9 **(a)** State what is meant by the mass defect of a nucleus.

....

....

.... [2]

(b) The nuclear fusion reaction for the formation of helium-4 from deuterium is represented by

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

Table 9.1 shows the masses of the nuclides involved in this reaction.

Table 9.1

nuclide	nuclide mass / u
$^{2}_{1}H$	2.013553
$^{4}_{2}He$	4.001505

Calculate the energy released in the formation of 1.00 mol of helium-4.

energy = ... J [4]

(c) The star Sirius has a radius of 1.19×10^{9} m and loses mass due to nuclear fusion at a rate of 1.09×10^{11} kg s^{-1}. Assume that the power of the radiation emitted by the star is equal to the power released by this process.

(i) Determine a value for the luminosity of Sirius. Give a unit with your answer.

luminosity = ... unit .... [2]

(ii) Use your answer in **(c)(i)** to determine the surface temperature of Sirius.

surface temperature = ... K [2]

(d) Explain how cosmologists use standard candles to estimate the distance of a galaxy from the Earth.

....

....

....

....

.... [3]

8 **(a)** State what is meant by a photon.

....

....

.... [2]

(b) A stationary nucleus of uranium-238 ($^{238}_{92}U$) undergoes alpha decay to produce a nucleus of thorium-234 ($^{234}_{90}Th$). The kinetic energy of the emitted alpha particle is 4.200 MeV. A gamma-ray photon is also emitted during the decay.

Assume that the rebound kinetic energy of the thorium nucleus is negligible.

Table 8.1 shows the masses of the nuclides involved in the decay reaction. The mass of the uranium-238 nuclide is missing.

Table 8.1

nuclide	nuclide mass / u
$^{4}_{2}\alpha$	4.000 407
$^{234}_{90}Th$	233.915 174
$^{238}_{92}U$	

The total energy released in the decay of the nucleus of uranium-238 is 4.274 MeV.

(i) Calculate the mass, in u, of the uranium-238 nuclide. Give your answer to five decimal places.

mass = ... u [3]

(ii) Determine a value for the wavelength of the gamma radiation emitted during the decay of the uranium-238 nucleus.

wavelength = ... m [3]

(iii) In practice, the rebound kinetic energy of the thorium nucleus is **not** negligible.

Explain, without further calculation, how your answer in **(b)(ii)** compares with the true wavelength of gamma radiation emitted during the decay of the uranium-238 nucleus.

....

....

.... [1]

(c) Gamma radiation emitted during the decay of a sample of uranium-238 has a single wavelength.

Nuclei of cobalt-60 ($^{60}_{27}Co$) decay by beta emission, and also emit gamma radiation in the process.

Suggest why there is **not** a single wavelength for the gamma radiation emitted during the decay of a sample of cobalt-60.

....

....

.... [2]

11 The deuterium nucleus ($^2_1$H) has a mass defect of 0.002 388 u. The helium-4 nucleus ($^4_2$He) has a mass defect of 0.030 377 u. Helium-4 is formed from deuterium in a nuclear reaction that can be represented by the equation

$$3\,{}^2_1\mathrm{H} \longrightarrow {}^4_2\mathrm{He} + {}^1_1\mathrm{p} + {}^1_0\mathrm{n}.$$

(a) **(i)** State the name of this type of nuclear reaction.

.... [1]

(ii) Show that the energy released when one nucleus of helium-4 is formed from deuterium is 3.47×10^{-12} J.

[3]

(b) A star has a radius of 6.96×10^{8} m. Helium-4 is produced in this star, from deuterium, at a mass rate of 7.34×10^{11} kg s^{-1}. All the energy released from this process is radiated away from the star. All the energy that is radiated from the star is released by this process.

(i) Calculate the luminosity of the star.

luminosity = ... W [3]

(ii) Use your answer in **(b)(i)** to determine the surface temperature of the star.

temperature = ... K [2]

10 **(a)** Radioactive decay is a spontaneous process.

State the meaning, in this context, of the term spontaneous.

....

.... [1]

(b) Two radioactive isotopes X and Y each decay to form a stable isotope.
A sample initially contains only atoms of isotope X. At this time, its activity is $4A$.
Another sample initially contains only atoms of Y. At this time, its activity is A.

Fig. 10.1 shows the variation of the activity of each sample with time t between $t = 0$ and $t = 6T$.

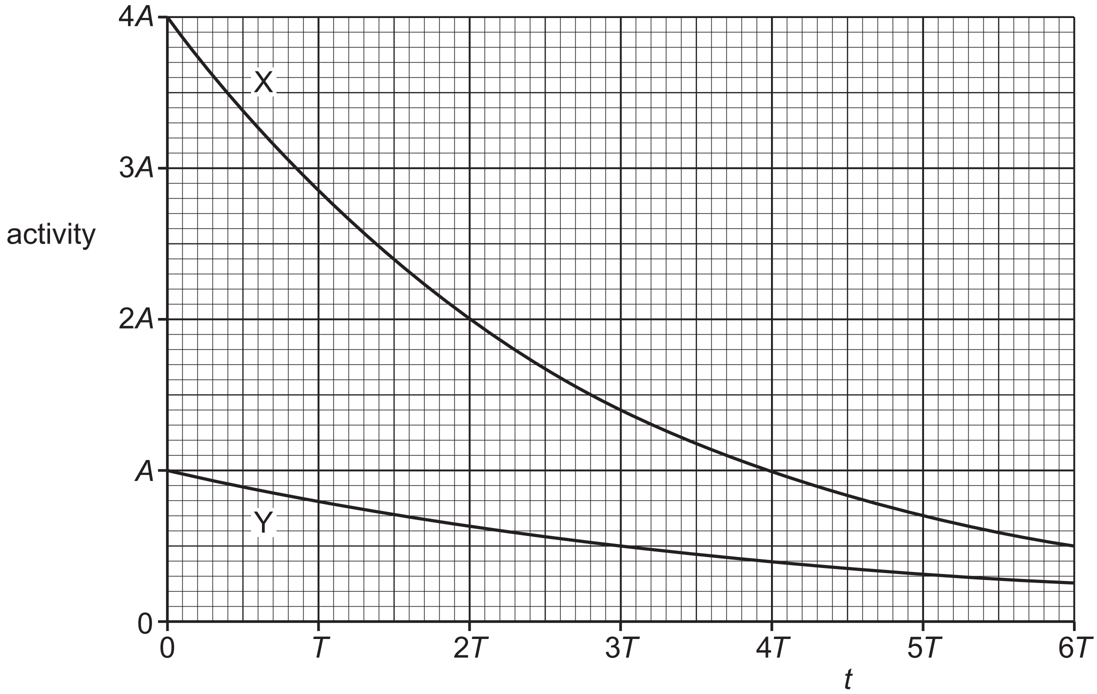

Fig. 10.1

(i) Complete Table 10.1 to give expressions, in terms of either or both of A and T, for the quantities indicated for each of the samples.

Table 10.1

sample	half-life	decay constant	initial activity	initial number of nuclei
X			$4A$	
Y			A	

[3]

(ii) Determine, in terms of T, the time at which the two samples will have equal activities.

time = ... T [3]

(c) A radiation detector is placed near to one of the samples in **(b)**.

Explain why the count rate measured by the detector is less than the activity of the sample.

....

....

.... [2]

9 **(a)** Define activity of a radioactive sample.

....

.... [1]

(b) Explain why the variation with time of the activity of a radioactive sample is exponential in nature.

....

....

....

....

.... [3]

(c) A sample contains a single radioactive isotope that decays to form a stable isotope.

The sample has an activity of 180 Bq at time $t = 0$.
At a time 8.4 minutes later, the activity is 120 Bq.

(i) Determine the decay constant, in min^{-1}, of the radioactive isotope.

decay constant = ... min^{-1} [2]

(ii) Use your answer in **(c)(i)** to determine the half-life, in min, of the radioactive isotope.

half-life = ... min [1]

(iii) On Fig. 9.1, sketch the variation of the activity A of the sample with t for values of t between t = 0 and t = 24 min.

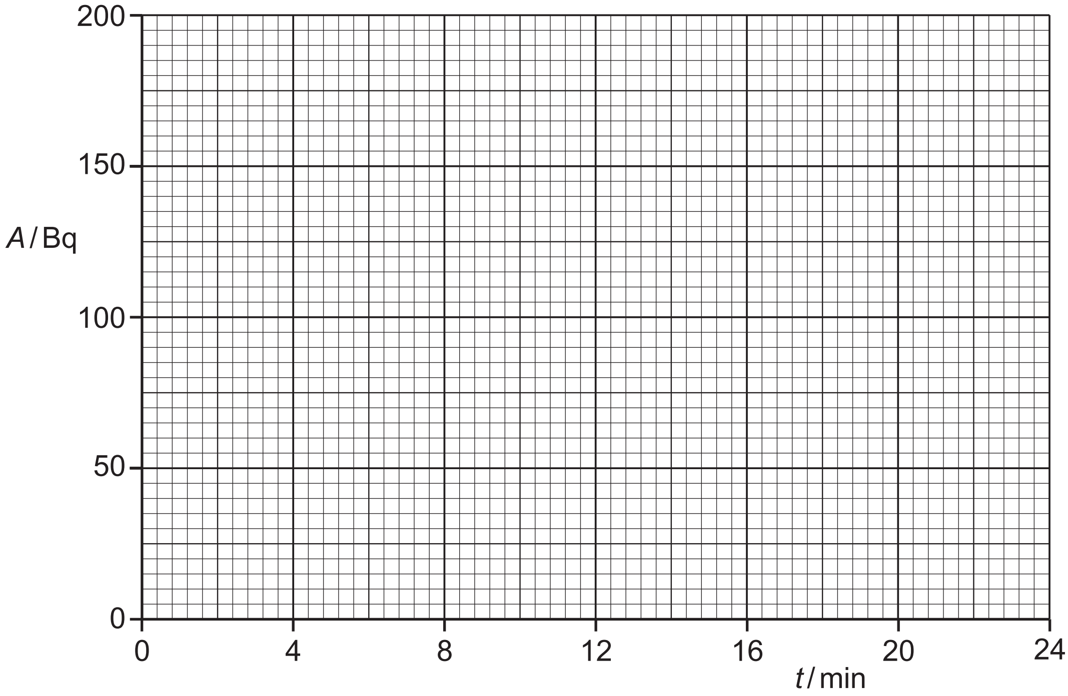

Fig. 9.1

[3]

9 Polonium-193 ($^{193}_{84}Po$) is an unstable nuclide. A nucleus of polonium-193 decays to a nucleus of lead-189 ($^{189}_{82}Pb$) by emitting an alpha-particle.

(a) Radioactive decay is both random and spontaneous.

State what is meant by:

(i) random

....

.... [1]

(ii) spontaneous.

....

.... [1]

(b) Define half-life.

....

....

.... [1]

(c) Data for the binding energy per nucleon of the particles involved in the decay of a nucleus of polonium-193 are given in Table 9.1.

Table 9.1

particle	binding energy per nucleon / eV
$^{193}_{84}Po$	7.774
$^{189}_{82}Pb$	7.826
$^{4}_{2}\alpha$	7.074

Determine the energy, in eV, released when a nucleus of polonium-193 decays into a nucleus of lead-189.

energy = ... eV [2]

(d) A pure sample of polonium-193 contains N_0 nuclei. After a time t the sample contains N nuclei of polonium-193. The variation of $\ln(N/N_0)$ with t is shown in Fig. 9.1.

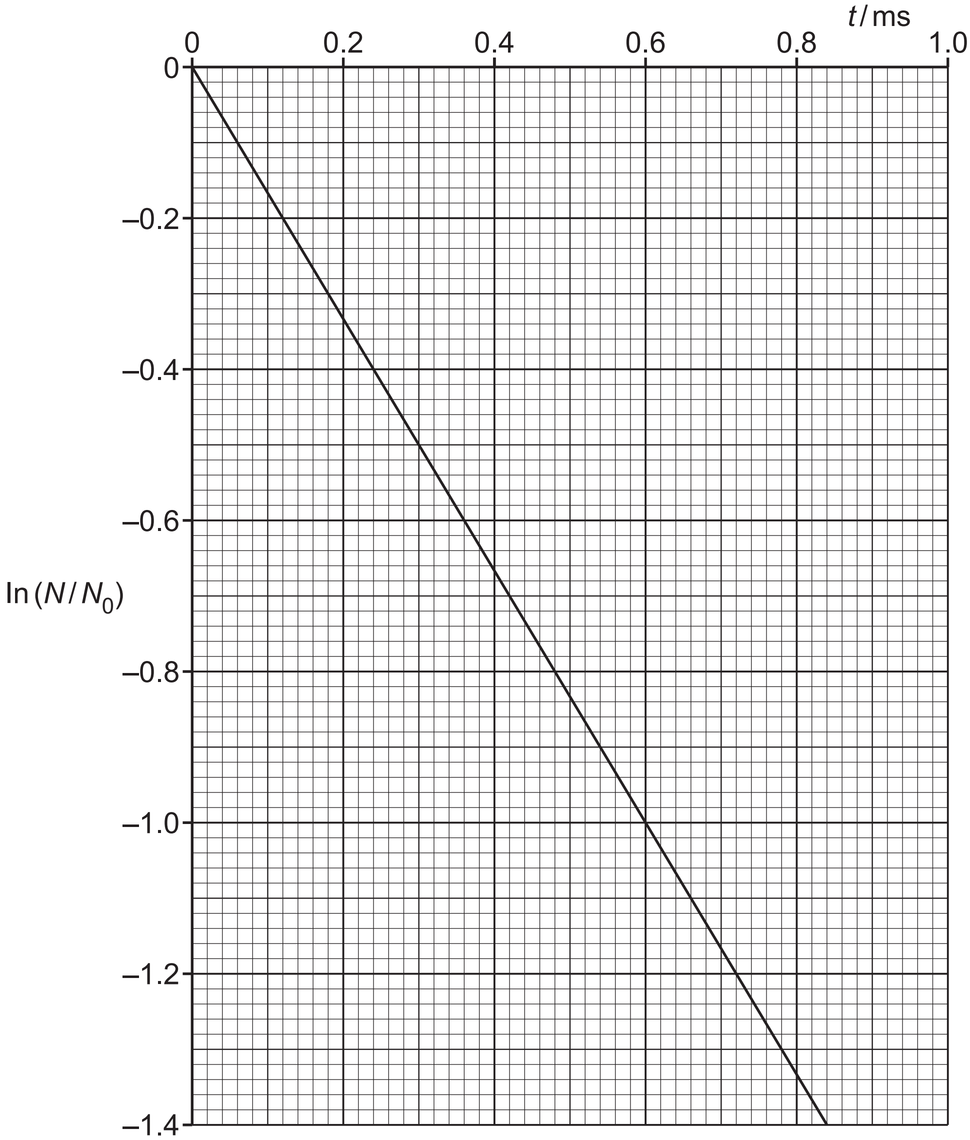

Fig. 9.1

(i) State the name of the quantity that is represented by the magnitude of the gradient of the line in Fig. 9.1.

.... [1]

(ii) Use Fig. 9.1 to determine the half-life, in ms, of polonium-193.

half-life = ... ms [2]

(e) Positron emission tomography (PET scanning) uses a radioactive tracer.

(i) State what happens to the positrons emitted by the tracer.

....

.... [1]

(ii) Explain why a tracer with a half-life of approximately 2 hours is a suitable tracer to use.

....

.... [1]

BLANK PAGE

10 **(a)** Radioactive decay is both random and spontaneous.

(i) State what is meant by random.

....

.... [1]

(ii) State what is meant by spontaneous.

....

.... [1]

(iii) State **one** piece of evidence for the random nature of decay.

....

.... [1]

(b) **(i)** Describe the differences between nuclear fission and nuclear fusion.

....

....

....

....

.... [3]

(ii) Explain, with reference to the variation of binding energy per nucleon with nucleon number, why the processes of nuclear fission and nuclear fusion both result in a release of energy.

....

....

.... [2]

BLANK PAGE

9 Fluorine-18 ($^{18}_{9}F$) decays by beta-plus (β^+) emission with a half-life of 110 minutes.

(a) **(i)** State the name of the beta-plus particle.

.... [1]

(ii) Show that the decay constant of fluorine-18 is $1.05 \times 10^{-4}\,s^{-1}$.

[1]

(iii) Determine the activity of 2.1×10^{-12} kg of fluorine-18.

activity = ... Bq [3]

(b) A small sample of fluorine-18 injected into the body acts as a tracer for use in medical imaging.

(i) Describe how the interaction of a β^+ particle with an electron in the body enables the formation of an image.

....

....

....

....

.... [3]

(ii) Suggest why 110 minutes is a suitable half-life for a nuclide used as a tracer in medical diagnosis.

....

....

.... [2]

9 **(a)** State what is meant by the binding energy of a nucleus.

....

....

.... [2]

(b) Table 9.1 shows the masses of two sub-atomic particles and a polonium-212 ($^{212}_{84}Po$) nucleus.

Table 9.1

	mass / u
proton	1.007 276
neutron	1.008 665
polonium-212 nucleus	211.942 749

For the polonium-212 nucleus, determine:

(i) the mass defect Δm, in kg

Δm = ... kg [3]

(ii) the binding energy

binding energy = ... J [2]

(iii) the binding energy per nucleon.

binding energy per nucleon = ... J [1]

(c) **(i)** On Fig. 9.1, sketch the variation with nucleon number *A* of binding energy per nucleon for values of *A* from 1 to 250.

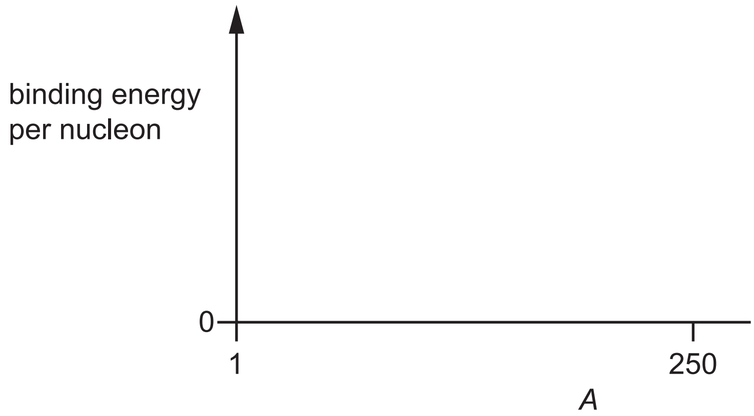

Fig. 9.1

[2]

(ii) On your line in Fig. 9.1, draw an X to show the approximate position of polonium-212. [1]

(iii) Polonium-212 is radioactive and undergoes alpha-decay.

Suggest and explain, with reference to Fig. 9.1, why the alpha-decay of polonium-212 results in a release of energy.

....

....

.... [2]

9 **(a)** Define half-life of a radioactive isotope.

....

....

.... [1]

(b) Radioactive isotope X decays to isotope Y.

A sample contains only nuclei of X at time $t = 0$. Fig. 9.1 shows the variation with t of the numbers of nuclei of X and of Y as the sample decays.

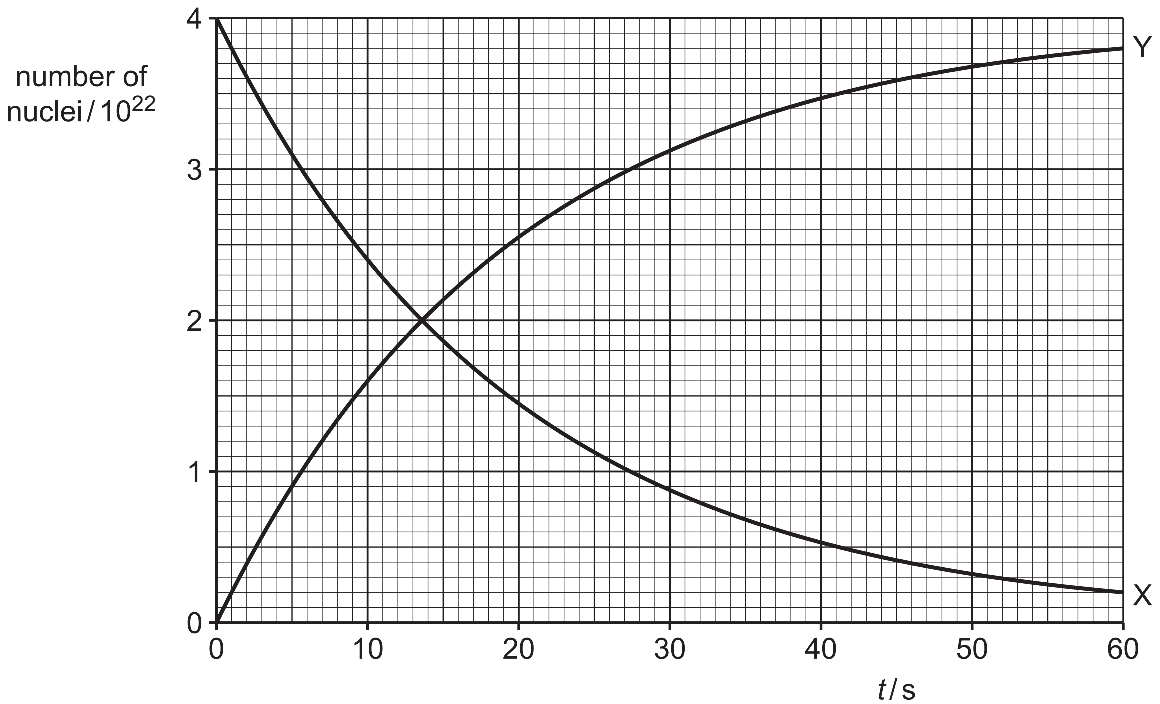

Fig. 9.1

(i) State the name of the quantity represented by the magnitude of the gradient of line X in Fig. 9.1.

.... [1]

(ii) State **three** conclusions about X or Y that may be drawn from Fig. 9.1. The conclusions may be qualitative or quantitative. Use the space below for any working that you need.

1 ....

....

2 ....

....

3 ....

....
[3]

(c) The mass of radioactive isotope X in the sample in **(b)** is 7.3×10^{-4} kg at time $t = 0$.

Determine the nucleon number of isotope X.

nucleon number = ... [3]

8 **(a)** State what is meant by the binding energy of a nucleus.

....

....

.... [2]

(b) A nucleus of uranium-235 absorbs a neutron and becomes unstable. It then undergoes a fission reaction. One possible reaction is

$${}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{142}_{54}\text{Xe} + {}^{90}_{38}\text{Sr} + \text{neutrons.}$$

(i) Determine the number of neutrons produced in this fission reaction.

number = ... [1]

(ii) Data for the binding energies per nucleon for this fission reaction are given in Table 8.1.

Table 8.1

isotope	binding energy per nucleon / MeV
uranium-235	7.59
xenon-142	8.37
strontium-90	8.72

Calculate the energy released, in MeV, from the fission of one nucleus of uranium-235.

energy = ... MeV [2]

(iii) The isotope xenon-142 is unstable. The isotope xenon-132 is stable.

Suggest a reason why xenon-142 is unstable.

....

.... [1]

(iv) Xenon-142 decays into the isotope caesium-142.

A sample initially contains only nuclei of xenon-142. After a time equal to 6.0 s, the ratio

$$\frac{\text{number of decayed nuclei of xenon-142}}{\text{number of undecayed nuclei of xenon-142}}$$

is equal to 31.

Calculate the half-life of xenon-142. Show your working.

half-life = ... s [3]

9 Fluorine-18 ($^{18}_{9}F$) is a radioactive nuclide that is used as a tracer in positron emission tomography (PET scanning). Fluorine-18 decays to a nuclide of oxygen (O) according to

$$^{18}_{9}F \longrightarrow \, ^{Q}_{P}X + \, ^{R}_{8}O.$$

(a) **(i)** State what is meant by a tracer.

....

.... [1]

(ii) State the symbol of the particle that is represented by X and the values of P, Q and R.

X: .... P: ....

Q: .... R: ....

[2]

(b) **(i)** Explain how the radioactive decay of fluorine-18 results in the emission from the body of the gamma-ray photons that are detected during a PET scan.

....

....

....

.... [2]

(ii) Explain how the detection of the gamma-ray photons is used to produce an image of the tissue being examined.

....

....

....

.... [2]

(c) The half-life of fluorine-18 is T.
A patient is injected with amount of substance n of fluorine-18.

(i) Determine an expression for the initial value R_0 of the rate R of production of gamma-ray photons by the tracer, in terms of n, T and the Avogadro constant N_A.

R_0 = ... [3]

(ii) On Fig. 9.1, sketch the variation with time t of R.

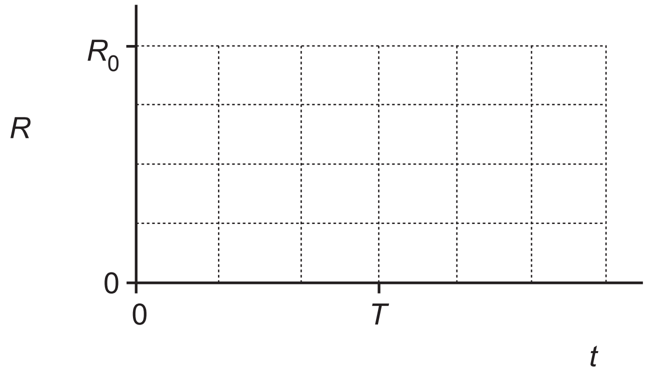

Fig. 9.1

[2]

9 **(a)** State what is meant by nuclear fusion.

....

....

.... [2]

(b) On Fig. 9.1, sketch the variation of binding energy per nucleon with nucleon number *A* for values of *A* between 1 and 250.

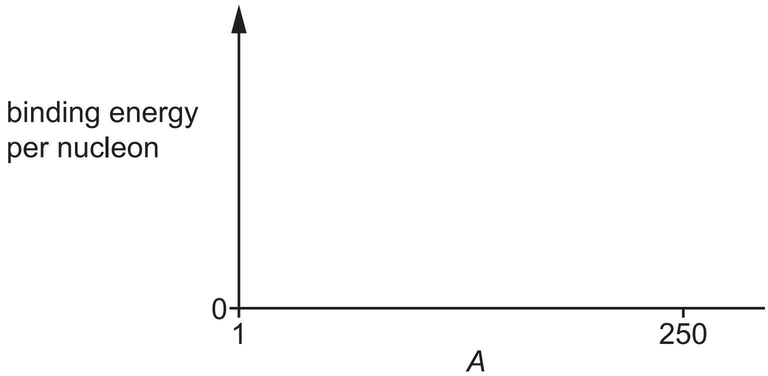

Fig. 9.1

[2]

(c) On your line in Fig. 9.1, label:

(i) a point X that could represent a nucleus that undergoes alpha-decay [1]

(ii) a point Y that could represent a nucleus that undergoes nuclear fusion. [1]

(d) A nucleus Z undergoes nuclear fission to form strontium-93 ($^{93}_{38}Sr$) and xenon-139 ($^{139}_{54}Xe$) according to

$$^{1}_{0}n + Z \longrightarrow {}^{93}_{38}Sr + {}^{139}_{54}Xe + 2{}^{1}_{0}n.$$

Table 9.1 shows the binding energies of the strontium-93 and xenon-139 nuclei.

Table 9.1

nucleus	binding energy / J
$^{93}_{38}Sr$	1.25×10^{-10}
$^{139}_{54}Xe$	1.81×10^{-10}

The fission of 1.00 mol of Z releases 1.77×10^{13} J of energy.

Determine the binding energy per nucleon, in MeV, of Z.

binding energy per nucleon = ... MeV [4]

9 **(a)** Define mass defect.

....

....

.... [2]

(b) Table 9.1 shows the mass defects of three nuclei.

Table 9.1

nucleus	mass defect / u
${}^{2}_{1}H$	0.002 388
${}^{3}_{1}H$	0.009 105
${}^{4}_{2}He$	0.030 377

The nuclear fusion process in a particular star is described by

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

where X is a particle that has no mass defect.

(i) State the name of particle X.

.... [1]

(ii) Show that the energy released when one nucleus of ${}^{4}_{2}He$ is formed in this fusion reaction is 2.8×10^{-12} J.

[3]

(c) The star in **(b)** has a radius of 2.3×10^9 m and a luminosity of 1.4×10^{28} W.
All the energy released from the formation of ${}^4_2He$ is radiated away from the star.
All the energy that is radiated from the star has been released in the formation of ${}^4_2He$.

Determine:

(i) the mass of ${}^4_2He$ produced per unit time by the fusion process

mass per unit time = ... $kg\,s^{-1}$ [3]

(ii) the surface temperature of the star.

temperature = ... K [2]

9 Carbon-11 is radioactive and decays by β^+ emission to form boron-11. Carbon-11 has a half-life of 20 minutes. Boron-11 is stable.

(a) Define half-life.

....

.... [1]

(b) A sample contains N_0 nuclei of carbon-11 and no other nuclei at time t = 0.

On Fig. 9.1, sketch the variation with t of the number of nuclei of **boron-11** in the sample.

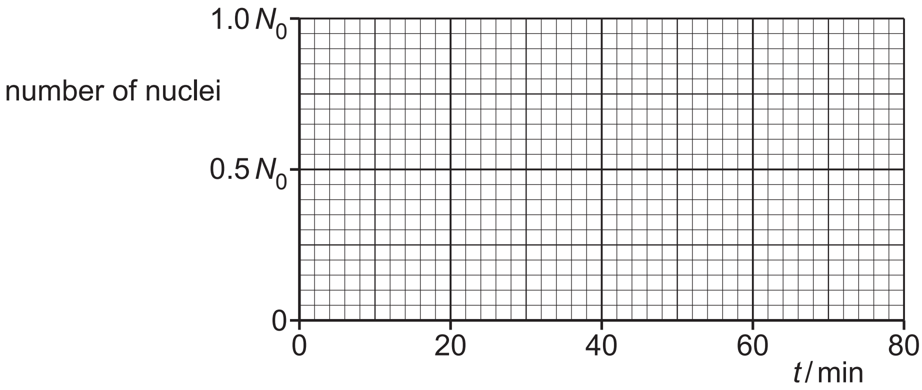

Fig. 9.1

[3]

(c) **(i)** Explain, with reference to the random nature of radioactive decay, why the activity of the carbon-11 sample in **(b)** decreases with time.

....

....

.... [2]

(ii) State, with reasons, whether a radiation detector placed near to the sample of carbon-11 indicates a measured count rate from the sample that is less than, the same as or greater than the activity of the sample.

....

....

....

....

.... [3]

8 Plutonium-238 ($^{238}_{94}Pu$) is unstable and undergoes alpha decay.

(a) Complete the equation to show the decay of plutonium-238.

$$^{238}_{94}\mathrm{Pu} \rightarrow \,^{\cdots\cdots}_{\cdots\cdots}\mathrm{U} + \,^{\cdots\cdots}_{\cdots\cdots}\alpha$$

[2]

(b) The power source in a space probe contains 0.874 kg of plutonium-238. Each nucleus of plutonium-238 that decays emits 5.59 MeV of energy. The half-life of plutonium-238 is 87.7 years.

(i) Calculate the initial number N_o of nuclei of plutonium-238 in the power source.

N_o = ... [1]

(ii) Determine the initial activity of the source. Give a unit with your answer.

activity = ... unit .... [2]

(iii) Use your answer in **(b)(ii)** to determine the initial power output from the source due to the decay of plutonium-238.

power output = ... W [2]

(iv) The space probe will continue to function until the power output from the plutonium in the source decreases to 65.3% of its initial value.

Calculate the time, in years, for which the space probe will function.

time = ... years [2]

(c) An alternative power source uses energy generated from the radioactive decay of polonium-210. This isotope has a half-life of 0.378 years. The mass of the isotope needed for the same initial power output as in **(b)** is 3.37 g.

Suggest **one** advantage and **one** disadvantage of using polonium-210 as the source of energy.

advantage ....

....

disadvantage ....

....
[2]

10 Carbon-15 ($^{15}_{6}C$) is an isotope of carbon that undergoes radioactive decay to nitrogen-15 ($^{15}_{7}N$), which is a stable isotope of nitrogen.

Radioactive decay is both a random and a spontaneous process.

(a) State what is meant by:

(i) random

....

.... [1]

(ii) spontaneous.

....

.... [1]

(ii) On Fig. 10.1, draw the straight line of best fit. [1]

(b) A small sample of carbon-15 decays. The mass M of carbon-15 in the sample decreases with time t.

Fig. 10.1 shows the variation with t of the value of $\ln (M / 10^{-16}\,g)$.

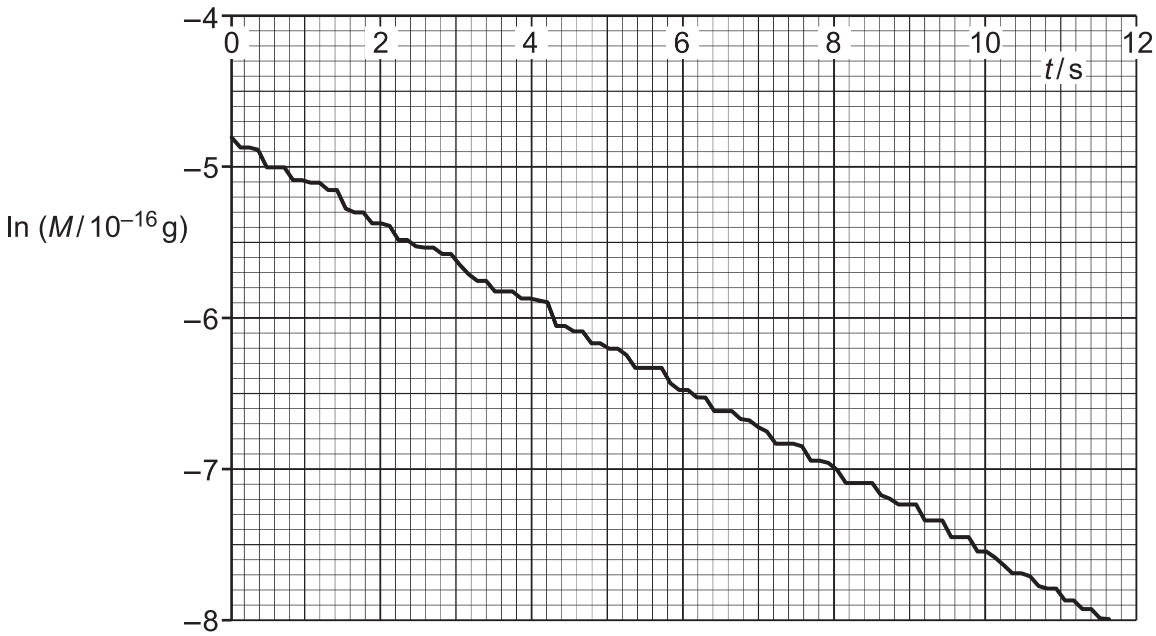

Fig. 10.1

(i) State how Fig. 10.1 demonstrates that radioactive decay is random.

....

.... [1]

(iii) Show that the decay constant λ of carbon-15 is given by the magnitude of the gradient of your line in **(b)(ii)**.

[1]

(iv) Use your line in **(b)(ii)** to determine λ. Give a unit with your answer.

λ = ... unit .... [2]

(v) Use your answer in **(b)(iv)** to calculate the half-life of carbon-15.

half-life = ... s [1]

(c) The equation for the decay of carbon-15 can be written as

$$^{15}_{6}\text{C} \rightarrow {}^{15}_{7}\text{N} + {}^{0}_{-1}\beta + {}^{0}_{0}\bar{\nu}.$$

State and explain how the mass of the products of the decay must compare with the mass of the carbon-15 nucleus.

....

....

.... [2]