Nuclear and Particle Physics

1. When a nucleus of uranium-238 absorbs a neutron, one combination of fission products can be tin-126 and a nucleus of element **X**. 13 neutrons are also emitted.

$$^{238}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow \mathbf{X} + {}^{126}_{50}\text{Sn} + 13\,{}^{1}_{0}\text{n}$$

How many neutrons are there in the nucleus of element **X**?

A. 30
B. 42
C. 58
D. 100

Your answer

[1]

2. The total energy released in a single fusion reaction is 4.0 MeV.

What is the change in mass in this fusion reaction?

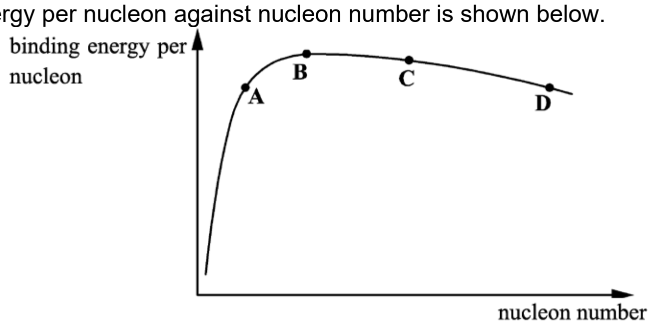
A 7.1×10^{-36} kg
B 7.1×10^{-30} kg
C 2.1×10^{-21} kg
D 4.4×10^{-17} kg

Your answer **[1]**

3. State what is meant by the *decay constant* of an isotope.

[1]

4. A graph of binding energy per nucleon against nucleon number is shown below.



Which nucleus, **A**, **B**, **C**, or **D**, shown on the graph has the largest magnitude of binding energy?

Your answer

[1]

5. The nuclei of uranium-235 ($^{235}_{92}U$) and carbon-12 ($^{12}_{6}C$) have different radii.

What is the ratio

$$\frac{\text{radius of the uranium nucleus}}{\text{radius of the carbon nucleus}}?$$

A 2.5
B 2.7
C 15
D 20

Your answer

[1]

6. A contrast material is used while taking an X-ray image of a patient.
Which statement is correct?

A Iodine is a contrast material.
B Technetium is a contrast material.
C A contrast material must have a short half-life.
D A contrast material is used for acoustic matching.

Your answer **[1]**

7. A positive pion (π^+) is an unstable particle produced when high-speed hadrons collide in particle accelerators.
The π^+ particle has a charge of +*e*.

What is the quark combination of the π^+ particle?

A $u\,\bar{u}$
B $u\,\bar{d}$
C $d\,\bar{u}$
D $d\,\bar{d}$

Your answer

[1]

8. Which lepton is emitted in the decay of an up quark and is affected by a magnetic field?

A neutrino
B electron
C positron
D antineutrino

Your answer **[1]**

9. The table shows data on four freshly prepared radioactive samples **A**, **B**, **C** and **D**.

Sample	Number of active nuclei in the sample	Half-life of the sample
A	N	T
B	N	$3T$
C	$5N$	$0.5T$
D	$8N$	$4T$

Which sample has the **smallest** activity?

Your answer

[1]

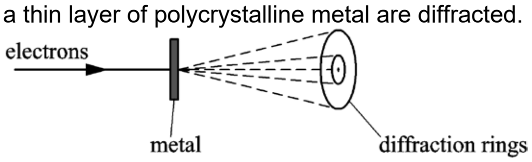
10. The table below shows the quark compositions of four particles **A**, **B**, **C** and **D**.

A	B	C	D
u u d	u d d	u d s	s s s

Which particle has a positive charge?

Your answer **[1]**

11. Electrons travelling through a thin layer of polycrystalline metal are diffracted.



Which statement is correct about these electrons?

A. The electrons travel as photons through the metal.
B. The electrons have a wavelength of about 10^{-10} m.
C. The electrons are diffracted by holes in the metal.
D. The electrons repel each other to produce the diffraction.

Your answer

[1]

12. A proton collides with a stationary oxygen-18 nucleus. The collision produces a fluorine-18 nucleus and particle X.

$$^{1}_{1}p + ^{18}_{8}O \rightarrow ^{18}_{9}F + X$$

What is particle X?

A neutron
B proton
C electron
D positron

Your answer **[1]**

13. A student is modelling the decay of a radioactive source using the equation $\Delta N / \Delta t = -0.5 N$.
The student decides to use $\Delta t = 0.10$ s.
The number N of radioactive nuclei is 2000 at $t = 0$.

Part of the modelling spreadsheet from the student is shown below.

***t* / s**	**Number *N* of radioactive nuclei remaining at time *t***	**Number of nuclei decaying in the next 0.10 s**
0	2000	100
0.10	1900	
0.20		
0.30		

What is the value of N at $t = 0.30$ s?

A 1700
B 1710
C 1715
D 1805

Your answer [1]

14. Which statement is correct?

A Hadrons are made up of protons and neutrons.
B A positron and a proton are examples of leptons.
C The positron and the electron have the same mass.
D The weak nuclear force is responsible for alpha-decay.

Your answer [1]

15. The radius of a gold nucleus with 197 nucleons is 7.3×10^{-15} m.

What is the best estimate for the volume of a uranium nucleus with 235 nucleons?

A 1.6×10^{-42} m^3
B 1.9×10^{-42} m^3
C 2.1×10^{-42} m^3
D 2.8×10^{-42} m^3

Your answer [1]

16. Two leptons are emitted when a down quark decays into an up quark.

Which of the following is correct about this decay?

	force responsible for the decay	**leptons emitted**
A	strong nuclear	positron and antineutrino
B	weak nuclear	positron and neutrino
C	strong nuclear	electron and neutrino
D	weak nuclear	electron and antineutrino

Your answer ☐

[1]

17. A radiation detector is placed in front of a beta-emitting source.
The count-rate is measured and recorded every 10 minutes.
The results are shown below.

$311\ s^{-1}$ $309\ s^{-1}$ $299\ s^{-1}$ $307\ s^{-1}$ $321\ s^{-1}$

What term can be used to describe the data shown?

A exponential
B linear
C random
D spontaneous

Your answer ☐ **[1]**

18. The nucleus of thorium-232 $\left({}^{232}_{90}\mathrm{Th}\right)$ emits two alpha particles and two beta-minus particles to become a nucleus of an isotope of radium.

What is the nucleon number *A* and the proton number *Z* for the nucleus of this radium isotope?

A A = 224, Z = 88
B A = 228, Z = 86
C A = 224, Z = 84
D A = 228, Z = 88

Your answer ☐ **[1]**

19. Which is the correct decay of a quark?

A $u \rightarrow d + {}^{0}_{-1}e + \overline{\nu_e}$

B $u \rightarrow d + {}^{0}_{-1}e + \nu_e$

C $d \rightarrow u + {}^{0}_{-1}e + \nu_e$

D $d \rightarrow u + {}^{0}_{-1}e + \overline{\nu_e}$

Your answer

[1]

20. State what is meant by *induced nuclear fission*.

---

[1]

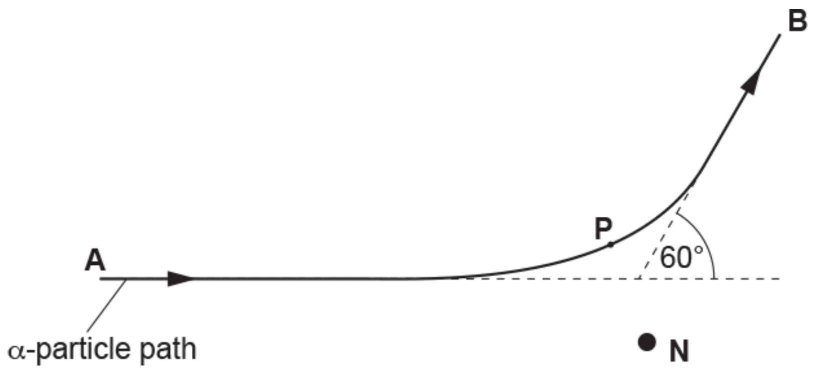
21. Write a decay equation for beta-minus in terms of a quark model.

[2]

22. A beam of α-particles is incident on a thin gold foil. Most α-particles pass straight through the foil. A few are deflected by gold nuclei.

The diagram shows the path of one α-particle which passes close to a gold nucleus **N** in the foil. The α-particle is deflected through an angle of 60° as it travels from **A** to **B**.

P marks its position of closest approach to the gold nucleus.



Another α-particle in the beam is deflected by the same gold nucleus **N** through an angle of 30°.

Sketch its path onto the diagram above. **[2]**

23. A radioactive substance has 2000 nuclei. The decay constant of the isotope of the substance is 0.10 s^{-1}.

Use the equation $\frac{\Delta N}{\Delta t} = -\lambda N$ and Δt = 1.0 s to estimate the number of nuclei left after time t = 2.0 s.

number of nuclei left = ... **[2]**

24. Fig. 21 shows stable and unstable nuclei of some light elements plotted on a grid. This grid has number of neutrons *N* on the vertical axis and number of protons *Z* on the horizontal axis.

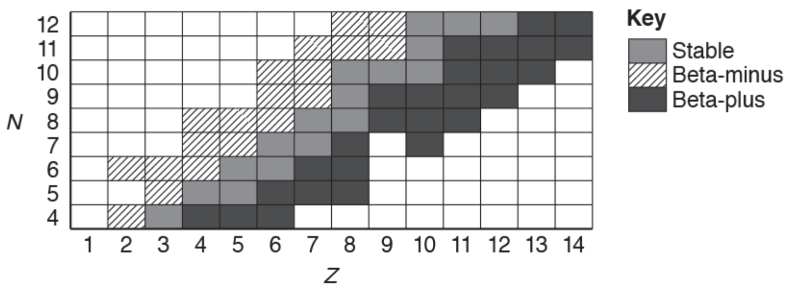


Fig. 21

The key on Fig. 21 shows whether a nucleus is stable, emits a beta-plus particle or emits a beta-minus particle to become stable.

For *Z* = 7, suggest in terms of *N* why an isotope may emit

i. a beta-minus particle

[1]

ii. a beta-plus particle.

[1]

25 (a). A stationary uranium-238 nucleus $\left({}^{238}_{92}\mathrm{U}\right)$ decays into a nucleus of thorium-234 by emitting an alpha-particle.

The chemical symbol for thorium is Th. Write a nuclear equation for this decay.

[2]

(b). The mass of the uranium nucleus is 4.0×10^{-25} kg. After the decay the thorium nucleus has a speed of 2.4×10^{5} m s^{-1}.

Calculate the kinetic energy, in MeV, of the alpha-particle.

kinetic energy = ... MeV **[4]**

(c). The uranium-238 $\left({}^{238}_{92}\mathrm{U}\right)$ nucleus starts the decay chain which ends with a nucleus of lead-206 $\left({}^{206}_{82}\mathrm{Pb}\right)$. Show that 14 particles are emitted during this decay chain. Explain your reasoning.

[3]

26 (a). Stars produce energy by nuclear fusion.
One particular fusion reaction between two protons $\left({}^{1}_{1}\mathrm{H}\right)$ is shown below.

$${}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{2}_{1}\mathrm{H} + {}^{0}_{+1}\mathrm{e} + \nu$$

In this reaction 2.2 MeV of energy is released.

Only one of the particles shown in the reaction has binding energy.
Determine the binding energy per nucleon of this particle. Explain your answer.

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[2]

(b). Explain why high temperatures are necessary for fusion reactions to occur in stars.

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[2]

(c). In this reaction 2.2 MeV of energy is released.

A gamma photon in a star can spontaneously create an electron-positron pair.
Calculate the **maximum** wavelength of a gamma photon for this creation event.

maximum wavelength = ... m **[3]**

27 (a). Describe the nature of the *strong nuclear force*.

---

[2]

(b).

i. Name a hadron found in the nucleus of an atom and state its quark combination.

name of hadron: ....   quark combination: ....   **[1]**

ii. Write a decay equation in terms of a quark model for beta-minus decay.

[2]

(c). The radius of a nucleus is directly proportional to $A^{1/3}$, where A is the nucleon number.
The mass of a proton and a neutron are similar.
Explain why the mean density of all nuclei is about the same.

---

[2]

28. A researcher is doing an experiment on a radioactive solution in a thin **glass** tube.
The solution has two radioactive materials **X** and **Y**.
The table below shows some data on these two materials.

	Material X	**Material Y**
Half-life	10 minutes	10 hours
Particles emitted	Alpha	Beta-minus
Daughter nuclei	Stable	Stable

The solution has the same number of nuclei of **X** and **Y** at the start.

i. State and explain which material has the greatest activity at the start.

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[1]

ii. State why it is dangerous for the researcher to handle the test tube with bare hands.

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[1]

29. Fig. 24 shows two horizontal metal plates in a vacuum.

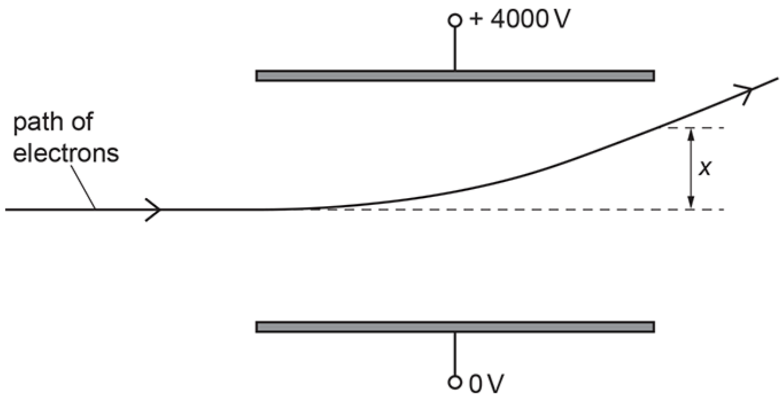

Fig. 24

The arrangement shown in **Fig. 24** is now used to investigate positrons emitted from a radioactive source.
The speed of the positrons is also 6.0×10^{7} m s^{-1}.

The initial path of the positrons is the same as that of the electrons in **Fig. 24**.

On **Fig. 24**, sketch the path of the positrons between the plates. **[2]**

30. Explain the function of the control rods and the moderator in a nuclear fission reactor.

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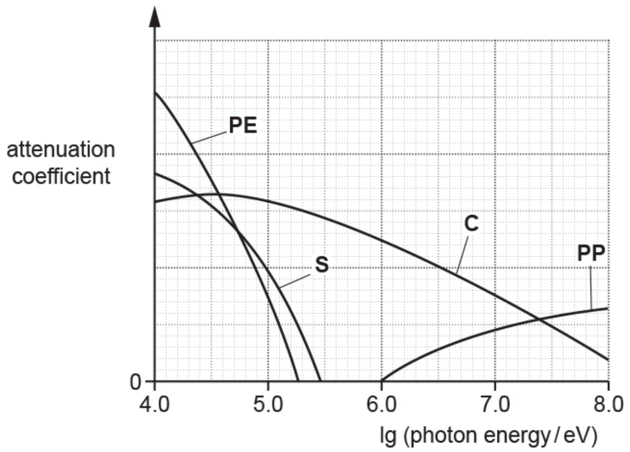
[2]

31. X-ray photons interact with atoms.

The attenuation coefficient against lg(photon energy) graphs for simple scattering (**S**), photoelectric effect (**PE**), Compton effect (**C**) and pair production (**PP**) are shown below.



With the help of a calculation, explain the minimum photon energy for pair production.

[3]

32. $^{60}_{27}Co$ is produced by irradiating the stable isotope $^{59}_{27}Co$ with neutrons.

Each nucleus of $^{60}_{27}Co$ then decays into a nucleus of nickel (Ni) by the emission of a low energy beta-minus particle, one other particle and two gamma photons.

Complete the nuclear equations for these two processes.

$$^{59}_{27}Co + ^{\cdots\cdots}_{\cdots\cdots}n \longrightarrow ^{60}_{27}Co \longrightarrow ^{\cdots\cdots}_{\cdots\cdots}Ni + ^{\cdots\cdots}_{\cdots\cdots}e + \ldots\ldots\ldots + 2\gamma$$

[3]

33. Calculate the maximum wavelength of the X-rays for the pair production process.

maximum wavelength = ... m **[3]**

34. Fig. 22.1 shows the circular track of a positron moving in a uniform magnetic field.

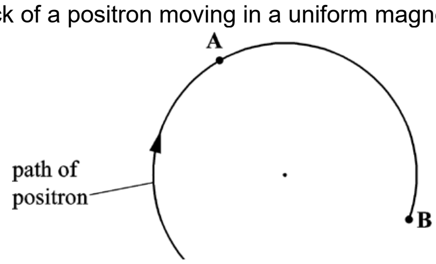


Fig. 22.1

The magnetic field is perpendicular to the plane of **Fig. 22.1**.
The speed of the positron is 5.0×10^{7} m s^{-1} and the radius of the track is 0.018 m.

At point **B** the positron interacts with a stationary electron and they annihilate each other. The annihilation process produces two identical gamma photons travelling in opposite directions.

Calculate the wavelength of the gamma photons. Assume the kinetic energy of the positron is negligible.

wavelength = ... m **[3]**

35 (a). An isotope of polonium-213 ($^{213}_{84}Po$) first decays into an isotope of lead-209 ($^{209}_{82}Pb$) and this lead isotope then decays into the stable isotope of bismuth (Bi).

Fig. 24 shows two arrows on a neutron number *N* against proton number *Z* chart to illustrate these two decays.

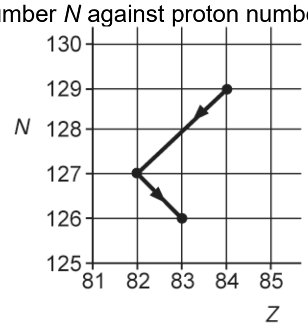


Fig. 24

Complete the nuclear decay equations for

i. the polonium isotope

$$^{213}_{84}Po \longrightarrow \, ^{209}_{82}Pb \; + $$ **[1]**

ii. the lead isotope.

$$^{209}_{82}Pb \longrightarrow \, ^{......}_{83}Bi \; + \; ^{0}_{-1}e \; + $$ **[2]**

(b). A pure sample of polonium-213 is being produced in a research laboratory.

The half-life of $^{213}_{84}Po$ is very small compared with the half-life of $^{209}_{82}Pb$.

After a very short time, the ionising radiation detected from the sample is mainly from the beta-minus decay of the lead-209 nuclei.

i. Briefly describe and explain an experiment that can be carried out to confirm the beta-minus radiation emitted from the lead nuclei.

---

[2]

ii. The activity of the sample of $^{209}_{82}Pb$ after 7.0 hours is 12 kBq.

The half-life of $^{209}_{82}Pb$ is 3.3 hours.

Calculate the initial number of lead-209 nuclei in this sample.

number of nuclei = **[4]**

36. The medical tracer technetium-99m is used in gamma scans. Technetium-99m has a half-life of 6.0 hours and it emits gamma rays.
A fresh sample of a radiopharmaceutical containing technetium-99m is prepared in the radiography department of a hospital. The initial activity of the radiopharmaceutical is 820 MBq. The radiopharmaceutical is injected into the patient some time later when its activity has dropped to 630 MBq.

Calculate the time in hours between the radiopharmaceutical being produced and it being injected into the patient.

time = ... h **[3]**

37. The nucleons inside a $^{3}_{1}H$ nucleus experience gravitational force and one other type of force.
Name this other type of force and describe its nature.

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[3]

38 (a). Fluorine-18 is a common radioactive isotope used in positron emission tomography (PET). Fluorine-18 emits positrons. A patient is injected with a radiopharmaceutical containing fluorine-18.

Describe how a PET scanner is used to locate an area of increased activity within the patient.

[4]

(b). The half-life of fluorine-18 is 110 minutes.
Calculate the time *t* in minutes for the activity of the radiopharmaceutical to decrease to 30% of its initial activity.

t = ... minutes **[3]**

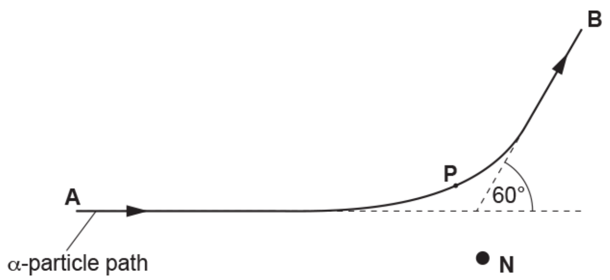
(c). PET scanners are not available in all hospitals. This is because fluorine-18 requires expensive on-site particle accelerators and fluorine-18 has a very small 'shelf-life'.
Suggest the impact this may have on the treatment and diagnosis of patients in the country.

[1]

39. A beam of α-particles is incident on a thin gold foil. Most α-particles pass straight through the foil.
A few are deflected by gold nuclei.

The diagram shows the path of one α-particle which passes close to a gold nucleus **N** in the foil.
The α-particle is deflected through an angle of 60° as it travels from **A** to **B**.

P marks its position of closest approach to the gold nucleus.



The distance between **P** and **N** is 6.8×10^{-14} m.

Calculate the magnitude of the electrostatic force *F* between the α-particle $({}^{4}_{2}He)$ and the gold nucleus $({}^{197}_{79}Au)$ when the α-particle is at **P**.

F = ... N **[4]**

40. Explain the role of the moderator and the control rods in a nuclear reactor.

---

[4]

41. The chemical composition of ancient rocks found on the Earth can be used to estimate the age of the Earth. Nuclei of rubidium-87 $({}^{87}_{37}Rb)$ decay spontaneously into nuclei of strontium-87 $({}^{87}_{38}Sr)$.
The half-life of rubidium-87 is 49 billion years.

i. Name the two leptons emitted in the decay of a rubidium-87 nucleus.

1.

2.

[1]

ii. The percentage of rubidium **left** in a sample of an ancient rock is 95%.

Estimate the age of the Earth in billion years.

age =... billion years **[3]**

42. Fluorodeoxyglucose (FDG) is a radioactive tracer often used for PET scans. It contains radioactive fluorine-18, which is a positron-emitter. Some information about FDG and fluorine-18 is given below.

- 9.9% of the mass of FDG is fluorine-18.
- The half-life of fluorine-18 is 6600 s.
- The molar mass of fluorine-18 is 0.018 kg mol^{-1}.

A patient is injected with FDG. The initial activity of FDG is 400 MBq.

Use the information given to calculate the initial mass of FDG given to the patient.

mass = ... kg **[4]**

43. The structure of atoms was deduced in the early 1900s by Rutherford and his co-workers from the scattering of alpha-particles by a very thin sheet of gold.

Rutherford assumed that the scattering of the alpha-particles was due to electrostatic forces. Fig. 23 shows a detector used to record the number *N* of alpha-particles scattered through an angle *θ*.

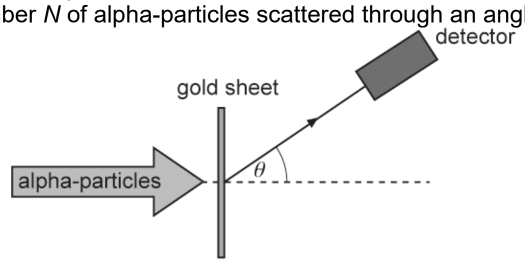


Fig. 23

At *θ* = 0°, *N* was too large to be measured. The table below summarises some of the collected data.

θ / °	lg (*N*)
150	1.5
75	2.3
60	2.7
30	3.9
15	5.1
0	*N* too large

i. Show that the number of alpha-particles scattered through 15° is about 4000 times more than those scattered through 150°.

[1]

ii. Use the evidence from the table to explain the structure of the atom.

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[3]

44. In the 1800s, the atom was considered to be a fundamental particle. It was an indivisible particle of matter. Modern physics shows that this idea is not correct.

Describe the fundamental particles within an atom of carbon-14 $({}^{14}_{6}C)$.
In your answer state the composition of the hadrons.

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[4]

45. Carbon-14 $({}^{14}_{6}C)$ is produced in the upper atmosphere of the Earth by collisions between nitrogen nuclei and fast-moving neutrons.
The nuclear transformation equation below shows the formation of a single carbon-14 nucleus.

$${}^{14}_{7}N + {}^{1}_{0}n \rightarrow {}^{14}_{6}C + X$$

Fig. 22

i. State the proton number of particle X.

proton number = ... **[1]**

ii. Use the data below to determine the binding energy per nucleon of the ${}^{14}_{6}C$ nucleus.
Write your answer to **3** significant figures.

mass of neutron = 1.675×10^{-27} kg
mass of proton = 1.673×10^{-27} kg
mass of ${}^{14}_{6}C$ nucleus = 14.000 u
1 u = 1.66×10^{-27} kg

binding energy per nucleon = ... J per nucleon **[4]**

46. The half-life of the isotope carbon-14 is 5700 years (y).

i. Show that the decay constant λ for this isotope is about 1.2×10^{-4} y^{-1}.

[1]

ii. Carbon-dating is a technique used to date an ancient wooden axe.
The ratio of carbon-14 to carbon-12 in the axe material is 78% of the current ratio of carbon-14 to carbon-12 in a living tree.

Calculate the age in years of the wooden axe.

age = ... y **[3]**

iii. State **one** assumption made in the calculation in **(ii)**.

---

[1]

47. The fusion of two ${}^{3}_{1}\mathrm{H}$ nuclei produces a stable nucleus of ${}^{4}_{2}\mathrm{He}$ and some fast-moving neutrons.

i. Explain why the fusion of the ${}^{3}_{1}\mathrm{H}$ nuclei must produce two neutrons.

---

[2]

ii. The total energy released in this fusion reaction is 11 MeV. The binding energy per nucleon of the ${}^{4}_{2}\mathrm{He}$ nucleus is 7.1 MeV.
Calculate in J the binding energy per nucleon of the ${}^{3}_{1}\mathrm{H}$ nucleus.

binding energy per nucleon =.. J **[3]**

48. Uranium-235 is used in many fission reactors as fuel and fusion reactors are still at an experimental stage.

i. State one major disadvantage of having fission reactors.

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[1]

ii. The fission of a uranium-235 nucleus releases about 200 MeV of energy, whereas the fusion of four hydrogen-1 nuclei releases about 28 MeV.
At first sight it would appear that fusion would produce less energy than fission. However the energy released in the fission of one kilogramme of uranium-235 is about eight times less than the energy released in the fusion of one kilogramme of hydrogen-1.

Explain this by considering the initial number of particles in one kilogramme of each.

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[4]

49 (a). A grain of a radioactive powder which emits gamma rays accidentally falls onto the workbench.

A sensitive gamma-ray detector is used to look for this grain. The grain can be assumed to be a point source which emits radiation **uniformly in all** directions.

The background count-rate before the accident was negligible.

The detector registers a count-rate of 20 s^{-1} when it is 1.0 m from the grain.

i. Explain why the count-rate rises to 320 s^{-1} when the detector is moved to 0.25 m from the grain.

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[2]

ii. A thin lead sheet is now placed on the bench over the grain. This causes the count-rate to halve to 160 s^{-1}. The detector is moved from its position at 0.25 m towards the grain until the count-rate returns to 320 s^{-1}.

1 State the value of the count-rate if the sheet is now removed.

count-rate = ... s^{-1} **[1]**

2 Calculate the distance of the detector from the grain.

distance = ... m **[2]**

(b). *Fig. 5 shows a thin slice of rock mounted on the face of a lead holder. The rock contains several different radioactive elements.

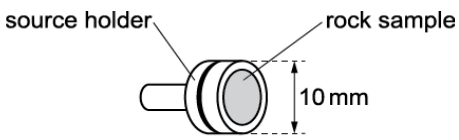

Fig. 5

Plan one or more experiments to determine the **nature** of the emissions from the sample.

A space has been left for you to draw one or more diagrams to show the arrangement of your apparatus

[6]

50. A possible fission reaction is

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{236}_{92}U \rightarrow ^{98}_{38}Sr + ^{136}_{54}Xe + k\,^{1}_{0}n$$

where *k* is the number of neutrons released in the reaction. The $^{236}_{92}U$ nucleus is very unstable.

i. State the number *k* of neutrons released in this reaction.

k = ... **[1]**

ii. State the binding energy of the released neutrons.

----

[1]

iii. A nuclear reactor uses uranium-235 as fuel. The output power from the reactor is 1.0 GW. The mass of the $^{236}_{92}U$ nucleus is 236.053 u. The total mass of the fission products is 235.840 u.

Calculate the number of fission reactions per second.

number of reactions per second = ... s^{-1} **[4]**

51. * Describe the processes of fission and fusion of nuclei stating one similarity and one difference between the two processes. Describe the conditions required for each process to occur in a sustained manner.

[6]

52. * A group of students are investigating the decay of protactinium.
A fresh sample of protactinium is prepared. The activity of the sample was measured at intervals of 1.0 minutes for 6.0 minutes.
The table shows the activity corrected for background radiation.

time *t* / min	0	1.0	2.0	3.0	4.0	5.0	6.0
activity *A* / Bq	943	523	287	161	79	61	20

Fig. 20 shows the variation of ln(*A*) with time *t*.

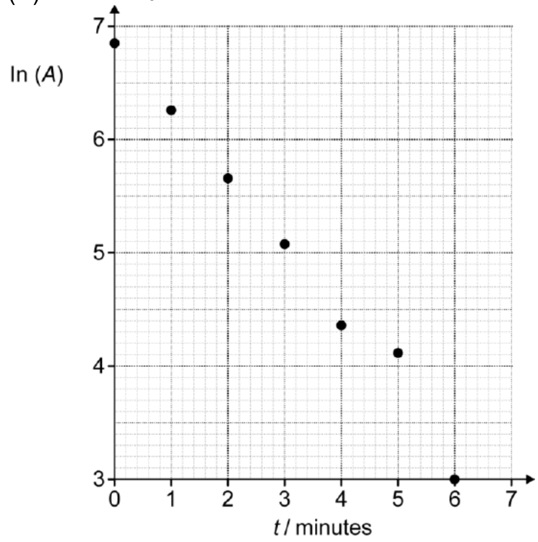

Fig. 20

Explain how the graph in Fig. 20 can be used to determine the half-life of protactinium. Determine the half-life of protactinium. Include an uncertainty in your value.

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[6]

53. This question is about the Sun and its radiation.

* A student attends a lecture about the Sun and makes the following notes.

1. The Sun loses more than 4×10^9 kg of its mass every second to maintain its luminosity.
2. Treating hydrogen nuclei (protons) as an ideal gas, a temperature of 10^{10} K provides a kinetic energy of about 1 MeV, which is necessary for fusion.
3. However, the Sun's core temperature is only 10^7 K, so the chance of protons fusing on collision is very small. This explains why the Sun has such a long lifetime.

Explain the principles of physics which are involved in each of the three points.
You should include relevant formulae, but no numbers or calculations are required.

[6]

54. * Lead of different thicknesses can be used to investigate the absorption of gamma photons from a radioactive source.
Fig. 23.1 shows a graph of gamma photon energy against the half-thickness of lead. Half-thickness of lead is the thickness of lead which will reduce the original count-rate by half.

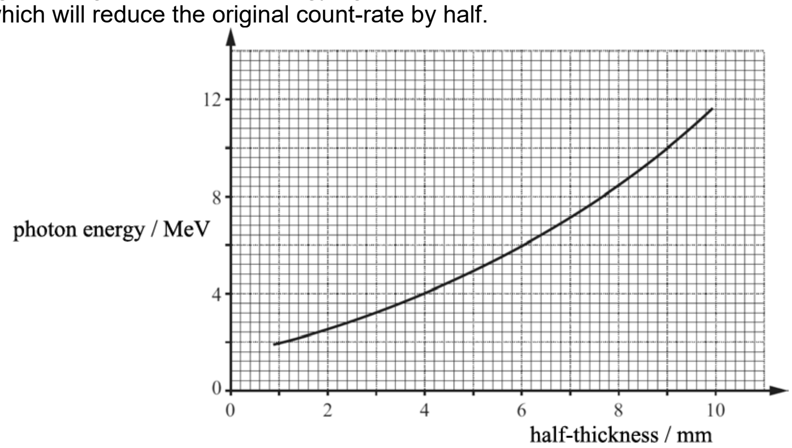


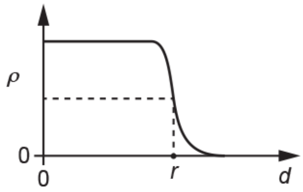
Fig. 23.1

Describe an experiment that can be carried out to determine the half-thickness of lead and how you would use your results with **Fig. 23.1** to determine the energy of a gamma photon from a radioactive gamma source in your laboratory.

Include the equipment used, any safety precautions necessary and how the quality of the results may be improved.

[6]

55. * A graph of the density ρ of a nucleus against distance d from the centre of the nucleus is shown below.



The radius of the nucleus r is taken as the distance d where the density is half the maximum density.

Fig. 21.1 shows the density ρ variation for three different nuclei and **Table 21.1** shows the nucleon number A of each nucleus.

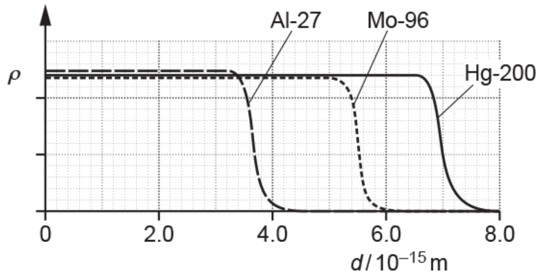


Fig. 21.1

Nucleus	**Nucleon number *A***
Al-27	27
Mo-96	96
Hg-200	200

Table 21.1

Use the information provided opposite to

- describe how the density of a nucleus depends on its nucleon number A
- show numerically that $r \propto A^{1/3}$
- estimate the mean density of the nuclei.

----

[6]

56. This question is about a space probe which is in orbit around the Sun.

The power source for the instrumentation on board the space probe is plutonium-238, which provides 470 W initially.

Plutonium-238 decays by α-particle emission with a half-life of 88 years.
The kinetic energy of each α-particle is 8.8×10^{-13} J.

i. Calculate the number N of plutonium-238 nuclei needed to provide the power of 470 W.

N = ...**[3]**

ii. Calculate the power P still available from the plutonium-238 source 100 years later.

P = ... W**[3]**

57. Some nuclear fission reactors use uranium-235 as fuel. In the future, there is possibility of using hydrogen-2 as fuel in fusion reactors.

Here is some information and data on fission and fusion reactions.

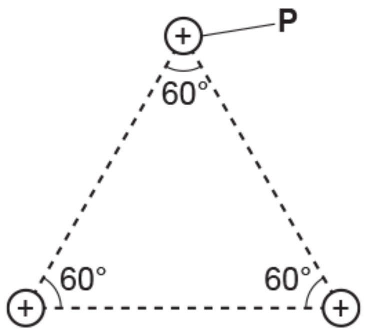
	Fission reactor	**Fusion reactor**
Typical reaction	${}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{144}_{56}Ba + {}^{89}_{36}Kr + 3{}^{1}_{0}n$	${}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{1}H + {}^{1}_{1}H$
Approximate energy produced in each reaction	200 MeV	4 MeV
Molar mass of fuel material	uranium-235: 0.235 kg mol^{-1}	hydrogen-2: 0.002 kg mol^{-1}

- Describe the similarities and the differences between fission and fusion reactions.
- Explain with the help of calculations, which fuel produces more energy per kilogram.

-----

[6]

58. The diagram below shows the arrangement of the 3 protons inside the nucleus of lithium-6 ($^{6}_{3}Li$).



The separation between each proton is about 1.0×10^{-15} m.

i. Calculate the magnitude of the repulsive electric force *F* experienced by the proton **P**.

F = ... N **[4]**

ii. On the diagram above, draw an arrow to show the direction of the electric force *F* experienced by **P**.

[1]

iii. Explain how protons stay within the nucleus of lithium-6.

---

[2]

59. The nuclear reaction below shows how the isotope of fluorine-18 ($^{18}_{9}F$) is made from the isotope of oxygen-18 ($^{18}_{8}O$).

$$^{18}_{8}O + ^{1}_{1}p \rightarrow ^{18}_{9}F + ^{1}_{0}n + \gamma$$

The oxygen-18 nucleus is **stationary** and the proton has kinetic energy of 0.25×10^{-11} J.
The binding energy of the $^{18}_{8}O$ nucleus is 2.24×10^{-11} J and the binding energy of the $^{18}_{9}F$ nucleus is 2.20×10^{-11} J.
The proton and the neutron have zero binding energy.

i. Explain why a high-speed proton is necessary to trigger the nuclear reaction shown above.

---

[2]

ii. Estimate the minimum wavelength *λ* of the gamma ray photon (*γ*).

λ = m **[3]**

iii. Fluorine-18 is a positron emitter.
Name a medical imaging technique that uses fluorine-18 and state one benefit of the technique.

---

[2]

60. Inside a nuclear reactor, fission reactions are controlled and **chain reactions** are prevented. A typical fission reaction of the uranium-235 nucleus ($^{235}_{92}U$) is illustrated below.

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{141}_{55}Cs + ^{93}_{37}Rb + 2^{1}_{0}n$$

The neutron triggering the fission reaction moves slowly. The neutrons produced in the fission reaction move fast.

i. Describe what is meant by **chain reaction**.

---

[2]

ii. Explain how chain reactions are prevented inside a nuclear reactor.

---

[2]

iii. The energy released in each fission reaction is equivalent to a decrease in mass of 0.19 u.
A fuel rod in a nuclear reactor contains 3.0% of uranium-235 by mass.

Estimate the total energy produced from 1.0 kg of fuel rod.

molar mass of uranium-235 = 0.235 kg mol^{-1}
1 u = 1.66 × 10^{-27} kg

energy = ...J **[4]**

61. $^{60}_{27}Co$ is produced by irradiating the stable isotope $^{59}_{27}Co$ with neutrons.

Each nucleus of $^{60}_{27}Co$ then decays into a nucleus of nickel (Ni) by the emission of a low energy beta-minus particle, one other particle and two gamma photons.

Students want to carry out an investigation into gamma photon absorption using a source of $^{60}_{27}Co$. They add sheets of lead between the source **S** and a radiation detector **T**, to give a total thickness *d* of lead. **S** and **T** remain in fixed positions, as shown in Fig. 2.1.

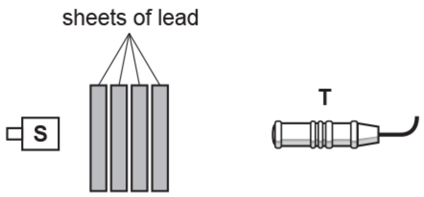


Fig. 2.1

i. The $^{60}_{27}Co$ source emits beta radiation as well as gamma radiation.

Explain why this would not affect the experiment.

---

[1]

ii. The students record the number *N* of gamma photons detected by **T** in 10 minutes for each different thickness *d* of lead. The background count is negligible.

The results are shown in a table. The table includes values of ln *N*, including the absolute uncertainties.

N	***d / mm***	***ln N***
4300 ± 440	0	8.37 ± 0.10
2500 ± 250	0	7.82 ± 0.10
1400 ± 150	20	7.24 ± 0.11
800 ± 90	30	6.68 ± 0.11
500 ± 60	40	6.21 ± 0.12
300 ± 40	50	

N and *d* are related by the equation $N = N_0 e^{-\mu}$ where N_0 and μ are constants.

1. The students decide to plot a graph of ln *N* against *d*.

Show that this should give a straight line with gradient = – μ and *y*-intercept = ln N_0.

[1]

2. Complete the missing value of ln N in the table, including the absolute uncertainty.

   Show your calculation of the absolute uncertainty in the space below.

[2]

3. In **Fig. 2.2**, five of the data points have been plotted, including error bars for ln N

   - Plot the missing data point and error bar.
   - Draw a straight line of best fit and one of worst fit.

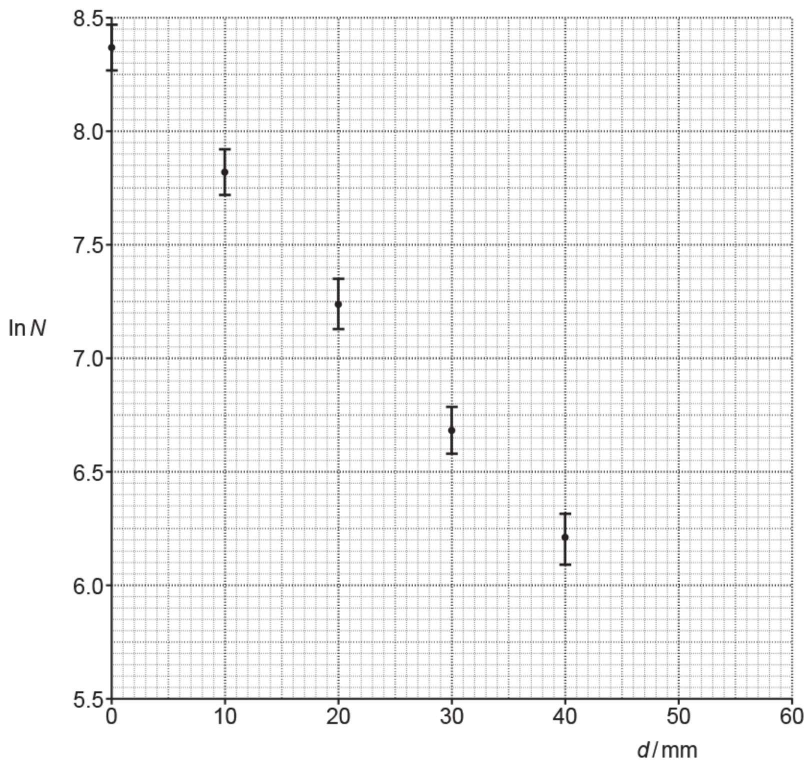


Fig. 2.2

[2]

4. Use Fig. 2.2 to determine the value of μ in m^{-1}, including the absolute uncertainty.

μ =.....................± .... m^{-1} **[4]**

5. Determine the thickness, $d_{½}$, of lead which halves the number of gamma photons reaching **T**.

$d_{½}$ = ... m **[2]**

62. This question is about helium in the atmosphere of the Earth.

Experiment shows that most of the Earth's atmosphere is contained within a very thin shell around the surface of the Earth. Less than 0.0001% of this is helium.

The height of the atmosphere is negligible compared with the radius *R* of the Earth.

i. Show that the minimum speed v_E required for an atom or molecule to escape from the top of the Earth's atmosphere is given by the expression

$$v_E = \sqrt{2gR}.$$

[3]

ii. The radius *R* of the Earth is 6.4 × 10^6 m. Calculate this escape speed v_E.

v_E = ... m s $^{-1}$ **[1]**

iii. Calculate the temperature *T* in kelvin required at the top of the Earth's atmosphere for the root mean square speed $c_{r.m.s.}$ of the helium atoms there to equal this escape speed.

Molar mass of helium = 0.004 kg mol^{-1}

T = ... K **[3]**

iv. Fig. 1 shows the distribution of the speeds of the atoms of an ideal gas.

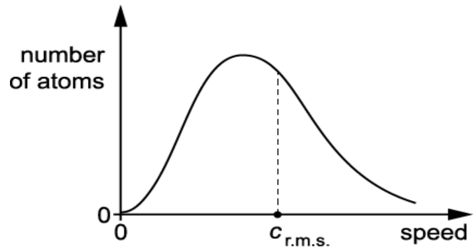


Fig. 1

Use your knowledge of the kinetic theory of gases to describe the shape of this distribution and explain why some helium is able escape from the Earth.

----

[4]

v. Over a very long period of time all of the helium should have escaped from the Earth. Suggest why there is still a small amount of helium, about 0.0001%, in the Earth's atmosphere.

----

[2]

END OF QUESTION PAPER