1)

Question			Answers	Marks	Guidance
	(a)	(i)	One proton / (same) charge / (same) element and (same) chemical property / one electron	B1	**Allow** (same) number of protons. **Allow** (same) number of electrons.
		(ii)	mass of nucleus < (total) mass of nucleons Energy must be supplied to the nucleus to free the nucleons / energy released when nucleons combine (to form the nucleus). $(\Delta)E = (\Delta)mc^2$ and $(\Delta)E$ is the (binding) energy and $(\Delta)m$ is the mass defect or the difference in mass.	B1 B1 B1	 **Allow** nucleus has binding energy.
	(b)	(i)	${}^1_0n \rightarrow {}^1_1p + {}^0_{-1}e + \bar{\nu}_{(e)}$	B1,B1	**Allow** proton or ${}^1_1H$ or H^+ or p and (electron) antineutrino.
		(ii)	(Average) time taken for half of the neutrons (in a sample) to decay.	B1	**Note**: Must have reference to 'half' and 'neutrons' **Allow** 'the time taken for the activity of neutrons to halve'.
	(c)	(i)	$F = \dfrac{1.6\times10^{-19}\times1.6\times10^{-19}}{4\pi\varepsilon_0\times(10^{-14})^2}$ force = 2.3 (N)	C1 A1	**Not** $Q = q = 1$
		(ii)	$E = 7.0\times10^4\times1.6\times10^{-19}$ (= 1.12×10^{-14} J) ($E = \frac{3}{2}kT$); $7.0\times10^4\times1.6\times10^{-19} = \frac{3}{2}\times1.38\times10^{-23}\times T$ temperature = 5.4×10^8 (K)	C1 C1 A1	 **Allow** any subject. Also, allow $E \approx kT$ since it is an estimate. **Allow** 1 sf answer.
		(iii)	Some nuclei will be travelling faster / have greater (kinetic) energy (to overcome electrostatic repulsion and hence cause fusion).	B1	**Allow** the pressures are high (enough to cause fusion). **Not** 'nuclei get close enough'.
		(iv)	($\Delta E = \Delta mc^2$); $18\times10^6\times1.6\times10^{-19} = \Delta m\times(3.0\times10^8)^2$ change in mass = 3.2×10^{-29} (kg)	C1 A1	**Allow** any subject **Allow** a maximum of 1 mark for 18MeV ± 70 keV.
		(v)	Helium (nucleus) has greater charge / more protons. The (electrostatic) repulsive force (between the deuterium and helium nuclei) is greater (hence smaller chance of fusion).	B1 B1	 Do **not** award this mark if 'helium nuclei are moving slower' is also given as the reason for smaller probability for fusion.
			Total	**17**	

2)

Question			Answers	Marks	Guidance
	(a)	(i)	**C**	B1	
		(ii)	Zero	B1	
	(b)	(i)	proton / ${}^1_1H$ / ${}^1_1p$ / p	B1	
		(ii)	$\lambda = \dfrac{0.693}{5700\times3.16\times10^7}$ or $\lambda = 3.847...\times10^{-12}$ (s^{-1}) ($A = \lambda N$); $N = \dfrac{1.1\times10^{19}}{3.847...\times10^{-12}}$ or $N = 2.859..\times10^{30}$ mass = $\dfrac{2.859...\times10^{30}}{6.02\times10^{23}}\times0.014$ mass = $6.649...\times10^4$ (kg) or 6.6×10^4 (kg)	C1 C1 A1	 **Allow** any subject **Allow** ecf within the calculation for an incorrect λ. **Allow** 6.7×10^4 (kg)
	(c)		A (thermal / slow-moving) neutron splits the nucleus into two (smaller) nuclei and (fast-moving) neutron(s).	B1 B1	**Allow** 'fast neutron'; **allow** 'decays' instead of 'splits'. **Not** 'splitting the atom'. **Not** 'particles' or 'fragments' in place of '(smaller) nuclei'.
	(d)		Any **three** from: 1. Fission reactions produce fast neutrons. 2. The moderator / water slows down (the fast-moving) neutrons. 3. Slow-moving neutrons have a greater chance of causing fission (of U-235). (ora) 4. The control rods absorb (some of the) neutrons. 5. (On average) one neutron survives between successive (fission) reactions. QWC: The neutrons make collisions with the (moderator) nuclei and transfer (some of) their (kinetic) energy.	B1×3 B1	 **Allow** boron / cadmium instead of control rods in 4. **Not** graphite for 4. **Allow** atoms / molecules instead of nuclei.
			Total	**12**	

3)

Question			Answer	Marks	Guidance
	(a)		The (minimum) energy needed to separate / remove all the nucleons / protons and neutrons (to infinity)	B1	**Allow**: The energy released when (stationary) nucleons combine to form the nucleus **Allow**: The (minimum) energy required to break the nucleus into its (separate) nucleons **Allow**: binding energy = mass defect × speed of light² **Allow**: 'Work (done)' in place of 'energy'
	(b)		BE per nucleon = $4.53 \times 10^{-12}/4$ BE per nucleon = 1.13×10^{-12} (J)	B1	**Allow** 2 sf answer of 1.1×10^{-12} (J)
	(c)		The helium nucleus has greater charge / The helium nucleus experience greater repulsive force Helium nuclei need to get close together (for the strong force to initiate fusion)	B1 B1	
	(d)		($\frac{1}{2} m v^2 = \frac{3}{2} kT$) $\frac{1}{2} \times 6.6 \times 10^{-27} \times v^2 = \frac{3}{2} \times 1.38 \times 10^{-23} \times 10^8$ speed = 7.9×10^5 (m s^{-1})	C1 A1	**Allow**: KE ≈ kT; this gives an answer of 6.47×10^5 (m s^{-1})
			Total	**6**	

4)

Question			Answer	Marks	Guidance
	(a)		Impossible to predict when a nucleus will decay or impossible to predict which nucleus will decay	B1	
	(b)		$N = N_0 e^{-\lambda t}$ (λ =) 0.693/7.1 ×10⁸ $\lambda = 9.76 \times 10^{-10}$ y^{-1} $0.011 = e^{-(9.76 \times 10^{-10} \times t)}$ (age =) $\frac{\ln(0.011)}{-9.76 \times 10^{-10}}$ age = 4.6×10^9 (y)	C1 C1 A1	**Alternatives:** $N = N_0 e^{-\lambda t}$ (λ =) $0.693/[7.1 \times 10^8 \times 3.16 \times 10^7]$ C1 $\lambda = 3.089 \times 10^{-17}$ s^{-1} $0.011 = e^{-(3.089 \times 10^{-17} \times t)}$ C1 (age =) $\frac{\ln(0.011)}{-3.089 \times 10^{-17}}$ age = $1.46... \times 10^{17}$ (s) age = 4.6×10^9 (y) A1 Or $0.011 = \frac{1}{2^n}$ C1 $n = -\frac{\ln(0.011)}{\ln 2}$ or $n = 6.5$ C1 age = $6.5 \times 7.1 \times 10^8$ (y) age = 4.6×10^9 (y) A1
	(c)	(i)	number in the range 50 to 70	B1	
		(ii)	Correct reference to binding energy. Eg: The BE per nucleon will decrease for fusion (which is impossible unless external energy is supplied) (AW)	B1	

Question			Answer	Marks	Guidance
		(iii)	(mass of nucleons =) $4 \times 1.673 \times 10^{-27} + 4 \times 1.675 \times 10^{-27}$ (Δm =) $[4{\times}1.673 \times 10^{-27} + 4{\times}1.675 \times 10^{-27}] - 1.329 \times 10^{-26}$ (mass defect =) 1.020×10^{-28} (kg) BE = mass defect × c^2 (BE =) $1.020 \times 10^{-28} \times (3.0 \times 10^8)^2$ (= 9.180×10^{-12} J) (BE per nucleon) = $9.180 \times 10^{-12}/8$ BE per nucleon = 1.148×10^{-12} (J)	C1 C1 C1 A1	**Allow**, due to misinterpretation of Data, Formulae and Relationship Booklet, the following (though incorrect): (nucleon mass =) $8 \times 1.661 \times 10^{-27}$ (kg) C1 (Δm =) $[8 \times 1.661 \times 10^{-27}] - 1.329 \times 10^{-26}$ (kg) C1 (BE =) (-) $2.0 \times 10^{-30} \times (3.0 \times 10^8)^2$ (= 1.8×10^{-13} J) C1 (BE per nucleon =) $1.8 \times 10^{-13}/8$ BE per nucleon = 2.25×10^{-14} (J) A1 **Allow** 2 sf or 3 sf answer
			Total	**10**	

5)

Question			Answers	Marks	Guidance
	(a)		(Minimum) energy to separate (all) nucleons / protons <u>and</u> neutrons (of a nucleus)	M1 A1	**Alternative**: B.E. = mass <u>defect</u> × c^2 M1 mass defect = mass of nucleons – mass of nucleus A1
	(b)	(i)	BE of ^{2}H = $2 \times 1.8 \times 10^{-13}$ (J) or BE of ^{4}He = $4 \times 1.1 \times 10^{-12}$ (J) energy = $(4 \times 1.1 \times 10^{-12}) - 2 \times (2 \times 1.8 \times 10^{-13})$ energy = 3.68×10^{-12} (J) / 3.7×10^{-12} (J)	C1 C1 A0	**Note**: Ignore signs
		(ii)1	total surface area = $4\pi \times (1.5 \times 10^{11})^2$ power = $1400 \times (2.83{\times}\ 10^{23})$ power = 3.96×10^{26} (W) / 4.0×10^{26} (W)	C1 C1 A0	
		(ii)2	number = $4.0 \times 10^{26}/3.7 \times 10^{-12}$ number = 1.1×10^{38} (s^{-1}) or 1.08×10^{38} (s^{-1})	C1 A1	**Allow**: 10^{38} (s^{-1}) because the question is about an estimate
			Total	**8**	

6)

Question			Expected Answers	Marks	Additional guidance
	(a)		A neutron is absorbed by a (massive / uranium) nucleus The nucleus splits into two (smaller/daughter) nuclei and (one or more) neutrons	B1 B1	
	(b)		In a fission reaction there is a decreases in the mass (According to $\Delta E = \Delta mc^2$) mass is converted into energy Or The (total) binding energy of the products / smaller nuclei is greater than the binding energy of the original nucleus The difference in the binding energies is released as energy	M1 A1 M1 A1	**Allow:** The 'BE increases (in the reaction)'
	(c)		Moderator: water / graphite / carbon It slows down the (fast-moving) neutrons / reduces the (kinetic) energy of neutrons Slow-moving neutrons have greater chance of causing fission (than fast-moving neutrons)	B1 B1 B1	**Note**: If boron is mentioned, then do not award this B1 mark **Allow**: They become thermal neutrons
			Total	**7**	

7)

Question			Expected Answers	Marks	Additional Guidance
	a	(i)	mass of uranium is greater than (the sum of) the mass of the products $E = \Delta mc^2$ OR binding energy of the products is greater than that of uranium energy available is the difference between the binding energies of uranium and the sum of the products	M1 A1 M1 A1	
		(ii)	kinetic energy	B1	
	b	(i)	the neutron is a single nucleon / cannot be split further / no binding has occurred	B1	The neutron is not bound to anything
		(ii)	binding energy of uranium = 235 x 7.6 =1786 binding energy of products = 141 x 8.3 + 92 x 8.7 = 1170.3 + 800.4 energy available = 184.7 (MeV)	 C1 A1	An answer of 9.4 (not using the number of nucleons) scores zero Allow ≥ 2 sf (180, 185, 184.7) Penalise 184 as an AE
			Total	**[6]**	

8)

Question			Answer	Marks	Guidance
	(a)	(i)	momentum / mass-energy / charge / proton number / baryon number / nucleon number	B1	**Not**: 'energy' on its own
		(ii)	Some basic labelling of neutron(s), Xe and Sr Correct extension of diagram showing at least one of the neutrons interacting with <u>U-235</u> nucleus and producing neutron(s) and 'fragments'	B1 B1	
	(b)	(i)	initial $m = 6.686 \times 10^{-27}$ (kg) or final $m = 6.681 \times 10^{-27}$ (kg) or $\Delta m = 0.005 \times 10^{-27}$ (kg) $\Delta E = 0.005 \times 10^{-27} \times (3.0 \times 10^8)^2$ energy = 4.5×10^{-13} (J)	C1 C1 A1	
		(ii)	kinetic (energy)	B1	**Not**: heat / sound **Allow**: (gamma) photons / EM radiation
		(iii)	KE = $\frac{3}{2}kT$ KE = $\frac{3}{2} \times 1.38 \times 10^{-23} \times 10^9$ KE = 2.1×10^{-14} (J)	 C1 A1	**Allow**: 1 sf answer or 10^{-14} (J) because the temperature is given as 10^9 K
		(iv)	Some nuclei will have KE greater than the mean KE (and hence cause fusion) (AW)	B1	
			Total	**10**	