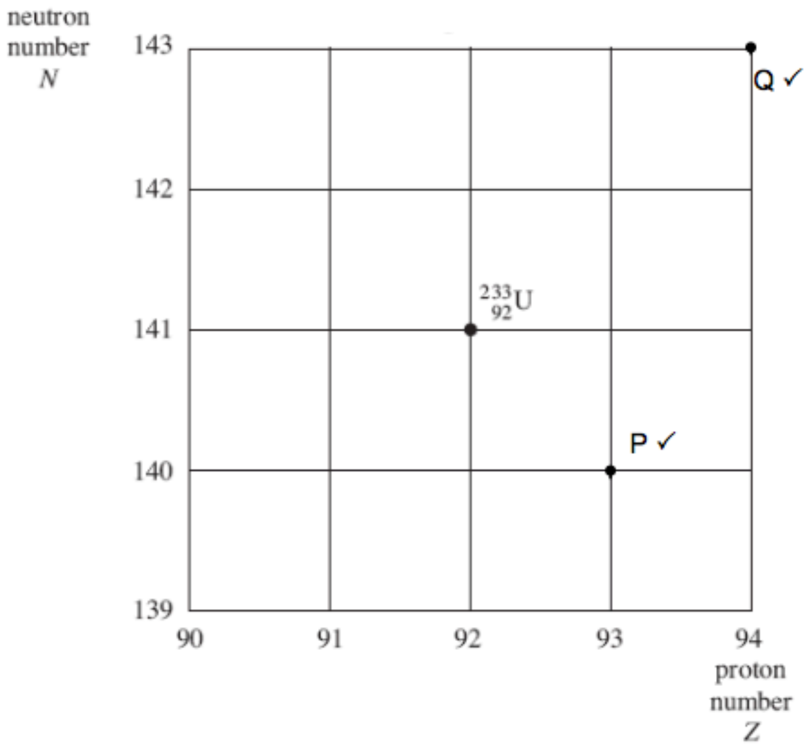
1)

(a)	probability of decay per unit time/given time period **or** fraction of atoms decaying per second **or** the rate of radioactive decay is proportional to the number of (unstable) nuclei and nuclear decay constant is the constant of proportionality ✓	**1**
(b)	use of $T_{\frac{1}{2}} = \frac{ln2}{\lambda}$ $T_{\frac{1}{2}}$ = ln2/3.84 × 10^{-12} s ✓ (1.805 × 10^{11} s) = (1.805 × 10^{11}/3.15 × 10^{7}) = 5730 y ✓ answer given to 3 sf ✓	**3**
(c)	number of nuclei = N = 3.00 × 10^{23} × 1/10^{12} ✓ (= 3.00 × 10^{11} nuclei) (using $\frac{\Delta N}{\Delta t} = -\lambda N$) rate of decay = 3.84 × 10^{-12} × 3.00 × 10^{11} ✓ (= 1.15 Bq)	**2**
(d)	($N = N_0 e^{-\lambda t}$ and activity is proportional to the number of nuclei $A \propto N$ use of $A = A_0 e^{-\lambda t}$) 0.65 = 1.15 × $e^{-3.84 \times 10^{-12} t}$ ✓ $t = \frac{ln\left(\frac{1.15}{0.65}\right)}{3.84 \times 10^{-12}}$ or $\frac{ln\left(\frac{0.651}{1.15}\right)}{-3.84 \times 10^{-12}}$ ✓ t = 4720 y ✓	**3**
(e)	the boat may have been made with the wood some time after the tree was cut down the background activity is high compared to the observed count rates the count rates are low or sample size/mass is small or there is statistical variation in the recorded results possible contamination uncertainty in the ratio of carbon-14 in carbon thousands of years ago any two ✓✓	**2**
	Total	**11**

2)

a	$^{233}_{91}\text{Pa}$ ✓ anti (electron) neutrino ✓	**2**
b		**2**

3)

a	$^{27}_{13}\text{Al} + \alpha \rightarrow ^{30}_{15}\text{P} + ^{(1)}_{(0)}\text{n}$ ✓	**1**
b	kinetic energy lost by the α particle approaching the nucleus is equal to the potential energy gain ✓ $2.18 \times 10^{-12} = \frac{1}{4\pi \times 8.85 \times 10^{-12}} \times \frac{13 \times 1.6 \times 10^{-19} \times 2 \times 1.6 \times 10^{-19}}{r}$ ✓ $r = 2.75 \times 10^{-15}$ (m) ✓	**3**
	Total	**4**

4)

a		$({}^{206}_{76}\mathrm{X} \rightarrow {}^{206}_{82}\mathrm{Pb} + \beta \times {}^{0}_{-1}\beta + \beta \times \overline{\nu_e})$ $\beta = 6$ ✓	1
b	i	the energy **required** to split up the nucleus ✓ into its individual neutrons and protons/nucleons ✓ (or the energy **released** to form/hold the nucleus ✓ from its individual neutrons and protons/nucleons ✓)	2
b	ii	$7.88 \times 206 = 1620$ MeV ✓ (allow 1600-1640 MeV)	1
c	i	U, a graph starting at 3×10^{22} showing exponential fall passing through 0.75×10^{22} near 9×10^{9} years ✓ Pb, inverted graph of the above so that the graphs cross at 1.5×10^{22} near 4.5×10^{9} years ✓	2
c	ii	(u represents the number of uranium atoms then) $\frac{u}{3 \times 10^{22} - u} = 2$ $u = 6 \times 10^{22} - 2u$ ✓ $u = 2 \times 10^{22}$ atoms	1
c	iii	(use of $N = N_0 e^{-\lambda t}$) $2 \times 10^{22} = 3 \times 10^{22} \times e^{-\lambda t}$ ✓ $t = \ln 1.5 / \lambda$ (use of $\lambda = \ln 2 / t_{1/2}$) $\lambda = \ln 2 / 4.5 \times 10^{9} = 1.54 \times 10^{-10}$ ✓ $t = 2.6 \times 10^{9}$ years ✓(or 2.7×10^{9} years)	3

5)

a		any 2 from: the sun, cosmic rays, radon (in atmosphere), nuclear fallout (from previous weapon testing) , any radioactive leak(may be given by name of incident) nuclear waste, carbon-14 ✓	1

b	i	(ratio of area of detector to surface area of sphere) ratio = $\frac{0.0015}{4\pi(0.18)^2}$ ✓ 0.0037 ✓ (0.00368)	2

b	ii	activity = 0.62/(0.00368 × 1/400) give first mark if either factor is used. 67000 ✓ Bq accept s^{-1} or decay/photons/disintegrations s^{-1} but not counts s^{-1}✓ (67400 Bq)	3

c		(use of the inverse square law) $\frac{I_1}{I_2} = \left(\frac{r_2}{r_1}\right)^2$ or calculating k = 0.020 from $I = k/x^2$ ✓ $I_2 = 0.62 \times \left(\frac{0.18}{0.28}\right)^2$ ✓ 0.26 counts s^{-1} ✓(allow 0.24-0.26)	3

6)

a		graph starting (steeply) near/at the origin and decreasing in gradient ✓	1

b	i	(use of density = mass/volume) $\frac{197 \times 1.67 \times 10^{-27}}{\frac{4}{3}\pi\,(6.87 \times 10^{-15})^3}$ ✓✓mark for top line and mark for bottom line (allow use of 1.66×10^{-27}) Lose mass line mark if reference is made to mass of electrons $= 2.4(2) \times 10^{17}$ kg m^{-3}	2

b	ii	$R_{Al} = R_{Au}\left(\frac{A_{Al}}{A_{Au}}\right)^{\frac{1}{3}} = 6.87 \times 10^{-15}\left(\frac{27}{197}\right)^{\frac{1}{3}}$ ✓ = 3.54 × 10^{-15} m ✓ or $r_0 = \frac{R}{A^{\frac{1}{3}}} = \frac{6.87 \times 10^{-15}}{197^{\frac{1}{3}}} = 1.18 \times 10^{-15}$ m ✓ $R = 1.18 \times 10^{-15} \times 27^{\frac{1}{3}} = 3.54 \times 10^{-15}$ m ✓ or volume = mass/density = $\frac{27 \times 1.67 \times 10^{-27}}{2.42 \times 10^{17}} = \frac{4}{3}\pi \times R^3$ ✓ = 3.54 × 10^{-15} m ✓	2

c		**The candidate's writing should be legible and the spelling, punctuation and grammar should be sufficiently accurate for the meaning to be clear.** The candidate's answer will be assessed holistically. The answer will be assigned to one of three levels according to the following criteria. **High Level (Good to excellent): 5 or 6 marks** The information conveyed by the answer is clearly organised, logical and coherent, using appropriate specialist vocabulary correctly. The form and style of writing is appropriate to answer the question. *The candidate makes 5 to 6 points concerning the principles of the method, the limitations to the accuracy and the advantages and disadvantages of a particular method* **Intermediate Level (Modest to adequate): 3 or 4 marks** The information conveyed by the answer may be less well organised and not fully coherent. There is less use of specialist vocabulary, or specialist vocabulary may be used incorrectly. The form and style of writing is less appropriate. *The candidate makes 3 to 4 points concerning the principles of the method, the limitations to the accuracy and the advantages and disadvantages of a particular method* **Low Level (Poor to limited): 1 or 2 marks** The information conveyed by the answer is poorly organised and may not be relevant or coherent. There is little correct use of specialist vocabulary. The form and style of writing may be only partly appropriate. *The candidate makes 1 to 2 points concerning the principles of the method, the limitations to the accuracy and the advantages and disadvantages of a particular method*	max 6

			The explanation expected in a competent answer should include a coherent selection of the following points concerning the physical principles involved and their consequences. **principles** • α scattering involves coulomb or electrostatic repulsion • electron diffraction treats the electron as a wave having a de Broglie wavelength • some reference to an equation, for example $\lambda = h/mv$; $eV = mv^2/2$; $Qq/4\pi\varepsilon_o r = E_\alpha$; $\sin\theta = 0.61\lambda/R$ • reference to first minimum for electron diffraction **accuracy** • α's only measure the least distance of approach, not the radius • α's have a finite size which must be taken into account • electrons need to have high speed/kinetic energy • to have a small wavelength or wavelength comparable to nuclear diameter, the wavelength determines the resolution • the wavelength needs to be of the same order as the nuclear diameter for significant diffraction • requirement to have a small collision region in order to measure the scattering angle accurately • importance in obtaining monoenergetic beams • cannot detect alpha particles with exactly 180° scattering • need for a thin sample to prevent multiple scattering **advantages and disadvantages** • α-particle measurements are disturbed by the nuclear recoil • Mark for α-particle measurements are disturbed by the SNF when coming close to the nucleus or electrons are not subject to the strong nuclear force. • A second mark can be given for reference to SNF if they add electrons are leptons or alpha particles are hadrons. • α's are scattered only by the protons and not all the nucleons that make up the nucleus • visibility – the first minimum of the electron diffraction is often difficult to determine as it superposes on other scattering events	

7)

	QWC	Descriptor	Mark range	
		The mark scheme for this part of the question includes an overall assessment for the Quality of Written Communication (QWC).		
	QWC	**Descriptor**	**Mark range**	
	High Level (Good to excellent)	The candidate refers to all the necessary apparatus and records the count-rate at various distances (or thicknesses of absorber). The background is accounted for and a safety precaution is taken. The presence of an α source is deduced from the rapid fall in the count rate at 2 – 5 cm in air. The presence of a γ source is deduced from the existence of a count-rate above background beyond 30 -50 cm in air (or a range in any absorber greater than that of beta particles, e.g. 3 – 6 mm in Al) or from the intensity in air falling as an inverse square of distance or from an exponential fall with the thickness of a material e.g. lead. *The information should be well organised using appropriate specialist vocabulary. There should only be one or two spelling or grammatical errors for this mark.*	5-6	If more than one source is used or a different experiment than the question set is answered limit the mark to 4
	Intermediate Level (Modest to adequate)	The candidate refers to all the necessary apparatus and records the count-rate at different distances (or thicknesses of absorber). A safety precaution is stated. The presence of an α source is deduced from the rapid fall in the count rate at 2 – 5 cm in air and the γ source is deduced from the existence of a count-rate beyond 30 -50 cm in air (or appropriate range in any absorber, e.g. 3 -6 mm in Al). Some safety aspect is described. One other aspect of the experiment is given such as the background. *The grammar and spelling may have a few shortcomings but the ideas must be clear.*	3-4	To get an idea of where to place candidate look for 6 items: 1.Background which must be used in some way either for a comparison or subtracted appropriately 2.Recording some data with a named instrument
	Low Level (Poor to limited)	The candidate describes recording some results at different distances (or thicknesses of absorber) and gives some indication of how the presence of α or γ may be deduced from their range. Some attempt is made to cover another aspect of the experiment, which might be safety or background. *There may be many grammatical and spelling errors and the information may be poorly organised.*	1 - 2	3.Safety reference appropriate to a school setting – not lead lined gown for example 4.Record data with more than one absorber or distances 5.α source determined from results taken 6.γ source determined
		The description expected in a competent answer should include a coherent selection of the following points. apparatus: source, lead screen, ruler, γ ray and α particle detector such as a Geiger Muller tube, rate-meter or counter and stopwatch, named absorber of varying thicknesses may be used. safety: examples include, do not have source out of storage longer than necessary, use long tongs, use a lead screen between source and experimenter. measurements: with no source present switch on the counter for a fixed period measured by the stopwatch and record the number of counts or record the rate-meter reading with the source present measure and record the distance between the source and detector (or thickness of absorber) then switch on the counter for a fixed period measured by the stopwatch and record the number of counts or record the rate-meter reading repeat the readings for different distances (or thicknesses of absorber).		from results taken this is a harder mark to achieve it may involve establishing an inverse square fall in intensity in air or an exponential fall using thicknesses of lead if a continuous distribution is not used an absorber or distance in air that would just eliminate β (30-50cm air / 3-6mm Al) must be used with and without the source being present or compared to background
		use of measurements: for each count find the rate by dividing by the time if a rate-meter was not used subtract the background count-rate from each measured count-rate to obtain the corrected count-rate longer recording times may be used at longer distances (or thickness of absorber). plot a graph of (corrected) count-rate against distance (or thickness of absorber) or refer to tabulated values plot a graph of (corrected) count-rate against reciprocal of distance squared or equivalent linear graph to show inverse square relationship in air analysis: the presence of an α source is shown by a rapid fall in the (corrected) count-rate when the source detector distance is between 2 – 5 cm in air the presence of a γ source is shown if the corrected count-rate is still present when the source detector distance is greater than 30 cm in air (or at a range beyond that of beta particles in any other absorber, e.g. 3 mm in Al) the presence of a γ source is best shown by the graph of (corrected) count-rate against reciprocal of distance squared being a straight line through the origin		

Question	Answers	Additional Comments/Guidance	Mark	ID details
8 (a)	the amount of energy required to separate a nucleus ✓ into its separate neutrons and protons/nucleons ✓ (or energy released on formation of a nucleus ✓ from its separate neutrons and protons/constituents ✓)	1st mark is for correct energy flow direction 2nd mark is for binding or separating nucleons (nucleus is in the question but a reference to an atom will lose the mark) ignore discussion of SNF etc both marks are independent	2	
(b)(i)	$2\,^{1}_{0}\text{n}$ or $^{1}_{0}\text{n} + {}^{1}_{0}\text{n}$ ✓	must see subscript and superscripts	1	
(b)(ii)	binding energy of U = 235 × 7.59 ✓ (= 1784 (MeV)) binding energy of Tc and In = 112 × 8.36 + 122 × 8.51✓ (= 1975 (MeV)) energy released (=1975 – 1784) = 191 (MeV) ✓ (allow 190 MeV)	1st mark is for 235 × 7.59 seen anywhere 2nd mark for 112 × 8.36 + 122 × 8.51 or 1975 is only given if there are no other terms or conversions added to the equation (ignore which way round the subtraction is positioned) Correct final answer can score 3 marks	3	
(b)(iii)	energy released $= 191 \times 1.60 \times 10^{-13}$ ✓ $(= 3.06 \times 10^{-11}$ J)	Allow CE from (b)(ii) working must be shown for a CE otherwise full marks can be given	2	
	loss of mass $(= E / c^2)$ $= 2.91 \times 10^{-11} / (3.00 \times 10^8)^2)$ $= 3.4 \times 10^{-28}$ (kg) ✓ or = 191/931.5 u ✓ (= 0.205 u) $= 0.205 \times 1.66 \times 10^{-27}$ (kg) $= 3.4 \times 10^{-28}$ (kg) ✓	for correct answer only note for CE answer = (b)(ii) $\times 1.78 \times 10^{-30}$ $(2.01 \times 10^{-27}$ is a common answer)		
(c)(i)	line or band from origin, starting at 45° up to *Z* approximately = 20 reading *Z* =80, *N* = 110→130 ✓	Initial gradient should be about 1 (ie Z=20 ; N = 15 → 25) and overall must show some concave curvature. (ignore slight waviness in the line) If band is shown take middle as the line If line stops at N>70 extrapolate line to N = 80 for marking	1	
(c)(ii)	Fission fragments are (likely) to be above/to the left of the line of stability ✓ fission fragments are (likely) to have a larger *N*/*Z* ratio than stable nuclei or fission fragments are neutron rich owtte ✓ and become neutron or β^- emitters ✓	Ignore any reference to α emission. A candidate must make a choice for the first two marks. Stating that there are more neutrons than protons is not enough for a mark. 1st mark reference to graph 2nd mark – high N/Z ratio or neutron rich 3rd mark beta minus Note not just beta.	3	
Total			**12**	

9)

(a)(i)	λ (= ln 2 / $T_{1/2}$ = 0.693 / 5740) = 1.2×10^{-4} (yr^{-1}) ✓ (1.21×10^{-4} yr^{-1})	only allow 3.83×10^{-12} s^{-1} if the unit has been changed working is not necessary for mark	1	
(a)(ii)	(use of $N_t = N_o e^{-\lambda t}$ and activity is proportional to *N* $A_t = A_o e^{-\lambda t}$) 0.375 = exp - ($1.21 \times 10^{-4} \times t$) ✓ $t = \frac{\ln\left(\frac{1}{0.375}\right)}{1.21\times10^{-4}}$ ✓ t = 8100 or 8200(yr) ✓	1^{st} mark substitution, allow EC from (a)(i) 2^{nd} mark rearranging, allow EC from (a)(i) Allow t / $T_{1/2}$ = 2^n approach 3^{rd} mark no EC (so it is not necessary to evaluate a CE) So max 2 for a CE Full marks can be given for final answer alone. A minus in the final answer will lose the last mark.	3	
(b)(i) (b)(ii)	(it is difficult to measure accurately) the small drop/change in activity/count-rate the small change/drop in the ratio of C-14 to C-12 ✓ the activity would be very small/comparable to the background or the ratio of C-14 to C-12 is too small or there are too few C-14 atoms or there is very little decay	1^{st} mark needs some reference to a change in count-rate or activity for the mark Be lenient in 2^{nd} mark In reading a script assume C-14 is the subject. Eg 'there is little activity to work with' scores mark. Also allow any reasonable suggestion. Eg carbon may have been removed by bonding to surrounding material. Don't allow, 'All the carbon has	2	
	or the level of C-14 (in the biosphere) is uncertain (this long ago)✓	decayed'.		
Total			**6**	

10)

Question	Answers	Additional Comments/Guidance	Mark	ID details
(a)	A α particles ✓	[auto mark question]	1	
(b)(i)	<table><tr><td>type of radiation</td><td>Typical range in air/m</td></tr><tr><td>α</td><td>0.04 ✓</td></tr><tr><td>β</td><td>0.40 ✓</td></tr></table>	allow students to use their own distance units in the table α allow 0.03 → 0.07 m β allow 0.20 → 3.0 m If a range is given in the table use the larger value. A specific number is required eg not just a few cm.	2	
b)(ii)	reference to the inverse square law of (γ radiation) or reference to lowering of the solid angle (subtended by the detector as it moves away) or radiation is spread out (over a larger surface area as the detector is moved away)✓	(owtte) Ignore any references to other types of radiation. Any contradiction loses the mark. For example, follows inverse square law so intensity falls exponentially.	1	
(c)	dust may be ingested/taken into the body/breathed in ✓ causing (molecules in human tissue/cells) to be made cancerous / killed / damaged by ionisation ✓	first mark for ingestion not just on the body second mark for idea of damage from ionisation	2	

Total			6

11)

Question	Answers	Additional Comments/Guidance	Mark	ID details
(a)(i)	electromagnetic/electrostatic/Coulomb (repulsion between the alpha particles and the nuclei) ✓	The interaction must be named not just described.	1	
(a)(ii)	the scattering distribution remains the same (because the alpha particles interact with a nucleus) whose charge/proton number/atomic number remains the same or the (repulsive) force remains the same Or the scattering distribution changes/becomes less distinct because there is a mixture of nuclear <u>masses</u> (which gives a mixture of nuclear recoils) ✓ (owtte)	The mark requires a described distribution <u>and the reason</u> for it. A reference must be made to mass and not density or size.	1	
(b)(i)	use of graph to find r_0 eg $r_0 = 6.0 \times 10^{-15} / 75^{1/3}$ ✓ (or $8.0 \times 10^{-15} / 175^{1/3}$) ($r_0 = 1.43 \times 10^{-15}$ m)	Substitution and calculation t must be shown. Condone a gradient calculation on <u>R against $A^{1/3}$</u> graph (not graph of Fig 1) as $R \propto A^{1/3}$	1	
(b)(ii) Escalate if clip shows $^{27}_{13}\mathrm{Al}$ in the question giving $R \approx 4 \times 10^{-15}$ m.				
(b)(ii)	(using $R = r_0 A^{1/3}$) $R = 1.43 \times 10^{-15} \times 51^{1/3}$ ✓ $R = 5.3 \times 10^{-15}$ (m) ✓ ($R = 5.2 \times 10^{-15}$ m from $r_0 = 1.4 \times 10^{-15}$ m)	first mark for working second mark for evaluation which must be 2 or more sig figs allow CE from b(i) $R = 3.71 \times$ b(i) **Possible escalation**	2	
(c) Escalate if clip shows $^{27}_{13}\mathrm{Al}$ in the question and/or the use of 27 in the working.				
(c)	density = mass / volume $m = 51 \times 1.67 \times 10^{-27}$ (= 8.5×10^{-26} kg) $v = 4/3\pi(5.3 \times 10^{-15})^3$ ($6.2(4) \times 10^{-43}$ m^3) Or density = $A \times u / 4/3\pi(r_0 A^{1/3})^3$	give the first mark for substitution of data into the top line or bottom line of the calculation of density. In the second alternative the mark for the substitution is only given if the working equation is given as well. $51 \times 1.67 \times 10^{-27}$ would gain a mark on its own but 1.66×10^{-27}	3	

12)

Question	Answers	Additional Comments/Guidance	Mark	ID details
(a)	${}^{239}_{93}\text{Np} \rightarrow {}^{239}_{94}\text{Pu} + {}^{(0)}_{(-1)}\beta^- + {}^{(0)}_{(0)}\bar{\nu}$ ✓✓	First mark for one anti-neutrino or one beta minus particle in any form eg. e^-. If subscript and superscripts are given for these they must be correct but ignore the type of neutrino if indicated. The second mark is for both particles and the rest of the equation. Ignore the full sequence if it is shown but the Np to Pu must be given separately for the mark.	2	
(b)(i)	$T_{1/2}$ 2.0 → 2.1 × 10^5 s ✓ then substitute and calculate $\lambda = \ln 2 / T_{1/2}$ ✓ Or (substitute two points from the graph into $A = A_o e^{-\lambda t}$) e.g. 0.77 × 10^{12} = 4.25 × 10^{12} exp(-λ×5×10^5) ✓ then make λ the subject and	$T_{1/2}$ may be determined from graph not starting at zero time. Look for the correct power of 10 in the half-life – possible AE. Allow the rare alternative of using the time constant of the decay $A = A_o \exp(-t/t_{tc})$ from graph t_{tc} = 2.9→3.1 × 10^5 s✓ $\lambda = 1/t_{tc}$ = 3.4 × 10^{-6} s^{-1} ✓	2	

	calculate ✓ (the rearrangement looks like $\lambda = [\ln (A_o / A)] / t$ or $\lambda = -[\ln (A / A_o)] / t$) both alternatives give $\lambda = 3.3 \rightarrow 3.5 \times 10^{-6}\ s^{-1}$ ✓	No CE is allowed within this question. For reference $T_{1/2} = 2.0 \times 10^5$ s gives $\lambda = 3.5 \times 10^{-6}\ s^{-1}$ and $T_{1/2} = 2.1 \times 10^5$ s gives $\lambda = 3.3 \times 10^{-6}\ s^{-1}$		
(b)(ii)	(using $A = N\lambda$ $N = 0.77 \times 10^{12} / 3.4 \times 10^{-6}$ $= 2.2(6) \times 10^{17}$) allow $2.2 \rightarrow 2.4 \times 10^{17}$ nuclei ✓	A possible route is find $N_o = A_o/\lambda$ then use $N = N_o e^{-\lambda t}$ condone lone answer	1	
(c)(i)	uranium (– 235 captures) a neutron (and splits into 2 smaller nuclei/fission fragments) releasing more neutrons ✓ (at least one of) these neutrons go on to cause further/more splitting/fissioning (of uranium–235) ✓	first mark for uranium + neutron gives more neutrons Ignore which isotope of uranium is used. second mark for released neutron causes more fission The word 'reaction' may replace 'fission' here provided 'fission/splitting of uranium' is given somewhere in the answer.	2	
(c)(ii) Escalate if clip shows critical mass in the question.				
(c)(ii)	the moderator slows down/reduces the kinetic energy of neutrons ✓ so neutrons are absorbed/react/fission (efficiently) by the uranium/fuel ✓	owtte **Possible escalation**	2	
(c)(iii)	neutrons are absorbed/collide with (by the nuclei in the shielding) ✓ converting the nuclei/atoms (of the shielding) into unstable isotopes (owtte) ✓	Second mark is only given if neutrons appear somewhere in the answer. No neutrons = no marks making it neutron rich implies making them unstable.	2	

Total			**11**