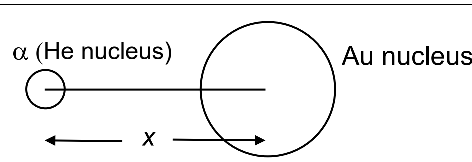
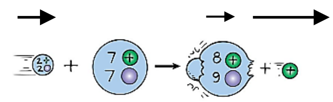
No	Solution	Ans/Mark
1	The reason that most of the α-particles are either undeflected or deflected through very small angles is because the nucleus is much smaller than the atom. A few α-particles were deflected through angles as large as 90° or more. Only if the positive charge of the atom[1] is <u>concentrated in a more compact region</u> that a <u>much larger force</u> will occur at near impacts. The large-angle scattering obtained experimentally could result only from a single encounter of the α-particle with a massive charge confined to a volume much smaller than that of the whole atom.	**[D]**
2	A neutron has no charge, thus will not be affected by electric or magnetic fields. The mass of a neutron is the same as that of a proton. *Can you identify the other 3 particles?*	**[D]**
3	x = 255 + 3 (4) y = 101 + 3 (2) bohrium $^{x}_{y}\mathrm{Bh} \longrightarrow$ dubnium + $^{4}_{2}\alpha$ $\longrightarrow$ lawrencium + $^{4}_{2}\alpha$ $\longrightarrow$ mendelevium $^{255}_{101}\mathrm{Md}$ + $^{4}_{2}\alpha$ According to the conservation of mass number and atomic number, Mass number of bohrium, x = 255 + 3(4) = 267, i.e., 267 nucleons Also, proton number of bohrium, y = 101 + 3(2) = 107, i.e., 107 protons.	**[A]**
4	**(a)** $F = \dfrac{Q_1 Q_2}{4\pi\varepsilon_0 x^2}$ $= \dfrac{(2e)(79e)}{4\pi\varepsilon_o x^2} = \dfrac{3.64\times10^{-26}}{x^2}$.	1 1
	(b) (i) Loss in K.E. = gain in P.E. 1.8 MeV $= \dfrac{3.64\times10^{-26}}{x^2}(x)$ $x = \dfrac{3.64\times10^{-26}}{1.8(1.6\times10^{-13})} = 1.26\times10^{-13}$ m.	1 1
	(ii)  Radii of the two nuclei are less than 1.26×10^{-13} m, ☺: What are the approximate radii of the two nuclei?	1

[1] If the atom consisted of a positively charged sphere of radius 10^{-10} m, containing electrons as in the Thomson model, only a very small deflection could result from a single encounter between an α-particle and an atom, even if the α-particle penetrated into the atom. The Thomson atomic model could not possibly account for the number of large-angle scatterings that Rutherford saw.

5	The graph of binding energy per nucleon B_E against nucleon number shows that, with increasing nucleon number, B_E increases steeply initially but reaches a peak at ^{56}Fe and decreases gradually beyond that. This shows that A, B and D are false. Energy will be released if a massive nucleus with low B_E is broken up, as a result of particle bombardment, into two or more lighter nuclei, each with greater B_E. The daughter nuclei are more stable. **Ans: [C]**		
6	Since 0.001 u has an energy equivalent of 0.9 MeV and α particle has to travel and collide with nitrogen, thus the kinetic energy of the reactants exceeds the kinetic energy of the products by 0.9 MeV. **Ans: [C]** *Option D seems possible but it cannot be the correct answer. Why? [Consider using the principle of conservation of linear momentum.]*		
7	(a)	Energy released = $\Delta m.c^2$ $= [\,3.753 - (3.686+0.066)]\times10^{-25}$ kg $(3\times10^8 \text{ m s}^{-1})^2$ $= 9.0\times10^{-12}$ J.	 1 1
	(b)	$E = hf = \dfrac{hc}{\lambda}$ So, $\lambda = \dfrac{hc}{E} = \dfrac{(6.63\times10^{-34}\text{ J s})(3\times10^{8}\text{ m s}^{-1})}{(9.0\times10^{-12}\text{ J})(4/100)}$ $= 5.53\times10^{-13}$ m.	1 1
	(c)	The remaining 96% of the energy is in the form of K.E. of ^{222}Rn and ^{4}He .	1
8	(a)	Loss of mass = (4.00260 u + 9.01212 u) − (1.00867 u + 12.00000 u) $= 6.05\times10^{-3}\ u$	1 1
	(b)	Energy equivalence of this mass = mc^2 $= (6.05\times10^{-3}\ u)\ c^2$ $= (6.05\times10^{-3}\times1.66\times10^{-27})(\,3.00\times10^{8}\,)^2$ $= 9.04\times10^{-13}$ J	 1 1
9	(a)	$^{17}_{8}$O **nucleus** comprises <u>8 protons</u> and <u>9 neutrons</u>.	1,1
	(b)	$$^{14}_{7}\text{N} + {}^{4}_{2}\text{He} \rightarrow {}^{17}_{8}\text{O} + {}^{1}_{1}\text{H}$$ Change in mass, Δm = 18.00696 u - 18.00568 u = 0.00128 u $= (0.00128)(1.66\times10^{-27}\text{ kg})$ $= 2.125\times10^{-30}$ kg. The minimum K.E. of the α-particle is the energy equivalent of this Δm, i.e. $E = \Delta m\,c^2 = (2.125\times10^{-30}\text{ kg})(3\times10^{8}\text{ m s}^{-1})^2$ $= 1.91\times10^{-13}$ J.	 1 1 1 1

(c) Taking to the right as positive, $({}^{14}_{7}N + {}^{4}_{2}He \rightarrow {}^{17}_{8}O + {}^{1}_{1}H)$

$(mv)_\alpha = (mv)_o + (mv)_p$

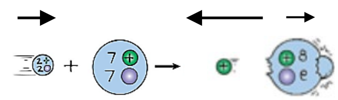


$(4\ u)(3.0\times10^{7}\ m\ s^{-1}) = (17\ u)\ v_o + (1\ u)(6.0\times10^{7}\ m\ s^{-1})$ 1

$\Rightarrow v_o = \underline{3.53\times10^{6}}\ m\ s^{-1}$ --- case (1)

same direction as the initial velocity of the alpha particle

Note:
If the proton moves in the opposite direction of the initial velocity of the alpha particle, then



$(4\ u)(3.0\times10^{7}\ m\ s^{-1}) = (17\ u)\ v_o - (1\ u)(6.0\times10^{7}\ m\ s^{-1})$

$\Rightarrow v_o = 1.06\times10^{7}\ m\ s^{-1}$ --- case (2)

Using conservation of mass-energy,

total final kinetic energy of system 1

= (total initial kinetic energy of system) – (energy equivalent of the increase in mass)

$= [\tfrac{1}{2}(4\ u)(3.0\times10^{7})^{2}] - (1.91\times10^{-13})$

$= \underline{2.8} \times 10^{-12}$ J ----- (*)

For case (1),

total final kinetic energy of system

$= \tfrac{1}{2}(17\ u)(3.53\times10^{6})^{2} + \tfrac{1}{2}(1\ u)(6.0\times10^{7})^{2}$

$= \underline{3.2} \times 10^{-12}$ J [very close to the value in (*); they are equal, to 1 s.f.] 1

For case (2),

total final kinetic energy of system

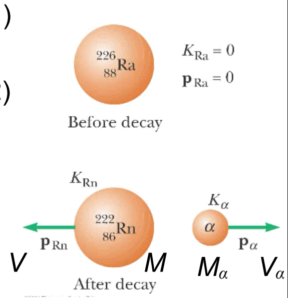
$= \tfrac{1}{2}(17\ u)(1.06\times10^{7})^{2} + \tfrac{1}{2}(1\ u)(6.0\times10^{7})^{2}$

$= \underline{4.6} \times 10^{-12}$ J [larger than the value in (*) – defy conservation of mass-energy!]

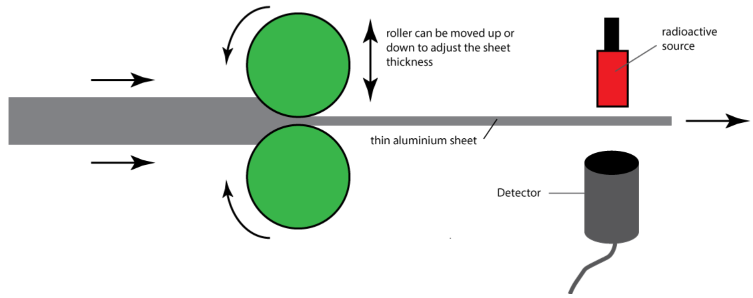
Thus, the oxygen-17 and the proton move in the same direction as that of the initial velocity of the alpha particle, after the nuclear reaction, and the velocity of the oxygen-17 nucleus is $3.53\times10^{6}\ m\ s^{-1}$.

10	The total mass of the products of this process is *equivalent* to 939 MeV + 940 MeV = 1879 MeV. The mass of the original deuteron is *equivalent* to 1876 MeV For the deuteron to disintegrate to a proton and a neutron, there is a mass defect *equivalent* to 1879 MeV – 1876 MeV = 3 MeV **Therefore, the deuteron needs to <u>capture</u> a γ-ray photon of energy 3 MeV.** This 3 MeV is the binding energy of the deuteron, which is the minimum energy required for the deuteron to break into a proton and a neutron.	**[D]**
11	The process may be represented by $^{27}_{13}\text{Al} \rightarrow {}^{4}_{2}\text{He} + {}^{23}_{11}\text{Na}$ The total mass of the products = 4.0026 u + 22.9898 u = 26.9924 u This is more than the mass of $^{27}_{13}\text{Al}$ (which is 26.9815 u) by 26.9924 u – 26.9815 u = 0.0109 u Mass-energy equivalence: $E = mc^2$: $E = (0.0109\ u) \times c^2 = 0.0109 \times 1.66 \times 10^{-27} \times (3 \times 10^8)^2 = 1.63 \times 10^{-12}$ J Thus 0.0109 u is equivalent to 1.63×10^{-12} J of energy. So 1.63×10^{-12} J of energy is required for this process to occur, and it would not occur spontaneously. <u>Note</u> - The balanced nuclear equation for the induced transmutation of Aluminum-27 into Sodium-24 by neutron bombardment, with release of an alpha particle in the reaction: $^{27}_{13}\text{Al} + {}^{1}_{0}n \rightarrow {}^{4}_{2}\text{He} + {}^{24}_{11}\text{Na}$	1 1 1 1
12	current = rate of flow of charges $0.01\times10^{-6} = \frac{N}{t} \times 1\times10^{-19}$ where $\frac{N}{t}$ is the number of ions per second $\Rightarrow \frac{N}{t} = 1 \times 10^{11}$ $\Rightarrow$ Average number of ions produced by each α-particle = $\frac{1\times10^{11}}{1\times10^{6}}$ $= 1 \times 10^5$	**[A]**
13	γ – radiation is chosen over β– particles because of its relatively better penetrating power so that it is not easily blocked through the 0.40 m of <u>solid obstacles beneath the field</u>. The half-life of the radioactive material needs to be <u>small</u> so that its activity will <u>fall to a biologically safe level quicker</u>.	**[C]**

	Note: If the half-life is too long (several years), the radioactive material will remain hazardous for a more extended period, requiring additional safety measures and disposal considerations.	
14	fraction of undecayed nuclei remained, $\dfrac{N}{N_0}=\left(\dfrac{1}{2}\right)^{\frac{t}{t_{1/2}}}$ where $t_{1/2}$ is the half-life. Therefore $\dfrac{N}{N_0}=\left(\dfrac{1}{2}\right)^{\frac{16}{32}}=\left(\dfrac{1}{2}\right)^{\frac{1}{2}}=0.71$	**[D]**
15	fraction of undecayed nuclei remained, $\dfrac{N}{N_0}=\left(\dfrac{1}{2}\right)^{\frac{t}{t_{1/2}}}$ total activity (at $t=48$ years) $=$ activity of X $+$ activity of Y $=A_0\left(\dfrac{1}{2}\right)^{\frac{48}{24}}+A_0\left(\dfrac{1}{2}\right)^{\frac{48}{16}}=\dfrac{3}{8}A_0$	**[D]**
16	Use $\dfrac{N}{N_0}=\left(\dfrac{1}{2}\right)^{\frac{t}{t_{1/2}}}$ where $t_{1/2}$ is the half-life. For X: $\dfrac{N_X}{(N_0)_X}=\dfrac{N_X}{6.4\times10^{11}}=\left(\dfrac{1}{2}\right)^{\frac{t}{2\text{ days}}}$ For Y: $\dfrac{N_Y}{(N_0)_Y}=\dfrac{N_Y}{8\times10^{10}}=\left(\dfrac{1}{2}\right)^{\frac{t}{3\text{ days}}}$ For N_X and N_Y to be the same in the same time, $N_X = N_Y$ $\left(6.4\times10^{11}\right)\left(\dfrac{1}{2}\right)^{\frac{t}{2\text{ days}}}=\left(8\times10^{10}\right)\left(\dfrac{1}{2}\right)^{\frac{t}{3\text{ days}}}$ Therefore, $\Rightarrow 8=\left(\dfrac{1}{2}\right)^{\left(\frac{t}{3\text{ days}}-\frac{t}{2\text{ days}}\right)}=\left(\dfrac{1}{2}\right)^{\left(-\frac{t}{6}\right)}$ $\Rightarrow 3=\dfrac{t}{6}\Rightarrow t=18$ days	**[D]**
17	Activity $A = \lambda N$ $A=\left(\dfrac{\ln 2}{t_{1/2}}\right)N$ $=\left(\dfrac{\ln 2}{14\times24\times3600}\right)\left(3.0\times10^{16}\right)$ $=1.7\times10^{10}$ Bq	1 1

18		$\dfrac{A}{A_0}=\left(\dfrac{1}{2}\right)^{\frac{t}{t_{1/2}}}=\left(\dfrac{1}{2}\right)^{\frac{2.0}{6.05}}$ $\Rightarrow A=A_0\left(\dfrac{1}{2}\right)^{\frac{2.0}{6.05}}=\left(1.1\times10^4\right)\left(\dfrac{1}{2}\right)^{\frac{2.0}{6.05}}$ $=8.7\times10^3\ \text{Bq}$	 1 1
19	**(a)**	Decay constant = $\dfrac{\ln 2}{t_{1/2}}$ $=\dfrac{\ln 2}{8.04\times24\times60\times60}$ $= 9.98 \times 10^{-7}\ \text{s}^{-1}$	 1 1
	(b)	Activity $A = \lambda N$ $N=\dfrac{0.50\times10^{-6}\times3.7\times10^{10}}{9.98\times10^{-7}}$ $= 1.9 \times 10^{10}$	 1 1
20	**(a)**	*spontaneous* - Nuclear decay is not affected by external or environmental factors (not affected by external pressure, temperature, humidity, chemical reactions, the presence of other nuclei, etc.). → process of radioactive decay cannot be sped up or slowed down by physical or chemical means *random* – Nucleus has constant probability of decay per unit time, but time of decay of a nucleus cannot be predicted. → unpredictable emission of radiation	1 1
	(b)(i)	$Q=(M_{Ra}-M_{Rn}-M_{\alpha})c^2$ $=(226.0254-222.0176-4.0026)\times\left(1.66\times10^{-27}\right)\times\left(3\times10^8\right)^2$ $=7.7688\times10^{-13}\ \text{J}$ $=4.86\ \text{MeV}$ Q is the reaction energy.	 1 1
	(b)(ii)	Conservation of momentum: $-MV+M_{\alpha}V_{\alpha}=0$ --------- (1) Conservation of energy: $Q=\dfrac{1}{2}MV^2+\dfrac{1}{2}M_{\alpha}V_{\alpha}{}^2$ --------- (2) where V and V_α are the speeds of Rn and alpha particle, respectively after the decay. From (1): $V=\dfrac{M_\alpha}{M}V_\alpha$ -------------- (3)  	1 1

		Sub (3) into (2): $Q = \frac{1}{2}MV^2 + \frac{1}{2}M_\alpha V_\alpha^2$ $= \frac{1}{2}M\left(\frac{M_\alpha}{M}V_\alpha\right)^2 + \frac{1}{2}M_\alpha V_\alpha^2$ $= \frac{1}{2}M_\alpha V_\alpha^2\left(\frac{M_\alpha}{M}+1\right)$ $= K_\alpha\left(\frac{M_\alpha}{M}+1\right)$	1
	(b)(iii)	$4.86 = K_\alpha\left(\frac{4.0026}{222.0176}+1\right)$ (Show correct substitutions.) $K_\alpha = 4.77$ MeV The alpha particle carries away most (98 %) of the reaction energy.	1 1 1
	(c)(i)	activity after 30 months (or 2.5 years) $\geq 37\times10^{10}$ $\Rightarrow A_0 e^{-\left(\frac{\ln 2}{5.2}\times 2.5\right)} \geq 37\times10^{10}$ $\Rightarrow A_0 \geq 5.16\times10^{11}$ Bq $\therefore A_0 = 5.2\times10^{11}$ Bq	1 1
	(c)(ii)	$\lambda = \ln 2/(5.2\times365\times24\times60\times60)$ $= 4.2268\times10^{-9}$ s^{-1} $A_0 = \lambda N_0$ $N_0 = \frac{5.2\times10^{11}\text{ Bq}}{(\ln 2)/(5.2\times365\times24\times60\times60)}$ = 1.23 × 10^{20} Let the initial minimum mass be m_0. $N_0 = N_A \times (\text{number of moles of } ^{60}\text{Co})$ $1.23\times10^{20} = 6.02\times10^{23}\times\left(\frac{m_0}{60\text{ g mol}^{-1}}\right)$ $\Rightarrow m_0 = 12.3\times10^{-3}\text{ g} = 12.3\text{ mg}$	1 1 1 1
	(c)(iii)	energy emitted per decay = (0.31+1.17+1.33) MeV = 2.81 MeV = 2.81 × 1.60 × 10^{-13} J = 4.50 × 10^{-13} J Rate of energy emitted = energy emitted per decay × number of decays per second = (4.50 × 10^{-13} J) × (37 × 10^{10} s^{-1}) = 166 mW	1 1 1
	(c)(iv)	The β-decay energy is low compared to the γ-ray.	1

		Hence the (two) strong γ radiations, could be used as a γ-ray source to check for uniformity of the thickness of metal sheets in the industries. When γ rays interact with the metal, their attenuation (reduction in intensity) depends on the thickness and density of the material. Thicker regions of the metal sheet will absorb more gamma rays, leading to a decrease in the detected gamma ray intensity. 	
21	**(a)**	Activity in terms of Bq kg^{-1} = Total activity / mass of section Activity of concrete = 2.3 × 10^{12} / (8000 × 1000) = 2.88 × 10^5 Bq kg^{-1} Activity of graphite = 190 × 10^{12} / (2200 × 1000) = 8.64 × 10^7 Bq kg^{-1} Activity of steel = 3300 × 10^{12} / (3400 × 1000) = 9.71 × 10^8 Bq kg^{-1}	 1 1 1
	(b)	The half-life of iron-56 is relatively shorter than that of nickel. After 10 years, its activity will decrease to below the activity (about 80%) of Ni-63, which has 93% of undecayed nuclei remained. The activity of Ni-59 effectively does not decrease. Activity of Fe-56 after 10 years $= A_0 e^{-\left(\frac{\ln 2}{t_{1/2}}\right)t} = 2400\times10^{12} e^{-\left(\frac{\ln 2}{2.7}\right)10} = 184\times10^{12}\ \text{Bq}$ Activity of Ni-59 after 10 years $= A_0 e^{-\left(\frac{\ln 2}{t_{1/2}}\right)t} = 2.2\times10^{12} e^{-\left(\frac{\ln 2}{80000}\right)10} \approx 2.2\times10^{12}\ \text{Bq}$ Activity of Ni-63 after 10 years $= A_0 e^{-\left(\frac{\ln 2}{t_{1/2}}\right)t} = 250\times10^{12} e^{-\left(\frac{\ln 2}{92}\right)10} = 232\times10^{12}\ \text{Bq}$	1 1
	(c)	A nuclide with a long half-life takes a long time for half of its nuclei to decay. In each time period, the number of nuclei that will actually decay will be small. Hence, the activity is likely to be low if the long half-life nuclides listed in the table have low number of unstable nuclei, N. i.e., $A = \lambda N = \left(\ln 2 / t_{1/2}\right) N$	1 1

	(d)	From the table, the half-life of $^{3}_{1}H$ is 12 years and its total activity is 110 × 10^{12} Bq 10 years after reactor's shutdown. $\frac{A}{A_0} = \left(\frac{1}{2}\right)^n$ where n is the number of half-lives needed for activity to drop from A_0 to A, so $\frac{0.43 \times 10^{12}}{110 \times 10^{12}} = \left(\frac{1}{2}\right)^n$ $\Rightarrow n = \frac{\lg(0.039)}{\lg(0.50)} = 8.0$ Since A_0 is the activity of $^{3}_{1}H$ 10 years after reactor's shutdown, it will take 8.0 × 12 + 10 = 106 years after shutdown before the activity of $^{3}_{1}H$ in the reactor fall below 0.43 × 10^{12} Bq.	1 1 1 1 1
	(e)	The nuclide $^{36}_{17}Cl$ will determine the time required to isolate the reactor because it has the longest half-life. It takes the longest time for its activity to fall to a sufficiently low level.	1 1
	(f)	$^{36}_{17}Cl$ has significant activity only in the graphite section. Since it is determinant for time required for isolation, we shall focus on the acceptable activity in the graphite. Acceptable activity in 2200 tonnes of graphite = (2200 × 10^3 kg) × (400 Bq kg^{-1}) = 8.8 × 10^8 Bq $A = A_0 e^{-\left(\frac{\ln 2}{t_{1/2}}\right)t} \Rightarrow 8.8 \times 10^8 = 1.3 \times 10^{12} e^{-\left(\frac{\ln 2}{310000}\right)t}$ $\Rightarrow t = 3.3 \times 10^6$ years NB: although the activity values used from the table is for 10 years after shutdown, 10 years is insignificant compared to the order of 10^6 years. Therefore, for ease of calculations, we ignore it.	1 1 1 1

~ THE END ~