CHAPTER 25
NUCLEAR CHEMISTRY
PRACTICE EXAMPLES

1A  (E) A $\beta^-$ has a mass number of zero and an “atomic number” of $-1$. Emission of this electron has the effect of transforming a neutron into a proton. $^{241}\text{Pu} \rightarrow ^{241}\text{Am} + _{-1}^0 \beta$

1B  (E) $^{58}\text{Ni}$ has a mass number of 58 and an atomic number of 28. A positron has a mass number of 0 and an effective atomic number of +1. Emission of a positron has the seeming effect of transforming a proton into a neutron. The parent nuclide must be copper-58.

$^{58}\text{Cu} \rightarrow ^{58}\text{Ni} + ^0_{+1} \beta$

2A  (E) The sum of the mass numbers $(139 + 12 = ? + 147)$ tells us that the other product species has $A = 4$. The atomic number of La is 57, that of C is 6, and that of Eu is 63. The atomic number sum $(57 + 6 = ? + 63)$ indicates that the atomic number of this product species is zero. Therefore, four neutrons must have been emitted.

$^{139}_{57}\text{La} + ^{12}_{6}\text{C} \rightarrow ^{147}_{63}\text{Eu} + 4^0_1 n$

2B  (E) An alpha particle is $^4_2\text{He}$ and a positron is $^0_{+1} \beta$. We note that the total mass number in the first equation is 125; the mass number of the additional product is 1. The total atomic number is 53; the atomic number of the additional product is 0; it is a neutron.

$^{121}_{51}\text{Sb} + ^4_2\text{He} \rightarrow ^{124}_{53}\text{I} + ^0_1 n$

In the second equation, the positron has a mass number of 0, meaning that the mass number of the product is 124. Because the atomic number of the positron is +1, that of the product is 52; it is $^{124}_{52}\text{Te}$.

$^{124}_{53}\text{I} \rightarrow ^0_{+1} \beta + ^{124}_{52}\text{Te}$

3A  (M)  (a)  The decay constant is found from the 8.040-day half-life.

$$\lambda = \frac{0.693}{8.040 \text{ d}} = 0.0862 \text{ d}^{-1} \times \frac{1 \text{ d}}{24 \text{ h}} \times \frac{1 \text{ h}}{60 \text{ min}} \times \frac{1 \text{ min}}{60 \text{ s}} = 9.98 \times 10^{-7} \text{ s}^{-1}$$

(b)  The number of $^{131}\text{I}$ atoms is used to find the activity.

$$\text{no.}^{131}\text{I atoms} = 2.05 \text{ mg} \times \frac{1 \text{ g}}{1000 \text{ mg}} \times \frac{1 \text{ mol}^{131}\text{I}}{131 \text{ g}^{131}\text{I}} \times \frac{6.022 \times 10^{23} \text{ atoms}}{1 \text{ mol}^{131}\text{I}}$$

$$= 9.42 \times 10^{18} \text{ atoms}^{131}\text{I}$$

$$\text{activity} = \lambda N = 9.98 \times 10^{-7} \text{ s}^{-1} \times 9.42 \times 10^{18} \text{ atoms} = 9.40 \times 10^{12} \text{ disintegrations / second}$$
(c) We now determine the number of atoms remaining after 16 days. Because two half-lives elapse in 16 days, the number of atoms has been halved twice, to one-fourth (25%) the original number of atoms.

\[ N_t = 0.25 \times N_0 = 0.25 \times 9.42 \times 10^{18} \text{ atoms} = 2.36 \times 10^{18} \text{ atoms} \]

(d) The rate after 14 days is determined by the number of atoms present on day 14.

\[
\text{rate} = \lambda N_t = 9.98 \times 10^{-7} \text{ s}^{-1} \times 2.36 \times 10^{18} \text{ atoms} = 2.36 \times 10^{12} \text{ dis/s}
\]

3B (M) First we determine the value of \( \lambda \):

\[
\lambda = \frac{0.693}{t_{1/2}} = \frac{0.693}{11.4 \text{ d}} = 0.0608 \text{ d}^{-1}
\]

Then we set \( N_t = 1\%N_0 = 0.010N_0 \) in equation (25.12).

\[
\ln \frac{N_t}{N_0} = -\lambda t = \ln \frac{0.010N_0}{N_0} = \ln (0.010) = -\left(0.0608 \text{ d}^{-1}\right)t
\]

\[
t = \frac{-4.61}{-0.0608 \text{ d}^{-1}} = 75.8 \text{ d}
\]

4A (M) The half-life of \(^{14}\text{C}\) is 5730 y and \( \lambda = 1.21 \times 10^{-4} \text{ y}^{-1} \). The activity of \(^{14}\text{C}\) when the object supposedly stopped growing was 15 dis/min per g C. We use equation (25.12) with activities \((\lambda N)\) in place of numbers of atoms \((N)\).

\[
\ln \frac{A_t}{A_0} = -\lambda t = \ln \frac{8.5 \text{ dis/min}}{15 \text{ dis/min}} = -\left(1.21 \times 10^{-4} \text{ y}^{-1}\right)t = -0.568; \quad t = \frac{0.57}{1.21 \times 10^{-4} \text{ y}^{-1}} = 4.7 \times 10^3 \text{ y}
\]

4B (M) The half-life of \(^{14}\text{C}\) is 5730 y and \( \lambda = 1.21 \times 10^{-4} \text{ y}^{-1} \). The activity of \(^{14}\text{C}\) when the object supposedly stopped growing was 15 dis/min per g C. We use equation (25.12) with activities \((\lambda N)\) in place of numbers of atoms \((N)\).

\[
\ln \frac{A_t}{A_0} = -\lambda t = \ln \frac{A_t}{15 \text{ dis/min}} = -\left(1.21 \times 10^{-4} \text{ y}^{-1}\right)(1100 \text{ y}) = -0.13
\]

\[
\frac{A_t}{15 \text{ dis/min}} = e^{-0.13} = 0.88 , A_t = 0.88 \times 15 \text{ dis/min} = 13 \text{ dis/min (per gram of C)}
\]

5A (M) mass defect. = 145.913053 u \( ^{146}\text{Sm} \) – 141.907719 u \( ^{142}\text{Nd} \) – 4.002603 u \( ^4\text{He} \) = 0.002731 u

Then, from the text, we have 931.5 MeV = 1 u \( E = 0.002731 u \times \frac{931.5 \text{ MeV}}{1 \text{ u}} = 2.544 \text{ MeV} \)

5B (M) Unfortunately, we cannot use the result of Example 25–5 (0.0045 u = 4.2 MeV) because it is expressed to only two significant figures, and here we begin with four significant figures. But, we essentially work backwards through that calculation. The last conversion factor is from Table 2-1.
Chapter 25: Nuclear Chemistry

\[
E = 5.590 \text{ MeV} \times \frac{1.602 \times 10^{-13} \text{ J}}{1 \text{ MeV}} = 8.955 \times 10^{-13} \text{ J} = me^2 = m\left(2.9979 \times 10^8 \text{ m/s}\right)^2
\]

\[
m = \frac{8.955 \times 10^{-13} \text{ J}}{(2.9979 \times 10^8 \text{ m/s})^2} \times 1000 \text{ g} \times \frac{1.0073 \text{ u}}{1 \text{ kg}} \times \frac{1.673 \times 10^{-24} \text{ g}}{1.0073 \text{ u}} = 0.005999 \text{ u}
\]

Or we could use \[m = 5.590 \text{ MeV} \times \frac{1 \text{ u}}{931.5 \text{ MeV}} = 0.006001 \text{ u}\]

6A (E) (a) \(^{88}\text{Sr}\) has an even atomic number (38) and an even neutron number (50); its mass number (88) is not too far from the average mass (87.6) of Sr. It should be stable.

(b) \(^{118}\text{Cs}\) has an odd atomic number (55) and a mass number (118) that is pretty far from the average mass of Cs (132.9). It should be radioactive.

(c) \(^{30}\text{S}\) has an even atomic number (16) and an even neutron number (14); but its mass number (30) is too far from the average mass of S (32.1). It should be radioactive.

6B (M) We know that \(^{19}\text{F}\) is stable, with approximately the same number of neutrons and protons: 9 protons, and 10 neutrons. Thus, nuclides of light elements with approximately the same number of neutrons and protons should be stable. In Practice Example 25–1 we saw that positron emission has the effect of transforming a proton into a neutron. \(\beta^-\) emission has the opposite effect, namely, the transformation of a neutron into a proton. The mass number does not change in either case. Now let us analyze our two nuclides.

\(^{17}\text{F}\) has 9 protons and 8 neutrons. Replacing a proton with a neutron would produce a more stable nuclide. Thus, we predict positron emission by \(^{17}\text{F}\) to produce \(^{17}\text{O}\).

\(^{22}\text{F}\) has 9 protons and 13 neutrons. Replacing a neutron with a proton would produce a more stable nuclide. Thus, we predict \(\beta^-\) emission by \(^{22}\text{F}\) to produce \(^{22}\text{Ne}\).

**INTEGRATIVE EXAMPLE**

A. (M) \[\lambda = \frac{0.693}{1.25 \times 10^9 \text{ y}} = 5.54 \times 10^{-10} \text{ y}^{-1}\] Calculate the fraction of \(^{40}\text{K}\) that remains after \(1.5 \times 10^9\) y.

\[\ln \frac{N_t}{N_0} = -\lambda t = -5.54 \times 10^{-10} \text{ y}^{-1} \times 1.5 \times 10^9 \text{ y} = -0.83 \quad \frac{N_t}{N_0} = 0.44\]

Thus, the fraction of \(^{40}\text{K}\) that has decayed is \(1.00 - 0.44 = 0.56\).

The fraction of the \(^{40}\text{K}\) that has decayed into \(^{40}\text{Ar}\) is \(0.110 \times 0.56 = 0.062\).
This fraction is proportional to the mass of $^{40}\text{Ar}$. Then the ratio of masses is determined.

\[
\frac{\text{mass of } ^{40}\text{Ar}}{\text{mass of } ^{40}\text{K}} = \frac{0.062}{0.44} = 0.14
\]

**B. (M) (a)** $\text{Zr}(s) + 6\text{H}_2\text{O}(l) \rightarrow \text{ZrO}_2(s) + 4 \text{H}_3\text{O}^+(aq) + 4 \text{e}^- \quad 1.43 \text{ V}

\[
4 \text{H}_2\text{O}(l) + 4 \text{e}^- \rightarrow 2 \text{H}_2(\text{g}) + 4 \text{OH}^-(aq) \quad -0.828 \text{ V}
\]

\[
\text{Zr}(s) + 2 \text{H}_2\text{O}(l) \rightarrow \text{ZrO}_2(s) + 2 \text{H}_2(\text{g}) \quad 0.602 \text{ V (spont)}
\]

Yes, Zr can reduce water under standard conditions.

\[(b)\quad E^\circ = \frac{0.0592}{n} \log K_{eq} \quad 0.602 \text{ V} = \frac{0.0592}{4} \log K_{eq} \quad K_{eq} = 4.67 \times 10^{40}\]

\[(c)\quad \text{pH} = 7 \quad \text{Therefore,} \quad [\text{OH}^-] = [\text{H}_3\text{O}^+] = 1.0 \times 10^{-7}

\[
E_{\text{ox}} = E_{\text{ox}}^\circ - \frac{0.0592}{n} \log Q = 1.43 \text{ V} - \frac{0.0592}{4} \log(1.0 \times 10^{-7})^4 = 1.84 \text{ V}
\]

\[
E_{\text{red}} = E_{\text{red}}^\circ - \frac{0.0592}{n} \log Q = -0.828 \text{ V} - \frac{0.0592}{4} \log(1 \times 10^{-7})^4 = -0.414 \text{ V}
\]

\[
E_{\text{cell}} = E_{\text{ox}} + E_{\text{red}} = 1.84 + (-0.414) = 1.43 \text{ V (spontaneous)}
\]

\[(d)\quad \text{Zr may be the culprit responsible for the } \text{H}_2(\text{g}) \text{ formation. In the Chernobyl accident, the reaction of carbon with superheated steam played a major role.}

\text{Reaction: } \text{H}_2\text{O}(\text{g}) + \text{C(s)} \rightarrow \text{CO(g)} + \text{H}_2(\text{g})
\]

**EXERCISES**

**Radioactive Processes**

1. **(E) (a)\quad ^{234}_{94}\text{Pu} \rightarrow ^{230}_{92}\text{U} + ^4_2\text{He}

   \[(b)\quad ^{248}_{97}\text{Bk} \rightarrow ^{248}_{98}\text{Cf} + _{-1}^0\text{e}

   \[(c)\quad ^{196}_{82}\text{Pb} + _{-1}^0\text{e} \rightarrow ^{196}_{81}\text{Tl} ; \quad ^{196}_{81}\text{Tl} + _{-1}^0\text{e} \rightarrow ^{196}_{80}\text{Hg}

   \[(c)\quad ^{214}_{82}\text{Pa} \rightarrow ^{214}_{83}\text{Bi} + _{-1}^0\text{e} ; \quad ^{214}_{83}\text{Bi} \rightarrow ^{214}_{84}\text{Po} + _{-1}^0\text{e}

   \[(b)\quad ^{226}_{88}\text{Ra} \rightarrow ^{226}_{86}\text{Rn} + ^4_2\text{He} ; \quad ^{226}_{86}\text{Rn} \rightarrow ^{218}_{84}\text{Po} + ^4_2\text{He} ; \quad ^{218}_{84}\text{Po} \rightarrow ^{214}_{82}\text{Pb} + ^4_2\text{He}

   \[(c)\quad ^{69}_{33}\text{As} \rightarrow ^{69}_{32}\text{Ge} + _{-1}^0\text{e}
3. (E) We would expect a neutron:proton ratio that is closer to 1:1 than that of $^{14}_6\text{C}$. This would be achieved if the product were $^{14}_7\text{N}$, which is the result of $\beta^-$ decay:

$$^{14}_6\text{C} \rightarrow ^{14}_7\text{N} + ^0_\text{e}. $$

4. (E) A nuclide with a closer to 1:1 neutron:proton ratio (than that of tritium) is helium-3, arrived at by beta emission: $^1_1\text{H} \rightarrow ^2_2\text{He} + ^0_\text{e}$. Another possible product is deuterium, which is arrived at by neutron emission: $^1_1\text{H} \rightarrow ^2_1\text{H} + ^1_0\text{n}$

**Radioactive Decay Series**

5. (M) We first write conventional nuclear reactions for each step in the decay series.

$$^{232}_{90}\text{Th} \rightarrow ^{228}_{88}\text{Ra} + ^4_2\text{He} \quad ^{228}_{88}\text{Ra} \rightarrow ^{228}_{89}\text{Ac} + ^0_\text{e} \quad ^{228}_{89}\text{Ac} \rightarrow ^{228}_{90}\text{Th} + ^0_\text{e}$$

$$^{228}_{90}\text{Th} \rightarrow ^{224}_{88}\text{Ra} + ^4_2\text{He} \quad ^{224}_{88}\text{Ra} \rightarrow ^{220}_{86}\text{Rn} + ^4_2\text{He} \quad ^{220}_{86}\text{Rn} \rightarrow ^{216}_{84}\text{Po} + ^4_2\text{He}$$

Now for a branch in the series:

these two $^{216}_{84}\text{Po} \rightarrow ^{212}_{82}\text{Pb} + ^4_2\text{He}$

or these two $^{216}_{84}\text{Po} \rightarrow ^{217}_{85}\text{At} + ^0_\text{e}$

And now a second branch:

these two $^{212}_{83}\text{Bi} \rightarrow ^{208}_{81}\text{Tl} + ^4_2\text{He}$

or these two $^{212}_{83}\text{Bi} \rightarrow ^{212}_{84}\text{Pb} + ^0_\text{e}$

Both branches end at the isotope $^{208}_{82}\text{Pb}$. The graph, similar to Figure 25-2, is drawn below.
6. (M) The series begins with uranium-235, and ends with lead-207.

\[
\begin{align*}
^{235}_{92} \text{U} & \rightarrow ^{231}_{90} \text{Th} + ^{4}_{2} \text{He} \\
^{231}_{90} \text{Th} & \rightarrow ^{231}_{91} \text{Pa} + ^{0}_{-1} \text{e} \\
^{231}_{91} \text{Pa} & \rightarrow ^{227}_{89} \text{Ac} + ^{4}_{2} \text{He}
\end{align*}
\]

Now the series branches:

these two \( ^{227}_{89} \text{Ac} \rightarrow ^{223}_{87} \text{Fr} + ^{4}_{2} \text{He} \)

or these two \( ^{227}_{89} \text{Ac} \rightarrow ^{227}_{90} \text{Th} + ^{0}_{-1} \text{e} \)

then \( ^{223}_{88} \text{Ra} \rightarrow ^{219}_{86} \text{Rn} + ^{4}_{2} \text{He} \)

\( ^{219}_{86} \text{Rn} \rightarrow ^{215}_{84} \text{Po} + ^{4}_{2} \text{He} \)

\( ^{215}_{84} \text{Po} \rightarrow ^{211}_{82} \text{Pb} + ^{4}_{2} \text{He} \)

The series branches again:

these two \( ^{211}_{83} \text{Bi} \rightarrow ^{207}_{81} \text{Tl} + ^{4}_{2} \text{He} \)

or these two \( ^{211}_{83} \text{Bi} \rightarrow ^{211}_{84} \text{Po} + ^{0}_{-1} \text{e} \)

The plot of atomic mass versus atomic number for these decay series is shown below.

7. (E) In Figure 25–2, only the following mass numbers are represented: 206, 210, 214, 218, 222, 226, 230, 234, and 238. We see that these mass numbers are separated from each other by 4 units. The first of them, 206, equals \((4 \times 51) + 2\), that is \(4n + 2\), where \(n = 51\).

8. (M) The series to which each nuclide belongs is determined by dividing its mass number by 4 and obtaining the remainder.

(a) The mass number of \( ^{214}_{83} \text{Bi} \) is 214, and the remainder following its division by 4 is 2. This nuclide is a member of the \(4n + 2\) series.
(b) The mass number of $^{216}_{84}\text{Po}$ is 216, and the remainder following its division by 4 is 0. This nuclide is a member of the $4n$ series.

(c) The mass number of $^{215}_{85}\text{At}$ is 215, and the remainder following its division by 4 is 3. This nuclide is a member of the $4n + 3$ series.

(d) The mass number of $^{235}_{92}\text{U}$ is 235, and the remainder following its division by 4 is 3. This nuclide is a member of the $4n + 3$ series.

Nuclear Reactions

9. (E) (a) $^{160}_{74}\text{W} \rightarrow ^{156}_{72}\text{Hf} + ^{4}_{2}\text{He}$
   (b) $^{38}_{17}\text{Cl} \rightarrow ^{38}_{18}\text{Ar} + ^{0}_{-1}\beta$
   (c) $^{214}_{83}\text{Bi} \rightarrow ^{214}_{84}\text{Po} + ^{0}_{-1}\beta$
   (d) $^{32}_{17}\text{Cl} \rightarrow ^{32}_{16}\text{S} + ^{0}_{+1}\beta$

10. (E) (a) $^{23}_{11}\text{Na} + ^{7}_{2}\text{H} \rightarrow ^{24}_{11}\text{Na} + ^{1}_{1}\text{H}$
    (b) $^{59}_{27}\text{Co} + ^{1}_{0}\text{n} \rightarrow ^{56}_{25}\text{Mn} + ^{4}_{2}\text{He}$
    (c) $^{238}_{92}\text{U} + ^{2}_{1}\text{H} \rightarrow ^{240}_{94}\text{Pu} + ^{0}_{-1}\beta$
    (d) $^{246}_{96}\text{Cm} + ^{13}_{6}\text{C} \rightarrow ^{254}_{102}\text{No} + ^{5}_{0}\text{n}$
    (e) $^{238}_{92}\text{U} + ^{14}_{7}\text{N} \rightarrow ^{246}_{99}\text{Es} + ^{6}_{0}\text{n}$

11. (E) (a) $^{7}_{3}\text{Li} + ^{1}_{1}\text{H} \rightarrow ^{8}_{4}\text{Be} + \gamma$
    (b) $^{9}_{4}\text{Be} + ^{2}_{1}\text{H} \rightarrow ^{10}_{1}\text{B} + ^{0}_{0}\text{n}$
    (c) $^{14}_{7}\text{N} + ^{1}_{0}\text{n} \rightarrow ^{14}_{6}\text{C} + ^{1}_{1}\text{H}$

12. (E) (a) $^{238}_{92}\text{U} + ^{4}_{2}\text{He} \rightarrow ^{239}_{94}\text{Pu} + ^{3}_{0}\text{n}$
    (b) $^{3}_{1}\text{H} + ^{2}_{1}\text{H} \rightarrow ^{4}_{2}\text{He} + ^{0}_{0}\text{n}$
    (c) $^{33}_{16}\text{S} + ^{1}_{0}\text{n} \rightarrow ^{33}_{15}\text{P} + ^{1}_{1}\text{H}$

13. (E) $^{209}_{83}\text{Bi} + ^{64}_{28}\text{Ni} \rightarrow ^{272}_{111}\text{Rg} + ^{1}_{0}\text{n}$; $^{272}_{111}\text{Rg} \rightarrow 5^4_{2}\text{He} + ^{252}_{101}\text{Md}$

14. (E) $^{208}_{82}\text{Pb} + ^{86}_{36}\text{Kr} \rightarrow ^{293}_{118}\text{E} + ^{1}_{0}\text{n}$; $^{293}_{118}\text{E} \rightarrow 6^4_{2}\text{He} + ^{269}_{106}\text{Sg}$

15. (M) $^{48}_{20}\text{Ca} + ^{249}_{98}\text{Cf} \rightarrow ^{249}_{118}\text{Unk} + ^{1}_{0}\text{n} + ^{1}_{0}\text{n} + ^{1}_{0}\text{n}$

16. (M) $^{293}_{118}\text{Unk} \rightarrow ^{289}_{116}\text{Unk} + ^{4}_{2}\text{He}$

17. (M) $^{58}_{26}\text{Fe} + ^{244}_{94}\text{Pu} \rightarrow ^{302}_{120}\text{Unk}$

18. (M) $^{238}_{92}\text{U} + ^{64}_{28}\text{Ni} \rightarrow ^{302}_{120}\text{Unk}$

Rate of Radioactive Decay

19. (M) (a) Since the decay constant is inversely related to the half-life, the nuclide with the smallest half-life also has the largest value of its decay constant. This is the nuclide $^{214}_{84}\text{Po}$, with a half-life of $1.64 \times 10^{-4}$ s.
(b) The nuclide that displays a 75% reduction in its radioactivity has passed through two half-lives in a period of one month. Thus, this is the nuclide with a half-life of approximately two weeks. This is the nuclide $^{32}\text{P}$, with a half-life of 14.3 days.

(c) If more than 99% of the radioactivity is lost, less than 1% remains. Thus $(\frac{1}{2})^n < 0.010$. Now, when $n = 7$, $(\frac{1}{2})^7 = 0.0078$. Thus, seven half-lives have elapsed in one month, and each half-life approximates 4.3 days. The longest lived nuclide that fits this description is $^{222}\text{Rn}$, which has a half-life of 3.823 days. Of course, all other nuclides with shorter half-lives also meet this criterion, specifically the following nuclides: $^{13}\text{O}$ (8.7 × $10^{-3}$ s), $^{28}\text{Mg}$ (21 h), $^{80}\text{Br}$ (17.6 min), and $^{214}\text{Po}$ (1.64 × $10^{-4}$ s).

20. (M) Since $16 = 2^4$, four half-lives have elapsed in 18.0 h, and each half-life equals 4.50 h. The half-life of isotope B thus is $2.5 \times 4.50 = 11.25$ h. Now, since $32 = 2^5$, five half-lives must elapse before the decay rate of isotope B falls to $\frac{1}{32}$ of its original value. Thus, the time elapsed for this amount of decay is:

$$\text{time elapsed} = 5 \text{half-lives} \times \frac{11.25}{1 \text{ half-life}} = 56.3 \text{ h}$$

21. (M) We use equation (25.13) to determine $\lambda$ and then equation (25.11) to determine the number of atoms.

$$\lambda = \frac{0.693}{5.2 \text{ y}} \times \frac{1 \text{ y}}{365.25 \text{ d}} \times \frac{1 \text{ d}}{24 \text{ h}} = 1.52 \times 10^{-5} \text{ h}^{-1}$$

$$N = \frac{\text{rate of decay}}{\lambda} = \frac{6740 \text{ atoms/h}}{1.52 \times 10^{-5} \text{ h}^{-1}} = 4.4 \times 10^8 \text{ }^{60}\text{Co atoms}$$

22. (M) This follows first-order kinetics (as do all radioactive decay processes) with a rate of decay directly proportional to the number of atoms. We therefore use equation (25.12), with rates substituted for numbers of atoms.

$$\frac{\text{dis}}{\text{h}} \times \frac{1 \text{ h}}{60 \text{ min}} = 112 \frac{\text{dis}}{\text{min}}$$

$$\ln \frac{R_t}{R_0} = -\lambda t = \ln \frac{101 \text{ dis/min}}{112 \text{ dis/min}} = -1.5 \times 10^{-5} \text{ h}^{-1} t = -0.103$$

$$t = \frac{0.103}{1.5 \times 10^{-5} \text{ h}^{-1}} = 6.9 \times 10^3 \text{ h} \times \frac{1 \text{ d}}{24 \text{ h}} \times \frac{1 \text{ y}}{365.25 \text{ d}} = 0.79 \text{ y}$$

23. (M) Let us use the first and the last values to determine the decay constant.

$$\ln \frac{R_t}{R_0} = -\lambda t = \ln \frac{138 \text{ cpm}}{1000 \text{ cpm}} = -\lambda \frac{250 \text{ h}}{1.981} = -0.1981$$

$$\lambda = \frac{1.981}{250 \text{ h}} = 0.00792 \text{ h}^{-1}$$

$$t_{1/2} = \frac{0.693}{\lambda} = \frac{0.693}{0.00792 \text{ h}^{-1}} = 87.5 \text{ h}$$

A slightly different value of $t_{1/2}$ may result from other combinations of $R_0$ and $R_t$. 

1203
24. (M) First we calculate the decay constant.
\[
\lambda = \frac{0.693}{1.7 \times 10^7 \text{ y}} \times \frac{1 \text{ y}}{365.25 \text{ d}} \times \frac{1 \text{ d}}{24 \text{ h}} \times \frac{1 \text{ h}}{3600} = 1.3 \times 10^{-15} \text{ s}^{-1}
\]
\[
N = 1.00 \text{ mg} \times \frac{1 \text{ g}}{1000 \text{ mg}} \times \frac{1 \text{ mol}^{129}\text{I}}{129 \text{ g}} \times \frac{6.022 \times 10^{23} \text{ atoms}}{1 \text{ mol}^{129}\text{I}} = 4.67 \times 10^{18} \text{^{129}I atoms}
\]
decay rate = \(\lambda N = 1.3 \times 10^{-15} \text{ s}^{-1} \times 4.67 \times 10^{18} \text{ atoms} = 6.1 \times 10^3 \text{ dis/s}
\]

25. (M) \(^{32}\text{P}\) half-life = 14.3 d. We need to determine the time necessary to get to the detectable limit, \(\frac{1}{1000}\) of the initial value. Use \(\lambda = \frac{0.693}{14.3 \text{ d}} = 0.0485 \text{ d}^{-1}\)
\[
\ln \left( \frac{1}{1000} \right) = -0.0485 \text{ d}^{-1}(t) \quad t = 142 \text{ days}
\]

26. (M) 1.00 mCi = 1.00 \times 10^{-3} (3.70 \times 10^{10} \text{ dis s}^{-1}) = 3.70 \times 10^7 \text{ dis s}^{-1}
\[
\lambda = \frac{0.693}{5730 \text{ y}} = \frac{0.693}{5730 \text{ y}} = 1.21 \times 10^{-4} \text{ y}^{-1} \quad (1 \text{ y} = 365.25 \text{ d} = 3.156 \times 10^7 \text{ s})
\]
\[
\lambda = \frac{1.21 \times 10^{-4} \text{ y}^{-1}}{3.156 \times 10^7 \text{ s}^{-1}} = 3.83 \times 10^{-12} \text{ s}^{-1}
\]
\[
1.00 \text{ mCi} = 3.70 \times 10^7 \text{ dis s}^{-1} = \lambda N = 3.83 \times 10^{-12} \text{ s}^{-1}\text{(N)}
\]
\[
N = 9.66 \times 10^{18} \text{ atoms of } ^{14}\text{C} \text{ or } 1.604 \times 10^{-5} \text{ mol }^{14}\text{C}
\]
\[
\text{mass of }^{14}\text{C} = 1.604 \times 10^{-5} \text{ mol }^{14}\text{C} \times \frac{14.00 \text{ g}^{14}\text{C}}{1 \text{ mol }^{14}\text{C}} = 2.25 \times 10^{-4} \text{ g }^{14}\text{C}
\]

Age Determinations with Radioisotopes

27. (E) Again we use equations (25.12) and (25.13) to determine the time elapsed. The initial rate of decay is about 15 dis/min. First we compute the decay constant.
\[
\lambda = \frac{0.693}{5730 \text{ y}} = 1.21 \times 10^{-4} \text{ y}^{-1}
\]
\[
\ln \left( \frac{10 \text{ dis/min}}{15 \text{ dis/min}} \right) = -0.40; \quad -\lambda t; \quad t = \frac{0.40}{1.21 \times 10^{-4} \text{ y}^{-1}} = 3.4 \times 10^3 \text{ y}
\]
The object is a bit more than 3000 years old, and thus is probably not from the pyramid era, which occurred about 3000 B.C.
28. (E) We use the value of $\lambda$ from the previous exercise.
\[
\ln \frac{R_t}{R_0} = -\lambda t = -(1.21 \times 10^{-4} \text{ y}^{-1})t = \ln \frac{0.03 \text{ dis min}^{-1} \text{ g}^{-1}}{15 \text{ dis min}^{-1} \text{ g}^{-1}} = -6.2
\]
\[
t = \frac{6.2}{1.21 \times 10^{-4} \text{ y}^{-1}} = 5.1 \times 10^4 \text{ y}
\]

29. (M) First we determine the decay constant.
\[
\lambda = \frac{0.693}{1.39 \times 10^{10} \text{ y}} = 4.99 \times 10^{-11} \text{ y}^{-1}
\]

Then we can determine the ratio of ($N_t$), the number of thorium atoms after $2.7 \times 10^9$ y, to ($N_0$), the initial number of thorium atoms:
\[
\ln \frac{N_t}{N_0} = -kt = -(4.99 \times 10^{-11} \text{ y}^{-1})(2.7 \times 10^9 \text{ y}) = -0.13
\]
\[
\frac{N_t}{N_0} = 0.88
\]

Thus, for every mole of $^{232}$Th present initially, after $2.7 \times 10^9$ y there are
0.88 mol $^{232}$Th and 0.12 mol $^{208}$Pb. From this information, we can compute the mass ratio.
\[
\frac{0.12 \text{ mol } ^{208}\text{Pb} \times 1 \text{ mol } ^{232}\text{Th} \times 208 \text{ g } ^{208}\text{Pb}}{0.88 \text{ mol } ^{232}\text{Th} \times 232 \text{ g } ^{232}\text{Th} \times 1 \text{ mol } ^{208}\text{Pb}} = \frac{0.12 \text{ g } ^{208}\text{Pb}}{1 \text{ g } ^{232}\text{Th}}
\]

30. (M) First we determine the decay constant.
\[
\lambda = \frac{0.693}{1.39 \times 10^{10} \text{ y}} = 4.99 \times 10^{-11} \text{ y}^{-1}
\]

The rock currently contains 1.00 g $^{232}$Th and 0.25 g $^{208}$Pb. We can calculate the mass of $^{232}$Th that must have been present to produce this 0.25 g $^{208}$Pb, and from that find the original mass of $^{232}$Th.
\[
\text{original mass } ^{232}\text{Th} = 1.00 \text{ g } ^{232}\text{Th now} + \left( 0.25 \text{ g } ^{208}\text{Pb} \times \frac{232 \text{ g } ^{232}\text{Th}}{208 \text{ g } ^{208}\text{Pb}} \right)
\]
\[
= (1.00 + 0.28) \text{ g} = 1.28 \text{ g}
\]
\[
\ln \frac{N_t}{N_0} = -\lambda t = \ln \frac{1.00 \text{ g } ^{232}\text{Th now}}{1.28 \text{ g originally}} = -0.247 = -4.99 \times 10^{-11} \text{ y}^{-1} t;
\]
\[
t = \frac{0.247}{4.99 \times 10^{-11} \text{ y}^{-1}} = 4.95 \times 10^9 \text{ y}
\]

31. (M) First convert argon-40 to the number of atoms/g in the sample. Next, convert % potassium to atoms/g in the sample. Finally, use equation (25.21) to determine the final answer $3.03 \times 10^9$ y.

32. (M) Apply equation (25.22) to obtain $t = 1.5 \times 10^9$ y.
Energetics of Nuclear Reactions

33. (M) The principal equation that we shall employ is \( E = mc^2 \), along with conversion factors.

(a) \[ E = 6.02 \times 10^{-23} \text{ g} \times \frac{1 \text{ kg}}{1000 \text{ g}} \times (3.00 \times 10^8 \text{ m/s})^2 = 5.42 \times 10^{-9} \text{ kg m}^2 \text{ s}^{-2} = 5.42 \times 10^{-9} \text{ J} \]

(b) \[ E = 4.0015 \text{ u} \times \frac{931.5 \text{ MeV}}{1 \text{ u}} = 3727 \text{ MeV} \]

34. (M) mass of individual particles = \[ \left( 47 \text{ p} \times \frac{1.0073 \text{ u}}{1 \text{ p}} \right) + \left( 60 \text{ n} \times \frac{1.0087 \text{ u}}{1 \text{ n}} \right) \]
\[ = 47.3431 \text{ u} + 60.5220 \text{ u} = 107.8651 \text{ u} \]

binding energy = \[ \frac{107.8651 \text{ u} - 106.879289 \text{ u}}{107 \text{ nucleons}} \times \frac{931.5 \text{ MeV}}{1 \text{ u}} = 8.58 \text{ MeV/nucleon} \]

35. (E) The mass defect is the difference between the mass of the nuclide and the sum of the masses of its constituent particles. The binding energy is this mass defect expressed as an energy.

particle mass = \[ 9 \text{ p} + 10 \text{n} + 9 \text{ e} = 9 \left( \text{p} + \text{n} + \text{e} \right) + \text{n} \]
\[ = 9 \left( 1.0073 + 1.0087 + 0.0005486 \right) \text{ u} + 1.0087 \text{ u} = 19.1576 \text{ u} \]

mass defect = 19.1576 u - 18.998403 u = 0.1592 u

binding energy per nucleon = \[ \frac{0.1592 \text{ u} \times \frac{931.5 \text{ MeV}}{1 \text{ u}}}{19 \text{ nucleons}} = 7.805 \text{ MeV/nucleon} \]

36. (E) The mass defect is the difference between the mass of the nuclide and the sum of the masses of its constituent particles. The binding energy is this mass defect expressed as an energy.

particle mass = \[ 26 \text{ p} + 30 \text{n} + 26 \text{ e} = 26 \left( \text{p} + \text{n} + \text{e} \right) + 4 \text{n} \]
\[ = 26 \left( 1.0073 + 1.0087 + 0.0005486 \right) \text{ u} + 4 \times 1.0087 \text{ u} = 56.4651 \text{ u} \]

mass defect = 56.4651 u - 55.934939 u = 0.5302 u

binding energy per nucleon = \[ \frac{0.5302 \text{ u} \times \frac{931.5 \text{ MeV}}{1 \text{ u}}}{56 \text{ nucleons}} = 8.819 \text{ MeV/nucleon} \]
37. (E) mass defect = (10.01294 u + 4.00260 u) − (13.00335 u + 1.00783 u) = 0.00436 u
   energy = 0.00436 u × \frac{931.5 \text{ MeV}}{1 \text{ u}} = 4.06 \text{ MeV}

38. (E) mass defect = (6.01513 u + 1.008665 u) − (4.00260 u + 3.01604 u) = 0.00516 u
   energy = 0.00516 u × \frac{931.5 \text{ MeV}}{1 \text{ u}} = 4.81 \text{ MeV}

39. (E) 1 neutron ≈ 1 amu = 1.66 × 10^{-27} \text{ kg}
   \[ E = mc^2 = 1.66 \times 10^{-27} \text{ kg} \left(2.998 \times 10^8 \text{ m s}^{-1}\right)^2 = 1.49 \times 10^{-10} \text{ J} \] (1 neutron)
   1 eV = 1.602 × 10^{-19} \text{ J},
   Hence, 1 neutron = \[ 1.49 \times 10^{-10} \text{ J} \times \frac{1 \text{ eV}}{1.602 \times 10^{-19} \text{ J}} = 9.30 \times 10^8 \text{ eV} \text{ or } 930 \text{ MeV} \]
   \[ 6.75 \times 10^6 \text{ MeV} \times \frac{1 \text{ neutron}}{930 \text{ MeV}} = 7.26 \times 10^3 \text{ neutrons} \]

40. (M) \( \beta^+ + \beta^- \) collide → produce two \( \gamma \)-rays.
   Basically the mass of \( \beta^+ = \beta^- \) = mass of an electron \( (9.11 \times 10^{-31} \text{ kg}) \)
   Each \( \gamma \)-ray has the same energy as the complete conversion of one electron into pure energy.
   \[ E = mc^2 = (9.11 \times 10^{-31} \text{ kg}) \left(2.998 \times 10^8 \text{ m s}^{-1}\right)^2 = 8.19 \times 10^{-14} \text{ J} \]
   In electron volts: \[ 8.19 \times 10^{-14} \text{ J} \times \frac{1 \text{ eV}}{1.602 \times 10^{-19} \text{ J}} = 5.11 \times 10^5 \text{ eV} \text{ or } 0.511 \text{ MeV} \]
   Each \( \gamma \)-ray has an energy of 0.511 MeV

Nuclear Stability

41. (E) (a) We expect \( ^{20}\text{Ne} \) to be more stable than \( ^{22}\text{Ne} \). A neutron-to-proton ratio of 1-to-1 is associated with stability for elements of low atomic number (with \( Z \leq 20 \)).

   (b) We expect \( ^{18}\text{O} \) to be more stable than \( ^{17}\text{O} \). An even number of protons and an even number of neutrons are associated with a stable isotope.

   (c) We expect \( ^{7}\text{Li} \) to be more stable than \( ^{6}\text{Li} \). Both isotopes have an odd number of protons, but only \( ^{7}\text{Li} \) has an even number of neutrons.

42. (E) (a) We expect \( ^{40}\text{Ca} \) to be more stable than \( ^{42}\text{Ca} \). A neutron-to-proton ratio of 1-to-1 is associated with stability for elements of low atomic number (with \( Z \leq 20 \)).

   (b) We expect \( ^{31}\text{P} \) to be more stable than \( ^{32}\text{P} \). Both isotopes have an odd number of protons, but only \( ^{31}\text{P} \) has an even number of neutrons.
(c) We expect $^{64}\text{Zn}$ to be more stable than $^{65}\text{Zn}$. An even number of protons and an even number of neutrons are associated with a stable isotope.

43. (M) $\beta^-$ emission has the effect of “converting” a neutron to a proton. $\beta^+$ emission, on the other hand, has the effect of “converting” a proton to a neutron.

(a) The most stable isotope of phosphorus is $^{31}\text{P}$, with a neutron-to-proton ratio of close to 1-to-1 and an even number of neutrons. Thus, $^{29}\text{P}$ has “too few” neutrons, or too many protons. It should decay by $\beta^+$ emission. In contrast, $^{33}\text{P}$ has “too many” neutrons, or “too few” protons. Therefore, $^{33}\text{P}$ should decay by $\beta^-$ emission.

(b) Based on the atomic mass of I (126.90447), we expect the isotopes of iodine to have mass numbers close to 127. This means that $^{120}\text{I}$ has “too few” neutrons and therefore should decay by $\beta^+$ emission, whereas $^{134}\text{I}$ has “too many” neutrons (or “too few” protons) and therefore should decay by $\beta^-$ emission.

44. (M) $\beta^-$ emission has the effect of converting a neutron to a proton, while $\beta^+$ emission has the effect of converting a proton to a neutron.

(a) Based on the fact that elements of low atomic number have about the same number of protons as neutrons, $^{15}\text{P}$—with 15 protons and 13 neutrons—has too few neutrons. Therefore, it should decay by $\beta^+$ emission.

(b) Once again, elements of low atomic number have about the same number of protons as neutrons. $^{45}\text{K}$ with 19 protons and 26 neutrons—has too many neutrons. Therefore, it should decay by $\beta^-$ emission.

(c) Based on the atomic mass of zinc (65.39) we expect most of its isotopes to have about 36 neutrons. There are 42 neutrons in $^{72}\text{Zn}$, more than we expect. Thus we expect this nuclide to decay by $\beta^-$ emission.

45. (M) A “doubly magic” nuclide is one in which the atomic number is a magic number (2, 8, 20, 28, 50, 82, 114) and the number of neutrons also is a magic number (2, 8, 20, 28, 50, 82, 126, 184). Nuclides that fit this description are given below.

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$^4\text{He}$</th>
<th>$^{16}\text{O}$</th>
<th>$^{40}\text{Ca}$</th>
<th>$^{56}\text{Ni}$</th>
<th>$^{208}\text{Pb}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of protons</td>
<td>2</td>
<td>8</td>
<td>20</td>
<td>28</td>
<td>82</td>
</tr>
<tr>
<td>No. of neutrons</td>
<td>2</td>
<td>8</td>
<td>20</td>
<td>28</td>
<td>126</td>
</tr>
</tbody>
</table>

46. (M) For isotopes of high atomic number, stable nuclides are characterized by a neutron-to-proton ratio greater than 1, which increases with increasing atomic number. Naturally occurring isotopes of high atomic number decrease their atomic number by losing an alpha particle, which has a neutron-to-proton ratio of 1. This leaves the neutron-to-proton ratio for the daughter that is higher than that of the parent, when it should be slightly lower. In order to redress this, the number of neutrons needs to be decreased and the number of...
protons increased. Beta emission accomplishes this. In contrast, artificially produced isotopes have no definite neutron-to-proton ratio. Thus, sometimes, the number of neutrons needs to be decreased, which is accomplished by beta emission, while at other times the number of protons needs to be decreased, which is accomplished by positron emission.

**Fission and Fusion**

47. **(E)** We use the conversion factor between number of curies and mass of $^{131}\text{I}$ which was developed in the Integrative Example.

$$\text{no. g } ^{131}\text{I} = 170 \text{ curies} \times \frac{18.8 \text{ g } ^{131}\text{I}}{2.33 \times 10^6 \text{ curie}} = 1.37 \times 10^{-3} \text{ g} = 1.37 \text{ mg}$$

48. **(M)** Nuclear fission is the process by which a heavy nucleus disintegrates into neutrons and stable nuclei with smaller mass numbers. For instance, uranium-238 undergoes fission according to the equation

$$^{238}_{92}\text{U} \rightarrow ^{234}_{90}\text{Th} + ^4_2\text{He}$$

The nuclear binding energy for uranium-238 is less than the sum of the binding energies for thorium-234 and helium-4. Consequently, when a uranium-238 nucleus splits apart, energy is released. Nuclear fusion, by contrast, involves the amalgamation of light nuclei into heavier, more stable nuclei. For instance, part of the energy released by our Sun is believed to come from the fusion of hydrogen to form deuterium:

$$^1_1\text{H} + ^1_1\text{H} \rightarrow ^2_1\text{H} + ^0_1\text{e}$$

Although both fusion and fission release vast amounts of energy, fusion releases far more energy on a per nucleon basis. To understand why this is so, we need to refer to Figure 25-6, which is a plot of average binding energy per nucleon as a function of atomic number. The graph clearly shows that the increase in binding energy observed for the formation of the lightest nuclides (e.g., deuterium, tritium, helium-3) is much more dramatic than the decrease in binding energy that is seen for the fragmentation of heavier nuclei such as uranium-235. Thus, the plot indicates that more energy should be released by the combination of light nuclei (nuclear fusion) than by the disintegration of heavy nuclei (nuclear fission).

**Effect of Radiation on Matter**

49. **(E)** The term “rem” is an acronym for “radiation equivalent-man,” and takes into account the quantity of biological damage done by a given dosage of radiation. On the other hand, the rad is the dosage that places 0.010 J of energy into each kilogram of irradiated matter. Thus, for living tissue, the rem provides a good idea of how much tissue damage a certain kind and quantity of radiation damage will do. But for nonliving materials, the rad is usually preferred, and indeed is often the only unit of utility.

50. **(M)** Low-level radiation is very close in its dosage to background radiation and one problem is to separate out the effects of the two sources (low-level and background). The other problem is that low-level radiation does not produce severe damage in a short
period of time. Thus the effects of low-level radiation will only be observed over a long
time period. Of course other effects, such as chemical and biological toxins, will also be
observed over these time periods, and we have to try to separate these two types of
effects. (There also is the genetic heritage of the organism to consider, of course.)

51. (M) One reason why \(^{90}\text{Sr}\) is hazardous is because strontium is in the same family of the
periodic table as calcium, and hence often reacts in a similar fashion to calcium. The most
likely place for calcium to be incorporated into the body is in bones, where it resides for a long
time. Strontium is expected to behave in a similar fashion. Thus, it will be retained in the body
for a long time. Bone is an especially dangerous place for a radioisotope to be present—even if
it has low penetrating power, as do \(\beta^+\) rays—because blood cells are produced in bone
marrow.

52. (M) It is not particularly hazardous to be near a flask of \(^{222}\text{Rn}\), because it is unlikely that
the alpha particles can get through the walls of the flask. (Note that since radon is a gas, the
flask must be sealed.) The decay products of \(^{222}\text{Rn}\) may produce other forms of radiation
that are more penetrating, such as \(\beta^-\) particles and \(\gamma\) rays, so being near the flask may
still pose a risk. \(^{222}\text{Rn}\) can be potentially hazardous if one breathes the gas.

Applications of Radioisotopes

53. (M) Mix a small amount of tritium with the \(\text{H}_2(\text{g})\) and detect where the radioactivity
appears with a Geiger counter.

54. (M) In neutron activation analysis, the sample is bombarded with neutrons. Radioisotopes
are produced by this process. These radioisotopes can be easily detected even in very small
quantities, much smaller, in fact, than the quantities that can be detected by conventional
means of quantitative analysis. These radioisotopes are produced in quantities that are
proportional to the quantity of each element originally present in the sample. And each
radioisotope is characteristic of the element from which it was produced by neutron
bombardment. Even microscopic samples can be analyzed by this technique. Finally,
neutron activation analysis is a nondestructive technique, while the conventional techniques
of precipitation or titration require that all of the sample, or at least part of it, be destroyed.

55. (M) The recovered sample will be radioactive. When \(\text{NaCl(s)}\) and \(\text{NaNO}_3(\text{s})\) are
dissolved in solution, the ions (\(\text{Na}^+, \text{Cl}^-, \text{and NO}_3^-\)) are free to move throughout the
solution. A given anion does not remain associated with a particular cation. Thus, all the
anions and cations are shuffled and some of the radioactive \(^{24}\text{Na}\) will end up in the
crystallized \(\text{NaNO}_3\).

56. (M) We would expect the tritium label to appear in both the \(\text{NH}_3(\text{g})\) and \(\text{H}_2\text{O(l)}\). When
\(\text{NH}_4^+\) (aq) is formed, one of the four chemically and spatially equivalent H atoms is
occasionally a tritium atom. In the subsequent reaction between the marked \(\text{NH}_4\text{Cl}\) and
\(\text{NaOH}\) to form \(\text{NH}_3(\text{g})\) and \(\text{H}_2\text{O(l)}\), there are three chances in four that a tritium atom
will remain attached to N in NH₃, and one chance in four that a tritium ion will react with a hydroxide ion to form H₂O(l).

INTEGRATIVE AND ADVANCED EXERCISES

57. (M) In the cases where rounding off the atomic mass produces the mass number of the most stable isotope, there often is but one stable isotope. This frequently is the case when the atomic number of the element is an odd number. For instance, think of situation with ⁹⁰K (Z = 19) and ⁸⁵Rb (Z = 37), but not ⁸⁸Sr (Z = 38). In the cases where this technique of rounding does not work, there are two or more stable isotopes of significant abundance. Note that the rounding off does not work in situations where it predicts a nuclide with an odd number of neutrons and an odd number of protons (such as ⁶⁴Cu with 29 protons and 35 neutrons), whereas the rounding off technique works when the predicted nuclide has an even number of protons, an even number of neutrons, or both.

58. (M) Each α particle contains two protons and has a mass number of 4. Thus each α particle emission reduces the mass number by 4 and the atomic number by 2. The emission of 8 α particles would reduce the mass number by 32 and the atomic number by 16. Thus the overall reaction would be as follows: ²³⁸U → ⁴He + ²⁰⁶Os (76 protons and 130 neutrons). In Figure 25-7, a nuclide with 76 protons and 130 neutrons lies above, to the left of the belt of stability; it is radioactive.

59. (M) We use ΔH_f[CO₂(g)] = -393.51 kJ/mol as the heat of combustion of 1 mole of carbon. In the text, the energy produced by the fission of 1.00 g ²³⁵U is determined as 8.20 × 10⁷ kJ.

\[
\text{metric tons of coal required} = 1.00 \text{ kg } ²³⁵\text{U} \times \frac{1000 \text{ g}}{1 \text{ kg}} \times \frac{8.20 \times 10^7 \text{kJ}}{1.00 \text{ g } ²³⁵\text{U}} \times \frac{1 \text{ mol C}}{393.5 \text{ kJ}} \times \frac{12.01 \text{ g C}}{1 \text{ mol C}} \times \frac{1 \text{ metric ton}}{1000 \text{ kg}} \times \frac{0.85 \text{ gC}}{1000 \text{ g}} = 2.9 \times 10^3 \text{ metric tons}
\]

60. (M) Since the two nuclides have the same mass number, the ratio of their masses is the same as the ratio of the number of atoms of each type. We use equation (25.12) to determine the time required for the Rb to decrease from 1.004 to 1.00. First we compute the decay constant.

\[
\lambda = \frac{0.693}{5 \times 10^{11}} = 1.4 \times 10^{-12} \text{ y}^{-1}
\]

\[
\ln \frac{1.00}{1.004} = -4.0 \times 10^{-3} = -\lambda t = -1.4 \times 10^{-12} \text{ y}^{-1} \quad t = \frac{-4.0 \times 10^{-3}}{-1.4 \times 10^{-12} \text{ y}^{-1}} = 3 \times 10^9 \text{ y}
\]
61. (M) \( \lambda = \frac{0.693}{27.7 \text{ y}} \times \frac{1 \text{ y}}{365.25 \text{ d}} \times \frac{1 \text{ d}}{24 \text{ h}} \times \frac{1 \text{ h}}{3600 \text{ s}} = 7.93 \times 10^{-10} \text{ s}^{-1} \)

\[ N = 5.10 \text{ mg} \times \frac{1 \text{ g}}{1000 \text{ mg}} \times \frac{1 \text{ mol} \text{ }^{229}\text{Th}}{229 \text{ g} \text{ }^{229}\text{Th}} \times \frac{6.022 \times 10^{23} \text{ }^{229}\text{Th} \text{ atoms}}{1 \text{ mol} \text{ }^{229}\text{Th}} = 1.34 \times 10^{99} \text{Th atoms} \]

decay rate in disintegrations/s = \( \lambda N = 2.99 \times 10^{-12} \text{ s}^{-1} \times 1.34 \times 10^{19} \text{ atoms} \times \frac{1 \text{ Ci}}{3.7 \times 10^{10} \text{ dis/s}} \times \frac{1000 \text{ mCi}}{1 \text{ Ci}} = 1.1 \text{ mCi} \)

62. (D) First we find the decay constant. The activity (\( \lambda N \)) is the product of the decay constant and the number of atoms.

\( \lambda = \frac{0.693}{27.7 \text{ y}} \times \frac{1 \text{ y}}{365.25 \text{ d}} \times \frac{1 \text{ d}}{24 \text{ h}} \times \frac{1 \text{ h}}{3600 \text{ s}} = 7.93 \times 10^{-10} \text{ s}^{-1} \)

radioactivity = \( 1.00 \text{ mCi} \times \frac{1 \text{ Ci}}{1000 \text{ mCi}} \times \frac{3.7 \times 10^{10} \text{ dis/s}}{1 \text{ Ci}} = 3.7 \times 10^7 \text{ dis/s} \)

\[ N = \frac{\lambda}{\lambda} = \frac{3.7 \times 10^7 \text{ dis/s}}{7.93 \times 10^{-10} \text{ s}^{-1}} = 4.7 \times 10^{16} \text{ }^{90}\text{Sr atoms} \times \frac{1 \text{ mol} \text{ }^{90}\text{Sr}}{6.022 \times 10^{23} \text{ atoms}} \times \frac{90 \text{ g} \text{ }^{90}\text{Sr}}{1 \text{ mol} \text{ }^{90}\text{Sr}} \]

= \( 7.0 \times 10^{-6} \text{ g} \text{ }^{90}\text{Sr} = 7.0 \mu g \text{ }^{90}\text{Sr} \)

63. (D) decay rate = \( 89.8 \text{ mCi} \times \frac{1 \text{ Ci}}{1000 \text{ mCi}} \times \frac{3.7 \times 10^{10} \text{ dis/s}}{1 \text{ Ci}} = 3.3 \times 10^9 \text{ dis/s} \)

\[ N = 1.00 \text{ mg} \times \frac{1 \text{ g}}{1000 \text{ mg}} \times \frac{1 \text{ mol} \text{ }^{137}\text{Cs}}{137 \text{ g} \text{ }^{137}\text{Cs}} \times \frac{6.022 \times 10^{23} \text{ atoms}}{1 \text{ mol}} = 4.40 \times 10^{18} \text{ }^{137}\text{Cs atoms} \]

decay rate = \( \lambda N \)

\[ \lambda = \frac{\text{decay rate}}{N} = \frac{3.3 \times 10^9 \text{ dis/s}}{4.40 \times 10^{18} \text{ atoms}} = 7.5 \times 10^{-10} \text{ s}^{-1} \]

\[ t_{1/2} = \frac{\lambda}{0.693} = \frac{0.693}{7.5 \times 10^{-10} \text{ s}^{-1}} \times \frac{1 \text{ h}}{3600 \text{ s}} \times \frac{1 \text{ d}}{24 \text{ h}} \times \frac{1 \text{ y}}{365.25 \text{ d}} = 29 \text{ y} \]

64. (D) \( \lambda = \frac{0.693}{1.25 \times 10^9 \text{ y}} \times \frac{1 \text{ y}}{365.25 \text{ d}} \times \frac{1 \text{ d}}{24 \text{ h}} \times \frac{1 \text{ h}}{3600 \text{ s}} = 1.76 \times 10^{-17} \text{ s}^{-1} \)

\[ N = 1.00 \text{ g} \text{ KAI} \text{SiO}_8 \times \frac{1 \text{ mol} \text{ KAI} \text{SiO}_8}{278.3 \text{ g} \text{ KAI} \text{SiO}_8} \times \frac{1 \text{ mol} \text{ K}}{1 \text{ mol} \text{ KAI} \text{SiO}_8} \times \frac{0.000117 \text{ mol} \text{ }^{40}\text{K}}{1 \text{ mol} \text{ KAI} \text{SiO}_8} \times \frac{6.022 \times 10^{23} \text{ }^{40}\text{K atoms}}{1 \text{ mol} \text{ }^{40}\text{K}} = 2.53 \times 10^{17} \text{ }^{40}\text{K atoms} \]

rate = \( 0.89 \lambda N = 0.89 \times 1.76 \times 10^{-17} \text{ s}^{-1} \times 2.53 \times 10^{17} \text{ atoms} = 4.0 \text{ dis/s} \)
65. (D) $^{14}$C is produced from $^{14}$N by neutron bombardment. Since $^{14}$N is a common element, constituting 78% of the atmosphere, any activity that increases the emission of neutrons will increase the production of $^{14}$C. A major source used to be thermonuclear explosions, particularly atmospheric detonations. But most tests now take place underground. Nonetheless, the extensive thermonuclear testing that took place during the 1950s and 1960s could have produced sufficient $^{14}$C to invalidate the radiocarbon dating of materials that were alive during that period. Nuclear power plants are a very minor source of $^{14}$C, as is bringing to the surface neutron-emitting isotopes by mining activities.

Although we might suspect ozone depletion of playing a role in increasing the quantity of $^{14}$C, such is not the case. Ozone absorbs ultraviolet radiation, not neutrons. And, in any case, there is about the same proportion of $^{14}$N in the upper atmosphere as there is further down, in layers that recently have become exposed to ultraviolet radiation because of the depletion of ozone.

66. (D) product masses = $^{17}$O + $^1$H = 16.99913 u + 1.00783 u = 18.00696 u
reactant masses = $^4$He + $^{14}$N = 4.00260 u + 14.00307 u = 18.00567 u

The products have more mass than the reactants. The difference must be supplied as energy from the reactants. This difference in energy ends up entirely to the $E_{\text{kinetic}}$ of the $\alpha$ particle. Compute this energy in MeV.

\[
\text{energy} = (18.00696 \text{ u} - 18.00567 \text{ u}) \times \frac{931.5 \text{ MeV}}{1 \text{ u}} = 1.20 \text{ MeV}
\]

67. (D) Assume we have in our possession 100 g of the hydrogen/tritium mixture. This sample

\[
\text{mol hydrogen} = \frac{95.00 \text{gH}}{1.008 \text{g/mol}} = 94.246 \text{mol hydrogen}
\]

\[
\text{mol tritium} = \frac{5.00 \text{gH}}{3.02 \text{g/mol}} = 1.656 \text{mol tritium}
\]

\[
\text{mole fraction tritium} = \frac{1.656 \text{mol tritium}}{1.656 \text{mol tritium} + 94.246 \text{mol hydrogen}} = 1.72 \times 10^{-2}
\]

\[
\text{total moles of gas in mixture} = \frac{PV}{RT} = \frac{(1.05 \text{atm})(4.65 \text{L})}{0.0821 \text{L atm mol}^{-1} \text{K}^{-1}(298.15 \text{K})} = 0.199 \text{ mol}
\]

will afford us 95 g hydrogen and 5 g tritium.
mols of tritium = (0.1995 mol)(1.727 x 10^{-2} mol tritium / mol mixture) = 3.445 x 10^{-3} mol tritium

# of tritium atoms (N) = (2 x 3.445 x 10^{-3} mol tritium)(6.022 x 10^{23} tritium atoms/mol) = 4.15 x 10^{21} tritium atoms

rate = \frac{0.693}{t_{1/2}} N = \frac{0.693}{12.3 \text{ y} \times 365 \text{ d} \times 24 \text{ h} \times 60 \text{ min} \times 60 \text{ s}} \times 4.15 \times 10^{21} \text{ disintegrations/s}

activity in curies = \frac{7.42 \times 10^{12} \text{ disintegrations/s}}{3.7 \times 10^{10} \text{ disintegrations/s}} = 2.0 \times 10^{3} \text{ Ci}

68. (D) energy = 1.00 \times 10^{3} \text{ cm}^{3} \times \frac{2.5 \text{ g}}{1 \text{ cm}^{3}} \times \frac{0.006 \text{ g U}}{100.000 \text{ g shale}} \times \frac{1 \text{ mol U}}{238 \text{ g U}}

\times \frac{6.022 \times 10^{23} \text{ U atoms}}{1 \text{ mol U}} \times \frac{3.20 \times 10^{-11} \text{ J}}{1 \text{ U atom}} \times \frac{1 \text{ kJ}}{1000 \text{ J}} = 1.2 \times 10^{7} \text{ kJ}

69. (D) O
R-C\overline{O}H\underline{H}O^{18}\underline{R}

versus
O
R-C\overline{O}H\underline{H}=O^{18}\underline{R}'

It is evident that the O^{18}-R' bond does not break like an OH bond (Na^+ = R'). From this labeling experiment, we see that it must be the C-O bond in the organic acid that breaks.

70. (D) 6 \text{ CO}_2(\text{g}) + 6 \text{ H}_2\text{O}^{18}(\text{l}) \rightarrow \text{C}_6\text{H}_12\text{O}_6(\text{s}) + 6 \text{ O}_2^{18} (\text{g})

6 \text{ CO}^{18}_2(\text{g}) + 6 \text{ H}_2\text{O}(\text{l}) \rightarrow \text{C}_6\text{H}_12\text{O}_6(\text{s}) + 6 \text{ O}_2(\text{g})

Basically, the results shows that the O_2 arises from the oxidation of H_2O and that the CO_2 involved in this reaction remains intact. Simplicisticly, this can be explained by using two half-reactions:

12 \text{ H}_2\text{O}^{18}(\text{l}) \rightarrow 6 \text{ O}_2^{18}(\text{g}) + 24 \text{ H}^+ + 24 \text{ e}^-

24 \text{ e}^- + 24 \text{ H}^+ + 6 \text{ CO}_2(\text{g}) \rightarrow \text{C}_6\text{H}_12\text{O}_6(\text{s}) + 6 \text{ H}_2\text{O}

6 \text{ CO}_2(\text{g}) + 6 \text{ H}_2\text{O}^{18}(\text{l}) \rightarrow \text{C}_6\text{H}_12\text{O}_6(\text{s}) + 6 \text{ O}_2^{18} (\text{g})

In reality, the reaction is not this simple, however. What this labeling study shows is that the O_2 is evolved from the oxidation of water (the only time O_2^{18}(g) forms is when H_2O^{18} is used).
71. (D) Initially \( \frac{U^{238}}{U^{235}} = 1 \) \( U^{238} t_{1/2} = 4.5 \times 10^9 \) years \( U^{235} t_{1/2} = 7.1 \times 10^8 \) years

Currently \( \frac{U^{238}}{U^{235}} = 0.9928 \)

Remember \( t_{1/2} = \frac{0.693}{\lambda} \)

Hence \( \lambda = \frac{0.693}{t_{1/2}} \)

\( \lambda_{U^{238}} = 1.54 \times 10^{-10} \)

\( \lambda_{U^{235}} = 9.76 \times 10^{-10} \)

For any radioactive isotope, the amount remaining is \( e^{-\lambda t} \).

Currently, \( \frac{e^{-\lambda t} (U^{238})}{e^{-\lambda t} (U^{235})} = 138 = \frac{e^{-1.54 \times 10^{-10} t} (U^{238})}{e^{-9.76 \times 10^{-10} t} (U^{235})} = e^{8.22 \times 10^{-10} t} = 138 \) (take ln of both sides)

\( 8.22 \times 10^{-10} t = \ln 138 = 4.927 \)

\( t = \frac{4.927}{8.22 \times 10^{-10}} = 6.0 \times 10^9 \) years

**FEATURE PROBLEMS**

72. (D) First tabulate the isotope symbols, the mass of the isotope and its associated packing fraction.

<table>
<thead>
<tr>
<th>Isotope Symbol</th>
<th>Mass of Isotope (u)</th>
<th>Packing Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>^1H</td>
<td>1.007825</td>
<td>0.007825</td>
</tr>
<tr>
<td>^4He</td>
<td>4.002603</td>
<td>0.000651</td>
</tr>
<tr>
<td>^9Be</td>
<td>9.012186</td>
<td>0.001354</td>
</tr>
<tr>
<td>^12C</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>^16O</td>
<td>15.994915</td>
<td>-0.000318</td>
</tr>
<tr>
<td>^20Ne</td>
<td>19.992440</td>
<td>-0.000378</td>
</tr>
<tr>
<td>^24Mg</td>
<td>23.985042</td>
<td>-0.000623</td>
</tr>
<tr>
<td>^32S</td>
<td>31.972074</td>
<td>-0.000873</td>
</tr>
<tr>
<td>^40Ar</td>
<td>39.962384</td>
<td>-0.000940</td>
</tr>
<tr>
<td>^40Ca</td>
<td>39.962589</td>
<td>-0.000935</td>
</tr>
<tr>
<td>^48Ti</td>
<td>47.947960</td>
<td>-0.001084</td>
</tr>
<tr>
<td>^52Cr</td>
<td>51.940513</td>
<td>-0.001144</td>
</tr>
<tr>
<td>^56Fe</td>
<td>55.934936</td>
<td>-0.001162</td>
</tr>
<tr>
<td>^58Ni</td>
<td>57.935342</td>
<td>-0.001115</td>
</tr>
<tr>
<td>^64Zn</td>
<td>63.929146</td>
<td>-0.001107</td>
</tr>
<tr>
<td>^80Se</td>
<td>79.916527</td>
<td>-0.001043</td>
</tr>
<tr>
<td>^84Kr</td>
<td>83.911503</td>
<td>-0.001054</td>
</tr>
<tr>
<td>^90Zr</td>
<td>89.904700</td>
<td>-0.001059</td>
</tr>
<tr>
<td>^102Ru</td>
<td>101.904348</td>
<td>-0.000938</td>
</tr>
<tr>
<td>^114Cd</td>
<td>113.903360</td>
<td>-0.000848</td>
</tr>
<tr>
<td>^130Te</td>
<td>129.906238</td>
<td>-0.000721</td>
</tr>
</tbody>
</table>
This graph and Fig. 25-6 are almost exactly the inverse of one another, with the maxima of one being the minima of the other. Actual nuclidic mass is often a number slightly less than the number of nucleons (mass number). This difference divided by the number of nucleons (packing fraction) is proportional to the negative of the mass defect per nucleon.

73. (D) (a) The rate of decay depends on both the half-life and the number of radioactive atoms present. In the early stages of the decay chain, the larger number of radium-226, atoms multiplied by the very small decay constant is still larger than the product of the very small number of radon-222 atoms and its much larger decay constant. Only after some time has elapsed, does the rate of decay of radon-222 approach the rate at which it is formed from radium-226 and the amount of radon-222 reaches a maximum. Beyond this point, the rate of decay of radon-222 exceeds its rate of formation.

(b) \[ \frac{dD}{dt} = \lambda_p P - \lambda_a D = \lambda_p P_0 e^{-\lambda_p t} - \lambda_a D \]

(c) The number of radon-222 atoms at the proposed times are: 2.90 \times 10^{15} atoms after 1 day; 1.26 \times 10^{16} after 1 week; 1.75 \times 10^{16} after 1 year; 1.68 \times 10^{16} after one century; and 1.13 \times 10^{16} after 1 millennium. The actual maximum comes after about 2 months, but the amount after 1 year is only slightly smaller.

74. (D) (a) Average atomic mass of Sr in the rock

Let \( x = \frac{86\text{Sr}}{86\text{Sr}} \), \( y = \frac{88\text{Sr}}{88\text{Sr}} \), \( z = \frac{87\text{Sr}}{87\text{Sr}} \), \( w = \frac{84\text{Sr}}{84\text{Sr}} \), \( x + y + z + w = 15.5 \text{ ppm} \)

Set \( x = \frac{86\text{Sr}}{86\text{Sr}} = 1 \) and find the relative atom ratio of the other

Hence, \( x = 2.25 \), \( y = 0.119 \), \( w = 0.007 \)

As a percent abundance, we find the following for the Sr in the sample.

\( \% \frac{86\text{Sr}}{86\text{Sr}} = \frac{1}{11.712} \times 100 \% = 8.538 \% \)
\( \% \frac{88\text{Sr}}{88\text{Sr}} = \frac{8.403}{11.712} \times 100 \% = 71.75 \% \)
\( \% \frac{87\text{Sr}}{87\text{Sr}} = \frac{2.25}{11.712} \times 100 \% = 19.21 \% \)
\( \% \frac{84\text{Sr}}{84\text{Sr}} = \frac{0.0588}{11.712} \times 100 \% = 0.5 \% \)
av. mass Sr = mass$^{86}$Sr (%$^{86}$Sr) + mass$^{88}$Sr (%$^{88}$Sr) + mass$^{87}$Sr (%$^{87}$Sr) + mass$^{84}$Sr (%$^{84}$Sr)

av. mass Sr = 8.538% (85.909 u) + 71.75% (87.906 u) + 19.21% (86.909 u) + 0.5% (83.913 u)

average atomic mass Sr = 7.335 u + 63.07 u + 16.695 u + 0.42 u = 87.5 u

current atom ratio is $\frac{^{87}\text{Rb}}{^{85}\text{Rb}} = 0.330$

Set 1000 atoms for $^{85}$Rb and 330 atoms $^{87}$Rb or a total of 1330 atoms of Rb

Percent abundance of each isotope: $^{85}$Rb = (1000/1330)×100% = 75.2% $^{85}$Rb

$^{87}$Rb = (1000/1330)×100% = 24.8% $^{87}$Rb

av. mass Rb = mass$^{85}$Rb (%$^{85}$Rb) + mass$^{87}$Rb (%$^{87}$Rb)

av. mass Rb = 75.2% (84.912 u) + 24.8% (86.909 u)

average atomic mass Rb = 63.85 u + 21.55 u = 85.4 u

(b) Original Rb in rock?

Need to convert atom ratio → isotope concentration in ppm.

$^{85}$Rb concentration in ppm

$= \frac{1000 \text{ atoms } ^{85}\text{Rb}}{1330 \text{ atoms Rb}} \times \frac{1 \text{ atom Rb}}{85.4 \text{ u Rb}} \times \frac{84.912 \text{ u } ^{85}\text{Rb}}{1 \text{ atom } ^{85}\text{Rb}} \times 265.4 \text{ ppm Rb} = 198.4 \text{ ppm } ^{85}\text{Rb}$

$^{87}$Rb concentration in ppm

$= \frac{330 \text{ atoms } ^{87}\text{Rb}}{1330 \text{ atoms Rb}} \times \frac{1 \text{ atom Rb}}{85.4 \text{ u Rb}} \times \frac{86.909 \text{ u } ^{87}\text{Rb}}{1 \text{ atom } ^{87}\text{Rb}} \times 265.4 \text{ ppm Rb} = 67.0 \text{ ppm } ^{87}\text{Rb}$

Currently 265.4 ppm (198.4 ppm $^{85}$Rb + 67.0 ppm $^{87}$Rb)

Recall earlier calculations showed: $\%^{86}\text{Sr} = 8.538\%$; $\%^{88}\text{Sr} = 71.75\%$;

$\%^{87}\text{Sr} = 19.21\%$; $\%^{84}\text{Sr} = 0.5\%$

Consider 100,000 atoms of Sr. Calculate the concentration (in ppm) of $^{86}$Sr and $^{87}$Sr.

$^{86}$Sr concentration in ppm

$= \frac{8538 \text{ atoms } ^{86}\text{Sr}}{100,000 \text{ atoms Sr}} \times \frac{1 \text{ atom Sr}}{87.5 \text{ u Sr}} \times \frac{85.909 \text{ u } ^{86}\text{Sr}}{1 \text{ atom } ^{86}\text{Sr}} \times 15.5 \text{ ppm Sr} = 1.299 \text{ ppm } ^{86}\text{Sr}$

$^{87}$Sr concentration in ppm

$= \frac{19,210 \text{ atoms } ^{87}\text{Sr}}{100,000 \text{ atoms Sr}} \times \frac{1 \text{ atom Sr}}{87.5 \text{ u Sr}} \times \frac{86.909 \text{ u } ^{87}\text{Sr}}{1 \text{ atom } ^{87}\text{Sr}} \times 15.5 \text{ ppm Sr} = 2.957 \text{ ppm } ^{87}\text{Sr}$

Currently: $\frac{^{87}\text{Sr}}{^{86}\text{Sr}} = 2.25 = \frac{19,210 \text{ atoms } ^{87}\text{Sr}}{8,538 \text{ atoms } ^{86}\text{Sr}}$

Originally: $\frac{^{87}\text{Sr}}{^{86}\text{Sr}} = 0.700$ or $^{87}\text{Sr} = ^{86}\text{Sr} \times 0.700 = 8,538 \times 0.700 = 5,977 \text{ atoms } ^{87}\text{Sr}$

Change in $^{87}\text{Sr} = 19,210 - 5,977 = 13,233 \text{ atoms } ^{87}\text{Sr}$ (per 100,000 Sr atoms)
Currently, 19210 per 100,000 atoms is $^{87}\text{Sr}$ which represents 2.957 ppm. A change of 13233 atoms represents $(13233/19210) \times 2.957$ ppm = 2.037 ppm $^{87}\text{Sr}$

The source of $^{87}\text{Sr}$ is radioactive decay from $^{87}\text{Rb}$ (a 1:1 relation).

Change in the $^{87}\text{Rb}$ (through radioactive decay) = change in $^{87}\text{Sr} = 2.037$ ppm

<table>
<thead>
<tr>
<th>Isotope:</th>
<th>$^{87}\text{Rb}$</th>
<th>$^{85}\text{Rb}$</th>
<th>Total Rb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current concentration</td>
<td>67.0 ppm</td>
<td>198.4 ppm</td>
<td>265.4 ppm</td>
</tr>
<tr>
<td>Change concentration</td>
<td>+2.037 ppm</td>
<td>—</td>
<td>+2.037 ppm</td>
</tr>
<tr>
<td>Original concentration</td>
<td>69.04 ppm</td>
<td>198.4 ppm</td>
<td>267.44 ppm</td>
</tr>
</tbody>
</table>

(c) $\%$ $^{87}\text{Rb}$ decayed = $\left( \frac{2.037 \text{ ppm}}{69.04 \text{ ppm}} \right) \times 100\% = 2.95\%$ ($^{87}\text{Rb}$ remaining = 97.05%)

(d) $\ln(0.9705) = -\lambda t$ ($\lambda = \frac{0.693}{t_{1/2}} = \frac{0.693}{4.8 \times 10^{10} \text{ y}} = 1.444 \times 10^{-11} \text{ y}^{-1}$)

$\ln(0.9705) = -1.444 \times 10^{-11} \text{ y}^{-1} t; \quad t = 2.07 \times 10^9 \text{ years}$

**SELF-ASSESSMENT EXERCISES**

75. (E) (a) Alpha particles are the nuclei of helium-4 atoms, $^4_2\text{He}^{2+}$, ejected spontaneously from the nuclei of certain radioactive atoms.
(b) $\beta^-$ particles are electrons, but they are electrons that originate from the nuclei of atoms in nuclear decay processes.
(c) $\beta^+$ particle, also called a positron, has properties similar to the $\beta^-$ particle, except that it carries a positive charge.
(d) Gamma ($\gamma$) rays are highly penetrating form of radiation that are undeflected by electric and magnetic fields.
(e) $t_{1/2}$ is the half-life of a reaction, i.e. a time required for the reaction to go to 50% completion.

76. (E) (a) All naturally occurring radioactive nuclides of high atomic number are members of a radioactive decay series that originates with a long-lived isotope of high atomic number and terminates with a stable isotope.
(b) A charged particle accelerator is a device that uses electric fields to propel charged particles to high speeds and to contain them in well-defined beams.
(c) The stable nuclides of low atomic numbers have a neutron-to-proton ratio of one, or nearly so. At higher atomic numbers, the neutron-to-proton ratios increase to about 1.5.
(d) The energy change accompanying a nuclear reaction can be described by using the mass–energy relationship derived by Albert Einstein: $E=mc^2$. 
(e) All life exists against a background of naturally occurring ionizing radiation-cosmic rays, ultraviolet light, and emanations from radioactive elements, such as uranium in rocks. The level of this radiation varies from point to point on Earth, being greater, for instance, at higher elevations.

77. (E) (a) Electrons are negatively charged species, whereas positrons are positive.
   (b) Half-life is the time taken for the activity of a given amount of a radioactive substance to decay to half of its initial value. Decay constant ($\lambda$) is the inverse of the mean lifetime. (c) The difference between the unbound system calculated mass and experimentally measured mass of nucleus is called mass defect. It is denoted by $\Delta m$. The amount of energy required to break the nucleus of an atom into its isolated nucleons is called nuclear binding energy.
   (d) In nuclear chemistry, nuclear fission is a nuclear reaction in which the nucleus of an atom splits into smaller parts, often producing free neutrons and lighter nuclei. Nuclear fusion, on the other hand, is the process by which multiple atomic nuclei join together to form a single heavier nucleus. It is accompanied by the release or absorption of energy.
   (e) The ionized electrons produced directly by the collisions of particles of radiation with atoms are called primary electrons. These electrons may themselves possess sufficient energies to cause secondary ionizations.

78. (E) (c)

79. (E) (b)

80. (E) (d)

81. (E) (c)

82. (E) (c)

83. (E) (d)

84. (E) (d)

85. (M) (a) $^{214}_{88}\text{Ra} \rightarrow ^{210}_{86}\text{Rn} + ^{4}_{2}\text{He}$
   (b) $^{205}_{85}\text{At} \rightarrow ^{205}_{84}\text{Po} + ^{0}_{0}\text{b}$
   (c) $^{212}_{87}\text{Fr} + ^{-1}_{0}\text{e} \rightarrow ^{212}_{86}\text{Rn}$
   (d) $^{2}_{1}\text{H} + ^{2}_{1}\text{H} \rightarrow ^{4}_{2}\text{He} + ^{0}_{0}\text{n}$
   (e) $^{241}_{95}\text{Am} + ^{4}_{2}\text{He} \rightarrow ^{243}_{97}\text{Bk} + ^{2}_{0}\text{n}$
   (f) $^{232}_{90}\text{Th} + ^{4}_{2}\text{He} \rightarrow ^{232}_{92}\text{U} + ^{4}_{0}\text{n}$
86. (M) First use the equation \( t_{1/2} = \frac{0.693}{\lambda} \) to determine \( \lambda \) from \( t_{1/2} \):
\[
\lambda = \frac{0.693}{t_{1/2}} = \frac{0.693}{11.4\text{d}} = 0.0608\text{d}^{-1}
\]
Then use the equation \( \ln \left( \frac{N_t}{N_0} \right) = -\lambda t \) with \( \frac{N_t}{N_0} = 0.01 \) and solve for \( t \):
\[
\ln(0.01) = -0.0608t \Rightarrow t = \frac{-4.605}{-0.0608} = 76\text{days}
\]

87. (M) First use the equation \( t_{1/2} = \frac{0.693}{\lambda} \) to determine \( \lambda \) from \( t_{1/2} \):
\[
\lambda = \frac{0.693}{t_{1/2}} = \frac{0.693}{87.9\text{d}} = 7.88 \times 10^{-3}\text{d}^{-1}
\]
Then use the equation \( \ln \left( \frac{N_t}{N_0} \right) = -\lambda t \) with \( \frac{N_t}{N_0} = \frac{253}{1000}, \frac{104}{1000}, \text{and} \frac{52}{1000} \) and solve for \( t \):
\[
t_a = \frac{\ln 253}{7.88 \times 10^{-3}} = 174\text{days}
\]
\[
t_b = \frac{\ln 104}{7.88 \times 10^{-3}} = 287\text{days}
\]
\[
t_c = \frac{\ln 52}{7.88 \times 10^{-3}} = 375\text{days}
\]

88. (M) (b)

89. (M) (d)

90. (M) (c)

91. (M) (a)

92. (M) (b)