Chapter 32

Nuclear Physics

Answers to Even-numbered Conceptual Questions

2. **(a)** The radius of the daughter nucleus is less than that of the original nucleus, because the daughter nucleus contains four fewer nucleons. **(b)** The radius of the daughter nucleus is the same as that of the original nucleus, because the daughter nucleus contains the same number of nucleons.

4. The difference is that in an α decay only a single particle is emitted – the α particle – and it carries the energy released by the decay. In the case of β decay, two particles are emitted – the β particle (electron) and the corresponding antineutrino. These two particles can share the energy of decay in different amounts, which accounts for the range of observed energies for the β particles. (Of course, the antineutrinos are very difficult to detect.)

6. In general, the amount of deflection is *inversely* proportional to the radius of curvature – after all, a large radius implies very little deflection. Recall, however, that the radius of curvature in a magnetic field (Equation 22-3) is directly proportional to a particle's mass and inversely proportional to its charge. Therefore, the α particle – which has twice the charge but roughly 8000 times the mass – has a larger radius of curvature by a factor of 4000. It follows that the β particle deflects by the greater amount.

8. The 14 decays in this series are as follows: α decay; β decay; β decay; α decay; α decay; α decay; α decay; β decay; β decay; α decay; α decay; β decay; α decay; β decay.

10. A change in isotope is simply a change in the number of neutrons in a nucleus. The electrons in the atom, however, respond only to the protons with their positive charge. Since electrons are responsible for chemical reactions, it follows that chemical properties are generally unaffected by a change in isotope.

12. Carbon-14 dating is useful for objects that are of biological origin and – at most – on the order of thousands of years old. Therefore, it is useful for dating human or animal remains from early civilizations. It is not useful for dating inorganic materials, like rocks, or biological materials that are millions of years old, like dinosaur fossils.

14. Above the $N = Z$ line, a nucleus contains more neutrons than protons. This helps to make the nucleus stable, by spreading out the positive charge of the protons. If a nucleus were below the $N = Z$ line, it would have more protons than neutrons, and electrostatic repulsion would blow the nucleus apart.

16. No. Fossil dinosaur skeletons represent organic material – which is necessary for carbon-14 dating – but they are thousands of times too old for the technique to be practical.

18. A radioactive sample will decrease by a factor of two in one half life, and by a factor of four in two half lives. Therefore, this sample has been in the closed container for two half lives. It follows that its half life is one day.

20. Yes. If the different isotopes have different decay rates – which is generally the case – they can still have the same activity if they are present in different amounts.

22. In two half lives, the activity of sample A will be reduced to one-quarter its initial value. The initial activity of sample B was half that of sample A, but after two half lives of sample A its activity is now one-quarter the initial activity of sample A – that is, the two samples have the same activity. It follows that the activity of sample B decreased by a factor of two in the same time that the activity of sample A decreased by a factor of four. Therefore, the half-life of sample B is twice as long as the half-life of sample A.

24. The amount of coal burned in a conventional power plant is much greater than the amount of uranium consumed in a nuclear power plant. The reason is that in a coal-powered plant, energy is released as a result of chemical reactions. In a nuclear-powered plant the reactions occur within the nucleus, and therefore they release millions of times more energy than comparable chemical reactions. As a result, much less uranium needs to be consumed for a given amount of energy production.

Solutions to Problems

1. (a) ${}^{238}_{92}\mathrm{U}$

$Z = \boxed{92}$

$N = A - Z = 238 - 92 = \boxed{146}$

$A = \boxed{238}$

(b) ${}^{239}_{94}\mathrm{Pu}$

$Z = \boxed{94}$

$N = A - Z = 239 - 94 = \boxed{145}$

$A = \boxed{239}$

(c) ${}^{144}_{60}\mathrm{Nd}$

$Z = \boxed{60}$

$N = A - Z = 144 - 60 = \boxed{84}$

$A = \boxed{144}$

2. (a) ${}^{202}_{80}\mathrm{Hg}$

$Z = \boxed{80}$

$N = A - Z = 202 - 80 = \boxed{122}$

$A = \boxed{202}$

(b) ${}^{220}_{86}\mathrm{Rn}$

$Z = \boxed{86}$

$N = A - Z = 220 - 86 = \boxed{134}$

$A = \boxed{220}$

(c) $^{93}_{41}\text{Nb}$

$Z = \boxed{41}$

$N = A - Z = 93 - 41 = \boxed{52}$

$A = \boxed{93}$

3. (a) $^{197}_{79}\text{Au}$

$r = (1.2\times10^{-15}\text{ m})A^{1/3} = (1.2\times10^{-15}\text{ m})(197)^{1/3} = \boxed{7.0\times10^{-15}\text{ m}}$

(b) $^{60}_{27}\text{Co}$

$r = (1.2\times10^{-15}\text{ m})(60)^{1/3} = \boxed{4.7\times10^{-15}\text{ m}}$

4. $r = (1.2\times10^{-15}\text{ m})A^{1/3}$

$$A = \frac{r^3}{(1.2\times10^{-15}\text{ m})^3} = \left(\frac{4.0\times10^{-15}\text{ m}}{1.2\times10^{-15}\text{ m}}\right)^3 = 37$$

$N = A - Z = 37 - 17 = \boxed{20}$

5. (a) $^{228}_{90}\text{Th}$

$$\rho = \frac{M}{V} = \frac{Am}{\frac{4}{3}\pi r^3} = \frac{228(1.67\times10^{-27}\text{ kg})}{\frac{4}{3}\pi(1.2\times10^{-15}\text{ m})^3(228)} = \boxed{2.3\times10^{17}\text{ kg/m}^3}$$

(b) $\boxed{\text{same as}}$ Nuclear density is independent of the number of nucleons in the nucleus.

(c) $$\rho = \frac{4(1.67\times10^{-27}\text{ kg})}{\frac{4}{3}\pi(1.2\times10^{-15}\text{ m})^3(4)} = \boxed{2.3\times10^{17}\text{ kg/m}^3}$$

6. (a) $$K_\text{i} = E_\text{f} = \frac{kZeq}{d} = \frac{\left(8.99\times10^9\ \frac{\text{N}\cdot\text{m}^2}{\text{C}^2}\right)(79)(2)(1.60\times10^{-19}\text{ C})^2}{35\times10^{-15}\text{ m}} = \boxed{1.0\times10^{-12}\text{ J}}$$

(b) The kinetic energy is reduced by a factor of 4. As a result, the alpha particle is unable to get as close to the gold nucleus. Since the potential energy is inversely proportional to distance, the distance of closest approach $\boxed{\text{increases by a factor of 4}}$.

7. (a) $K = \frac{1}{2}mv^2$

$$
\begin{aligned}
v &= \sqrt{\frac{2K}{m}} \\
&= \sqrt{\frac{2K}{m_{\text{He}} - 2m_e}} \\
&= \sqrt{\frac{2(0.50\text{ MeV})}{(4.002603\text{ u})\left(\frac{931.494\ \frac{\text{MeV}}{c^2}}{1\text{ u}}\right) - 2\left(0.511\ \frac{\text{MeV}}{c^2}\right)}} \\
&= c\sqrt{\frac{1.0\text{ MeV}}{3727.38\text{ MeV}}} \\
&= \left(3.00\times10^8\ \tfrac{\text{m}}{\text{s}}\right)\sqrt{\frac{1.0}{3727.38}} \\
&= \boxed{4.9\times10^6\text{ m/s}}
\end{aligned}
$$

(b) $d = \frac{kZeq}{K} = \frac{\left(8.99\times10^9\ \frac{\text{N}\cdot\text{m}^2}{\text{C}^2}\right)(79)(2)(1.60\times10^{-19}\text{ C})^2}{(0.50\times10^6\text{ eV})\left(\frac{1.60\times10^{-19}\text{ J}}{1\text{ eV}}\right)} = \boxed{450\text{ fm}}$

(c) Since $Z = 29$ for copper and $Z = 79$ for gold, the repulsive force the alpha particle experiences is much less when it approaches the copper nucleus. Thus, the distance of closest approach would be $\boxed{\text{less than}}$ that found in part (b).

8. (a) $m = \rho V = (2.3\times10^{17}\text{ kg/m}^3)\frac{4}{3}\pi(0.012\text{ m})^3 = \boxed{1.7\times10^{12}\text{ kg}}$

(b) number of marbles $= \frac{M_{\text{E}}}{m} = \frac{5.97\times10^{24}\text{ kg}}{1.66\times10^{12}\text{ kg}} = \boxed{3.6\times10^{12}}$

9. ${}^{30}_{15}\text{P}$

(a) $r = (1.2\times10^{-15}\text{ m})(30)^{1/3} = \boxed{3.7\text{ fm}}$

(b) Since the mass number is proportional to the radius cubed, doubling the radius requires $2^3 = 8$ times the mass number. So, $A = 8(30) = \boxed{240}$.

(c)

$$
\begin{aligned}
2(1.2\times10^{-15}\text{ m})(30)^{1/3} &= (1.2\times10^{-15}\text{ m})A^{1/3} \\
A^{1/3} &= 2(30)^{1/3} \\
A &= 8(30) \\
&= \boxed{240}
\end{aligned}
$$

10. (a) Since the mass number is proportional to the radius cubed, doubling the radius requires $2^3 = 8$ times the mass number.
(4)(8) = $\boxed{32}$

(b) $\boxed{{}^{32}_{15}\text{P}}$

11. (a) When the volume is reduced by a factor of 2, the radius becomes $\sqrt[3]{(1/2)} \approx 0.8$ times the initial radius. So the new radius is $\boxed{\text{more than}}$ one-half the original radius.

(b) $r = (1.2\times10^{-15}\text{ m})(236)^{1/3} = \boxed{7.4\times10^{-15}\text{ m}}$

(c) $r = (1.2\times10^{-15}\text{ m})(118)^{1/3} = \boxed{5.9\times10^{-15}\text{ m}}$

12. (a) $A = \dfrac{M}{m} = \dfrac{\frac{W}{g}}{m} = \dfrac{W}{mg} = \dfrac{(1\text{ lb})\left(\frac{4.448\text{ N}}{\text{lb}}\right)}{(1.67\times10^{-27}\text{ kg})\left(9.81\ \frac{\text{m}}{\text{s}^2}\right)} = \boxed{3\times10^{26}\text{ nucleons}}$

(b) $r = (1.2\times10^{-15}\text{ m})A^{1/3} = (1.2\times10^{-15}\text{ m})(3\times10^{26})^{1/3} = \boxed{800\text{ nm}}$

13. ${}^{7}_{3}\text{Li} + {}^{1}_{1}\text{H} \rightarrow {}^{4}_{2}\text{He} + \boxed{{}^{4}_{2}\text{He}}$

14. ${}^{234}_{90}\text{Th} \rightarrow {}^{230}_{88}\text{Ra} + \boxed{{}^{4}_{2}\text{He}}$

15. $\boxed{{}^{14}_{6}\text{C}} \rightarrow {}^{14}_{7}\text{N} + \text{e}^- + \bar{\upsilon}$

16. $\boxed{{}^{3}_{1}\text{H} \rightarrow {}^{3}_{2}\text{He} + \text{e}^- + \bar{\upsilon}}$
$m_\text{i} = 3.016049\text{ u}$
$m_\text{f} = 3.016029\text{ u}$
$\Delta m = m_\text{f} - m_\text{i} = 3.016029\text{ u} - 3.016049\text{ u} = -0.000020\text{ u}$

$$E = |\Delta m|c^2 = (0.000020\text{ u})\left(\frac{931.494\ \frac{\text{MeV}}{c^2}}{1\text{ u}}\right)c^2 = \boxed{19\text{ keV}}$$

17. (a) $\boxed{{}^{212}_{84}\text{Po} \rightarrow {}^{208}_{82}\text{Pb} + {}^{4}_{2}\text{He}}$
$m_\text{i} = 211.988852\text{ u}$
$m_\text{f} = 207.97664\text{ u} + 4.002603\text{ u} = 211.97924\text{ u}$
$\Delta m = m_\text{f} - m_\text{i} = 211.97924\text{ u} - 211.988852\text{ u} = -0.00961\text{ u}$

$$E = |\Delta m|c^2 = (0.00961\text{ u})\left(\frac{931.494\ \frac{\text{MeV}}{c^2}}{1\text{ u}}\right)c^2 = \boxed{8.95\text{ MeV}}$$

(b) $\boxed{{}^{239}_{94}\text{Pu} \to {}^{235}_{92}\text{U} + {}^{4}_{2}\text{He}}$

$m_\text{i} = 239.052158\text{ u}$
$m_\text{f} = 235.043925\text{ u} + 4.002603\text{ u} = 239.046528\text{ u}$
$\Delta m = m_\text{f} - m_\text{i} = 239.046528\text{ u} - 239.052158\text{ u} = -0.005630\text{ u}$

$$E = |\Delta m|c^2 = (0.005630\text{ u})\left(\frac{931.494\ \frac{\text{MeV}}{c^2}}{1\text{ u}}\right)c^2 = \boxed{5.244\text{ MeV}}$$

18. (a) $\boxed{{}^{35}_{16}\text{S} \to {}^{35}_{17}\text{Cl} + \text{e}^- + \bar{\upsilon}}$

$m_\text{i} = 34.969033\text{ u}$
$m_\text{f} = 34.968853\text{ u}$
$\Delta m = 34.968853\text{ u} - 34.969033\text{ u} = -0.000180\text{ u}$

$$E = |\Delta m|c^2 = (0.000180\text{ u})\left(\frac{931.494\ \frac{\text{MeV}}{c^2}}{1\text{ u}}\right)c^2 = \boxed{168\text{ keV}}$$

(b) $\boxed{{}^{212}_{82}\text{Pb} \to {}^{212}_{83}\text{Bi} + \text{e}^- + \bar{\upsilon}}$

$m_\text{i} = 211.99188\text{ u}$
$m_\text{f} = 211.991272\text{ u}$
$\Delta m = 211.991272\text{ u} - 211.99188\text{ u} = -0.00061\text{ u}$

$$E = |\Delta m|c^2 = (0.00061\text{ u})\left(\frac{931.494\ \frac{\text{MeV}}{c^2}}{1\text{ u}}\right)c^2 = \boxed{570\text{ keV}}$$

19. (a) $\boxed{{}^{18}_{9}\text{F} \to {}^{18}_{8}\text{O} + \text{e}^+ + \upsilon}$

$m_\text{i} = 18.000938\text{ u}$
$m_\text{f} = 17.999159\text{ u} + 2(5.49\times10^{-4}\text{ u})$
$\Delta m = 18.000257\text{ u} - 18.000938\text{ u} = -6.81\times10^{-4}\text{ u}$

$$E = |\Delta m|c^2 = (6.81\times10^{-4}\text{ u})\left(\frac{931.494\ \frac{\text{MeV}}{c^2}}{1\text{ u}}\right)c^2 = \boxed{0.634\text{ MeV}}$$

(b) $\boxed{{}^{22}_{11}\text{Na} \to {}^{22}_{10}\text{Ne} + \text{e}^+ + \upsilon}$

$m_\text{i} = 21.994435\text{ u}$
$m_\text{f} = 21.991384\text{ u} + 2(5.49\times10^{-4}\text{ u})$
$\Delta m = 21.992482\text{ u} - 21.994435\text{ u} = -0.001953\text{ u}$

$$E = |\Delta m|c^2 = (0.001953\text{ u})\left(\frac{931.494\ \frac{\text{MeV}}{c^2}}{1\text{ u}}\right)c^2 = \boxed{1.819\text{ MeV}}$$

20. $^{211}_{82}\text{Pb} \rightarrow {}^{211}_{83}\text{Bi} + \text{e}^- + \bar{\upsilon}$

$m_\text{i} = 210.98874\text{ u}$

$m_\text{f} = 210.98726\text{ u}$

$\Delta m = 210.98726\text{ u} - 210.98874\text{ u} = -0.00148\text{ u}$

$$E = |\Delta m| c^2 = (0.00148\text{ u})\left(\frac{931.494\ \frac{\text{MeV}}{c^2}}{1\text{ u}}\right)c^2 = \boxed{1.38\text{ MeV}}$$

21. **(a)** $^{66}_{28}\text{Ni} \rightarrow \boxed{^{66}_{29}\text{Cu}} + \text{e}^- + \bar{\upsilon}$

(b) $E = |\Delta m| c^2 = (65.9291\text{ u} - 65.9289\text{ u})\left(\frac{931.494\ \frac{\text{MeV}}{c^2}}{1\text{ u}}\right)c^2 = \boxed{0.2\text{ MeV}}$

22. $N = \frac{1}{2}N_0 = N_0 e^{-\lambda t}$

$$\frac{1}{2} = e^{-\lambda t}$$

$$e^{\lambda t} = 2$$

$$\lambda = \frac{\ln 2}{t} = \frac{\ln 2}{3.82\text{ d}} = \boxed{0.181\text{ d}^{-1}}$$

23. $N = \frac{1}{2}N_0 = N_0 e^{-\lambda T_{1/2}}$

$$\frac{1}{2} = e^{-\lambda T_{1/2}}$$

$$\ln\frac{1}{2} = -\lambda T_{1/2}$$

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{\ln 2}{8.9\times 10^{-3}\text{ s}^{-1}} = \boxed{78\text{ s}}$$

24. $N = \frac{1}{16}N_0 = N_0 e^{-\lambda t}$

$$\frac{1}{16} = e^{-\lambda t}$$

$$e^{\lambda t} = 16$$

$$\lambda = \frac{\ln 16}{t} = \frac{\ln 16}{15\text{ d}}$$

$$\begin{aligned} N &= \frac{1}{2}N_0 = N_0 e^{-\lambda T_{1/2}} \\ \frac{1}{2} &= e^{-\lambda T_{1/2}} \\ e^{\lambda T_{1/2}} &= 2 \\ T_{1/2} &= \frac{\ln 2}{\lambda} \\ &= (\ln 2)\left(\frac{15\text{ d}}{\ln 16}\right) \\ &= \boxed{3.8\text{ d}} \end{aligned}$$

25.

$$\begin{aligned} \frac{1}{2} &= e^{-\lambda T_{1/2}} \\ e^{\lambda T_{1/2}} &= 2 \\ \lambda &= \frac{\ln 2}{T_{1/2}} \\ &= \frac{\ln 2}{122\text{ s}} \\ N &= (10^{-4})N_0 = N_0 e^{-\lambda t} \\ 10^{-4} &= e^{-\lambda t} \\ e^{\lambda t} &= 10^4 \\ t &= \frac{\ln 10^4}{\lambda} \\ &= (4\ln 10)\left(\frac{122\text{ s}}{\ln 2}\right) \\ &= \boxed{27.0\text{ min}} \end{aligned}$$

26. (a) $\lambda = \dfrac{\ln 2}{T_{1/2}}$

$$R = \lambda N = \frac{\ln 2}{T_{1/2}}N = \frac{\ln 2}{8.04\text{ d}}(4.5\times 10^{16})\left(\frac{1\text{ d}}{86{,}400\text{ s}}\right)\left(\frac{1\text{ Ci}}{3.7\times 10^{10}\ \frac{\text{decays}}{\text{s}}}\right) = \boxed{1.2\text{ Ci}}$$

(b) Since R is inversely proportional to $T_{1/2}$, halving $T_{1/2}$ would double R. So, R would be $\boxed{\text{increased}}$.

(c) $R' = \dfrac{\ln 2}{\frac{T_{1/2}}{2}}N = \dfrac{2\ln 2}{T_{1/2}}N = 2R$

$$\frac{R'}{R} = \boxed{2}$$

27. (a) $\lambda = \dfrac{\ln 2}{T_{1/2}} = \dfrac{\ln 2}{6.05\text{ h}} = \boxed{0.115\text{ h}^{-1}}$

(b) $N = \dfrac{R}{\lambda} = \left(\dfrac{6.05\text{ h}}{\ln 2}\right)(1.50\times10^{-6}\text{ Ci})\left(\dfrac{3600\text{ s}}{\text{h}}\right)\left(\dfrac{3.7\times10^{10}\ \frac{\text{decays}}{\text{s}}}{1\text{ Ci}}\right) = \boxed{1.7\times10^{9}\text{ nuclei}}$

28. $\lambda = \dfrac{\ln 2}{T_{1/2}} = \dfrac{\ln 2}{6.05\text{ h}}$

$N_0 = 1.744\times10^{9}$ nuclei (where two additional significant digits were kept for accuracy)

$R = \lambda N_0 e^{-\lambda t} = \left(\dfrac{\ln 2}{6.05\text{ h}}\right)(1.744\times10^{9})\left(\dfrac{1\text{ h}}{3600\text{ s}}\right)e^{-(\ln 2/6.05\text{ h})(1.25\text{ h})}\left(\dfrac{1\text{ Ci}}{3.7\times10^{10}\ \frac{\text{decays}}{\text{s}}}\right) = \boxed{1.3\ \mu\text{Ci}}$

29. $\lambda = \dfrac{\ln 2}{T_{1/2}} = \dfrac{\ln 2}{5730\text{ y}}$

$0.0925N_0 = N_0 e^{-\lambda t}$

$e^{\lambda t} = \dfrac{1}{0.0925}$

$t = \dfrac{-\ln 0.0925}{\lambda}$

$= -(\ln 0.0925)\left(\dfrac{5730\text{ y}}{\ln 2}\right)$

$= \boxed{19{,}700\text{ y}}$

30. $t = \dfrac{1}{\lambda}\ln\dfrac{R_0}{R} = \dfrac{T_{1/2}}{\ln 2}\ln\dfrac{R_0}{R} = \dfrac{5730\text{ y}}{\ln 2}\ln\dfrac{1}{0.150} = \boxed{15{,}700\text{ y}}$

31. $t = \dfrac{1}{\lambda}\ln\dfrac{R_0}{R} = \dfrac{T_{1/2}}{\ln 2}\ln\dfrac{R_0}{R} = \dfrac{5730\text{ y}}{\ln 2}\ln\dfrac{1}{0.175} = \boxed{14{,}400\text{ y}}$

32. $m = \dfrac{198}{N_\text{A}}N = \dfrac{198}{N_\text{A}}\left(\dfrac{R}{\lambda}\right) = \dfrac{198R}{N_\text{A}}\left(\dfrac{T_{1/2}}{\ln 2}\right) = \dfrac{198(225\text{ Ci})(2.70\text{ d})}{(6.02\times10^{23}\text{ g}^{-1})\ln 2}\left(\dfrac{86{,}400\text{ s}}{\text{d}}\right)\left(\dfrac{3.7\times10^{10}\ \frac{\text{decays}}{\text{s}}}{\text{Ci}}\right) = \boxed{0.92\text{ mg}}$

33. $t = \dfrac{1}{\lambda}\ln\dfrac{R_0}{R} = \dfrac{T_{1/2}}{\ln 2}\ln\dfrac{R_0}{R} = \dfrac{432\text{ y}}{\ln 2}\ln 500 = \boxed{4000\text{ y}}$

34. $\dfrac{N}{N_0} = e^{-\lambda t} = e^{-(\ln 2/T_{1/2})t} = e^{-(\ln 2/28.8\text{ y})t}$

(a) $e^{-(\ln 2/28.8\text{ y})(50.0\text{ y})} = 0.300 = \boxed{30.0\%}$

(b) $e^{-(\ln 2/28.8\text{ y})(60.0\text{ y})} = 0.236 = \boxed{23.6\%}$

(c) $e^{-(\ln 2/28.8\text{ y})(70.0\text{ y})} = 0.185 = \boxed{18.5\%}$

35. $^{197}_{79}\text{Au}$

$m_\text{i} = 196.96654\text{ u}$

$m_\text{f} = (79)(1.007825\text{ u}) + (118)(1.008665\text{ u}) = 198.640645\text{ u}$

$\Delta m = 1.67411\text{ u}$

$$E = \Delta mc^2 = (1.67411\text{ u})\left(\frac{931.494\ \frac{\text{MeV}}{c^2}}{1\text{ u}}\right)c^2 = \boxed{1559.42\text{ MeV}}$$

36. $^{7}_{3}\text{Li}$

$m_\text{i} = 7.01435\text{ u}$

$m_\text{f} = (3)(1.007825\text{ u}) + (4)(1.008665\text{ u}) = 7.058135\text{ u}$

$\Delta m = 0.04379\text{ u}$

$$E = \Delta mc^2 = (0.04379\text{ u})\left(\frac{931.494\ \frac{\text{MeV}}{c^2}}{1\text{ u}}\right)c^2 = \boxed{40.79\text{ MeV}}$$

37. (a) $^{56}_{26}\text{Fe}$

$m_\text{i} = 55.934939\text{ u}$

$m_\text{f} = 26(1.007825\text{ u}) + 30(1.008665\text{ u}) = 56.463400\text{ u}$

$\Delta m = 56.463400\text{ u} - 55.934939\text{ u} = 0.528461\text{ u}$

$$\frac{E}{56} = \frac{|\Delta m|c^2}{56} = \frac{(0.528461\text{ u})\left(\frac{931.494\ \frac{\text{MeV}}{c^2}}{1\text{ u}}\right)c^2}{56} = \boxed{8.79033\text{ MeV/nucleon}}$$

(b) $^{238}_{92}\text{U}$

$m_\text{i} = 238.050786\text{ u}$

$m_\text{f} = 92(1.007825\text{ u}) + 146(1.008665\text{ u}) = 239.984990\text{ u}$

$\Delta m = 239.984990\text{ u} - 238.050786\text{ u} = 1.934204\text{ u}$

$$\frac{E}{238} = \frac{|\Delta m|c^2}{238} = \frac{(1.934204\text{ u})\left(\frac{931.494\ \frac{\text{MeV}}{c^2}}{1\text{ u}}\right)c^2}{238} = \boxed{7.57017\text{ MeV/nucleon}}$$

38. (a) $^{4}_{2}\text{He}$

$m_\text{i} = 4.002603\text{ u}$

$m_\text{f} = 2(1.007825\text{ u}) + 2(1.008665\text{ u}) = 4.032980\text{ u}$

$\Delta m = 4.032980\text{ u} - 4.002603\text{ u} = 0.030377\text{ u}$

$$\frac{E}{4} = \frac{|\Delta m|c^2}{4} = \frac{(0.030377\text{ u})\left(\frac{931.494\ \frac{\text{MeV}}{c^2}}{1\text{ u}}\right)c^2}{4} = \boxed{7.0740\text{ MeV/nucleon}}$$

(b) ${}^{64}_{30}\text{Zn}$

$m_\text{i} = 63.929145\text{ u}$

$m_\text{f} = 30(1.007825\text{ u}) + 34(1.008665\text{ u}) = 64.529360\text{ u}$

$\Delta m = 64.529360\text{ u} - 63.929145\text{ u} = 0.600215\text{ u}$

$$\frac{E}{64} = \frac{|\Delta m|c^2}{64} = \frac{(0.600215\text{ u})\left(\frac{931.494\ \frac{\text{MeV}}{c^2}}{1\text{ u}}\right)c^2}{64} = \boxed{8.73589\text{ MeV/nucleon}}$$

39. ${}^{16}_{8}\text{O} + \text{energy} \rightarrow {}^{15}_{8}\text{O} + {}^{1}_{0}\text{n}$

$m_\text{i} = 15.994915\text{ u}$

$m_\text{f} = 15.003065\text{ u} + 1.008665\text{ u} = 16.011730\text{ u}$

$\Delta m = 16.011730\text{ u} - 15.994915\text{ u} = 0.016815\text{ u}$

$$E = |\Delta m|c^2 = (0.016815\text{ u})\left(\frac{931.494\ \frac{\text{MeV}}{c^2}}{1\text{ u}}\right)c^2 = \boxed{15.663\text{ MeV}}$$

40. (a) ${}^{16}_{8}\text{O} + \text{energy} \rightarrow {}^{15}_{7}\text{N} + {}^{1}_{1}\text{H}$

$m_\text{i} = 15.994915\text{ u}$

$m_\text{f} = 15.000109\text{ u} + 1.007825\text{ u} = 16.007934\text{ u}$

$\Delta m = 16.007934\text{ u} - 15.994915\text{ u} = 0.013019\text{ u}$

$$E = |\Delta m|c^2 = (0.013019\text{ u})\left(\frac{931.494\ \frac{\text{MeV}}{c^2}}{1\text{ u}}\right)c^2 = \boxed{12.127\text{ MeV}}$$

(b) ${}^{16}_{8}\text{O} + \text{energy} \rightarrow {}^{15}_{8}\text{O} + {}^{1}_{0}\text{n}$

$m_\text{i} = 15.994915\text{ u}$

$m_\text{f} = 15.003065\text{ u} + 1.008665\text{ u} = 16.011730\text{ u}$

$\Delta m = 16.011730\text{ u} - 15.994915\text{ u} = 0.016815\text{ u}$

$$E = |\Delta m|c^2 = (0.016815\text{ u})\left(\frac{931.494\ \frac{\text{MeV}}{c^2}}{1\text{ u}}\right)c^2 = \boxed{15.663\text{ MeV}}$$

(c) The neutron is more tightly bound than the proton because the proton is repulsed by the other protons in the nucleus. The fact that the energy required to remove the neutron is more than that required to remove the proton is verification that the neutron is more tightly bound.

41. ${}^{1}_{0}\text{n} + {}^{235}_{92}\text{U} \rightarrow {}^{132}_{50}\text{Sn} + {}^{101}_{42}\text{Mo} + \text{neutrons}$

Sn neutrons = 132 −50 = 82

Mo neutrons = 101 − 42 = 59

U neutrons = 235 − 92 = 143

neutrons released = 1 + 143 − 82 − 59 = $\boxed{3}$

42. ${}^{1}_{0}\text{n} + {}^{235}_{92}\text{U} \to {}^{133}_{51}\text{Sb} + ? + 5\,{}^{1}_{0}\text{n}$

U neutrons = 235 – 92 = 143
Sb neutrons = 133 – 51 = 82
$Z = 92 - 51 = 41$
$N = 1 + 143 - 82 - 5 = 57$
$A = 41 + 57 = 98$
The missing atom is $\boxed{{}^{98}_{41}\text{Nb}}$.

$m_\text{i} = 1.008665\text{ u} + 235.043925\text{ u} = 236.052590\text{ u}$
$m_\text{f} = 132.915237\text{ u} + 97.910331\text{ u} + 5(1.008665\text{ u}) = 235.868893\text{ u}$
$\Delta m = 235.868893\text{ u} - 236.052590\text{ u} = -0.183697\text{ u}$

$$E = |\Delta m|c^2 = (0.183697\text{ u})\left(\frac{931.494\ \frac{\text{MeV}}{c^2}}{1\text{ u}}\right)c^2 = \boxed{171.113\text{ MeV}}$$

43. ${}^{1}_{0}\text{n} + {}^{235}_{92}\text{U} \to {}^{88}_{38}\text{Sr} + {}^{136}_{54}\text{Xe} + \text{neutrons}$

U neutrons = 235 – 92 = 143
Sr neutrons = 88 – 38 = 50
Xe neutrons = 136 – 54 = 82
neutrons released = 1 + 143 – 50 – 82 = 12
The complete reaction is $\boxed{{}^{1}_{0}\text{n} + {}^{235}_{92}\text{U} \to {}^{88}_{38}\text{Sr} + {}^{136}_{54}\text{Xe} + 12\,{}^{1}_{0}\text{n}}$.

$m_\text{i} = 1.008665\text{ u} + 235.043925\text{ u} = 236.052590\text{ u}$
$m_\text{f} = 87.905625\text{ u} + 135.90722\text{ u} + 12(1.008665\text{ u}) = 235.91683\text{ u}$
$\Delta m = 235.91683\text{ u} - 236.052590\text{ u} = -0.13576\text{ u}$

$$E = |\Delta m|c^2 = (0.13576\text{ u})\left(\frac{931.494\ \frac{\text{MeV}}{c^2}}{1\text{ u}}\right)c^2 = \boxed{126.46\text{ MeV}}$$

44. N = number of gallons of gas
Set NE_gas = the total energy released by 1 lb of ${}^{235}_{92}\text{U}$.

$$NE_\text{gas} = \frac{m_\text{U}}{M_\text{U}}E_\text{U}$$

$$N = \frac{m_\text{U}E_\text{U}}{M_\text{U}E_\text{gas}}$$

$$= \frac{(1\text{ lb})\left(\frac{1\text{ kg}}{2.2\text{ lb}}\right)(173\text{ MeV})\left(\frac{1.60\times10^{-19}\text{ J}}{1\text{ eV}}\right)}{(235.043925\text{ u})\left(\frac{1.66\times10^{-27}\text{ kg}}{1\text{ u}}\right)(2\times10^{8}\text{ J})}$$

$$= \boxed{2\times10^{5}\text{ gallons of gas}}$$

45. $m = \left({}^{235}_{92}\text{U mass}\right)\dfrac{\text{total energy}}{\text{energy per reaction}}$

$$= (235.043925\text{ u})\left(\frac{1.66\times10^{-27}\text{ kg}}{1\text{ u}}\right)\frac{8.4\times10^{19}\text{ J}}{(173\times10^{6}\text{ eV})\left(\frac{1.60\times10^{-19}\text{ J}}{1\text{ eV}}\right)}$$

$$= \boxed{1.2\times10^{6}\text{ kg}}$$

46. number of reactions per second $= \dfrac{\text{power output}}{\text{energy per reaction}}$

$$= \frac{150\times10^{6}\text{ W}}{(173\times10^{6}\text{ eV})\left(\frac{1.60\times10^{-19}\text{ J}}{\text{eV}}\right)}$$

$$= \boxed{5.4\times10^{18}\text{ reactions/s}}$$

47. ${}^{2}_{1}\text{H} + {}^{2}_{1}\text{H} \rightarrow {}^{3}_{1}\text{H} + {}^{1}_{1}\text{H}$

$m_\text{i} = 2(2.014102\text{ u}) = 4.028204\text{ u}$

$m_\text{f} = 3.016049\text{ u} + 1.007825\text{ u} = 4.023874\text{ u}$

$\Delta m = 4.023874 - 4.028204\text{ u} = -0.004330\text{ u}$

$$E = |\Delta m|c^2 = (0.004330\text{ u})\left(\frac{931.494\ \frac{\text{MeV}}{c^2}}{1\text{ u}}\right)c^2 = \boxed{4.033\text{ MeV}}$$

48. ${}^{1}_{1}\text{H} + {}^{1}_{0}\text{n} \rightarrow {}^{2}_{1}\text{H}$

$m_\text{i} = 1.007825\text{ u} + 1.008665\text{ u} = 2.016490\text{ u}$

$m_\text{f} = 2.014102\text{ u}$

$\Delta m = 2.014102\text{ u} - 2.016490\text{ u} = -0.002388\text{ u}$

$$E = |\Delta m|c^2 = (0.002388\text{ u})\left(\frac{931.494\ \frac{\text{MeV}}{c^2}}{1\text{ u}}\right)c^2 = \boxed{2.224\text{ MeV}}$$

49. ${}^{1}_{1}\text{H} + {}^{2}_{1}\text{H} \rightarrow {}^{3}_{2}\text{He} + \gamma$

$m_\text{i} = 1.007825\text{ u} + 2.014102\text{ u} = 3.021927\text{ u}$

$m_\text{f} = 3.016029\text{ u}$

$\Delta m = 3.016029\text{ u} - 3.021927\text{ u} = -0.005898\text{ u}$

$$E = |\Delta m|c^2 = (0.005898\text{ u})\left(\frac{931.494\ \frac{\text{MeV}}{c^2}}{1\text{ u}}\right)c^2 = \boxed{5.494\text{ MeV}}$$

50. **(a)** ${}^{2}_{1}\text{H}+{}^{3}_{1}\text{H}\rightarrow ?+{}^{1}_{0}\text{n}$

$Z=1+1-0=2$

$N=2-1+3-1-1=2$

$A=2+3-1=4$

The complete reaction is $\boxed{{}^{2}_{1}\text{H}+{}^{3}_{1}\text{H}\rightarrow {}^{4}_{2}\text{He}+{}^{1}_{0}\text{n}}$.

$$E=|\Delta m|c^2=|4.002603\text{ u}+1.008665\text{ u}-2.014102\text{ u}-3.016049\text{ u}|\left(\frac{931.494\ \frac{\text{MeV}}{c^2}}{1\text{ u}}\right)c^2=\boxed{17.589\text{ MeV}}$$

(b) $\left(\frac{\text{energy}}{\text{reaction}}\right)\left(\frac{\text{reactions}}{\text{second}}\right)=P$

$$\frac{\text{reactions}}{\text{second}}=P\left(\frac{\text{energy}}{\text{reaction}}\right)^{-1}=(25\times10^{6}\text{ W})\left[(17.589\times10^{6}\text{ eV})\left(\frac{1.60\times10^{-19}\text{ J}}{1\text{ eV}}\right)\right]^{-1}=\boxed{8.9\times10^{18}\text{ reactions/s}}$$

51. $P_{\text{Sun}}=3.90\times10^{26}\text{ W}$

(a) $$\frac{\Delta m}{\Delta t}=\frac{P_{\text{Sun}}}{c^2}=\frac{3.90\times10^{26}\text{ W}}{\left(3.00\times10^{8}\ \frac{\text{m}}{\text{s}}\right)^2}=\boxed{4.33\times10^{9}\text{ kg/s}}$$

(b) mass burned = m

initial mass = M_0

current mass = M

$\frac{M_0-M}{M_0}\times100\%$ = percentage of the original mass converted to energy

$$M_0=M+m=M+\frac{\Delta m}{\Delta t}t$$

$$\frac{M_0-M}{M_0}=\frac{\frac{\Delta m}{\Delta t}t}{M+\frac{\Delta m}{\Delta t}t}=\frac{1}{1+\frac{M}{t}\left(\frac{\Delta m}{\Delta t}\right)^{-1}}=\frac{1}{1+\left(\frac{2.00\times10^{30}\text{ kg}}{4.50\times10^{9}\text{ y}}\right)\left(\frac{1\text{ y}}{3.1536\times10^{7}\text{ s}}\right)\left(4.33\times10^{9}\ \frac{\text{kg}}{\text{s}}\right)^{-1}}=3.07\times10^{-4}$$

Approximately $\boxed{0.0307\%}$ of the Sun's original mass has been converted to energy.

52. Dose in rem due to α = Dose in rad × RBE = (52 rad)(20)

Dose in rad due to protons $=\frac{(52\text{ rad})(20)}{10}=\boxed{100\text{ rad}}$

53. Dose in rem due to heavy ions = (50 rad)(20)

Dose in rad due to X-rays $=\frac{(50\text{ rad})(20)}{1}=\boxed{1000\text{ rad}}$

54. **(a)** Dose in rad $=\frac{52\times10^{-3}\text{ rem}}{15}$

$$E=(\text{Dose in rad})m=\left(\frac{52\times10^{-3}\text{ rem}}{15}\right)\left(\frac{1\text{ J}}{100\times0.01\text{ J}}\right)(68\text{ kg})=\boxed{2.4\text{ mJ}}$$

(b) Since the energy absorbed is inversely proportional to the RBE, the energy absorbed will $\boxed{\text{decrease}}$ if the RBE is increased.

55. (a) $E = (\text{Dose in rad})m = (215\text{ rad})(0.17\text{ kg})\left(\dfrac{1\text{ J}}{100\times 0.01\text{ J}}\right) = \boxed{0.37\text{ J}}$

(b) $\Delta T = \dfrac{Q}{mc} = \dfrac{E}{mc} = \dfrac{(215\text{ rad})(0.17\text{ kg})\left(\frac{1\text{ J}}{100\times 0.01\text{ J}}\right)}{(0.17\text{ kg})\left(4186\ \frac{\text{J}}{\text{kg}\cdot\text{K}}\right)} = \boxed{0.51\text{ mK}}$

56. (a) $\text{Dose in rem} = (\text{Dose in rad})(\text{RBE}) = (32\times 10^{-3}\text{ rad})(13) = \boxed{0.42\text{ rem}}$

(b) $E = (\text{Dose in rad})m = (32\times 10^{-3}\text{ rad})(66\text{ kg})\left(\dfrac{1\text{ J}}{100\times 0.01\text{ J}}\right) = \boxed{21\text{ mJ}}$

57. (a) Number of electrons = Number of ${}^{32}_{15}\text{P}$ decayed

$$
\begin{aligned}
&= N_0 - N \\
&= N_0 - N_0 e^{-\lambda t} \\
&= N_0(1-e^{-\lambda t}) \\
&= \frac{R_0}{\lambda}(1-e^{-\lambda t}) \\
&= R_0\left(\frac{T_{1/2}}{\ln 2}\right)\left[1-e^{-\left(\frac{\ln 2}{14.28\text{ d}}\right)(7\text{ d})}\right] \\
&= \left(1.34\times 10^{6}\ \frac{\text{decays}}{\text{s}}\right)\frac{(14.28\text{ d})\left(\frac{86{,}400\text{ s}}{1\text{ d}}\right)}{\ln 2}\left[1-e^{-\left(\frac{\ln 2}{14.28\text{ d}}\right)(7\text{ d})}\right] \\
&= \boxed{7\times 10^{11}\text{ electrons}}
\end{aligned}
$$

(b) $E = \left(705\times 10^{3}\ \dfrac{\text{eV}}{\text{electron}}\right)(7\times 10^{11}\text{ electrons}) = \boxed{5\times 10^{17}\text{ eV}}$

(c)

$$
\begin{aligned}
\text{dose in rem} &= (\text{dose in rad})(\text{RBE}) \\
&= (\text{Energy in } 0.01\text{ J/kg})(\text{RBE}) \\
&= \frac{(5\times 10^{17}\text{ eV})\left(\frac{1.60\times 10^{-19}\text{ J}}{1\text{ eV}}\right)(100)}{0.125\text{ kg}}(1.50) \\
&= \boxed{100\text{ rem}}
\end{aligned}
$$

58. (a) ${}^{232}_{90}\text{Th}$

neutrons = 232 – 90 = $\boxed{142}$
protons = $\boxed{90}$

(b) ${}^{211}_{82}\text{Pb}$

neutrons = 211 – 82 = $\boxed{129}$
protons = $\boxed{82}$

(c) $^{60}_{27}\text{Co}$

neutrons = 60 – 27 = $\boxed{33}$

protons = $\boxed{27}$

59. (a) $^{210}_{82}\text{Pb} \rightarrow {}^{A}_{Z}\text{X} + {}^{4}_{2}\text{He}$

$A = 210 - 4 = 206$

$Z = 82 - 2 = 80$

$^{A}_{Z}\text{X} = {}^{206}_{80}\text{X} = \boxed{^{206}_{80}\text{Hg}}$

(b) $^{239}_{92}\text{U} \rightarrow {}^{A}_{Z}\text{X} + \text{e}^{-} + \bar{\upsilon}$

$A = 239 - 0 = 239$

$Z = 92 - (-1) = 93$

$^{A}_{Z}\text{X} = {}^{239}_{93}\text{X} = \boxed{^{239}_{93}\text{Np}}$

(c) $^{11}_{6}\text{C} \rightarrow {}^{A}_{Z}\text{X} + \text{e}^{+} + \upsilon$

$A = 11 - 0 = 11$

$Z = 6 - 1 = 5$

$^{A}_{Z}\text{X} = {}^{11}_{5}\text{X} = \boxed{^{11}_{5}\text{B}}$

60. Dose in rem due to alpha = Dose in rad × RBE

$$\text{Dose in rad} = \frac{3500\text{ rem}}{10\text{ to }20} = \boxed{175\text{ rad to }350\text{ rad}}$$

61. For gamma rays, RBE = 1.

Dose in rem = Dose in rad × RBE

= (250)(1)

= $\boxed{250\text{ rem}}$

62. (a) $$t = -\frac{1}{\lambda}\ln\frac{R}{R_0} = -\frac{T_{1/2}}{\ln 2}\ln\frac{R}{R_0} = -\frac{1.20\times10^9\text{ y}}{\ln 2}\ln 0.195 = \boxed{2.83\times10^9\text{ y}}$$

(b) $$t = -\frac{1.20\times10^9\text{ y}}{\ln 2}\ln 0.100 = 3.99\times10^9\text{ y}$$

$$\Delta t = 3.99\times10^9\text{ y} - 2.83\times10^9\text{ y} = \boxed{1.16\times10^9\text{ y}}$$

63. (a) $R=\lambda N=\left(\frac{\ln 2}{T_{1/2}}\right)N$

$$N=\frac{\text{mass of thorium}}{\text{mass of thorium atom}}=\frac{\text{mass of thorium}}{\frac{\text{atomic mass of thorium}}{N_A}}$$
$$=\frac{(0.325\text{ g})(6.022\times10^{23}\text{ mol}^{-1})}{232.04\text{ g}}$$
$$=8.43\times10^{20}\text{ atoms}$$
$$R=\left(\frac{\ln 2}{1.405\times10^{10}\text{ y}}\right)(8.43\times10^{20})\left(\frac{1\text{ y}}{3.16\times10^{7}\text{ s}}\right)=\boxed{1.32\times10^{3}\text{ decays/s}}$$

(b) It would be [reduced by a factor of 2], because activity is inversely proportional to half-life.

64. ${}^{A}_{Z}\text{X}\rightarrow{}^{A}_{Z+1}\text{Y}+\text{e}^-+\bar{\upsilon}$

$${}^{214}_{84}\text{Po}\rightarrow{}^{A}_{Z+1}\text{Y}+{}^{4}_{2}\text{He}$$
$$A=214-4=210$$
$$Z+1=84-2=82$$
$${}^{A}_{Z+1}\text{Y}={}^{210}_{82}\text{Y}={}^{210}_{82}\text{Pb}$$
$${}^{A}_{Z}\text{X}={}^{210}_{82-1}\text{X}={}^{210}_{81}\text{X}=\boxed{{}^{210}_{81}\text{Tl}}$$

65. (a) $F=\frac{kqQ}{r^2}=\frac{k(2e)(28e)}{d^2}=\frac{56\left(8.99\times10^{9}\ \frac{\text{N}\cdot\text{m}^2}{\text{C}^2}\right)(1.60\times10^{-19}\text{ C})^2}{(12\times10^{-15}\text{ m})^2}=\boxed{90\text{ N}}$

(b) $U=\frac{kqQ}{r}=\frac{56ke^2}{d}=\frac{56\left(8.99\times10^{9}\ \frac{\text{N}\cdot\text{m}^2}{\text{C}^2}\right)(1.60\times10^{-19}\text{ C})^2}{12\times10^{-15}\text{ m}}=\boxed{1.1\text{ pJ}}$

(c) $K_\text{i}=U_\text{f}=\boxed{1.1\text{ pJ}}$

66. $R=\lambda N=\left(\frac{\ln 2}{T_{1/2}}\right)\left(\frac{m}{M}\right)=\left(\frac{\ln 2}{1.60\times10^{3}\text{ y}}\right)\left(\frac{1\text{ y}}{3.1536\times10^{7}\text{ s}}\right)\left(\frac{0.001\text{ kg}}{226.025406\text{ u}}\right)\left(\frac{1\text{ u}}{1.66\times10^{-27}\text{ kg}}\right)$

$$=\boxed{4\times10^{10}\text{ decays/s}}$$
$$\frac{4\times10^{10}\ \frac{\text{decays}}{\text{s}}}{3.7\times10^{10}\ \frac{\text{decays}}{\text{s}\cdot\text{Ci}}}=\boxed{1\text{ Ci}}$$

67. (a) Since type A is decaying at a faster rate than type B, $\boxed{\text{type B}}$ has the longer half-life.

(b) $$N_\text{B} = N_{0\text{B}}e^{-\lambda_\text{B}t}$$
$$e^{\lambda_\text{B}t} = \frac{N_{0\text{B}}}{N_\text{B}}$$
$$\lambda_\text{B}t = \ln\frac{N_{0\text{B}}}{N_\text{B}}$$
$$\frac{\ln 2}{T_{1/2\text{B}}}t = \ln\frac{N_{0\text{B}}}{N_\text{B}}$$
$$T_{1/2\text{B}} = \frac{t\ln 2}{\ln\frac{N_{0\text{B}}}{N_\text{B}}} = \frac{t\ln 2}{\ln\frac{\frac{1}{4}N_{0\text{A}}}{N_\text{A}}} = \frac{t\ln 2}{\ln\left[\frac{1}{4}e^{\left(\frac{\ln 2}{T_{1/2\text{A}}}\right)t}\right]} = \frac{(2\text{ d})\ln 2}{-\ln 4 + \frac{\ln 2}{0.500\text{ d}}(2\text{ d})} = \boxed{1\text{ d}}$$

68. (a) $$r_\text{min} = (1.2\times10^{-15}\text{ m})(1)^{1/3} = 1.2\times10^{-15}\text{ m}$$
$$r_\text{max} = (1.2\times10^{-15}\text{ m})(209)^{1/3} = 7.1\times10^{-15}\text{ m}$$
$$\boxed{1.2\times10^{-15}\text{ m} \le r \le 7.1\times10^{-15}\text{ m}}$$

(b) $$\frac{S_\text{max}}{S_\text{min}} = \frac{4\pi r_\text{max}{}^2}{4\pi r_\text{min}{}^2} = \left(\frac{r_\text{max}}{r_\text{min}}\right)^2 = \left[\frac{(1.2\times10^{-15}\text{ m})(209)^{1/3}}{(1.2\times10^{-15}\text{ m})(1)^{1/3}}\right]^2 = 209^{2/3} = \boxed{35.2}$$

(c) $$\frac{V_\text{max}}{V_\text{min}} = \frac{\frac{4}{3}\pi r_\text{max}{}^3}{\frac{4}{3}\pi r_\text{min}{}^3} = \left(\frac{r_\text{max}}{r_\text{min}}\right)^3 = \left[\frac{(1.2\times10^{-15}\text{ m})(209)^{1/3}}{(1.2\times10^{-15}\text{ m})(1)^{1/3}}\right]^3 = 209^{3/3} = \boxed{209}$$

69. $$V = \frac{4}{3}\pi r^3 = \frac{m}{\rho}$$
$$r = \left(\frac{3m}{4\pi\rho}\right)^{1/3} = \left[\frac{3(0.50)(2.00\times10^{30}\text{ kg})}{4\pi\left(2.3\times10^{17}\ \frac{\text{kg}}{\text{m}^3}\right)}\right]^{1/3} = \boxed{10\text{ km}}$$

70. $$\frac{{}^{14}_{6}\text{C}}{{}^{12}_{6}\text{C}} = 1.20\times10^{-12} = \frac{\frac{m_{0,14}}{M_{14}}}{\frac{m_{0,12}}{M_{12}}} = \frac{M_{12}m_{0,14}}{M_{14}m_{0,12}} = \frac{12.0m_{0,14}}{14.0m_{0,12}} = \frac{12.0}{14.0}\left(\frac{m_{0,14}}{7.82\text{ g} - m_{0,14}}\right)$$

$$\frac{7.82\text{ g}}{m_{0,14}} - 1 = \frac{1}{1.40\times10^{-12}}$$

$$\frac{7.82\text{ g}}{m_{0,14}} = 1 + \frac{1}{1.40\times10^{-12}}$$

$$m_{0,14} = \frac{7.82\text{ g}}{1+\frac{1}{1.40\times10^{-12}}}$$

$$N_{14} = \frac{R}{\lambda} = \frac{RT_{1/2}}{\ln 2}$$

$$\frac{N_{14}}{N_{0,14}} = \left(\frac{RT_{1/2}}{\ln 2}\right)\left(\frac{M_{14}}{m_{0,14}}\right)$$

$$\frac{N_{14}}{N_{0,14}} = e^{-\lambda t}$$

$$e^{\lambda t} = \frac{N_{0,14}}{N_{14}}$$

$$t = \frac{1}{\lambda}\ln\frac{N_{0,14}}{N_{14}}$$

$$= \frac{T_{1/2}}{\ln 2}\ln\frac{m_{0,14}\ln 2}{M_{14}RT_{1/2}}$$

$$= \frac{5730\text{ y}}{\ln 2}\ln\frac{\left(\frac{7.82\times10^{-3}\text{ kg}}{1+\frac{1}{1.40\times10^{-12}}}\right)(\ln 2)\left(\frac{1\text{ y}}{3.1536\times10^{7}\text{ s}}\right)}{(14.0\text{ u})\left(\frac{1.66\times10^{-27}\text{ kg}}{1\text{ u}}\right)(1.38\text{ Bq})(5730\text{ y})}$$

$$= \boxed{2230\text{ y}}$$

71. (a) $E = P_{\text{bulb}}t$

$E = \varepsilon E_{\text{fission}} N_{\text{reaction}}$

$$N_{\text{reaction}} = \frac{P_{\text{bulb}}t}{\varepsilon E_{\text{fission}}} = \frac{(100\text{ W})(24\text{ h})\left(\frac{3600\text{ s}}{1\text{ h}}\right)}{(0.32)(212\times10^{6}\text{ eV})\left(\frac{1.60\times10^{-19}\text{ J}}{1\text{ eV}}\right)} = \boxed{8.0\times10^{17}\text{ reactions}}$$

(b) $$m = N_{\text{reaction}}M_{\text{U}} = (7.96\times10^{17})(235.043925\text{ u})\left(\frac{1.66\times10^{-27}\text{ kg}}{1\text{ u}}\right) = \boxed{3.1\times10^{-7}\text{ kg}}$$

72. (a) The release of energy is the result of some of the alpha particles' mass being converted to energy. So, the mass of carbon-12 is $\boxed{\text{less than}}$ the mass of the three alpha particles.

(b) $m_\text{i} = 3(4.002603 \text{ u}) = 12.007809 \text{ u}$

$m_\text{f} = 12.000000 \text{ u}$

$\Delta m = 12.000000 \text{ u} - 12.007809 \text{ u} = -0.007809 \text{ u}$

$$E = |\Delta m|c^2 = (0.007809 \text{ u})\left(\frac{931.494 \ \frac{\text{MeV}}{c^2}}{1 \text{ u}}\right)c^2 = \boxed{7.274 \text{ MeV}}$$

73. $$\gamma \text{ dose} = \frac{\text{energy in } 0.01 \text{ J}}{\text{kg}} = \text{dose in rad}$$

$$\frac{\text{heat energy}}{\text{mass}} = L_\text{ice} \times 100 = \text{dose in rad}$$

$$100\left(33.5\times10^4 \ \frac{\text{J}}{\text{kg}}\right) = \boxed{33.5\times10^6 \text{ rad}}$$

74. (a) $$\frac{Q}{m}\times100 = c_\text{w}\Delta T\times100 = \text{dose in rad}$$

$$100\left(4186 \ \frac{\text{J}}{\text{kg}\cdot\text{K}}\right)(1.0 \text{ K}) = \boxed{4.2\times10^5 \text{ rad}}$$

(b) The dosage in rad is the energy per unit mass required to heat the water. The dosage $\boxed{\text{stays the same}}$.

75. $$E = \frac{\text{dose in rem}}{\text{RBE}}(\text{mass exposed})$$

$$= \left(\frac{35\times10^{-3} \text{ rem}}{0.85}\right)\left(\frac{0.01 \ \frac{\text{J}}{\text{kg}}}{\text{rem}}\right)\left(\frac{1}{4}\right)(72 \text{ kg})$$

$$= \boxed{7.4 \text{ mJ}}$$

76. $$p_\text{i} = p_\text{f}$$

$$0 = p_\text{Ra} + p_\gamma$$

$$= -mv + \frac{E}{c}$$

$$v = \frac{E}{mc}$$

$$= \frac{(0.186\times10^6 \text{ eV})\left(\frac{1.60\times10^{-19} \text{ J}}{1 \text{ eV}}\right)}{(226.025406 \text{ u})\left(\frac{1.66\times10^{-27} \text{ kg}}{1 \text{ u}}\right)\left(3.00\times10^8 \ \frac{\text{m}}{\text{s}}\right)}$$

$$= \boxed{264 \text{ m/s}}$$

77. ${}^{239}_{94}\text{Pu} \rightarrow {}^{235}_{92}\text{U} + {}^{4}_{2}\text{He}$

Determine the number of decays in one hour.

$n = \text{number of decays} = N_0 - N = N_0 - N_0 e^{-\lambda t} = N_0(1 - e^{-\lambda t})$

$N_0 = \dfrac{\text{total mass of Pu}}{\text{mass per Pu atom}} = \dfrac{m}{M}$ and $\lambda = \dfrac{\ln 2}{T_{1/2}}$.

$$n = \frac{m}{M}\left[1 - e^{-\left(\frac{\ln 2}{T_{1/2}}\right)t}\right]$$

Determine the total energy released.

$E = nE_{\text{decay}} = n|\Delta m|c^2$

$m_\text{i} = 239.052158 \text{ u}$

$m_\text{f} = 235.043925 \text{ u} + 4.002603 \text{ u} = 239.046528 \text{ u}$

$\Delta m = 239.046528 \text{ u} - 239.052158 \text{ u} = -0.005630 \text{ u}$

Determine the increase in temperature.

$$\begin{aligned}\Delta T &= \frac{Q}{m_\text{w} c_\text{w}} \\ &= \frac{E}{m_\text{w} c_\text{w}} \\ &= \frac{n|\Delta m|c^2}{m_\text{w} c_\text{w}} \\ &= \frac{m|\Delta m|c^2\left[1 - e^{-\left(\frac{\ln 2}{T_{1/2}}\right)t}\right]}{M m_\text{w} c_\text{w}} \\ &= \frac{(0.0500 \text{ kg})(0.005630 \text{ u})\left(\frac{931.494\times10^6 \ \frac{\text{eV}}{c^2}}{1 \text{ u}}\right)c^2\left(\frac{1.60\times10^{-19} \text{ J}}{1 \text{ eV}}\right)\left[1 - e^{-\left(\frac{\ln 2}{2.41\times10^4 \text{ y}}\right)\left(\frac{1 \text{ y}}{8760 \text{ h}}\right)(1 \text{ h})}\right]}{(239.052158 \text{ u})\left(\frac{1.66\times10^{-27} \text{ kg}}{1 \text{ u}}\right)(4.50 \text{ kg})\left(4186 \frac{\text{J}}{\text{kg}\cdot\text{K}}\right)} \\ &= \boxed{20 \text{ mK}}\end{aligned}$$

78. Determine the activity of ${}^{235}_{92}\text{U}$.

$$R = \lambda N = \lambda N_0 e^{-\lambda t} = \frac{\ln 2}{T_{1/2}} N_0 e^{-(\ln 2/T_{1/2})t}$$

Determine the power generated by decay.

${}^{235}_{92}\text{U} \rightarrow {}^{231}_{90}\text{Th} + {}^{4}_{2}\text{He}$

$$P = ER = |\Delta m|c^2 \frac{\ln 2}{T_{1/2}} N_0 e^{-(\ln 2/T_{1/2})t}$$

Equate the power generated by decay to the radiated power.

$P_\text{rad} = e\sigma A(T^4 - T_\text{s}^4) = e\sigma(4\pi r^2)(T^4 - T_\text{s}^4)$

$$4\pi r^2 e\sigma(T^4 - T_\text{s}^4) = \frac{N_0|\Delta m|c^2 \ln 2}{T_{1/2}} e^{-(\ln 2/T_{1/2})t}$$

$$
\begin{aligned}
T &= \left[T_\text{s}^{\,4} + \frac{N_0\,|\Delta m|c^2 \ln 2}{4\pi r^2 e\sigma T_{1/2}} e^{-(\ln 2/T_{1/2})t}\right]^{1/4} \\
&= \left[T_\text{s}^{\,4} + \frac{\frac{4\pi r^3 \rho}{3M}|\Delta m|c^2 \ln 2}{4\pi r^2 e\sigma T_{1/2}} e^{-(\ln 2/T_{1/2})t}\right]^{1/4} \\
&= \left[T_\text{s}^{\,4} + \frac{r\rho|\Delta m|c^2 \ln 2}{3Me\sigma T_{1/2}} e^{-(\ln 2/T_{1/2})t}\right]^{1/4} \\
&= \left[(293\text{ K})^4 + \frac{(0.0200\text{ m})\left(18.95\times 10^3\ \frac{\text{kg}}{\text{m}^3}\right)|231.036297\text{ u} + 4.002603\text{ u} - 235.043925\text{ u}|\left(3.00\times 10^8\ \frac{\text{m}}{\text{s}}\right)^2 \ln 2}{3(235.043925\text{ u})(1)\left(5.67\times 10^{-8}\ \frac{\text{W}}{\text{m}^2\cdot\text{K}^4}\right)(7.038\times 10^8\text{ y})\left(\frac{3.1536\times 10^7\text{ s}}{1\text{ y}}\right)} e^0\right]^{1/4} \\
&= \boxed{293\text{ K}}
\end{aligned}
$$

$$\Delta T = T - T_\text{s} = 1\text{ mK}$$