

Question	Answer	Marks	Guidance
1 (a) (i)	${}_{92}^{238}\text{U} + {}_0^1\text{n} \rightarrow {}_{92}^{239}\text{U}$	1	
1 (a) (ii)	β^- particle(s) Electron antineutrinos	1 1	
1 (b)	For: <ul style="list-style-type: none"> Natural uranium is 98% uranium-238 which would be otherwise unused. Plutonium-239 would not need to be stored long-term as it would be used. World's uranium reserves would last many more years. Carbon emissions would be reduced if a higher % of world's energy was from nuclear power. Against: <ul style="list-style-type: none"> More radioactive waste in the form of fission products would be produced. Plutonium-239 would need to be transported safely to these reactors. There would be major security issues about the transport of plutonium-239. Funding of a fast breeder program would be better used on proven renewables. Private companies more likely to fund proven renewables than unproven fast breeders. 	Any 5	
2 (a)	<i>Relevant points include the following listed here.</i>	Any 4	The confusing thing about nuclear binding energy is that it is <i>not</i> what a nucleus possesses, but what it <i>does not</i> possess: it is the energy that is released when the nucleus is formed. The strong nuclear force is attractive at small separations, enabling it to overcome the repulsion of the positively charged protons. When particles are brought together by an attractive force their potential energy decreases, just like a mass attracted by the Earth's gravity. According to $E = mc^2$, the mass of the nucleus must decrease when its potential energy decreases. Therefore the release of binding energy causes a decrease in the mass of a nucleus, which is known as the mass difference.
2 (a) (i)	<ul style="list-style-type: none"> Binding energy is the energy released when a nucleus is formed from separate nucleons (or the energy required to break up a nucleus into separate nucleons). It is energy associated with the strong nuclear force. The strong force does work on the nucleons in bringing them together (or the potential energy of the nucleons decreases when they are attracted together). 		
2 (a) (ii)	<ul style="list-style-type: none"> The mass of a nucleus is less than the total mass of its constituent nucleons. Mass difference = (total mass of nucleons) – (mass of nucleus) 		
2 (a) (iii)	<ul style="list-style-type: none"> The binding energy is the energy equivalent of the mass difference, by $E = mc^2$ (or $E_b = (\Delta m)c^2$) 		
2 (b)	Mass of ${}_{30}^{64}\text{Zn}$ nucleus = $63.92915 - (30 \times 0.00055) = 63.91265 \text{ u}$ Mass difference $\Delta m = (30 \times 1.00728) + (34 \times 1.00867) - 63.91265$ $= 0.60053 \text{ u}$ Binding energy of nucleus $E_b = 0.60053 \times 931.3 = 559.3 \text{ MeV}$ Average binding energy per nucleon $= \frac{559.3}{64} = 8.74 \text{ MeV nucleon}^{-1}$	1 1 1 1 1	Data for mass of a proton, mass of a neutron and mass of an electron is given in the Data and Formulae Booklet. The conversion from u to MeV (1 u is equivalent to 931.3 MeV) is also listed there. Once you understand the principles, this type of calculation becomes a simple exercise in arithmetic. You must ensure that you retain all the significant figures in the earlier stages, because mass differences can be very small.

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2 (c)	The zinc nucleus is very stable because it has a high value of average binding energy per nucleon (or is near the maximum of the curve of average binding energy per nucleon against mass number).	1	Binding energy <i>per nucleon</i> is an important measure of nuclear stability. Binding energy itself is a less useful concept: larger nuclei will always have larger binding energies.
3 (a)	<i>Relevant points include the following listed here.</i>	Any 6	Be very clear about which process is which. Examiners often encounter muddled (or badly written) answers in which candidates appear to have written about <i>fussion</i> ! The principal obstacle to fusion is the repulsion of like charges. Once two nuclei are forced together to the point where the strong force becomes greater than this repulsion, fusion should occur. Spontaneous fission can occur, but it is extremely rare. Fission is normally induced by hitting large nuclei with neutrons. In each process, the origin of the energy released is an increase in the nuclear binding energy when the reaction takes place.
3 (a) (i)	<ul style="list-style-type: none"> Two small (or light) nuclei combine. Electrostatic repulsion has to be overcome. Nuclei have to be given kinetic energy for them to meet. 		
3 (a) (ii)	<ul style="list-style-type: none"> A large (or heavy) nucleus splits into two smaller nuclei. Neutrons are released. Fission is usually brought about by neutron bombardment. 		
3 (a) (iii)	<ul style="list-style-type: none"> Binding energy per nucleon increases when light nuclei (e.g. $Z < 10$) combine. Binding energy per nucleon also increases when heavy nuclei split. 		
3 (b)	Mass difference Δm between parent nucleus and products $= 219.96410 - (215.95572 + 4.00150)$ $= 0.00688 \text{ u}$ Energy released $= 0.00688 \times 931.3$ $= 6.41 \text{ MeV}$ $= 6.41 \times 10^6 \times 1.6 \times 10^{-19}$ $= 1.03 \times 10^{-12} \text{ J}$	1 1 1	Natural α decay processes release energies in the range 4 to 9 MeV. <i>Alternative approach</i> to final stages of calculation: $\Delta m = 0.00688 \text{ u}$ $= 0.00688 \times 1.661 \times 10^{-27} \text{ kg}$ $= 1.14 \times 10^{-29} \text{ kg}$ energy released $= (\Delta m)c^2$ $= 1.14 \times 10^{-29} \times (3.00 \times 10^8)^2$ $= 1.03 \times 10^{-12} \text{ J}$
4 (a) (i)	Use of $P = IV$ gives power output of panel $P_{\text{out}} = 2.4 \times 20 = 48 \text{ W}$	1	Each m^2 of the panel receives solar power of 1400 W, and the panel has an area of 2.5 m^2 . The efficiency of any device is the ratio of the useful output power to the input power.
4 (a) (ii)	Incident solar power $P_{\text{in}} = 1.4 \times 2.5 = 3.5 \text{ kW}$ Efficiency $= \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{48}{3500}$ $= 0.0137$ (or 1.37%)	1 1 1	
4 (b) (i)	Energy emitted in each decay $= 5.1 \times 10^6 \times 1.6 \times 10^{-19}$ $= 8.16 \times 10^{-13} \text{ J}$ Energy emitted per second $= 1.1 \times 10^{14} \times 8.16 \times 10^{-13} = 89.8 \text{ J}$ (which is 90 J to 2 sig figs)	1 1	
4 (b) (ii)	Decay constant $\lambda = \frac{\ln 2}{T_{1/2}}$ $= \frac{\ln 2}{90 \times 365 \times 24 \times 3600}$ $= 2.44 \times 10^{-10} \text{ s}^{-1}$	1 1	Part (ii) gives further practice on the relationship between decay constant and half-life.

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4 (b) (iii)	$\frac{\Delta N}{\Delta t} = \lambda N$ gives, for an activity of 1.1×10^{14} Bq, number of nuclei in sample $N = \frac{1.1 \times 10^{14}}{2.44 \times 10^{-10}}$ $= 4.51 \times 10^{23}$ Mass of sample = $\frac{4.51 \times 10^{23} \times 0.239}{6.02 \times 10^{23}} = 0.179$ kg	1 1	Part (iii) gives yet more practice on radioactivity. Note that the molar mass of a nuclide of nucleon number $A = 239$ is 0.239 kg. One mole of it contains $N_A (= 6.02 \times 10^{23})$ nuclei), so the mass of one nucleus is $\frac{0.239}{N_A}$ kg. Answers of 180 kg (from anyone thinking that the molar mass is 239 kg) would not be given any credit!
5 (a) (i)	Point marked S at maximum of curve.	1	The most stable nucleus is the one with the greatest value of binding energy per nucleon. The binding energy of this nucleus is $A \times$ binding energy per nucleon.
5 (a) (ii)	Nucleon number $A = 56$ (54 to 58 allowed) Binding energy per nucleon = 8.8 MeV	1	
5 (a) (iii)	Binding energy of this nuclide = $56 \times 8.8 = 493$ MeV	1	
5 (b) (i)	$_1^0 e$ is a positron v is a neutrino	1 1	You could be mistaken in thinking that $_1^0 e$ is an electron, but an electron would be $_{-1}^0 e$.
5 (b) (ii)	charge: $+1 + 1 \rightarrow +1 + 1 + 0 + 0$ baryon number: $1 + 1 \rightarrow 2 + 0 + 0 + 0$ lepton number: $0 + 0 \rightarrow 0 + (-1) + 1 + 0$	1 1 1	All three are conserved, and so the reaction is possible. Remember that the lepton number of a positron is -1 , because it is an antiparticle.
5 (b) (iii)	Energy of photon = $0.51 \times 1.60 \times 10^{-13}$ = 8.16×10^{-14} J Wavelength of photon $\lambda = \frac{hc}{E} = \frac{6.63 \times 10^{-34} \times 3.00 \times 10^8}{8.16 \times 10^{-14}}$ = 2.44×10^{-12} m	1	
		1	
		1	
5 (c)	Relevant points include the following listed here. • Fission involves the splitting of a large nucleus into two smaller nuclei. • Fusion involves two small nuclei joining to form a slightly larger nucleus. • Both processes cause an increase in the binding energy per nucleon. • This energy is released as the kinetic energy of the products of the reaction. • The increase in binding energy per nucleon is greater in a fusion reaction than in a fission reaction. • The binding energy of a large nucleus is very much greater than that of a small nucleus, because the former contains many more nucleons. • The net increase in binding energy during the fission of a large nucleus is therefore greater than that occurring during the fusion of two small nuclei	Any 5	Part (c) should get you to think hard about the difference between the binding energy of a nucleus and its binding energy per nucleon. It is useful to look at the slopes of the fusion and fission sections of the binding energy per nucleon curve. One fusion reaction may release about 5 MeV nucleon ⁻¹ , but only a few nucleons are involved, and so the total energy released may be only about 20 MeV. The fission of ${}_{92}^{235}\text{U}$ releases about 0.9 MeV nucleon ⁻¹ , but almost 240 nucleons are involved and so around 200 MeV of energy is released.

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6 (a)	<p><i>Relevant points include the following listed here.</i></p> <p>Energy is released because</p> <ul style="list-style-type: none"> • fusion of two nuclei increases their binding energy per nucleon • the fusion reaction produces an increase in the mass difference (or the nucleus formed is more stable than the two original nuclei). <p>Fusion is difficult to achieve because</p> <ul style="list-style-type: none"> • each of the two original nuclei has a positive charge • the electrostatic repulsion of these positive charges has to be overcome. 	Any 3	Every nucleus (except ${}^1_1\text{H}$) has a mass difference. When fusion takes place, the mass difference of the nucleus produced is greater than the sum of the mass differences of the two original nuclei. This decrease in mass is accompanied by the release of an equivalent amount of energy. If fusion is to be achieved, the nuclei have to be brought together to the point where the attractive strong nuclear force exceeds the repulsion of the positive charges. This means that the nuclei have to be given large kinetic energies.
6 (b) (i)	<p>Mass difference produced by fusion Δm</p> $= (2 \times 2.01355) - (3.01493 + 1.00867)$ $= 3.50 \times 10^{-3} \text{ u}$	1	<p><i>Alternative approach:</i></p> <p>(i) $\Delta m = 3.50 \times 10^{-3} \times 1.66 \times 10^{-27}$</p> $= 5.81 \times 10^{-30} \text{ kg}$
6 (b) (ii)	<p>Energy released by fusion</p> $= 3.50 \times 10^{-3} \times 931.3 = 3.26 \text{ MeV}$ $= 3.26 \times 1.60 \times 10^{-13}$ $= 5.22 \times 10^{-13} \text{ J}$	1 1	<p>(ii) energy released</p> $= (\Delta m)c^2$ $= 5.81 \times 10^{-30} \times (3.00 \times 10^8)^2$ $= 5.23 \times 10^{-13} \text{ J}$
7 (a)	<p><i>Relevant points include the following listed here.</i></p>	Any 5	Thermal neutrons have a much greater probability of inducing fission than fast neutrons. They are called thermal neutrons because they have similar kinetic energies to the thermally agitated molecules of the gases in air. Fission can occur naturally, but the process is very rare. When a neutron strikes a fissionable nucleus and is absorbed, the nucleus becomes even more unstable. This large nucleus then splits, and energy is released. The important factor here is that fission causes fission. In a chain reaction, one event leads to another – such as the ignition of one match leading to the explosion of a whole bundle of matches.
7 (a) (i)	<p><i>thermal neutrons</i></p> <ul style="list-style-type: none"> • have low kinetic energies e.g. 0.03 eV (or low speeds); 		
7 (a) (ii)	<p><i>induced fission is:</i></p> <ul style="list-style-type: none"> • the splitting of a large nucleus into two smaller nuclei • that is brought about by bombardment by neutrons; 		
7 (a) (iii)	<p><i>in a self-sustaining chain reaction</i></p> <ul style="list-style-type: none"> • the fission reaction gives out neutrons • these neutrons cause further fissions • the reaction is self-sustaining when one fission leads to at least one further fission. 		
7 (b)	<p><i>Relevant points include the following listed here.</i></p>		

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7 (b) (i)	<p><i>Moderation</i></p> <ul style="list-style-type: none"> • The neutrons from fission are fast (high energy) neutrons e.g. 2 MeV. • The fission reaction is more favourable with thermal (low energy) neutrons. • Moderation involves slowing down the neutrons... • by collision with moderator atoms. • A large number of collisions (e.g. 50) is required to do this. • The collisions are elastic (or kinetic energy is passed to the atoms). • The moderator atoms should have a (relatively) low mass. • The moderator must not absorb neutrons. • Suitable materials are graphite or water. 	Any 7	In order to improve the chance of causing further fission reactions, the emitted neutrons have to be slowed down. Neutrons are uncharged, and so the only realistic method of reducing their kinetic energy is by colliding them into particles of a similar size to them. Yet the particles with which they collide must <i>not absorb</i> the neutrons. The mass of a carbon (graphite) atom is 12 times larger than a neutron, so each collision removes only a little kinetic energy from the neutron. Therefore many collisions have to take place before the kinetic energy is reduced to thermal levels.
7 (b) (ii)	<p><i>Control</i></p> <ul style="list-style-type: none"> • Involves limiting the number of neutrons. • Neutrons are absorbed by control rods... • which are inserted into the reactor to slow the reaction rate (or vice-versa). • Boron and cadmium are suitable materials to absorb neutrons. 		The control material <i>does absorb</i> neutrons; it doesn't simply slow them down. In a power reactor the control rods are inserted into (or removed from) the core so that, on average, one fission leads to just one further fission.
8 (a)	<p><i>Relevant points include the following listed here.</i></p> <ul style="list-style-type: none"> • The amount of fissionable uranium-235 in the fuel rods decreases. • Nuclei of some fission fragments can absorb neutrons. • Nuclei of the fission fragments are radioactive. • They emit β^- and γ radiation. • Some fission fragments have short half-lives (or high activities). 	Any 3	As they age, the fuel rods are sometimes moved progressively inwards towards the centre of the core. This is because the neutron flux will be higher there, helping to maintain a greater power output from rods that contains fewer $^{235}_{92}\text{U}$ atoms. Ironically, newly made fuel rods are fairly harmless – because uranium is an α -emitter and the rods have metal canning. The longer the rods stay in a reactor, the more radioactive they become.
8 (b)	<p><i>Relevant points include the following listed here.</i></p> <ul style="list-style-type: none"> • Rods are removed by remote control. • Rods placed in cooling ponds. • Kept in ponds for several months (or to allow short half-life isotopes to decay). • Reference to transport precautions, such as impact resistant flasks. • Uranium is separated from active wastes. • High level waste is stored (as a liquid). • Reference to storage precautions, for example shielded tanks, monitoring of emissions. • Possibility of long-term storage by sealing active wastes in glass (vitrification) and storing the material at a geologically stable site. 	Any 5	The topic of nuclear power requires you to be familiar with quite a lot of facts, especially those concerning nuclear hazards and treatment of wastes. The answer suggested here refers to the treatment of spent rods by reprocessing them, so that some of the remaining $^{235}_{92}\text{U}$ can be extracted from them and re-used in new rods. In some countries it is more usual to discard the used fuel rods by burying them deep underground well away from human activity, such as in disused salt mines.