1. Explain the main features of the estimated abundance curve of the elements, given below:

Elements become rarer as one proceeds from low Z to high Z because only H and a little He was present after the big bang, and each element has been generated by combination of elements before it on the periodic table through fusion reactions in stars or supernovae.

Just like electrons in atomic orbitals, nucleons pack into ‘shells’ and are most stable energetically when these shells are filled. The sharp fall between He and C is due to the fact that Li, Be, and B have a very reactive unfilled shell under the conditions where nuclei are formed.

The peaks at 56Fe and 183Bi correspond to cases where both n and p are at ‘filled shell’ configurations. 56Fe is the nucleus with the lowest energy per nucleon, and 183 Bi is the last stable nucleus.

The ‘sawtooth’ shape of the curve arises from the fact that nuclei with unpaired protons are less stable, just as molecules with unpaired electrons are less stable; thus elements with even-Z are more frequent in the universe.
2.

(a) Rank the reactions below in order of their likely harm to living organisms.

Neglect non-ionising radiation; consider the rate of generation of ionising radiation and the energy of the particles generated.

\[ ^{238}_{94}\text{Pu} \rightarrow \alpha (5.50 \text{ MeV}) + \gamma (0.044 \text{ MeV}) + ^{234}_{92}\text{U} \quad (t_{1/2} = 87.7 \text{ years}) \]

\[ k = \frac{\ln 2}{(87.7 \text{ years})} = 7.90 \times 10^{-3} \text{ years}^{-1} \]

\[ k \times E = 7.90 \times 10^{-3} \text{ years}^{-1} \times 0.044 \text{ MeV} = 3.48 \times 10^{-4} \text{ MeV/years} \]

\[ ^{239}_{94}\text{Pu} \rightarrow \alpha (5.16 \text{ MeV}) + \gamma (0.374 \text{ MeV}) + ^{235}_{92}\text{U} \quad (t_{1/2} = 2.41 \times 10^4 \text{ years}) \]

\[ k \times E = \frac{\ln 2}{(24 100 \text{ years})} \times 0.374 \text{ MeV} = 1.08 \times 10^{-5} \text{ MeV/years} \]

\[ ^{240}_{94}\text{Pu} \rightarrow \alpha (5.26 \text{ MeV}) + \gamma (0.104 \text{ MeV}) + ^{236}_{92}\text{U} \quad (t_{1/2} = 6537 \text{ years}) \]

\[ k \times E = \frac{\ln 2}{(6537 \text{ years})} \times 0.104 \text{ MeV} = 1.10 \times 10^{-5} \text{ MeV/years} \]

\[ ^{241}_{94}\text{Pu} \rightarrow \beta^- (4.85 \text{ MeV}) + \gamma (0.149 \text{ MeV}) + ^{242}_{94}\text{Am} \quad (t_{1/2} = 14.4 \text{ years}) \]

\[ k \times E = \frac{\ln 2}{(14.4 \text{ years})} \times 4.999 \text{ MeV} = 0.241 \text{ MeV/years} \]

\[ ^{242}_{94}\text{Pu} \rightarrow \alpha (4.98 \text{ MeV}) + \gamma (0.104 \text{ MeV}) + ^{238}_{92}\text{U} \quad (t_{1/2} = 3.76 \times 10^5 \text{ years}) \]

\[ k \times E = \frac{\ln 2}{(376 000 \text{ years})} \times 0.104 \text{ MeV} = 1.92 \times 10^{-7} \text{ MeV/years} \]

\[ \therefore 241\text{Pu} \gg 238\text{Pu} > 240\text{Pu} \sim 239\text{Pu} \gg 242\text{Pu} \]
(b) Typical compositions of reactor grade and weapons grade plutonium are given below (Institute for Energy and Environmental Research, 1997). If the LD50 for rats fed weapons grade plutonium is 400 µg, what would be a likely LD50 for rats fed reactor grade plutonium?

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Reactor grade (%)</th>
<th>Weapons grade (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}\text{Pu}$</td>
<td>1.3</td>
<td>4.52 $\times 10^{-4}$</td>
</tr>
<tr>
<td>$^{239}\text{Pu}$</td>
<td>56.6</td>
<td>6.13 $\times 10^{-4}$</td>
</tr>
<tr>
<td>$^{240}\text{Pu}$</td>
<td>23.2</td>
<td>2.55 $\times 10^{-4}$</td>
</tr>
<tr>
<td>$^{241}\text{Pu}$</td>
<td>13.9</td>
<td>3.35</td>
</tr>
<tr>
<td>$^{242}\text{Pu}$</td>
<td>4.9</td>
<td>9.41 $\times 10^{-6}$</td>
</tr>
</tbody>
</table>

Total dose (arbitrary units)  

Calculate dose by multiplying the ‘reaction deadliness’ of the above question by the percentage values of each isotope, then add them together…

LD50 for weapons grade = 400 µg

LD50 for reactor grade = 400 µg $\times$ 0.12/3.35 = 14 µg

3. Which of these isotopes is most stable? What decay modes are the unstable ones most likely to undergo, and what product(s) would be formed?

(a) $^{19}\text{Ne}$, $^{20}\text{Ne}$, $^{23}\text{Ne}$

$^{19}\text{Ne} \rightarrow^{19}\text{Fe} + \beta^+$

$^{23}\text{Ne} \rightarrow^{23}\text{Na} + \beta^+$

(b) $^{58}\text{Ni}$, $^{59}\text{Ni}$, $^{66}\text{Ni}$

$^{59}\text{Ni} \rightarrow^{59}\text{Cu} + \beta^+$

$^{66}\text{Ni} \rightarrow^{66}\text{Cu} + \beta^+$
4. Positron-emission tomography (PET) may be used to image soft tissue and relies on emission of a positron from a radioactive isotope. $^{15}$O labeled water may be used. What isotope is formed by positron emission from $^{15}$O?

A $^{16}$O  
B $^{16}$F  
C $^{16}$N  
D $^{15}$F  
E $^{15}$N  

\[ ^{15}$O \rightarrow ^{15}$N + _{1}\beta \]

5. If an isotope with an atomic number of $Z$ and atomic mass of $A$ undergoes radioactive decay by emission of a $\beta$-particle, the resulting nuclide will have the following characteristics:

A Atomic number = $Z$, Atomic mass = $A$  
B Atomic number = $Z+1$, Atomic mass = $A$  
C Atomic number = $Z+1$, Atomic mass = $A+1$  
D Atomic number = $Z-2$, Atomic mass = $A-4$  
E Atomic number = $Z-1$, Atomic mass = $A$  

6. The half-life of radioactive $^{14}$C is 5730 years. What is the first order rate constant for this decay?

A $5.73 \times 10^3$ year$^{-1}$  
B $3.97 \times 10^3$ year$^{-1}$  
C $1.74 \times 10^4$ year$^{-1}$  
D $1.21 \times 10^{-4}$ year$^{-1}$  
E $5.25 \times 10^{-5}$ year$^{-1}$  

\[ k = \ln(2)/t_{1/2} = 0.693 / 5730 \]

7. The function of the thyroid gland may be monitored using $^{131}$I which decays by $\beta$ emission with a rate constant of 0.086 day$^{-1}$. How long does it take for the concentration of $^{131}$I to fall to 10% of its original value?

A 12 minutes  
B 2.1 hours  
C 21 hours  
D 8.1 days  
E 27 days  

\[ \ln(A_0/A_t) = kt \]  
so \[ \ln(100/10) = 0.086 t \]

8. A solution of sodium radio-iodide ($^{131}$I) has an activity of 32 millicuries (mCi) per litre when freshly prepared. Fifteen days later, a patient is given 1.00 mL of this solution by intravenous injection, in a test to study iodine uptake by the thyroid gland. Calculate the dose of $^{131}$I in microcuries (µCi) received by the patient. $t_{1/2}(^{131}$I) = 8.04 days.

\[ t_{1/2}(^{131}$I) = 8.04 \text{ days} \text{ so } k = 0.693 / 8.04 = 0.0862 \text{ day}^{-1} \]

\[ \ln(A_0/A_t) = \ln(A_0) - \ln(A_t) = kt \] rearranging gives \[ \ln(A_t) = \ln(A_0) - kt \]

\[ \ln(A_t) = \ln(32) - (0.0862 \text{ day}^{-1} \times 15 \text{ day}) = 2.173 \]

\[ A_t = 8.8 \text{ mCi in } 1 \text{ L} \]

so in 1 mL the activity after 15 days would be $8.8 \times 10^{-3}$ mCi = $8.8 \mu$Ci