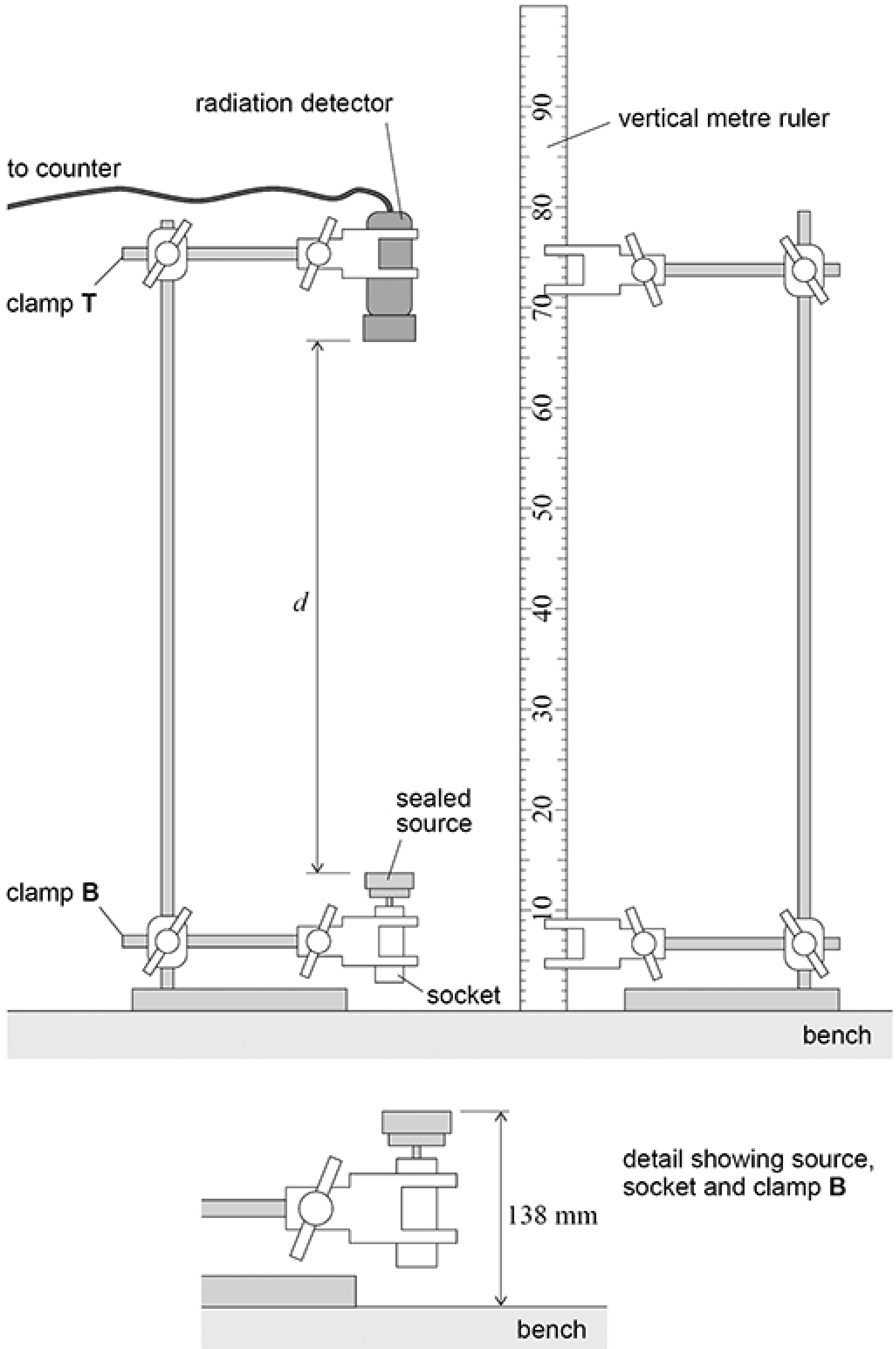
1. **Figure 1** shows apparatus used to investigate the inverse-square law for gamma radiation.

Figure 1



A sealed source that emits gamma radiation is held in a socket attached to clamp **B**. The vertical distance between the open end of the source and the bench is 138 mm. A radiation detector, positioned vertically above the source, is attached to clamp **T**.

A student is told **not** to move the stands closer together.

(a) Describe a procedure for the student to find the value of d, the vertical distance between the open end of the source and the radiation detector.

In your answer, annotate above the figure to show how a set-square can be used in this procedure.

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(2)

(b) Before the source was brought into the room, a background count C_b was recorded.

C_b = 630 counts in 15 minutes

With the source and detector in the positions shown in the figure above, d = 530 mm. Separate counts C_1, C_2 and C_3 are recorded.

C_1 = 90 counts in 100 s
C_2 = 117 counts in 100 s
C_3 = 102 counts in 100 s

R_C is the mean count rate corrected for background radiation.

Show that when d = 530 mm, R_C is about 0.3 s^{-1}.

(2)

(c) The apparatus is adjusted so that d = 380 mm.
Counts are made that show $R_C = 0.76\ s^{-1}$.

The student predicts that:

$$R_C = \frac{k}{d^2}$$

where k is a constant.

Explain whether the values of R_C in parts (b) and (c) support the student's prediction.

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(2)

(d) Describe a safe procedure to reduce d. Give a reason for your procedure.

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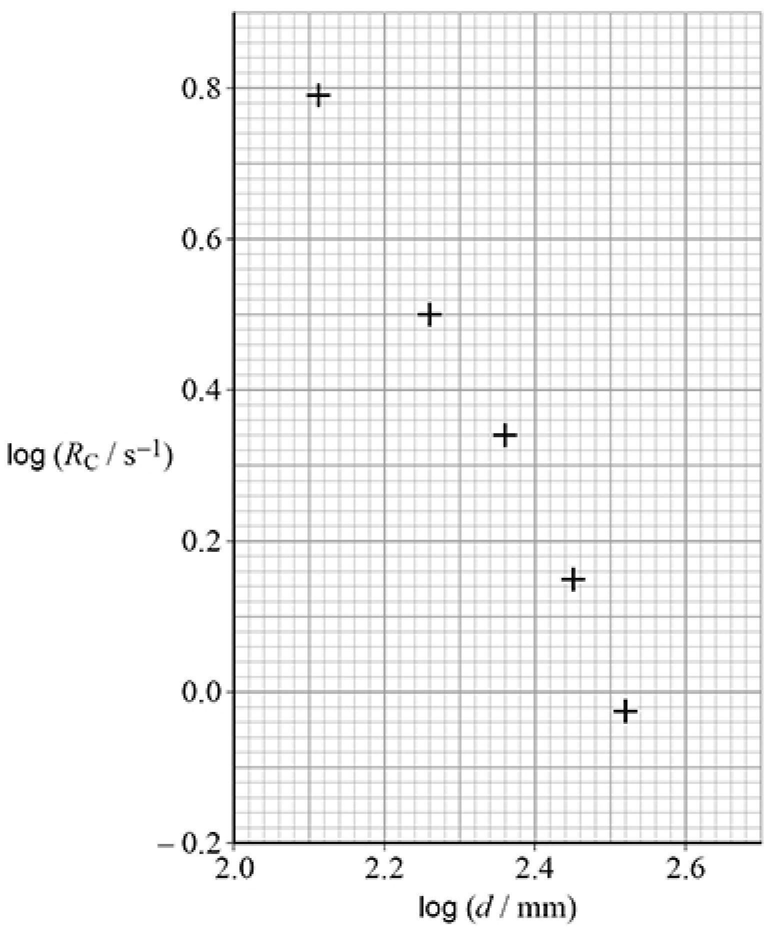
(2)

The student determines R_C for further values of d.
The values of d change by the same amount Δd between each measurement.
Figure 2 shows these data.

Figure 2



(e) Determine Δd.

Δd = ________________ mm

(2)

(f) Explain how the student could confirm whether the graph above supports the prediction:

$$R_C = \frac{k}{d^2}$$

No calculation is required.

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(3)

When a gamma photon is detected by the detector, another photon cannot be detected for a time t_d called the dead time.

It can be shown that:

$$t_d = \frac{R_2 - R_1}{R_1 \times R_2}$$

where R_1 is the measured count rate
R_2 is the count rate when R_1 is corrected for dead time error.

(g) The distance between the source and the detector is adjusted so that d is very small and R_1 is 100 s^{-1}.
On average, two of the gamma photons that enter the detector every second are not detected.

Calculate t_d for this detector.

t_d = ____________________ s

(1)

(h) A student says that if 100 gamma photons enter a detector in one second and t_d is 0.01 s, all the photons should be detected.

Explain, with reference to the nature of radioactive decay, why this idea is **not** correct.

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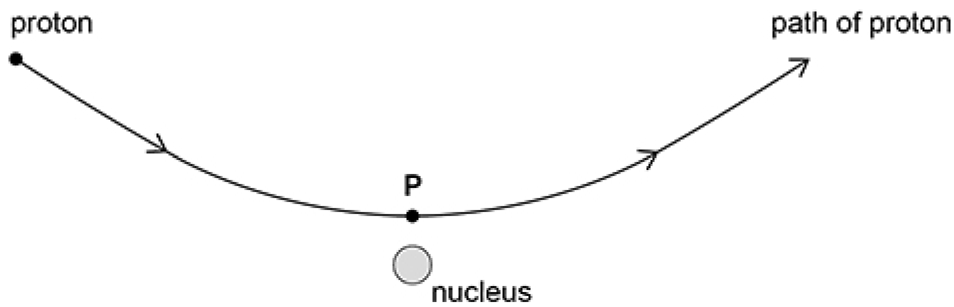
(2)

(Total 16 marks)

2. The diagram shows the path of a proton being deflected by the nucleus of an atom.
Point **P** is the position of the proton when it is closest to the nucleus.



What is **not** true about the proton along its path at **P**?

A Its rate of change of momentum is at a minimum. ☐

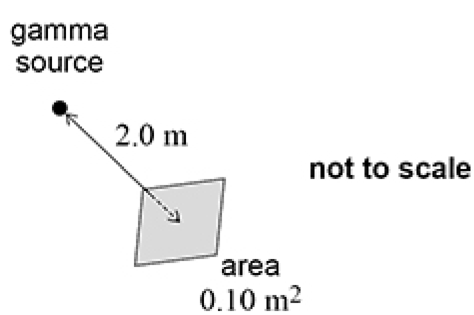
B Its kinetic energy is at a minimum. ☐

C Its potential energy is at a maximum. ☐

D Its acceleration is at a maximum. ☐

(Total 1 mark)

3. The diagram shows an area of 0.10 m^2 normal to a line connecting it to a point source of gamma radiation. The source emits photons uniformly in all directions.
The area and the source are separated by a distance of 2.0 m.



The source emits 5000 gamma photons per second.

How many photons pass through the area every second?

A 500 ☐

B 250 ☐

C 10 ☐

D 2.5 ☐

(Total 1 mark)

4. **X** and **Y** are two radioactive nuclides. **X** has a half-life of 3.0 minutes and **Y** has a half-life of 9.0 minutes.

Two freshly prepared samples of **X** and **Y** start decaying at the same time. After 18 minutes the number of radioactive nuclei in both samples is the same. The sample of **Y** initially contained N radioactive nuclei.

What was the initial number of radioactive nuclei in the sample of **X**?

A $4N$ ⬭

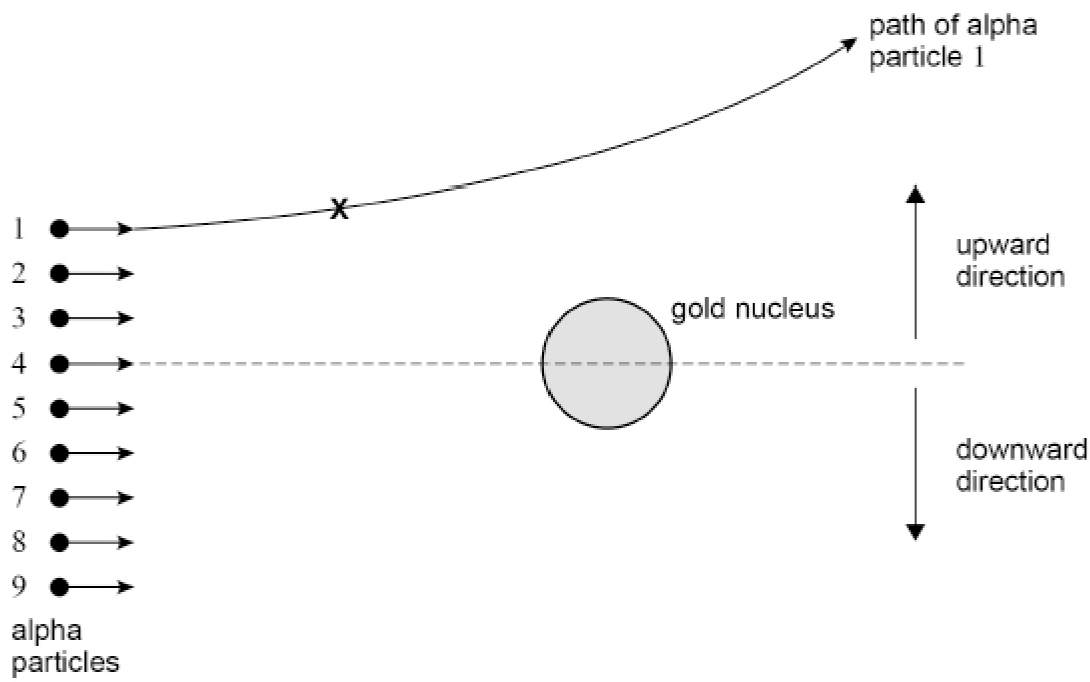
B $16N$ ⬭

C $32N$ ⬭

D $64N$ ⬭

(Total 1 mark)

5. The diagram shows alpha particles all travelling in the same direction at the same speed. The alpha particles are scattered by a gold ($^{197}_{79}\mathrm{Au}$) nucleus.
The path of alpha particle **1** is shown.



(a) State the fundamental force involved when alpha particle **1** is scattered by the nucleus in the diagram.

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(1)

(b) Draw an arrow at position **X** on the diagram above to show the direction of the rate of change in momentum of alpha particle **1**

(1)

(c) Suggest **one** of the alpha particles in the diagram above which may be deflected downwards with a scattering angle of 90°

Justify your answer.

alpha particle number = ________________

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(2)

(d) Alpha particle **4** comes to rest at a distance of 5.5×10^{-14} m from the centre of the $^{197}_{79}Au$ nucleus.

Calculate the speed of alpha particle **4** when it is at a large distance from the nucleus. Ignore relativistic effects.

mass of alpha particle = 6.8×10^{-27} kg

speed = ________________ m s^{-1}

(3)

(e) The nuclear radius of $^{197}_{79}\mathrm{Au}$ is 6.98×10^{-15} m.

Calculate the nuclear radius of $^{107}_{47}\mathrm{Ag}$.

radius = _______________ m

(2)

(f) All nuclei have approximately the same density.

State **one** conclusion about the nucleons in a nucleus that can be deduced from this fact.

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(1)

(Total 10 marks)

6. What is the main purpose of a moderator in a thermal nuclear reactor?

A to shield the surroundings from ionising radiations ⬭

B to decrease the number of fission chain reactions ⬭

C to decrease neutron speeds ⬭

D to prevent the core from overheating ⬭

(Total 1 mark)

7. In the core of a nuclear reactor, the mass of fuel decreases at a rate of 9.0×10^{-6} kg hour^{-1} due to nuclear reactions.

What is the maximum power output of the reactor?

A 2.3×10^{8} W ⬭

B 1.4×10^{11} W ⬭

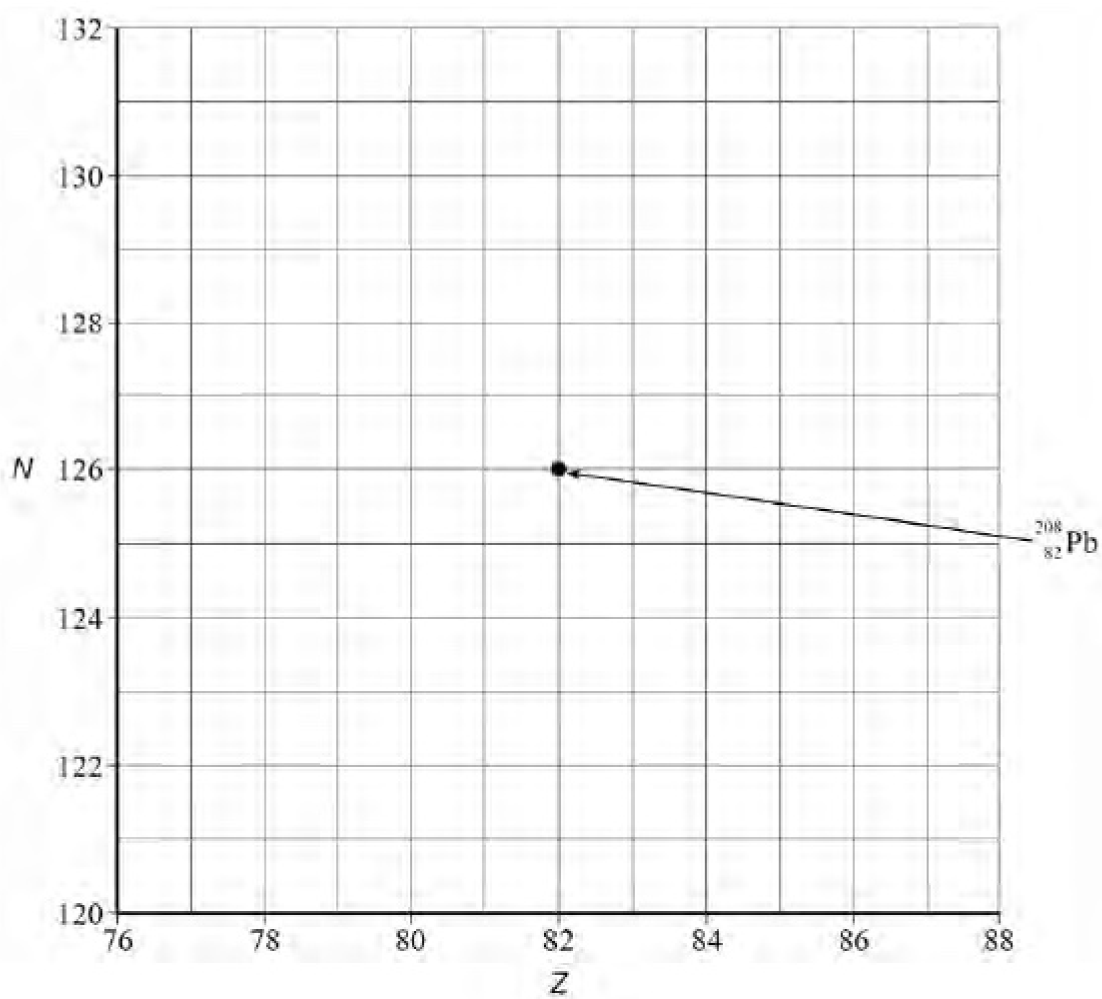
C 8.1×10^{11} W ⬭

D 2.9×10^{15} W ⬭

(Total 1 mark)

8. A nucleus of polonium Po may decay to the stable isotope of lead $^{208}_{82}\mathrm{Pb}$ through a chain of emissions following the sequence α β⁻ β⁻ α.

The graph shows the position of the isotope $^{208}_{82}\mathrm{Pb}$ on a grid of neutron number N against proton number Z.



(a) Draw **four** arrows on the graph to show the sequence of changes to *N* and *Z* that occur as the polonium nucleus is transformed into ${}^{208}_{82}\text{Pb}$.

(2)

(b) A nucleus of the stable isotope ${}^{208}_{82}\text{Pb}$ has more neutrons than protons.

Explain why there is this imbalance between proton and neutron numbers by referring to the forces that operate within the nucleus. Your explanation should include the range of the forces and which particles are affected by the forces.

(4)

(c) Many, but not all, isotopes of lead are stable. For example, ${}^{208}_{82}\text{Pb}$ decays by electron capture to become an isotope of thallium, Tl.

Write the equation to represent this decay, including the isotope of thallium produced.

(1)

(d) The thallium nucleus is formed in an excited state. Electromagnetic radiation is emitted from the thallium atom following its formation.

Explain the origin and location of **two** sources of this radiation.

Source 1 ____

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Source 2 ____

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(2)

(e) Other nuclides also emit electromagnetic radiation.

Explain why the metastable form of the isotope of technetium $^{99}_{43}\mathrm{Tc}$ is a radioactive source suitable for use in medical diagnosis.

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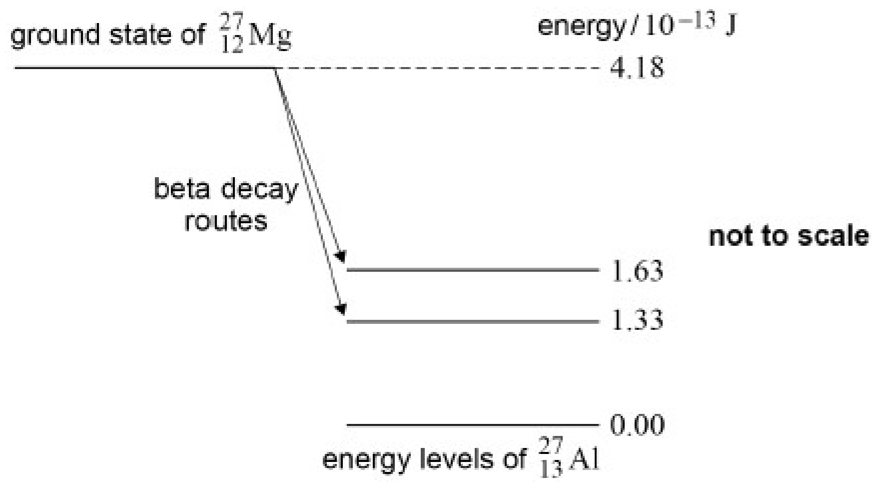
(2)

(Total 11 marks)

9. $^{27}_{12}\text{Mg}$ can decay by beta minus emission to one of two possible excited states of $^{27}_{13}\text{Al}$.

Both excited states decay by the emission of a gamma photon directly to the ground state.



The diagram shows the energy levels and two routes for the beta decay.

One route results in the emission of a gamma photon with a higher frequency than the other photon.

What is the maximum possible kinetic energy for the beta particle emitted in this route?

A 1.33×10^{-13} J ⬭

B 1.63×10^{-13} J ⬭

C 2.55×10^{-13} J ⬭

D 2.85×10^{-13} J ⬭

(Total 1 mark)

10. A point source emits gamma radiation. The intensity I of the radiation is measured at different distances d from the source.

Which graph will show a straight line through the origin?

A I plotted against d ⬭

B I plotted against d^2 ⬭

C I plotted against d^{-1} ⬭

D I plotted against d^{-2} ⬭

(Total 1 mark)

11. A thermal nuclear reactor uses enriched uranium as its fuel.
This is fuel in which the ratio of U-235 to U-238 has been artificially increased from that found in naturally-occurring ore.

(a) Describe what happens when neutrons interact with U-235 and U-238 nuclei in a thermal nuclear reactor.

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(3)

(b) The amounts of U-235 and U-238 in the ore decrease due to radioactive decay at different rates.

A sample of uranium ore today contains 993 g of U-238
The mass of U-238 in this sample was greater 2.00×10^9 years ago.

Show that the mass of U-238 in this sample at that time was about 1.4 kg.

decay constant of U-238 = 1.54×10^{-10} year^{-1}

(2)

(c) A thermal nuclear reactor requires a minimum of 3.0% of its uranium mass to be U-235

The ratio of U-235 to U-238 in the ore has changed over time.
2.00×10^9 years ago, the sample in part (b) contained 52 g of U-235

Deduce whether the sample had a high enough U-235 content to be used in a reactor 2.00×10^9 years ago.

(1)

(Total 6 marks)

12. The mass of the fuel in a fission reactor decreases at a rate of 6.0×10^{-6} kg hour^{-1}.

What is the maximum possible power output of the reactor?

A 75 MW

B 150 MW

C 300 MW

D 9000 MW

(Total 1 mark)

13. The table shows the masses of three particles.

Particle	Mass / u
proton	1.00728
neutron	1.00867
nucleus of lithium $^{7}_{3}\mathrm{Li}$	7.01436

What is the mass difference of a $^{7}_{3}\mathrm{Li}$ nucleus?

A 4.99841 u ⬭

B 0.04216 u ⬭

C 0.04147 u ⬭

D 0.04077 u ⬭

(Total 1 mark)

14. When a small radioactive source is placed in a cloud chamber, straight tracks about 4 cm long are observed. The same source is placed 10 cm from a Geiger tube and a count rate is detected. When a sheet of aluminium 5 mm thick is placed between the source and the Geiger tube the count rate falls to the background count rate.

Which types of radiation are emitted by the source?

A α, β and γ ⬭

B β and γ ⬭

C α and γ ⬭

D α and β ⬭

(Total 1 mark)

15. A thermal nuclear reactor uses a moderator to lower the kinetic energy of fast-moving neutrons.

(a) Explain why the kinetic energy of neutrons must be reduced in a thermal nuclear reactor.

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(1)

(b) As a result of a collision with an atom of a particular moderator, a neutron loses 63% of its kinetic energy.

A neutron has an initial kinetic energy of 2.0 MeV.

Calculate the kinetic energy of the neutron after five collisions.

kinetic energy = ____________________ eV

(2)

(c) The kinetic energy of a neutron in a thermal nuclear reactor is reduced from about 2 MeV to about 1 eV.

Explain why the number of collisions needed to do this depends on the nucleon number of the moderator atoms.

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(2)

(d) One fission process which can occur in a thermal nuclear reactor is represented by the equation

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} = ^{142}_{54}\mathrm{Xe} + ^{90}_{38}\mathrm{Sr} + 4^{1}_{0}\mathrm{n}$$

Calculate in MeV the energy released in this fission process.

mass of $^{235}_{92}\mathrm{U}$ = 235.044 u

mass of $^{142}_{54}\mathrm{Xe}$ = 141.930 u

mass of $^{90}_{38}\mathrm{Sr}$ = 89.908 u

mass of $^{1}_{0}\mathrm{n}$ = 1.0087 u

energy released = ____________________ MeV

(3)

(e) Many magazine and newspaper articles focus on the risks of using nuclear power.

State **three benefits** of using nuclear power.

1 ____

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2 ____

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3 ____

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(3)

(Total 11

16. The number of parent nuclei in a sample of a radioactive element is N at time t. The radioactive element has a half-life $t_{\frac{1}{2}}$

The rate of decay is proportional to

A N ⬭

B t ⬭

C $\frac{1}{t}$ ⬭

D $t_{\frac{1}{2}}$ ⬭

(Total 1 mark)

17. A deuterium nucleus and a tritium nucleus fuse together to form a helium nucleus and a particle **X**. The equation for this process is:

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + X$$

What is **X**?

A electron ⬭

B neutron ⬭

C positron ⬭

D proton ⬭

(Total 1 mark)

18. What effect are the control rods intended to have on the average kinetic energy and number of fission neutrons in a thermal nuclear reactor?

	Average kinetic energy of fission neutrons	Number of fission neutrons	
A	unchanged	unchanged	⬭
B	reduced	unchanged	⬭
C	unchanged	reduced	⬭
D	increased	reduced	⬭

(Total 1 mark)

19. **Figure 1** shows a sealed radioactive source used in schools and colleges.

Figure 1

(a) State **two** safety procedures to reduce risk when using this type of source.

Safety procedure 1 ____

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Safety procedure 2 ____

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(2)

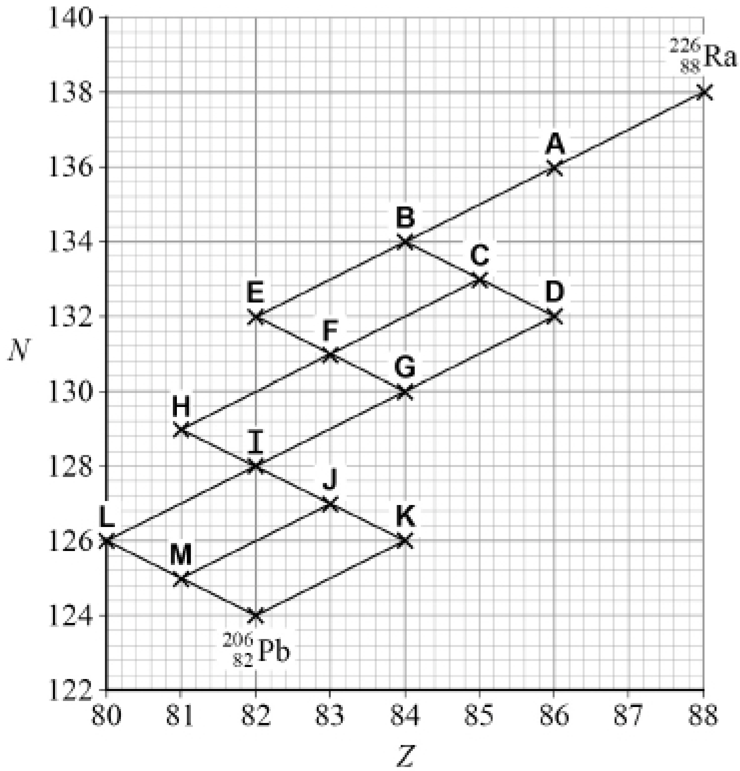
(b) A sealed source contains radium-226 ($^{226}_{88}Ra$).

$^{226}_{88}Ra$ decays by emitting α and β⁻ particles to produce $^{206}_{82}Pb$ which is stable.

Figure 2 is a graph of neutron number N against proton number Z, showing the different ways that $^{226}_{88}Ra$ can decay into $^{206}_{82}Pb$.

Points **A** to **M** represent **all** the unstable nuclei that may be formed as $^{226}_{88}Ra$ decays into $^{206}_{82}Pb$.

Figure 2



Determine the number of routes by which **B** can change into **K**.

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(1)

(c) Identify which of the nuclei **A** to **M** are common to all the possible ways that $^{226}_{88}Ra$ decays into $^{206}_{82}Pb$.

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(3)

(d) The sealed source emits γ radiation in addition to α and β^- particles.

A student uses the sealed source to investigate the inverse-square law for γ radiation.

The student begins by making measurements to find the count rate A_b for the background radiation.

State and explain procedures

- to eliminate systematic error in the measurements used to find A_b
- to reduce the percentage uncertainty in A_b.

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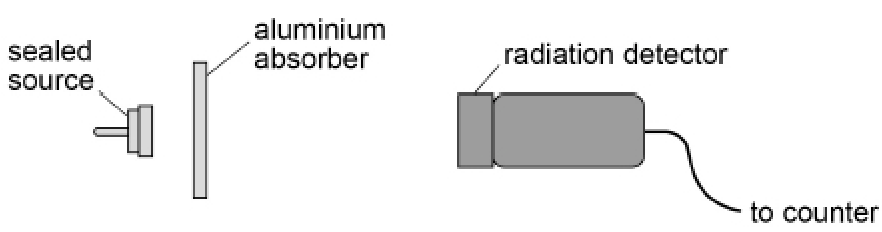
(3)

(e) **Figure 3** shows an aluminium absorber placed between the sealed source and a radiation detector. This is to make sure that only γ radiation from the source reaches the detector.

Figure 3

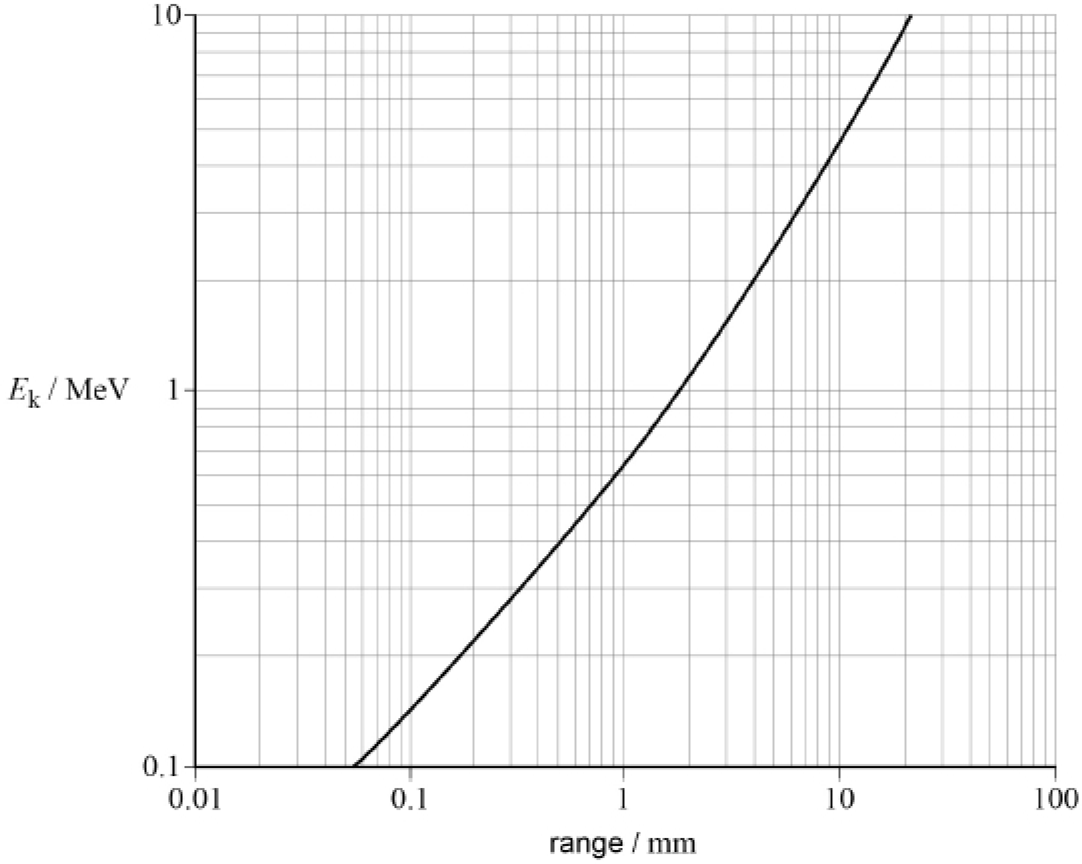


The sealed source emits:

- α particles with energy E_k between 3.8 MeV and 7.8 MeV
- β^- particles with energy E_k between zero and 5.5 MeV.

Figure 4 shows how the range of β^- particles in aluminium depends on E_k.

Figure 4



Deduce the minimum thickness of the aluminium absorber that should be used in the experiment.

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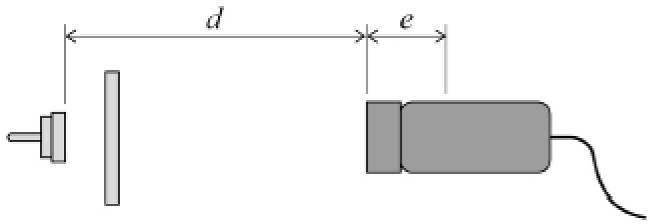
minimum thickness = ____________________ mm

(3)

(f) Ionisation takes place inside the detector. The effective distance travelled by γ radiation from the source is $(d + e)$.

The distance e, shown in **Figure 5**, cannot be measured directly.

Figure 5



From the inverse-square law for γ radiation, it can be shown that

$$(d + e) = \sqrt{\frac{k}{A}}$$

where A is the count rate, corrected for background radiation
k is a constant.

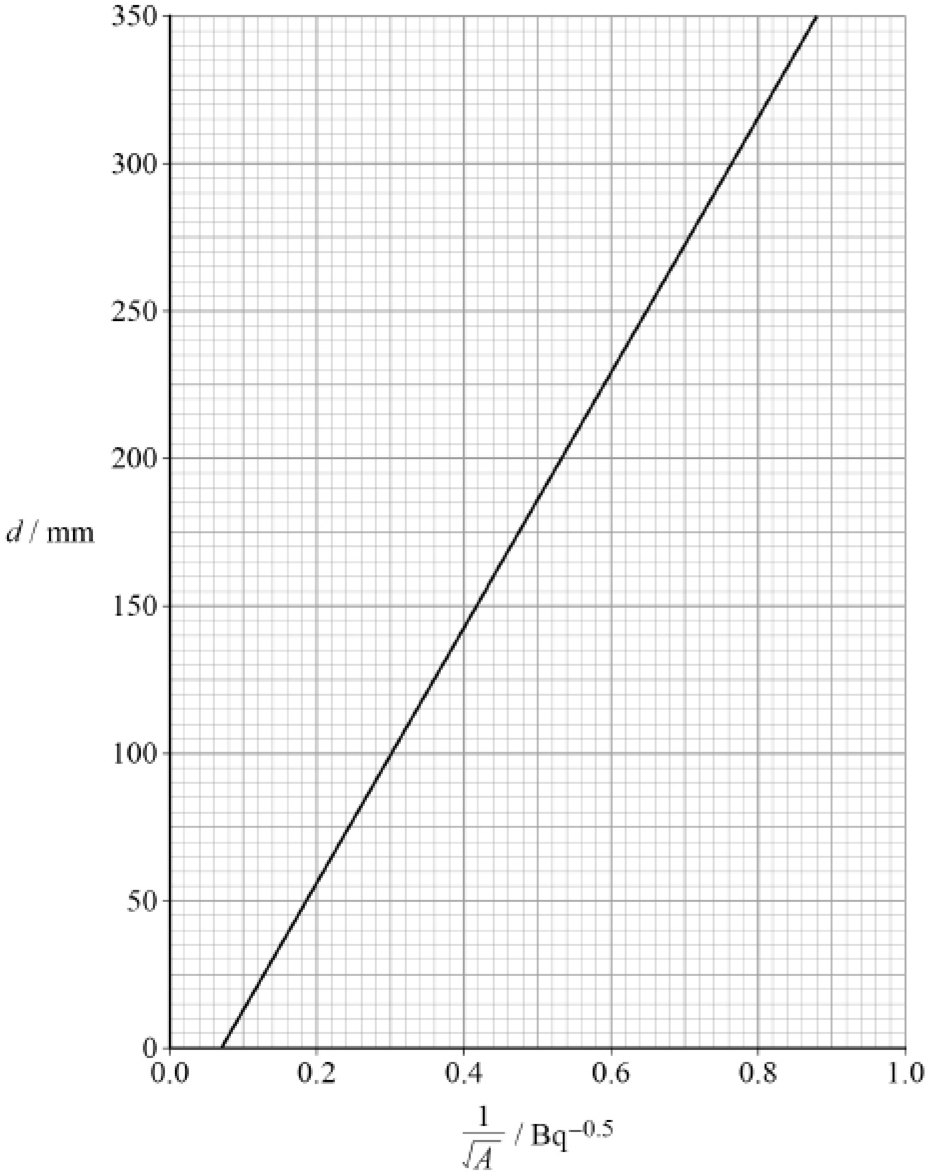
The student plots the graph of d against $\frac{1}{\sqrt{A}}$ shown in **Figure 6**.

Deduce k using **Figure 6**.
Explain your reasoning.
Give a suitable unit for your result.

k = ____________________ unit ________

(5)

Figure 6



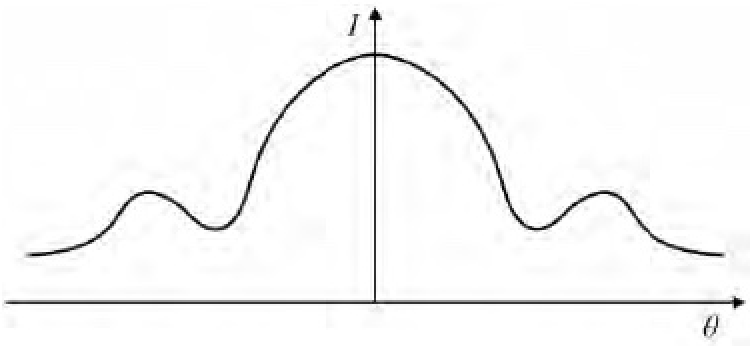
(g) Determine e using **Figure 6**.

e = ____________________ mm

(2)

(Total 19 marks)

20. Which graph shows how intensity I varies with angle θ when electrons are diffracted by a nucleus?

A 

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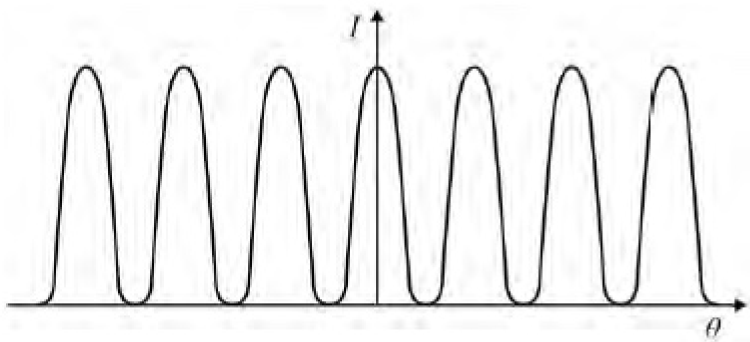
B 

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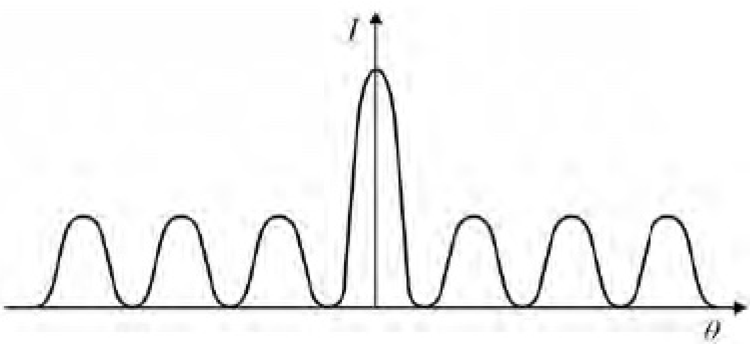
C 

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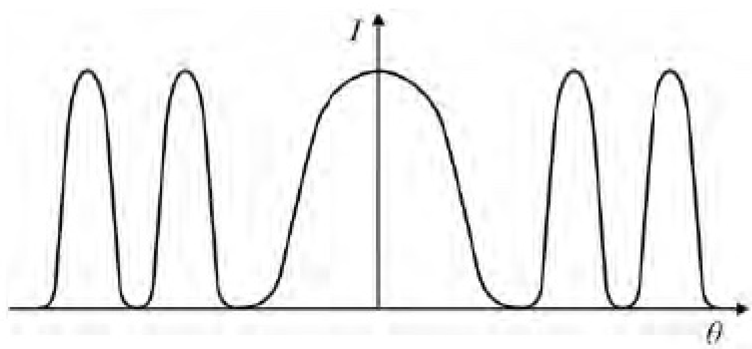
D 

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(Total 1 mark)

21. The radius of a uranium $^{238}_{92}U$ nucleus is 7.75×10^{-15} m

What is the radius of a $^{12}_{6}C$ nucleus?

A 1.10×10^{-18} m ⬭

B 3.91×10^{-16} m ⬭

C 2.86×10^{-15} m ⬭

D 3.12×10^{-15} m ⬭

(Total 1 mark)

22. (a) Suggest, with a reason, which type of radiation is likely to be the most appropriate for the sterilisation of metallic surgical instruments.

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(1)

(b) Explain why the public need not worry that irradiated surgical instruments become radioactive once sterilised.

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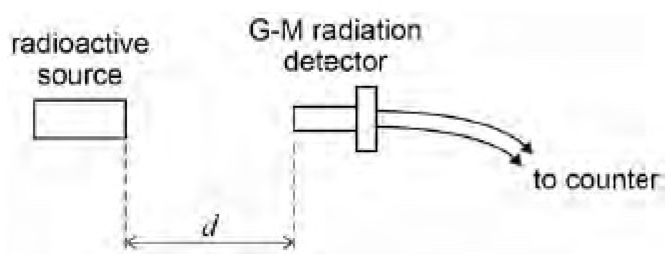
(1)

(c) A student detects the counts from a radioactive source using a G-M radiation detector as shown in the diagram.



The student measures the count rate for three different distances d. The table shows the count rate, in counts per minute, corrected for background for each of these distances.

d/m	**Corrected count rate / counts per minute**			
0.20	9013			
0.50	1395			
1.00	242			

Explain, with the aid of suitable calculations, why the data in the table are **not** consistent with an inverse-square law. You may use the blank columns for your working.

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(2)

(d) State **two** possible reasons why the results do **not** follow the expected inverse-square law.

Reason 1 ____

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Reason 2 ____

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(2)

(Total 6 marks)

23. During a single fission event of uranium-235 in a nuclear reactor the total mass lost is 0.23 u. The reactor is 25% efficient.

How many events per second are required to generate 900 MW of power?

A 1.1×10^{14} ☐

B 6.6×10^{18} ☐

C 1.1×10^{20} ☐

D 4.4×10^{20} ☐

(Total 1 mark)

24. Which of the following substances can be used as a moderator in a nuclear reactor?

A Boron ☐

B Concrete ☐

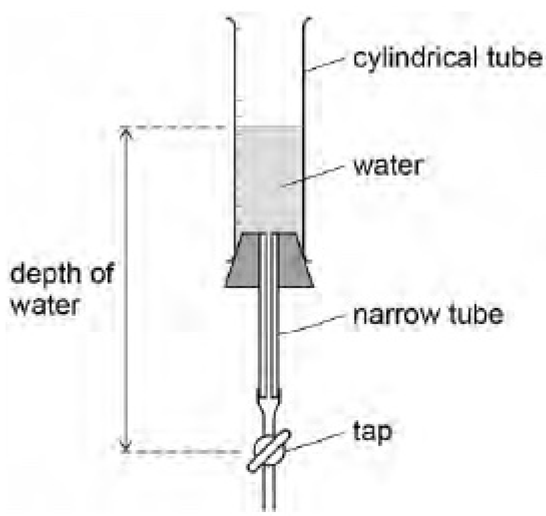
C Uranium-238 ☐

D Water ☐

(Total 1 mark)

25. **Figure 1** shows how radioactive decay of one nuclide can be modelled by draining water through a tap from a cylindrical tube.

Figure 1

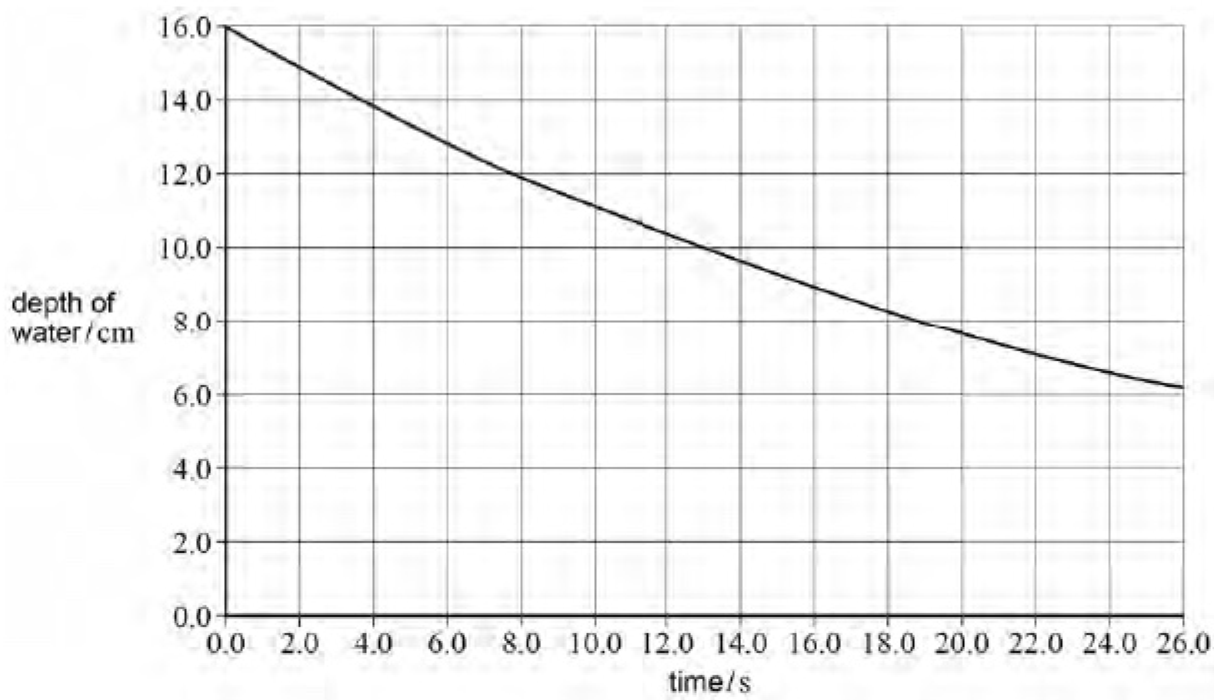


The water flow-rate is proportional to the pressure of the water. The pressure of the water is proportional to the depth of the water. Therefore the rate at which the depth decreases is proportional to the depth of the water.

Before the tap is opened the depth is 16.0 cm

The tap is opened and the depth is measured at regular intervals. These data are plotted on the graph in **Figure 2**.

Figure 2



(a) Determine the predicted depth of water when the time is 57 s

depth = ____________________ cm

(1)

(b) Suggest how the apparatus in **Figure 1** may be changed to represent a radioactive sample of the same nuclide with a greater number of nuclei.

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(1)

(c) Suggest how the apparatus in **Figure 1** may be changed to represent a radioactive sample of a nuclide with a smaller decay constant.

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(d) The age of the Moon has been estimated from rock samples containing rubidium (Rb) and strontium (Sr), brought back from Moon landings.

$^{87}_{37}Rb$ decays to $^{87}_{38}Sr$ with a radioactive decay constant of 1.42×10^{-11} year^{-1}

Calculate, in years, the half-life of $^{87}_{37}Rb$

half-life = ____________________ years

(1)

(e) A sample of Moon rock contains 1.23 mg of $^{87}_{37}Rb$.

Calculate the mass, in g, of $^{87}_{37}Rb$ that the rock sample contained when it was formed 4.47×10^9 years ago.

Give your answer to an appropriate number of significant figures.

mass = ____________________ g

(3)

(f) Calculate the activity of a sample of $^{87}_{37}Rb$ of mass 1.23 mg

Give an appropriate unit for your answer.

activity = ____________________ unit ___________

(3)

(Total 10

26. The Rutherford scattering experiment led to

A the discovery of the electron. ⬭

B the quark model of hadrons. ⬭

C the discovery of the nucleus. ⬭

D evidence for wave-particle duality. ⬭

(Total 1 mark)

27. A Geiger counter is placed near a radioactive source and different materials are placed between the source and the Geiger counter.

The results of the tests are shown in the table.

Material	Count rate of Geiger counter / s^{-1}
None	1000
Paper	1000
Aluminium foil	250
Thick steel	50

What is the radiation emitted by the source?

A α only ⬭

B α and γ ⬭

C α and β ⬭

D β and γ ⬭

(Total 1 mark)

28. The core of a thermal nuclear reactor contains a number of components that are exposed to moving neutrons.

(a) State what happens to a neutron that is incident on the moderator.

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(1)

(b) State what happens to a neutron that is incident on a control rod.

____

____

(1)

(c) A slow-moving neutron is in collision with a nucleus of an atom of the fuel which causes fission.

Describe what happens in the process.

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(3)

(d) A thermal nuclear reactor produces radioactive waste.

State the source of this waste and discuss some of the problems faced in dealing with the waste at various stages of its treatment.

Your answer should include:

- the main source of the most dangerous waste
- a brief outline of how waste is treated
- problems faced in dealing with the waste, with suggestions for overcoming these problems.

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(6)

(Total 11 marks)

29. Nobelium-259 has a half-life of 3500 s.

What is the decay constant of nobelium-259?

A 8.7×10^{-5} s^{-1} ☐

B 2.0×10^{-4} s^{-1} ☐

C 1.7×10^{-2} s^{-1} ☐

D 1.2×10^{-2} s^{-1} ☐

(Total 1 mark)

30. A pure sample of nuclide **X** containing N nuclei has an activity A.
The half-life of **X** is 6000 years.

A pure sample of nuclide **Y** containing $3N$ nuclei has an activity $6A$.

What is the half-life of nuclide **Y**?

A 1000 years ⬭

B 3000 years ⬭

C 12 000 years ⬭

D 18 000 years ⬭

(Total 1 mark)

31. (a) Calculate the binding energy, in MeV, of a nucleus of $^{59}_{27}Co$.

nuclear mass of $^{59}_{27}Co$ = 58.93320 u

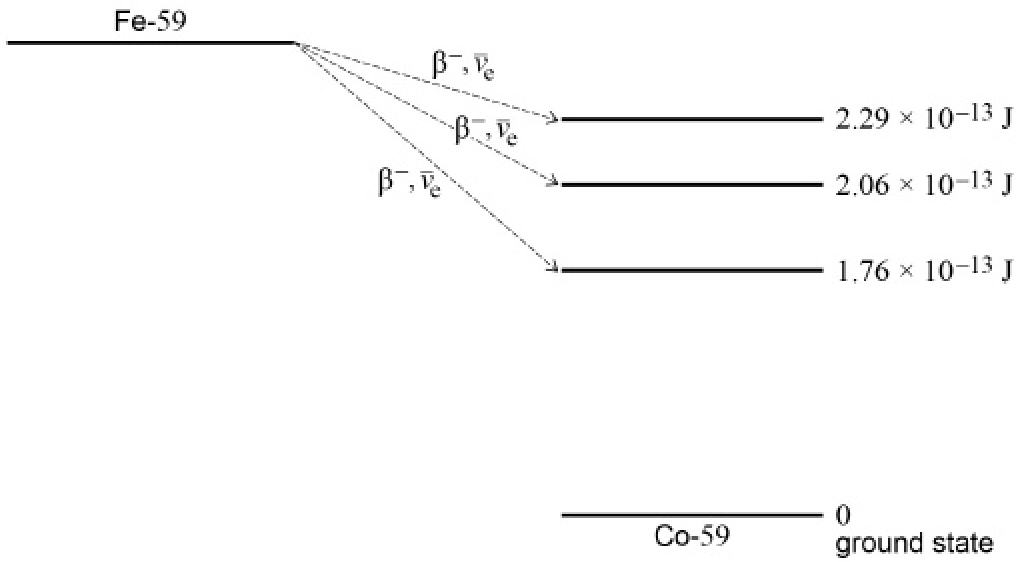
binding energy = ______________________ MeV

(3)

(b) A nucleus of iron Fe-59 decays into a stable nucleus of cobalt Co-59. It decays by β^- emission followed by the emission of γ-radiation as the Co-59 nucleus de-excites into its ground state.

The total energy released when the Fe-59 nucleus decays is 2.52×10^{-13} J.

The Fe-59 nucleus can decay to one of three excited states of the cobalt-59 nucleus as shown below. The energies of the excited states are shown relative to the ground state.



Calculate the maximum possible kinetic energy, in MeV, of the β^- particle emitted when the Fe-59 nucleus decays into an excited state that has energy above the ground state.

maximum kinetic energy = ____________________ MeV

(2)

(c) Following the production of excited states of $^{59}_{27}Co$, γ-radiation of discrete wavelengths is emitted.

State the maximum number of discrete wavelengths that could be emitted.

maximum number = ____________________

(d) Calculate the longest wavelength of the emitted γ-radiation.

Longest wavelength = ____________________ m

(3)

(Total 9 marks)

32. Cobalt-60 has a half-life of 5.27 years.

What is the total activity of 1.0 g of cobalt-60?

A 4.2×10^{13} Bq ☐

B 2.2×10^{14} Bq ☐

C 2.5×10^{15} Bq ☐

D 1.3×10^{21} Bq ☐

(Total 1 mark)

33. The radius of a nucleus of the iron nuclide $^{56}_{27}Fe$ is 4.35×10^{-15} m.

What is the radius of a nucleus of the uranium nuclide $^{238}_{92}U$?

A 2.69×10^{-15} m ☐

B 2.89×10^{-15} m ☐

C 6.55×10^{-15} m ☐

D 7.05×10^{-15} m ☐

(Total 1 mark)

34. Uranium-236 undergoes nuclear fission to produce barium-144, krypton-89 and three free neutrons.

What is the energy released in this process?

Nuclide	**Binding energy per nucleon / MeV**
$^{236}_{92}U$	7.5
$^{144}_{56}Ba$	8.3
$^{89}_{36}Kr$	8.6

A 84 MeV ⬭

B 106 MeV ⬭

C 191 MeV ⬭

D 3730 MeV ⬭

(Total 1 mark)