# CHAPTER 31: Nuclear Energy; Effects and Uses of Radiation

## Answers to Questions

1. (*a*) $n + {}^{137}_{56}Ba \rightarrow ? + \gamma$

   Conserve nucleon number: 1 + 137 = A + 0. Thus, A = 138. Conserve charge: 0 + 56 = Z + 0. Thus, Z = 56. This is ${}^{138}_{56}Ba$ or Barium-138.

   (*b*) $n + {}^{137}_{56}Ba \rightarrow {}^{137}_{55}Cs + ?$

   Conserve nucleon number: 1 + 137 = 137 + A. Thus, A = 1. Conserve charge: 0 + 56 = 55 + Z. Thus, Z = 1. This is ${}^{1}_{1}H$ or p (a proton).

   (*c*) $d + {}^{2}_{1}H \rightarrow {}^{4}_{2}He + ?$

   Conserve nucleon number: 2 + 2 = 4 + A. Thus, A = 0. Conserve charge: 1 + 1 = 2 + Z. Thus, Z = 0. This is $\gamma$ or a gamma ray (a photon).

   (*d*) $\alpha + {}^{197}_{79}Au \rightarrow ? + d$

   Conserve nucleon number: 4 + 197 = A + 2. Thus, A = 199. Conserve charge: 2 + 79 = Z + 1. Thus, Z = 80. This is ${}^{199}_{80}Hg$ or Mercury-199.

2. The products have 16 protons and 33 nucleons, and so must have 17 neutrons. Thus the reactants must also have 16 protons and 17 neutrons as well. Since one reactant is a neutron, the other reactant must have 16 protons and 16 neutrons, for a total of 32 nucleons. That nucleus is ${}^{32}_{16}S$.

3. The reaction is ${}^{22}_{11}Na + {}^{2}_{1}H \rightarrow \alpha + ?$. The reactants have 12 protons and 24 nucleons, and so must have 12 neutrons. Thus the products must have 12 protons and 12 neutrons as well. Since the alpha has 2 protons and 2 neutrons, the other product must have 10 protons and 10 neutrons. That nucleus is ${}^{20}_{10}Ne$.

4. Neutrons are good projectiles for producing nuclear reactions because they are neutral and they are massive. If you want a particle to hit the nucleus with a lot of energy, a more massive particle is the better choice. A light electron would not be as effective. Using a positively charged projectile like an alpha or a proton means that the projectile will have to overcome the large electrical repulsion from the positively charged nucleus. Neutrons can penetrate directly to the nucleus and cause nuclear reactions.

5. The reaction is $p + {}^{20}_{10}Ne \rightarrow \alpha + ?$. The reactants have 11 protons and 21 nucleons, and so must have 10 neutrons. Thus the products must have 11 protons and 10 neutrons as well. Since the alpha has 2 protons and 2 neutrons, the other product must have 9 protons and 8 neutrons. That nucleus is ${}^{17}_{9}F$.

6. Fission fragments are neutron-rich. They have Z values, though, in a range where stable nuclei should have nearly equal numbers of neutrons and protons. Thus, these fission fragments are unstable with more neutrons than protons. For them to become more stable they will emit $\beta^-$ particles. The emission of a $\beta^-$ particle essentially converts a neutron in the nucleus to a proton

(while ejecting an electron), which brings the nuclei closer to the stable numbers of neutrons and protons.

7. Yes, since the multiplication factor is greater than 1 ($f = 1.5$), a chain reaction can be sustained. The difference would be that the chain reaction would proceed more slowly and to make sure the chain reaction continued you would need to be very careful about leakage of the neutrons to the surroundings.

8. The critical mass of ${}^{239}_{94}\mathrm{Pu}$ ($f = 2.9$) would be less than that for ${}^{235}_{92}\mathrm{U}$ ($f = 2.5$). Since there are more neutrons created per Pu-239 nuclei decay we can have a smaller number of these nuclei and still create the needed chain reaction in this smaller volume of material (enough of the neutrons will strike other nuclei before escaping the smaller sample size).

9. The thermal energy from nuclear fission appears in the kinetic energy of the fission products (daughter nuclei and neutrons). In other words, the fission products are moving very fast (especially the neutrons, due to the conservation of momentum).

10. Uranium can't be enriched by chemical means because chemical reactions occur similarly with all of the isotopes of a given element. The number of neutrons in the nucleus does not influence the chemistry, which is primarily due to the valence electrons. Thus, trying to enrich uranium by chemical means, which means trying to increase the percent of ${}^{235}_{92}\mathrm{U}$ in the sample versus ${}^{238}_{92}\mathrm{U}$, is impossible.

11. First of all, the neutron can get close to the nucleus at such slow speeds due to the fact that it is neutral and will not be electrically repelled by either the electron cloud or the protons in the nucleus. Then, once it hits a nucleus, it is held due to the strong nuclear force. It adds more energy than just kinetic energy to the nucleus due to $E = mc^2$. This extra amount of mass-energy leaves the nucleus in an excited state. To decay back to a lower energy state, the nucleus will fission.

12. For a nuclear chain reaction to occur in a block of porous uranium (which would lead to an explosion), the neutrons being emitted by the decays must be slowed down. If the neutrons are too fast, they will pass through the block of uranium without interacting, effectively prohibiting a chain reaction. Water contains a much higher density of protons and neutrons than does air, and those protons and neutrons will slow down (moderate) the neutrons, enabling them to take part in nuclear reactions. Thus, if water is filling all of the porous cavities, the water will slow the neutrons, allowing them to be captured by other uranium nuclei, and allow the chain reaction to continue, which might lead to an explosion.

13. If the uranium is highly enriched, it won't matter that the ordinary water is a poorer moderator of neutrons than the heavy water. There will still be enough fissionable nuclei that even with the lower number of slowed (moderated) neutrons in ordinary water, the chain reaction will proceed. If the uranium is not highly enriched, there are not as many fissionable nuclei. If ordinary water is used, too many neutrons would be lost to absorption in the ordinary water and the relative amount of moderated neutrons would decrease. In that case heavy water is better than ordinary water for sustaining the chain reaction.

14. To get nuclei to fission, they must be bombarded by neutrons. This can be done using an external source, but then there is a large input of energy into the system, making it less efficient and so less useful. To make the fission reaction useful, it needs to be self-sustaining. To create such a chain reaction, each time a nuclei captures a neutron and fissions, one or more neutrons must be emitted in order to sustain the process.

15. Fossil fuels: Pros = inexpensive to build, the technology is already working. Cons = air pollution, greenhouse gas, limited supply of coal and oil. Fission: Pros = the technology is already working, no air pollution, no greenhouse gas. Cons = expensive to build, thermal pollution, disposal of radioactive waste, accidents are extremely dangerous. Fusion: Pros = no radioactive waste, no air pollution, no greenhouse gas. Cons = the technology is not yet working in a sustainable manner, expensive to build.

16. It is desirable to keep the radioactive materials as confined as possible to avoid accidental leakage and contamination. In the electric generating portion of the system, waste heat must be given off to the surroundings, and keeping all of the radioactive portions of the energy generation process as far away from this "release point" as possible is a major safety concern.

17. A heavy nucleus decays because it is neutron-rich, especially after neutron capture. With too many neutrons, when compared to protons, the nucleus is unstable and will fission into two daughter nuclei. These two daughter nuclei would still be neutron-rich and relatively unstable, and so the fission process is always accompanied by the emission of neutrons to alleviate this imbalance. Lighter nuclei are more stable with approximately equal numbers of protons and neutrons.

18. Gamma particles penetrate better than beta particles because they are neutral and have no mass. Thus, gamma particles do not interact with matter as easily or as often as beta particles, allowing them to better penetrate matter.

19. To ignite these fusion reactions the nuclei need to be given enough energy (higher temperature) to the point where the nucleus of one particle actually touches the nucleus of another particle during the collisions. To do this, the nuclei need to overcome their electrostatic repulsion in order to get close enough to fuse. Each of these nuclei has a single positive charge. The deuterium (d) has two neutrons and the tritium (t) has three neutrons. Electrostatic repulsion is proportional to the charge of each nucleus and inversely proportional to the square of the distance between the centers of the two nuclei. In both the d-d ignition and the d-t ignition, the charge of each nucleus is the same, and so the charge effect is the same in both ignitions. However, the distance between the centers of the two nuclei in the d-t ignition will be larger than in the d-d ignition (since the tritium nucleus is larger than the deuterium nucleus), which means there is less electrostatic repulsion to overcome in the d-t ignition. Thus a lower temperature will ignite the fusion process.

20. The large amount of mass of a star creates an enormous gravitational attraction of all of that mass, which causes the gas to be compressed to a very high density. This high density creates a very high pressure and high temperature situation. The high temperatures give the gas particles a large amount of kinetic energy, which allows them to fuse when they collide. Thus, these conditions at the center of the Sun and other stars make the fusion process possible.

21. Stars, which include our Sun, maintain confinement of the fusion plasma with gravity. The huge amount of mass in a star creates an enormous gravitational attraction on the gas molecules and this attractive force overcomes the outward repulsive forces from electrostatics and radiation pressure.

22. Fission is the process in which heavier, less-stable nuclei break apart into two or more lighter, more-stable nuclei, which releases particles and energy. Fusion is the process in which lighter, less-stable nuclei combine with each other to create heavier, more-stable nuclei, which releases particles and energy.

23. Alpha particles cannot penetrate a person's skin, so they do no biological damage even when a person works with or touches an alpha emitter. But, even if dust-sized pieces of the alpha emitter are ingested, then they can do a large amount of ionization damage directly to the exposed cells in your body. Thus, strict rules for employees that prohibit any eating and drinking while working around alpha emitters is an extremely wise precaution. Also, machining of alpha emitters is usually strictly prohibited, due to the fact that this process might create fine dust particles of the radioactive substance that could be inhaled.

24. During a woman's child-bearing years (and earlier) it is possible for radiation damage to occur to the reproductive organs in such a way as to pass on the possible genetic defects to her children. The risk of this type of damage is greater than the risk of damage to just the woman. Thus once the child-bearing years are over, the acceptable dose goes up.

25. Radiation can kill or deactivate bacteria and viruses on medical supplies and even in food. Thus, the radiation will sterilize these things, making them safer for humans to use.

26. Absorbed dose is the amount of radiation energy deposited per mass. The SI unit is the Gray = Gy = 1 J/kg. Effective dose is the amount of biological damage that will occur due to the energy deposited per mass. The SI unit is the Sievert = Sv. The effective dose is related to the absorbed dose by the quality factor: effective dose = (absorbed dose)(quality factor).

27. Put a radioactive tracer in the liquid that flows through the pipe. Choose a tracer that emits particles that cannot penetrate the walls of the pipe. Follow the pipe with a Geiger counter until the tracer is detected on the outside of the pipe. This is where the leak is located.

## Solutions to Problems

1. By absorbing a neutron, the mass number increases by one and the atomic number is unchanged. The product nucleus is $\boxed{{}^{28}_{13}\text{Al}}$. Since the nucleus now has an "extra" neutron, it will decay by $\boxed{\beta^-}$, according to this reaction: ${}^{28}_{13}\text{Al} \rightarrow {}^{28}_{14}\text{Si} + \beta^- + \overline{\nu}_e$. Thus the product is $\boxed{{}^{28}_{14}\text{Si}}$.

2. If the $Q$-value is positive, then no threshold energy is needed.

$$Q = 2m_{{}^2_1\text{H}}c^2 - m_{{}^3_2\text{He}}c^2 - m_{\text{n}}c^2 = \left[2\left(2.014102\,\text{u}\right) - 3.016029\,\text{u} - 1.008665\,\text{u}\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2$$
$$= 3.270\,\text{MeV}$$

Thus $\boxed{\text{no threshold energy is required}}$.

$\boxed{3.}$ A "slow" neutron means that it has negligible kinetic energy. If the $Q$-value is positive, then the reaction is possible.

$$Q = m_{{}^{238}_{92}\text{U}}c^2 + m_{\text{n}}c^2 - m_{{}^{239}_{92}\text{U}}c^2 = \left[238.050783\,\text{u} + 1.008665\,\text{u} - 239.054288\,\text{u}\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2$$
$$= 4.807\,\text{MeV}$$

Thus $\boxed{\text{the reaction is possible}}$.

4. The $Q$-value tells whether the reaction requires or releases energy.

$$Q = m_{\text{p}}c^2 + m_{{}^7_3\text{Li}}c^2 - m_{{}^4_2\text{He}}c^2 - m_\alpha c^2 = \left[1.007825\,\text{u} + 7.016004\,\text{u} - 2(4.002603)\,\text{u}\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2$$

$$= 17.35\,\text{MeV}$$

The reaction $\boxed{\text{releases } 17.35\,\text{MeV}}$.

5. The $Q$-value tells whether the reaction requires or releases energy.

$$Q = m_\alpha c^2 + m_{{}^9_4\text{Be}}c^2 - m_{{}^{12}_6\text{He}}c^2 - m_{\text{n}}c^2$$

$$= \left[4.002603\,\text{u} + 9.012182\,\text{u} - 12.000000\,\text{u} - 1.008665\,\text{u}\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2 = 5.701\,\text{MeV}$$

The reaction $\boxed{\text{releases } 5.701\,\text{MeV}}$.

6. (*a*) If the $Q$-value is positive, then no threshold energy is needed.

$$Q = m_{\text{n}}c^2 + m_{{}^{24}_{12}\text{Mg}}c^2 - m_{{}^{23}_{11}\text{Na}}c^2 - m_{\text{d}}c^2$$

$$= \left[1.008665\,\text{u} + 23.985042\,\text{u} - 22.989770\,\text{u} - 2.014102\,\text{u}\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2 = -9.469\,\text{MeV}$$

Thus more energy is required if this reaction is to occur. The 10.00 MeV of kinetic energy is more than sufficient, and so $\boxed{\text{the reaction can occur}}$.

(*b*) $10.00\,\text{MeV} - 9.469\,\text{MeV} = \boxed{0.53\,\text{MeV of energy is released}}$

7. (*a*) If the $Q$-value is positive, then no threshold energy is needed.

$$Q = m_{\text{p}}c^2 + m_{{}^7_3\text{Li}}c^2 - m_{{}^4_2\text{He}}c^2 - m_\alpha c^2$$

$$= \left[1.007825\,\text{u} + 7.016004\,\text{u} - 2(4.002603\,\text{u})\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2 = 17.35\,\text{MeV}$$

Since the $Q$-value is positive, $\boxed{\text{the reaction can occur}}$.

(*b*) The total KE of the products will be the $Q$-value plus the incoming kinetic energy.

$$\text{KE}_{\text{total}} = \text{KE}_{\text{reactants}} + Q = 2.500\,\text{MeV} + 17.35\,\text{MeV} = \boxed{19.85\,\text{MeV}}$$

8. (*a*) If the $Q$-value is positive, then no threshold energy is needed.

$$Q = m_\alpha c^2 + m_{{}^{14}_7\text{N}}c^2 - m_{{}^{17}_8\text{O}}c^2 - m_{\text{p}}c^2$$

$$= \left[4.002603\,\text{u} + 14.003074\,\text{u} - 16.999131\,\text{u} - 1.007825\,\text{u}\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2 = -1.191\,\text{MeV}$$

Thus more energy is required if this reaction is to occur. The 7.68 MeV of kinetic energy is more than sufficient, and so $\boxed{\text{the reaction can occur}}$.

(*b*) The total KE of the products will be the $Q$-value plus the incoming kinetic energy.

$$\text{KE}_{\text{total}} = \text{KE}_{\text{reactants}} + Q = 7.68\,\text{MeV} - 1.191\,\text{MeV} = \boxed{6.49\,\text{MeV}}$$

9. $Q = m_\alpha c^2 + m_{^{16}_{8}\text{O}} c^2 - m_{^{20}_{10}\text{Ne}}$

$$= [4.002603\,\text{u} + 15.994915\,\text{u} - 19.992440\,\text{u}]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2 = \boxed{4.730\,\text{MeV}}$$

10. The $Q$-value tells whether the reaction requires or releases energy.

$$Q = m_\text{d}c^2 + m_{^{13}_{6}\text{C}}c^2 - m_{^{14}_{7}\text{N}}c^2 - m_\text{n}c^2$$

$$= [2.014102\,\text{u} + 13.003355\,\text{u} - 14.003074\,\text{u} - 1.008665\,\text{u}]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2 = 5.326\,\text{MeV}$$

The total KE of the products will be the $Q$-value plus the incoming kinetic energy.

$$\text{KE}_\text{total} = \text{KE}_\text{reactants} + Q = 36.3\,\text{MeV} + 5.326\,\text{MeV} = \boxed{41.6\,\text{MeV}}$$

11. The nitrogen-14 absorbs a neutron. Carbon-12 is a product. Thus the reaction is $\text{n} + {}^{14}_{7}\text{N} \rightarrow {}^{14}_{6}\text{C} + ?$. The reactants have 7 protons and 15 nucleons, which means 8 neutrons. Thus the products have 7 protons and 15 nucleons. The unknown product must be a proton. Thus the reaction is $\text{n} + {}^{14}_{7}\text{N} \rightarrow {}^{14}_{6}\text{C} + \text{p}$.

$$Q = m_\text{n}c^2 + m_{^{14}_{7}\text{N}}c^2 - m_{^{14}_{6}\text{C}}c^2 - m_\text{p}c^2$$

$$= [1.008665\,\text{u} + 14.003074\,\text{u} - 14.003242\,\text{u} - 1.007825\,\text{u}]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2 = \boxed{0.626\,\text{MeV}}$$

12. (*a*) The deuteron is ${}^{2}_{1}\text{H}$, and so the reactants have 4 protons and 8 nucleons. Therefore the reactants have 4 neutrons. Thus the products must have 4 protons and 4 neutrons. That means that X must have 3 protons and 4 neutrons, and so X is $\boxed{{}^{7}_{3}\text{Li}}$.

(*b*) This is called a "stripping" reaction because the lithium nucleus has "stripped" a neutron from the deuteron.

(*c*) The $Q$-value tells whether the reaction requires or releases energy.

$$Q = m_\text{d}c^2 + m_{^{6}_{3}\text{Li}}c^2 - m_{^{7}_{3}\text{Li}}c^2 - m_\text{p}c^2$$

$$= [2.014102\,\text{u} + 6.015122\,\text{u} - 7.016004\,\text{u} - 1.007825\,\text{u}]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2 = \boxed{5.025\,\text{MeV}}$$

Since the $Q$-value is positive, the reaction is $\boxed{\text{exothermic}}$.

13. (*a*) This is called a "pickup" reaction because the helium has "picked up" a neutron from the carbon nucleus.

(*b*) The alpha is ${}^{4}_{2}\text{He}$. The reactants have 8 protons and 15 nucleons, and so have 7 neutrons. Thus the products must also have 8 protons and 7 neutrons. The alpha has 2 protons and 2 neutrons, and so X must have 6 protons and 5 neutrons. Thus X is $\boxed{{}^{11}_{6}\text{C}}$.

(*c*) The $Q$-value tells whether the reaction requires or releases energy.

$$Q = m_{^{3}_{2}\text{He}}c^2 + m_{^{12}_{6}\text{C}}c^2 - m_{^{11}_{6}\text{C}}c^2 - m_\alpha c^2$$

$$=\left[3.016029\,\text{u}+12.000000\,\text{u}-11.011434\,\text{u}-4.002603\,\text{u}\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2=\boxed{1.856\,\text{MeV}}$$

Since the $Q$-value is positive, the reaction is $\boxed{\text{exothermic}}$ .

14. (*a*) The product has 16 protons and 16 neutrons. Thus the reactants must have 16 protons and 16 neutrons. Thus the missing nucleus has 15 protons and 16 neutrons, and so is $\boxed{{}^{31}_{15}\text{P}}$

(*b*) The $Q$-value tells whether the reaction requires or releases energy.

$$Q=m_\text{p}c^2+m_{{}^{31}_{15}\text{P}}c^2-m_{{}^{32}_{16}\text{S}}c^2$$

$$=\left[1.007825\,\text{u}+30.973762\,\text{u}-31.972071\,\text{u}\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2=\boxed{8.864\,\text{MeV}}$$

15. We assume that all of the particles are essentially at rest, and so ignore conservation of momentum. To just make the fluorine nucleus, the $Q$-value plus the incoming KE should add to 0.

$$\text{KE}+Q=\text{KE}+m_\text{p}c^2+m_{{}^{18}_{8}\text{O}}c^2-m_{{}^{18}_{9}\text{F}}c^2-m_\text{n}c^2=0\quad\rightarrow$$

$$m_{{}^{18}_{9}\text{F}}c^2=\text{KE}+m_\text{p}c^2+m_{{}^{18}_{8}\text{O}}c^2-m_\text{n}c^2=$$

$$=2.453\,\text{MeV}+\left[1.007825\,\text{u}+17.999160\,\text{u}-1.008665\,\text{u}\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2$$

$$=1.676789\times10^4\,\text{MeV}$$

$$m_{{}^{18}_{9}\text{F}}=\left(1.676788\times10^4\,\text{MeV}\right)c^2\left(\frac{1\,\text{u}}{931.5\,\text{MeV}/c^2}\right)=\boxed{18.000953\,\text{u}}$$

16. The $Q$-value gives the energy released in the reaction, assuming the initial kinetic energy of the neutron is very small.

$$Q=m_\text{n}c^2+m_{{}^{235}_{92}\text{U}}c^2-m_{{}^{88}_{38}\text{Sr}}c^2-m_{{}^{136}_{54}\text{Xe}}c^2-12m_\text{n}c^2$$

$$=\left[1.008665\,\text{u}+235.043923\,\text{u}-87.905614\,\text{u}-135.907220\,\text{u}-12\left(1.008665\,\text{u}\right)\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2$$

$$=\boxed{126.5\,\text{MeV}}$$

17. The $Q$-value gives the energy released in the reaction, assuming the initial kinetic energy of the neutron is very small.

$$Q=m_\text{n}c^2+m_{{}^{235}_{92}\text{U}}c^2-m_{{}^{141}_{56}\text{Ba}}c^2-m_{{}^{92}_{36}\text{Kr}}c^2-3m_\text{n}c^2$$

$$=\left[1.008665\,\text{u}+235.043923\,\text{u}-140.914411\,\text{u}-91.926156\,\text{u}-3\left(1.008665\,\text{u}\right)\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2$$

$$=\boxed{173.3\,\text{MeV}}$$

18. The power released is the energy released per reaction times the number of reactions per second.

$$P=\frac{\text{energy}}{\text{reaction}}\times\frac{\#\text{ reactions}}{\text{s}}\quad\rightarrow$$

$$\frac{\#\text{ reactions}}{\text{s}}=\frac{P}{\dfrac{\text{energy}}{\text{reaction}}}=\frac{200\times10^{6}\text{ W}}{\left(200\times10^{6}\text{ eV/reaction}\right)\left(1.60\times10^{-19}\text{ J/eV}\right)}=\boxed{6\times10^{18}\text{ reactions/s}}$$

19. Compare the energy per fission with the rest mass energy.

$$\frac{\text{energy per fission}}{\text{rest mass energy } mc^2}=\frac{200\text{ MeV}}{\left(235\text{ u}\right)\left(931.5\text{ MeV}/c^2\right)c^2}=9.1\times10^{-4}\approx\boxed{\frac{1}{1100}}$$

20. (*a*) The total number of nucleons for the reactants is 236, and so the total number of nucleons for the products must also be 236. The two daughter nuclei have a total of 231 nucleons, so $\boxed{\text{5 neutrons}}$ must be produced in the reaction: ${}^{235}_{92}\text{U}+\text{n}\rightarrow{}^{133}_{51}\text{Sb}+{}^{98}_{41}\text{Nb}+5\text{n}$ .

(*b*) $Q=m_{{}^{235}_{92}\text{U}}c^2+m_{\text{n}}c^2-m_{{}^{133}_{51}\text{Sb}}c^2-m_{{}^{98}_{41}\text{Nb}}c^2-5m_{\text{n}}c^2$

$$=\left[235.043923\text{ u}+1.008665\text{ u}-132.915250\text{ u}-97.910328\text{ u}-5\left(1.008665\text{ u}\right)\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2$$

$$=\boxed{171.1\text{ MeV}}$$

21. We assume as stated in problems 18 and 19 that an average of 200 MeV is released per fission of a uranium nucleus.

$$\left(3\times10^{7}\text{ J}\right)\left(\frac{1\text{ eV}}{1.60\times10^{-19}\text{ J}}\right)\left(\frac{1\text{ MeV}}{1\times10^{6}\text{eV}}\right)\left(\frac{1\text{ nucleus}}{200\text{ MeV}}\right)\left(\frac{0.238\text{ kg}}{6.02\times10^{23}\text{ nuclei}}\right)=\boxed{3.7\times10^{-7}\text{ kg }{}^{238}_{92}\text{U}}$$

22. Convert the power rating to a mass of uranium using the factor-label method.

$$950\frac{\text{J}}{\text{s}}\times\frac{1\text{ atom}}{200\times10^{6}\text{eV}}\times\frac{1\text{eV}}{1.60\times10^{-19}\text{ J}}\times\frac{0.235\text{ kg U}}{6.02\times10^{23}\text{ atoms}}\times\frac{3.156\times10^{7}\text{ s}}{1\text{ y}}=\boxed{3.7\times10^{-4}\text{ kg U}}$$

23. Since the reaction is 40% efficient, the fission needs to generate $\left(650/0.40\right)\text{MW}$ of power. Convert the power rating to a mass of uranium using the factor-label method. We assume 200 MeV is released per fission, as in other problems.

$$\frac{650\times10^{6}}{0.40}\frac{\text{J}}{\text{s}}\times\frac{1\text{ atom}}{200\times10^{6}\text{eV}}\times\frac{1\text{eV}}{1.60\times10^{-19}\text{ J}}\times\frac{0.235\text{ kg U}}{6.02\times10^{23}\text{ atoms}}\times\frac{3.156\times10^{7}\text{ s}}{1\text{ y}}=626\text{ kg U}\approx\boxed{630\text{ kg U}}$$

24. If the uranium splits into roughly equal fragments, each will have an atomic mass number of about half of 236, or 118. Each will have a nuclear charge of about half of 92, or 46. Calculate the electrical potential energy using a relationship developed in Ex. 17-7. The distance between the nuclei will be twice the radius of a nucleus, and the radius is given in Eq. 30-1.

$$\text{PE}=\frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{r}=\left(9.0\times10^{9}\text{ N}\bullet\text{m}^2/\text{C}^2\right)\frac{\left(46\right)^2\left(1.60\times10^{-19}\text{C}\right)^2}{2\left(1.2\times10^{-15}\text{m}\right)\left(118\right)^{1/3}}$$

$$= 4.142\times10^{-11}\,\text{J}\left(\frac{1\,\text{eV}}{1.60\times10^{-19}\,\text{J}}\right) = 2.59\times10^{8}\,\text{eV} = \boxed{259\,\text{MeV}}$$

This is about $\boxed{30\%\ \text{larger}}$ than the nuclear fission energy released.

$\boxed{25.}$ $\text{KE} = \frac{3}{2}kT = \frac{3}{2}\left(1.38\times10^{-23}\,\text{J/K}\right)\left(10^{7}\,\text{K}\right) = \boxed{2.1\times10^{-16}\,\text{J}}$

$$= \tfrac{3}{2}\left(1.38\times10^{-23}\,\text{J/K}\right)\left(10^{7}\,\text{K}\right)\left(\frac{1\,\text{eV}}{1.60\times10^{-19}\,\text{J}}\right) = \boxed{1300\,\text{eV}}$$

26. The $Q$-value gives the energy released in the reaction.

$$Q = m_{^2_1\text{H}}c^2 + m_{^3_1\text{H}}c^2 - m_{^4_2\text{He}}c^2 - m_{\text{n}}c^2$$

$$= \left[2.014102\,\text{u} + 3.016049\,\text{u} - 4.002603\,\text{u} - 1.008665\,\text{u}\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2 = \boxed{17.59\,\text{MeV}}$$

27. Calculate the $Q$-value for the reaction $^2_1\text{H} + {}^2_1\text{H} \rightarrow {}^3_2\text{He} + \text{n}$

$$Q = 2m_{^2_1\text{H}}c^2 - m_{^3_2\text{He}}c^2 - m_{\text{n}}c^2$$

$$= \left[2\left(2.014102\,\text{u}\right) - 3.016029\,\text{u} - 1.008665\,\text{u}\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2 = \boxed{3.27\,\text{MeV}}$$

28. For the reaction in Eq. 31-6a, if atomic masses are to be used, then one more electron needs to be added to the products side of the equation. Notice that charge is not balanced in the equation as written. The reaction is $^1_1\text{H} + {}^1_1\text{H} \rightarrow {}^2_1\text{H} + \text{e}^+ + \nu + \text{e}^-$

$$Q = 2m_{^1_1\text{H}}c^2 - m_{^2_1\text{H}}c^2 - m_{\text{e}^+}c^2 - m_{\text{e}^-}c^2$$

$$= \left[2\left(1.007825\,\text{u}\right) - 2.014102\,\text{u} - 2\left(0.000549\,\text{u}\right)\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2 = \boxed{0.42\,\text{MeV}}$$

For the reaction in Eq. 31-6b, use atomic masses since there would be two electrons on each side.

$$Q = m_{^1_1\text{H}}c^2 + m_{^2_1\text{H}}c^2 - m_{^3_2\text{He}}c^2$$

$$= \left[1.007825\,\text{u} + 2.014102\,\text{u} - 3.016029\,\text{u}\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2 = \boxed{5.49\,\text{MeV}}$$

For the reaction in Eq. 31-6c, use atomic masses since there would be two electrons on each side.

$$Q = 2m_{^3_2\text{He}}c^2 - m_{^4_2\text{He}}c^2 - 2m_{^1_1\text{H}}c^2$$

$$= \left[2\left(3.016029\,\text{u}\right) - 4.002603 - 2\left(1.007825\,\text{u}\right)\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2 = \boxed{12.86\,\text{MeV}}$$

29. Reaction 31-8a: $\dfrac{4.03\,\text{MeV}}{2\left(2.014\,\text{u}\right)} \times \dfrac{1\,\text{u}}{1.66\times10^{-27}\,\text{kg}} \times \dfrac{1\,\text{kg}}{1000\,\text{g}} = \boxed{6.03\times10^{23}\,\text{MeV/g}}$

Reaction 31-8b: $\dfrac{3.27\,\text{MeV}}{2\left(2.014\,\text{u}\right)} \times \dfrac{1\,\text{u}}{1.66\times10^{-27}\,\text{kg}} \times \dfrac{1\,\text{kg}}{1000\,\text{g}} = \boxed{4.89\times10^{23}\,\text{MeV/g}}$

Reaction 31-8c: $\dfrac{17.59\,\text{MeV}}{(2.014\,\text{u}+3.016\,\text{u})}\times\dfrac{1\,\text{u}}{1.66\times10^{-27}\,\text{kg}}\times\dfrac{1\,\text{kg}}{1000\,\text{g}}=\boxed{2.11\times10^{24}\,\text{MeV/g}}$

Uranium fission (200 MeV per nucleus):

$$\frac{200\,\text{MeV}}{(235\,\text{u})}\times\frac{1\,\text{u}}{1.66\times10^{-27}\,\text{kg}}\times\frac{1\,\text{kg}}{1000\,\text{g}}=\boxed{5.13\times10^{23}\,\text{MeV/g}}$$

All are within about a factor of 5 of each other.

30. Calculate the $Q$-value for the reaction ${}^{238}_{92}\text{U}+\text{n}\rightarrow{}^{239}_{92}\text{U}$

$$Q=m_{{}^{238}_{92}\text{U}}c^2+m_\text{n}c^2-m_{{}^{239}_{92}\text{U}}c^2$$

$$=\left[238.050783\,\text{u}+1.008665\,\text{u}-239.054288\,\text{u}\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2=\boxed{4.807\,\text{MeV}}$$

31. The reaction of Eq. 31-8b consumes 2 deuterons and releases 3.27 MeV of energy. The amount of energy needed is the power times the elapsed time, and the energy can be related to the mass of deuterium by the reaction.

$$\left(950\frac{\text{J}}{\text{s}}\right)(1\text{ yr})\left(3.156\times10^7\frac{\text{s}}{\text{yr}}\right)\left(\frac{1\,\text{eV}}{1.60\times10^{19}\,\text{J}}\right)\left(\frac{1\,\text{MeV}}{10^6\,\text{eV}}\right)\left(\frac{2\,\text{d}}{3.27\,\text{MeV}}\right)\left(\frac{2.01\times10^{-3}\text{kg}}{6.02\times10^{23}\,\text{d}}\right)$$

$$=3.8\times10^{-4}\,\text{kg}=\boxed{0.38\,\text{g}}$$

32. We assume that the reactants are at rest when they react, and so the total momentum of the system is 0. As a result, the momenta of the two products are equal in magnitude. The available energy of 17.59 MeV is much smaller than the masses involved, and so we use the non-relativistic relationship between momentum and kinetic energy, $\text{KE}=\dfrac{p^2}{2m}\rightarrow p=\sqrt{2m\text{KE}}$

$$\text{KE}_{{}^4_2\text{He}}+\text{KE}_\text{n}=\text{KE}_\text{total}=17.59\,\text{MeV}\qquad p_{{}^4_2\text{He}}=p_\text{n}\rightarrow\sqrt{2m_{{}^4_2\text{He}}\text{KE}_{{}^4_2\text{He}}}=\sqrt{2m_\text{n}\text{KE}_\text{n}}\rightarrow$$

$$m_{{}^4_2\text{He}}\text{KE}_{{}^4_2\text{He}}=m_\text{n}\text{KE}_\text{n}\rightarrow m_{{}^4_2\text{He}}\text{KE}_{{}^4_2\text{He}}=m_\text{n}\left(\text{KE}_\text{total}-\text{KE}_{{}^4_2\text{He}}\right)\rightarrow$$

$$\text{KE}_{{}^4_2\text{He}}=\frac{m_\text{n}}{m_{{}^4_2\text{He}}+m_\text{n}}\text{KE}_\text{total}=\left(\frac{1.008665}{4.002603+1.008665}\right)17.59\,\text{MeV}=3.54\,\text{MeV}\approx\boxed{3.5\,\text{MeV}}$$

$$\text{KE}_\text{n}=\text{KE}_\text{total}-\text{KE}_{{}^4_2\text{He}}=17.59\,\text{MeV}-3.54\,\text{MeV}=14.05\,\text{MeV}\approx\boxed{14\,\text{MeV}}$$

If the plasma temperature were significantly higher, then the approximation of 0 kinetic energy being brought into the reaction would not be reasonable. Thus the results would depend on plasma temperature. A higher plasma temperature would result in higher values for the energies.

33. Assume that the two reactions take place at equal rates, so they are both equally likely. Then from the reaction of 4 deuterons, there would be a total of 7.30 MeV of energy released, or 1.825 MeV per deuteron on the average. A total power of $\dfrac{1000\,\text{MW}}{0.30}=3333\,\text{MW}$ must be obtained from the fusion reactions to provide the required 1000 MW output, because of the 30% efficiency. We convert the power rating to a number of deuterons based on the energy released per reacting deuteron, and then convert that to an amount of water using the natural abundance of deuterium.

$$3333\,\text{MW} \rightarrow \left[\left(3333\times10^{6}\,\frac{\text{J}}{\text{s}}\right)\left(\frac{3600\,\text{s}}{1\,\text{h}}\right)\left(\frac{1\,\text{MeV}}{1.60\times10^{-13}\,\text{J}}\right)\left(\frac{1\text{ d}}{1.825\,\text{MeV}}\right)\left(\frac{1\text{ H atoms}}{0.000115\text{ d's}}\right)\times \left(\frac{1\,\text{H}_2\text{O molecule}}{2\text{ H atoms}}\right)\left(\frac{0.018\text{ kg H}_2\text{O}}{6.02\times10^{23}\,\text{molecules}}\right)\right]$$

$$= 5342\,\text{kg/h} \approx \boxed{5300\,\text{kg/h}}$$

34. In Eq. 31-8a, 4.03 MeV of energy is released for every 2 deuterium atoms. The mass of water can be converted to a number of deuterium atoms.

$$\left(1.0\,\text{kg H}_2\text{O}\right)\left(\frac{6.02\times10^{23}\,\text{H}_2\text{O}}{0.018\,\text{kg H}_2\text{O}}\right)\left(\frac{2\,\text{H}}{1\,\text{H}_2\text{O}}\right)\left(\frac{1.15\times10^{-4}\,\text{d}}{1\text{H}}\right) = 7.692\times10^{21}\,\text{d nuclei} \rightarrow$$

$$\left(7.692\times10^{21}\,\text{d nuclei}\right)\left(\frac{4.03\times10^{6}\,\text{eV}}{2\,\text{d atoms}}\right)\left(\frac{1.60\times10^{-19}\,\text{J}}{1\,\text{eV}}\right) = \boxed{2.48\times10^{9}\,\text{J}}$$

As compared to gasoline: $\frac{2.48\times10^{9}\,\text{J}}{5\times10^{7}\,\text{J}} = \boxed{\text{50 times more than gasoline}}$

35. (*a*) No carbon is consumed in this cycle because one ${}^{12}_{6}\text{C}$ nucleus is required in the first step of the cycle, and one ${}^{12}_{6}\text{C}$ nucleus is produced in the last step of the cycle. The net effect of the cycle can be found by adding all the reactants and all the products together, and canceling what appears on both sides of the reaction.

$${}^{12}_{6}\text{C} + {}^{1}_{1}\text{H} \rightarrow {}^{13}_{7}\text{N} + \gamma$$
$${}^{13}_{7}\text{N} \rightarrow {}^{13}_{6}\text{C} + \text{e}^{+} + v$$
$${}^{13}_{6}\text{C} + {}^{1}_{1}\text{H} \rightarrow {}^{14}_{7}\text{N} + \gamma$$
$${}^{14}_{7}\text{N} + {}^{1}_{1}\text{H} \rightarrow {}^{15}_{8}\text{O} + \gamma$$
$${}^{15}_{8}\text{O} \rightarrow {}^{15}_{7}\text{N} + \text{e}^{+} + v$$
$${}^{15}_{7}\text{N} + {}^{1}_{1}\text{H} \rightarrow {}^{12}_{6}\text{C} + {}^{4}_{2}\text{He}$$

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$${}^{12}_{6}\text{C} + {}^{1}_{1}\text{H} + {}^{13}_{7}\text{N} + {}^{13}_{6}\text{C} + {}^{1}_{1}\text{H} + {}^{14}_{7}\text{N} + {}^{1}_{1}\text{H} + {}^{15}_{8}\text{O} + {}^{15}_{7}\text{N} + {}^{1}_{1}\text{H}$$
$$\rightarrow {}^{13}_{7}\text{N} + \gamma + {}^{13}_{6}\text{C} + \text{e}^{+} + v + {}^{14}_{7}\text{N} + \gamma + {}^{15}_{8}\text{O} + \gamma + {}^{15}_{7}\text{N} + \text{e}^{+} + v + {}^{12}_{6}\text{C} + {}^{4}_{2}\text{He}$$

---

$$4\,{}^{1}_{1}\text{H} \rightarrow {}^{4}_{2}\text{He} + 2\,\text{e}^{+} + 2v + 3\gamma$$

There is a difference of one gamma ray in the process, as mentioned in the text.

(*b*) To use the values from Appendix B, we must be sure that number of electrons is balanced as well as the number of protons and electrons. The above "net" equation does not consider the electrons that neutral nuclei would have, because it does not conserve charge. What the above reaction really represents (ignoring the gammas and neutrinos) is the following.

$$4\,{}^{1}_{1}\text{H} \rightarrow {}^{4}_{2}\text{He} + 2\,\text{e}^{+} \quad \Rightarrow \quad 4\,{}^{1}_{1}\text{p} \rightarrow 2\,{}^{1}_{1}\text{p} + 2\,{}^{1}_{0}\text{n} + 2\text{e}^{+}$$

To use the values from Appendix B, we must add 4 electrons to each side of the reaction.

$$\left(4\,{}^{1}_{1}\text{p} + 4\text{e}^{-}\right) \rightarrow \left(2\,{}^{1}_{1}\text{p} + 2\text{e}^{-} + 2\,{}^{1}_{0}\text{n}\right) + 2\text{e}^{+} + 2\text{e}^{-} \quad \Rightarrow \quad 4\,{}^{1}_{1}\text{H} \rightarrow {}^{4}_{2}\text{He} + 2\text{e}^{+} + 2\text{e}^{-}$$

The energy produced in the reaction is the *Q*-value.

$$Q = 4m_{{}^1_1\text{H}}c^2 - m_{{}^4_2\text{He}}c^2 - 4m_\text{e}$$

$$= \left[4(1.007825\,\text{u}) - 4.002603\,\text{u} - 4(0.000549\,\text{u})\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2 = \boxed{24.69\,\text{MeV}}$$

(*c*) In some reactions extra electrons must be added in order to use the values from Appendix B. The first equation is electron-balanced, and so Appendix B can be used.

$$Q = m_{{}^{12}_6\text{C}}c^2 + m_{{}^1_1\text{H}}c^2 - m_{{}^{13}_7\text{N}}c^2$$

$$= \left[12.000000\,\text{u} + 1.007825\,\text{u} - 13.005739\,\text{u}\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2 = \boxed{1.943\,\text{MeV}}$$

The second equation needs to have another electron, so that ${}^{13}_7\text{N} \rightarrow {}^{13}_6\text{C} + \text{e}^- + \text{e}^+ + v$.

$$Q = m_{{}^{13}_7\text{N}}c^2 - m_{{}^{13}_6\text{C}}c^2 - 2m_\text{e}c^2$$

$$= \left[13.005739\,\text{u} - 13.003355\,\text{u} - 2(0.000549\,\text{u})\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2 = \boxed{1.198\,\text{MeV}}$$

The third equation is electron-balanced.

$$Q = m_{{}^{13}_6\text{C}}c^2 + m_{{}^1_1\text{H}}c^2 - m_{{}^{14}_7\text{N}}c^2$$

$$= \left[13.003355\,\text{u} + 1.007825\,\text{u} - 14.003074\,\text{u}\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2 = \boxed{7.551\,\text{MeV}}$$

The fourth equation is electron-balanced.

$$Q = m_{{}^{14}_7\text{N}}c^2 + m_{{}^1_1\text{H}}c^2 - m_{{}^{15}_8\text{O}}c^2$$

$$= \left[14.003074\,\text{u} + 1.007825\,\text{u} - 15.003065\,\text{u}\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2 = \boxed{7.297\,\text{MeV}}$$

The fifth equation needs to have another electron, so that ${}^{15}_8\text{O} \rightarrow {}^{15}_7\text{N} + \text{e}^- + \text{e}^+ + v$.

$$Q = m_{{}^{15}_8\text{O}}c^2 - m_{{}^{15}_7\text{N}}c^2 - 2m_\text{e}c^2$$

$$= \left[15.003065\,\text{u} - 15.000109\,\text{u} - 2(0.000549\,\text{u})\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2 = \boxed{1.731\,\text{MeV}}$$

The sixth equation is electron-balanced.

$$Q = m_{{}^{15}_7\text{N}}c^2 + m_{{}^1_1\text{H}}c^2 - m_{{}^{12}_6\text{C}}c^2 - m_{{}^4_2\text{He}}c^2$$

$$= \left[15.000109\,\text{u} + 1.007825\,\text{u} - 12.000000\,\text{u} - 4.002603\,\text{u}\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2$$

$$= \boxed{4.966\,\text{MeV}}$$

The total is found as follows.

$$1.943\,\text{MeV} + 1.198\,\text{MeV} + 7.551\,\text{MeV} + 7.297\,\text{MeV} + 1.731\,\text{MeV} + 4.966\,\text{MeV}$$

$$= 24.69\,\text{MeV}$$

(*d*) It takes a higher temperature for this reaction than for a proton-proton reaction because the reactants have to have more initial kinetic energy to overcome the Coulomb repulsion of one nucleus to another. In particular, the carbon and nitrogen nuclei have higher Z values leading to the requirement of a high temperature.

36. (*a*) We follow the method of Example 31-9. The reaction is ${}^{12}_{6}\text{C} + {}^{1}_{1}\text{H} \rightarrow {}^{13}_{7}\text{N} + \gamma$. We calculate the potential energy of the particles when they are separated by the sum of their radii. The radii are calculated from Eq. 30-1.

$$\text{KE}_{\text{total}} = \frac{1}{4\pi\varepsilon_0}\frac{q_C q_H}{r_C + r_H} = \left(9.0\times10^9\ \text{N}\bullet\text{m}^2/\text{C}^2\right)\frac{(6)(1)\left(1.60\times10^{-19}\,\text{C}\right)^2}{\left(1.2\times10^{-15}\text{m}\right)\left(1^{1/3}+12^{1/3}\right)}\left(\frac{1\,\text{MeV}}{1.60\times10^{-13}\,\text{J}}\right)$$
$$= 2.19\,\text{MeV}$$

For the d-t reaction, Example 31-9 shows $\text{KE}_{\text{total}} = 0.45\,\text{MeV}$. Find the ratio of the two energies.

$$\frac{\text{KE}_C}{\text{KE}_{d-t}} = \frac{2.19\,\text{MeV}}{0.45\,\text{MeV}} = 4.9$$

The carbon reaction requires about 5 times more energy than the d-t reaction.

(*b*) Since the kinetic energy is proportional to the temperature by $\overline{\text{KE}} = \frac{3}{2}kT$, since the kinetic energy has to increase by a factor of 5, so does the temperature. Thus we estimate $T \approx 1.5\times10^9\,\text{K}$.

37. Use Eq. 31-10b to relate Sv to Gy. From Table 31.1, the quality factor of gamma rays is 1, and so the number of Sv is equal to the number of Gy. Thus $4.0\,\text{Sv} = \boxed{4.0\,\text{Gy}}$.

38. Because the quality factor of alpha particles is 20 and the quality factor of X-rays is 1, it takes 20 times as many rads of X-rays to cause the same biological damage as compared to alpha particles. Thus the fifty rads of alpha particles is equivalent to $50\,\text{rad}\times20 = \boxed{1000\,\text{rad}}$ of X-rays.

39. The biological damage is measured by the effective dose, Eq. 31-10b.

$$75\,\text{rad fast neutrons}\times10 = x\,\text{rad slow neutrons}\times3 \ \rightarrow\ x = \frac{75\,\text{rad}\times10}{3} = \boxed{250\,\text{rad slow neutrons}}$$

40. A gray is 1 Joule per kg, according to Eq. 31-9.

$$2.0\frac{\text{J}}{\text{kg}}\times65\,\text{kg} = \boxed{130\,\text{J}}$$

41. The counting rate will be 85% of 25% of the activity.

$$\left(0.025\times10^{-6}\,\text{Ci}\right)\left(\frac{3.7\times10^{10}\,\text{decays/s}}{1\,\text{Ci}}\right)\left(\frac{1\beta}{1\,\text{decays}}\right)(0.25)(0.85) = 196.6\frac{\text{counts}}{\text{s}} \approx \boxed{200\,\text{counts/s}}$$

42. (*a*) Since the quality factor is 1, the effective dose (in rem) is the same as the absorbed dose (in rad). Thus the absorbed dose is 1 rad or 0.01 Gy.

(*b*) A Gy is a J per kg.

$$(0.01\,\text{Gy})\left(\frac{1\,\text{J/kg}}{1\,\text{Gy}}\right)(0.25\,\text{kg})\left(\frac{1\,\text{eV}}{1.60\times10^{-19}\,\text{J}}\right)\left(\frac{1\,\text{p}}{1.2\times10^6\,\text{eV}}\right) = \boxed{1.3\times10^{10}\,\text{p}}$$

43. Let us start by approximating the decay rate as constant, and finding the time to administer 36 Gy. If that calculated time is significantly shorter than the half-life of the isotope, then our approximation is reasonable.

$$\text{dose} = \text{rate} \times \text{time} \quad \rightarrow \quad \text{time} = \frac{\text{dose}}{\text{rate}} = \frac{36\,\text{Gy}}{10\times10^{-3}\,\text{Gy/min}} = 3600\,\text{min} \times \frac{1\,\text{day}}{1440\,\text{min}} = \boxed{2.5\,\text{day}}$$

This is only about 17% of a half life, so our approximation is reasonable.

44. The two definitions of roentgen are $1.6\times10^{12}$ ion pairs/g produced by the radiation, and $0.878\times10^{-2}$ J/kg deposited by the radiation. Start with the current definition, and relate them by the value of 35 eV per ion pair.

$$\left(0.878\times10^{-2}\,\text{J/kg}\right)\left(1\,\text{kg}/1000\,\text{g}\right)\left(1\,\text{eV}/1.60\times10^{-19}\,\text{J}\right)\left(1\,\text{ion pair}/35\,\text{eV}\right)$$
$$= 1.567\times10^{12}\ \text{ion pairs/g}$$

The two values are within about 2% of each other.

45. Each decay releases one gamma ray of energy 122 keV. Half of that energy is deposited in the body. The activity tells at what rate the gamma rays are released into the body. We assume the activity is constant.

$$\left(1.85\times10^{-6}\,\text{Ci}\right)\left(3.70\times10^{10}\,\frac{\text{gammas}}{\text{s}}\right)\left(86400\frac{\text{s}}{\text{day}}\right)\left(61\frac{\text{keV}}{\text{gamma}}\right)\left(1.60\times10^{-16}\,\frac{\text{J}}{\text{keV}}\right)\left(\frac{1}{70\,\text{kg}}\right)$$
$$= 8.25\times10^{-7}\,\frac{\text{J/kg}}{\text{day}} = \boxed{8.25\times10^{-7}\,\frac{\text{Gy}}{\text{day}}}$$

46. Since the half-life is long (5730 yr) we can consider the activity as constant over a short period of time. Use the definition of the curie from section 31-5.

$$1.00\times10^{-6}\,\text{Ci}\times\frac{3.70\times10^{10}\,\text{decays/s}}{1\,\text{Ci}} = 3.70\times10^{4}\,\text{decays/s} = \frac{\Delta N}{\Delta t} = \frac{0.693}{T_{\frac{1}{2}}}N \quad \rightarrow$$

$$N = \frac{\Delta N}{\Delta t}\frac{T_{\frac{1}{2}}}{0.693} = \left(3.70\times10^{4}\,\text{decays/s}\right)\frac{5730\,\text{y}}{0.693}\left(3.156\times10^{7}\,\text{s/y}\right) = 9.655\times10^{15}\,\text{nuclei}$$

$$9.655\times10^{15}\,\text{nuclei}\left(\frac{0.014\,\text{kg}}{6.02\times10^{23}\,\text{nuclei}}\right) = \boxed{2.25\times10^{-10}\,\text{kg}}$$

47. (*a*) According to Appendix B, ${}^{131}_{53}\text{I}$ decays by beta decay.

$${}^{131}_{53}\text{I} \rightarrow {}^{131}_{54}\text{Xe} + \beta^{-} + \overline{\nu}$$

(*b*) The number of nuclei present is given by Eq. 30-4.

$$N = N_0 e^{-\lambda t} \quad \rightarrow \quad t = -\frac{\ln\frac{N}{N_0}}{\lambda} = -\frac{T_{1/2}\ln\frac{N}{N_0}}{0.693} = -\frac{\left(8.0\,\text{d}\right)\ln 0.10}{0.693} = 26.58\,\text{d} \approx \boxed{27\,\text{d}}$$

(*c*) The activity is given by $\frac{\Delta N}{\Delta t} = \lambda N$. This can be used to find the number of nuclei, and then the mass can be found.

$$\frac{\Delta N}{\Delta t} = \lambda N \quad \rightarrow$$

$$N = \frac{\Delta N/\Delta t}{\lambda} = \frac{(T_{1/2})(\Delta N/\Delta t)}{0.693} = \frac{(8.0\,\text{d})(86400\,\text{s/d})(1\times10^{-3}\,\text{Ci})(3.70\times10^{10}\text{ decays/s})}{0.693}$$

$$= 3.69\times10^{13}\,\text{nuclei}$$

$$3.69\times10^{13}\,\text{nuclei}\left(\frac{0.131\,\text{kg}}{6.02\times10^{23}\,\text{nuclei}}\right) = \boxed{8.0\times10^{-12}\,\text{kg}}$$

48. The activity is converted to decays per day, then to energy per year, and finally to a dose per year. The potassium decays by gammas and betas, according to Appendix B. Gammas and betas have a quality factor of 1, so the number of Sv is the same as the number of Gy, and the number of rem is the same as the number of rad.

$$\left(2000\times10^{-12}\,\frac{\text{Ci}}{\text{L}}\right)\left(3.70\times10^{10}\,\frac{\text{decays/s}}{1\,\text{Ci}}\right)\left(12\,\text{hr}\,\frac{3600\,\text{s}}{\text{hr}}\right)\left(0.5\,\frac{\text{L}}{\text{day}}\right) = 1.598\times10^{6}\,\frac{\text{decays}}{\text{day}}$$

$$\left(1.598\times10^{6}\,\frac{\text{decays}}{\text{day}}\right)\left(365\,\frac{\text{day}}{\text{yr}}\right)\left(0.15\times10^{6}\,\frac{\text{eV}}{\text{decay}}\right)\left(\frac{1.60\times10^{-19}\,\text{J}}{\text{eV}}\right) = 1.400\times10^{-5}\,\frac{\text{J}}{\text{yr}}$$

(*a*) $$\left(1.400\times10^{-5}\,\frac{\text{J}}{\text{yr}}\right)\left(\frac{1}{50\,\text{kg}}\right)\left(\frac{1\,\text{Gy}}{1\,\text{J/kg}}\right) = 2.80\times10^{-7}\,\frac{\text{Gy}}{\text{year}} \approx \boxed{3\times10^{-7}\,\frac{\text{Sv}}{\text{year}}}$$

$$\left(2.80\times10^{-7}\,\frac{\text{Gy}}{\text{year}}\right)\left(\frac{100\,\text{rad}}{1\,\text{Gy}}\right) = 2.80\times10^{-5}\,\frac{\text{rad}}{\text{year}} \approx \boxed{3\times10^{-5}\,\frac{\text{rem}}{\text{year}}}$$

$$\text{fraction of allowed dose} = \frac{2.80\times10^{-5}\,\frac{\text{rem}}{\text{year}}}{100\times10^{-3}\,\frac{\text{rem}}{\text{year}}} \approx \boxed{3\times10^{-4}\text{ times the allowed dose}}$$

(*b*) For the baby, the only difference is that the mass is 10 times smaller, so the effective dose is 10 times bigger. The results are as follows.

$$\boxed{3\times10^{-6}\,\frac{\text{Sv}}{\text{year}},\ 3\times10^{-4}\,\frac{\text{rem}}{\text{year}},\ 3\times10^{-4}\text{ times the allowed dose}}$$

49. (*a*) The reaction has 86 protons and 222 total nucleons in the parent nucleus. Thus the alpha and the daughter nucleus must have a total of 86 protons and 222 total nucleons. The alpha has 2 protons and 4 total nucleons, so the daughter nucleus must have 84 protons and 218 total nucleons. That makes the daughter nucleus $\boxed{{}^{218}_{84}\text{Po}}$

(*b*) From figure 30-11, polonium-218 is $\boxed{\text{radioactive}}$. It decays via both $\boxed{\text{alpha and beta decay}}$, each with a half-life of $\boxed{3.1\text{ minutes}}$.

(*c*) The daughter nucleus is not a noble gas, so it is $\boxed{\text{chemically reacting}}$. It is in the same group as oxygen, so it might react with many other elements chemically.

(*d*) The activity is given by $\dfrac{\Delta N}{\Delta t} = \dfrac{0.693}{T_{\frac{1}{2}}}N$.

$$\frac{\Delta N}{\Delta t}=\frac{0.693}{T_{\frac{1}{2}}}N=\frac{0.693}{(3.8235\,\text{d})(86400\,\text{s/d})}\left(1.0\times10^{-9}\,\text{g}\right)\frac{6.02\times10^{23}\,\text{nuclei}}{222\text{ g}}$$

$$=5.689\times10^{6}\text{ decays/s}\approx\boxed{5.7\times10^{6}\,\text{Bq}}$$

To find the activity after 1 month, use Eq. 30-5.

$$\frac{\Delta N}{\Delta t}=\left(\frac{\Delta N}{\Delta t}\right)_0 e^{-\frac{0.693}{T_{1/2}}t}=\left(5.689\times10^{6}\text{ decays/s}\right)e^{-\frac{0.693}{(3.8235\,\text{d})}(30\text{ d})}=2.475\times10^{4}\text{ decays/s}$$

$$\approx\boxed{2.5\times10^{5}\,\text{Bq}}$$

50. The frequency is given in section 31-9 to be 42.58 MHz. Use that to find the wavelength.

$$c=f\lambda\ \rightarrow\ \lambda=\frac{c}{f}=\frac{2.998\times10^{8}\text{ m/s}}{42.58\times10^{6}\,\text{Hz}}=\boxed{7.041\,\text{m}}$$

This lies in the $\boxed{\text{radio wave}}$ portion of the spectrum.

51. (*a*) The reaction is ${}^{9}_{4}\text{Be}+{}^{4}_{2}\text{He}\rightarrow \text{n}+?$. There are 6 protons and 13 nucleons in the reactants, and so there must be 6 protons and 13 nucleons in the products. The neutron is 1 nucleon, so the other product must have 6 protons ad 12 nucleons. Thus it is $\boxed{{}^{12}_{6}\text{C}}$.

(*b*) $Q=m_{{}^{9}_{4}\text{Be}}c^2+m_{{}^{4}_{2}\text{He}}c^2-m_{\text{n}}c^2-m_{{}^{12}_{6}\text{U}}c^2$

$$=\left[9.012182\,\text{u}+4.002603\,\text{u}-1.008665\,\text{u}-12.000000\,\text{u}\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2=\boxed{5.701\,\text{MeV}}$$

52. If $\overline{\text{KE}}=kT$, then to get from kelvins to keV, the Boltzmann constant would be used. It must simply be put in the proper units.

$$k=1.381\times10^{-23}\,\frac{\text{J}}{\text{K}}\times\frac{1\,\text{eV}}{1.602\times10^{-19}\,\text{J}}\times\frac{1\,\text{keV}}{1000\,\text{eV}}=\boxed{8.62\times10^{-8}\text{ keV/K}}$$

$\boxed{53.}$ From Eq. 13-9, the average speed of a gas molecule (root mean square speed) is inversely proportional to the square root of the mass of the molecule, if the temperature is constant. We assume that the two gases are in the same environment and so at the same temperature. We use $UF_6$ molecules for the calculations.

$$\frac{v_{{}^{235}_{92}\text{UF}_6}}{v_{{}^{238}_{92}\text{UF}_6}}=\sqrt{\frac{m_{{}^{238}_{92}\text{UF}_6}}{m_{{}^{235}_{92}\text{UF}_6}}}=\sqrt{\frac{238+6(19)}{235+6(19)}}=\boxed{1.0043:1}$$

54. (*a*) We assume that the energy produced by the fission was 200 MeV per fission, as in problems 18 and 19.

$$\left(20\,\text{kilotons TNT}\right)\left(\frac{5\times10^{12}\text{J}}{1\,\text{kiloton}}\right)\left(\frac{1\,\text{MeV}}{1.60\times10^{-13}\text{J}}\right)\left(\frac{1\,\text{fission atom}}{200\,\text{MeV}}\right)\left(\frac{0.235\,\text{kg}}{6.02\times10^{23}\,\text{atom}}\right)$$

$$=1.220\,\text{kg}\approx\boxed{1\,\text{kg}}$$

(*b*) Use $E = mc^2$.

$$E = mc^2 \quad \rightarrow \quad m = \frac{E}{c^2} = \frac{(20\,\text{kilotons TNT})\left(\dfrac{5\times10^{12}\,\text{J}}{1\,\text{kiloton}}\right)}{\left(3.0\times10^{8}\,\text{m/s}\right)^2} = 1.11\times10^{-3}\,\text{kg} \approx \boxed{1\,\text{g}}$$

55. The effective dose (in rem) is equal to the actual dose (in rad) times the quality factor.

$$\text{dose}(\text{rem}) = \left(21\times10^{-3}\,\text{rad/yr X-ray, }\gamma\text{-ray}\right)(1) + \left(3.0\times10^{-3}\,\text{rad/yr}\right)(10) = \boxed{5.1\times10^{-2}\,\text{rem/yr}}$$

56. The oceans cover about 70% of the Earth, to an average depth of approximately 4 km. The density of the water is approximately $1000\,\text{kg/m}^3$. Find the volume of water using the surface area of the Earth. Then convert that volume of water to mass, to the number of water molecules, to the number of hydrogen atoms, and then finally to the number of deuterium atoms using the natural abundance of deuterium from Appendix B.

$$\text{Mass of water} = (\text{surface area})(\text{depth})(\text{density}) = 4\pi\left(6.38\times10^{6}\,\text{m}\right)^2(4000\,\text{m})\left(1000\,\text{kg/m}^3\right)$$

$$= 2.05\times10^{21}\,\text{kg water}$$

$$\left(2.05\times10^{21}\,\text{kg water}\right)\times\frac{6.02\times10^{23}\,\text{molecules}}{0.018\,\text{kg water}}\times\frac{2\text{ H atoms}}{1\text{ molecule}}\times\frac{0.000115\text{ d atoms}}{1\text{ H atom}}$$

$$= 1.58\times10^{43}\,\text{d} \approx \boxed{2\times10^{43}\,\text{d atoms}}$$

$$= 1.58\times10^{43}\,\text{d}\times\frac{2\times10^{-3}\,\text{kg}}{6.02\times10^{23}\,\text{d atoms}} \approx \boxed{5\times10^{16}\,\text{kg d}}$$

From Eqs. 31-8a and 31-8b, we see that, if the two reactions are carried out at the same rate, that 4 deuterons would produce 7.30 MeV of energy. Use that relationship to convert the number of deuterons in the oceans to energy.

$$\left(1.58\times10^{43}\,\text{d}\right)\times\frac{7.30\,\text{MeV}}{4\text{ d}}\times\frac{1.60\times10^{-13}\,\text{J}}{1\,\text{MeV}} = 4.61\times10^{30}\,\text{J} \simeq \boxed{5\times10^{30}\,\text{J}}$$

57. Because the quality factor for gamma rays is 1, the dose in rem is equal in number to the dose in rad. Since the intensity falls off as the square of the distance, the exposure rate times the square of the distance will be constant.

$$\text{Allowed dose} = \frac{5\,\text{rem}}{\text{year}}\times\frac{1\,\text{rad}}{1\,\text{rem}}\frac{1\text{ year}}{52\text{ weeks}}\times\frac{1\,\text{week}}{40\,\text{hours}} = 2.404\times10^{-3}\,\frac{\text{rad}}{\text{hour}}$$

$$\left(2.404\times10^{-3}\,\frac{\text{rad}}{\text{hour}}\right)r^2 = \left(5.2\times10^{-2}\,\frac{\text{rad}}{\text{hour}}\right)(1\,\text{m})^2 \quad\rightarrow\quad r = \sqrt{\frac{\left(5.2\times10^{-2}\,\dfrac{\text{rad}}{\text{hour}}\right)(1\,\text{m})^2}{\left(2.404\times10^{-3}\,\dfrac{\text{rad}}{\text{hour}}\right)}} = \boxed{4.7\,\text{m}}$$

58. (*a*) The reaction is of the form $? \rightarrow {}^{4}_{2}\text{He} + {}^{222}_{86}\text{Rn}$. There are 88 protons and 226 nucleons as products, so there must be 88 protons and 226 nucleons as reactants. Thus the parent nucleus is ${}^{226}_{88}\text{Ra}$.

$${}^{226}_{88}\text{Ra} \rightarrow {}^{4}_{2}\text{He} + {}^{222}_{86}\text{Rn}$$

(*b*) If we ignore the KE of the daughter nucleus, then the KE of the alpha particle is the *Q*-value of the reaction.

$$\mathrm{KE}_\alpha = m_{^{226}_{88}\mathrm{Ra}}c^2 - m_{^{4}_{2}\mathrm{He}}c^2 - m_{^{222}_{86}\mathrm{Rn}}c^2$$

$$= \left[226.025403\,\mathrm{u} - 4.002603\,\mathrm{u} - 222.017570\,\mathrm{u}\right]\left(931.5\frac{\mathrm{MeV}/c^2}{\mathrm{u}}\right)c^2 = 4.872\,\mathrm{MeV}$$

(*c*) From momentum conservation, the momentum of the alpha particle will be equal in magnitude to the momentum of the alpha particle. At the energy above, the alpha particle is not relativistic, and so $\mathrm{KE}_\alpha = \frac{p_\alpha^2}{2m_\alpha} \rightarrow p_a = \sqrt{2m_a\mathrm{KE}_a}$.

$$p_\alpha = \sqrt{2m_a\mathrm{KE}_a} = \sqrt{2\left(4.003\,\mathrm{u}\right)\left(\frac{931.5\,\mathrm{MeV}/c^2}{1\,\mathrm{u}}\right)\left(4.872\,\mathrm{MeV}\right)} = 191\,\mathrm{MeV}/c$$

(*d*) Since $p_\alpha = p_{\mathrm{daughter}}$, $\mathrm{KE}_{\mathrm{daughter}} = \frac{p_{\mathrm{daughter}}^2}{2m_{\mathrm{daughter}}} = \frac{p_\alpha^2}{2m_{\mathrm{daughter}}}$.

$$\mathrm{KE}_{\mathrm{daughter}} = \frac{p_\alpha^2}{2m_{\mathrm{daughter}}} = \frac{\left(191\,\mathrm{MeV}/c\right)^2}{2\left(222\,\mathrm{u}\right)\left(\frac{931.5\,\mathrm{MeV}/c^2}{1\,\mathrm{u}}\right)} = \boxed{8.82\times10^{-2}\,\mathrm{MeV}}$$

Thus we see that our original assumption of ignoring the KE of the daughter nucleus is valid. The KE of the daughter is less than 2% of the *Q*-value.

59. (*a*) The mass of fuel can be found by converting the power to energy to number of nuclei to mass.

$$\left(3400\times10^6\,\mathrm{J/s}\right)\left(1\,\mathrm{y}\right)\left(\frac{3.156\times10^7\mathrm{s}}{1\,\mathrm{y}}\right)\left(\frac{1\,\mathrm{MeV}}{1.60\times10^{-13}\mathrm{J}}\right)\left(\frac{1\,\text{fission atom}}{200\,\mathrm{MeV}}\right)\left(\frac{0.235\,\mathrm{kg}}{6.02\times10^{23}\,\mathrm{atom}}\right)$$

$$= 1.309\times10^3\,\mathrm{kg} \approx \boxed{1300\,\mathrm{kg}}$$

(*b*) The product of the first 5 factors above gives the number of U atoms that fission.

$$\#\mathrm{Sr\ atoms} = 0.06\left(3400\times10^6\,\mathrm{J/s}\right)\left(1\,\mathrm{y}\right)\left(\frac{3.156\times10^7\mathrm{s}}{1\,\mathrm{y}}\right)\left(\frac{1\,\mathrm{MeV}}{1.60\times10^{-13}\mathrm{J}}\right)\left(\frac{1\,\text{fission atom}}{200\,\mathrm{MeV}}\right)$$

$$= 2.01\times10^{26}\,\mathrm{Sr\ atoms}$$

The activity is given by Eq. 30-3b.

$$\frac{\Delta N}{\Delta t} = \lambda N = \frac{0.693}{T_{1/2}}N = \frac{0.693}{\left(29\,\mathrm{yr}\right)\left(3.156\times10^7\,\mathrm{s/yr}\right)}\left(2.01\times10^{26}\right) = 1.522\times10^{17}\,\frac{\mathrm{decays}}{\mathrm{s}}$$

$$= \left(1.522\times10^{17}\,\mathrm{decays/s}\right)\left(\frac{1\,\mathrm{Ci}}{3.70\times10^{10}\,\mathrm{decays/s}}\right) = \boxed{4.1\times10^6\,\mathrm{Ci}}$$

60. This "heat of combustion" is 26.2 MeV / 4 hydrogen atoms.

$$\frac{26.2\,\mathrm{MeV}}{4\ \mathrm{H\ atoms}}\times\frac{10^6\,\mathrm{eV}}{1\,\mathrm{MeV}}\times\frac{1.60\times10^{-19}\,\mathrm{J}}{1\,\mathrm{eV}}\times\frac{1\,\mathrm{H\,atom}}{1.008\,\mathrm{u}}\times\frac{1\,\mathrm{u}}{1.66\times10^{-27}\,\mathrm{kg}} = \boxed{6.26\times10^{14}\,\mathrm{J/kg}}$$

This is about $\boxed{2\times10^7}$ times the heat of combustion of coal.

61. (*a*) The energy is radiated uniformly over a sphere with a radius equal to the orbit radius of the Earth.

$$\left(1400\frac{\text{W}}{\text{m}^2}\right)4\pi\left(1.496\times10^{11}\,\text{m}\right)^2 = 3.937\times10^{26}\,\text{W} \approx \boxed{4.0\times10^{26}\,\text{W}}$$

(*b*) The reaction of Eq. 31-7 releases 26.7 MeV for every 4 protons consumed.

$$\left(3.937\times10^{26}\,\frac{\text{J}}{\text{s}}\right)\times\frac{4\text{ protons}}{26.7\,\text{MeV}}\times\frac{1\,\text{MeV}}{1.60\times10^{-13}\,\text{J}} = 3.686\times10^{38}\text{ protons/s} \approx \boxed{3.7\times10^{38}\text{ protons/s}}$$

(*c*) Convert the Sun's mass to a number of protons, and then use the above result to estimate the Sun's lifetime.

$$2.0\times10^{30}\,\text{kg}\left(\frac{1\,\text{proton}}{1.673\times10^{-27}\text{kg}}\right)\left(\frac{1\,\text{s}}{3.686\times10^{38}\,\text{protons}}\right)\left(\frac{1\,\text{yr}}{3.156\times10^{7}}\right) \approx \boxed{1.0\times10^{11}\,\text{yr}}$$

62. (*a*) The energy released is given by the *Q*-value.

$$Q = 2m_{^{12}_{6}\text{C}}c^2 - m_{^{24}_{12}\text{Mg}}c^2 = \left[2\left(12.000000\,\text{u}\right) - 23.985042\,\text{u}\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2 = 13.93\,\text{MeV}$$

(*b*) The total kinetic energy of the two nuclei must equal their potential energy when separated by 6.0 fm.

$$2\text{KE} = \frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{r} \quad\rightarrow$$

$$\text{KE} = \tfrac{1}{2}\frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{r} = \tfrac{1}{2}\left(9.0\times10^9\ \text{N}\bullet\text{m}^2/\text{C}^2\right)\frac{\left[(6)\left(1.60\times10^{-19}\,\text{C}\right)\right]^2}{6.0\times10^{-15}\text{m}} = \boxed{6.912\times10^{-13}\,\text{J}}$$

$$= 6.912\times10^{-13}\,\text{J}\left(1\text{eV}/1.60\times10^{-19}\,\text{J}\right)\left(1\,\text{MeV}/10^6\,\text{eV}\right) = \boxed{4.32\,\text{MeV}}$$

(*c*) The kinetic energy and temperature are related by Eq.13-8.

$$\text{KE} = \tfrac{3}{2}kT \quad\rightarrow\quad T = \tfrac{2}{3}\frac{\text{KE}}{k} = \tfrac{2}{3}\frac{6.912\times10^{-13}\,\text{J}}{1.38\times10^{-23}\ \text{J/K}} = \boxed{3.3\times10^{10}\,\text{K}}$$

63. (*a*) $\left(0.10\times10^{-6}\,\text{Ci}\right)\left(3.7\times10^{10}\text{ decays/s}\right) = \boxed{3700\,\text{decays/s}}$

(*b*) The beta particles have a quality factor of 1. We calculate the dose in gray and then convert to sieverts. The half life is over a billion years, so we assume the activity is constant.

$$\left(3700\,\text{decays/s}\right)\left(1.4\times10^6\ \text{eV/decay}\right)\left(1.60\times10^{-19}\ \text{J/eV}\right)\left(3.156\times10^7\ \text{s/y}\right)\left(\frac{1}{50\,\text{kg}}\right) =$$

$$= 5.23\times10^{-4}\ \text{J/kg/y} = 5.23\times10^{-4}\ \text{Gy/y} = \boxed{5.23\times10^{-4}\ \text{Sv/y}}$$

This is about $\dfrac{5.23\times10^{-4}\ \text{Sv/y}}{3.6\times10^{-3}\ \text{Sv/y}} = 0.15$ or $\boxed{\text{15\% of the background rate}}$.

64. The surface area of a sphere is $4\pi r^2$.

$$\frac{\text{Activity}}{\text{m}^2} = \frac{2.0\times10^7\,\text{Ci}}{4\pi r_{\text{Earth}}^2} = \frac{\left(2.0\times10^7\,\text{Ci}\right)\left(3.7\times10^{10}\text{ decays/s}\right)}{4\pi\left(6.38\times10^6\,\text{m}\right)^2} = \boxed{1.4\times10^3\ \frac{\text{decays/s}}{\text{m}^2}}$$

65. $Q = 3m_{{}^4_2\text{He}}c^2 - m_{{}^{12}_6\text{C}}c^2 = \left[3\left(4.002603\,\text{u}\right) - 12.000000\,\text{u}\right]\left(931.5\frac{\text{MeV}/c^2}{\text{u}}\right)c^2 = \boxed{7.274\,\text{MeV}}$

66. Since the half-life is 30 years, we assume that the activity does not change during the 2.0 hours of exposure. We calculate the total energy absorbed, and then calculate the effective dose. The two energies can be added directly since the quality factor for both gammas and betas is about 1.

$$\text{Energy} = \left[\begin{matrix}\left(1.0\times10^{-6}\,\text{Ci}\right)\left(3.7\times10^{10}\,\frac{\text{decays}}{\text{s}}\right)\left(2.0\,\text{hr}\right)\left(3600\frac{\text{s}}{1\,\text{hr}}\right)\times \\ \left(850\times10^{3}\,\frac{\text{eV}}{\text{decay}}\right)\left(1.60\times10^{-19}\,\frac{\text{J}}{\text{eV}}\right)\end{matrix}\right] = 3.367\times10^{-5}\,\text{J}$$

$$\text{dose} = \frac{3.367\times10^{-5}\,\text{J}}{75\,\text{kg}}\times\frac{100\text{rad}}{1\,\text{J}/\text{kg}} = 4.83\times10^{-5}\,\text{rad} \approx \boxed{4.8\times10^{-5}\,\text{rem}}$$

67. The half life of the strontium isotope is 28.79 years. Use that with Eq. 30-5 to find the time for the activity to be reduced to 10% of its initial value.

$$\frac{\Delta N}{\Delta t} = \left(\frac{\Delta N}{\Delta t}\right)_0 e^{-\frac{0.693}{T_{1/2}}t} \rightarrow 0.10\left(\frac{\Delta N}{\Delta t}\right)_0 = \left(\frac{\Delta N}{\Delta t}\right)_0 e^{-\frac{0.693}{T_{1/2}}t} \rightarrow 0.10 = e^{-\frac{0.693}{T_{1/2}}t} \rightarrow$$

$$\ln\left(0.10\right) = -\frac{0.693}{T_{1/2}}t \rightarrow t = -\frac{T_{1/2}\ln\left(0.10\right)}{0.693} = -\frac{\left(28.79\,\text{y}\right)\ln\left(0.10\right)}{0.693} \approx \boxed{96\,\text{y}}$$

68. Source B is more dangerous than source A because of its higher energy. Since both sources have the same activity, they both emit the same number of gammas. Source B can deposit more energy per gamma and therefore cause more biological damage.

Source C is more dangerous than source B because the alphas have a quality factor up to 20 times larger than the gammas. Thus a number of alphas may have an effective dose up to 20 times higher than the effective dose of the same number of like-energy gammas.

So from most dangerous to least dangerous, the ranking of the sources is $\boxed{\text{C} - \text{B} - \text{A}}$ .

69. The whole-body dose can be converted into a number of decays, which would be the maximum number of nuclei that could be in the Tc sample. The quality factor of gammas is 1.

$$50\,\text{mrem} = 50\,\text{mrad} \rightarrow \left(50\times10^{-3}\,\text{rad}\right)\times\frac{1\,\text{J}/\text{kg}}{100\,\text{rad}}\times\left(70\,\text{kg}\right)\times\frac{1\,\text{eV}}{1.60\times10^{-19}\,\text{J}} = 2.19\times10^{17}\,\text{eV}$$

$$\left(2.19\times10^{17}\,\text{eV}\right)\times\frac{1\text{ effective }\gamma}{140\times10^{3}\text{eV}}\times\frac{2\,\gamma\text{ decays}}{1\text{ effective }\gamma}\times\frac{1\text{ nucleus}}{1\gamma\text{ decay}} = 3.13\times10^{12}\,\text{nuclei}$$

This then is the total number of decays that will occur. The activity for this number of nuclei can be calculated from Eq. 30-3b.

$$\text{Activity} = \frac{\Delta N}{\Delta t} = \lambda N = \frac{0.693N}{T_{1/2}} = \frac{0.693\left(3.13\times10^{12}\,\text{decays}\right)}{\left(6\,\text{h}\right)\left(3600\,\text{s}/\text{h}\right)}\left(\frac{1\,\text{Ci}}{3.70\times10^{10}\,\text{decays}/\text{s}}\right)$$

$$= 2.71\times10^{-3}\,\text{Ci} \simeq \boxed{3\,\text{mCi}}$$