A-2 NUCLEAR PHYSICS (CIE Past Paper Questions)

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Data & Formulae provided in CAIE paper:

unified atomic mass unit	$1\,\text{u} = 1.66 \times 10^{-27}\,\text{kg}$
rest mass of electron	$m_e = 9.11 \times 10^{-31}\,\text{kg}$
rest mass of proton	$m_p = 1.67 \times 10^{-27}\,\text{kg}$
radioactive decay	$x = x_0 \exp(-\lambda t)$
decay constant	$\lambda = \dfrac{0.693}{t_{\frac{1}{2}}}$

Q.1 /{*Q.12/June 2020/41*}

(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]

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

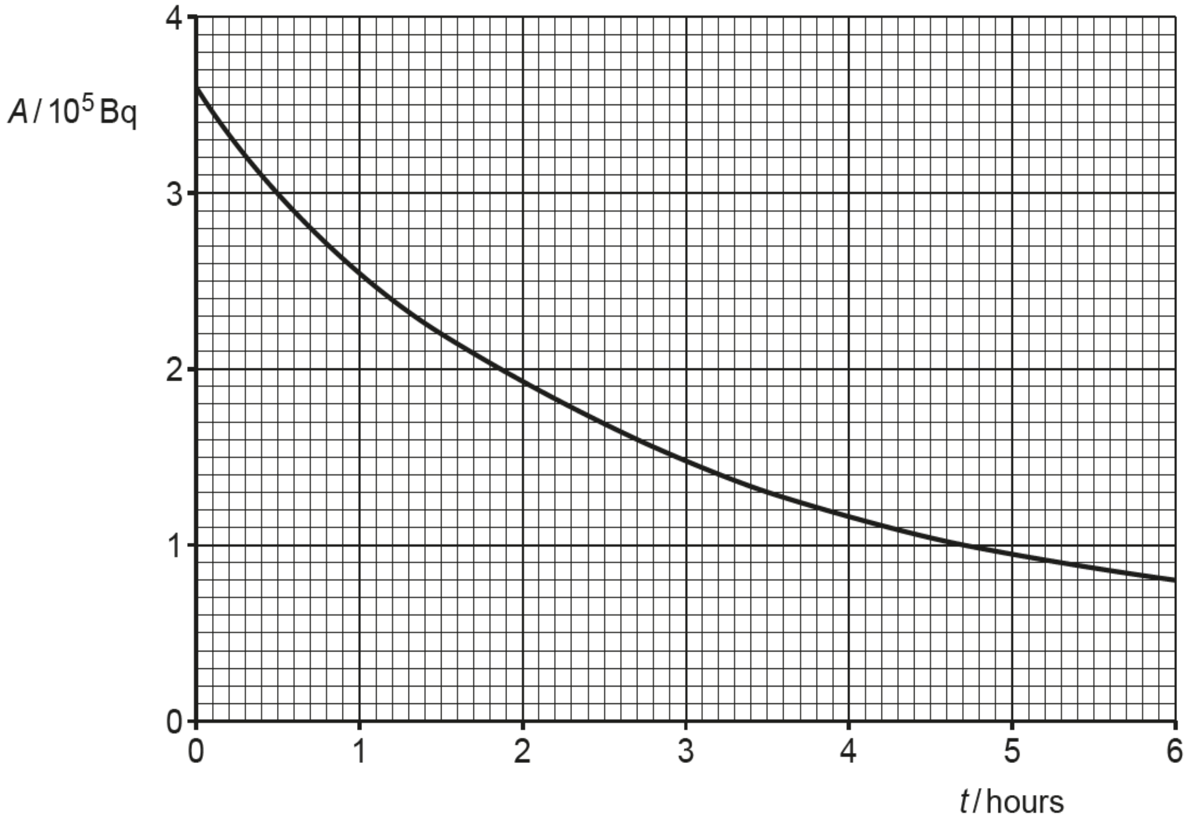

Fig. 12.1

(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]

Q.2 **{*Q.12/June 2020/42*}**

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

....

....

.... [2]

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(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]

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Q.3 ***{Q.12/March 2020/42}***

(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]

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Q.4{ ***Q.12/June 2019/41***}

(a) A sample of a radioactive isotope contains N nuclei of the isotope at time T.
At time $(T + \Delta T)$, the sample contains $(N - \Delta N)$ nuclei of the isotope. The time interval ΔT is short.

Use the symbols N, ΔN, T and ΔT to give expressions for:

(i) the average activity of the sample during the time ΔT

.... [1]

(ii) the probability of decay of a nucleus in the time ΔT

.... [1]

(iii) the decay constant λ of the isotope.

.... [1]

(b) The isotope polonium-208 ($^{208}_{84}Po$) is radioactive and decays to form lead-204 ($^{204}_{82}Pb$).
The nuclear equation for this decay is

$$^{208}_{84}Po \longrightarrow {}^{204}_{82}Pb + {}^{4}_{2}He.$$

Data for nuclear masses are given in Fig. 12.1.

	mass / u
$^{4}_{2}He$	4.002 603
$^{204}_{82}Pb$	203.973 043
$^{208}_{84}Po$	207.981 245

Fig. 12.1

(i) Determine, for the decay of one nucleus of polonium-208:

1. the change, in u, of the mass

mass change = ... u [1]

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2. the total energy, in pJ, released.

energy = ... pJ [3]

(ii) The polonium-208 nucleus is initially stationary. The initial kinetic energy of the $^4_2$He nucleus (α-particle) is found to be less than the energy calculated in **(i) part 2**.

Suggest **two** possible reasons for this difference.

1. ....

....

2. ....

....
[2]

Q.5 ***{Q.12/June 2018/42}***

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

....

....

....

....[2]

(b) An unstable nuclide P has decay constant λ_P and decays to form a nuclide D.
This nuclide D is unstable and decays with decay constant λ_D to form a stable nuclide S. The decay chain is illustrated in Fig. 12.1.

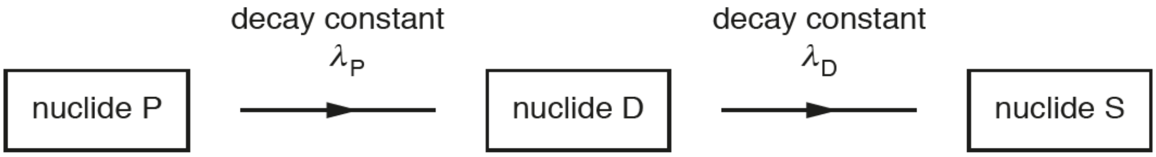

Fig. 12.1

The symbols P, D and S are not the nuclide symbols.

Initially, a radioactive sample contains only nuclide P.

The variation with time *t* of the number of nuclei of each of the three nuclides in the sample shown in Fig. 12.2.

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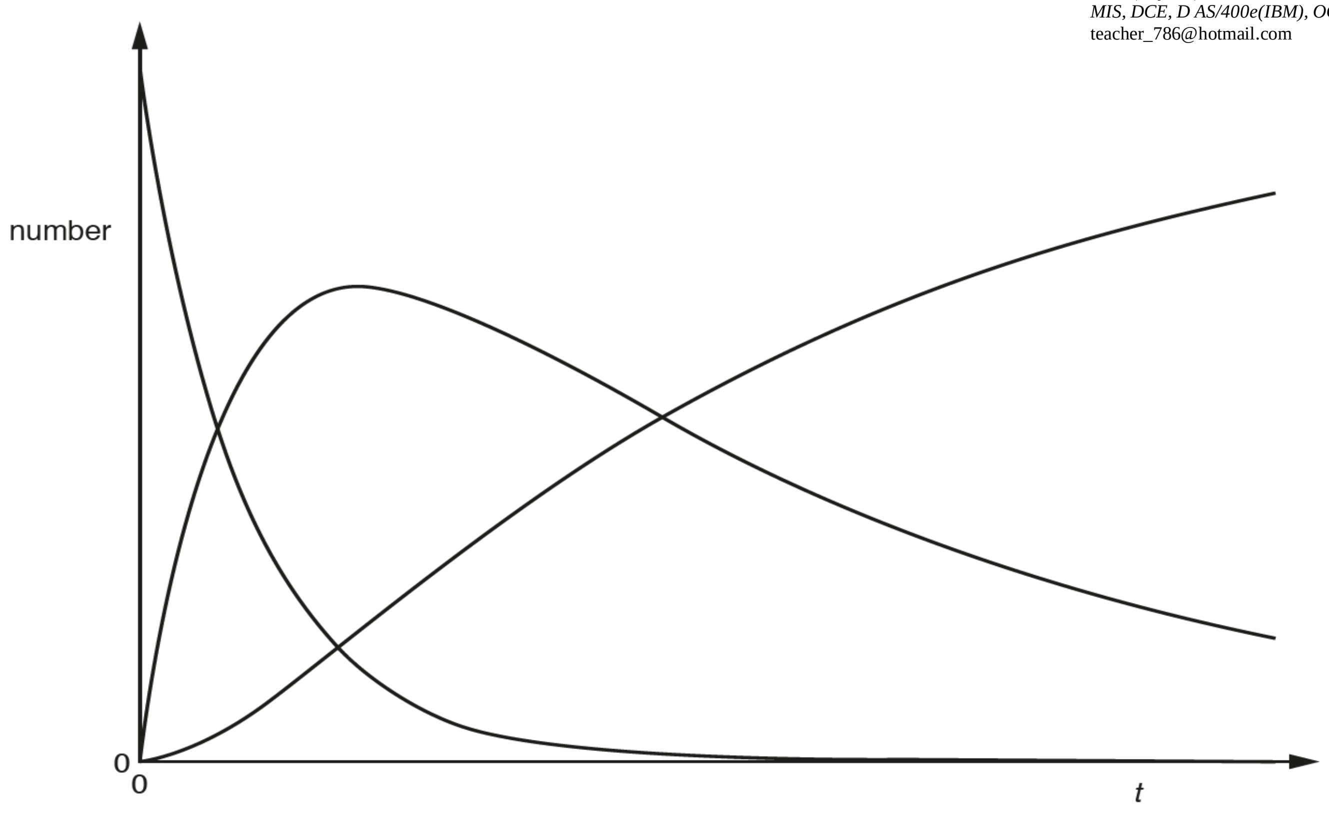

Fig. 12.2

(i) On Fig. 12.2, use the symbols P, D and S to identify the curve for each of the three nuclides. [2]

(ii) The half-life of nuclide P is 60.0 minutes.

Calculate the decay constant λ_P, in s^{-1}, of this nuclide.

λ_P = ... s^{-1} [2]

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(c) In the decay chain shown in Fig. 12.1, λ_P is approximately equal to $5\lambda_D$.

The decay chain of a different nuclide E is illustrated in Fig. 12.3.

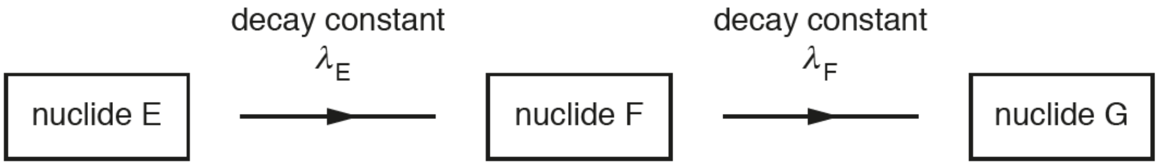

Fig. 12.3

The decay constant λ_F of nuclide F is very much larger than the decay constant λ_E of nuclide E.

By reference to the half-life of nuclide F, explain why the number of nuclei of nuclide F in the sample is always small.

....

....

....[2]

Q.6 ***{Q.7/Nov. 2007/4}***

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

....

....[1]

(b) Fig. 7.1 shows the variation with nucleon number (mass number) A of the binding energy per nucleon E_B of nuclei.

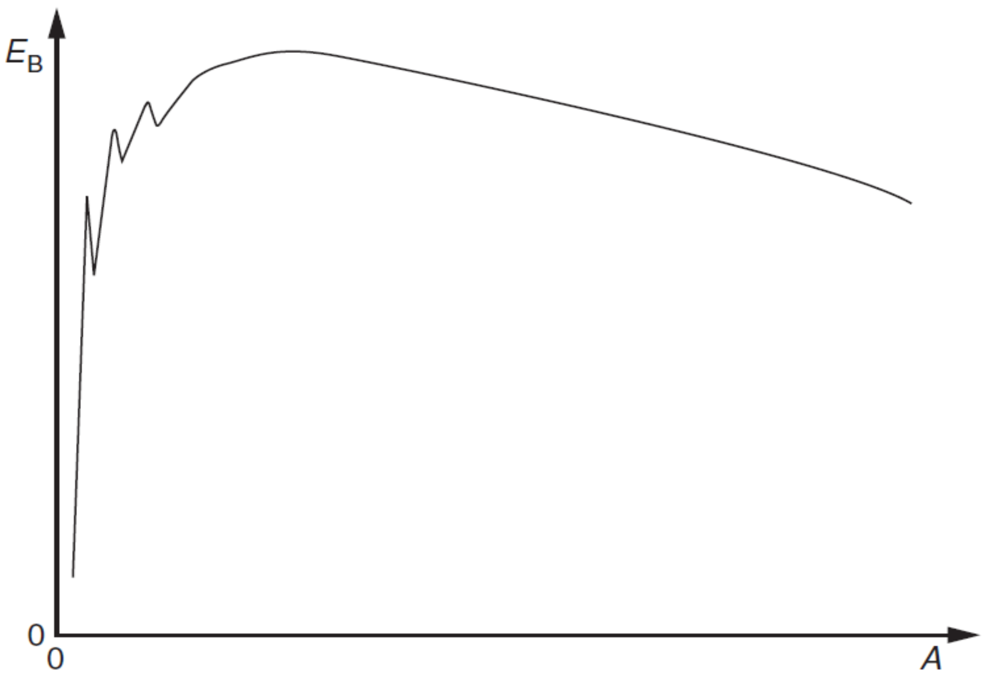

Fig. 7.1

One particular fission reaction may be represented by the nuclear equation

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$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n.$$

(i) On Fig. 7.1, label the approximate positions of

1. the uranium ($^{235}_{92}U$) nucleus with the symbol U,

2. the barium ($^{141}_{56}Ba$) nucleus with the symbol Ba,

3. the krypton ($^{92}_{36}Kr$) nucleus with the symbol Kr. [2]

(ii) The neutron that is absorbed by the uranium nucleus has very little kinetic energy. Explain why this fission reaction is energetically possible.

....

....

....[2]

(c) Barium-141 has a half-life of 18 minutes. The half-life of Krypton-92 is 3.0 s.
In the fission reaction of a mass of Uranium-235, equal numbers of barium and krypton nuclei are produced.
Estimate the time taken after the fission of the sample of uranium for the ratio

$$\frac{\text{number of Barium-141 nuclei}}{\text{number of Krypton-92 nuclei}}$$

to be approximately equal to 8.

time = ... s [3]

Q.7
(a) Define the term radioactive decay constant.

....

....

.... [2]

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(b) State the relation between the activity A of a sample of a radioactive isotope containing N atoms and the decay constant λ of the isotope

…………………………………………………………………………………………………[1]

(c) Radon is a radioactive gas with half-life 56s. For health reasons,the maximum permissible level of radon in air in a building is set at 1 radon atom for every 1.5×10^{21}molecules of air. 1 mol of air in the building is contained in $0.024m^3$.

Calculate, for this building,

(i) the number of molecules of air in 1.0 m^3,

number: …………………………….

(ii) the maximum permissible number of radon atoms in 1.0 $m^3$of air,

number: …………………………….

(iii) the maximum permissible activity of radon per cubic metre of air.

Activity: …………………………… Bq [5]

Q.8 Strontium-90 decays with the emission of a β-particle to form Yttrium-90. The reaction is represented by the equation

$$^{90}_{38}Sr \rightarrow ^{90}_{39}Y + ^{0}_{-1}e + 0.55\text{ MeV}.$$

The decay constant is 0.025 $year^{-1}$.

(a) Suggest, with a reason, which nucleus, $^{90}_{38}Sr$ or $^{90}_{39}Y$, has the greater binding energy.

……………………………………………………………………………………………………

……………………………………………………………………………………………………

…………………………………………………………………………………………………… [2]

(b) Explain what is meant by the decay constant.

……………………………………………………………………………………………………

……………………………………………………………………………………………………

…………………………………………………………………………………………………… [2]

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(c) At the time of purchase of a Strontium-90 source, the activity is 3.7×10^6 Bq.

(i) Calculate, for this sample of strontium,

1. the initial number of atoms,

number: ………………………….. [3]

2. the initial mass.

mass: …………………………………. Kg [2]

(ii) Determine the activity A of the sample 5.0 years after purchase, expressing the answer as a fraction of the initial activity A_0. That is, calculate the ratio $\frac{A}{A_0}$.

ratio = ………………………………….. [2]

ANSWER KEYS

Q.1	***Q.12/June 2020/41***			
	12(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**
Q. 2	***Q.12/June 2020/42***			
	12(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)**
Q. 3	***Q.12/March 2020/42***			
	12(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)**

Q. 4	***Q.12/June 2019/41***

12(a)(i)	$\Delta N / \Delta T$	B1
12(a)(ii)	$\Delta N / N$	B1
12(a)(iii)	$\Delta N / (N \Delta T)$	B1
12(b)(i)	**1.** mass change = 5.60×10^{-3} u	A1
	2. energy = $(\Delta)mc^2$	C1
	$= 5.6 \times 10^{-3} \times 1.66 \times 10^{-27} \times (3.0 \times 10^8)^2$ $(= 8.36 \times 10^{-13}$ J)	C1
	= 0.84 pJ	A1
12(b)(ii)	kinetic energy (of recoil) of lead (nucleus)	B1
	energy of γ-ray photon	B1

Q. 5	***Q.12/June 2018/42***

12(a)	emission of particles/radiation by <u>unstable nucleus</u>	B1
	spontaneous emission	B1
12(b)(i)	P – the curve that starts with a high number D – the curve with the peak S – the curve that increases from zero throughout *(one correct 1 mark, all three correct 2 marks)*	B2
12(b)(ii)	$\lambda t_{½} = 0.693$ $\lambda = 0.693 / (60.0 \times 60)$	C1
	$= 1.93 \times 10^{-4}$ s^{-1}	A1
12(c)	half-life of F is much shorter than half-life of E	B1
	<u>nuclei</u> of F decay (almost) as soon as they are produced	B1

Q.6	***Q.7/Nov. 2007/4***

(a) energy required to (completely) separate the nucleons (in a nucleus) .... B1 [1]

(b) (i) U labelled near right-hand end of line B1
Ba and Kr in approximately correct positions .... B1 [2]

(ii) binding energy is $A \times E_B$ B1
either binding energy of U < binding energy of (Ba + Kr)
or E_B of U < E_B of (Ba + Kr) .... B1 [2]

(c) Krypton-92 reduced to 1/8 in 9 s M1
in 9 s, very little decay of Barium-141 .... M1
so, approximately 9 s .... A1 [3]
OR
$\lambda_{Kr} = 0.231$ or $\lambda_{Ba} = 6.42 \times 10^{-4}$ (M1)
$8 = e^{-\lambda B \times t}/e^{-\lambda K \times t}$ (C1)
$t = 9.0$ s (A1)