Nuclear Radiation and Radioactive Decay

Q1.

In 2011, a tsunami was caused by a massive earthquake centred some distance off the coast of Japan. The tsunami caused a cooling system failure at the Fukushima Nuclear Power Plant. This resulted in a nuclear meltdown and radioactive materials were released into the surroundings.

A reservoir beside one of the reactor buildings contained a large volume of water. In 2013, this water was found to have an extremely high concentration of caesium-137.

Caesium-137 is a radioactive isotope of caesium.

The most common radionuclide amongst the fission products in the fuel was iodine-131, which decays with a half-life of 8.0 days to form a stable isotope of the gas xenon.

Deduce whether enough xenon would have collected in 32 days to exert a pressure of 1.0×10^5 Pa in a volume of 450 m^3. Assume that no gas escapes.

temperature = 20 °C

initial number of iodine nuclei = 1.25×10^{28}

(6)

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(Total for question = 6 marks)

Q2.

Astronauts on the 1971 Apollo 14 mission to the Moon brought back many rock samples. It is now believed that one of these contains a piece of rock that originated on Earth about 4 billion years (4×10^9 years) ago.

The piece of rock is believed to have been launched into space when an asteroid struck the Earth.

The rock sample contains uranium. The radioactive decay of uranium allows it to be used to determine the time since the rock was formed on the Earth.

(i) The uranium isotope $^{238}_{92}\text{U}$ becomes the lead isotope $^{206}_{82}\text{Pb}$ through a series of radioactive decays.

Calculate the number of α particles and the number of β particles emitted for one nucleus of $^{238}_{92}\text{U}$ to decay to become a nucleus of $^{206}_{82}\text{Pb}$.

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Number of α particles = ...

Number of β particles = ...

(ii) The half-life of $^{238}_{92}\text{U}$ is 4.47×10^9 years.

The half-lives of the other stages in the decay to $^{206}_{82}\text{Pb}$ are relatively so short that they can be ignored.
There was no lead in the rock when it formed, so all the $^{206}_{82}\text{Pb}$ in the sample is a product of $^{238}_{92}\text{U}$ decay. In the sample, for every 103 uranium nuclei present at the start, 50 are now lead nuclei.
Show that the age of the sample is about 4×10^9 years.

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(Total for question = 5 marks)

Q3.

A student used a Geiger-Müller (GM) tube to determine a value for the background count. He recorded the count for 2 minutes, every 15 minutes, as shown in the table.

Time / min	Count for 2 min
0	34
15	39
30	28

The counts are not the same.

Which of the following is the reason for this?

☒ **A** The background count rate is random.

☒ **B** The counter is incorrectly calibrated.

☒ **C** The temperature has not stayed constant.

☒ **D** There is a systematic error in the measurement.

(Total for question = 1 mark)

Q4.

A hundred years ago, a method to determine the age of certain rocks was developed. An unstable isotope of rubidium is present in some rocks when they form. Over time the rubidium decays to a stable isotope of strontium.

Rubidium decays to strontium via β⁻ decay. Complete the nuclear equation representing the decay.

(2)

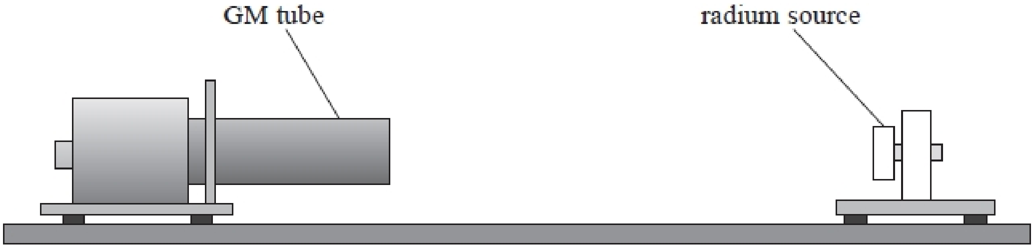
$${}^{\dots\dots}_{37}\mathrm{Rb} \longrightarrow {}^{87}_{\dots\dots}\mathrm{Sr} + {}^{\dots\dots}_{\dots\dots}\beta^{-} + \overline{\nu}_{e}$$

(Total for question = 2 marks)

Q5.

A student used a Geiger-Müller (GM) tube to determine the activity of a radium source. Radium emits α, β, and γ radiation.

He positioned the source 20 cm from the GM tube, as shown, and recorded the count for 1 minute. He repeated the measurement and calculated a mean count.



The student recorded the following results.

Count 1	Count 2	Mean count
183	178	181

Criticise the student's method for determining the count at this position.

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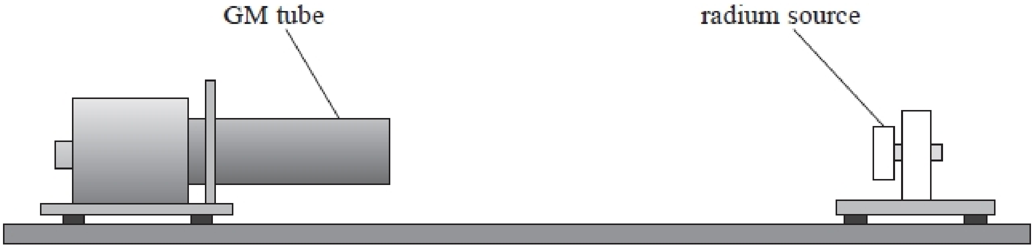
(Total for question = 3 marks)

Q6.

A student used a Geiger-Müller (GM) tube to determine the activity of a radium source. Radium emits α, β, and γ radiation.

He positioned the source 20 cm from the GM tube, as shown, and recorded the count for 1 minute. He repeated the measurement and calculated a mean count.



The student recorded the following results.

Count 1	Count 2	Mean count
183	178	181

From his results the student determined that the activity of the source was 3.0 Bq.

Comment on his value for the activity of the source.

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(Total for question = 5 marks)

Q7.

A school science department keeps a sample of potassium chloride to use as a test source for Geiger-Müller tubes.

Potassium contains 0.012% of the unstable isotope potassium-40.

The science department also has a sample of strontium-90. This undergoes beta decay with a half-life of 29 years.

State why the half-life of potassium-40 makes the potassium chloride a more suitable material than strontium-90 for the test.

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(Total for question = 1 mark)

Q8.

An old type of camping lamp used a 'gas mantle'. The gas mantle is heated by the gas flame on the lamp and emits a bright white light. Gas mantles used to contain thorium-230.

Thorium-230 decays by alpha emission to form an isotope of radium. A student keeps a radioactive gas mantle in a sealed polythene bag. The student suggests that over a period of a year a significant volume of helium gas will be collected, since an alpha particle is a helium nucleus.

Give reasons why the sealed plastic bag is suitable for collecting the gas.

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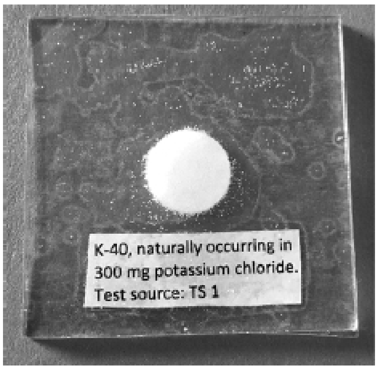
(Total for question = 2 marks)

Q9.

A school science department keeps a sample of potassium chloride to use as a test source for Geiger-Müller tubes.



Potassium contains 0.012% of the unstable isotope potassium-40.

Potassium-40 undergoes β^- decay, producing a stable isotope of calcium.

Complete the nuclear equation for this decay.

(2)

$$^{40}_{19}\text{K} \rightarrow {}^{\cdots\cdots}_{\cdots\cdots}\text{Ca} + {}^{\cdots\cdots}_{\cdots\cdots}\beta$$

(Total for question = 2 marks)

Q10.

In 2011, a tsunami was caused by a massive earthquake centred some distance off the coast of Japan. The tsunami caused a cooling system failure at the Fukushima Nuclear Power Plant. This resulted in a nuclear meltdown and radioactive materials were released into the surroundings.

A reservoir beside one of the reactor buildings contained a large volume of water. In 2013, this water was found to have an extremely high concentration of caesium-137.

Caesium-137 is a radioactive isotope of caesium.

(i) Complete the nuclear equation for the decay of caesium-137.

$$^{137}_{55}\text{Cs} \rightarrow {}^{\cdots\cdots}_{\cdots\cdots}\text{Ba} + {}^{\cdots\cdots}_{\cdots\cdots}\beta^- + {}^{0}_{0}\overline{\nu}_e$$

(2)

(ii) An activity of 2.35 × 1012 Bq per m^3 of water in the reservoir was measured. It is suggested that a safe level for the activity of all water in the reservoir would be 100 Bq.

Calculate the time in years for the caesium-137 to decay to a safe level.

volume of water in reservoir = 5000 m^3

half-life of caesium-137 = 30 years

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Time = ... years

(Total for question = 6 marks)

Q11.

The photograph shows a vase made of uranium glass. Uranium glass is radioactive.

Uranium glass usually contains a maximum of 2% uranium. Uranium glass made in the early part of the 20th century can contain up to 25% uranium.

A student carried out an investigation to determine the percentage of uranium in the glass.

The student measured the count rate by placing a Geiger Muller (GM) tube against the vase at a single position. This value was used to calculate the decay rate for the whole vase.

(i) Show that the decay constant for uranium is about 5×10^{-18} s^{-1}

half-life of uranium = 1.41×10^{17} s

(2)

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(ii) Calculate the percentage of uranium, by mass, in the glass.

area of GM tube window = 6.36×10^{-5} m^2
surface area of vase = 0.0177 m^2
background count rate = 525 counts in 10 minutes
count rate when GM tube next to vase = 3623 counts in 5 minutes
mass of vase = 149 g
mass of uranium atom = 238 u

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Percentage of uranium = ...

(iii) The uranium decays by emitting alpha particles.

Criticise the method used to determine the percentage of uranium in the vase.

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(Total for question = 10 marks)

Q12.

The photograph shows a vase made of uranium glass. Uranium glass is radioactive.

Uranium glass usually contains a maximum of 2% uranium. Uranium glass made in the early part of the 20th century can contain up to 25% uranium.

A uranium nucleus decays to thorium by emission of an alpha particle.

It can be assumed that all the energy of the decay is transferred to kinetic energy of the alpha particle.

Calculate the speed of the emitted alpha particle.

mass of uranium nucleus = 238.0003 u
mass of thorium nucleus = 233.9942 u
mass of alpha particle = 4.0015 u

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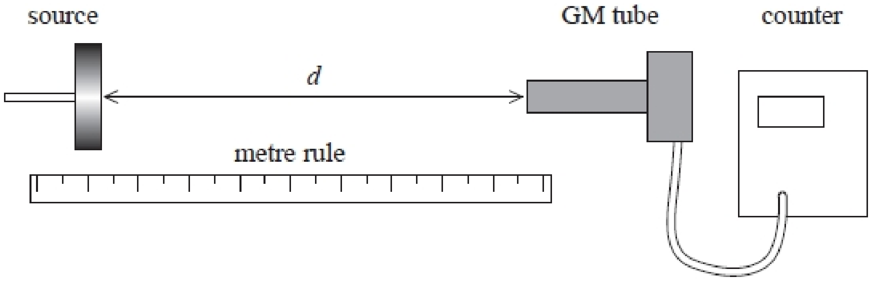
Speed of alpha particle = ...

(Total for question = 5 marks)

Q13.

A student investigated the way in which gamma radiation spreads out from a source.
He placed a cobalt-60 source in a source holder and set up a Geiger-Müller (GM) tube a short distance *d* away. He connected the GM tube to a counter as shown.



The student recorded the count for 2 minutes.

Describe how to determine the corrected count rate from the source.

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(Total for question = 2 marks)

Q14.

The photograph shows the containers of two radioactive sources kept in a school.

The isotope Ra 226 undergoes a series of decays until it produces the stable isotope Pb 206.

Determine the number of α particles and β particles emitted during this process to complete the nuclear equation.

(3)

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$$^{226}_{88}\text{Ra} \rightarrow {}^{206}_{82}\text{Pb} + \ldots\ldots \times {}^{\ldots\ldots}_{\ldots\ldots}\alpha + \ldots\ldots \times {}^{\ldots\ldots}_{\ldots\ldots}\beta$$

(Total for question = 3 marks)

Q15.

A detector is placed 30 cm from a gamma source, the count rate is 64 counts per minute.

The detector is then placed 60 cm from the source. The background rate is presumed to be a constant 24 counts per minute.

Which of the following gives the expected counts per minute?

☒ **A** 16
☒ **B** 32
☒ **C** 34
☒ **D** 44

(Total for question = 1 mark)

Q16.

A student investigated the way in which gamma radiation spreads out from a source. He placed a cobalt-60 source in a source holder and set up a Geiger-Müller (GM) tube a short distance *d* away. He connected the GM tube to a counter as shown.

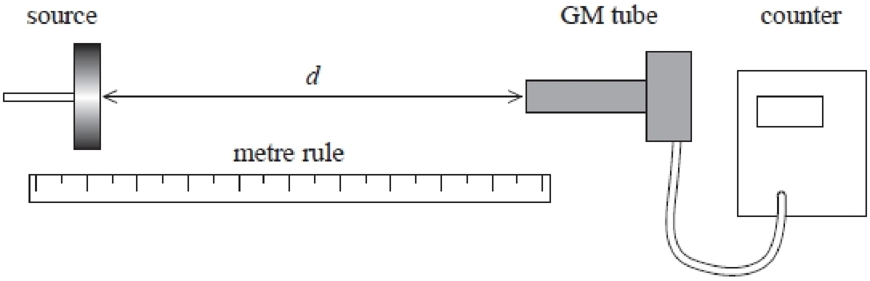

Figure 1

The student recorded the count for 2 minutes.

His teacher turned the GM tube through 90° so that the side of the tube faced the source as shown below.

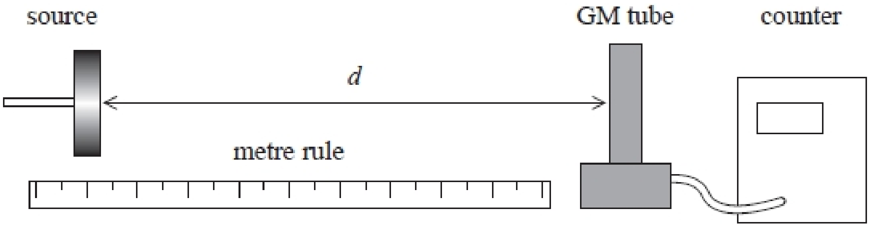

Figure 2

It is suggested that the investigation into the way in which gamma radiation spreads out from a source, using the apparatus as shown in **Figure 2**, could be carried out successfully using a radium-226 source.

Radium-226 emits α, β and γ radiation.

Justify this suggestion.

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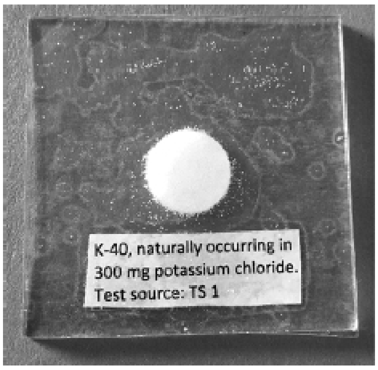
(Total for question = 2 marks)

Q17.

A school science department keeps a sample of potassium chloride to use as a test source for Geiger-Müller tubes.



Potassium contains 0.012% of the unstable isotope potassium-40.

A teacher makes some measurements using the potassium chloride test source to determine whether a Geiger-Müller tube is sufficiently efficient at detecting β radiation.

(i) The potassium chloride sample has a mass of 300 mg.

Show that the number of nuclei of potassium-40 in the sample is about 3×10^{17}.
number of potassium nuclei in 1 g of potassium chloride = 8.1×10^{21}

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(ii) Show that the activity of this sample is about 5 Bq.

half-life of potassium-40 = 1.25 × 10^9 years

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(iii) With no sample in front of the Geiger-Müller tube, a count rate of 15 counts per minute is recorded. When the potassium chloride test sample is placed next to the Geiger-Müller tube 176 counts are recorded in a period of 10 minutes.

A detector is considered efficient if it detects at least 7.5% of beta emissions from the source.
Determine whether this Geiger-Müller tube can be considered efficient.

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(iv) Explain a possible reason why only a low proportion of the decays are detected.

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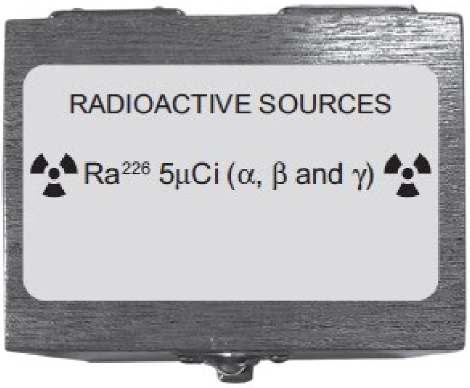
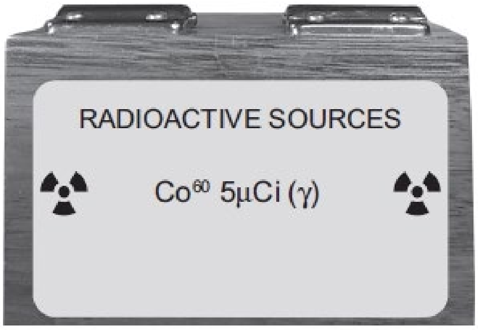
(Total for question = 10 marks)

Q18.

The photograph shows the containers of two radioactive sources kept in a school.





The sources are tested every year and a record of the activity of the sources has to be kept.

The school has incomplete records. The table shows the test entries for cobalt for 2015 and for a year X, which is the year the source was purchased.

Year	Background: counts in 60 s	Source: counts in 60 s
X	22	12227
2015	15	322

The school records show that sources were purchased in 1980, 1987 and 1995, but there is no record of which source was purchased in which year.

(i) Determine the age of the cobalt source in order to establish in which year the school purchased this source.

half-life of Co 60 = 5.3 years

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Year = ...

(ii) Explain a factor that may affect the reliability of this date.

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(Total for question = 7 marks)

Q19.

An old type of camping lamp used a 'gas mantle'. The gas mantle is heated by the gas flame on the lamp and emits a bright white light. Gas mantles used to contain thorium-230.

Thorium-230 decays by alpha emission to form an isotope of radium. A student keeps a radioactive gas mantle in a sealed polythene bag. The student suggests that over a period of a year a significant volume of helium gas will be collected, since an alpha particle is a helium nucleus.

A particular gas mantle contains 5.18×10^{-5} g of thorium-230.

(i) Show that the activity of the thorium-230 in the mantle is about 4.0×10^{4} Bq.

230 g of thorium-230 contains 6.02×10^{23} atoms
half-life of thorium-230 = 75 400 years
number of seconds in 1 year = 3.15×10^{7}

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(ii) Determine the volume of helium gas that could be collected in a year as a result of alpha emission.

Assume that the temperature is 22.0 °C and the pressure is 1.00×10^5 Pa.

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Volume = ...

(iii) Calculate the root mean square speed of the atoms in the helium gas at a temperature of 22.0 °C.

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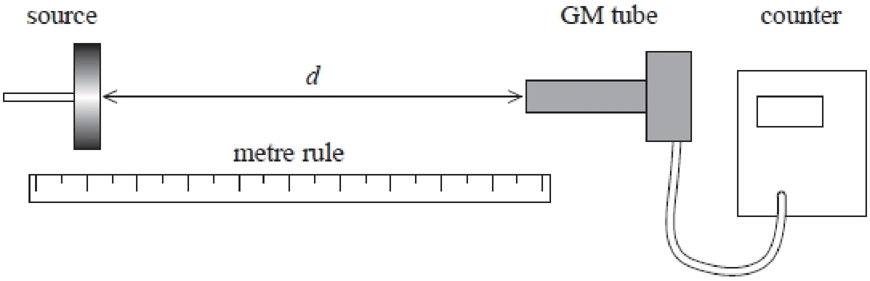
Root mean square speed = ...

(Total for question = 11 marks)

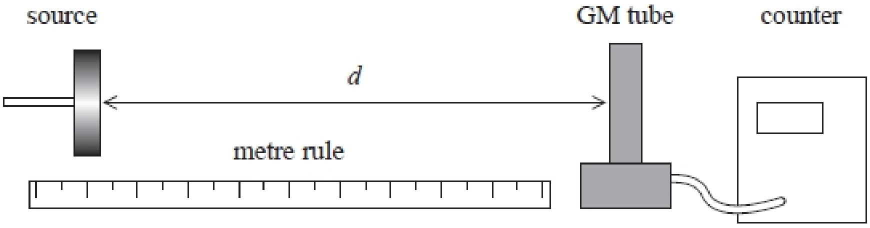
Q20.

A student investigated the way in which gamma radiation spreads out from a source.
He placed a cobalt-60 source in a source holder and set up a Geiger-Müller (GM) tube a short distance *d* away. He connected the GM tube to a counter as shown.



The student recorded the count for 2 minutes.

His teacher turned the GM tube through 90° so that the side of the tube faced the source as shown below.



(i) Explain why this arrangement could lead to more accurate data.

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(ii) Explain another modification to the experimental method which would improve the accuracy of the data.

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(Total for question = 4 marks)

Q21.

Pions (π^+, π^-, π^0) are created in the upper atmosphere when cosmic rays collide with protons. Pions are unstable and decay rapidly.

(a) Pions are the lightest of the hadrons. Charged pions (π^+ and π^-) decay to produce muons which then decay to positrons or electrons.

(i) A positive pion π^+ has a quark composition $u\bar{d}$.
State with a justification the possible quark compositions of a neutral pion π^0.

(2)

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(ii) Muons are examples of leptons whereas pions are examples of mesons.
State a structural difference between leptons and mesons.

(1)

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(b) Muons with a speed of 0.99*c* travel a distance of 15 km to reach the surface of the Earth from the upper atmosphere.

(i) Show that the time it takes a muon to travel this distance is about 51 μs.

(2)

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(ii) The muons are unstable particles.
Calculate the fraction of muons which would remain after a time of 51 μs.
half-life of muon = 2.2 μs

(4)

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Fraction = ...

(iii) In fact the fraction of muons reaching the surface of the Earth is about 0.1 Explain the discrepancy.

(4)

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(Total for question = 11 marks)

Q22.

The photograph shows the containers of two radioactive sources kept in a school.

[Same image as on Q14 & Q18]

The school is required to make a safety inspection of the sources every year.

(i) Explain how the sources can be tested to ensure that each source is in the correct container.

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(ii) Explain a safety precaution that must be applied during this procedure.

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Q23.

Radioactive decay is often described in textbooks as a spontaneous, random process.

* Explain why there is an exponential decrease in the rate of decay for a sample containing a large number of unstable nuclei.

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(Total for question = 6 marks)

Q24.

Actinium-225 and bismuth-210 are radioactive isotopes. A sample of each isotope is prepared so that each sample has the same number of nuclei initially.

Explain why the activity of each sample would be the same after 10 days.

half-life of actinium-225 = 10 days
half-life of bismuth-210 = 5 days

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(Total for question = 4 marks)

Q25.

The Sun is believed to be about 4.5 billion years old. To determine this, scientists measure the ratios of the lead isotopes found in meteorites. Since uranium undergoes radioactive decay in a chain to eventually become an isotope of lead, the ratios of lead isotopes can be used to find the age of a meteorite.

(i) $^{238}_{92}\mathrm{U}$ decays to $^{206}_{82}\mathrm{Pb}$ via the emission of α and β^- radiation.
In the transition of U-238 to Pb-206 eight alpha decays must occur.
State the number of beta decays that must occur. Justify your answer.

(2)

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Number of β^- decays = ...

(ii) One isotope produced in the chain is thorium-230, which decays to an isotope of radium with a half-life of 75,000 years.
Calculate the time in years it would take for 90% of an initial sample of thorium to have decayed.

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Time taken = ... years

(Total for question = 6 marks)

Q26.

A hundred years ago, a method to determine the age of certain rocks was developed. An unstable isotope of rubidium is present in some rocks when they form. Over time the rubidium decays to a stable isotope of strontium.

A sample of Moon rock from the Apollo 11 mission was analysed to determine the age of the rock. When the sample was analysed the number of rubidium atoms was N_R and the number of strontium atoms was N_S.

As strontium atoms have all been produced from the decay of rubidium, the original number of rubidium atoms in the sample was ($N_R + N_S$).

From the analysis of the sample, it was determined that $\frac{N_S}{N_R} = 0.0532$

Deduce whether this ratio is consistent with the Earth and the Moon forming at the same time.

age of Earth = 4.5×10^9 years
half-life of rubidium isotope = 4.88×10^{10} years

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(Total for question = 5 marks)

Q27.

Radioactive decay is often described in textbooks as a spontaneous, random process.

State what is meant by spontaneous decay.

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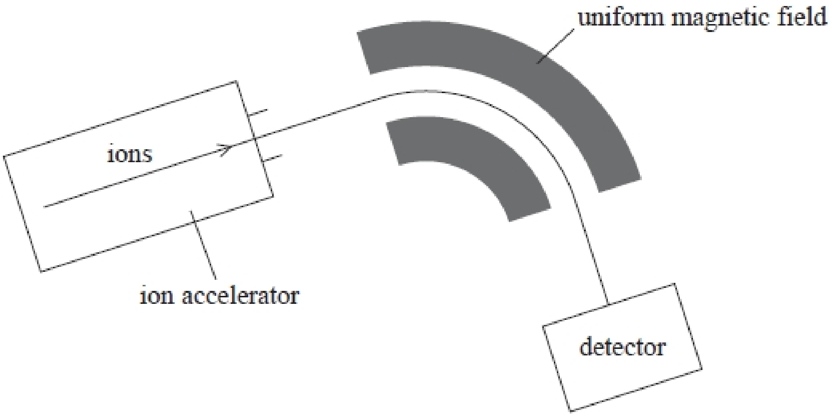
(Total for question = 1 mark)

Q28.

Mass spectrometry is a technique used to separate ions based on their charge to mass ratio.

The atoms in a sample are ionised and then accelerated and formed into a fine beam.
This beam is passed into a region of uniform magnetic field and the ions are deflected by different amounts according to their mass.



Analysis of mass spectrometer data shows that chlorine exists in nature as two isotopes, chlorine-35 and chlorine-37.

State what is meant by isotopes.

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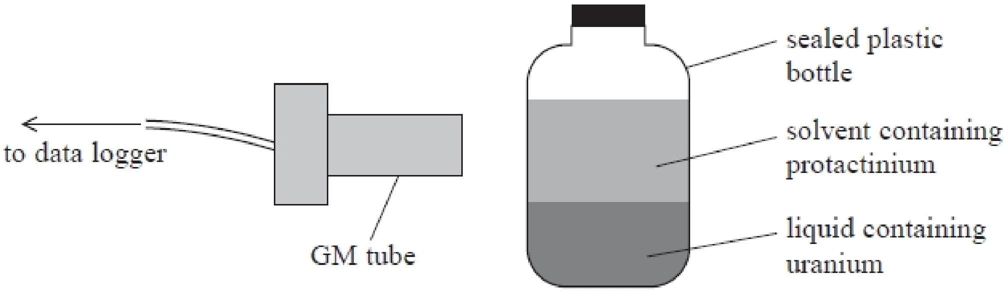
(Total for question = 1 mark)

Q29.

A teacher demonstrated the decay of protactinium using a Geiger-Müller (GM) tube connected to a data logger.

A sealed plastic bottle contains a solvent floating above a liquid containing a uranium salt. Protactinium is produced from the decay of uranium and is present in the solvent as shown.



Deduce whether alpha radiation or beta radiation from the inside of the bottle is detected by the GM tube.

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(Total for question = 2 marks)

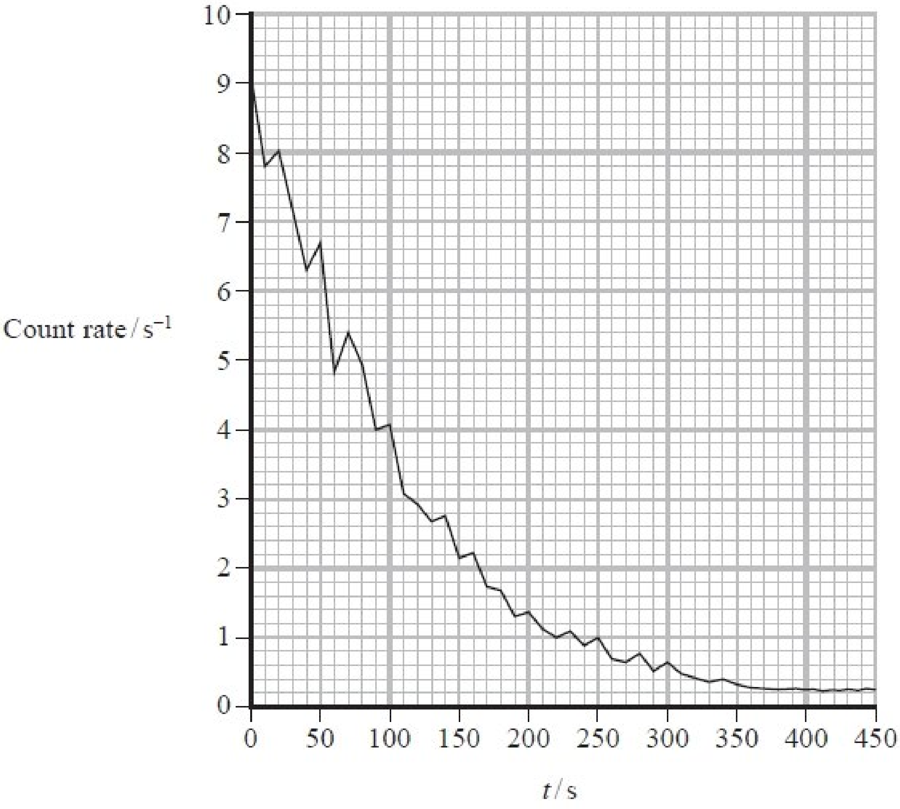
Q30.

A teacher demonstrated the decay of protactinium using a Geiger-Müller (GM) tube connected to a data logger.

A sealed plastic bottle contains a solvent floating above a liquid containing a uranium salt. Protactinium is produced from the decay of uranium and is present in the solvent as shown.

[Same image as on Q29]

The data logger output is shown below.



(i) Determine the half-life of the protactinium.

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Half-life of protactinium = ...

(ii) Explain why the count rate doesn't reach zero.

(2)

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(Total for question = 6 marks)

Q31.

A hundred years ago, a method to determine the age of certain rocks was developed. An unstable isotope of rubidium is present in some rocks when they form. Over time the rubidium decays to a stable isotope of strontium.

Recent investigations suggest that the half-life of the rubidium isotope may be larger than the traditionally accepted value.

Explain how this would affect the ages obtained by this dating method.

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(Total for question = 2 marks)

Mark Scheme - Nuclear Radiation and Radioactive Decay

Q1.

Question Number	Acceptable Answer	Additional Guidance	Mark
	- Calculation of number of half-lives elapsed **(1)** - Use of number of half-lives to calculate number of iodine nuclei remaining **(1)** - Calculation of number of iodine nuclei decayed **(1)** - Conversion of temperature to kelvin **(1)** - Use of $ppVV = NNNNTT$ **(1)** - Pressure is 1.1×10^5 Pa (compared with 1.0×10^5) and so there is sufficient gas **(1)** **Or** 1.1×10^{28} gas atoms needed to give required pressure compared with 1.2×10^{28} actual gas atoms, so there is sufficient gas	MP1 & MP2: Allow use of $\lambda = \frac{\ln 2}{t_{1/2}}$ and $A = A_0 e^{-\lambda t}$ Example of calculation $N = \frac{N_0}{2^4} = \frac{1.25 \times 10^{28}}{16} = 7.81 \times 10^{26}$ $N = 1.25 \times 10^{28} - 7.81 \times 10^{26} = 1.17 \times 10^{28}$ $p \times 450\ \text{m}^3 = 1.17 \times 10^{28} \times 1.38 \times 10^{-23}\ \text{J K}^{-1} \times (20 + 273)\text{K}$ $\therefore p = \frac{4.73 \times 10^7\ \text{J}}{450\ \text{m}^3} = 1.05 \times 10^5$ Pa	6

Q2.

Question Number	Acceptable answers	Additional guidance	Mark
(i)	- 8 alpha (1) - 6 beta (1)	Example of calculation 238–206 = 32 32 ÷ 4 = 8 alpha 92–82 = 10, 8 × 2 = 16 16 – 10 = 6 beta	2
(ii)	- Use of $\ln 2 = t_{½} \times \lambda$ (1) - Use of $N = N_0\ e^{-\lambda t}$ (1) - $t = 4.3 \times 10^9$ (year) (1)	Example of calculation $\ln 2 = 4.47 \times 10^9$ year $\times \lambda$ $\lambda = 1.55 \times 10^{-10}$ year^{-1} $53 = 103\ e^{-1.55 \times 10^{-10}\ \text{year}^{-1} \times t}$ $\ln 53 = \ln 103 - 1.55 \times 10^{-10}$ year$^{-1} \times t$ $t = 4.3 \times 10^9$ year	3

Q3.

Question Number	Answers	Mark
	The only correct answer is A ***B*** *is incorrect because an incorrect calibration would give a consistently high or low reading* ***C*** *is incorrect because temperature does not affect the background count rate* ***D*** *is incorrect because a systematic error would be a constant difference between the actual and the recorded count rate*	1

Q4.

Question Number	Acceptable answers	Additional guidance	Mark
	• Top line correct (1) • Bottom line correct (1)	Example of calculation: $^{87}_{37}\text{Rb} \rightarrow ^{87}_{38}\text{Sr} + ^{0}_{-1}\beta^- + \bar{\nu}_e$	2

Q5.

Question Number	Acceptable Answer	Additional Guidance	Mark
	• Counting for 1 minute is too short a time **Or** he should count for at least 3 minutes (1) • He hasn't recorded the background count rate (1) • More than one reading taken and a mean calculated **Or** should have taken more than two readings (to calculate mean) (1)		3

Q6.

Question Number	Acceptable Answer	Additional Guidance	Mark
	MAX 5 An explanation that makes reference to the following points: • The student has calculated the coun rate rather than the activity of the source (1) • The counts haven't been corrected for background (so there is systematic error in his data) (1) • The GM tube is too far away from the source (1) • α-radiation won't reach the GM-tube as it only has a short range in air (1) • Radiation spreads out from the source, so not all the emitted radiation reaches the GM-tube (1) • GM tube won't detect all the gammas which enter it (1)		5

Q7.

Question Number	Acceptable answers	Additional guidance	Mark
	• so the proportion of unstable nuclei does not change significantly over time **Or** activity does not change significantly over time (1)		1

Q8.

Question Number	Acceptable answers	Additional guidance	Mark
	• Alpha won't penetrate the plastic so the gas can't escape (1) • Alpha won't penetrate the plastic so there is no risk (1)	For MP1, accept answers in terms of the small range of alpha particles in the air in the bag	2

Q9.

Question Number	Acceptable answers	Additional guidance	Mark
	• top: 40, 0 (1) • bottom: 20, -1 (1)		2

Q10.

Question Number	Acceptable Answer	Additional Guidance	Mark
(i)	• Top line correct (1) • Bottom line correct (1)	Example of equation $^{137}_{55}\text{Cs} \rightarrow {}^{137}_{56}\text{Ba} + {}^{0}_{-1}\beta^{-} + {}^{0}_{0}\bar{\nu}_e$	2

Question Number	Acceptable Answer		Additional Guidance	Mark
(ii)	• Use of $\lambda = \frac{\ln 2}{t_{1/2}}$ • Use of 5000 m^3 • Use of $A = A_0 e^{-\lambda t}$ • t = 1400 year	(1) (1) (1) (1)	Example of calculation $\lambda = \frac{\ln 2}{30\text{ year}} = 0.0231\text{ year}^{-1}$ $100\text{ Bq} = (5000 \times 2.35 \times 10^{12})\text{Bq} \times e^{-0.0231\text{ year}^{-1} \times t}$ $\therefore t = \frac{\ln(8.51 \times 10^{-15})}{-0.0231\text{ year}^{-1}} = 1402\text{ year}$	4

Q11.

Question Number	Acceptable answers		Additional guidance	Mark
(i)	• Use of ln2 = $\lambda t_{1/2}$ • $\lambda = 4.92 \times 10^{-18}$ (s^{-1})	(1) (1)	Example of calculation λ = ln 2 / 1.41 × 10^{17} s = 4.92 × 10^{-18} s^{-1}	2
(ii)	• Calculate rate = counts / time • Subtract background radiation • Use of $A = -\lambda N$ • Calculates N × atomic mass • Calculates percentage by mass • Answer = 0.17% (ecf for λ from (a)(i))	(1) (1) (1) (1) (1) (1)	Example of calculation background rate = 525 / (10 × 60) s = 0.875 s^{-1} vase count rate = 3623 / (5 × 60) s = 12.077 s^{-1} corrected rate = 11.2 s^{-1} for whole vase = 11.2 s^{-1} × 0.0177 m^2 / 6.36 × 10^{-5} m^2 = 3117 s^{-1} N = 3117 / 4.91 × 10^{-18} s^{-1} = 6.348 × 10^{20} Mass = 6.348 × 10^{20} × 238 × 1.66 × 10^{-27} kg = 2.51 × 10^{-4} kg Percentage = 2.51 × 10^{-4} kg × 100 / 0.149 = 0.17%	6
(iii)	Max 2 from: • Alpha particles could have been absorbed by the glass • Alpha particles will be emitted in all directions, not just towards the detector • Some alpha particles could have been detected from other parts of the vase • The count could include radiation from decay products	(1) (1) (1) (1) (1)		2
	• Some alpha particles could be absorbed by the GM tube window			

Q12.

Question Number	Acceptable answers	Additional guidance	Mark
	• Calculates change in mass (1) • Converts from u to kg (1) • Use of $\Delta E = c^2\Delta m$ (1) • Use of $E_k = ½\,mv^2$ (1) • $v = 1.4 \times 10^7$ m s^{-1} (1)	Example of calculation $\Delta m = 238.0003u - (233.9942 + 4.0015)u$ $= 0.00463 \times 1.66 \times 10^{-27}$ kg $= 7.636 \times 10^{-30}$ kg $\Delta E = (3.00 \times 10^8 \text{ m s}^{-1})^2 \times 7.636 \times 10^{-30}$ kg $= 6.872 \times 10^{-13}$ J $6.872 \times 10^{-13} \text{ J} = ½\,(4.0015\,u)\,v^2$ $v = 1.4 \times 10^7$ m s^{-1}	5

Q13.

Question Number	Acceptable Answer	Additional Guidance	Mark
	A description that makes reference to the following: • (Remove the source and) record background count for specified time and subtract from equivalent quantity (1) • Divide by time to give a count rate. (1)	There needs to be two clear steps. Subtract a count from a count, or a count rate from a count rate and divide a count by time to obtain a count rate.	2

Q14.

Question Number	Acceptable answers	Additional guidance	Mark
	• correct values of *A* and *Z* for α and β • 5 α • 4 β	Example of calculation: $^{226}_{88}\text{Ra} \rightarrow {}^{206}_{82}\text{Pb} + x\,{}^{4}_{2}\alpha + y\,{}^{0}_{-1}\beta$ $226 - 206 = 4x$ $x = 5$ $88 - 82 - (5 \times 2) = -y$ $y = 4$ $^{226}_{88}\text{Ra} \rightarrow {}^{206}_{82}\text{Pb} + 5\,{}^{4}_{2}\alpha + 4\,{}^{0}_{-1}\beta$	(3)

Q15.

Question Number	Acceptable answer	Additional guidance	Mark
	C	The only correct answer is C because the corrected count rate at 30 cm is 40 counts per minute, the corrected rate at twice the distance is a quarter of this value, which is 10 counts per minute, and adding the background gives the value of 34 A is not the correct answer because it is 16 C is not the correct answer because it is 32 D is not the correct answer because it is 44	1

Q16.

Question Number	Acceptable Answer	Additional Guidance	Mark
	• α-particles would only travel a few cm (in air), and so wouldn't reach the GM-tube (1)	Accept a reference to α-particles not passing through the side of the tube (even if they reached it when d was small) and so not contributing to the count (rate)	
	• β-particles would probably not pass through the sides of the GM-tube, and so wouldn't be detected so suggestion is correct. (1)	For 2 marks expect a valid conclusion, as well as a statement of the likelihood of the α-particles and β-particles contributing to the count (rate)	2

Q17.

Question Number	Acceptable answers	Additional guidance	Mark
(i)	• Use of ratio of atoms and atoms per g (1) • Number of nuclei = 2.9×10^{17} (1)	$N = 0.3\text{ g} \times 8.1 \times 10^{21}\text{ g}^{-1} \times 0.012/100$ $= 2.9 \times 10^{17}$	2

Question Number	Acceptable answers	Additional guidance	Mark
(ii)	• use of $\ln 2 = \lambda t_{1/2}$ (1) • use of activity = λN (ecf from (b)(i)) (1) • activity = 5.1 (Bq) (use of show that value gives 5.3 Bq) (1)	$\ln 2 = \lambda \times 1.25 \times 10^9$ years $= \lambda \times (1.25 \times 10^9 \times 365 \times 24 \times 60 \times 60)$ s $\lambda = 1.76 \times 10^{-17}\text{ s}^{-1}$ $A = 1.76 \times 10^{-17}\text{ s}^{-1} \times 2.9 \times 10^{17}$ $= 5.1$ Bq	3

Question Number	Acceptable answers		Additional guidance	Mark
(iii)	• use of count rate = (counts – background counts) / time	(1)	**MP3** can only be awarded if Activity from (ii) is used. A clear comparison with the corresponding value must be made e.g. percentage = 0.8 % which is < 7.5 % so not efficient **Or** detects 176 but should detect 379 counts in 10 min, so not efficient **Or** should detect a rate of at least 0.63 Bq, so not efficient <u>Example of calculation</u> Recorded count rate = (176 - 150) ÷ 600 s = 0.04 Bq 0.04 Bq × 100 ÷ 5.1 Bq = 0.78 % (ecf from (b)(ii) for MP3)	3
	• calculates percentage of activity from (b)(ii) **Or** applies 7.5% to activity from (b)(ii)	(1)		
	• Comparative statement consistent with their values	(1)		

Question Number	Acceptable answers		Additional guidance	Mark
(iv)	**Max two from**			
	• emissions are in all directions	(1)		
	• some emitted particles may be absorbed by the material in the sample	(1)		
	• some emitted particles may be absorbed by the window	(1)		
	• some emitted particles pass (right) through detector	(1)		2

Q18.

Question Number	Acceptable answers		Additional guidance	Mark
(i)	• subtracts background from counts in 60 s	(1)	<u>Example of calculation:</u> 12227 - 22 = 12205 322 - 15 = 307 $307 = 12205 \times e^{-\ln 2t/5.3\ y}$ $\ln 307 = \ln 12205 - \ln 2 \times t / 5.3\ y$ $t = 28$ years Year = 2015 - 28 = 1987	
	• use of half life × λ = ln 2	(1)		
	• use of $A = A_0\ e^{-\lambda t}$	(1)		
	• correct logarithmic conversion	(1)		
	• year = 1987	(1)		**(5)**

Question Number	Acceptable answers		Additional guidance	Mark
(ii)	An explanation that makes reference to one of the following pairs:			
	• if the measurement in 2015 were at a larger distance than X, the count rate would be less	(1)	Allow reverse arguments	
	• the source would appear to be older than it really is	(1)		
	OR • 307 is a relatively small count	(1)		
	• the equations apply for large numbers of decays therefore you cannot be sure of the accuracy of the age	(1)		
	OR • if the sensitivity of the GM tube were greater in 2015, the count rate would be larger	(1)		
	• the source would appear to be younger than it really is	(1)		**(2)**

Q19.

Question Number	Acceptable answers	Additional guidance	Mark
(i)	• Calculate no of nuclei (1) • Use of ln 2 = $t_{½} \times \lambda$ (1) • Use of $A = \lambda N$ (1) • $A = 3.97 \times 10^4$ Bq) (1)	Example of calculation $N = (5.18 \times 10^{-5}\text{ g}/230\text{ g}) \times 6.02 \times 10^{23}$ $= 1.36 \times 10^{17}$ $\lambda \times (75\,400 \times 3.15 \times 10^7)\text{ s} = \ln 2$ $\lambda = 2.92 \times 10^{-13}\text{ s}^{-1}$ $A = 2.92 \times 10^{-13}\text{ s}^{-1} \times 1.36 \times 10^{17}$ $A = 3.97 \times 10^4$ Bq	4
(ii)	• Calculates decays in one year (ecf from (b)(i)) (1) • Use of $pV = NkT$ (1) • uses $T = 295$ K (1) • $V = 5.09 \times 10^{-14}\text{ m}^3$ (1)	Example of calculation ecf λ from (a) decays in one year = 3.97×10^4 Bq × 3.15×10^7 s $= 1.25 \times 10^{12}$ 1.00×10^5 Pa × $V = 1.25 \times 10^{12} \times 1.38 \times 10^{-23}\text{ J K}^{-1} \times 295$ K $V = 5.09 \times 10^{-14}\text{ m}^3$	4
(iii)	• Use of $½\, m <c^2> = 3/2\, kT$ **Or** Use of $pV = \frac{1}{3}Nm < c^2 >$ (allow ecf for N, V from (b)(ii)) (1) • uses $m = 4u$ (1) • $\sqrt{<c^2>} = 1360\text{ m s}^{-1}$ (1)	Example of calculation $½\, m <c^2> = 3/2\, kT$ $½ \times (4 \times 1.66 \times 10^{-27}\text{ kg}) \times <c^2> = 3/2 \times 1.38 \times 10^{-23}\text{ J K}^{-1} \times 295$ K $<c^2> = 1\,840\,000\text{ m}^2\text{ s}^{-2}$ $\sqrt{<c^2>} = 1360\text{ m s}^{-1}$ Accept the use of proton/neutron mass instead of u	3

Q20.

Question Number	Acceptable Answer	Additional Guidance	Mark
(i)	**Either** • The GM-tube has a low efficiency for γ-ray detection **Or** there is an increased area exposed to γ-rays (1) • (So) placing the tube side on to the radiation would increase the count rate (1) **Or** • The γ-radiation could be detected anywhere inside the GM-tube (1) • So placing the tube side on to the radiation would reduce the uncertainty in the distance measurement (1)	For low efficiency, accept GM tube poor at detecting γ-rays.	2

Question Number	Acceptable Answer	Additional Guidance	Mark
(ii)	• Record the count (at least) twice and then determine an average count rate **Or** record the count for a much longer time (1) • This reduces the effect of (random) errors in the measurement of the count rate (1)		2

Q21.

Question Number	Acceptable Answer	Additional Guidance	Mark
(a)(i)	• a π^0 may be $u\bar{u}$ **Or** $d\bar{d}$ (1) • it must be a quark combined with its own antiquark so that overall charge is 0 (1) <u>OR</u> it can only contain up or down quarks (as it is not a strange particle)	Allow $s\bar{s}$	**(2)**
(a)(ii)	mesons are made up of quarks, whereas leptons are fundamental particles (1)		**(1)**

Question Number	Acceptable Answer	Additional Guidance	Mark
(b)(i)	• use of v = s/t (1) • t = 5.05 × 10^{-5} s (1)	<u>Example of calculation:</u> $t = \frac{s}{v} = \frac{15 \times 10^3 \mathrm{m}}{0.99 \times 3 \times 10^8 \mathrm{ms}^{-1}} = 5.05 \times 10^{-5} \mathrm{s}$	**(2)**
(b)(ii)	• use of $\lambda t_{1/2} = 0.693$ (1) • λ = 3.15 × 10^5 s^{-1} (1) • use of $N = N_0 e^{-\lambda t}$ (1) • $\frac{N}{N_0} = 1.23 \times 10^{-7}$ (1)	<u>Example of calculation:</u> $\lambda = \frac{\ln 2}{t_{1/2}} = \frac{0.693}{2.2 \times 10^{-6} \mathrm{s}} = 3.15 \times 10^5 \mathrm{s}^{-1}$ $\frac{N}{N_0} = e^{-\lambda t} = \mathrm{e}^{-3.15 \times 10^5 \mathrm{s}^{-1} \times 5.05 \times 10^{-5} \mathrm{s}} = 1.23 \times 10^{-7}$ $\frac{N}{N_0} = 1.1 \times 10^{-7}$ if "show that" value used	**(4)**
(b)(iii)	• This is much smaller than 10% indicating the muon lifetime is much greater than the expected value (1) • The high speed of the muon has led to relativistic effects (1)		**(2)**

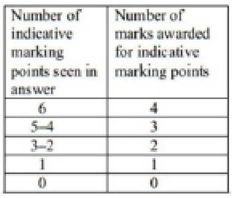
Q22.

Question Number	Acceptable answers	Additional guidance	Mark
(i)	An explanation that makes reference to the following:		
	• use a GM tube and counter to measure the number of counts in a known time (1)	Answers may refer to the use of a ratemeter instead of a counter	
	• place a piece of aluminium a few mm thick between the source and the detector (1)		
	• α and β will not penetrate aluminium but γ will (1)		
	• so the source that is unchanged is Co 60 and the one with a decreased count is Ra 226 (1)		
	OR use a GM tube and counter to measure the number of counts in a known time		
	• place a strong magnet near the source (1)		**(4)**
	• α and β will be deviated but γ will not (1)		
	• so the source that is unchanged is Co 60 and the one with a decreased count is Ra 226 (1)		

Question Number	Acceptable answers	Additional guidance	Mark
(ii)	An explanation that makes reference to a precaution and the reason for it • make sure the source remains at a distance of at least 30 cm from your body to minimise exposure (1) <u>OR</u> make sure the source is always pointed away from you to minimise exposure (1) <u>OR</u> only use one source at a time to minimise exposure (1) • the sources emit ionising radiation which can be harmful to your cells (1)		**(2)**

Q23.

<table>
<tr><th>Question Number</th><th>Acceptable Answer</th><th>Additional Guidance</th><th>Mark</th></tr>
<tr><td>*</td><td>This question assesses a student's ability to show a coherent and logical structured answer with linkage and fully-sustained reasoning.
Indicative content:
IC1 There is a fixed probability (λ) of an individual nucleus undergoing decay (in the next second)
IC2 For a sample with large number of unstable nuclei there is a predictable pattern
IC3 The fraction of nuclei decaying in the next second is equal to the decay constant (λ)</td><td>Marks are awarded for indicative content and for how the answer is structured and shows lines of reasoning.
The following table shows how the marks should be awarded for indicative content.



<table>
<tr><th>Number of indicative marking points seen in answer</th><th>Number of marks awarded for indicative marking points</th></tr>
<tr><td>6</td><td>4</td></tr>
<tr><td>5–4</td><td>3</td></tr>
<tr><td>3–2</td><td>2</td></tr>
<tr><td>1</td><td>1</td></tr>
<tr><td>0</td><td>0</td></tr>
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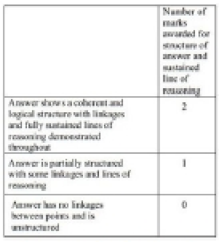

<table>
<tr><th></th><th>Number of marks awarded for structure of answer and sustained line of reasoning</th></tr>
<tr><td>Answer shows a coherent and logical structure with linkages and fully sustained lines of reasoning demonstrated throughout</td><td>2</td></tr>
<tr><td>Answer is partially structured with some linkages and lines of reasoning</td><td>1</td></tr>
<tr><td>Answer has no linkages between points and is unstructured</td><td>0</td></tr>
</table>

Total marks awarded is the sum of marks for indicative content and the marks for structure and lines of reasoning

<table>
<tr><th>IC points</th><th>IC mark</th><th>Max linkage mark</th><th>Max final mark</th></tr>
<tr><td>6</td><td>4</td><td>2</td><td>6</td></tr>
<tr><td>5</td><td>3</td><td>2</td><td>5</td></tr>
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</table>
</td><td>6</td></tr>
<tr><td></td><td>IC4 Hence the number of nuclei decaying (in the next second) depends on the number of (unstable) nuclei
Or activity = λN
IC5 The number of unstable nuclei decreases</td><td></td><td></td></tr>
</table>

	exponentially (with time) **Or** number of (unstable) nuclei = $N_0 e^{-\lambda t}$ IC6 So the rate of decay decreases exponentially (with time) **Or** rate of decay = $A_0 e^{-\lambda t}$		

Q24.

Question Number	Acceptable answers	Additional guidance	Mark
	An explanation that makes reference to the following points: • Use of $\lambda = \frac{\ln 2}{t_{1/2}}$ (1) • (Hence) initial activity of Ac is 50% that of Bi **Or** (Hence) decay constant of Ac is 50% that of Bi (1) • Applies one or two half lives to show fraction of initial activity/number after 10 days for one isotope **Or** Use of exponential decay equation to show fraction of initial activity/number after 10 days for one isotope (1) • Demonstrates quantitatively that both isotopes have the same activity (1)	Alternative approach: $\lambda_{\text{Ac}} = \frac{\ln 2}{10}$ $A_{\text{Ac}} = \lambda_{\text{Ac}}N = \frac{\ln 2}{10} \times N$ After 10 days $A_{\text{Ac}} = \frac{1}{2} \times \frac{ln2}{10} \times N = \frac{\ln 2}{20} \times N$ $\lambda_{\text{Bi}} = \frac{\ln 2}{5}$ $A_{\text{Bi}} = \lambda_{\text{Bi}}N = \frac{\ln 2}{5} \times N$ After 10 days $A_{\text{Bi}} = \frac{1}{2} \times \frac{1}{2} \times \frac{\ln 2}{5} \times N = \frac{ln2}{20} \times N$ $A_{\text{Ac}} = A_{\text{Bi}}$ **MP2** can be awarded for use of **both** decay constants in exponential decay equations All four marks may be awarded for a full mathematical demonstration, e.g.: $\lambda_{\text{Ac}} = \frac{\ln 2}{10} = 0.0693\ \text{day}^{-1}$ $A_{\text{Ac}} = \lambda_{\text{Ac}}N = 0.0693\ \text{day}^{-1} \times N$ 10 days: $A_{\text{Ac}} = ½ \times 0.0693\ \text{day}^{-1} \times N = 0.0345\ \text{day}^{-1} \times N$ $\lambda_{\text{Bi}} = \frac{\ln 2}{5} = 0.139\ \text{day}^{-1}$ $A_{\text{Bi}} = \lambda_{\text{Bi}}N = 0.139\ \text{day}^{-1} \times N$ 10 days: $A_{\text{Bi}} = ½ \times ½ \times 0.139\ \text{day}^{-1} \times N = 0.0345\ \text{day}^{-1}$ $A_{\text{Ac}} = A_{\text{Bi}}$	4

Q25.

Question Number	Acceptable answers	Additional guidance	Mark
(i)	• 8 alpha decays reduce the proton number by 16 **(1)** • proton number decreases by only 10, so there must be 6 β decays **(1)** **OR** • balanced equation written for overall decay **(1)** • explicit solution to give 6 β^- decays **(1)**	Example of calculation: $^{238}_{92}U \rightarrow ^{206}_{82}Pb + 8\times ^{4}_{2}\alpha + N\times ^{0}_{-1}\beta^-$ $92 = 82 + (8\times2) - N$ $92 = 82 + 16 - N$ $N = 98 - 92 = 6$ Proof must be given to obtain these marks.	**2**
(ii)	• use of $\lambda t_{1/2} = \ln 2$ **(1)** • use of $N = N_0 e^{-\lambda t}$ **(1)** • $N/N_0 = 0.1$ **(1)** • $t = 2.5 \times 10^5$ years **(1)**	Example of calculation: $\lambda = \frac{0.693}{75000} = 9.24\times10^{-6}\,\mathrm{y}^{-1}$ $\lambda t = -\ln\left(\frac{N}{N_0}\right)$ $\therefore t = \frac{-\ln(0.1)}{9.24\times10^{-6}\,\mathrm{y}^{-1}} = 2.49\times10^{5}\,\mathrm{y}$	**4**

Q26.

Question Number	Acceptable answers	Additional guidance	Mark
	• Use of $\lambda = \frac{\ln 2}{t_{1/2}}$ (1) • Use of $N = N_0 e^{-\lambda t}$ (1) • Use of N_S/N_R to determine N/N_0 (1) • $t = 3.7 \times 10^9$ year (1) • Comparison of their value with corresponding value in question and valid conclusion (1) **Or** • Use of $\lambda = \frac{\ln 2}{t_{1/2}}$ • Use of $N = N_0 e^{-\lambda t}$ • Use of N/N_0 to determine N_S/N_R • $\frac{N_S}{N_R} = 0.066$ if t = age of Earth • Comparison of their value with corresponding value in question and valid conclusion	Example of calculation: $\lambda = \frac{\ln 2}{4.88 \times 10^{10}\,\text{year}} = 1.42 \times 10^{-11}\,\text{year}^{-1}$ $\frac{N_0}{N} = \frac{N_R + N_S}{N_R} = 1 + \frac{N_S}{N_R} = 1.0532$ $1.0532 = e^{1.42\times10^{-11}\,\text{year}^{-1}\times t}$ $\therefore t = \frac{\ln(1.0532)}{1.42 \times 10^{-11}\,\text{year}^{-1}} = 3.65 \times 10^{9}\,\text{year}$	5

Q27.

Question Number	Acceptable Answer	Additional Guidance	Mark
	• decay happens without any external stimulus **Or** decay is unaffected by external factors (such as temperature) (1)	Do not credit references to the randomness of the decay	1

Q28.

Question Number	Acceptable Answer	Additional Guidance	Mark
	• (isotopes are atoms/nuclides with the) same number of protons but different numbers of neutrons/nucleons (in the nucleus) (1)	Ignore references to the number of electrons in the atoms Do not credit mass number or atomic number	1

Q29.

Question Number	Acceptable Answer	Additional Guidance	Mark
	• α radiation would be absorbed by the plastic bottle (1) • β radiation can penetrate the plastic bottle therefore it could/must be β radiation (1)		2

Q30.

Question Number	Acceptable Answer		Additional Guidance	Mark
(i)	• Smooth best fit curve drawn on graph • Time for count rate to fall by half once • Time for count rate to fall by half twice and mean time calculated • $t_{1/2}$ = 60 s → 80 s	(1) (1) (1) (1)	Alternative approaches for MP2 and MP3 Read 2 values from graph and use exponential equation **Or** draw tangent to curve at t = 0 and read off the time intercept Example of calculation 9.0 s^{-1} → 4.5 s^{-1} t = 75 s 4.5 s^{-1} → 2.25 s^{-1} t = 75 s If background count is taken into consideration, t will be lower	4

Question Number	Acceptable Answer		Additional Guidance	Mark
(ii)	An explanation that makes reference to the following points: • There will be background radiation **Or** decay is exponential and so count rate will "never" reach zero • The data logger output includes counts due to background radiation as well as the source radiation **Or** The count rate can't be corrected automatically	(1) (1)	MP2: accept references to GM-tube	2

Q31.

Question Number	Acceptable answers		Additional guidance	Mark
	An explanation that makes reference to the following points: **Either** • $t_{1/2}$ is larger, λ will be smaller • $N = N_0 e^{-\lambda t}$ so the calculated value of time would be greater MP2 dependent upon MP1 **OR** • If half-life is larger, it would take more time for the ratio $\frac{N_S}{N_R}$ to reach the current value • Hence the rock would be older than originally determined. MP2 dependent upon MP1	(1) (1)		2