1

(a) **(i)** energy required to separate nucleons of nucleus to infinity

(ii) Binding energy per nucleon is a maximum at around A = 56. Products (of splitting a ^{56}Fe nucleus) must have a lower total binding energy. Hence reaction would require a net input of energy.

(b) **(i)** mass defect of uranium, $\Delta m = 236.909\,u - 235.044\,u$
$= 1.865\,u$

given that energy equivalent to a mass of 1.00 u *is* 934 MeV,
binding energy of uranium = $1.865\,u \times 934 = 1.742\,MeV$
binding energy per nucleon of uranium = $1.742 / 235 = 7.412\,MeV$

(ii) energy = $(95 \times 8.443) + (139 \times 8.189) - (235 \times 7.412)$
$= 199\,MeV$

(iii) number of reactions = $1.2 \times 10^{-7} \times 6.02 \times 10^{23}$
$= 7.22 \times 10^{16}$

energy release (for one reaction) = $199 \times 1.60 \times 10^{-13} = 3.18 \times 10^{-11}\,J$

power = $(7.22 \times 10^{16} \times 3.18 \times 10^{-11}) / (25 \times 10^{-3})$
$= 9.2 \times 10^{7}\,W$

2

(a) **(i)** cannot predict when and which particular nucleus will decay next.

(ii) decay is not affected by external environmental factors

(b) There are fluctuations in count rate.

(c) The average time taken for the initial number of nuclei of that particular radioactive nuclide to reduce to half of its initial value.

(d) **(i)** activity of X at time t

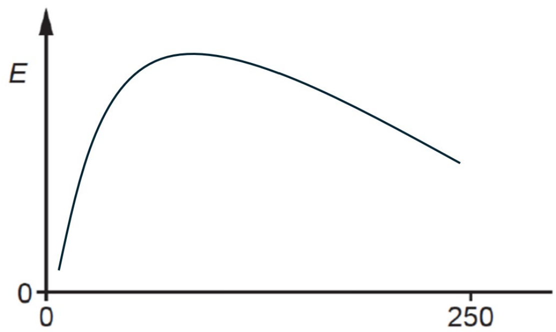
(ii) Y is a stable isotope
total number of nuclei is constant
half-life of X is 13.6 s

(e) mass of 1 nucleus = $(7.3 \times 10^{-4}) / (4.0 \times 10^{22})$
nucleon number = $mass\ of\ nucleus / (1.66 \times 10^{-27})$
$= (7.3 \times 10^{-4}) / (4.0 \times 10^{22} \times 1.66 \times 10^{-27})$
$= 11$

3

(a) **(i)** energy required to separate the nucleons to infinity

(ii)



(b) **(i)** Nuclear fusion

(ii) both particles have low A values and He-3 has higher binding energy (per nucleon) than the total binding energy of both H-2

(c) $\Delta m = [(2 \times 2.014102) - (3.016029 + 1.008665)]u$
$= 0.00351\ u$
$\Delta E = \Delta mc^2$
$= 0.00351 \times 1.66 \times 10^{-27} \times (3.00 \times 10^8)^2$
$= 5.24 \times 10^{-12}\ J$
1 mol of deuterium forms 0.5 mol of Helium-3
Total energy $= 0.500 \times 6.20 \times 10^{23} \times 5.24 \times 10^{-13} = 1.58 \times 10^{11} J$

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(b) **(i)** From the figure, at $t = 0, C_0 = 475\ s^{-1}$.
When the count rate is halved, $C_t = \frac{475}{2} = 237.5\ s^{-1}$.
To reach this value, reading from the graph, half-life is 15 $days$

At $t = 10\ days$, $C = 300\ s^{-1}$.
This is halved at $C = 150\ s^{-1}$, which is at $t = 25\ days$. This also gives a half-life of 15 $days$.

The (averaged) half-life is thus 15 $days$.

(ii) Beta particles have a sufficiently long range that could cross the entire lab, so the student is exposed to it even when not conducting the experiment.

(iii) If the product is not stable, it can decay and that will contribute to the count rate measured which will not be just due to the decay of phosphorous-32 alone.

5

(a) **(i)** It is defined as the energy needed just to separate the nucleons in the nucleus completely to infinity.

(ii) Mass defect is defined as the difference between the total mass of the nucleons of the atom taken separately and the mass of the nucleus.

(b) $\Delta m = 9(1.007825u) + (19 - 9)(1.008665u) - 18.998402u$
$= 0.158672u$
$= 2.633955 \times 10^{-28}\ kg$

$\Delta E = \Delta mc^2$
$= \frac{(2.6339555 \times 10^{-28})(3.00 \times 10^8)^2}{19}$
$= 1.247663 \times 10^{-12}\, J$
$= 7.80\, MeV$

(c) Total KE = total $BE_{products}$ − total $BE_{reactants}$ + input energy
$= 7.72(16) + 6.82(4) - 7.80(19) + 5$
$= 7.60\, MeV$
$= 1.22 \times 10^{-12}\, J$

(d) $\Delta E = \Delta mc^2$
$16(7.72)(1.6 \times 10^{-13})$
$= (mass\ of\ 8\ protons + 8\ neutrons - rest\ mass\ of\ oxygen)(3.00 \times 10^8)^2$
$rest\ mass\ of\ oxygen = 8(1.007825 + 1.008665)(1.66 \times 10^{-27}) - 2.195911 \times 10^{-28}$
$= 2.655940 \times 10^{-26}\, kg = 2.66 \times 10^{-26}\, kg$

6

(a) **(i)** Nuclei that have the same number of protons but different number of neutrons.

(ii) Time taken for the number of undecayed nuclei to be reduced to half its original number.

(b) **(i)** ${}^{40}_{19}K \rightarrow {}^{40}_{20}Ca + {}^{0}_{-1}\beta^- + v$

(ii) $\Delta E = \Delta mc^2$
$= (39.963998 - 39.962591)(1.66 \times 10^{-27})(3.00 \times 10^8)^2$
$= 2.102058 \times 10^{-13}\, J$
$= 1.31\, MeV$

(c) The ratio of potassium to argon to calcium is $2:1:9$.
$N = N_0 e^{-\lambda t}$
$\ln\left(\frac{N}{N_0}\right) = -\lambda t$
$t = \frac{1}{\lambda}\ln\left(\frac{N}{N_0}\right)$
$= \frac{t_{\frac{1}{2}}}{ln2}\ln\left(\frac{N_0}{N}\right)$
$= \frac{1.25 \times 10^9}{\ln 2}\ln\left(\frac{2+1+9}{2}\right)$
$= 3.23 \times 10^9\ years$

7

(a) After fission, products have smaller nucleons with higher binding energy per nucleon more stable, so energy will be released.

(b) $\Delta m = 235.123 + 1.009 - (94.945 + 138.955 + 2 \times 1.009) = 0.214u$
$\Delta E = \Delta mc^2$
$= 0.214 \times 1.66 \times 10^{-27} \times (3.00 \times 10^8)^2 = 3.197 \times 10^{-11} = 200\, MeV$

(c) Number of reactions $= \frac{6.02 \times 10^{23}}{235} \times 1.0 = 2.56 \times 10^{21}$

$\Delta E = 2.56 \times 10^{21} \times 3.197 \times 10^{-11} = 8.19 \times 10^{10}\, J$

(d) Energy required from nuclear reactions

$$= \frac{500 \times 10^6 \times 60 \times 60}{0.3} = 6.0 \times 10^{12}$$

Mass $= \frac{6.0\times10^{12}}{8.19\times10^{10}} = 73.3\ g$

8

(a) **(i)** $0 = 4mV + (A-4)m(-v)$
$4V = -(A-4)v$

(ii)
$$ratio = \frac{4mV^2}{(A-4)mv^2}$$
$$= \frac{4\left(\frac{(A-4)^2}{4^2}\right)v^2}{(A-4)v^2}$$
$$= \frac{1}{4}A - 1$$

(b) **(i)** $\Delta E = [m_{Bi} - (m_\alpha + m_{Th})]c^2$
$$= [211.9459 - (4.0015 + 207.9374)]1.66 \times 10^{-27}\frac{(3.00\times10^8)^2}{1.60\times10^{-13}}$$
$$= 654\ MeV$$

(ii)
$$\frac{E_\alpha}{E_{Th}} = \frac{A}{4} - 1$$
$$\frac{E_\alpha}{6.54 - E_\alpha} = \frac{212}{4} - 1 = 52$$
$$\frac{6.54}{E_\alpha} - 1 = \frac{1}{52}$$
$$E_\alpha = 6.42\ MeV$$

(c) **(i)** Gamma ray is also emitted in the process. Hence energy of alpha particle is smaller

(ii) Gamma ray is likely to carry off part of the momentum in a direction different from that of thallium nucleus and alpha particle. By conservation of momentum, the 2 particles cannot move in opposite direction

(iii) The expression would apply to an isolated charge. But there are two charged objects here.

(d) **(i)** $3600\ s$

(ii) Two hours is equivalent to two half lives of bismuth. Hence, number of radioactive bismuth nuclei remaining is approximately $\frac{N}{4}$, forming $\frac{3N}{4}$ thallium nuclei.

However, thallium has a much smaller half-life and would decay quickly to form other nuclei hence number of thallium nuclei is less than $\frac{3N}{4}$.

9

(a) Binding energy is the energy required to separate to infinity all the constituent nucleons in the nucleus.
It is the energy equivalent of mass defect and related to mass defect in the equation
$Binding\ energy\ = (mass\ defect) \times\ c^2$.

(b) **(i)** H-1 is a proton which is a free particle of the. Hence it has no binding energy.

(ii) 1. $\Delta E = BE_f - BE_i$
$= (144 \times 8.3) + (90 \times 8.7) - (235 \times 7.6)$
$= 192.2\ MeV$
$= 190\ MeV$

(ii) 2. $\Delta E = no\ of\ reactions \times 190\ MeV$
$= \left(\frac{1}{235} u\right) \times 190\ MeV$
$= 4.9 \times 10^{26} MeV$

(c) **(i)** Conservation of momentum and Conservation of mass-energy.

(ii) ${}^{90}_{38}Sr \rightarrow {}^{90}_{39}Y + {}^{0}_{-1}\beta + \bar{\upsilon}$

(iii) 1. Fluctuations on the curve

(iii) 2. Background count rate $= 40\ min^{-1}$

$actual\ count\ rate\ at\ t = 0, is\ 840 - 40 = 800\ min^{-1}$
After $t_{\frac{1}{2}}$ actual count rate $= 400\ min^{-1}$
Measured count rate $= 440\ min^{-1}$
From graph, $t_{\frac{1}{2}} = 35 - 0 = 35\ years$

$actual\ count\ rate\ at\ t = 50\ yr, is\ 300 - 40 = 260\ min^{-1}$
After $t_{\frac{1}{2}}$ actual count rate $= 130\ min^{-1}$
Measured count rate $= 170\ min^{-1}$
From graph, $t_{\frac{1}{2}} = 75 - 50 = 25\ years$

Average $t_{\frac{1}{2}} = \frac{35+25}{2} = 30\ years$

(iii) 3. Probability of decay in 1 yr = Probability of decay per unit time × 1 yr
$= \lambda \times 1\ yr$
$= \left(\frac{\ln 2}{t_{\frac{1}{2}}}\right) \times 1\ yr$
$= \frac{\ln 2}{30\ yr} \times 1\ yr$
0.023

(d) **(i)** By conservation of energy
Total initial KE = total final EPE
$= \frac{(+e)(+e)}{4\pi\epsilon_0 d} = \frac{(1.6 \times 10^{-19})^2}{4\pi\epsilon_0 \times 2 \times 0.0010 \times 10^{-12}}$
$= 1.15 \times 10^{-13}\ J$
$= 1.2 \times 10^{-12}\ J$

(ii) Average KE $= \frac{3}{2}kT$
$\frac{1.2 \times 10^{-13}}{2} = \frac{3}{2}kT$
$T = 2.9 \times 10^9\ K$

(iii) Actual temperature of Sun is much cooler than temp calculated in (ii). So Sun's core must involve nuclei with actual KE far above the average KE calculated in (i) (since fusion must occur).

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(b) **(i)** $^{210}_{84}Po \rightarrow ^{206}_{82}Pb + ^{4}_{2}He$

(ii)
$$E_K = \frac{\rho^2}{2m}$$
$$\frac{E_{K,\alpha}}{E_{k,Pb}} = \frac{m_{Pb}}{m_\alpha} = \frac{206}{4}$$
$$\frac{E_{K,\alpha}}{E_{k,Pb}} = 51.5$$

(iii)
$$A_0 = \lambda N_0 = \frac{\ln 2}{138 \times 24 \times 60^2}(4.2 \times 10^{11}) = 2.44 \times 10^4\ Bq$$
$$A = A_0 e^{-\left(\frac{\ln 2}{t_{\frac{1}{2}}}\right)t} = A_0 e^{-\left(\frac{\ln 2}{138}\right)600}$$
$$A = 1200\ bq$$

(iv) The reading will be lower. Particles are emitted in all directions and only a proportion will be detected by the counter.

(c) **(i)** By conservation of momentum, for a two particle system, the ratio of the speeds of the particles is fixed.

By conservation of energy, energy released per decay is constant, the speed of the beta particle emitted should be constant. However, the range of KE suggest that there must be a third particle.

(ii) Half-life of platinum is much longer than that of gold. Formation of gold is slower than its decay, hence gold will be the nuclei of the smallest percentage.

11

(a) Energy from 1 nucleus $= \frac{1.77\times10^{13}}{6.02\times10^{23}}$
$= 2.94 \times 10^{-11} J$

$\Delta E = (1.25 + 1.81) \times 10^{-10} - 2.94 \times 10^{-11}$
$= 2.77 \times 10^{-10}\ J$

Nucleon number $= 93 + 139 + 2 - 1 = 233$

Binding energy per nucleon $= \frac{2.77\times10^{-10}}{233\times1.6\times10^{-19}} = 7.43\ MeV$

(b) **(i)**
$$N_0 = \frac{0.874}{238 \times 1.66 \times 10^{-27}} = 2.212 \times 10^{24} = 2.21 \times 10^{24}$$

(ii)
$$A = \lambda N = \frac{\ln 2}{t_{\frac{1}{2}}} N$$
$$= \frac{\ln 2}{87.7 \times 365 \times 24 \times 3600} \times 2.21 \times 10^{24}$$
$$= 5.54 \times 10^{14}\ Bq$$

(iii)
$$A = A_0 e^{-\lambda t}$$
$$\ln 0.653 = -\left(\frac{\ln 2}{87.7}\right)t$$

$t = 53.9\ years$

(iv) half-life shorter, will not provide power for long enough.