NUCLEAR PHYSICS
WORKSHEET
A-Level Physics 9702

ON24/42/Q10

1 **(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]

2 **(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.

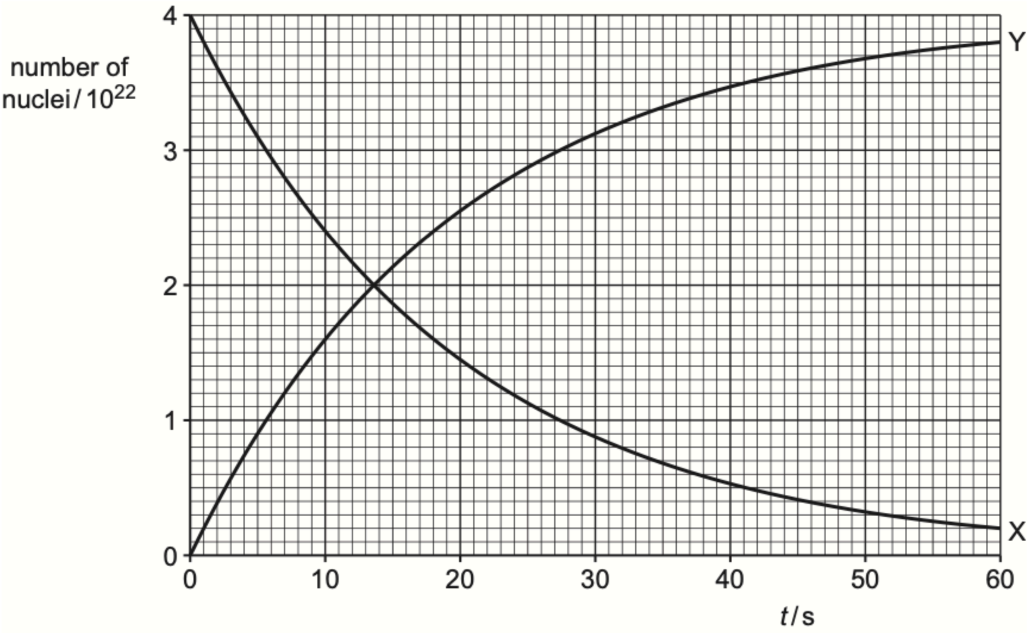


Fig. 9.1

(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]

[Total: 8]

MJ24/42/Q9

3 **(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.

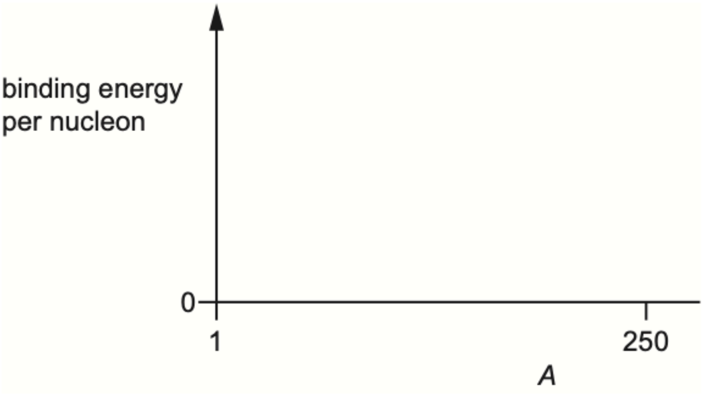


Fig. 9.1

[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]

[Total: 13]

March24/42/Q9

4 **(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]

[Total: 9]

ON23/41/Q9

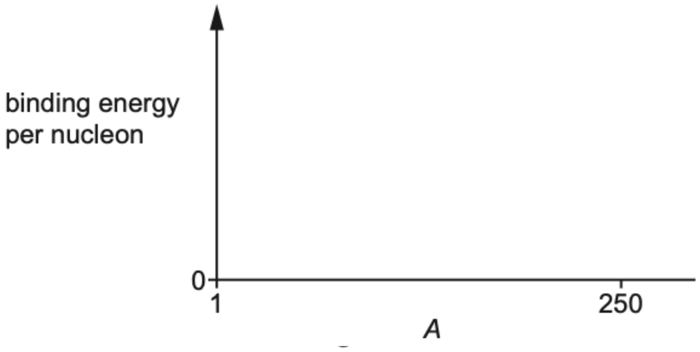
5 **(a)** State what is meant by nuclear fusion.

....

....

.... [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.



[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 ($^{93}_{38}\text{Sr}$) and xenon-139 ($^{139}_{54}\text{Xe}$) according to

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

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

Table 9.1

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

[Total: 10]

6 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.

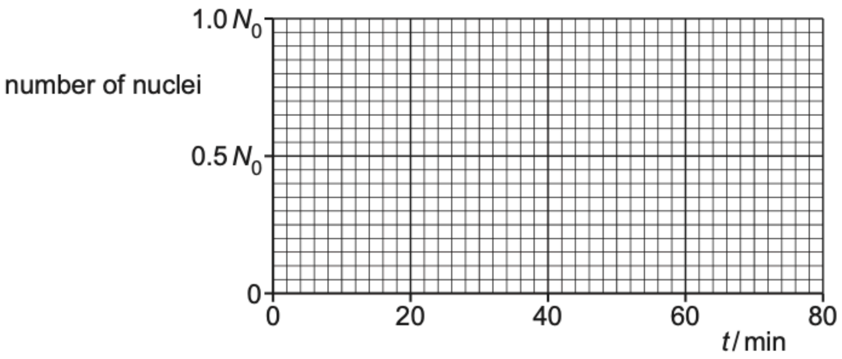


Fig. 9.1

[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]

[Total: 9]

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

....

....

.... [2]

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

Table 9.1

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

The nuclear fusion process in a particular star is described by

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

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 ${}^{4}_{2}\mathrm{He}$ 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 ${}^{4}_{2}\text{He}$ is radiated away from the star.
All the energy that is radiated from the star has been released in the formation of ${}^{4}_{2}\text{He}$.

Determine:

(i) the mass of ${}^{4}_{2}\text{He}$ 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]

[Total: 11]

8 Plutonium-238 (${}^{238}_{94}\text{Pu}$) is unstable and undergoes alpha decay. **March23/42/Q8**

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

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

[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]

[Total: 11]

9 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]

(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).

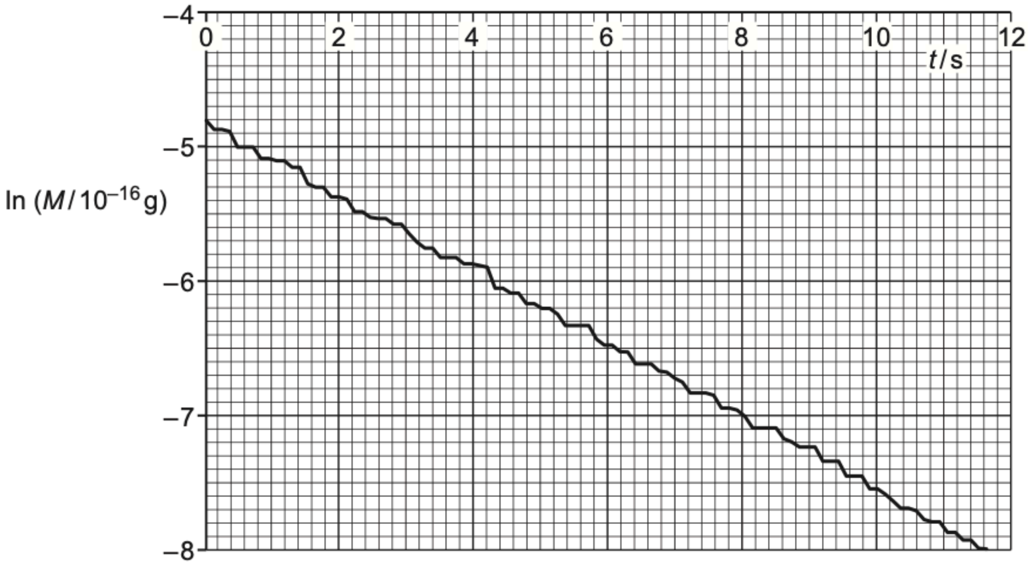


Fig. 10.1

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

....

.... [1]

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

[Total: 10]

MJ22/41/Q8

10 **(a)** **(i)** State what is meant by nuclear binding energy.

....

....

.... [2]

(ii) On Fig. 8.1, sketch a line to show the variation with nucleon number *A* of the binding energy per nucleon *E* of a nucleus.

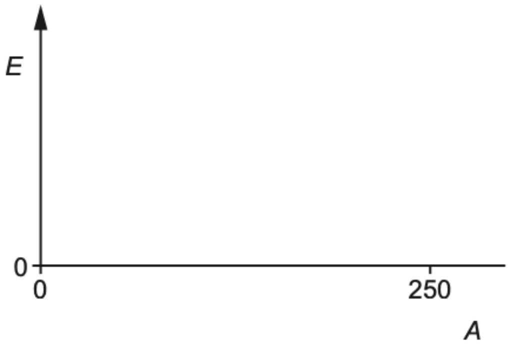


Fig. 8.1

[2]

(b) In one type of nuclear process, deuterium (${}^{2}_{1}H$) undergoes the reaction

$${}^{2}_{1}H + {}^{2}_{1}H \longrightarrow {}^{3}_{2}He + {}^{1}_{0}n.$$

(i) State the name of this type of nuclear process.

.... [1]

(ii) Explain, with reference to your line in **(a)(ii)**, why this reaction results in the release of energy.

....

....

.... [2]

(c) Table 8.1 shows the masses of the particles involved in the reaction in **(b)**.

Table 8.1

particle	mass/u
${}^{1}_{0}n$	1.008665
${}^{2}_{1}H$	2.014102
${}^{3}_{2}He$	3.016029

Calculate the energy released when 1.00 mol of deuterium undergoes the reaction.

energy = ... J [5]

[Total: 12]

MJ22/42/Q10

11 **(a)** State what is meant by radioactive decay.

....

....

.... [2]

(b) A radioactive sample consists of an isotope X of half-life *T* that decays to form a stable product. Only X and the stable product are present in the sample.

At time $t = 0$, the sample has an activity of A_0 and contains N_0 nuclei of X.

(i) On Fig. 10.1, sketch the variation with *t* of the number *N* of nuclei of X present in the sample. Your line should extend from time $t = 0$ to time $t = 3T$.

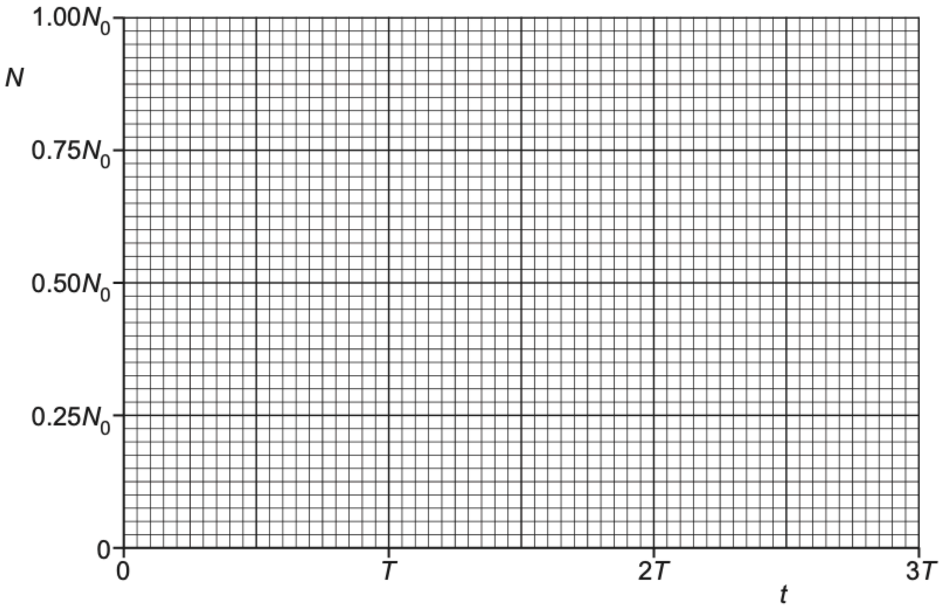


Fig. 10.1

[3]

(ii) On Fig. 10.2, sketch the variation with N of the activity A of the sample for values of N between $N = 0$ and $N = N_0$.

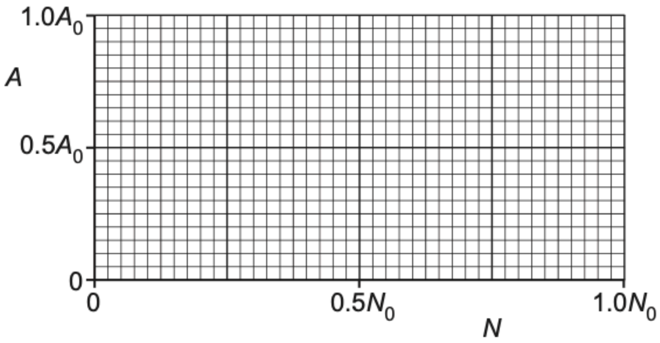


Fig. 10.2

[2]

(c) State the name of the quantity represented by the gradient of your line in:

(i) Fig. 10.1

.... [1]

(ii) Fig. 10.2.

.... [1]

(d) For the sample in **(b)**, calculate the fraction $\frac{N}{N_0}$ at time $t = 1.70T$.

$\frac{N}{N_0}$ = ... [2]

[Total: 11]

12 Polonium-211 ($^{211}_{84}\text{Po}$) decays by alpha emission to form a stable isotope of lead (Pb).

(a) Complete the equation for this decay.

$$^{211}_{84}\text{Po} \rightarrow \,^{\dots\dots}_{\dots\dots}\text{Pb} + \,^{\dots\dots}_{\dots\dots}\alpha$$

[2]

(b) The variation with time *t* of the number of unstable nuclei *N* in a sample of polonium-211 is shown in Fig. 9.1.

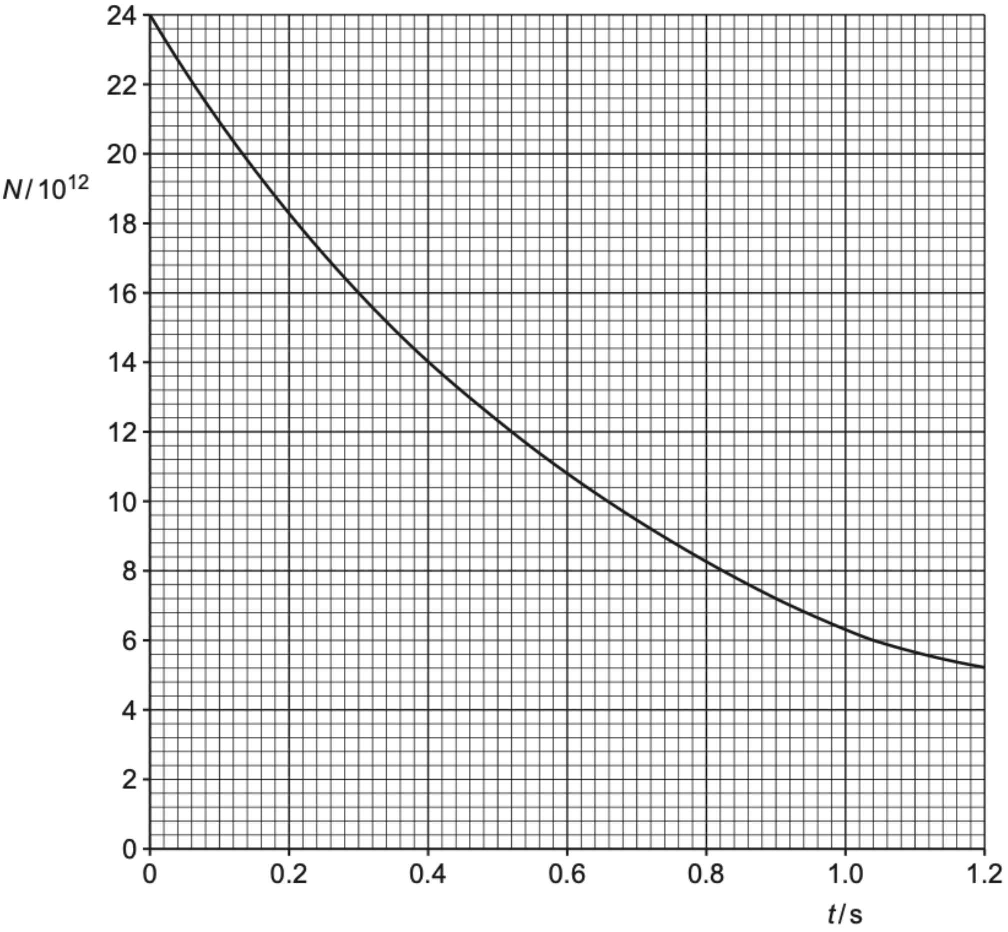


Fig. 9.1

At time *t* = 0, the sample contains only polonium-211.

(i) Use Fig. 9.1 to determine the decay constant *λ* of polonium-211. Give a unit with your answer.

λ = ... unit .... [2]

(ii) Use your answer in **(b)(i)** to calculate the activity at time $t = 0$ of the sample of polonium-211.

activity = ... Bq [1]

(iii) On Fig. 9.1, sketch a line to show the variation with t of the number of lead nuclei in the sample. [2]

(c) Each decay releases an alpha particle with energy 6900 keV.

(i) Calculate, in J, the total amount of energy given to alpha particles that are emitted between time $t = 0.30\,\text{s}$ and time $t = 0.90\,\text{s}$.

energy = ... J [3]

(ii) Suggest why the total amount of energy released by the decay process between time $t = 0.30\,\text{s}$ and time $t = 0.90\,\text{s}$ is greater than your answer in **(c)(i)**.

....

....

.... [1]

[Total: 11]

13 **(a)** Define radioactive *decay constant*. **ON21/41/Q12**

....

....

.... [2]

(b) A sample of radioactive iodine-131 ($^{131}_{53}\text{I}$) of mass 5.87×10^{-10} kg has an activity of 2.92×10^{9} Bq.

Determine the decay constant of iodine-131.

decay constant = ... s^{-1} [3]

(c) Suggest **two** reasons why a detector placed near to the sample in **(b)** would record a count rate much less than 2.92×10^{9} counts per second.

1. ....

....

2. ....

....

[2]

[Total: 7]

ON21/42/Q12

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

State what is meant by:

(i) *random*

....

.... [1]

(ii) *spontaneous*.

....

.... [1]

(b) A sample of radioactive material contains atoms of an unstable nuclide X. The activity of the sample due to the atoms of X is *A*. The variation with time *t* of ln *A* is shown in Fig. 12.1.

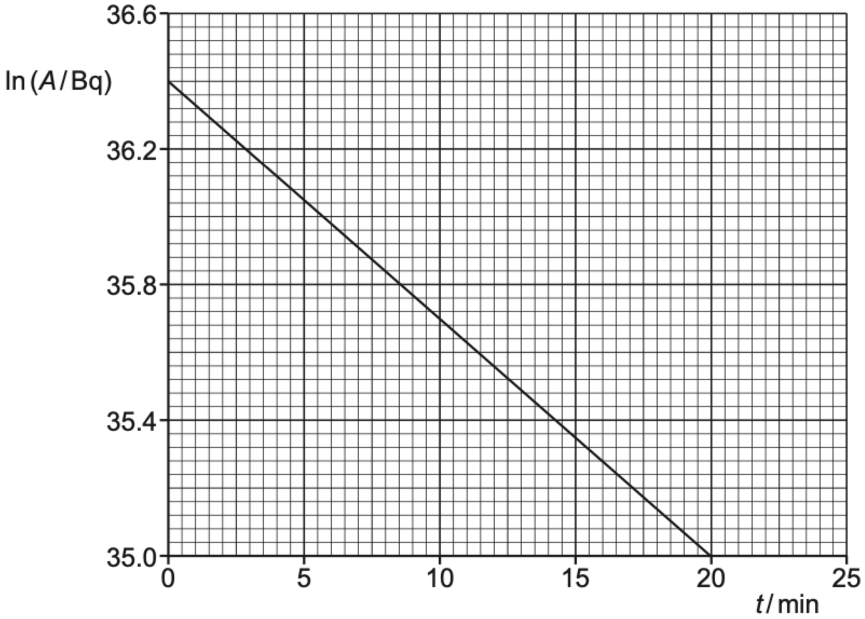


Fig. 12.1

(i) Use Fig. 12.1 to determine the half-life, in minutes, of nuclide X.

half-life = ... min [3]

(ii) At time $t = 0$, the mass of the atoms of X in the sample is 5.66×10^{-7} kg.

Determine the nucleon number of X.

nucleon number = ... [3]

[Total: 8]

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

State what is meant by:

1. *spontaneous decay* ....

....

2. *random decay.* ....

.... [2]

(b) Strontium-90 ($^{90}_{38}$Sr) is an unstable nuclide.

The activity of a sample of 1.0×10^{-9} kg of strontium-90 is 5.2 MBq.

(i) Determine the decay constant λ of strontium-90.

λ = ... s^{-1} [3]

(ii) The activity of the sample after a time of 1.0 half lives is found to be greater than the expected 2.6 MBq.

Suggest a possible reason for this.

....

.... [1]

[Total: 6]

16 Iodine-131 ($^{131}_{53}\text{I}$) is a radioactive isotope with a decay constant of $9.9 \times 10^{-7}\,\text{s}^{-1}$.

(a) State what is meant by:

(i) *radioactive*

....

....

.... [2]

(ii) *decay constant.*

....

....

.... [2]

(b) Some water becomes contaminated with iodine-131.
The activity of the iodine-131 in 1.0 kg of water is 560 Bq.

Determine the number of iodine-131 atoms in 1.0 kg of water.

number = ... [2]

(c) Regulations require that the activity of iodine-131 in 1.0 kg of water is to be less than 170 Bq.

Calculate the time, in days, for the activity of the contaminated water in **(b)** to be reduced to 170 Bq.

time = ... days [3]

[Total: 9]

17 **(a)** **(i)** Define nuclear *binding energy*. **ON20/42/Q12**

....

....

.... [2]

(ii) Explain what is meant by a *nuclear fission* reaction.

....

....

.... [2]

(b) A student suggests that one possible nuclear reaction is

$$^{56}_{26}\text{Fe} + ^{1}_{0}\text{n} \rightarrow ^{20}_{9}\text{F} + ^{37}_{17}\text{C}l$$

The binding energy per nucleon of a nucleus varies with the nucleon number.
Use this variation to explain why the reaction would **not** result in an overall release of energy.

....

....

....

....

.... [3]

[Total: 7]

MJ20/41/Q12

18 **(a)** The decay of a sample of a radioactive isotope is said to be random and spontaneous.

Explain what is meant by the decay being:

(i) *random*

....

.... [1]

(ii) *spontaneous*.

....

.... [1]

(b) A radioactive isotope X has a half-life of 1.4 hours.

Initially, a pure sample of this isotope X has an activity of 3.6×10^5 Bq.

Determine the activity of the isotope X in the sample after a time of 2.0 hours.

activity = ... Bq [3]

(c) The variation with time *t* of the actual activity *A* of the sample in **(b)** is shown in Fig. 12.1.

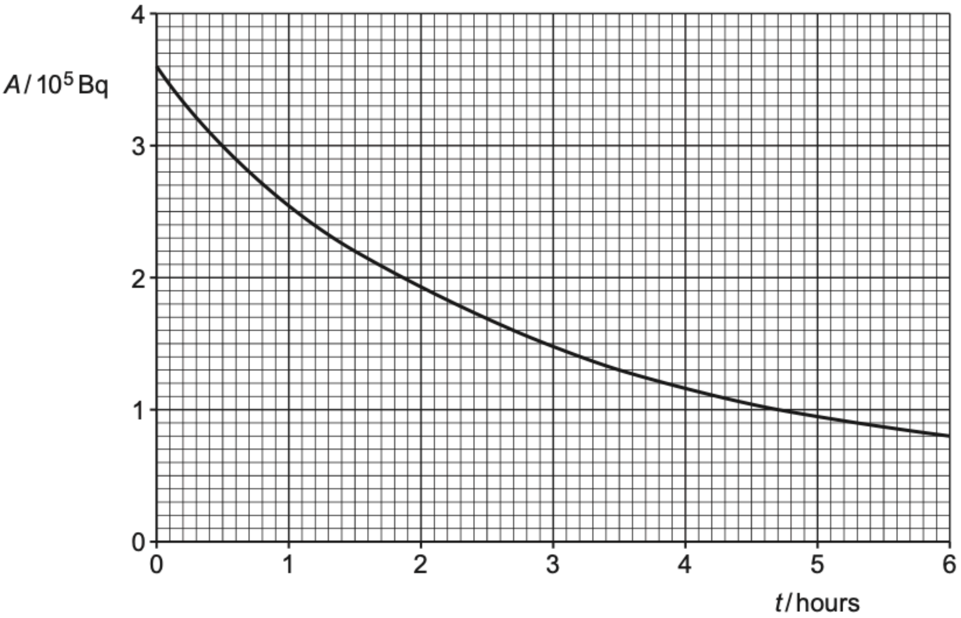


Fig. 12.1

(i) The initial activity of isotope X in the sample is 3.6×10^5 Bq.

Use information from **(b)** to sketch, on the axes of Fig. 12.1, the variation with time *t* of the activity of a pure sample of isotope X. [1]

(ii) Suggest an explanation for any difference between the actual activity of the sample shown in Fig. 12.1 and the curve you have drawn for the activity of isotope X.

....

....

.... [2]

[Total: 8]

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

....

....

.... [2]

(b) Some masses are shown in Table 12.1.

Table 12.1

	mass / u
proton $^{1}_{1}p$	1.007 276
neutron $^{1}_{0}n$	1.008 665
helium-4 ($^{4}_{2}He$) nucleus	4.001 506

Show that:

(i) the energy equivalence of 1.00 u is 934 MeV

[2]

(ii) the binding energy per nucleon of a helium-4 nucleus is 7.09 MeV.

[2]

(c) Isotopes of hydrogen have binding energies per nucleon of less than 3 MeV.

Suggest why a nucleus of helium-4 does not spontaneously break down to become nuclei of hydrogen.

....

....

.... [2]

[Total: 8]

20 **(a)** Explain what is meant by the *binding energy* of a nucleus.

....

....

.... [2]

(b) The following nuclear reaction takes place:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{144}_{55}Cs + ^{90}_{x}Rb + y\,^{1}_{0}n$$

(i) Determine the values of *x* and *y*.

x = ...

y = ...
[1]

(ii) State the name of this type of nuclear reaction.

.... [1]

(iii) Compare the binding energy per nucleon of uranium-235 with the binding energy per nucleon of caesium-144.

....

.... [1]

(c) Yttrium-90 decays into zirconium-90, a stable isotope.

A sample initially consists of pure yttrium-90.

Calculate the time, in days, when the ratio of the number of yttrium-90 nuclei to the number of zirconium-90 nuclei would be 2.0.

The half-life of yttrium-90 is 2.7 days.

time = ... days [3]

[Total: 8]

1 (a)(i)	cannot predict when a particular nucleus will decay **or** cannot predict which nucleus will decay next	**B1**
10(a)(ii)	(decay is) not affected by external (environmental) factors	**B1**
10(a)(iii)	fluctuations in (measured) count rate	**B1**
10(b)(i)	• large nuclei undergo fission whereas small nuclei undergo fusion • fission involves one nucleus splitting into two (or more) (smaller) nuclei • fusion involves two nuclei joining together to form one (larger) nucleus • fission is (usually) initiated by neutron bombardment • fusion is (usually) initiated by (very) high temperatures *Any three points, 1 mark each*	**B3**
10(b)(ii)	binding energy per nucleon is greatest for intermediate nucleon numbers (may be shown on sketch graph with axes labelled 'binding energy per nucleon' and 'nucleon number')	**B1**
	both fusion and fission involve an increase in binding energy (per nucleon)	**B1**

2)(a)	time for activity (of sample) to halve	**B1**
9(b)(i)	activity (of X at time *t*)	**B1**
9(b)(ii)	• Y is a stable isotope • total number of nuclei is constant • half-life (of X) is 13.6 s • decay constant (of X) is $0.051\ s^{-1}$ • amount (of X) at $t = 0$ is 0.066 mol • activity (of X) at $t = 0$ is 2.0×10^{21} Bq *Any three points, 1 mark each*	**B3**
9(c)	mass of 1 nucleus = $(7.3 \times 10^{-4}) / (4.0 \times 10^{22})$	**C1**
	nucleon number = mass of nucleus / (1.66×10^{-27})	**C1**
	$= (7.3 \times 10^{-4}) / (4.0 \times 10^{22} \times 1.66 \times 10^{-27})$ = 11 **and** given as an integer	**A1**

3 a)	energy required to separate (all) the nucleons (in the nucleus)	**M1**
	to infinity	**A1**
9(b)(i)	$\Delta m = \{[(84 \times 1.007276) + (128 \times 1.008665)] - 211.942749\}$ (u) (= 1.778 u)	**C1**
	$= 1.778 \times 1.66 \times 10^{-27}$ (kg)	**C1**
	$= 2.95 \times 10^{-27}$ kg	**A1**
9(b)(ii)	$E = (\Delta)mc^2$	**C1**
	binding energy $= 2.95 \times 10^{-27} \times (3.00 \times 10^8)^2$ $= 2.66 \times 10^{-10}$ J	**A1**
9(b)(iii)	binding energy per nucleon $= (2.66 \times 10^{-10}) / 212$ $= 1.25 \times 10^{-12}$ J	**A1**
9(c)(i)	line rising to a single peak that is to the left of the '9' in the Fig. 9.1 label and then continually decreasing	**B1**
	steep positive gradient on the left of the peak and shallow negative gradient on the right	**B1**
9(c)(ii)	X shown on the line at a value of *A* that is to the right of the left-hand edge of the '*A*' in the axis label, and to the left of '2' in the 250 label	**B1**
9(c)(iii)	nucleus formed (as a result of the decay) has a lower nucleon number	**B1**
	(nucleus formed has a) greater binding energy per nucleon	**B1**

4 (a)	(minimum) energy required to separate the nucleons (of a nucleus)	**M1**
	to infinity	**A1**
8(b)(i)	4	**A1**
8(b)(ii)	energy= (142 × 8.37) + (90 × 8.72) – (235 × 7.59)	**C1**
	= 190 MeV	**A1**
8(b)(iii)	**either** it has too many neutrons (for the number of protons) **or** its neutron to proton ratio is too high	**B1**
8(b)(iv)	(when t = 6.0 s), N / N_0 = 1 / 32	**C1**
	either $(1 / 32) = \exp(-\ln 2 \times 6.0 / t_{\frac{1}{2}})$	**C1**
	$t_{\frac{1}{2}}$ = 1.2 s	**A1**
	or $32 / 2^n = 1$ so n = 5 (half-lives)	**(C1)**
	$t_{1/2}$ = 6.0 / 5 = 1.2 s	**(A1)**

5 (a)	(two small) nuclei join together	**M1**
	to form one larger nucleus	**A1**
9(b)	line with a peak at $A \approx 56$	**B1**
	line with steep initial positive gradient on the left of peak and shallower negative gradient at all points to the right of peak and line does not return to 0 binding energy	**B1**
9(c)(i)	X shown at value of A to the right of the peak	**B1**
9(c)(ii)	Y shown at value of A close to 1	**B1**
9(d)	energy from 1 nucleus = $(1.77 \times 10^{13}) / (6.02 \times 10^{23})$ $(= 2.94 \times 10^{-11}$ J)	**C1**
	binding energy of Z = $[(1.25 + 1.81) \times 10^{-10}] - 2.94 \times 10^{-11}$ $(= 2.77 \times 10^{-10}$ J)	**C1**
	nucleon number of Z = 93 + 139 + 2 – 1 (= 233)	**C1**
	binding energy per nucleon = $(2.77 \times 10^{-10}) / (233 \times 1.60 \times 10^{-13})$ = 7.43 MeV	**A1**

6 (a)	time for activity (of sample) to halve	**B1**
9(b)	sketch: line with positive gradient starting at (0,0) and extending to t = 80 min	**B1**
	exponential curve, extending from t = 0 to t = 80 min, with gradient of steadily decreasing magnitude	**B1**
	line passing through (0,0), (20, $0.5N_0$) and (40, $0.75\ N_0$)	**B1**
9(c)(i)	every (undecayed) nucleus has the same probability of decay	**M1**
	fewer (undecayed) nuclei remaining (with time), so fewer will decay (in a given time interval)	**A1**
9(c)(ii)	• sample emits in all directions but detector only captures emissions in one direction • some emissions are absorbed before reaching detector • some emissions are scattered within the sample • simultaneous arrival of multiple particles only registers once • some particles may reach detector but not cause ionisation *Any two points, 1 mark each*	**B2**
	measured count rate is less than the activity	**B1**

7 (a)	difference between mass of nucleus and (total) mass of nucleons	**M1**
	when infinitely separated	**A1**
9(b)(i)	neutron	**B1**
9(b)(ii)	$E = \Delta m\, c^2$	**C1**
	Δm = (0.030377 – 0.002388 – 0.009105)u (= 0.018884u)	**C1**
	energy release = (0.030377 – 0.002388 – 0.009105) × 1.66 × 10^{-27} × (3.00 × $10^8)^2$ = 2.8 × 10^{-12} J	**A1**
9(c)(i)	number of atoms per unit time = (1.4 × 10^{28}) / (2.8 × 10^{-12}) (= 5.0 × 10^{39} s^{-1})	**C1**
	mass of one atom = 4 × 1.66 × 10^{-27} or (4 × 10^{-3}) / (6.02 × 10^{23}) (= 6.64 × 10^{-27} kg)	**C1**
	mass per unit time = 6.64 × 10^{-27} × 5.0 × 10^{39} = 3.3 × 10^{13} kg s^{-1}	**A1**
9(c)(ii)	$L = 4\pi\sigma r^2 T^4$ 1.4 × 10^{28} = 4π × 5.67 × 10^{-8} × (2.3 × $10^9)^2$ × T^4	**C1**
	T = 7800 K	**A1**

8 (a)	234, 92 for the uranium nucleus	**B1**
	4, 2 for the alpha particle	**B1**
8(b)(i)	N_0 = 0.874 / (238 × 1.66 × 10^{-27}) = 2.21 × 10^{24}	**A1**
8(b)(ii)	$A = \lambda N$	**C1**
	$= \frac{\ln 2}{87.7\times365\times24\times3600}\times2.21\times10^{24}$ = 5.54 × 10^{14} Bq	**A1**
8(b)(iii)	power = 5.54 × 10^{14} × 5.59 × 10^6 × 1.60 × 10^{-19}	**C1**
	= 496 W	**A1**
8(b)(iv)	$65.3 = 100e^{-\frac{\ln 2}{87.7}t}$	**C1**
	ln 0.653 = – (ln 2 / 87.7) t t = 53.9 years	**A1**
8(c)	advantage: less mass so less energy needed to launch probe	**B1**
	disadvantage: half-life shorter so will not provide power for as long	**B1**

9 (a)(i)	cannot predict when a (particular) nucleus will decay **or** cannot predict which nucleus will decay next	**B1**
10(a)(ii)	not affected by external / environmental factors	**B1**
10(b)(i)	line fluctuates **or** trend is a straight line	**B1**
10(b)(ii)	straight line of best fit drawn on Fig. 10.1	**B1**
10(b)(iii)	$M = M_0 \exp(-\lambda t)$ so $\ln M = \ln M_0 - \lambda t$ so gradient = $-\lambda$ (and magnitude of gradient = λ)	**B1**
10(b)(iv)	gradient = (–) (8.0 – 4.8) / (11.6 – 0) (*allow any correct pair of values from Fig. 10.1*)	**C1**
	$\lambda = 0.28\ \text{s}^{-1}$	**A1**
10(b)(v)	half-life = $0.693 / \lambda$ = 0.693 / 0.28 = 2.5 s	**A1**
10(c)	(for reaction to occur,) energy is released	**B1**
	energy release comes from fall in mass so total mass of products must be less (than mass of carbon-15)	**B1**

10 (a)(i)	energy required to separate the nucleons (in the nucleus)	**M1**
	to infinity	**A1**
8(a)(ii)	curve starting close to the origin and forming a single peak	**B1**
	peak shown to left of centre, with steep line on LHS of peak and shallow line on RHS of peak	**B1**
8(b)(i)	fusion	**B1**
8(b)(ii)	both particles have low *A* values **or** both particles are at left-hand end of graph	**B1**
	He-3 has higher binding energy (per nucleon) than H-2	**B1**
8(c)	$\Delta m = [(2 \times 2.014102) - (3.016029 + 1.008665)]\ \text{u}$ $(= 0.00351\ \text{u})$	**C1**
	$E = \Delta mc^2$	**C1**
	$= 0.00351 \times 1.66 \times 10^{-27} \times (3.00 \times 10^8)^2$ $(= 5.24 \times 10^{-13}\ \text{J})$	**C1**
	1.00 mol of deuterium forms 0.500 mol of helium-3	**C1**
	total energy $= 0.500 \times 6.02 \times 10^{23} \times 5.24 \times 10^{-13}$ $= 1.58 \times 10^{11}\ \text{J}$	**A1**

11 a)	spontaneous emission of (ionising) radiation	**B1**
	emission from unstable nucleus	**B1**
10(b)(i)	curve with decreasing negative gradient passing through $(0, N_0)$	**B1**
	curve passing through $(T, 0.5N_0)$	**B1**
	curve passing through $(2T, 0.25N_0)$ **and** $(3T, 0.125N_0)$	**B1**
10(b)(ii)	line through origin with positive gradient	**B1**
	straight line passing through (N_0, A_0)	**B1**
10(c)(i)	activity	**B1**
10(c)(ii)	decay constant	**B1**
10(d)	$N = N_0 \exp(-\ln 2 \times 1.70T / T)$	**C1**
	$N / N_0 = 0.31$	**A1**

12 (a)	207, 82 for lead	**B1**
	4, 2 for alpha	**B1**
9(b)(i)	(half-life found as) 0.52 s or correctly read points substituted into $N = N_0 e^{-\lambda t}$ $\lambda = \frac{0.693}{t_{1/2}}$ $\lambda = \frac{0.693}{0.52}$	**C1**
	λ = **1.3 s^{-1}**	**A1**
9(b)(ii)	$A = \lambda N$ $= 1.3 \times 24 \times 10^{12}$ $= 3.1 \times 10^{13}$ Bq	**A1**
9(b)(iii)	upwards curve of decreasing gradient starting from (0,0)	**B1**
	passes through (0.52, 12) and (1.2, 18.8)	**B1**
9(c)(i)	16×10^{12} and 7.2×10^{12}	**C1**
	$6900 \times 10^{3} \times 1.6 \times 10^{-19}$ $(16 \times 10^{12} - 7.2 \times 10^{12}) \times 6900 \times 10^{3} \times 1.6 \times 10^{-19}$	**C1**
	= 9.7 J	**A1**
9(c)(ii)	lead nuclei have kinetic energy *or* gamma photons are also emitted	**B1**

13 (a)	probability of decay (of a nucleus)	**M1**
	per unit time	**A1**
12(b)	$A = \lambda N$	**C1**
	N = mass / (nucleon number $\times$ u)	**C1**
	$2.92 \times 10^{9} = (\lambda \times 5.87 \times 10^{-10}) / (131 \times 1.66 \times 10^{-27})$ $\lambda = 1.08 \times 10^{-6}$ s^{-1}	**A1**
12(c)	• sample emits radiation in all directions • some radiation is absorbed by air/detector window • self-absorption within the source • dead time/inefficiency of detector *Any two points, 1 mark each*	**B2**

14 (a)(i)	cannot predict when a particular nucleus will decay **or** cannot predict which nucleus will decay next	**B1**
12(a)(ii)	(decay is) not affected by external (environmental) factors	**B1**
12(b)(i)	$A = A_0 \exp(-\lambda t)$ and so $\ln A = \ln A_0 - \lambda t$ gradient of line = $(-)\lambda$	**C1**
	$\lambda = (36.4 - 35.0) / (20 - 0)$ $(= 0.07(0)\ \text{min}^{-1})$	**C1**
	half-life $= \ln 2 / \lambda$ $= \ln 2 / 0.070$ $= 10$ min	**A1**
	or	
	$A_0 = \exp(-36.4) = 6.43 \times 10^{15}$ (Bq)	**(C1)**
	$A_0 / 2 = 3.21 \times 10^{15}$ (Bq), so $\ln (A_0 / 2) = 35.7$	**(C1)**
	read off half-life = 10 min	**(A1)**
	or	
	(at one half-life,) $\ln A = 36.4 - \ln 2$	**(C1)**
	$= 35.7$	**(C1)**
	read off half-life = 10 min	**(A1)**

12(b)(ii)	$A = \lambda N$	**C1**
	N = mass / (nucleon number × u) **or** N = (mass / nucleon number) × N_A	**C1**
	$\exp(36.4) = (1.17 \times 10^{-3} \times 5.66 \times 10^{-7}) / (\text{nucleon number} \times 1.66 \times 10^{-27})$ **or** $\exp(36.4) = (1.17 \times 10^{-3} \times 5.66 \times 10^{-4} \times 6.02 \times 10^{23}) / \text{nucleon number}$ nucleon number = 62	**A1**

15 (a)	1 not affected by external factors	**B1**
	2 cannot predict when a (particular) nucleus will decay *or* cannot predict which nucleus will decay (next)	**B1**
12(b)(i)	Number of atoms = $\dfrac{1.0 \times 10^{-9}}{90 \times 1.66 \times 10^{-27}}$ *or* $\dfrac{1.0 \times 10^{-9} \times 6.02 \times 10^{23}}{90 \times 10^{-3}}$ $= 6.693 \times 10^{15}$	**C1**
	$A = \lambda N$ $\lambda = \dfrac{5.2 \times 10^{6}}{6.693 \times 10^{15}}$	**C1**
	$\lambda = 7.8 \times 10^{-10}\ \text{s}^{-1}$	**A1**
12(b)(ii)	daughter nucleus is unstable	**B1**

16 (a)(i)	unstable nucleus	**B1**
	emits ionising radiation **or** decays spontaneously	**B1**
12(a)(ii)	probability of decay (of a nucleus)	**M1**
	per unit time	**A1**
12(b)	$A = \lambda N$	**C1**
	$560 = 9.9 \times 10^{-7} \times N$ $N = 5.7 \times 10^{8}$	**A1**
12(c)	$A = A_0\,e^{-\lambda t}$ $170 = 560\,\exp(-9.9 \times 10^{-7} \times t)$	**C1**
	$t = 1.2 \times 10^{6}$ s	**C1**
	= 14 days	**A1**

17 (a)(i)	energy required to separate nucleons (of nucleus)	**M1**
	to infinity	**A1**
12(a)(ii)	a (single) large nucleus <u>divides</u> to form (smaller) nuclei	**B1**
	any one point from: • initiated by neutron bombardment • resulting nuclei are of similar size • binding energy per nucleon increases • total binding energy increases • neutrons released • combined mass of smaller nuclei is less than mass of large nucleus	**B1**
12(b)	binding energy per nucleon is a maximum at around A = 56	**B1**
	products of splitting a ^{56}Fe nucleus must have a lower total binding energy	**B1**
	(reaction would require) a net input of energy	**B1**

18 (a)(i)	time at which a nucleus will decay cannot be predicted **or** constant probability of decay of a nucleus	**B1**
12(a)(ii)	decay (of a nucleus) not affected by environmental factors	**B1**
12(b)	$A = A_0 e^{-\lambda t}$ **and** $\lambda = \ln 2 / t_{½}$	**C1**
	$= 3.6 \times 10^{5} \times \exp\,[-(2 \times \ln 2) / 1.4]$	**C1**
	or	
	$A = A_0 \times 0.5^{N}$	**(C1)**
	$= 3.6 \times 10^{5} \times 0.5^{N}$ where $N = 2 / 1.4$	**(C1)**
	$A = 1.3 \times 10^{5}$ Bq	**A1**
12(c)(i)	smooth curve, starting at (0, 3.6 × 10^{5}) and passing through (1.4, 1.8 × 10^{5}) and (2.0, 1.3 × 10^{5})	**B1**
12(c)(ii)	(activity of sample is greater than activity of X so) there must be an additional source of activity	**C1**
	the decay product (of isotope X) is radioactive	**A1**

19 (a)	difference between mass of nucleus and mass of (constituent) nucleons	**M1**
	where nucleons are separated to infinity	**A1**
12(b)(i)	$E = mc^2$	**C1**
	$= 1.66 \times 10^{-27} \times (3.00 \times 10^8)^2 / (1.60 \times 10^{-13}) = 934$ MeV	**A1**
12(b)(ii)	mass defect = $2 \times (1.007276 + 1.008665) - 4.001506$ (= 0.030376)	**B1**
	binding energy per nucleon = $(0.030376 \times 934) / 4 = 7.09$ MeV	**A1**
12(c)	binding energy per nucleon is much greater	**M1**
	so would require a large amount of energy to separate the nucleons in helium	**A1**
	or	
	amount of energy released in forming hydrogen isotopes	**(M1)**
	is less than energy required to break apart helium nucleus	**(A1)**

20 (a)	(minimum) energy required to separate the nucleons	**M1**
	to infinity	**A1**
12(b)(i)	**37** **2**	**B1**
12(b)(ii)	fission	**B1**
12(b)(iii)	binding energy per nucleon smaller for U than for Cs	**B1**
12(c)	Current ratio 2 Y to 1 Zr, so initially 3 Y $2 = 3\,e^{-\lambda t}$ $\lambda = 0.693 / 2.7$	**C1**
	$\ln(2/3) = -(\ln 2 / 2.7)t$	**C1**
	t = **1.6** days	**A1**
	or	
	$(½)^n = 2/3$	**(C1)**
	n = 0.585	**(C1)**
	time = 0.585×2.7 = **1.6** days	**(A1)**