IB · DP · Physics

3 hours 15 questions

Structured Questions

12.2 Nuclear Physics

12.2.1 Rutherford Scattering & Nuclear Radius / 12.2.2 Nuclear Scattering / 12.2.3 Deviations from Rutherford Scattering / 12.2.4 Nuclear Energy Levels / 12.2.5 The Neutrino / 12.2.6 The Law of Radioactive Decay / 12.2.7 Measuring Half-Life

Easy (5 questions)	/72
Medium (5 questions)	/49
Hard (5 questions)	/47
Total Marks	**/168**

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Easy Questions

1 (a) Outline how the density of a nucleus varies with nuclear radius.

(2 marks)

(b) Calculate the nuclear radius of carbon-14 $\left({}^{14}_{6}\text{C}\right)$, in m.

(2 marks)

(c) Carbon-14 is unstable and decays to nitrogen by beta minus emission.

In living tissue, such as plants and animals, the ratio of carbon-14 to carbon-12 atoms is constant.

State and explain what will happen to this ratio after the living tissue dies.

(3 marks)

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(d) When carbon-14 undergoes beta-minus decay, the energy gained by the emitted particles varies.

Nitrogen-14 is one of the products of this decay.

(i) State the other **two** particles that are emitted.

[1]

(ii) One of the emitted particles is very difficult to detect. Explain why, and outline the evidence that made the presence of this particle in beta decay necessary by completing the following sentences:

__________ are hard to detect because they are electrically ___________ and have an extremely small _____.

The energy released in beta decay must be _______________ the two particles emitted. Without the presence of the __________, the emitted ___________ would be expected to carry away the same amount of energy with each decay.

Energy distributions for beta decay are ________, as opposed to alpha decays which are ________.

[3]

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(4 marks)

2 (a) Outline what is meant by the term decay constant.

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(2 marks)

(b) A sample of 2.5 mol of the radioactive nuclide plutonium-239 decays into uranium-235 with the production of another particle.

$$^{239}_{94}Pu \rightarrow \, ^{235}_{92}\text{U} + \text{X}$$

(i) Identify particle X.

[1]

(ii) The radioactive decay constant of plutonium-239 is 9.5×10^{-13} s^{-1}. Determine the time required to produce 1 mol of uranium-235.

[4]

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(5 marks)

(c) Thorium-227 is one of the isotopes formed after a uranium-235 nucleus has undergone a series of decays.

One sample of thorium-227 has a decay constant of 0.037 day^{-1} and an initial activity of 46 Bq.

(i) State what is meant by the activity of a sample.

[2]

(ii) Calculate the activity of the sample after one week.

[3]

(5 marks)

(d) Particle X has an initial kinetic energy of 7.5 MeV after the decay in (b). In a scattering experiment, particle X is aimed head-on at a stationary gold-197 nucleus $\left(^{197}_{79}\text{Au}\right)$.

Particle X transfers all its kinetic energy to another form as it approaches the gold nucleus. At the distance of closest approach, *d*, to the gold nucleus:

(i) State the energy transfer taking place in particle X and the gold nucleus.

[1]

(ii) Write an expression for the total energy in terms of the Coulomb constant, *k*, the elementary charge, *e*, and distance, *d*.

[1]

(iii) Calculate the distance, *d*, between particle X and the gold nucleus at this point.

[2]

(4 marks)

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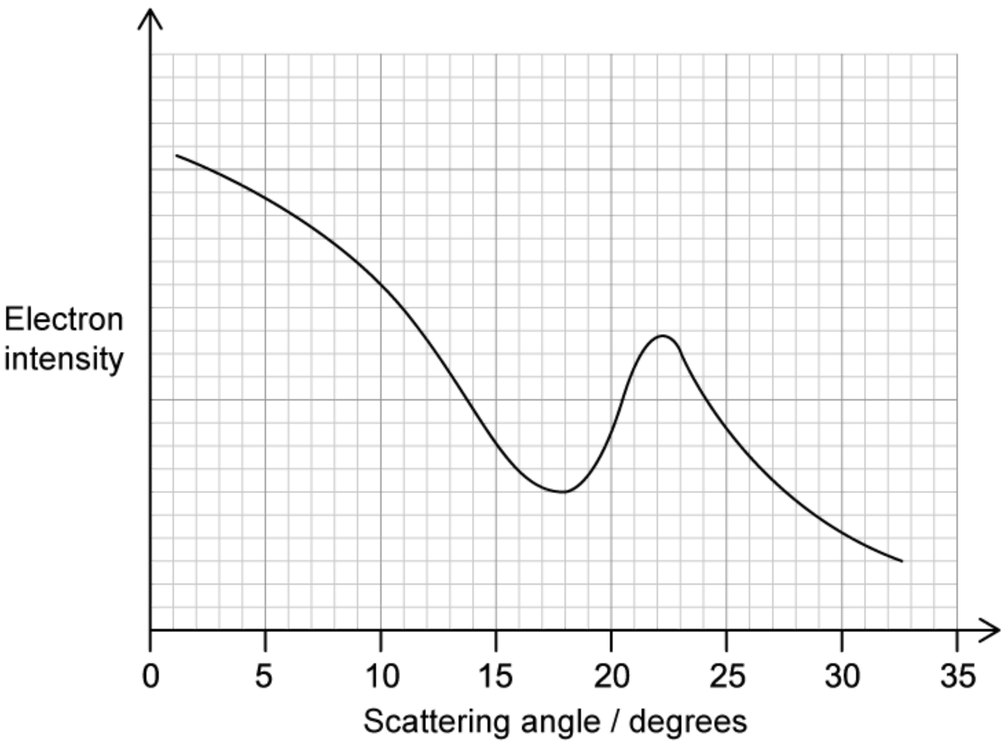
3 (a) A beam of electrons each of de Broglie wavelength 2.8×10^{-15} m is incident on a thin film of iron-56 $\left({}^{56}_{26}Fe\right)$. The variation in the electron intensity of the beam with scattering angle is shown.



Use the graph to determine the nuclear radius of iron-56.

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(3 marks)

(b) Using the result from part (a):

(i) Show that the constant of proportionality, R_0, is equal to 1.2 fm

[2]

(ii) Calculate the nuclear radius of radium-222 $\left({}^{222}_{88}Ra\right)$

[1]

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(3 marks)

(c) Two students debate whether beams of electrons or alpha particles, of the same energy, would be better for investigating the size of a nucleus.

Complete the sentences below to outline which student is correct.

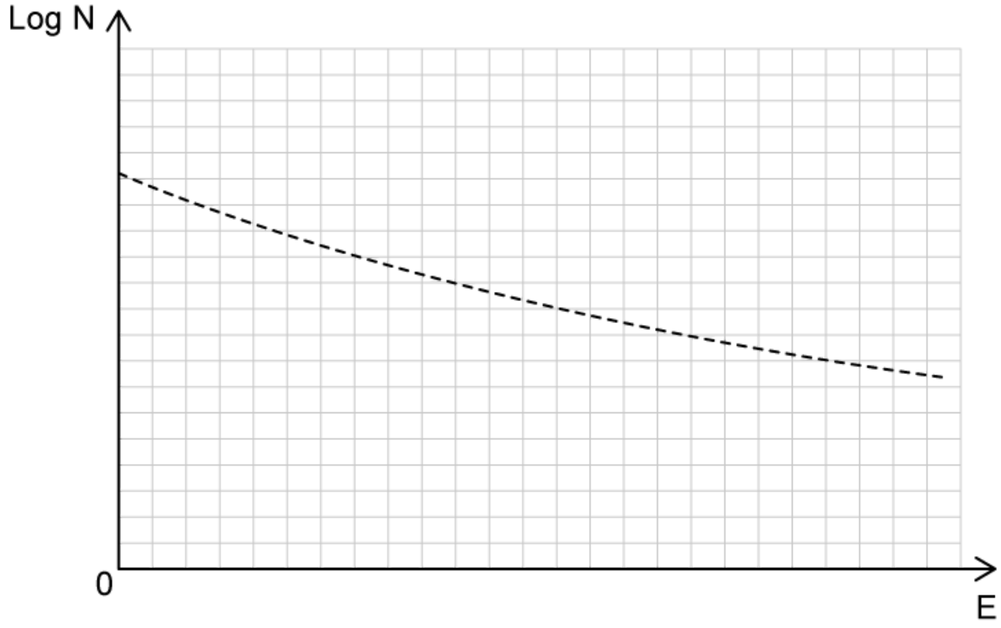
Beams of ___________ would be better for investigating the size of a nucleus.

This is because a beam of ___________ would provide a greater resolution since their de Broglie wavelength is ________ than the de Broglie wavelength of ___________.

Another reason is that ___________ are leptons meaning they are not subject to the ___________ force, therefore, they are ______ likely to interact with the nucleus being investigated.

(3 marks)

(d) The graph shows how the number of alpha particles that are observed at a fixed scattering angle, *N*, depends on alpha particle energy, *E*, according to Rutherford's scattering formula.



Deviations from Rutherford scattering are detected in experiments carried out at high energies.

(i) Outline an assumption of the Rutherford scattering formula.

[1]

(ii) Indicate the deviations from Rutherford scattering on the axes provided above.

[1]

(iii) Explain what these deviations provide evidence for.

[3]

(5 marks)

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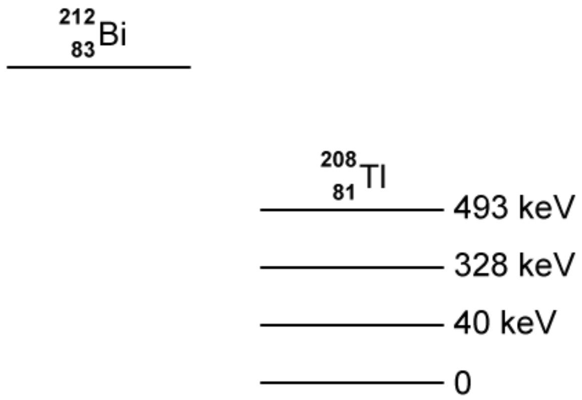
4 (a) The isotope bismuth-212 undergoes α-decay to an isotope of thallium-208. In this decay, a gamma-ray photon is also produced.



(i) Complete the nuclear energy level diagram to indicate the alpha decay of Bi-212 into Tl-208, followed by the emission of a photon of energy 0.493 MeV.

[2]

(ii) Outline how the alpha particle spectrum and the gamma spectrum of the decay of bismuth-212 give evidence for the existence of discrete nuclear energy levels, by completing the following sentences:

The emitted alpha particles have ________ energies.

The emitted gamma rays have _________ energies.

Therefore, nuclear energy levels must be discrete because the energies of the alpha particles and the gamma photons are determined by ____________________________________.

[3]

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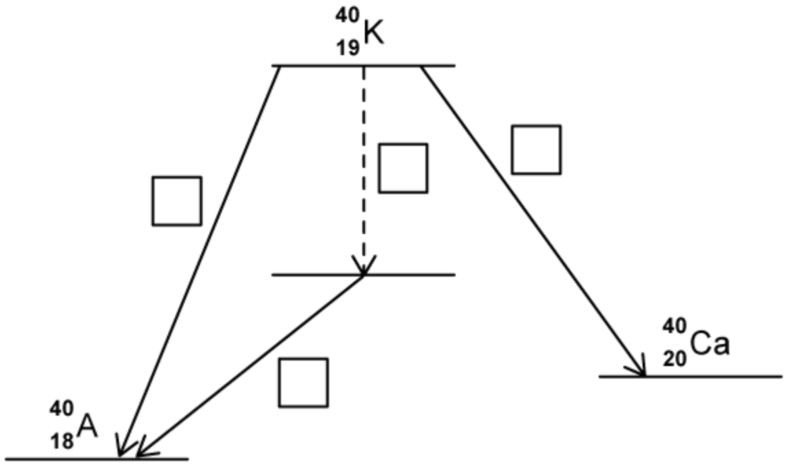
(5 marks)

(b) The isotope potassium-40 can decay via different decay modes to form isotopes of argon-40 or calcium-40.



(i) Complete the nuclear energy level diagram to indicate the different modes of decay.

[3]

(ii) Outline how the β spectrum of the decay of potassium-40 led to the existence of the neutrino being postulated, by completing the following sentences:

The total energy released in any beta decay is __________, however, the majority of beta particles are found to have energies ________ than this value.

The distribution of energy values for the beta particles is not _________, it is found to be a ___________ spectrum.

The existence of the neutrino was postulated to account for the ________________.

The total energy of the decay process must be divided between the ____________ and ________________.

[2]

(5 marks)

(c) The isotope potassium-40 occurs naturally in many rock formations. The composition of a particular rock sample is found to be 33% potassium-40 atoms out of the total number of argon and potassium-40 atoms.

The half-life of potassium-40 is 1.3×10^9 years.

Determine the age of the rock sample.

(4 marks)

(d) Bismuth-212 is a short-lived isotope with a half-life of 1 hour.

Briefly outline experimental methods which can measure the half-life of:

(i) Bismuth-212

[3]

(ii) Potassium-40

[3]

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(6 marks)

5 (a) Particles can be used in scattering experiments to estimate nuclear radius.

Outline how these experiments are carried out by completing the following sentences:

High _____________ particles have wave-like properties such as a ___________ wavelength and the ability to ___________ when incident on a thin ______________.

The ___________ of the ______________ particles can be measured using a detector.

A graph of intensity against ______________ can be obtained.

The _______________ of the first ____________ can be used to determine the nuclear radius of the atoms in the ________________.

The nuclear radius can then be determined using the equation ___________________.

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(5 marks)

(b) Electron scattering experiments indicate that the nuclear radius of oxygen-16 is 3.02 fm

The graph shows the variation of nuclear radius with nucleon number. The nuclear radius of the oxygen-16 has been plotted.

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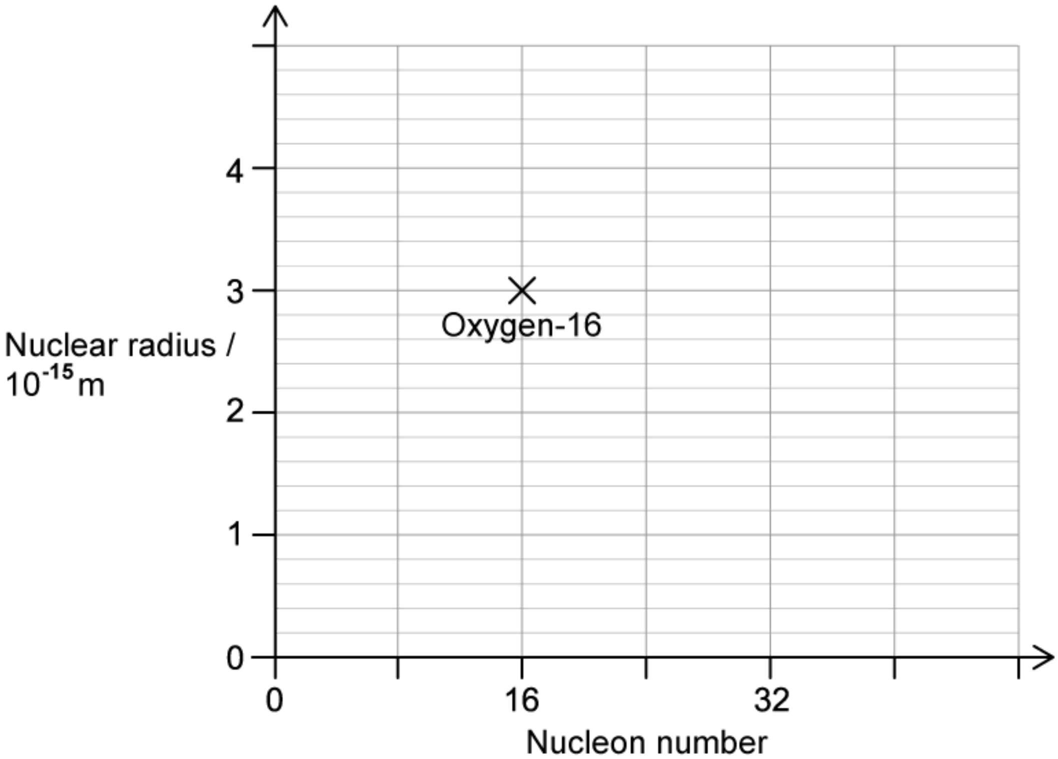

Plot the position of sulphur-32 on the graph.

(2 marks)

(c) Draw a line on the graph to show how nuclear radius varies with nucleon number.

(2 marks)

(d) The density of a nucleus, ρ, is given by the equation:

$$\rho = \frac{3u}{4\pi R_0^{\ 3}}$$

Where u is the atomic mass unit and R_0 is a constant of proportionality equal to approximately 1.20×10^{-15} m.

(i) State how the density of a nucleus changes after it undergoes radioactive decay.

[1]

(ii) Explain your answer to part (i).

[1]

(2 marks)

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Medium Questions

1 (a) Show that all nuclei have the same density.

(3 marks)

(b) A beam of neutrons is fired normally at a thin foil sheet made from tin. The beam has energy 75 MeV and the first diffraction minimum is observed at an angle of 15° relative to the central bright fringe.

Calculate an estimate for the radius of the tin nucleus.

(4 marks)

(c) The tin (^{50}Sn) foil was replaced by thin aluminium (^{13}Al) foil.

Deduce and explain the expected difference in the observations between the two experiments.

(3 marks)

(d) An isotope of tin has a half-life of 129 days. It undergoes beta-minus decay to a meta-stable isotope of antimony.

Calculate the percentage of the sample which will consist of antimony after 2 years.

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(2 marks)

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2 (a) Iodine-131 $\left({}^{131}_{53}\text{I}\right)$ has a half-life of 8.02 days.

Calculate the decay constant of ${}^{131}_{53}\text{I}$.

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(2 marks)

(b) The initial activity of the sample of Iodine−131 is 6.5×10^4 Bq.

Determine the activity after 16 days.

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(2 marks)

(c) Determine the mass of the iodine−131 in the sample after 16 days.

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(2 marks)

(d) Iodine−131 decays through a number of decay modes. Two of these are β^- decay of 606 keV and gamma emission of 364 keV. The product of the β^- decay is ${}^{131}_{54}\text{Xe}$.

Sketch a nuclear energy level diagram to represent these decays.

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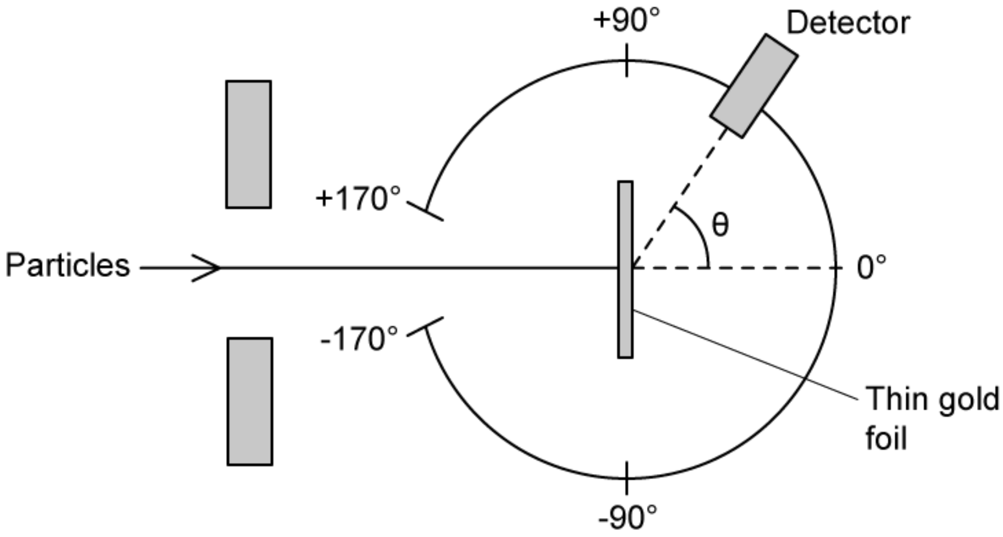
(2 marks)

3 (a) Ernest Rutherford was able to deduce a relationship for the size of the nucleus using the Rutherford scattering experiment shown below:



A radioisotope has a nuclear radius of 7.41 fm

Determine the nucleon number of the isotope.

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(2 marks)

(b) A beam of high-energy neutrons is directed at the nucleus and a pattern is formed on a detector screen.

Explain the pattern which is observed.

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(3 marks)

(c) The neutrons are accelerated to a speed of 2.88×10^8 m s^{-1}.

Determine the angle of the first minimum.

(2 marks)

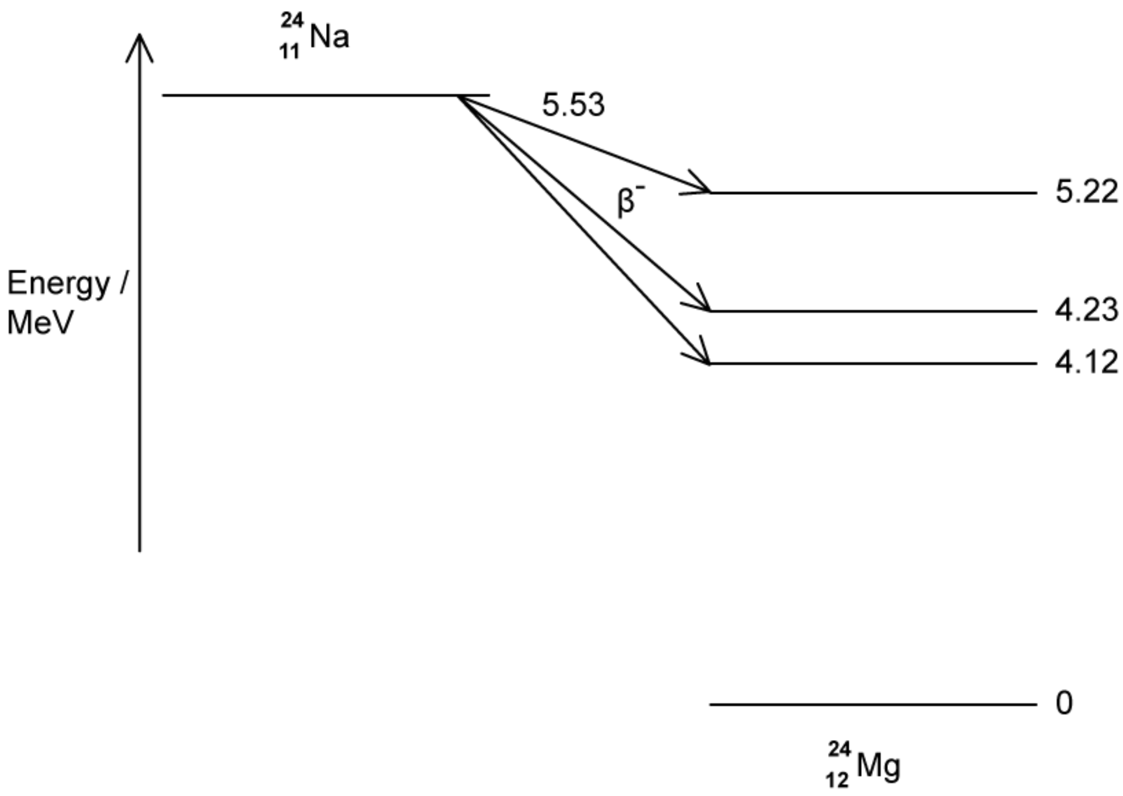
(d) The decay constant of the isotope is 9.72×10^{-10} yr^{-1}. The mass of a sample of this isotope is 600 g.

Determine the activity of the sample.

(3 marks)

4 (a) A nucleus of sodium−24 decays into a stable nucleus of magnesium−24. It decays by β^- emission followed by the emission of γ-radiation as the magnesium−24 nucleus de-excites into its ground state.

The sodium−24 nucleus can decay to one of three excited states of the magnesium−24 nucleus. This is shown in the diagram below:



The energies of the excited states are shown relative to the ground state.

Calculate the maximum possible speed of the emitted beta particle in MeV.

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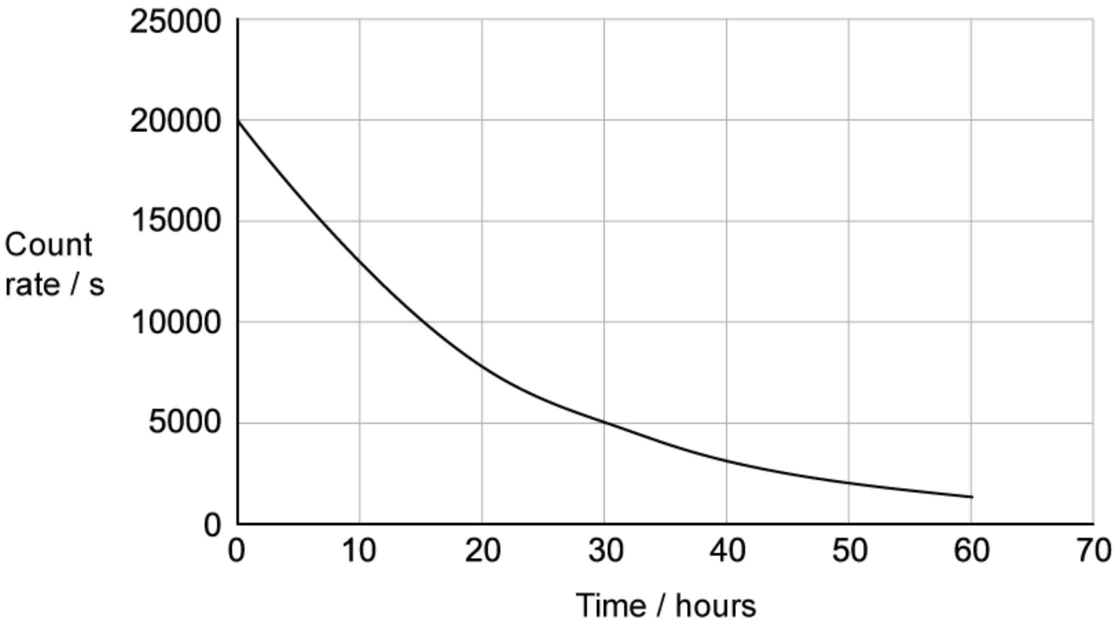
(2 marks)

(b) The excited magnesium nucleus de-excites through production of gamma radiation of discrete wavelengths.

Calculate the shortest wavelength of emitted radiation.

(3 marks)

(c) The graph shows the activity of a sample of sodium−24 with time.



Use the graph to calculate the decay constant of sodium−24.

(2 marks)

(d) The detector in this experiment measures 4% of the activity from the sample.

Determine the activity of sample after 27 hours from the start of the recording,

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(3 marks)

5 (a) Americium-241 has a half-life of 432 years. A small sample is held in a school for use in experiments.

The teacher uses a Geiger-Müller counter to measure the count rate at close range. The relationship between activity and count rate is a ratio of 6:1. Over 5 minutes, the count is 13 600.

Determine the activity of the sample.

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(2 marks)

(b) Determine the activity of the americium sample after 748 years.

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(2 marks)

(c) Americium−241 decays through a series of decays to uranium-233.

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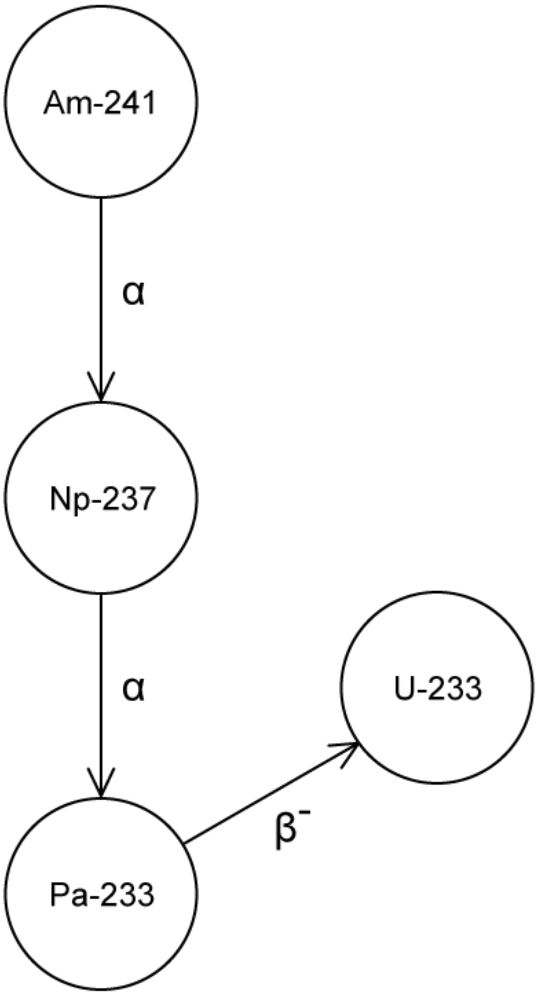

The energies from each decay path are recorded.

Explain the differences between the energy profiles for the alpha decays and the beta decays.

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(3 marks)

(d) The beta decay of protactinium−233 to uranium−233 has a half−life of 27 days. A sample of protactinium has an activity of 3879 Bq.

Determine the number of protactinium−233 nuclei in the sample.

(2 marks)

Hard Questions

1 (a) In a scattering experiment, a metal foil of thickness 0.4 μm scatters 1 in 20 000 alpha particles through an angle greater than 90°.

(i) Considering the metal foil as a number of layers of atoms, *n*, explain why the probability of an alpha particle being deflected by a given atom is approximately equal to

$$\frac{1}{20\,000n}$$

[2]

(ii) Estimate the diameter of the nucleus. Consider the nuclei as cubes and the atoms in the foil as cubes of side length 0.25 nm.

[3]

(5 marks)

(b) Deviations from Rutherford scattering are observed when high-energy alpha particles are incident on nuclei.

Outline the incorrect assumption used in the Rutherford scattering formula and suggest an explanation for the observed deviations.

(3 marks)

(c) In a scattering experiment, alpha particles were directed at five different thin metallic foils, as shown in the table.

Metal	Symbol
Silver	$^{108}_{47}Ag$
Aluminium	$^{27}_{13}Al$
Gold	$^{197}_{79}Au$
Tin	$^{119}_{50}Sn$
Tungsten	$^{184}_{74}W$

Initially, all alpha particles have the same energy. This energy is gradually increased.

Predict and explain the differences in deviations from Rutherford scattering that will be observed.

(3 marks)

(d) Outline why the particles must be accelerated to high energies in scattering experiments.

(3 marks)

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2 (a) Show that the decay constant is related to the half-life by the expression

$$\lambda T_{1/2} = \ln 2$$

(3 marks)

(b) Uranium-238 has a half-life of 4.47×10^9 years and decays to thorium-234. The thorium decays (by a series of further nuclear processes with short half-lives) to lead.

Assuming that a rock was originally entirely uranium and that at present, 1.5% of the nuclei are now lead, calculate the age of the rock. Give your answer in years to 2 significant figures.

(3 marks)

(c) The ionisation current *I* produced by α-particles emitted in the decay of radon can be measured experimentally. The logarithmic graph shows how current, ln *I*, varies with time, *t*.

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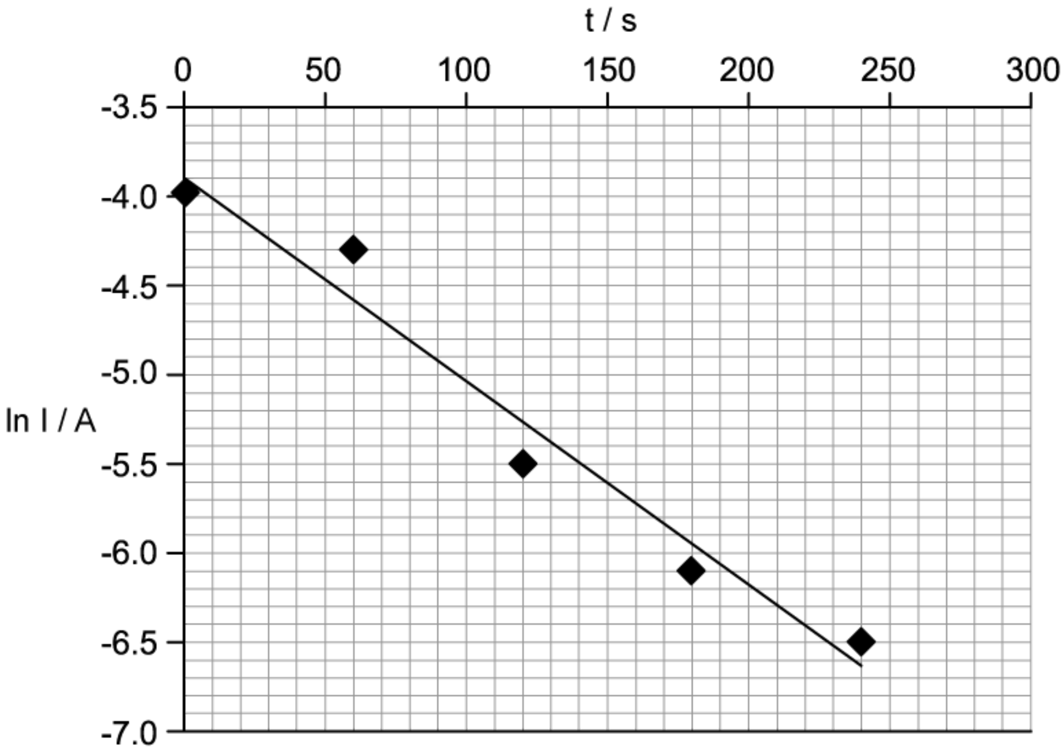

Using the graph, determine the half-life of radon.

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(3 marks)

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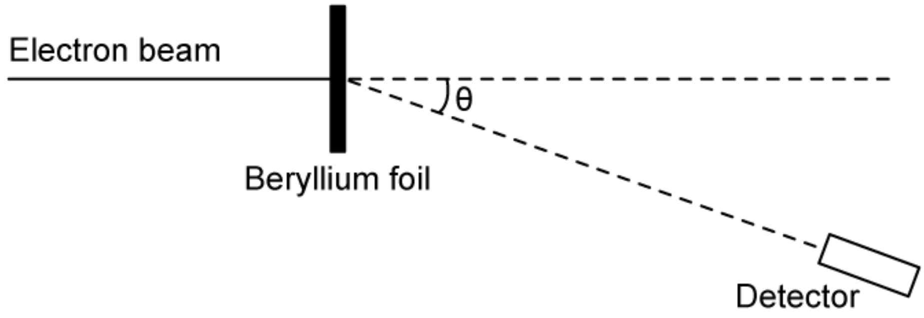
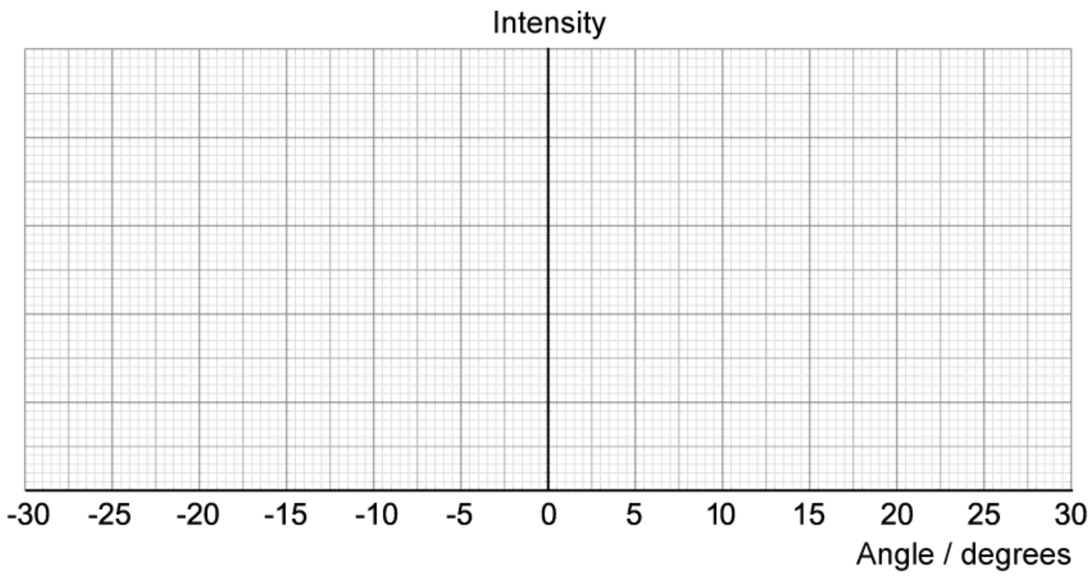
3 (a) An electron beam of energy 1.3×10^{-10} J is used to study the nuclear radius of beryllium-9. The beam is directed from the left at a thin sample of beryllium-9. A detector is placed at an angle θ relative to the direction of the incident beam.



The radius of a beryllium-9 nucleus is 2.9×10^{-15} m. The beryllium-9 nuclei behave like a diffraction grating.

Sketch the expected variation of electron intensity against the angle from the horizontal.



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(3 marks)

(b) The isotope beryllium-10 is formed when a nucleus of deuterium $\left({}^{2}_{1}\text{H}\right)$ collides with a nucleus of beryllium-9 $\left({}^{9}_{4}\text{Be}\right)$. The radius of a deuterium nucleus is 1.5 fm.

(i) Determine the minimum initial kinetic energy, in J, that the deuterium nucleus must have in order to produce the isotope beryllium-10.

[2]

(ii) Outline an assumption made in this calculation.

[1]

(3 marks)

(c) The nucleus of beryllium-9 is replaced by a nucleus of gold-197.

Suggest the change, if any, to the following:

(i) Distance of closest approach of a deuterium nucleus.

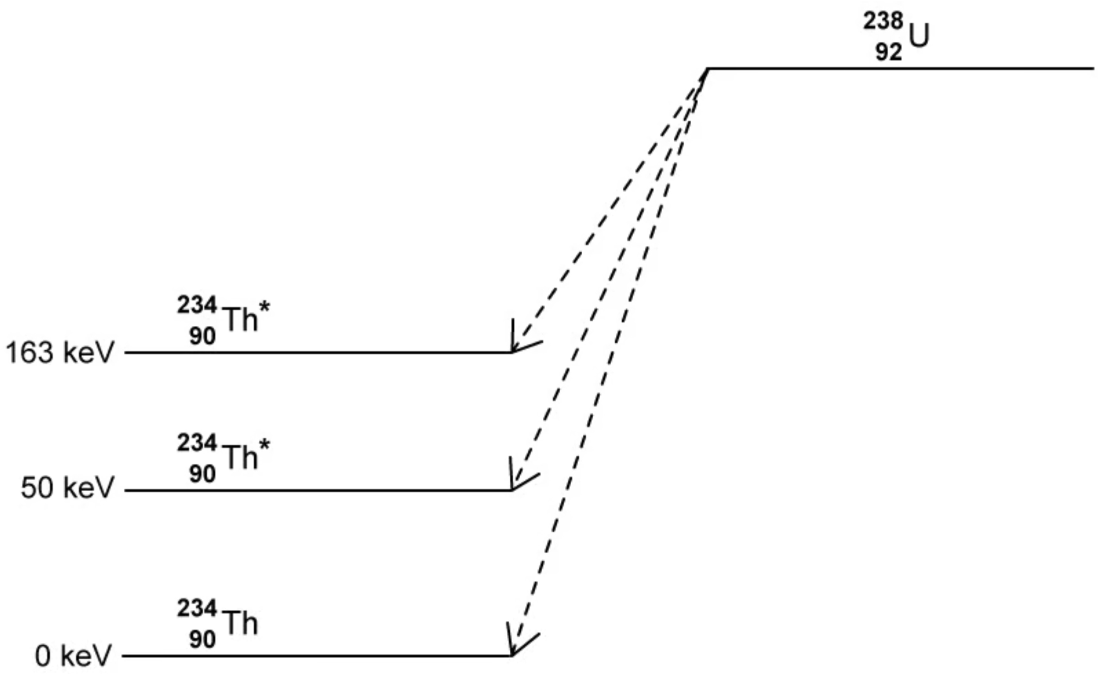
[2]

(ii) Angle of minimum intensity from electron scattering. Assume the electrons have the same energy as in part (a).

[2]

(4 marks)

4 (a) Unstable uranium-238 has various nuclear decay modes to become stable thorium-234. The total amount of energy released when it decays is measured to be 210 keV.



Outline, without calculation, the intermediate decay modes between the unstable uranium-238 to the stable thorium-234.

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(2 marks)

(b) A possible decay chain for uranium-238 is:

$$^{238}_{92}U \rightarrow {}^{234}_{90}Th^* + {}^{4}_{2}\alpha$$

$$^{234}_{90}Th^* \rightarrow {}^{234}_{90}Th^* + \gamma$$

$$^{234}_{90}Th^* \rightarrow {}^{234}_{90}Th + \gamma$$

Calculate the total amount of energy, in joules, carried away as gamma radiation in this decay chain.

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(4 marks)

(c) Deduce an alternative decay chain from unstable uranium-238 to stable thorium-234 which releases the same amount of energy in the form of gamma radiation as in part (b).

Justify your answer with a calculation.

(2 marks)

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5 (a) The half-life of uranium-238 is so long in comparison to any of the isotopes in its decay chain that we can assume the number of lead-206 nuclei, N_{Pb} at any time is equal to the number of uranium-238 that have decayed.

The number of uranium-238 nuclei N_U at time t is given by the equation:

$$N_U = N_0 e^{-\lambda t}$$

Where N_0 is the number of uranium-238 nuclei at t = 0.

Show that the ratio of N_{Pb} to N_U is given by:

$$\frac{N_{Pb}}{N_U} = e^{\lambda t} - 1$$

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(3 marks)

(b) Enriched uranium fuel is a mixture of the fissionable uranium-235 with the more naturally abundant uranium-238. Mixtures of radioactive nuclides such as this are very common in the nuclear power industry.

Two samples of radioactive nuclides X and Y each have an activity of A_0 at t = 0. They are subsequently mixed together.

The half-lives of X and Y are 16 and 8 years respectively.

Show that the total activity of the mixture at time t = 48 years is equal to:

$$\frac{9}{64} A_0$$

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(3 marks)

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