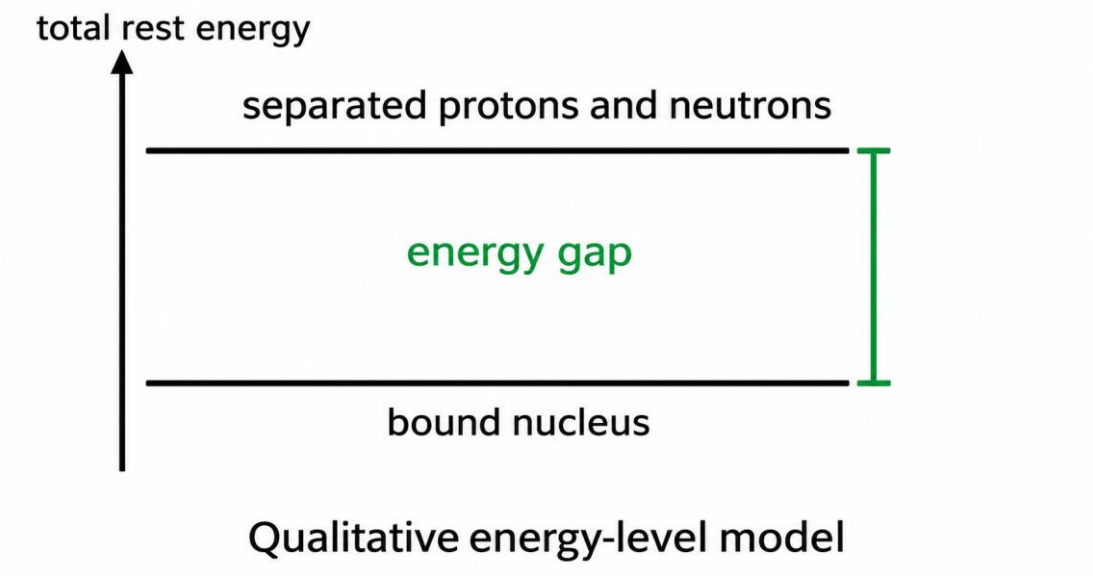


Figure 1 A qualitative energy-level model

1(a) Define the nuclear binding energy of a nucleus. Your definition must identify the starting system and the separated final particles. **[2 marks]**

1(b) Use Figure 1 to explain whether forming a bound nucleus from the same separated protons and neutrons releases or requires energy. **[2 marks]**

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2 Audit a helium mass measurement

2(a) A helium-4 nucleus has Z = 2 and measured nuclear mass 4.00151 u. Calculate the total mass of its constituent free protons and neutrons. **[1 mark]**

2(b) Calculate the mass defect of this nucleus, stating which mass is subtracted from which. **[1 mark]**

2(c) Calculate the total binding energy of this helium-4 nucleus in MeV and in joules. **[2 marks]**

2(d) Convert the helium mass defect to kilograms and check the binding energy using $E = \Delta mc^2$. **[2 marks]**

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3 Handle a different nucleus and a reverse problem

3(a) A carbon-12 nucleus has Z = 6 and nuclear mass 11.99671 u. Calculate its mass defect and total binding energy in MeV. **[2 marks]**

3(b) A model nucleus with A = 20 and Z = 10 has total binding energy 160.0 MeV. Use the supplied free-nucleon masses to calculate its nuclear mass in u. **[3 marks]**

3(c) A different instrument reports the mass of a neutral helium-4 atom as 4.00260 u. Use electron mass 0.0005486 u and neglect electronic binding energy to infer the nuclear mass. Explain why the atomic mass must not be inserted unchanged into the nuclear-mass formula. **[2 marks]**

3(d) The laboratory software rounds every mass to the nearest 0.1 u before calculating the helium mass defect. Explain why keeping only those rounded masses can destroy the result. **[1 mark]**

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4 Use complete reaction mass balances

Table 1 Rounded nuclear masses

Nucleus	Carbon-12	Helium-4	Oxygen-16
Nuclear mass / u	11.99671	4.00151	15.99053

4(a) The team models carbon-12 plus helium-4 forming oxygen-16 and one gamma photon. Write the nuclear equation and check the proton and nucleon totals. **[2 marks]**

4(b) Use the nuclear masses in Table 1 to calculate the rest-energy release Q for the reaction in 4(a). State whether Q is released or required. **[2 marks]**

4(c) In an ideal limiting case with negligible initial kinetic energy and negligible recoil energy, calculate the gamma-photon energy for this reaction in joules. **[1 mark]**

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4(d) In another run, the colliding nuclei have total initial kinetic energy 0.400 MeV and the oxygen nucleus leaves with kinetic energy 0.060 MeV. Calculate the gamma-photon energy. **[2 marks]**

5 Recognise an energy input and a measurement limit

5(a) For another nuclear reaction, the sum of final rest masses exceeds the sum of initial rest masses by 1.00×10^{-29} kg. Calculate Q in MeV, taking $Q = (M_{initial} - M_{final})c^2$. **[2 marks]**

5(b) For the reaction in 5(a), the particles initially have total kinetic energy 6.00 MeV. In a simple total-energy budget, calculate the total kinetic energy remaining in the products. Do not infer a laboratory threshold from this energy-only model. **[1 mark]**

5(c) A proposed reaction releases 2.80 MeV per event. Calculate the decrease in the system's total rest mass per event in kg. **[2 marks]**

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5(d) Two measured total masses each have absolute uncertainty ±0.000005 u. Their difference is 0.000100 u. Use the sum of the absolute uncertainties to estimate the percentage uncertainty in the difference. **[2 marks]**

6 Approve or reject the report's conclusions

6(a) The report states "helium's positive binding energy means the nucleus contains 28.3 MeV more rest energy than its separated nucleons". Correct this statement using the masses and the energy-level model. **[2 marks]**

6(b) The report compares carbon-12's total binding energy with helium-4's and calls the larger total proof that each carbon nucleon is more tightly bound. Explain what additional calculation is needed before making that comparison. **[1 mark]**

6(c) A reaction releases energy although the total number of nucleons is unchanged. Explain how that can happen without violating mass–energy conservation. **[2 marks]**

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