Marks 6

- In March 2011 after a tsunami flooded the Fukushima Daiichi nuclear power plant, three of the six reactors went into meltdown, and by 31 March had released large quantities of the nuclides detailed in the table below.

Radioisotope	Initial activity of quantity released (10^{15} Bq)	Half-life
^{131}I	511	8.02 days
^{137}Cs	13.6	30.17 years

Given that the only stable nuclide of iodine is ^{127}I, would you expect the primary decay mechanism for ^{131}I to be α, β^-, or β^+ decay? Briefly explain your reasoning.

^{131}I has Z = 53 and N = 78 giving an N / Z ratio of 1.47. This ratio suggests that β^- will be the primary decay mechanism. α becomes impoortant after Z = 82.

This decay route will lower this ratio as it involves a neutron being converted into a proton and a β^- particle: N will decrease by 1 and Z will increase by 1.

Calculate the decay constant for ^{131}I.

The decay constant, λ, is related to the half life, $t_{1/2} = \ln 2 / \lambda$:

$$\lambda = \ln 2 / t_{1/2} = \ln 2 / (8.02 \times 24 \times 60 \times 60)\ s^{-1} = 1.00 \times 10^{-6}\ s^{-1}$$

Answer: **1.00×10^{-6} s^{-1}**

Calculate the initial mass of ^{131}I released.

The initial activity of ^{131}I is 511×10^{15} Bq or 511×10^{15} nuclei s^{-1}. As activity, $A = \lambda N$:

$$N = A / \lambda = 511 \times 10^{15}\ \text{nuclei s}^{-1} / 1.00 \times 10^{-6}\ s^{-1} = 5.11 \times 10^{23}\ \text{nuclei}$$

The molar mass of ^{131}I is 131 g mol^{-1} so 6.022×10^{23} nuclei has a mass of 131 g. Therefore:

$$5.11 \times 10^{23}\ \text{nuclei corresponds to}\ 5.11 \times 10^{23} / 6.022 \times 10^{23} \times 131\ g = 111\ g$$

Answer: **111 g**

THIS QUESTION CONTINUES ON THE NEXT PAGE.

Marks **6**

One method of determining whether further radionuclide leaks are occurring is to monitor the relative activities of the different nuclides as a function of time. Calculate the expected activity due to each of these nuclides exactly 3 years after the release. Assume no more has subsequently escaped from the reactors.

If the initial number of nuclei is N_0, the number of radioactive nucleus after time t is N_t where $\ln(N_0/N_t) = \lambda t$. As $A = \lambda N$, this can also be written in terms of activities:

$$\ln(A_0/A_t) = \lambda t$$

From 2014-J-2, λ for ^{131}I is 1.00×10^{-6} s^{-1} and $A_0 = 511 \times 10^{15}$ Bq. Hence, after exactly 3 years:

$$\ln(511 \times 10^{15} \text{ Bq} / A_t) = (1.00 \times 10^{-6} \text{ s}^{-1}) \times (3.00 \times 365.25 \times 24 \times 60 \times 60 \text{ s})$$

$$A_t = 3.80 \times 10^{-24} \text{ Bq}$$

From 2014-J-2, $t_{1/2} = 30.17$ years for ^{137}Cs. Hence:

$$\lambda = \ln 2 / t_{1/2} = \ln 2 / (30.17 \times 365.25 \times 24 \times 60 \times 60) \text{ s}^{-1} = 7.28 \times 10^{-10} \text{ s}^{-1}$$

Using $A_0 = 13.6 \times 10^{15}$ Bq from 2014-J-2, after exactly 3 years:

$$\ln(13.6 \times 10^{15} \text{ Bq} / A_t) = (7.28 \times 10^{-10} \text{ s}^{-1}) \times (3.00 \times 365.25 \times 24 \times 60 \times 60 \text{ s})$$

$$A_t = 1.27 \times 10^{16} \text{ Bq}$$

Activities	^{131}I: **3.80×10^{-24} Bq**	^{137}Cs: **1.27×10^{16} Bq**

Caesium has no biological role in the human body, and is usually only present in trace amounts. On ingestion, even non-radioactive Cs isotopes are considered toxic as they are capable of partially substituting for chemically similar elements. Name a chemically similar element. State one chemically-significant difference between ions of this element and Cs^+ ions.

As a +1 ion, Cs^+ is chemically similar to Na^+ and K^+.

Cs^+ is larger than either of these ions. This will lead it to have higher coordination numbers: more anions will fit around it in ionic solids and more donor atoms (such as OH_2) will coordinate to it than can fit on Na^+ or K^+.

THE REMAINDER OF THIS PAGE IS FOR ROUGH WORKING ONLY.

Marks 8

- Calculate the activity (in Bq) of a 1.00 g sample of $^{137}Cs^{131}I$, if the half lives of the caesium and iodine are 30.17 years and 8.02 days respectively.

The molar mass of $^{137}Cs^{131}I$ is (137 + 131) g mol^{-1} = 268 g mol^{-1}. As each mole of $^{137}Cs^{131}I$ contains one mole of ^{137}Cs and one moles of ^{131}I:

number of moles of ^{137}Cs = number of moles of ^{131}I = mass / molar mass
= 1.00 g / 268 g mol^{-1} = 0.00373 mol

Each mole contains Avogadro's number of nuclei so:

number of nuclei of ^{137}Cs = number of nuclei of ^{131}I = number of moles × N_A
= 0.00373 mol × 6.022 × 10^{23} mol^{-1}
= 2.25 × 10^{25}

The activity coefficient, λ, is related to the half life, $t_{1/2}$, through $\lambda = \ln 2 / t_{1/2}$. Hence:

$$\lambda\,(^{137}Cs) = \ln 2 / (30.17 \times 365 \times 24 \times 60 \times 60\ s) = 7.28 \times 10^{-10}\ s^{-1}$$
$$\lambda\,(^{131}I) = \ln 2 / (8.02 \times 24 \times 60 \times 60\ s) = 1.00 \times 10^{-6}\ s^{-1}$$

The activity, A, is related to the number of nuclei, N, through $A = \lambda N$ and so:

$$A\,(^{137}Cs) = (7.28 \times 10^{-10}\ s^{-1}) \times (2.25 \times 10^{25}\ \text{nuclei}) = 1.64 \times 10^{12}\ Bq$$
$$A\,(^{131}I) = (1.00 \times 10^{-6}\ s^{-1}) \times (2.25 \times 10^{25}\ \text{nuclei}) = 2.25 \times 10^{15}\ Bq$$

As might have been anticipated from the relative sizes of the half lives, the activity is completely dominated by ^{131}I:

Overall activity = $A\,(^{137}Cs) + A\,(^{131}I)$ = 2.25 × 10^{15} Bq

Answer: **2.25 × 10^{15} Bq**

Both nuclides in $^{137}Cs^{131}I$ are beta emitters, and the daughter nuclides are stable. Describe the sample after it has been melted and allowed to resolidify after (a) 3 months and (b) 300 years.

The products formed by beta emission are:

$$^{137}_{55}Cs \rightarrow\ ^{137}_{56}Ba +\ ^{0}_{-1}\beta \qquad ^{131}_{53}I \rightarrow\ ^{131}_{54}Xe +\ ^{0}_{-1}\beta$$

The ^{131}I decays to ^{131}Xe which, being a gas, escapes on melting.

(a) As the half life of ^{131}I is only 8.02 days, after 3 months most of it will have decayed. As the half life of ^{137}Cs is 30.17 years, after 3 months little will have decay. The sample will be mainly ^{137}Cs with a little ^{137}Ba.

(b) After 300 years, the sample will be mainly ^{137}Ba with a little bit of ^{137}Cs remaining.

Marks 8

- The generation of energy in a nuclear reactor is largely based on the fission of either ^{235}U or ^{239}Pu. The fission products include every element from zinc through to the *f*-block. Explain why most of the radioactive fission products are β-emitters.

The optimal neutron : proton ratio increases as *Z* increases.

Splitting a large nucleus in two will almost certainly produce nuclides with similar neutron : proton ratios to the parent, which will now be too high. They will emit negative charge to convert neutrons to protons, bringing about a more satisfactory neutron : proton ratio. *i.e.* they will be β emitters.

Much of the fission yield is concentrated in two peaks, one in the second transition row and the other later in the periodic table. Identify the missing "sister" products of the following daughter nuclides of ^{235}U by writing balanced nuclear equations. The fission reactions are triggered by the absorption of one neutron, and release three neutrons upon disintegration of the short-lived ^{236}U nucleus.

^{141}Ba	${}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + \mathbf{3}\,{}^{1}_{0}n$
^{95}Sr	${}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{95}_{38}Sr + {}^{138}_{54}Xe + \mathbf{3}\,{}^{1}_{0}n$

Many of the fission products are short lived, and spent fuel rods are eventually contaminated by longer-lived species. The radioactivity of spent fuel can be modelled simply by the exponential decay of the ^{137}Cs and ^{90}Sr. The % yields and half lives of these nuclides are given in the table.

nuclide	%Yield *per fission event*	Half-life (years)
^{90}Sr	4.505	28.9
^{137}Cs	6.337	30.23

After use, nuclear fuel rods are stored in ponds of cooling water, awaiting safe disposal. If 3 % of the mass of used fuel rods consists of fission products of ^{235}U and ^{239}Pu, what percentage of the mass is made up by each of these nuclides?

Using:

percentage mass = percentage yield × (atomic mass / 235) × 3%

% ^{90}Sr = 0.04505 × (90/235) × 0.03 × 100% = 0.05%

% ^{137}Cs = 0.06337 × (137/235) × 0.03 × 100% = 0.11%

^{90}Sr: **0.05%**	^{137}Cs: **0.11%**

THIS QUESTION CONTINUES ON THE NEXT PAGE.

Marks 8

What are the specific activities of ^{90}Sr and ^{137}Cs in Bq g^{-1}?

For ^{90}Sr, the activity coefficient is given by

$$\lambda = \ln 2 / t_{1/2} = \ln 2 / (28.9 \times 365 \times 24 \times 60 \times 60)\ \mathrm{s^{-1}} = 7.61 \times 10^{-10}\ \mathrm{s^{-1}}$$

The number of nuclei, *N*, in a gram is

$$N = (6.022 \times 10^{23} / 90) = 6.69 \times 10^{21}$$

Hence, the activity, *A*, is

$$A = \lambda N = (7.61 \times 10^{-10}) \times (6.69 \times 10^{21})\ \mathrm{Bq\ g^{-1}} = 5.09 \times 10^{12}\ \mathrm{Bq\ g^{-1}}$$

For ^{137}Sr, the activity coefficient is given by

$$\lambda = \ln 2 / t_{1/2} = \ln 2 / (30.23 \times 365 \times 24 \times 60 \times 60)\ \mathrm{s^{-1}} = 7.271 \times 10^{-10}\ \mathrm{s^{-1}}$$

The number of nuclei, *N*, in a gram is

$$N = (6.022 \times 10^{23} / 137) = 4.40 \times 10^{21}$$

Hence, the activity, *A*, is

$$A = \lambda N = (7.271 \times 10^{-10}) \times (4.40 \times 10^{21})\ \mathrm{Bq\ g^{-1}} = 3.19 \times 10^{12}\ \mathrm{Bq\ g^{-1}}$$

^{90}Sr: **5.09×10^{12} Bq g^{-1}**	^{137}Cs: **3.19×10^{12} Bq g^{-1}**

Assuming the majority of the activity of a spent fuel rod to be due to these nuclides, what will be the activity of a 1 tonne fuel rod 100 years after placing it in the pond?

As ^{90}Sr represents 0.05% of the mass (from 2012-J-4) and has an activity of 5.09 × 10^{12} Bq g^{-1} (from above), its initial activity, A_0, is

$$A_0 = (1 \times 10^6) \times (5.09 \times 10^{12}) \times (0.05 / 100)\ \mathrm{Bq}$$

Activity decays with time according to

$$A_t = A_0 \exp(-\lambda t) = A_0 \exp(-t \times \ln 2 / t_{1/2})$$

Hence

$$A_t = (1 \times 10^6) \times (5.09 \times 10^{12}) \times (0.05 / 100) \exp(-100 \times \ln 2 / 28.9)\ \mathrm{Bq}$$
$$= 2.3 \times 10^{14}\ \mathrm{Bq}$$

As ^{137}Cs represents 0.11% of the mass (from 2012-J-4) and has an activity of 3.19 × 10^{12} Bq g^{-1} (from above), its initial activity, A_0, is

$$A_0 = (1 \times 10^6) \times (3.19 \times 10^{12}) \times (0.11 / 100)\ \mathrm{Bq}$$

Hence

$$A_t = (1 \times 10^6) \times (3.19 \times 10^{12}) \times (0.11 / 100) \exp(-100 \times \ln 2 / 30.23)\ \mathrm{Bq}$$
$$= 3.5 \times 10^{14}\ \mathrm{Bq}$$

The total activity is therefore $(2.3 \times 10^{14} + 3.5 \times 10^{14})$ Bq = 6×10^{14} Bq

Answer: **6×10^{14} Bq**

How long does it take 1.0 g of ^{231}Th to decay to the same activity as 1.0 g of ^{232}Th?

Marks 3

The half life of ^{231}Th is *very* short compared to that of ^{232}Th. *All* of the ^{231}Th will decay to ^{231}Pa in the time it takes for the ^{231}Th decay. Thus, the activity of 1.0 g of ^{231}Th will actually correspond to the activity of ^{231}Pa.

From 2010-J-4, the activity of 1.0 g of ^{232}Th is 4.1×10^3 Bq and the activity of 1.0 g of ^{231}Pa is 1.8×10^9 Bq. The time, *t*, it takes for the activity of ^{231}Pa to fall from 1.8×10^9 (A_0) to 4.1×10^3 Bq (A_t) needs to be calculated.

The number of nuclei varies with time according to $\ln(N_0/N_t) = \lambda t$. As activity is directly proportional to the number of nuclei, this can be rewritten in terms of activities:

$$\ln(A_0/A_t) = \lambda t = (\ln 2/t_{1/2}) \times t$$

Thus,

$$\ln(1.8 \times 10^9 / 4.1 \times 10^3) = \ln 2/(3.27 \times 10^4 \times 365.25 \times 60 \times 60 \text{ s}) \times t$$

$$t = 1.93 \times 10^{13} \text{ s} = 6.1 \times 10^5 \text{ years}$$

Answer: **6.1×10^5 years**

Marks

- The isotope ^{37}Ar has a half-life of 35 days. If each decay event releases an energy of 1.0 MeV, calculate how many days it would take for a 0.10 g sample of ^{37}Ar to release 22.57×10^3 kJ (enough energy to boil 10.0 L of water)? **3**

1.0 MeV = 1.0×10^6 eV corresponds to $(1.602\times10^{-19} \times 1.0\times10^{6})$ J = 1.602×10^{-13} J.

Each decay event releases 1.602×10^{-13} J and so to release 22.57×10^3 kJ requires:

$$\text{number of decay events required} = \frac{22.57 \times 10^{3} \times 10^{3}\ \text{J}}{1.602 \times 10^{-13}\ \text{J}} = 1.409 \times 10^{20}$$

0.10 g of ^{37}Ag corresponds to $\frac{0.1\ \text{g}}{37\ \text{g mol}^{-1}}$ = 0.0027 mol. This in turn corresponds to $(0.00270\ \text{mol} \times 6.022 \times 10^{23}\ \text{mol}^{-1}) = 1.63 \times 10^{21}$ nuclei. $N_0 = 1.63 \times 10^{21}$

As the initial number of nuclei present is 1.63×10^{21} and the number of decay events required is 1.409×10^{20}, the final number of nuclei will be:

$$(1.63 \times 10^{21} - 1.409 \times 10^{20}) = 1.49 \times 10^{21} = N_t$$

As the half life is 35 days, the decay constant is $\frac{\ln 2}{35\ \text{days}}$ = 0.0198 days^{-1}. Hence,

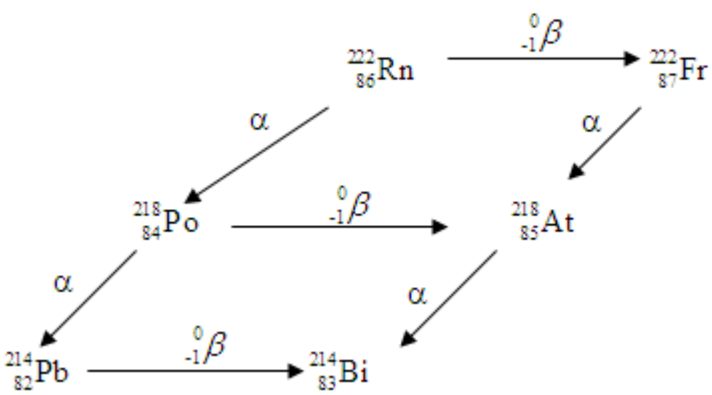
$$\ln\left(\frac{N_0}{N_t}\right) = \lambda t$$

$$\ln\left(\frac{1.63 \times 10^{21}}{1.49 \times 10^{21}}\right) = (0.0198\ \text{days}^{-1})\ t$$

$$t = 4.5\ \text{days}$$

Answer: **4.5 days**

- The isotope ^{222}Rn decays to ^{214}Bi in three steps. Identify all possible decay paths for this process, including all the intermediate isotopes along each path and the identity of the decay process involved in each individual step. **3**



Marks
1

- In the spaces provided, explain the meaning of the following term. You may use an example, equation or diagram where appropriate.

half-life

The time required for a material to decay to half its initial amount. Half-life is commonly used as a measure of radioactivity but is also used in studying the decrease in concentration of other materials during chemical or biochemical reactions.

Marks

- Explain why a sustained fission chain reaction can only occur when a critical mass is prepared. **2**

Below the critical mass, so many neutrons are lost from the material that a chain reaction cannot be sustained.

- The half life of ^{3}H is 12 years. Calculate how long it takes (rounded to the nearest year) for the activity of a sample of tritium to have dropped to 0.1% of its original value. **2**

From $t_{1/2} = \frac{\ln 2}{\lambda}$, the activity coefficient $\lambda = \frac{\ln 2}{t_{1/2}} = . \frac{\ln 2}{12 \text{ years}} = 0.058 \text{ years}^{-1}$

As the activity is directly proportional to the number of radioactive nuclei, the activity, A_t, at time t is related to the initial activity, A_0, by $\ln\left(\frac{A_0}{A_t}\right) = \lambda t$

With $A_t = 0.001 \times A_0$, the ratio $\frac{A_0}{A_t} = 1000$. Hence,

$\ln(1000) = (0.058)t$ or $t = 120$ years $= 1.2 \times 10^2$ years

Answer: **1.2×10^2 years**

- Consider the following list of unstable isotopes and their decay mechanisms. **3**

$^{33}_{17}Cl \rightarrow {}^{0}_{+1}e + {}^{33}_{16}S$ half-life = 2.5 s

$^{32}_{15}P \rightarrow {}^{0}_{-1}e + {}^{32}_{16}S$ half-life = 14.3 days

$^{199}_{82}Pb \rightarrow {}^{0}_{+1}e + {}^{199}_{81}Tl$ half-life = 90 minutes

$^{13}_{7}N \rightarrow {}^{0}_{+1}e + {}^{13}_{6}C$ half-life = 10 minutes

From this list, select the isotope that best satisfies the following requirements. Provide a reason for your choice in each case.

Requirement	Isotope	Reason for choice
Isotope used in medical imaging	**$^{13}_{7}N$**	**Positron emitter, non-toxic and has sufficiently long half life to be chemically incorporated.**
Decay represents the transformation of a neutron into a proton	**$^{32}_{15}P$**	**This nuclide is a β-emitter. The nuclear charge increases from 15 to 16 and the mass is unaffected. The charge is conserved by the emission of an electron.**
The isotope with the highest molar activity	**$^{35}_{17}Cl$**	**It has the shortest half-life and, as $\lambda = \frac{\ln 2}{t_{1/2}}$. it therefore has the highest activity.**

	Marks
• In the spaces provided, explain the meaning of the following term. You may use an example, equation or diagram where appropriate.	**1**
nucleogenesis **The generation of heavier nuclei by the fusion of lighter nuclei.**	

Marks

- Balance the following nuclear reactions by identifying the missing nuclide. **3**

$$^{36}_{17}\text{Cl} + {}^{0}_{-1}\text{e} \rightarrow \boxed{^{36}_{16}\textbf{S}}$$

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

$$^{238}_{92}\text{U} + {}^{12}_{6}\text{C} \rightarrow 4\,{}^{1}_{0}\text{n} + \boxed{^{246}_{98}\textbf{Cf}}$$

- The half life of ^{90}Sr is 29 years. Calculate the remaining activity (in Bq) of a sample containing ^{90}Sr after 100 years given that the initial activity was 1000 Bq. **2**

From $t_{1/2} = \frac{\ln 2}{\lambda}$, $\lambda = \frac{\ln 2}{29} = 0.0239\,\text{yr}^{-1}$.

The activity after 100 years is related to the initial activity by:

$$\ln\left(\frac{A_0}{A_t}\right) = \lambda t = (0.0239) \times 100 = 2.39 \text{ so } \frac{A_0}{A_t} = e^{2.39}$$

As $A_0 = 1000$ **Bq,** $A_t = \frac{1000}{e^{2.39}} = 92\,\text{Bq}$

Answer: **92 Bq**

- The three unstable isotopes $^{33}_{17}\text{Cl}$, $^{77}_{36}\text{Kr}$ and $^{27}_{12}\text{Mg}$ are unsuitable for use in medical imaging. For each isotope, provide a reason why it is unsuitable. The following data may be of use: **3**

$^{33}_{17}\text{Cl} \rightarrow {}^{0}_{+1}\text{e} + {}^{33}_{16}\text{S}$	half-life = 2.5 s
$^{77}_{36}\text{Kr} \rightarrow {}^{0}_{+1}\text{e} + {}^{77}_{35}\text{Br}$	half-life = 75 minutes
$^{27}_{12}\text{Mg} \rightarrow {}^{0}_{-1}\text{e} + {}^{27}_{13}\text{Al}$	half-life = 9.5 minutes

$^{33}_{17}$Cl - the half life of 2.5 s is too short to allow for synthesis of host molecules, administration of the nuclide to the patient and measurement of the radiation emitted.

$^{77}_{36}$Kr - krypton is a noble gas and cannot be incorporated into a suitable host molecule for administration to the patient.

$^{27}_{12}$Mg - this nuclide is a β-emitter so little useful radiation would escape the body and local radiation damage would occur.

Marks

- Balance the following nuclear reactions by identifying the missing nuclide. **3**

$$^{55}_{26}\text{Fe} + {}^{0}_{-1}\text{e} \rightarrow \boxed{\mathbf{^{55}_{25}Mn}}$$

$$^{63}_{28}\text{Ni} \rightarrow {}^{63}_{29}\text{Cu} + \boxed{\mathbf{^{0}_{-1}\beta}}$$

$$^{28}_{14}\text{Si} + {}^{2}_{1}\text{H} \rightarrow {}^{1}_{0}\text{n} + \boxed{\mathbf{^{29}_{15}P}}$$

- Identify the decay mechanism for the following three unstable nuclides given that the only stable isotopes of Pr and Eu are $^{141}_{59}\text{Pr}$, $^{151}_{63}\text{Eu}$ and $^{153}_{63}\text{Eu}$. There are no stable isotopes of Rn. **3**

Isotope	Nuclear Decay Mechanism
$^{142}_{59}\text{Pr}$	**Stable nucleus has fewer neutrons:** **β^- decay**
$^{150}_{63}\text{Eu}$	**Stable nucleus has more neutrons:** **β^+ decay or e^- capture**
$^{222}_{86}\text{Rn}$	**α decay**

Marks

3

- Balance the following nuclear reactions by identifying the missing nuclide.

$$^{55}_{26}\text{Fe} + {}^{0}_{-1}\text{e} \rightarrow \boxed{\mathbf{^{55}_{25}Mn}}$$

$$^{232}_{90}\text{Th} \rightarrow {}^{4}_{2}\alpha + \boxed{\mathbf{^{228}_{88}Ra}}$$

$$^{218}_{84}\text{Po} \rightarrow {}^{0}_{-1}\text{e} + \boxed{\mathbf{^{218}_{85}At}}$$

2

- Over 50 years, the activity of a sample of strontium-90 decreases from 1000 Bq to 303 Bq. Calculate the half-life of strontium-90 (in years) to the nearest year.

The number of radioactive nuclei N decreases with time according to the equation,

$$\ln\left(\frac{N_0}{N_t}\right) = \lambda t$$

where λ is the decay constant. As activity is proportional to the number of nuclei, the decay constant can be calculated from ratios of the activities:

$$\ln\left(\frac{1000}{303}\right) = \lambda \times 50 = 1.194$$

Hence, λ = 0.0239 year^{-1}. The half life is related to the decay constant by:

$$t_{1/2} = \frac{\ln 2}{\lambda} = \frac{\ln 2}{0.0239} = 29 \text{ years}$$

Answer: **29 years**

3

- Identify three desirable properties of an unstable isotope to be used in medical imaging.

- **non-toxic**
- **either a γ or β^+ emitter (not an α or β^- emitter)**
- **half-life within range of 1 minute to 10 hours**
- **chemically capable of being incorporated into appropriate molecule**
- **easily produced or produced onsite**

Marks

- Balance the following nuclear reactions by identifying the missing nuclear particle or nuclide. **3**

$$^{36}_{17}\mathrm{Cl} + {}^{0}_{-1}\mathrm{e} \rightarrow \boxed{\mathbf{^{36}_{16}S}}$$

$$^{236}_{92}\mathrm{U} \rightarrow {}^{92}_{36}\mathrm{Kr} + {}^{141}_{56}\mathrm{Ba} + 3\,\boxed{\mathbf{^{1}_{0}n}}$$

$$^{99}_{42}\mathrm{Mo} \rightarrow {}^{0}_{-1}\mathrm{e} + \boxed{\mathbf{^{99}_{43}Tc}}$$

- The half-life of plutonium-239 is 24110 years. How many years (to the nearest year) must pass after $^{239}_{94}\mathrm{Pu}$ is produced for the number of $^{239}_{94}\mathrm{Pu}$ atoms to decay to 0.01000 of the original number? **3**

The number of radioactive nuclei N decreases with time according to the equation,

$$\ln\left(\frac{N_0}{N_t}\right) = \lambda t$$

where λ is the decay constant. The decay constant is related to the half life by

$$\lambda = \frac{\ln 2}{t_{1/2}} = \frac{\ln 2}{24110} = 2.875 \times 10^{-5}\ \text{years}^{-1}$$

If $N_t = 0.01N_0$ then:

$$\ln\left(\frac{1}{0.01}\right) = 2.875 \times 10^{-5}\,t$$

Hence, t = 160, 183 years.

Answer: **t = 160, 183 years**

- Provide a brief explanation of the process by which nuclear radiation causes biological damage. **2**

Nuclear radiation is of sufficient energy to ionise atoms in living tissues. The free radicals thus formed are highly reactive (due to having unpaired electrons) and cause unwanted chemical reactions in the tissues. This in turn can lead to cell damage, destruction of DNA, etc.

- Tritium, ${}^{3}_{1}H$, in nuclear warheads decays with a half life of 12.26 years and must be replaced. What fraction of the tritium is lost in 5.0 years? **2**

The number of radioactive nuclei N decreases with time according to the equation,

$$\ln\left(\frac{N_0}{N_t}\right) = \lambda t$$

where λ is the decay constant. The decay constant is related to the half life by

$$\lambda = \frac{\ln 2}{t_{1/2}} = \frac{\ln 2}{12.26} = 0.05654\,\text{years}^{-1}$$

After 5 years,

$$\ln\left(\frac{N_0}{N_t}\right) = 0.05654 \times 5.0 = 0.28$$

or

$$\frac{N_0}{N_t} = e^{0.28} = 1.3$$

The fraction remaining is therefore $\frac{N_t}{N_0} = 0.75$ **and so 0.25 or 25% is lost.**

ANSWER: **0.25 or 25%**