5.4 Radiation, background correction and decay

Name: _____ Class: _____ Date: _____ **Total: 30 marks**

KEY WORDS Alpha radiation • Beta radiation • Gamma radiation • nuclear equations • Background radiation • Radioactive decay • Activity • becquerels • decay constant • half-life

Objective

Develop radiation, background correction and decay from the WPH15 specification and mapped 2025 exam demands. These are original training questions. Use the constants stated in each task.

1 Key knowledge and worked examples

■ Choose radiation by its interaction

Alpha radiation consists of helium nuclei: strongly ionising, short range and stopped by paper or a few centimetres of air. **Beta radiation** consists of electrons or positrons: less ionising, more penetrating, typically stopped by a few millimetres of aluminium. **Gamma radiation** is electromagnetic radiation: weakly ionising and highly penetrating; lead or concrete reduces its intensity but does not provide a sharp stopping thickness.

In a cloud chamber, alpha tracks are thick mainly because of strong ionisation, and relatively straight because the particles have large mass compared with beta particles. Beta tracks are thinner and more easily deflected. Do not swap these explanations. Beta radiation can monitor paper thickness because some passes through and some is absorbed; a change in thickness changes the transmitted count rate.

In **nuclear equations**, conserve nucleon number and charge number. Beta-minus decay converts a neutron to a proton; the mass number stays the same and atomic number increases by one. Include the antineutrino where required, as in Unit 4:

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

Alpha decay reduces A by four and Z by two. Gamma emission changes neither A nor Z. Nuclear equations conserve more than these two numbers: energy and momentum still matter.

■ Correct background before applying a model

Background radiation comes from sources such as rocks, cosmic rays and the environment. Measure it for a sufficiently long time with the test source absent. Subtract its count rate from every source-plus-background reading. Keep counting-time units consistent. Corrected detector count rate is proportional to source activity only when geometry and detection efficiency remain unchanged; it is not automatically the activity in becquerels.

Worked example. A detector reads 62 min^{-1} at distance r, including background 14 min^{-1}. Predict total rate at $2r$ for a small isotropic gamma source with negligible absorption.

$$R_{s,1} = R_{\mathrm{total},1} - R_b = (62 - 14)\ \mathrm{min}^{-1} = 48\ \mathrm{min}^{-1}$$

$$R_{s,2} = R_{s,1}\left(\frac{r}{2r}\right)^2 = 48\ \mathrm{min}^{-1} \times \frac{1}{4} = 12\ \mathrm{min}^{-1}$$

$$R_{\mathrm{total},2} = R_{s,2} + R_b = (12 + 14)\ \mathrm{min}^{-1} = 26\ \mathrm{min}^{-1}$$

Do not divide the background by four: it is not all coming from the test source.

■ Random events, predictable populations

Radioactive decay is spontaneous: an unstable nucleus decays without an external trigger. It is random: the exact time for an individual nucleus cannot be predicted. A large population has a predictable statistical decay pattern. **Activity** A is the number of decays per second, measured in **becquerels**, 1 Bq = 1 s^{-1}.

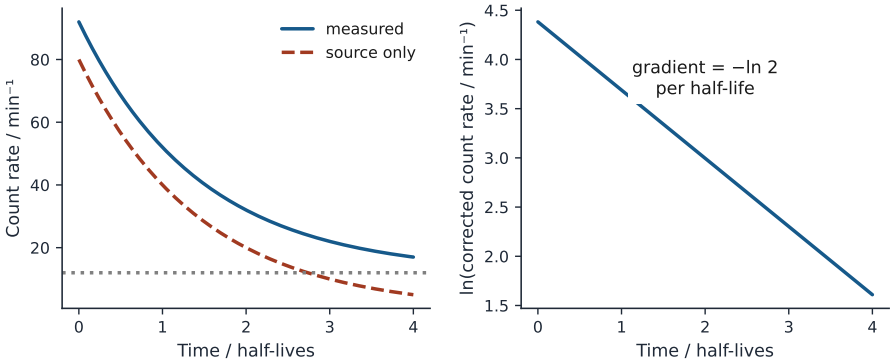
$$A = \lambda N \qquad \frac{dN}{dt} = -\lambda N \qquad N = N_0 e^{-\lambda t} \qquad A = A_0 e^{-\lambda t}$$

The **decay constant** λ is the probability per unit time of decay for a nucleus. The **half-life** $t_{1/2}$ is the time for the undecayed population, or activity, to halve on average.

At one half-life, $N/N_0 = 1/2 = e^{-\lambda t_{1/2}}$. Taking logs gives:

$$\lambda = \frac{\ln 2}{t_{1/2}} \qquad \ln N = \ln N_0 - \lambda t \qquad \ln(A/A_0) = -\lambda t$$

A log-activity–time line has gradient $-\lambda$. Take logarithms of corrected rates, not source-plus-background readings. Read several half-life intervals from a graph and average; measure from the corrected activity level, not from zero total counts.



Worked example. A source has half-life 3.0 years. When will activity fall to 2.0% of its initial value?

$$\lambda = \frac{\ln 2}{t_{1/2}} = \frac{\ln 2}{3.0 \text{ years}} = 0.231 \text{ year}^{-1}$$

$$t = -\frac{\ln(A/A_0)}{\lambda} = -\frac{\ln(0.020)}{0.231 \text{ year}^{-1}} = 16.9 \text{ years}$$

Use a fraction, not 2.0 inside the logarithm. If calculating power from a radioactive source, $P = AE_{\text{decay}}$, with energy per decay in joules. This is released nuclear power; useful electrical output may be smaller. Convert the half-life to seconds when activity must be in becquerels.

■ CP15: absorption of gamma radiation by lead

Keep source, absorber and detector in fixed positions. Measure background, then counts over equal known intervals for several total lead thicknesses. Repeat or extend the counting time because counts fluctuate. Subtract background rate before comparing transmission. If each equal thickness gives the same fractional reduction, the attenuation is exponential; a graph of log corrected rate against thickness is approximately straight. Three half-value thicknesses transmit 1/8, not 1/3.

The material-absorption constant is not the time-decay constant of the source. Avoid readings too close to background, where subtraction gives large relative uncertainty. Handle sources with the specified tools under supervision, keep distance, minimise exposure time and return them to shielding. Never touch a source or direct it at people. Keep lead handling clean and wash hands.

2 Practice

2.1 A source gives 74 counts min^{-1} at distance r, including background 10 counts min^{-1}. Predict the measured rate at $2r$, assuming inverse-square spreading. Explain why the whole measured rate cannot simply be divided by four. [4]

r and $2r$; background 10/min

2.2 A source has initial activity 800 Bq and half-life 6.0 h. Find activity after 18 h. Explain what randomness means for an individual nucleus. [3]

$A_0 = 800$ Bq | $t_{1/2} = 6.0$ h | $t = 18$ h

2.3 Complete beta-minus decay of carbon 14, including the missing neutral particle. Explain why a thin aluminium thickness monitor needs a suitable penetrating radiation rather than alpha radiation. [4]

thin aluminium sheet

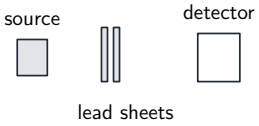
3 Exam-style questions

3.1 A radioactive source has half-life 4.0 years. Derive the relation between half-life and decay constant, then find time until activity is 0.50% of its initial value. [5]

$t_{1/2} = 4.0$ years $A/A_0 = 0.005$

3.2 An alpha source releases 5.0 MeV per decay. Its half-life is 30 years, sample mass 0.020 kg and nucleus mass 4.0×10^{-25} kg. Calculate initial nuclear power and power after 60 years. Use 1 year $= 3.15 \times 10^{7}$ s and 1 MeV $= 1.60 \times 10^{-13}$ J. Explain why electrical output need not equal this result. [7]

alpha source

0.020 kg
5.0 MeV per decay

3.3 Describe a gamma-absorption experiment with lead sheets. Include background, fixed geometry, counting time, a suitable graph, the effect of random counting variation and two radiation precautions. Explain why results near background are less reliable. [7]