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Investigating radioactive decay solutions

Graphs, half-life measurements, modelling and dating

Matching answers and examiner-style commentary

OCR A H556 | A-level physics | Module 6 | 45 marks

Specification points covered

6.4.3(e)(ii): experimental determination of half-life, for example using protactinium.

6.4.3(f)(ii): simulation of radioactive decay using dice.

6.4.3(g): graphical methods and spreadsheet modelling of $\Delta N/\Delta t = -\lambda N$.

6.4.3(h): radioactive dating, including carbon-14. Supporting ideas: 6.4.3(a), (d), (e)(i), (f)(i).

Use ln 2 = 0.693. For carbon-14, $t_{1/2}$ = 5730 years. In this sheet R means background-corrected count rate. The prepared short-lived sample gives a signal dominated by one decaying component.

1 Separate signal from background

A conservation laboratory checks a short-lived-source counter before dating carbon from a harbour timber. All numerical readings are illustrative data.

Figure 1 is a planning diagram, not instructions for preparing a radioactive source. In a protactinium half-life investigation, preparation and handling follow the authorised laboratory procedure.

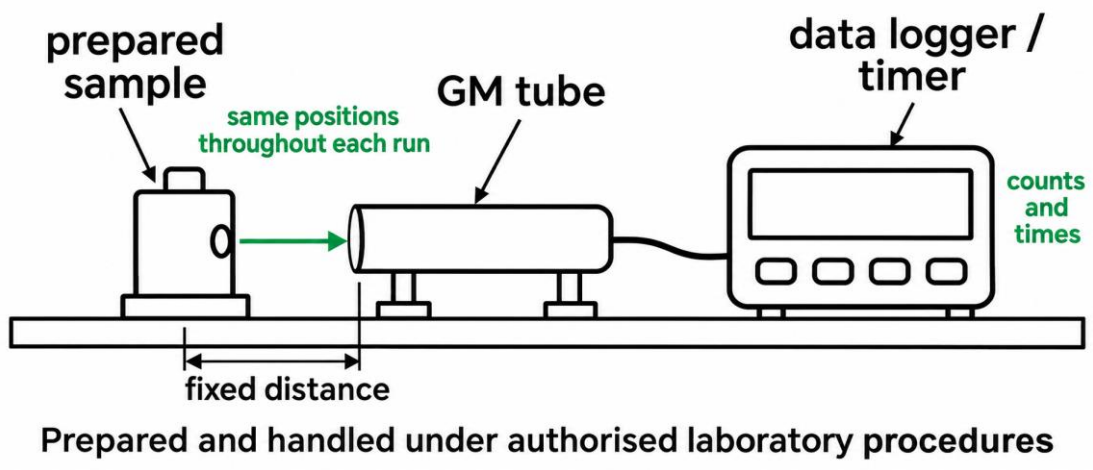


Figure 1 Record counts and times while preserving geometry.

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1(a) A sample is prepared by an authorised technician. Before measuring it, the counter records 6000 background counts in 300 s. Calculate the background rate. **[1 mark]**

$R_b = 6000 / 300 = 20.0\ s^{-1}$. A long background interval reduces the effect of random fluctuations in its estimated mean rate.

Marking guidance 1: 20.0 s^{-1}.

1(b) Explain why the prepared sample and the GM tube should remain in fixed positions throughout a decay run. **[1 mark]**

The fraction of emissions detected depends on geometry. Keeping the positions fixed lets a change in net rate be attributed to radioactive decay, rather than to a changing detected fraction.

Marking guidance 1: fixed geometry linked to a constant detected fraction.

1(c) An assistant wants to take only one reading at the start and one near the background level. Give one reason for collecting several intermediate readings instead. **[1 mark]**

Several readings show the trend and reveal anomalous/fluctuating values. They allow repeated half-life intervals or a best-fit graph; a late reading near background has a large fractional uncertainty after subtraction.

Marking guidance 1: a relevant data-quality or processing reason.

2 Extract a half-life from the data

Table 1 Rounded mean rates for a short-lived component

Time / s	0	35	70	105	140	175	210
Gross rate / s^{-1}	340	246	180	133	100	77	60

2(a) Copy Table 1 into the working space and add a row of net count rates R by subtracting the background rate of 20 s^{-1}. **[1 mark]**

Subtract the same background rate from each gross rate.

At times 0, 35, 70, 105, 140, 175 and 210 s, the net rates are respectively 320, 226, 160, 113, 80, 57 and 40 s^{-1}.

Marking guidance 1: all net rates, allowing one isolated arithmetic slip.

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2(b) Use two different intervals in Table 1 to estimate the half-life. State the pairs of net rates used. **[2 marks]**

320 → 160 s^{-1} occurs between t = 0 and 70 s, giving $t_{1/2}$ = 70 s.

160 → 80 s^{-1} occurs between t = 70 and 140 s, also giving $t_{1/2}$ = 70 s. The interval 80 → 40 s^{-1} from 140 to 210 s is another valid check.

Marking guidance 1 per correct halving interval and its 70 s duration, maximum 2.

2(c) Someone halves the initial gross rate, 340 s^{-1}, and looks for 170 s^{-1}. Explain why this gives the wrong half-life and state the gross rate that actually corresponds to half the initial source signal. **[2 marks]**

The constant background does not halve with the source. The initial source-only rate is 340 − 20 = 320 s^{-1}, whose half is 160 s^{-1}.

The corresponding gross rate is 160 + 20 = 180 s^{-1}. Looking for 170 s^{-1} waits until the source has fallen below half its initial signal and overestimates the half-life.

Marking guidance 1: background does not decay/halve. 1: correct gross target 180 s^{-1}, with processing.

2(d) The mean gross rate eventually approaches 20 s^{-1}. Explain why that does not mean that the activity approaches 20 Bq. **[1 mark]**

20 s^{-1} is the background detected rate. The source contribution tends towards zero; a detected rate is not an activity unless the detection fraction is known.

Marking guidance 1: distinguishes the background-rate baseline from source activity.

3 Linearise the decay

3(a) For t = 0, 70, 140 and 210 s, calculate y = ln[R/(1 s^{-1})] to three decimal places. Explain why the quantity inside the logarithm is dimensionless. **[2 marks]**

The four net rates are 320, 160, 80 and 40 s^{-1}.

The corresponding y values are 5.768, 5.075, 4.382 and 3.689.

R/(1 s^{-1}) is a rate divided by a rate, so its units cancel before the logarithm is taken.

Marking guidance 1: four logarithms, allowing one isolated slip. 1: unit cancellation in the ratio.

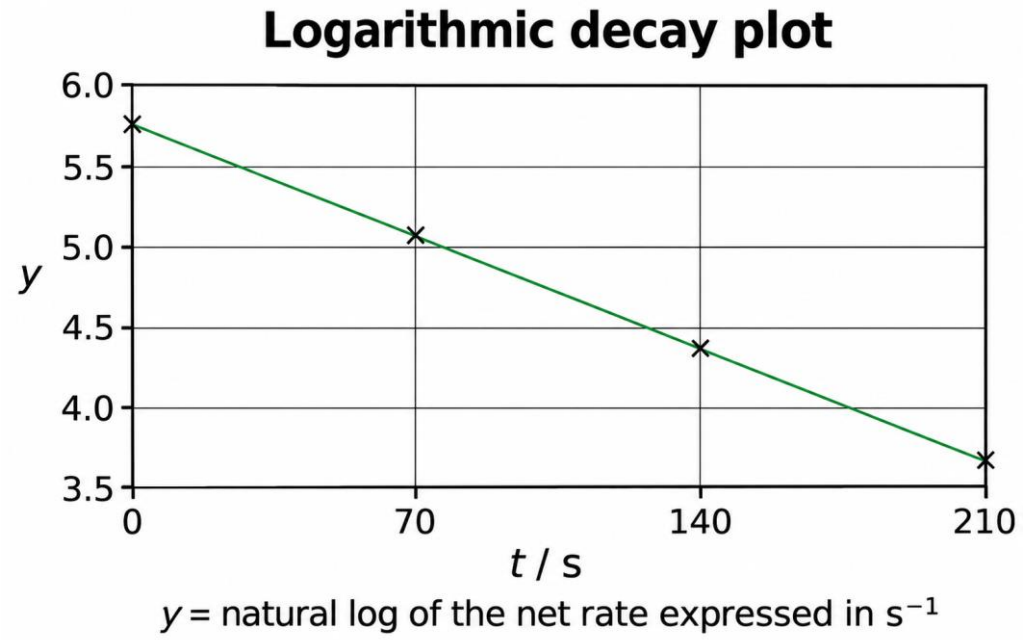
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3(b) Draw a graph of y against t using the four points from 3(a). Choose labelled linear scales that use the space well, then draw a straight best-fit line. The vertical scale need not start at zero. **[3 marks]**

Place t / s on the horizontal axis and the dimensionless y on the vertical axis. One suitable scale is t = 0–210 s and y = 3.5–6.0; a truncated vertical axis must be clear.

Plot (0, 5.768), (70, 5.075), (140, 4.382) and (210, 3.689). A straight descending best-fit line passes through these points to their rounding precision.

This is a straight line in logarithmic rate, not a straight-line decrease in R itself. Its constant gradient corresponds to a constant decay constant.



Model logarithmic plot. Other clear linear scales are acceptable.

Marking guidance 1: labelled linear axes with usable scales. 1: points accurately plotted. 1: appropriate descending straight best-fit line.

3(c) Use a large triangle on your line to determine λ and hence the half-life. Show the sign of the gradient and its units. **[3 marks]**

Step 1 The model is $\ln[R/(1\ s^{-1})] = \ln[R_0/(1\ s^{-1})] - \lambda t$, so the gradient is $-\lambda$.

Step 2 Using the endpoints, gradient = $(3.689 - 5.768)/(210 - 0) = -9.900 \times 10^{-3}\ s^{-1}$.

Step 3 $\lambda = +9.900 \times 10^{-3}\ s^{-1}$. Then $t_{1/2} = 0.693/0.009900 = 70.0$ s. Accept a suitable large-triangle estimate consistent with the plotted line.

Marking guidance 1: large-triangle negative gradient about $-0.00990\ s^{-1}$. 1: λ is the positive magnitude. 1: half-life about 70 s.

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3(d) A second run detects exactly half the fraction of source emissions, but that fraction is constant throughout the run. Predict how the logarithmic graph's gradient and intercept change. **[2 marks]**

Multiplying every net rate by 1/2 adds ln(1/2) = −0.693 to every y value. The intercept decreases by 0.693.

The gradient is unchanged because the vertical shift is constant; the inferred decay constant and half-life remain unchanged.

Marking guidance 1: intercept lower by ln 2 (or correct constant downward shift). 1: unchanged gradient with constant-fraction reason.

4 Test two models before trusting them

4(a) A dice model starts with 600 dice. On each throw, remove every die showing a six and throw only those remaining. Calculate the expected numbers remaining after one throw and after four throws. **[2 marks]**

Each die survives a throw with probability 5/6.

After one throw: 600(5/6) = 500 dice expected. After four: $600(5/6)^4$ = 289.35, approximately 289 dice expected.

An expectation can be non-integer even though an actual count is an integer. Actual runs fluctuate.

Marking guidance 1: 500. 1: about 289 from four successive surviving fractions.

4(b) Find the model half-life in throws using $600(5/6)^n = 300$. Explain one limitation of the dice model. **[3 marks]**

Step 1 Divide by 600 and take logarithms: n ln(5/6) = ln(1/2).

Step 2 n = ln(1/2)/ln(5/6) = 3.80 throws.

The model samples discrete throws; it does not give the continuous decay times of real nuclei. Also accept the small initial number/statistical fluctuations as a limitation when explained. The effective exponential constant per throw is −ln(5/6), not exactly 1/6.

Marking guidance 1: logarithmic rearrangement. 1: 3.80 throws. 1: relevant explained limitation.

4(c) A spreadsheet instead uses $N_{next} = N_{now} - \lambda N_{now}\Delta t$ with $\lambda = 0.0100\ s^{-1}$, $N_0 = 600$ and $\Delta t = 5.00$ s. Calculate the next two values of N. **[2 marks]**

The fraction removed each step is $\lambda\Delta t = 0.0100 \times 5.00 = 0.0500$.

First step: $N_1 = 600 - 0.0500(600) = 570$.

Second step: $N_2 = 570 - 0.0500(570) = 541.5$. The second loss uses 570, not the original 600.

Marking guidance 1: 570. 1: 541.5 using the updated population.

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4(d) For the same spreadsheet λ, a student chooses Δt = 150 s and obtains a negative population. Explain the failure and one way to improve the calculation. **[2 marks]**

λΔt = 1.50, so the approximation subtracts 150% of the current population in one step. This is not a physically possible decay and shows the time step is too large for this numerical approximation.

Use a much smaller step with $\lambda\Delta t \ll 1$ and check convergence as the step is reduced. Alternatively, use the exact step $N_{next} = N_{now}\, e^{-\lambda\Delta t}$.

Marking guidance 1: overlarge step removes more nuclei than exist. 1: justified smaller-step or exact-exponential improvement.

4(e) The spreadsheet models $\Delta N/\Delta t = -\lambda N$. On an N-against-t graph, find the initial tangent gradient for N = 600 and λ = 0.0100 s^{-1}. Explain how its magnitude changes as N decreases. **[2 marks]**

Initially the tangent gradient is $-\lambda N = -0.0100 \times 600 = -6.00$ nuclei s^{-1}.

As N decreases, the gradient remains negative but its magnitude decreases. The graph becomes less steep; it does not continue losing six nuclei every second.

Marking guidance 1: −6.00 nuclei s^{-1}. 1: smaller gradient magnitude as N decreases.

5 Date the harbour timber

5(a) Equal masses of carbon from living reference material and the timber give net rates 50.0 and 20.0 s^{-1} in the same geometry and detector. Calculate the surviving carbon-14 fraction in the timber and state why equal carbon masses matter. **[2 marks]**

The surviving fraction is 20.0/50.0 = 0.400.

Equal total carbon masses make the rate ratio a comparison of carbon-14 abundance, rather than a consequence of one sample simply containing more carbon. The same detection arrangement also makes the detection fraction cancel.

Marking guidance 1: fraction 0.400. 1: equal mass permits an abundance comparison.

5(b) Calculate the timber's age using the carbon-14 half-life of 5730 years. **[3 marks]**

Step 1 Find the decay constant in years: $\lambda = 0.693/5730 = 1.20942 \times 10^{-4}$ $year^{-1}$.

Step 2 Use $N/N_0 = 0.400 = e^{-\lambda t}$, so $t = -\ln(0.400)/\lambda$.

Step 3 t = 7576 years, approximately 7.58×10^3 years. The elapsed time is since carbon exchange with the environment ceased under the dating model.

Marking guidance 1: consistent λ in $year^{-1}$. 1: logarithmic age relationship. 1: about 7.58×10^3 years.

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5(c) State two assumptions needed for this simple dating estimate, beyond the measured half-life being correct. **[2 marks]**

The timber initially had the same carbon-14 abundance per unit carbon as the living reference used in the model.

After the organism died, the dated carbon did not exchange with the surroundings or become contaminated with younger/older carbon. Also accept equal/comparably corrected detector response or correct background subtraction when stated independently.

Marking guidance 1 per distinct relevant assumption, maximum 2.

5(d) Modern conservation adhesive adds carbon with a larger carbon-14 fraction than the timber. Predict the effect on an uncorrected age estimate and explain using the measured ratio. **[2 marks]**

The added modern carbon increases the carbon-14 count rate per unit total carbon and hence raises the measured surviving fraction relative to uncontaminated timber.

A larger fraction remaining gives a smaller positive value of $-\ln(N/N_0)/\lambda$, so the timber appears younger. More detected activity does not mean that the old nuclei have reversed their decay.

Marking guidance 1: ratio/fraction is increased. 1: younger inferred age, linked to the decay relationship.

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6 Bring the practical together

6(a) Write a method to determine the half-life of a short-lived component such as protactinium using Figure 1. The sample is prepared and handled under an authorised laboratory procedure. Explain the measurements, processing and checks needed for a defensible value. Include how you would use either repeated halvings or a logarithmic graph. **[6 marks]**

Use a suitable GM tube and counter/data logger. Measure background over a long recorded interval with the prepared source absent. Arrange the prepared sample and detector at fixed marked positions so the detection fraction stays constant.

Begin recording promptly after preparation, using short, equal counting intervals compared with the expected half-life. Record elapsed times and counts over several half-lives, while retaining a measurable signal above background. A logger avoids missed readings; use interval midpoints if treating each interval as a rate measurement.

Convert each count to a rate and subtract the background rate. Plot net rate against time and find the time for several successive halvings, then compare/average suitable estimates. Alternatively, plot $\ln[R/(1\ s^{-1})]$ against time, fit a straight line, find its gradient $-\lambda$ with a large triangle, and use $t_{1/2} = \ln 2/\lambda$.

Repeat runs where the preparation permits, compare scatter and estimates, and consider uncertainty in background, counts and timing. Late corrected readings close to zero are unreliable for logarithms. A changing geometry or an unaccounted second decaying component would undermine the single-exponential interpretation. Use the authorised handling arrangements throughout.

Assessing 6(a) Best-fit marking guidance

Level 3 (5–6): a coherent feasible timed-counting method with background measurement and controlled geometry AND correct net-rate processing and half-life determination with meaningful reliability/uncertainty checks The argument is clear, linked and scientifically sound.

Level 2 (3–4): a sound account of one strand with limited treatment of the other, or some relevant detail in both; links or evaluation are incomplete.

Level 1 (1–2): limited creditworthy method or analysis, presented as fragments with little connection. 0: no creditworthy response.

Use best fit, then the quality within the level. The exemplar is indicative, not a six-keyword checklist; accept other workable, justified approaches.

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