# 3.2 Particles and Radiation: 1-hour Pack

AQA 7408 · Calculator allowed · about 60 minutes

Total Marks

Name: _____ Date: ____ / ____ / _____

**Answer ALL questions. Show all your working.**

**1** A student determines the half-life of the radioisotope protactinium-234m, which is separated from a sealed generator bottle containing a uranium-238 salt. A Geiger-Muller (GM) tube connected to a counter is positioned just above the separated sample, and a stopclock is started at the moment the sample is isolated.

**(a)** State why the gross count rate recorded by the GM tube must be corrected by subtracting the background count rate before it is used to determine the half-life. **(1)**

**(b)** Before the experiment, the background count is measured over 300 s with no radioactive sample present, giving a total of 90 counts. Calculate the background count rate in counts per second. **(2)**

**(c)** After background correction, the count rate from the protactinium-234m sample is 32.0 counts/s at t = 20 s after the sample is isolated, falling to 4.0 counts/s at t = 160 s. Calculate the half-life of protactinium-234m from these two measurements, showing your working. **(4)**

**(d)** Each of the two count-rate readings used in part (c) has a percentage uncertainty of 4%, due to the random nature of radioactive decay. Estimate the percentage uncertainty in the ratio of the two count rates, and use it to comment on the precision of the half-life value calculated in part (c). **(2)**

**(e)** State one precaution, other than background correction, that should be taken when using the GM tube in this experiment to ensure the count-rate readings are reliable. **(1)**

**(Total for Question 1 is 10 marks)**


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**2** The fundamental forces between particles are mediated by the exchange of virtual particles (gauge bosons).

**(a)** An electron scatters elastically off a proton by exchanging a virtual particle associated with the electromagnetic force. State the name of this exchange particle and one property of it that distinguishes it from the W and Z bosons. **(2)**

**(b)** A neutron decays via the weak interaction: n -> p + e- + antineutrino$_e$. At the quark level, this occurs when a down quark inside the neutron emits a virtual W- boson and changes into an up quark; the W- boson then decays into an electron and an electron antineutrino. State the quark change that occurs at this interaction vertex, and the exchange particle emitted. **(2)**

**(c)** Explain why the range of the weak interaction is much shorter than the range of the electromagnetic force, referring to the exchange particles involved in each. **(3)**

**(Total for Question 2 is 7 marks)**

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**3** Dr Aisha Khan analyses a wooden artefact to estimate its age using carbon-14 dating. Carbon-14 has a half-life of 5730 years. Use the Physics Equations Sheet for $A = \lambda N$, $N = N0\ e^{-\lambda t}$ and $\lambda = \ln2 / t(1/2)$. Take 1 year = $3.156 \times 10^7$ s.

**(a)** Calculate the decay constant, λ, of carbon-14 in $s^{-1}$. **(3)**

**(b)** A 1.00 g sample of carbon from the artefact has an activity of 0.230 Bq from carbon-14 decay. Calculate the number of carbon-14 nuclei present in the sample, using $A = \lambda N$. **(2)**

**(c)** A freshly-cut sample of the same mass of wood has an activity of 0.250 Bq. Calculate the age of the artefact, using $A = A0\ e^{-\lambda t}$. **(3)**

**(d)** State one assumption made in using this method to estimate the age of the artefact. **(1)**

**(Total for Question 3 is 9 marks)**


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**4** Four proposed particle interactions are given below. For each, deduce whether the interaction is allowed, giving a reason based on the conservation of charge, baryon number, lepton number or strangeness (as appropriate). Where a proposed interaction is not allowed, state the conservation law that is violated.

**(a)** $\mu^- \rightarrow e^- + \text{antineutrino}_e + \text{neutrino}_\mu$ **(2)**

**(b)** $p \rightarrow e^+ + \pi^0$ (a proton decaying into a positron and a neutral pion) **(2)**

**(c)** $n \rightarrow p + e^-$ (a neutron decaying into a proton and an electron only, with no antineutrino) **(2)**

**(d)** $K^+ \rightarrow \mu^+ + \text{neutrino}_\mu$ (a positive kaon, strangeness +1, decaying into a muon and a muon-neutrino, both of strangeness 0) **(2)**

**(Total for Question 4 is 8 marks)**

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**5** Synoptic question. Caesium-137 is a radioactive isotope used in industrial and medical calibration sources. It decays by β-minus emission to an excited state of barium-137, which then de-excites to its ground state by emitting a single γ-ray photon of energy 0.662 MeV. The half-life of caesium-137 is 30.1 years. Take $h = 6.63 \times 10^{-34}$ Js, $c = 3.00 \times 10^8$ m/s and 1 MeV $= 1.60 \times 10^{-13}$ J.

**(a)** Calculate the frequency of the γ-ray photon emitted, given its energy is 0.662 MeV. **(2)**

**(b)** Calculate the wavelength of this γ-ray photon. **(2)**

**(c)** The γ photon emitted always has this one precise energy, rather than a continuous range of energies. Explain how this observation provides evidence that, like an atom, the barium-137 nucleus can only exist in discrete, quantised energy states. **(2)**

**(d)** A sealed calibration source initially contains $3.70 \times 10^8$ nuclei of caesium-137. Calculate the number of caesium-137 nuclei remaining in the source after 10.0 years. **(3)**

**(e)** State and explain one reason why an antineutrino must also be emitted alongside the β particle in this β-minus decay of caesium-137. **(2)**

**(Total for Question 5 is 11 marks)**


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# Mark scheme · 3.2 Particles and Radiation: 1-hour Pack

## Question 1

(a) the GM tube also detects background radiation (e.g. cosmic rays, other radioactive materials nearby) unrelated to the protactinium-234m sample, which would otherwise be wrongly counted as part of the sample's decay oe **B1**

**(a) Answer: Background radiation is also detected by the tube and must be removed so only counts from the sample are used**

(b) substitute into count rate = total counts / time = 90 / 300 **M1**

(b) 0.30 counts/s, cao **A1**

**(b) Answer: 0.30 counts/s**

(c) calculate the ratio of count rates: 32.0 / 4.0 = 8 **M1**

(c) recognise that a factor of 8 is $2^3$, so 3 half-lives have elapsed between the two measurements **M1**

(c) half-life = (160 - 20) / 3 **M1**

(c) 46.7 s, cao (3 s.f.) **A1**

**(c) Answer: 46.7 s**

(d) combine percentage uncertainties for a ratio by addition: 4% + 4% = 8% **M1**

(d) an 8% uncertainty is fairly large (a few seconds out of 46.7 s), so the half-life should be quoted with a substantial uncertainty (e.g. approximately 47 ± 4 s), and more repeat readings would improve the precision oe **A1**

**(d) Answer: Approximately 8% uncertainty in the ratio, so the half-life is only known to within a few seconds**

(e) e.g. keep the GM tube at a fixed distance from the sample throughout; avoid very high count rates that cause dead-time losses; use the same GM tube and settings for every reading oe (any one sensible precaution) **B1**

**(e) Answer: Keep the GM tube at a fixed distance from the sample for every reading (or other valid precaution)**

## Question 2

(a) the (virtual) photon **B1**

(a) the photon is massless and uncharged, whereas the W and Z bosons have (large) mass, and the W boson is charged **B1**

**(a) Answer: The photon; unlike the W and Z bosons, the photon is massless (and uncharged).**

(b) a down quark changes into an up quark **B1**

(b) a (virtual) W- boson is emitted **B1**

**(b) Answer: A down quark changes into an up quark, emitting a virtual W- boson.**

(c) the range of a force is inversely related to the mass of its exchange particle, because a more massive virtual particle can only exist for a shorter time/travel a shorter distance before violating energy conservation **B1**

(c) the W and Z bosons that mediate the weak interaction have a very large mass, giving the weak interaction a very short range (of order $10^{-18}$ m) **B1**

(c) the photon that mediates the electromagnetic force is massless, giving the electromagnetic force (in principle) an infinite range **B1**

**(c) Answer: The range of a force decreases as the mass of its exchange particle increases. The massive W/Z bosons give the weak force a very short range, while the massless photon gives the electromagnetic force an effectively infinite range.**

## Question 3

(a) converts the half-life to seconds: t(1/2) = 5730 x 3.156 x $10^7$ = 1.808 x $10^{11}$ s **M1**

(a) correct substitution: $\lambda = \ln 2 / 1.808 \times 10^{11}$ **M1**

(a) 3.83 x $10^{-12}$ $s^{-1}$ (awrt, cao) **A1**

**(a) Answer: $\lambda = 3.83 \times 10^{-12}$ $s^{-1}$**

(b) rearranges: N = A / λ = 0.230 / (their value of λ from a) **M1**

(b) 6.00 x $10^{10}$ nuclei (awrt, ft from a) **A1**

**(b) Answer: N = 6.00 x $10^{10}$ nuclei**

(c) rearranges to make t the subject: t = ln(A0/A) / λ **M1**

(c) correct substitution: t = ln(0.250/0.230) / (their value of λ from a) **M1**

(c) awrt 690 years (ft from a; accept 2.18 x $10^{10}$ s) **A1**

**(c) Answer: t = 690 years (2 s.f.)**

(d) the proportion (activity) of carbon-14 in the atmosphere, and hence in living wood, has remained constant over time; or the sample has not been contaminated since the tree died oe **B1**

**(d) Answer: The atmospheric (and hence living-wood) proportion of carbon-14 has remained constant over time, and the sample has not been contaminated.**

## Question 4

(a) allowed **B1**

(a) charge, muon lepton number and electron lepton number are all conserved (e.g. electron lepton number: 0 on the left = +1 - 1 = 0 on the right) oe **B1**

**(a) Answer: Allowed: charge and both lepton numbers (muon and electron) are conserved.**

(b) not allowed **B1**

(b) baryon number is not conserved: the proton has baryon number +1, but the positron and pion both have baryon number 0, so total baryon number changes from +1 to 0 **B1**

**(b) Answer: Not allowed: baryon number is violated (+1 on the left, 0 on the right).**

(c) not allowed **B1**

(c) lepton number is not conserved: the left-hand side has lepton number 0, but the electron alone gives a total of +1 on the right; an antineutrino$_e$ (lepton number -1) is needed to restore the balance to zero **B1**

**(c) Answer: Not allowed: lepton number is violated; the correct decay requires an antineutrino$_e$ as well.**

(d) allowed **B1**

(d) even though strangeness changes (from +1 to 0), this is a weak interaction, and strangeness only has to be conserved in strong and electromagnetic interactions, not in weak interactions oe **B1**

**(d) Answer: Allowed: strangeness need not be conserved in a weak interaction, only in strong and electromagnetic interactions.**


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## Question 5

(a) convert 0.662 MeV to J: 0.662 x 1.60 x $10^{-13}$ = 1.06 x $10^{-13}$ J **M1**

(a) f = E/h = 1.60 x $10^{20}$ Hz, cao **A1**

**(a) Answer: 1.60 x $10^{20}$ Hz**

(b) substitute into λ = c / f, ft from (a) **M1**

(b) 1.88 x $10^{-12}$ m, cao/ft **A1**

**(b) Answer: 1.88 x $10^{-12}$ m**

(c) a photon of one single, sharply-defined energy can only be produced if the nucleus drops between two specific, fixed energy levels (the excited state and the ground state), with the photon energy equal to the difference between these two discrete levels **B1**

(c) this is directly analogous to the discrete spectral lines produced when electrons in atoms fall between fixed, quantised atomic energy levels, showing that nuclei, like atoms, have quantised internal energy states rather than a continuous range of allowed energies oe **B1**

**(c) Answer: A single fixed photon energy shows the nucleus drops between two fixed energy levels, analogous to atomic energy levels producing line spectra**

(d) calculate λ = ln2 / 30.1 = 0.0230 per year **M1**

(d) substitute into N = N0 $e^{-\lambda t}$ with t = 10.0 years, ft **M1**

(d) 2.94 x $10^{8}$ nuclei, cao (3 s.f.) **A1**

**(d) Answer: 2.94 x $10^{8}$ nuclei**

(e) β particles from this decay are observed experimentally to have a continuous range of kinetic energies up to a fixed maximum, rather than a single fixed value, which could not be explained by energy and momentum conservation with only the β particle and the barium nucleus produced **B1**

(e) the antineutrino must be emitted to carry away the remaining energy and momentum in each individual decay (the split between β particle and antineutrino varying from decay to decay), so that energy, momentum and lepton number are all conserved overall oe **B1**

**(e) Answer: The antineutrino carries away the variable remaining energy and momentum, which explains the continuous β energy spectrum and conserves lepton number**


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