Chapter 17

Nuclear Chemistry

17.2 $\Delta E = h\nu$, $\nu = \dfrac{\Delta E}{h}$, $\lambda = \dfrac{c}{\nu}$

(a) $\nu = \dfrac{9.6\times10^{-13}\ \text{J}}{6.63\times10^{-34}\ \text{J}\cdot\text{s}} = 1.4\times10^{21}\ \text{Hz}$

$\lambda = \dfrac{3.00\times10^{8}\ \text{m}\cdot\text{s}^{-1}}{1.4\times10^{21}\,\text{s}^{-1}} = 2.1\times10^{-13}\ \text{m}$

(b) $\nu = \dfrac{2.2\times10^{-14}\ \text{J}}{6.63\times10^{-34}\ \text{J}\cdot\text{s}} = 3.3\times10^{19}\ \text{Hz}$

$\lambda = \dfrac{3.00\times10^{8}\ \text{m}\cdot\text{s}^{-1}}{3.3\times10^{19}\,\text{s}^{-1}} = 9.1\times10^{-12}\ \text{m}$

(c) $\nu = \dfrac{4.7\times10^{-16}\ \text{kJ}\ \times\left(\dfrac{10^{3}\ \text{J}}{1\ \text{kJ}}\right)}{6.63\times10^{-34}\ \text{J}\cdot\text{s}} = 7.1\times10^{20}\ \text{Hz}$

$\lambda = \dfrac{3.00\times10^{8}\ \text{m}\cdot\text{s}^{-1}}{7.1\times10^{20}\,\text{s}^{-1}} = 4.2\times10^{-13}\ \text{m}$

(d) $\nu = \dfrac{3.8\times10^{-16}\ \text{kJ}\ \times\left(\dfrac{10^{3}\ \text{J}}{1\ \text{kJ}}\right)}{6.63\times10^{-34}\ \text{J}\cdot\text{s}} = 5.7\times10^{20}\ \text{Hz}$

$\lambda = \dfrac{3.00\times10^{8}\ \text{m}\cdot\text{s}^{-1}}{5.7\times10^{20}\,\text{s}^{-1}} = 5.3\times10^{-13}\ \text{m}$

17.4 energy of 1 MeV = $\left(\dfrac{10^{6}\ \text{eV}}{1\ \text{MeV}}\right)\left(\dfrac{1.602\ \times\ 10^{-19}}{1\ \text{eV}}\right) = 1.602 \times 10^{-13}\ \text{J}\cdot\text{MeV}^{-1}$

(a) $\Delta E = (5.30\ \text{MeV})\left(\dfrac{1.602\ \times\ 10^{-13}}{1\ \text{MeV}}\right) = 8.49 \times 10^{-13}\ \text{J}$

$$v = \frac{\Delta E}{h} = \frac{8.49 \times 10^{-13}\ \text{J}}{6.63 \times 10^{-34}\ \text{J}\cdot\text{s}} = 1.28 \times 10^{21}\ \text{s}^{-1} = 1.28 \times 10^{21}\ \text{Hz}$$

$$\lambda = \frac{c}{v} = \frac{3.00 \times 10^{8}\ \text{m}\cdot\text{s}^{-1}}{1.28 \times 10^{21}\ \text{s}^{-1}} = 2.34 \times 10^{-13}\ \text{m}$$

(b) $\Delta E = (0.26\ \text{MeV})\left(\frac{1.602 \times 10^{-13}\ \text{J}}{1\ \text{MeV}}\right) = 4.2 \times 10^{-14}\ \text{J}$

$$v = \frac{\Delta E}{h} = \frac{4.2 \times 10^{-14}\ \text{J}}{6.63 \times 10^{-34}\ \text{J}\cdot\text{s}} = 6.3 \times 10^{19}\ \text{s}^{-1} = 6.3 \times 10^{19}\ \text{Hz}$$

$$\lambda = \frac{c}{v} = \frac{3.00 \times 10^{8}\ \text{m}\cdot\text{s}^{-1}}{6.3 \times 10^{19}\ \text{s}^{-1}} = 4.8 \times 10^{-12}\ \text{m}$$

(c) $\Delta E = (5.4\ \text{MeV})\left(\frac{1.602 \times 10^{-13}\ \text{J}}{1\ \text{MeV}}\right) = 8.7 \times 10^{-13}\ \text{J}$

$$v = \frac{\Delta E}{h} = \frac{8.7 \times 10^{-13}\ \text{J}}{6.63 \times 10^{-34}\ \text{J}\cdot\text{s}} = 1.3 \times 10^{21}\ \text{Hz}$$

$$\lambda = \frac{c}{v} = \frac{3.00 \times 10^{8}\ \text{m}\cdot\text{s}^{-1}}{1.3 \times 10^{21}\ \text{s}^{-1}} = 2.3 \times 10^{-13}\ \text{m}$$

17.6 (a) ${}^{228}_{89}\text{Ac} \rightarrow {}^{0}_{-1}\text{e} + {}^{228}_{90}\text{Th}$

(b) ${}^{212}_{86}\text{Rn} \rightarrow {}^{4}_{2}\alpha + {}^{208}_{84}\text{Po}$

(c) ${}^{221}_{87}\text{Fr} \rightarrow {}^{4}_{2}\alpha + {}^{217}_{85}\text{At}$

(d) ${}^{230}_{91}\text{Pa} + {}^{0}_{-1}\text{e} \rightarrow {}^{230}_{90}\text{Th}$

17.8 (a) ${}^{233}_{92}\text{U} \rightarrow {}^{0}_{-1}\text{e} + {}^{233}_{93}\text{Np}$

(b) ${}^{56}_{27}\text{Co} \rightarrow {}^{1}_{1}\text{p} + {}^{55}_{26}\text{Fe}$

(c) ${}^{158}_{67}\text{Ho} \rightarrow {}^{0}_{-1}\text{e} + {}^{158}_{66}\text{Dy}$

(d) ${}^{212}_{84}\text{Po} \rightarrow {}^{4}_{2}\alpha + {}^{208}_{82}\text{Pb}$

17.10 (a) ${}^{14}_{6}\text{C} \rightarrow {}^{14}_{7}\text{N} + {}^{0}_{-1}\text{e}$ (β emission)

(b) ${}^{19}_{10}\text{Ne} \rightarrow {}^{19}_{9}\text{F} + {}^{0}_{+1}\text{e}$ (positron emission)

(c) $^{188}_{79}Au \rightarrow {}^{188}_{78}Pt + {}^{0}_{+1}e$ (positron emission)

(d) $^{229}_{92}U \rightarrow {}^{225}_{90}Th + {}^{4}_{2}\alpha$ (α emission)

17.12 (a) $^{74}_{36}Kr \rightarrow ? + {}^{0}_{+1}e$

$^{74}_{36}Kr \rightarrow {}^{74}_{35}Br + {}^{0}_{+1}e$

(b) $^{174}_{72}Hf \rightarrow ? + {}^{4}_{2}\alpha$

$^{174}_{72}Hf \rightarrow {}^{170}_{70}Yb + {}^{4}_{2}\alpha$

(c) $^{98}_{43}Tc \rightarrow ? + {}^{0}_{-1}e$

$^{98}_{43}Tc \rightarrow {}^{98}_{44}Ru + {}^{0}_{-1}e$

(d) $^{41}_{20}Ca + {}^{0}_{-1}e \rightarrow ?$

$^{41}_{20}Ca + {}^{0}_{-1}e \rightarrow {}^{41}_{19}K$

17.14 (a) $^{60}_{29}Cu$ is proton rich (*A* is below the band of stability); β^+ decay is most likely:

$^{60}_{29}Cu \rightarrow + {}^{0}_{+1}e + {}^{60}_{28}Ni$

(b) $^{140}_{54}Xe$ is neutron rich (*A* is above the band of stability); β decay is most likely:

$^{140}_{54}Xe \rightarrow + {}^{0}_{-1}e + {}^{140}_{55}Cs$

(c) $^{246}_{95}Am$ has Z>83 and therefore, although neutron rich, most likely undergoes α decay:

$^{246}_{95}Am \rightarrow {}^{4}_{2}\alpha + {}^{242}_{93}Np$

(d) $^{240}_{93}Np$ has Z>83, and therefore, although slightly neutron rich, most likely undergoes α decay: $^{240}_{93}Np \rightarrow + {}^{4}_{2}\alpha + {}^{236}_{91}Pa$

17.16 α $^{237}_{93}Np \rightarrow {}^{4}_{2}\alpha + {}^{233}_{91}Pa$

β $^{233}_{91}Pa \rightarrow {}^{0}_{-1}e + {}^{233}_{92}U$

α $^{233}_{92}U \rightarrow {}^{4}_{2}\alpha + {}^{229}_{90}Th$

α $^{229}_{90}Th \rightarrow {}^{4}_{2}\alpha + {}^{225}_{88}Ra$

β $^{225}_{88}Ra \rightarrow {}^{0}_{-1}e + {}^{225}_{89}Ac$

α $^{225}_{89}Ac \rightarrow {}^{4}_{2}\alpha + {}^{221}_{87}Fr$

α $^{221}_{87}Fr \rightarrow {}^{4}_{2}\alpha + {}^{217}_{85}At$

α $^{217}_{85}At \rightarrow {}^{4}_{2}\alpha + {}^{213}_{83}Bi$

β $^{213}_{83}Bi \rightarrow {}^{0}_{-1}e + {}^{213}_{84}Po$

α $^{213}_{84}Po \rightarrow {}^{4}_{2}\alpha + {}^{209}_{82}Pb$

β $^{209}_{82}Pb \rightarrow {}^{0}_{-1}e + {}^{209}_{83}Bi$

17.18 (a) $^{20}_{10}Ne + {}^{1}_{1}p \rightarrow {}^{21}_{11}Na + \gamma$

(b) $^{1}_{1}H + {}^{1}_{1}p \rightarrow {}^{2}_{1}H + {}^{0}_{+1}e$

(c) $^{15}_{7}N + {}^{1}_{1}p \rightarrow {}^{12}_{6}C + {}^{4}_{2}\alpha$

(d) $^{20}_{10}Ne + {}^{4}_{2}\alpha \rightarrow {}^{24}_{12}Mg + \gamma$

17.20 (a) $^{20}_{9}F + \gamma \rightarrow {}^{0}_{-1}e + {}^{20}_{10}Ne$

(b) $^{44}_{22}Ti + {}^{0}_{-1}e \rightarrow {}^{0}_{+1}e + {}^{44}_{20}Ca$

(c) $^{241}_{95}Am + {}^{11}_{5}B \rightarrow 4\,{}^{1}_{0}n + {}^{248}_{100}Fm$

(d) $^{243}_{95}Am + {}^{1}_{0}n \rightarrow 4\,{}^{0}_{-1}e + {}^{244}_{96}Cm$

17.22 (a) $^{245}_{98}Cf + {}^{12}_{6}C \rightarrow {}^{257}_{104}Rf$

(b) $^{209}_{83}Bi + {}^{58}_{26}Fe \rightarrow {}^{266}_{109}Mt + {}^{1}_{0}n$

$^{266}_{109}Mt \rightarrow {}^{4}_{2}\alpha + {}^{262}_{107}Bh$

$^{262}_{107}Bh$ is the daughter nucleus.

17.24 (a) ununsepium, Uus (b) unbiennium, Ube (c) Bibibiium, Bbb

17.26 activity = $(10.7\ \text{Bq})\left(\dfrac{1\ \text{Ci}}{3.7\times10^{10}\ \text{Bq}}\right)\left(\dfrac{1\ \mu\text{Ci}}{10^{-6}\ \text{Ci}}\right) = 2.9\times10^{-4}\ \mu\text{Ci}$

17.28 dis = disintegration(s); dis·s^{-1} = disintegrations per second = dps = Bq

(a) activity = $\left(\dfrac{590\ \text{clicks}}{100\ \text{s}}\right)\left(\dfrac{1000\ \text{dis}}{1\ \text{click}}\right)\left(\dfrac{1\ \text{Ci}}{3.7\times10^{10}\ \text{dps}}\right) = 1.6\times10^{-7}\ \text{Ci}$

(b) activity = $\left(\dfrac{2.7\times10^{4}\ \text{clicks}}{1.5\ \text{h}}\right)\left(\dfrac{1\ \text{h}}{3600\ \text{s}}\right)\left(\dfrac{1000\ \text{dis}}{1\ \text{click}}\right)\left(\dfrac{1\ \text{Ci}}{3.7\times10^{10}\ \text{dps}}\right)$

$= 1.4\times10^{-7}\ \text{Ci}$

(c) activity = $\left(\dfrac{159\ \text{clicks}}{1.0\ \text{min}}\right)\left(\dfrac{1\ \text{min}}{60\ \text{s}}\right)\left(\dfrac{1000\ \text{dis}}{1\ \text{click}}\right)\left(\dfrac{1\ \text{Ci}}{3.7\times10^{10}\ \text{dps}}\right)$

$= 7.2\times10^{-8}\ \text{Ci}$

17.30 dose in rads = $\left(\dfrac{2.0\ \text{J}}{5.0\ \text{g}}\right)\left(\dfrac{10^{3}\ \text{g}}{1\ \text{kg}}\right)\left(\dfrac{1\ \text{rad}}{10^{-2}\ \text{J}\cdot\text{kg}^{-1}}\right) = 4.0\times10^{4}\ \text{rad}$

dose equivalent in rems = Q × dose in rads (for α radiation, Q is about 20 rem/rad)

$= \dfrac{20\ \text{rem}}{1\ \text{rad}}\times 4.0\times10^{4}\ \text{rad} = 8.0\times10^{5}\ \text{rem}$

8.0×10^{5} rem ÷ 100 rem/Sv = 8.0×10^{3} Sv

17.32 2.0 mrad·day^{-1} = 2.0×10^{-3} rad·day^{-1}

dose equivalent in rem = Q × dose in rad

dose rate in rem = Q × dose rate in rad (Q = about 20 for α radiation)

dose rate in rem = (20 rem·rad^{-1})(2.0×10^{-3} rad·day^{-1})

= 4.0×10^{-2} rem·day^{-1}

Then

100 rem = 4.0×10^{-2} rem·day^{-1} × time

time = $\dfrac{100\ \text{rem}}{4.0\times10^{-2}\ \text{rem}\cdot\text{day}^{-1}} = 2.5\times10^{3}$ day (not far from 7 years)

17.34 $t_{1/2} = \dfrac{0.693}{k}$ (or use the ln key on your calculator to obtain a more precise value for ln 2)

(a) $t_{1/2} = \dfrac{0.693}{5.3 \times 10^{-10}\ \text{y}^{-1}} = 1.3 \times 10^{9}\ \text{y}$

(b) $t_{1/2} = \dfrac{0.693}{0.132\ \text{y}^{-1}} = 5.25\ \text{y}$

(c) $t_{1/2} = \dfrac{0.693}{3.85 \times 10^{-3}\ \text{s}^{-1}} = 180\ \text{s}$

17.36 Activity = disintegrations per second

Initial activity $\propto N_0$, final activity $\propto N$

$N = N_0 e^{-kt}$

$$\frac{\text{final activity}}{\text{initial activity}} = \frac{N}{N_0} = e^{-kt}$$

final activity = initial activity × e^{-kt}

$k = \dfrac{0.693}{28.1\ \text{y}} = 2.47 \times 10^{-2}\ \text{y}^{-1}$

final activity = $3.0 \times 10^{4}\ \text{Bq} \times e^{-(2.47 \times 10^{-2}\ \text{y}^{-1} \times 50\ \text{y})} = 8.7 \times 10^{3}\ \text{Bq}$

17.38 $k = \dfrac{0.693}{t_{1/2}}$, percentage remaining = $100\% \times \dfrac{N}{N_0} = 100\% \times e^{-kt}$

(a) $k = \dfrac{0.693}{28.1\ \text{y}} = 0.0247\ \text{y}^{-1}$

percentage remaining = $100\% \times e^{-(0.0247\ \text{y}^{-1} \times 7.5\ \text{y})} = 83\%$

For this type of problem, an alternative relationship may be used:

$\left(\dfrac{1}{2}\right)^{h}$ = fraction of original sample remaining (h = number of half-lives)

Thus, $\left(\dfrac{1}{2}\right)^{\frac{7.5}{28.1}} = 0.83 = 83\%$

(b) $k = \dfrac{0.693}{8.05 \text{ d}} = 0.0861 \text{ d}^{-1}$

percentage remaining = 100% × $e^{-(0.0861 \text{ d}^{-1} \times 7.0 \text{ d})}$ = 55%

17.40 (a) $k = \dfrac{0.693}{t_{1/2}} = \dfrac{0.693}{10.8 \text{ y}} = 0.0642 \text{ y}^{-1}$

fraction remaining = $\dfrac{N}{N_0} = e^{-kt} = e^{-(0.0642 \text{ y}^{-1} \times 50.0 \text{ y})} = 0.0404$

(Alternatively, $\left(\dfrac{1}{2}\right)^{50.0/10.8} = 0.0404$)

(b) t = elapsed time

$$t = -\frac{t_{1/2}}{\ln 2}\ln\left(\frac{N}{N_0}\right)$$

$$t = -\frac{5.73 \times 10^3 \text{ y}}{\ln 2}\ln\left(\frac{0.75 \times N_0}{N_0}\right) = 2.4 \times 10^3 \text{ y}$$

17.42 activity $\propto N$

t = elapsed time

5500 disintegrations/24.0 h = 229 disintegrations/h

$$t = -\frac{t_{1/2}}{\ln 2}\ln\left(\frac{N}{N_0}\right)$$

$$t = -\frac{5.73 \times 10^3}{\ln 2}\ln\left(\frac{229}{920}\right) = 11\ 500 \text{ y}$$

17.44 In each case: $k = \dfrac{0.693}{t_{1/2} \text{ (in s)}}$

activity in Bq = $k \times N$, activity in Ci = $\dfrac{\text{activity in Bq}}{3.7 \times 10^{10} \text{ Bq/Ci}}$

Note: Bq (= disintegrating nuclei per second) has the units of nuclei·s^{-1}.

(a) $k = \left(\dfrac{0.693}{7.1\times10^{8}\text{ y}}\right)\left(\dfrac{1\text{ y}}{3.17\times10^{7}\text{ s}}\right) = 3.1 \times 10^{-7}\text{ s}^{-1}$

$N = (1.0\text{ g})\left(\dfrac{1\text{ mol}}{267\text{ g}}\right)\left(\dfrac{6.022\times10^{23}\ {}^{235}\text{U nuclei}}{1\text{ mol}}\right) = 2.3 \times 10^{21}\text{ nuclei}$

$\text{activity} = (3.1 \times 10^{-17}\text{ s}^{-1})(2.3 \times 10^{21}\text{ nuclei})\left(\dfrac{1\text{ Ci}}{3.7\times10^{10}\text{ Bq}}\right)$

$= 1.9 \times 10^{-6}\text{ Ci}$

(b) $k = \left(\dfrac{0.693}{5.26\text{ y}}\right)\left(\dfrac{1\text{ y}}{3.17\times10^{7}\text{ s}}\right) = 4.16 \times 10^{-9}\text{ s}^{-1}$

$N = (0.010)(1.0\text{ g})\left(\dfrac{1\text{ mol}}{60\text{ g}}\right)\left(\dfrac{6.022\times10^{23}\text{ nuclei}}{1\text{ mol}}\right)$

$= 1.0 \times 10^{20}\text{ nuclei}$

$\text{activity} = (4.16 \times 10^{-9}\text{ s}^{-1})(1.0 \times 10^{20}\text{ nuclei})\left(\dfrac{1\text{ Ci}}{3.7\times10^{10}\text{ Bq}}\right) = 11\text{ Ci}$

(c) $k = \left(\dfrac{0.693}{26.1\text{ h}}\right)\left(\dfrac{1\text{ h}}{3600\text{ s}}\right) = 7.38 \times 10^{-6}\text{ s}^{-1}$

$N = (5.0 \times 10^{-3}\text{ g})\left(\dfrac{1\text{ mol}}{200\text{ g}}\right)\left(\dfrac{6.022\times10^{23}\text{ nuclei}}{1\text{ mol}}\right) = 1.5 \times 10^{19}\text{ nuclei}$

$\text{activity} = (7.38 \times 10^{-6}\text{ s}^{-1})(1.5 \times 10^{19}\text{ nuclei})\left(\dfrac{1\text{ Ci}}{3.7\times10^{10}\text{ Bq}}\right)$

$= 3.0 \times 10^{3}\text{ Ci}$

17.46 $t_{1/2} = 0.0033\text{ s}$

$k = \dfrac{0.693}{t_{1/2}} = \dfrac{0.693}{0.0033\text{ s}} = 2.1 \times 10^{2}\text{ s}^{-1}$

activity $\propto N$; and, because $N = N_0e^{-kt}$

final activity = initial activity $\times\ e^{-kt} = 0.10\ \mu\text{Ci}\ e^{-(2.1\times10^{2}\text{ s}^{-1}\times1.0\text{ s})}$

$= 6.3 \times 10^{-93}\ \mu\text{Ci}$ (≈no activity)

Alternatively:

$$0.10\ \mu\text{Ci} \times \left(\frac{1}{2}\right)^{1.0/0.0033} = 6.0 \times 10^{-93}\ \mu\text{Ci (i.e., no activity)}$$

17.48 $1.20\ \text{Ci} \times \left(\frac{1}{2}\right)^{5.0/5.26} = 0.62\ \text{Ci}$

17.50 Activity = rate of decay = $\dfrac{\Delta N}{\Delta t} = k \times N$

$$k = \frac{\Delta N}{\Delta t \cdot N} = \frac{(3.4\times10^{13}\,\text{disintegrations})}{(15\,\text{min})(3.25\times10^{18}\,\text{atoms})}\left(\frac{60\,\text{min}}{1\ \text{hour}}\right)\left(\frac{24\ \text{hours}}{1\ \text{day}}\right)$$

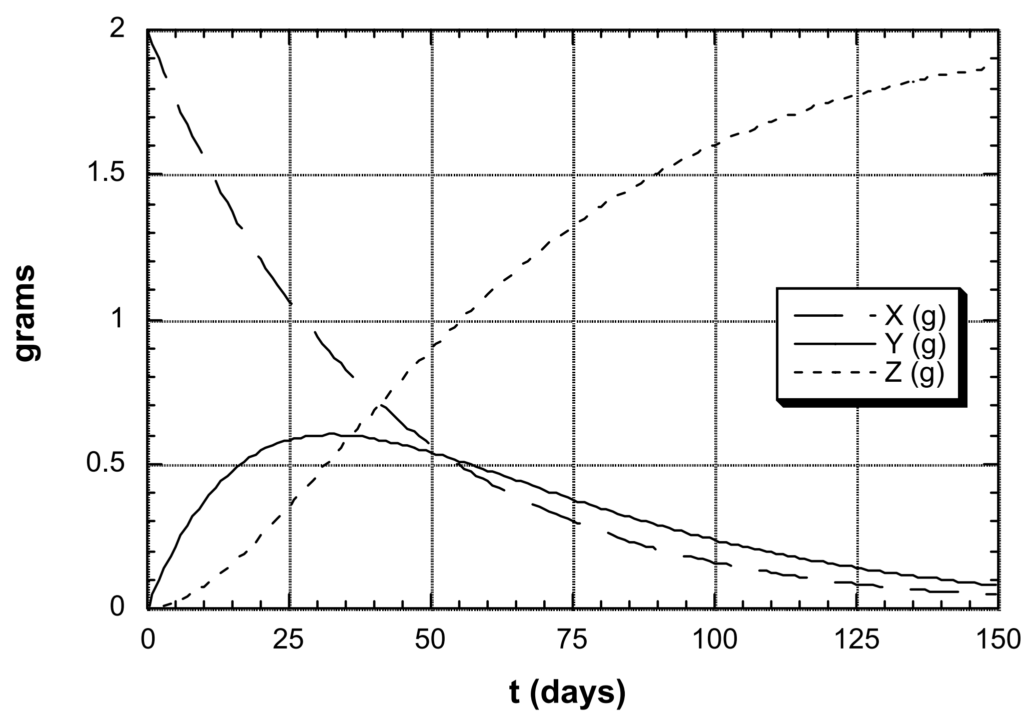
$= 0.0010\ \text{day}^{-1}$

(a) $\dfrac{\Delta N}{N}100\% = \left(1-e^{-k\Delta t}\right)\times100\% = \left(1-e^{-0.0010\times150}\right)\times100\% = 78\%$

(b) $N_{remain} = N_0 \times (1-0.78) = 3.25\times10^{18}\times0.22 = 7.2\times10^{17}\,\text{atoms}$

(c) $t_{\frac{1}{2}} = \dfrac{\ln 2}{k} = \dfrac{\ln 2}{0.0010\ \text{day}^{-1}} = 690\ \text{day}$

17.52 See full solution in Exercise 17.51. Plot below shows Y_{max}= 32 days.



17.54 A suitable radiolabeled compound can be dissolved in a solution at a known concentration and injected into the animal's bloodstream. After a few minutes the blood stream will be equilibrated. At this point, a blood sample can be taken so that the activity of the radioisotope in the blood can be determined. From this, one can calculate the dilution factor (the amount by which the original concentration of the injected material was diluted) and subsequently the total blood volume of the animal can be determined.

17.56 The O—D bond does not dissociate as readily as the O—H bond, as seen by the higher pK_a value for D_2O. This added reluctance to dissociate makes many reactions involving O—D bonds slower than those involving O—H bonds. Because many reactions occurring in the body involve the breaking of O—H bonds, these reactions will be significantly slowed if the H atoms are replaced by D atoms. So although D and H are chemically very similar, they do not behave exactly the same in subtle ways.

17.58 (a) $E = mc^2 = (1.00\text{ kg})(3.00 \times 10^8\text{ m·s}^{-1})^2$

$= 9.00 \times 10^{16}\text{ kg·m}^2\text{·s}^{-2} = 9.00 \times 10^{16}\text{ J}$

(b) $E = mc^2 = (0.454\text{ kg})(3.00 \times 10^8\text{ m·s}^{-1})^2$

$= 4.09 \times 10^{16}\text{ kg·m}^2\text{·s}^{-2} = 4.09 \times 10^{16}\text{ J}$

(c) $E = mc^2 = (1.674\ 93 \times 10^{-27}\text{ kg})(3.00 \times 10^8\text{ m·s}^{-1})^2$

$= 1.51 \times 10^{-10}\text{ kg·m}^2\text{·s}^{-2} = 1.51 \times 10^{-10}\text{ J}$

(d) $E = mc^2 = (0.001\ 0079\text{ kg·mol}^{-1} \div 6.02 \times 10^{23}\text{ atoms·mol}^{-1})$

$\times (3.00 \times 10^8\text{ m·s}^{-1})^2$

$= 1.51 \times 10^{-10}\text{ kg·m}^2\text{·s}^{-2} = 1.51 \times 10^{-10}\text{ J}$

17.60 (a) $\Delta m = \dfrac{\Delta E}{c^2} = \dfrac{3\times10^{11}\text{ J}}{(3.00\times10^8\text{ m}\cdot\text{s}^{-1})^2} = -3 \times 10^{-6}\text{ kg} = -3 \times 10^{-3}\text{ g}$

(b) The mass of a He atom is

$4.00 \div 6.02 \times 10^{23}$ g·mol^{-1} = 6.64×10^{-24} g or 6.64×10^{-27} kg.

The mass of an H atom is

$1.0079 \div 6.02 \times 10^{23}$ g·mol^{-1} = 1.67×10^{-24} g or 1.67×10^{-27} kg.

The mass of a neutron is $1.674\ 93 \times 10^{-27}$ kg.

$6\ D \rightarrow 2\ {}^{4}He + 2\ {}^{1}H + 2\ n$

The mass of the products side of the equation is

$(2 \times 6.64 \times 10^{-27}$ kg)

+ $(2 \times 1.67 \times 10^{-27}$ kg) + $(2 \times 1.67 \times 10^{-27}$ kg) = 2.00×10^{-26} kg.

The mass on the reactants side of the equation is given by

$6 \times (0.002\ 014$ g·mol$^{-1} \div 6.02 \times 10^{23}$ atoms·mol^{-1}) = 2.01×10^{-23} kg.

The difference in mass is 1×10^{-25} kg. The total loss of mass from (a) is 3×10^{-6} kg, so we need 3×10^{19} times the equation as written. This corresponds to $(3 \times 10^{19}) \times$ (6 atoms D) $\div 6.02 \times 10^{23}$ atoms·mol^{-1} = 3×10^{-4} mol D, or 6×10^{-4} g D.

17.62 (a) ${}^{98}_{42}Mo$

$42\ {}^{1}H + 56\ n \rightarrow {}^{98}_{42}Mo$

$\Delta m = 97.9055\ u - (42 \times 1.0078\ u + 56 \times 1.0087\ u) = -0.9093\ u$

$\Delta m = 0.9093\ u \times 1.6605 \times 10^{-27}\ kg{\cdot}u^{-1} = -1.510 \times 10^{-27}\ kg$

$E_{bind} = -1.510 \times 10^{-27}\ kg \times (2.998 \times 10^{8}\ m{\cdot}s^{-1})^2 = -1.357 \times 10^{-10}\ J$

$$E_{bind}/\text{nucleon} = \frac{-1.357 \times 10^{-10}\ J}{98\ \text{nucleons}} = -1.385 \times 10^{-12}\ J{\cdot}\text{nucleon}^{-1}$$

(b) ${}^{151}_{63}Eu$

$63\ {}^{1}H + 88\ n \rightarrow {}^{151}_{63}Eu$

$\Delta m = 150.9196\ u - (63 \times 1.0078\ u + 88 \times 1.0087\ u) = -1.3374\ u$

$\Delta m = -1.3374\ u \times 1.6605 \times 10^{-27}\ kg{\cdot}u^{-1} = -2.2208 \times 10^{-27}\ kg$

$E_{bind} = -2.2208 \times 10^{-27}\ kg \times (2.9979 \times 10^{8}\ m{\cdot}s)^2 = -1.9959 \times 10^{-10}\ J$

$$E_{bind}/\text{nucleon} = \frac{-1.9959 \times 10^{-10}\ J}{151\ \text{nucleons}} = -1.3218 \times 10^{-12}\ J{\cdot}\text{nucleon}^{-1}$$

(c) ${}^{56}_{26}\mathrm{Fe}$:

$26\ {}^{1}\mathrm{H} + 30\ \mathrm{n} \rightarrow {}^{56}_{26}\mathrm{Fe}$

Δm = 55.9349 u − (26 × 1.0078 u + 30 × 1.0087 u) = −0.5289 u

$$\Delta m = -0.5289\ \mathrm{u} \times \left(\frac{1.661\times10^{-27}\ \mathrm{kg}}{1\ \mathrm{u}}\right) = -8.785 \times 10^{-28}\ \mathrm{kg}$$

$E_{\mathrm{bind}} = -8.785 \times 10^{-28}\ \mathrm{kg} \times (2.998 \times 10^{8}\ \mathrm{m{\cdot}s^{-1}})^{-2} = -7.896 \times 10^{-11}\ \mathrm{J}$

$$E_{\mathrm{bind}}/\mathrm{nucleon} = \frac{-7.896\times10^{-11}\ \mathrm{J}}{56\ \mathrm{nucleons}} = -1.410 \times 10^{-12}\ \mathrm{J{\cdot}nucleon^{-1}}$$

(d) ${}^{232}_{90}\mathrm{Th}$

$90\ {}^{1}\mathrm{H} + 142\ \mathrm{n} \rightarrow {}^{232}_{90}\mathrm{Th}$

Δm = 232.0382 u − (90 × 1.0078 u + 142 × 1.0087 u) = −1.8992 u

$\Delta m = -1.8992\ \mathrm{u} \times 1.6605 \times 10^{-27}\ \mathrm{kg{\cdot}u^{-1}} = -3.154 \times 10^{-27}\ \mathrm{kg}$

$E_{\mathrm{bind}} = -3.154 \times 10^{-27}\ \mathrm{kg} \times (2.998 \times 10^{8}\ \mathrm{m{\cdot}s^{-1}})^{2} = -2.835 \times 10^{-10}\ \mathrm{J}$

$$E_{\mathrm{bind}}/\mathrm{nucleon} = \frac{-2.835\times10^{-10}\ \mathrm{J}}{232\ \mathrm{nucleons}} = -1.222 \times 10^{-12}\ \mathrm{J{\cdot}nucleon^{-1}}$$

(e) Because ${}^{56}\mathrm{Fe}$ has the largest binding energy per nucleon, it is the most stable.

17.64 (a) ${}^{7}_{3}\mathrm{Li} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{7}_{4}\mathrm{Be} + {}^{1}_{0}\mathrm{n}$

7.0160 u + 1.0078 u → 7.0169 u + 1.0087 u

8.0238 u → 8.0256 u

Δm = 0.0018 u

$$\Delta m = (0.0018\ \mathrm{u})\left(\frac{1.661\times10^{-27}\ \mathrm{kg}}{1\ \mathrm{u}}\right) = 3.0 \times 10^{-30}\ \mathrm{kg}$$

$\Delta E = \Delta mc^2 = (3.0 \times 10^{-30}\ \mathrm{kg})(3.00 \times 10^{8}\ \mathrm{m{\cdot}s^{-1}})^{2} = 2.7 \times 10^{-13}\ \mathrm{J}$

$$\left(\frac{2.7\times10^{-13}\ \mathrm{J}}{8.0238\ \mathrm{u}}\right)\left(\frac{1\ \mathrm{u}}{1.661\times10^{-24}\ \mathrm{g}}\right) = 2.0 \times 10^{10}\ \mathrm{J{\cdot}g^{-1}}$$

(b) ${}^{59}_{27}\mathrm{Co} + {}^{2}_{1}\mathrm{D} \rightarrow {}^{60}_{27}\mathrm{Co} + {}^{1}_{1}\mathrm{H}$

58.9332 u + 2.0141 u → 59.9529 u + 1.0078 u

$60.9473 \text{ u} \rightarrow 60.9607 \text{ u}$

$\Delta m = 0.0134 \text{ u}$

$$\Delta m = (0.0134 \text{ u})\left(\frac{1.6605\times10^{-27}\ \text{kg}}{1 \text{ u}}\right) = 2.23 \times 10^{-29}\ \text{kg}$$

$$\Delta E = \Delta mc^2 = (2.23 \times 10^{-29} \text{ kg})(3.00 \times 10^8 \text{ m·s}^{-1})^2 = 2.01 \times 10^{-12} \text{ J}$$

$$\left(\frac{2.01\times10^{-12}\ \text{J}}{60.9473 \text{ u}}\right)\left(\frac{1 \text{ u}}{1.661\times10^{-24}\ \text{g}}\right) = 1.99 \times 10^{10} \text{ J·g}^{-1}$$

(c) ${}^{40}_{19}\text{K} + {}^{0}_{-1}\text{e} \rightarrow {}^{40}_{18}\text{Ar}$

$39.9640 \text{ u} + 0.0005 \text{ u} \rightarrow 39.9624 \text{ u}$

$39.9645 \text{ u} \rightarrow 39.9624 \text{ u}$

$\Delta m = -0.0021 \text{ u}$

$$\Delta m = (-0.0021 \text{ u})\left(\frac{1.661\times10^{-27}\ \text{kg}}{1 \text{ u}}\right) = -3.5 \times 10^{-30}\ \text{kg}$$

$$\Delta E = \Delta mc^2 = (-3.5 \times 10^{-30} \text{ kg})(3.00 \times 10^8 \text{ m·s}^{-1})^2 = -3.2 \times 10^{-13} \text{ J}$$

$$\left(\frac{-3.2\times10^{-13}\ \text{J}}{39.9645 \text{ u}}\right)\left(\frac{1 \text{ u}}{1.661\times10^{-24}\ \text{g}}\right) = -4.8 \times 10^{9} \text{ J·g}^{-1}$$

(d) ${}^{10}_{5}\text{B} + {}^{1}_{0}\text{n} \rightarrow {}^{4}_{2}\text{He} + {}^{7}_{3}\text{Li}$

$10.0129 \text{ u} + 1.0087 \text{ u} \rightarrow 4.0026 \text{ u} + 7.0160 \text{ u}$

$11.0216 \text{ u} \rightarrow 11.0186 \text{ u}$

$\Delta m = -0.0030 \text{ u}$

$$\Delta E = \Delta mc^2 = (-0.0030 \text{ u})\left(\frac{1.661\times10^{-27}\ \text{kg}}{1 \text{ u}}\right) = -5.0 \times 10^{-30} \text{ J}$$

$$\left(\frac{-5.0\times10^{-30}\ \text{J}}{11.0216 \text{ u}}\right)\left(\frac{1 \text{ u}}{1.661\times10^{-24}\ \text{g}}\right) = -2.7 \times 10^{-7} \text{ J·g}^{-1}$$

17.66 (a) ${}^{234}_{94}\text{Pu} \rightarrow {}^{230}_{92}\text{U} + {}^{4}_{2}\alpha$

$\Delta m = 230.0339 \text{ u} + 4.0026 \text{ u} - 234.0433 \text{ u} = -0.0076 \text{ u}$

$\Delta E = \Delta mc^2 = (-0.0076 \text{ u}) \left(\dfrac{1.661\times10^{-27}\ \text{kg}}{1\ \text{u}}\right) (3.00 \times 10^8 \text{ m·s}^{-1})^2$

$= -1.1 \times 10^{-12}$ J

(b) $\dfrac{1.00\times10^{-6}\ \text{g}}{234.0433\ \text{g}\cdot\text{mol}^{-1}} = 4.27 \times 10^{-9}$ mol

$k = \dfrac{0.693}{t_{1/2}} = \dfrac{0.693}{8.8\ \text{h}} = 0.079\ \text{h}^{-1}$

$\dfrac{N}{N_0} = \text{e}^{-(0.070\ \text{h}^{-1})(24\ \text{h})} = 0.15$

If N is 0.15 N_0, then 85% of the sample decayed in the 24 h period.

4.27×10^{-9} mol × 0.85 × 6.02 × 10^{23} atoms·mol^{-1} = 2.2 × 10^{15} atoms

total energy released = 2.2 × 10^{15} atoms × 1.1 × 10^{-12} J·atom^{-1}

= 2.4 × 10^3 J, or 2.4 kJ

17.68 (a) ${}^{239}_{94}\text{Pu} + {}^{1}_{0}\text{n} \rightarrow {}^{98}_{42}\text{Mo} + {}^{138}_{52}\text{Te} + 4\ {}^{1}_{0}\text{n}$

(b) ${}^{239}_{94}\text{Pu} + {}^{1}_{0}\text{n} \rightarrow {}^{100}_{43}\text{Tc} + {}^{137}_{51}\text{Sb} + 4\ {}^{1}_{0}\text{n}$

(c) ${}^{239}_{94}\text{Pu} + {}^{1}_{0}\text{n} \rightarrow {}^{104}_{45}\text{Rh} + {}^{133}_{49}\text{In} + 3\ {}^{1}_{0}\text{n}$

17.70 (a) 99.0% removal corresponds to $N = 0.010\ N_0$

$k = \dfrac{\ln 2}{t_{1/2}} = \dfrac{0.693}{3.82\ \text{d}} = 0.181\ \text{d}^{-1}$

$\ln\left(\dfrac{N}{N_0}\right) = -kt$, or $\ln\left(\dfrac{N_0}{N}\right) = kt$, therefore

$t = \dfrac{1}{k}\ln\left(\dfrac{N_0}{N}\right) = \dfrac{1}{0.181\ \text{d}^{-1}}\ln\left(\dfrac{N_0}{0.010\ N_0}\right)$

$t = 25$ d

(b) Because it takes only 25 days for 99.0% of the radon to be removed by disintegration, it does not seem likely that radon formed deep in the earth's crust could leak to the surface in such a relatively short time. So, most of the radon observed must have been formed near the Earth's surface.

(c) Radon enters homes from the soil into the basements. It is naturally given off by concrete, cinder block, and stone building materials. An absorbing material could be used to absorb the emitted radon gas before it entered the basement. Most of the radon would disintegrate before it freed itself from the absorbing material, because the half-life is short. One such absorbing material is polyester cloth.

17.72 First, determine the decay constant from the half-life of ${}^{3}_{1}\mathrm{T}$. Then calculate the number of T nuclei in 1.0 mg of T. The activity is then given by

rate = $k \times N$

which is the number of disintegrations per second (Bq). Then convert to absorbed dose in rad and dose equivalent in rem, using the information in Table 17.4

$$k = \frac{0.693}{t_{1/2}} = \frac{0.693}{12.3\ \mathrm{y} \times 3.17 \times 10^{7}\ \mathrm{s \cdot y^{-1}}} = 1.78 \times 10^{-9}\ \mathrm{s^{-1}}$$

$$N = 1.0 \times 10^{-3}\ \mathrm{g} \times \frac{1\ \mathrm{mol}}{3.0\ \mathrm{g}} \times 6.022 \times 10^{23}\ \mathrm{mol^{-1}} = 2.0 \times 10^{20}\ \text{nuclei}$$

activity = $1.78 \times 10^{-9}\ \mathrm{s^{-1}} \times 2.0 \times 10^{20} = 3.6 \times 10^{11}$ dps = 3.6×10^{11} Bq

If 100% of the energy produced by these disintegrations were absorbed by the 1.0 g of tissue, then the energy absorbed per second would be

$E = 0.0186\ \mathrm{MeV} \times 1.602 \times 10^{-13}\ \mathrm{J{\cdot}MeV^{-1}} \times 3.6 \times 10^{11}\ \mathrm{s^{-1}}$

$= 1.1 \times 10^{-3}\ \mathrm{J{\cdot}s^{-1}}$

$$\text{absorbed dose} = 1.1 \times 10^{-3}\ \mathrm{J{\cdot}s^{-1}{\cdot}g^{-1}} \times 10^{3}\ \mathrm{g{\cdot}kg^{-1}} \times \left(\frac{1\ \mathrm{rad}}{1 \times 10^{-2}\ \mathrm{J \cdot kg^{-1}}}\right)$$

$= 1.1 \times 10^{2}\ \mathrm{rad{\cdot}s^{-1}}$

For 10% of the energy absorbed:

dose equivalent = $Q \times$ absorbed dose

$= 1\ \mathrm{rem/rad} \times 1.1 \times 10^{2}\ \mathrm{rad{\cdot}s^{-1}} \times 0.10$

$= 11\ \mathrm{rem{\cdot}s^{-1}}$

17.74 The decay process can generate much heat, which would speed up the corrosion rate. The decay process can also result in the production of new, possibly corrosive chemicals as a result of nuclear fission and nuclear transmutation. Chemical breakdown can occur as a result of nuclear bombardment, resulting in new, highly corrosive gases and other substances.

17.76 $t_{1/2}$ = 12.3 y; $k = \dfrac{0.693}{12.3\text{ y}} = 0.0563\text{ y}^{-1}$; activity $\propto$ N

$$t\ (=\text{age}) = -\frac{1}{k}\ln\left(\frac{N}{N_0}\right)$$

$$N = 0.091\ N_0;\ \frac{N}{N_0} = \frac{0.091\ N_0}{N_0} = 0.091$$

$$t\ (=\text{age}) = -\frac{1}{0.0563\text{ y}^{-1}}\ln(0.091) = 42.6\text{ y}$$

17.78 If $m = m_0 \times 2^{-\frac{t}{t_{1/2}}}$ then $m_0 = m \times 2^{\frac{t}{t_{1/2}}}$.

$$m_{\mathrm{P}}^0 = 0.0254\text{g} \times 2^{\frac{90}{14.28}} = 2.00\text{g}$$

$$m_{\mathrm{S}}^0 = 1.466\text{g} \times 2^{\frac{90}{87.2}} = 3.00\text{g}$$

$$m_{\mathrm{Fe}}^0 = 0.744\text{g} \times 2^{\frac{90}{44.6}} = 3.00\text{g}$$

Therefore

$$\text{P\%} = \frac{2.00}{8.00} \times 100\% = 25.0\%$$

$$\text{S\%} = \text{Fe\%} = \frac{3.00}{8.00} \times 100\% = 37.5\%$$

17.80 There are several important properties for any effective ligand. First, it must bond very strongly to the metal ion or else the metal ion will be liberated from the ligand and find its way into other body tissues.

Secondly, the ligand itself should not be toxic. Additionally, the ligand must have a very high specific binding attraction to the tissue in question.

17.82 (a) Pu^{3+}, Pu^{4+}; (b) Pu^{3+}, 108 pm; Pu^{4+}, 93 pm; Fe^{2+}, 82 pm; Fe^{3+}, 67 pm; (c) While the radii of the Pu ions are larger than those of iron, the charge to radius ratios are similar: Pu^{3+}, 0.028; Pu^{4+}, 0.043; Fe^{2+}, 0.024; Fe^{3+}, 0.045. Because of this, the Pu^{3+} binds similarly to Fe^{2+} and Pu^{4+} binds similarly to Fe^{3+}. The redox potentials for the reduction of the higher oxidation state species to the next lower oxidation number are also similar ($E°_{\text{red}}Pu^{4+} = 0.98$ V versus $E°_{\text{red}}Fe^{3+} = 0.77$ V) so that the plutonium also mimics the iron reasonably well in its redox chemistry.

17.84 ${}^{1}_{0}n + {}^{0}_{1}e \rightarrow {}^{1}_{1}p + 2\gamma$

$$\Delta E = \Delta m \cdot c^2 = 2m_e c^2 = 2 \times 9.10\ 939 \times 10^{-31}\,\text{kg} \times \left(2.99\ 792 \times 10^{8}\,\text{m} \cdot \text{s}^{-1}\right)^2$$

$$\Delta E = (1.63\ 742 \times 10^{-13}\,\text{J})\left(\frac{1\ \text{MeV}}{1.60\ 218 \times 10^{-13}\,\text{J}}\right) = 1.02\ 199\ \text{MeV}$$

17.86 (a) The boiling temperature can be calculated as:

$$T = \frac{\Delta H}{\Delta S}$$

Since the amount of energy required to vaporize each isotopomer varies with the zero-point energy of the two hydrogen bonds for each water molecule, ΔH can be represented as

$$\Delta H = \Delta H_0 - 2E_0$$

The zero point energy should be calculated as

$$E_0 = \frac{1}{2}h\nu,\ \nu = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

where m is supposed to be a reduced mass. As hydrogen is much lighter than the surrounding O network, the reduced mass is approximately just the mass of H (or D, or T). Combining these relationships, and assuming all quantities to be independent of temperature, we get following model for the normal boiling point:

$$T = a - \frac{b}{\sqrt{m}}$$

The unknown parameters *a* and *b* are

$$a = \frac{\Delta H_0}{\Delta S}, \; b = \frac{\hbar\sqrt{k}}{\Delta S}$$

These unknown parameters can be determined from the normal boiling points of H_2O (100.00 $^\circ\mathrm{C}$) and D_2O (101.42 $^\circ\mathrm{C}$):

$$373.15\ \mathrm{K} = a - \frac{b}{\sqrt{1.008\ \mathrm{u}}} = a - (0.99602\ \mathrm{u}^{-\frac{1}{2}})b$$

$$374.57\ \mathrm{K} = a - \frac{b}{\sqrt{2.0140\ \mathrm{u}}} = a - (0.70464\ \mathrm{u}^{-\frac{1}{2}})b$$

Subtracting the first expression from the second gives

$$1.42\ \mathrm{K} = (0.29138\ \mathrm{u}^{-\frac{1}{2}})b$$

$$b = 4.873\ \mathrm{K}\cdot\mathrm{u}^{\frac{1}{2}}$$

(Note that the subtraction yields 1.42 K on the left-hand side and limits *b* to three significant figures. We will keep one extra digit for use in subsequent calculations.)

Substituting *b* back into the first expression gives

$$373.15\ \mathrm{K} = a - \frac{4.873\ \mathrm{K}\cdot\mathrm{u}^{\frac{1}{2}}}{\sqrt{1.00797\ \mathrm{u}}}$$

$$a = 378.00\ \mathrm{K}$$

So our model for the boiling point of water, including different zero-point energies for different masses of hydrogen isotopes, is

$$T = 378.0 - \frac{4.873}{\sqrt{m}}$$

(b) The normal boiling point of T_2O can be predicted from our model.

$$T = 378.00\ \mathrm{K} - \frac{4.873\ \mathrm{K}\cdot\mathrm{u}^{\frac{1}{2}}}{\sqrt{3.01605\ \mathrm{u}}} = 375.19\ \mathrm{K}$$

$$= 102.04^\circ\mathrm{C}$$

Given the crude nature of our model, this prediction is in good agreement with the experimental value of $101.51\,^{\circ}\mathrm{C}$. (See W.M. Jones, *J. Chem. Phys.* **48**, 207 (1968).)

17.88 Nuclei that are positron emitters are proton-rich and lie below the band of stability.

(a) O stable at 16, so ^{18}O is neutron rich, will emit an electron rather than a positron; not good for PET. $^{18}_{8}\mathrm{O} \rightarrow {}^{18}_{9}\mathrm{F} + {}^{0}_{-1}e$

(b) N stable at 14, so ^{13}N is proton-rich, but it is likely to emit a proton to reach stable $^{12}_{6}\mathrm{C}$; not good for PET. $^{13}_{7}\mathrm{N} \rightarrow {}^{12}_{6}\mathrm{C} + {}^{1}_{1}p$

(c) C stable at 12, so ^{11}C is proton rich, will emit a positron; good for PET. $^{11}_{6}\mathrm{C} \rightarrow {}^{11}_{5}\mathrm{B} + {}^{0}_{1}e$

(d) F stable at 19, so ^{20}F is neutron rich, will emit an electron rather than a positron; not good for PET. $^{20}_{9}\mathrm{F} \rightarrow {}^{20}_{10}\mathrm{Ne} + {}^{0}_{-1}e$

(e) O stable at 16, so ^{15}O is proton-rich, but it will emit a proton to reach stable $^{14}_{7}\mathrm{N}$; not good for PET. $^{15}_{8}\mathrm{O} \rightarrow {}^{14}_{7}\mathrm{N} + {}^{1}_{1}p$