Radioactivity solutions

Radiation detection and absorption

Matching answers and examiner-style commentary

OCR A H556 | A-level physics | Module 6 | 38 marks

Specification points covered

6.4.3(a): spontaneous and random nuclear decay.

6.4.3(b)(i–ii): nature, penetration and ionising ability of alpha, beta and gamma radiation; identifying radiation experimentally.

6.4.3(c): balanced alpha, beta-minus and beta-plus nuclear decay equations. Gamma energy changes are covered under 6.4.3(b)(i).

Use count rate in s^{-1}. Activity is the number of nuclear decays per second, in Bq. All tabulated readings are illustrative mean values; background is included unless stated otherwise.

1 What the detector can tell us

A factory makes thin sterile-filter films. Its laboratory identifies calibration sources before choosing a non-contact thickness gauge.

The filter laboratory must use measurements of many decays, rather than predict the fate of an individual nucleus.

Use the apparatus in Figure 1 for the following tests.

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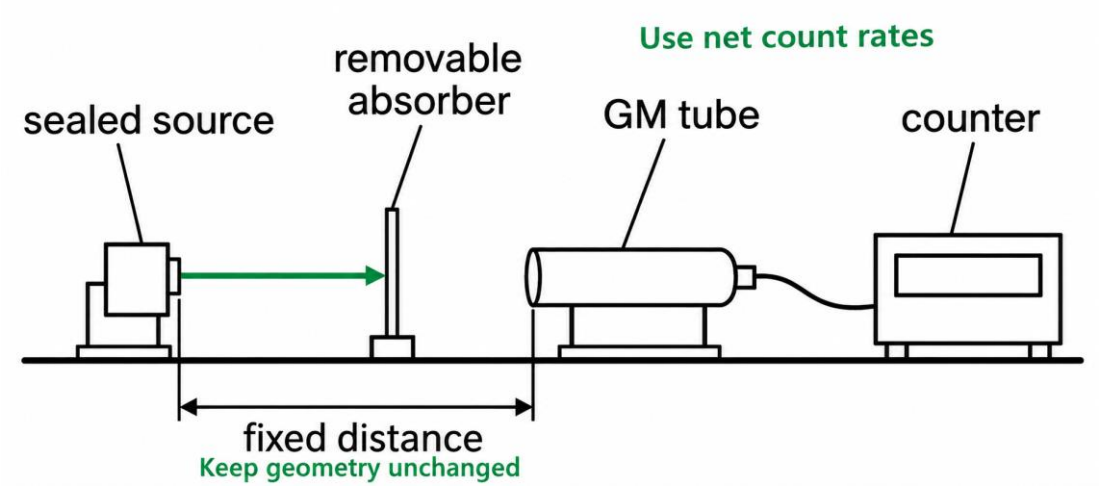


Figure 1 Keep the source and detector positions fixed; remove the source for the background measurement.

1(a) A technician says a particular unstable nucleus will decay exactly 20 s after the counter starts. Explain why this prediction is not possible. **[1 mark]**

Decay is random: it is not possible to predict when one specified nucleus will decay. A probability or a large-sample mean does not specify the time for that individual nucleus.

Marking guidance 1: unpredictable decay time for an individual nucleus.

1(b) Explain what spontaneous means in this context. Would cooling the source normally switch off its nuclear decay? **[1 mark]**

Spontaneous means the decay occurs without an external trigger. Ordinary changes of temperature do not switch off this nuclear process; cooling is not a way to stop the source emitting.

Marking guidance 1: no external trigger, correctly applied to cooling.

2 Correct the readings before using them

2(a) With the source removed, the counter records 1440 counts in 240 s. Calculate the background count rate. **[1 mark]**

A rate is a count divided by its measurement time.

$R_b = 1440 / 240 = 6.00\ s^{-1}$.

Marking guidance 1: $6.00\ s^{-1}$.

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2(b) With a source in place, the counter records 13 260 counts in 60.0 s. Calculate the count rate due to the source alone. **[2 marks]**

Step 1 Put both measurements on the same time basis.

Gross rate = 13 260 / 60.0 = 221 s^{-1}.

Step 2 Remove the background contribution to that rate.

R = 221 − 6.00 = 215 s^{-1}. Subtracting 1440 directly would mix different counting times.

Marking guidance 1: gross rate 221 s^{-1}. 1: subtracts background rate to obtain 215 s^{-1}.

2(c) The source activity is independently known to be 1.50 kBq. Calculate the fraction of decays recorded as counts in this arrangement. Assume at most one count is recorded per decay. **[2 marks]**

Step 1 Convert the activity to decays per second: 1.50 kBq = 1500 Bq.

Step 2 Compare detected events with all decays: fraction = 215 / 1500 = 0.143, or 14.3%.

The counter records only some emissions because of geometry, absorption and detection efficiency. The net count rate is not the activity.

Marking guidance 1: uses net count rate divided by 1500. 1: 0.143 or 14.3%.

2(d) When testing absorbers, why must the source–detector distance and the measurement time be controlled, or the time allowed for explicitly in processing? **[2 marks]**

Changing distance changes the fraction of radiation that reaches the detector, so it could imitate absorption. Different counting times change total counts even at the same rate; use equal times or compare count rates.

Marking guidance 1: distance linked to detected fraction. 1: time linked to total count, with rate correction accepted.

3 Identify three unknown sources

For this test the background rate is 6 s^{-1}. Absorbers are tested separately in the same holder, not stacked. Small differences near the original rate are within measurement variation.

Table 1 Gross mean count rates

Source	No absorber / s^{-1}	Paper / s^{-1}	3 mm Al / s^{-1}	Thick lead / s^{-1}
A	226	224	6	6
B	526	524	516	140
C	106	6	6	6

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3(a) Use Table 1 to identify the main radiation from A and justify the identification using both the paper and aluminium readings. **[2 marks]**

A mainly emits beta radiation. Paper leaves its reading essentially unchanged, while aluminium reduces the reading to background. This is the expected penetration pattern for beta radiation in this test.

Marking guidance 1: beta. 1: both appropriate absorber observations linked to the identification.

3(b) Identify the main radiation from B and C. Explain why the lead reading for B does not mean that lead emits the detected radiation. **[2 marks]**

B mainly emits gamma radiation; it penetrates paper and aluminium but lead reduces the count rate. C mainly emits alpha radiation; paper reduces its reading to background.

For B, some gamma photons are transmitted through the lead. The observed rate includes transmitted source radiation and background; it is not evidence that the lead is the radioactive source.

Marking guidance 1: B gamma and C alpha. 1: residual B reading explained by transmission/background, rather than lead emission.

3(c) Which of alpha, beta and gamma produces the greatest ionisation per unit path length in air, and which generally has the greatest penetration? Explain why these are different properties. **[2 marks]**

Alpha radiation produces the greatest ionisation per unit path length. Gamma radiation generally has the greatest penetration.

Strong ionisation transfers energy rapidly to the surroundings, so a highly ionising alpha particle has a short range. Penetration describes how far radiation gets through material, not how many ions it creates along each part of its path.

Marking guidance 1: alpha ionisation and gamma penetration. 1: energy-transfer/range distinction.

3(d) For the film gauge, a source must transmit through the film but give a useful change of count rate when thickness changes. Choose a suitable type of radiation and explain why the other two are less suitable for this thin film. **[2 marks]**

Beta radiation is a suitable choice when its energy is chosen for the film thickness. Some is transmitted, and the detected fraction changes appreciably with thickness.

Alpha would be stopped too readily by the air/window/film. Gamma is too penetrating here to give as sensitive a thickness-dependent change. A source must be calibrated for the actual material.

Marking guidance 1: beta with useful partial transmission. 1: contrasting limitations of alpha and gamma.

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4 Use the gauge to make a production decision

Table 2 Calibration at fixed geometry

Thickness / μm	50	100	150	200
Net rate / s^{-1}	800	650	500	350

4(a) A film produces 10 120 counts in 20.0 s. The background remains 6.00 s^{-1}. Use Table 2 to estimate the thickness. **[2 marks]**

Step 1 Correct the measured rate: 10 120 / 20.0 − 6.00 = 500 s^{-1}.

Step 2 Match the net rate to the calibration table: the thickness is 150 μm. The calibration uses net rates, so the gross rate must not be matched directly.

Marking guidance 1: net rate 500 s^{-1}. 1: thickness 150 μm.

4(b) The acceptable net count-rate band is 500–700 s^{-1}, including its boundaries. A later net reading is 350 s^{-1}. State whether the film is acceptable and whether the roller gap should be increased or decreased. A smaller roller gap produces a thinner film. **[2 marks]**

350 s^{-1} is below the permitted band and corresponds to a film that is too thick (200 μm in the table). Decrease the roller gap to make thinner film; less absorption will increase the net count rate towards the acceptable band.

Marking guidance 1: rejects film as too thick. 1: decreases gap, with count-rate/absorption reason.

4(c) In a separate low-background test, 2500 counts are recorded. For this question use count uncertainty √N and ignore background uncertainty. Calculate the percentage count uncertainty. What measurement duration would approximately halve it if the original duration was 20 s and the mean rate stayed the same? **[2 marks]**

The stated model gives uncertainty √2500 = 50 counts, so percentage uncertainty = (50 / 2500) × 100 = 2.0%.

The fractional uncertainty is 1/√N. Halving it requires four times as many counts, so use approximately 4 × 20 = 80 s. Doubling the time would not halve this uncertainty.

Marking guidance 1: 2.0%. 1: 80 s, supported by four times the counts.

4(d) A one-second reading fluctuates below the band once. Explain why the controller should not immediately conclude that the film has become too thick. **[1 mark]**

Radioactive emissions and detected counts fluctuate randomly. The controller should compare longer/repeated measurements and their variation with the calibration before attributing a single low count to thickness.

Marking guidance 1: random variation linked to need for more evidence.

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5 Describe the nuclear changes

5(a) A radium-226 nucleus (Z = 88) emits an alpha particle and forms radon. Write the balanced nuclear equation, including mass and proton numbers. **[2 marks]**

An alpha particle is a helium-4 nucleus. Subtract 4 from the parent mass number and 2 from its proton number.

$^{226}_{88}\mathrm{Ra} \rightarrow {}^{222}_{86}\mathrm{Rn} + {}^{4}_{2}\mathrm{He}.$

The totals are A = 226 and Z = 88 on both sides.

Marking guidance 1: helium-4 nucleus identified as the alpha particle. 1: correct radon nuclide and balanced equation.

5(b) An excited technetium-99 nucleus (Z = 43) emits only gamma radiation. State what happens to A, Z and the energy of the nucleus. **[2 marks]**

A stays 99 and Z stays 43: gamma emission does not remove a nucleon or convert a neutron into a proton. The nucleus moves to a lower energy state as a gamma photon carries away energy.

Marking guidance 1: both A and Z unchanged. 1: lower nuclear energy with photon emission.

5(c) Carbon-14 (Z = 6) emits beta-minus radiation. Write the full nuclear equation and name both emitted leptons. **[2 marks]**

A neutron changes into a proton, so A stays 14 and Z increases from 6 to 7.

$^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\mathrm{e} + \bar{\nu}_{\mathrm{e}}.$

The emitted leptons are an electron and an electron antineutrino. The beta electron is created in the nuclear process, rather than ejected from an atomic orbit.

Marking guidance 1: correct nitrogen nuclide and beta electron with balanced A/Z. 1: electron antineutrino, correctly distinguished from a neutrino.

5(d) Fluorine-18 (Z = 9) undergoes beta-plus decay to oxygen. Write the complete nuclear equation and name both emitted leptons. **[2 marks]**

A bound proton becomes a neutron: A stays 18 and Z decreases to 8.

$^{18}_{9}\mathrm{F} \rightarrow {}^{18}_{8}\mathrm{O} + {}^{0}_{+1}\mathrm{e} + \nu_{\mathrm{e}}.$

The emitted leptons are a positron and an electron neutrino. Beta-minus decay instead emits an electron and an electron antineutrino.

Marking guidance 1: correct oxygen nuclide and positron with balanced A/Z. 1: electron neutrino and correct lepton names.

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6 Write a defensible identification method

6(a) The laboratory receives a fourth sealed source. Write a method to determine whether its detectable emission is predominantly alpha, beta or gamma. Link the measurements, controls, background correction and absorber evidence. Include one way to improve confidence in the conclusion. Source handling is performed only under the laboratory's authorised procedures. **[6 marks]**

Use an appropriate thin-window GM tube connected to a counter. Fix the source and detector securely, with a short source–window distance suitable for testing alpha radiation; keep that geometry unchanged between absorber tests.

Measure background with the source removed, over a sufficiently long recorded interval. For the source, measure counts over recorded intervals with no absorber, then separately with paper, aluminium and thick lead in the same holder. Convert counts to rates and subtract the background rate from each source reading.

A reduction to background with paper indicates alpha radiation. If paper transmits but aluminium reduces the rate to background, beta is indicated. If paper and aluminium transmit and lead reduces, rather than necessarily removes, the rate, gamma is indicated.

Repeat or extend the counting intervals to assess random variation. Compare differences with this variation, rather than decide from one short count. A mixture can give a stepped pattern; describe the evidence as predominant radiation rather than assume every source emits only one type. Follow the authorised source-handling arrangements throughout.

Assessing 6(a) Best-fit marking guidance

Level 3 (5–6): a workable sequence of controlled source/background and absorber measurements AND correct rate processing and linked absorption-based identification with a justified reliability improvement 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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