CHAPTER 30

Quick Quizzes

1. (c). The total energy released was $E = (30 \times 10^3 \text{ ton})(4.0 \times 10^9 \text{ J/ton}) = 1.2 \times 10^{14}$ J. The mass equivalent of this quantity of energy is

$$m = \frac{E}{c^2} = \frac{1.2 \times 10^{14} \text{ J}}{(3.0 \times 10^8 \text{ m/s})^2} = 1.3 \times 10^{-3} \text{ kg} \sim 1 \text{ g}$$

2. (a). This reaction fails to conserve charge and cannot occur.

3. (b). This reaction fails to conserve charge and cannot occur.

4. (c), (e). The proton and the electron each have spin $s = \frac{1}{2}$. The two possible resultant spins after decay are 1 (spins aligned) or 0 (spins anti-aligned). Neither equal the spin of a neutron, $s = \frac{1}{2}$, so spin angular momentum is not conserved. The are no leptons present before the proposed decay and one lepton (the electron) present after decay. Thus, the decay also fails to conserve lepton number.

Problem Solutions

30.1 $\boxed{{}_0^1\text{n} + {}_{92}^{235}\text{U} \rightarrow {}_{56}^{141}\text{Ba} + {}_{36}^{92}\text{Kr} + 3\,{}_0^1\text{n}}$

To conserve both charge and the total number of nucleons, it is seen that this reaction must yield $\boxed{3\text{ neutrons}}$ in addition to the other fission products.

30.2 The energy released in the reaction ${}_0^1\text{n} + {}_{92}^{235}\text{U} \rightarrow {}_{40}^{98}\text{Zr} + {}_{52}^{135}\text{Te} + 3\,{}_0^1\text{n}$ is

$$Q = (\Delta m)c^2 = \left[m_{^{235}\text{U}} - 2m_n - m_{^{98}\text{Zr}} - m_{^{135}\text{Te}}\right]c^2$$

$$= \left[235.043\,924\text{ u} - 2(1.008\,665\text{ u}) - 97.912\,0\text{ u} - 134.908\,7\text{ u}\right](931.5\text{ MeV/u})$$

$$= \boxed{192\text{ MeV}}$$

30.3 The energy released in the reaction ${}_0^1\text{n} + {}_{92}^{235}\text{U} \rightarrow {}_{38}^{88}\text{Sr} + {}_{54}^{136}\text{Xe} + 12\,{}_0^1\text{n}$ is

$$Q = (\Delta m)c^2 = \left[m_{^{235}\text{U}} - 11m_n - m_{^{88}\text{Sr}} - m_{^{136}\text{Xe}}\right]c^2$$

$$= \left[235.043\,924\text{ u} - 11(1.008\,665\text{ u}) - 87.905\,618\text{ u} - 135.907\,215\text{ u}\right](931.5\text{ MeV/u})$$

$$= \boxed{126\text{ MeV}}$$

30.4 Three different fission reactions are possible:

$${}_0^1\text{n} + {}_{92}^{235}\text{U} \rightarrow {}_{38}^{90}\text{Sr} + {}_{54}^{144}\text{Xe} + 2\,{}_0^1\text{n} \qquad \boxed{{}_{54}^{144}\text{Xe}}$$

$${}_0^1\text{n} + {}_{92}^{235}\text{U} \rightarrow {}_{38}^{90}\text{Sr} + {}_{54}^{143}\text{Xe} + 3\,{}_0^1\text{n} \qquad \boxed{{}_{54}^{143}\text{Xe}}$$

$${}_0^1\text{n} + {}_{92}^{235}\text{U} \rightarrow {}_{38}^{90}\text{Sr} + {}_{54}^{142}\text{Xe} + 4\,{}_0^1\text{n} \qquad \boxed{{}_{54}^{142}\text{Xe}}$$

30.5 (a) With a specific gravity of 4.00, the density of soil is $\rho = 4000\text{ kg/m}^3$. Thus, the mass of the top 1.00 m of soil is

$$m = \rho V = \left(4000\ \frac{\text{kg}}{\text{m}^3}\right)\left[(1.00\text{ m})(43\,560\text{ ft}^2)\left(\frac{1\text{ m}}{3.281\text{ ft}}\right)^2\right] = 1.62\times 10^7\text{ kg}$$

At a rate of 1 part per million, the mass of uranium in this soil is then

$$m_{\text{U}} = \frac{m}{10^6} = \frac{1.62\times 10^7 \text{ kg}}{10^6} = \boxed{16.2 \text{ kg}}$$

(b) Since 0.720% of naturally occurring uranium is ^{235}U, the mass of ^{235}U in the soil of part (a) is

$$m_{^{235}\text{U}} = \left(7.20\times 10^{-3}\right)m_{\text{U}} = \left(7.20\times 10^{-3}\right)\left(16.2 \text{ kg}\right) = 0.117 \text{ kg} = \boxed{117 \text{ g}}$$

30.6 At 40.0% efficiency, the useful energy obtained per fission event is

$$E_{event} = 0.400\left(200 \text{ MeV/event}\right)\left(1.60\times 10^{-13} \text{ J/MeV}\right) = 1.28\times 10^{-11} \text{ J/event}$$

The number of fission events required each day is then

$$N = \frac{\wp \cdot t}{E_{event}} = \frac{\left(1.00\times 10^9 \text{ J/s}\right)\left(8.64\times 10^4 \text{ s/d}\right)}{1.28\times 10^{-11} \text{ J/event}} = 6.75\times 10^{24} \text{ events/d}$$

Each fission event consumes one ^{235}U atom. The mass of this number of ^{235}U atoms is

$$m = N m_{atom}$$

$$= \left(6.75\times 10^{24} \text{ events/d}\right)\left[\left(235.044 \text{ u}\right)\left(1.66\times 10^{-27} \text{ kg/u}\right)\right] = \boxed{2.63 \text{ kg/d}}$$

In contrast, a coal-burning steam plant producing the same electrical power uses more than 6×10^6 kg/d of coal.

30.7 The mass of ^{235}U in 1.0-kg of fuel is 0.017 kg, and the number of ^{235}U nuclei is

$$N = \frac{m}{m_{atom}} = \frac{0.017 \text{ kg}}{\left(235.044 \text{ u}\right)\left(1.66\times 10^{-27} \text{ kg/u}\right)} = 4.35\times 10^{22}$$

At 208 MeV per fission event and 20% efficiency, the useful energy available from this number of fission events is

$$E = \left(4.35\times 10^{22} \text{ events}\right)\left[\left(208 \text{ MeV/event}\right)\left(1.60\times 10^{-13} \text{ J/Mev}\right)\right]\left(0.20\right) = 2.9\times 10^{11} \text{ J}$$

From $Work = F_{drag} \cdot s = E$, the distance the ship can travel on this 1.0-kg of fuel is

$$s = \frac{E}{F_{drag}} = \frac{2.9\times 10^{11}\ \text{J}}{1.0\times 10^{5}\ \text{N}} = 2.9\times 10^{6}\ \text{m} = \boxed{2.9\times 10^{3}\ \text{km}}$$ (or about 1800 miles)

30.8 The total energy released was

$$E = \left(20\times 10^{3}\ \text{ton}\right)\left(4.0\times 10^{9}\ \text{J/ton}\right) = 8.0\times 10^{13}\ \text{J},$$

and the number of fission events required was

$$N = \frac{E}{E_{event}} = \frac{8.0\times 10^{13}\ \text{J}}{(208\ \text{MeV})\left(1.60\times 10^{-13}\ \text{J/MeV}\right)} = 2.4\times 10^{24}$$

The mass of this number of ^{235}U atoms is

$$m = N m_{atom} = \left(2.4\times 10^{24}\right)\left[(235.044\ \text{u})\left(1.66\times 10^{-27}\ \text{kg/u}\right)\right] = \boxed{0.94\ \text{kg}}$$

30.9 The total energy required for one year is

$$E = \left(2000\ \text{kWh/month}\right)\left(3.60\times 10^{6}\ \text{J/kWh}\right)\left(12.0\ \text{months}\right) = 8.64\times 10^{10}\ \text{J}$$

The number of fission events needed will be

$$N = \frac{E}{E_{event}} = \frac{8.64\times 10^{10}\ \text{J}}{(208\ \text{MeV})\left(1.60\times 10^{-13}\ \text{J/MeV}\right)} = 2.60\times 10^{21},$$

and the mass of this number of ^{235}U atoms is

$$m = N m_{atom} = \left(2.60\times 10^{21}\right)\left[(235.044\ \text{u})\left(1.66\times 10^{-27}\ \text{kg/u}\right)\right]$$

$$= 1.01\times 10^{-3}\ \text{kg} = \boxed{1.01\ \text{g}}$$

30.10 The energy released in the reaction $^{1}_{1}\text{H} + ^{2}_{1}\text{H} \rightarrow ^{3}_{2}\text{He} + \gamma$ is

$$Q = (\Delta m)c^2 = \left[m_{^1\text{H}} + m_{^2\text{H}} - m_{^3\text{He}}\right]c^2$$

$$= \left[1.007\,825\ \text{u} + 2.014\,102\ \text{u} - 3.016\,029\ \text{u}\right](931.5\ \text{MeV/u}) = \boxed{5.49\ \text{MeV}}$$

30.11 (a) $^4_2\text{He} + ^4_2\text{He} \to \boxed{^8_4\text{Be}} + \gamma$

(b) $^8_4\text{Be} + ^4_2\text{He} \to \boxed{^{12}_6\text{C}} + \gamma$

(c) The total energy released in this pair of fusion reactions is

$$Q = (\Delta m)c^2 = \left[3m_{^4\text{He}} - m_{^{12}\text{C}}\right]c^2$$

$$= \left[3(4.002\,602\text{ u}) - 12.000\,000\text{ u}\right](931.5\text{ MeV/u}) = \boxed{7.27\text{ MeV}}$$

30.12 (a) $^1_1\text{H} + ^{12}_6\text{C} \to ^{13}_7\text{N} + \gamma$ (b) $^{13}_7\text{N} \to \boxed{^{13}_6\text{C}} + ^0_{+1}\text{e} + \nu$

(c) $^{13}_6\text{C} + ^1_1\text{H} \to \boxed{^{14}_7\text{N}} + \gamma$ (d) $^{14}_7\text{N} + ^1_1\text{H} \to \boxed{^{15}_8\text{O}} + \gamma$

(e) $^{15}_8\text{O} \to \boxed{^{15}_7\text{N}} + ^0_{+1}\text{e} + \nu$ (f) $^{15}_7\text{N} + ^1_1\text{H} \to \boxed{^{12}_6\text{C}} + ^4_2\text{He}$

30.13 The energy released in the reaction $^2_1\text{H} + ^3_1\text{H} \to ^4_2\text{He} + ^1_0\text{n}$ is

$$Q = (\Delta m)c^2 = \left[m_{^2\text{H}} + m_{^3\text{H}} - m_{^4\text{He}} - m_n\right]c^2$$

$$= \left[2.014\,102\text{ u} + 3.016\,049\text{ u} - 4.002\,602\text{ u} - 1.008\,665\text{ u}\right](931.5\text{ MeV/u})$$

$$= 17.6\text{ MeV}\left(1.60\times10^{-13}\text{ J/MeV}\right) = 2.81\times10^{-12}\text{ J}$$

The total energy required for the year is

$$E = (2000\text{ kWh/month})(12.0\text{ months/yr})\left(3.60\times10^6\text{ J/kWh}\right) = 8.64\times10^{10}\text{ J/yr}$$

so the number of fusion events needed for the year is

$$N = \frac{E}{Q} = \frac{8.64\times10^{10}\text{ J/yr}}{2.81\times10^{-12}\text{ J/event}} = \boxed{3.07\times10^{22}\text{ events/yr}}$$

30.14 (a) From $\overline{KE} = \frac{1}{2}mv_{rms}^2 = \frac{3}{2}k_BT$, the rms speed is

$$v_{rms} = \sqrt{\frac{3k_BT}{m}} = \sqrt{\frac{3\left(1.38\times10^{-23}\text{ J/K}\right)\left(4.00\times10^8\text{ K}\right)}{(2.014\text{ u})\left(1.66\times10^{-27}\text{ kg/u}\right)}} = \boxed{2.23\times10^6\text{ m/s}}$$

(b) $t = \dfrac{d}{v_{rms}} = \dfrac{0.10\text{ m}}{2.23 \times 10^{6}\text{ m/s}} = 4.5 \times 10^{-8}\text{ s}$ or $\boxed{\sim 10^{-8}\text{ s}}$

30.15 (a) Hydrogen contributes $2/18$ or $1/9$ of the mass of a water molecule. Therefore the mass of hydrogen in the oceans is

$$m_H = \frac{m_{water}}{9} = \frac{1.32 \times 10^{21}\text{ kg}}{9} = 1.47 \times 10^{20}\text{ kg}$$

Of this mass of hydrogen, 0.0300% is deuterium, or

$$m_d = \left(0.0300 \times 10^{-2}\right)\left(1.47 \times 10^{20}\text{ kg}\right) = 4.40 \times 10^{16}\text{ kg}$$

The number of deuterium nuclei contained in the oceans is then

$$N = \frac{m_d}{m_{atom}} = \frac{4.40 \times 10^{16}\text{ kg}}{(2.014\text{ u})\left(1.66 \times 10^{-27}\text{ kg/u}\right)} = 1.32 \times 10^{43}$$

Two deuterium nuclei are consumed in each occurrence of the reaction $^{2}_{1}\text{H} + {}^{2}_{1}\text{H} \rightarrow {}^{3}_{2}\text{He} + {}^{1}_{0}\text{n}$, so $N/2$ such events will be possible. With an energy release of $Q = 3.27\text{ MeV}$ per event, the total energy available is

$$E = \left(\frac{N}{2}\right)Q = \left(\frac{1.32 \times 10^{43}}{2}\right)(3.27\text{ MeV})\left(1.60 \times 10^{-13}\text{ J/MeV}\right) = \boxed{3.44 \times 10^{30}\text{ J}}$$

(b) The time this could supply the world's electrical energy needs is

$$t = \frac{E}{\wp} = \frac{3.44 \times 10^{30}\text{ J}}{100\left(7.00 \times 10^{12}\text{ J/s}\right)} = 4.92 \times 10^{15}\text{ s}\left(\frac{1\text{ yr}}{3.156 \times 10^{7}\text{ s}}\right) = \boxed{1.56 \times 10^{8}\text{ yr}}$$

30.16 Minimum energy is released when both the proton and the antiproton are at rest before annihilation. In that case the energy released is $E_{min} = 2\left(E_0\right)_{proton}$. To conserve momentum, the two photons must go in opposite directions with equal magnitude momenta. Therefore, $E_\gamma = E_{min}/2 = \left(E_0\right)_{proton} = 938.3\text{ MeV}$, so

$$f = \frac{E_\gamma}{h} = \frac{(938.3\text{ MeV})\left(1.60 \times 10^{-13}\text{ J/MeV}\right)}{6.63 \times 10^{-34}\text{ J}\cdot\text{s}} = \boxed{2.26 \times 10^{23}\text{ Hz}},$$

and $\lambda = \dfrac{c}{f} = \dfrac{3.00 \times 10^{8}\text{ m/s}}{2.26 \times 10^{23}\text{ Hz}} = 1.32 \times 10^{-15}\text{ m} = \boxed{1.32\text{ fm}}$

30.17 Note that pair production cannot occur in a vacuum. It must occur in the presence of a massive particle which can absorb at least some of the momentum of the photon and allow total linear momentum to be conserved.

When a particle-antiparticle pair is produced by a photon having the minimum possible frequency, and hence minimum possible energy, the nearby massive particle absorbs all the momentum of the photon, allowing both components of the particle-antiparticle pair to be left at rest. In such an event, the total kinetic energy afterwards is essentially zero and the photon need only supply the total rest energy of the pair produced.

The minimum photon energy required to produce a proton-antiproton pair is

$$E_\gamma = 2(E_R)_{proton} = 2(938.3\text{ MeV})\left(1.60\times10^{-13}\text{ J/MeV}\right) = 3.00\times10^{-10}\text{ J}$$

Thus, $f = \dfrac{E_\gamma}{h} = \dfrac{3.00\times10^{-10}\text{ J}}{6.63\times10^{-34}\text{ J}\cdot\text{s}} = \boxed{4.53\times10^{23}\text{ Hz}}$

and $\lambda = \dfrac{c}{f} = \dfrac{3.00\times10^{8}\text{ m/s}}{4.53\times10^{23}\text{ Hz}} = 6.62\times10^{-16}\text{ m} = \boxed{0.662\text{ fm}}$

30.18 The total kinetic after the pair production is

$$KE_{total} = E_\gamma - 2(E_R)_{proton} = 2.09\times10^{3}\text{ MeV} - 2(938.3\text{ MeV}) = 213\text{ MeV}$$

The kinetic energy of the antiproton is then

$$KE_{\bar{p}} = KE_{total} - KE_p = 213\text{ MeV} - 95.0\text{ MeV} = \boxed{118\text{ MeV}}$$

30.19 The time for a particle traveling at (almost) the speed of light to move this distance is

$$\Delta t = \frac{d}{c} = \frac{3.0\times10^{-15}\text{ m}}{3.00\times10^{8}\text{ m/s}} = 1.0\times10^{-23}\text{ s}$$

The estimate of the time for a strong interaction is then $\boxed{\sim10^{-23}\text{ s}}$

30.20 The uncertainty principle limits the time the virtual proton can exist as

$$\Delta t = \frac{h/2\pi}{\Delta E} = \frac{h}{2\pi\left(m_p c^2\right)} = \frac{6.63\times10^{-34}\text{ J}\cdot\text{s}}{2\pi\left(938.3\text{ MeV}\right)\left(1.60\times10^{-13}\text{ J/MeV}\right)} = 7.03\times10^{-25}\text{ s}$$

The maximum distance the virtual proton could travel in this time is

$$d = c(\Delta t) = \left(3.00\times10^{8}\text{ m/s}\right)\left(7.03\times10^{-25}\text{ s}\right) = 2.11\times10^{-16}\text{ m}$$

The estimate of the range of this force is therefore $\boxed{\sim10^{-16}\text{ m}}$

30.21 The maximum lifetime of the virtual Z^0 boson is found from the uncertainty principle to be

$$\Delta t = \frac{h/2\pi}{\Delta E} = \frac{h}{2\pi E_R} = \frac{6.63\times10^{-34}\text{ J}\cdot\text{s}}{2\pi\left[\left(93\text{ GeV}\right)\left(1.60\times10^{-10}\text{ J/GeV}\right)\right]} = 7.1\times10^{-27}\text{ s}$$

The maximum distance the particle could travel is then

$$d_{max} = c(\Delta t) = \left(3.00\times10^{8}\text{ m/s}\right)\left(7.1\times10^{-27}\text{ s}\right) = 2.1\times10^{-18}\text{ m}$$

The range of the weak interaction is then estimated to be $\boxed{\sim10^{-18}\text{ m}}$

30.22 With zero momentum before the decay, conservation of momentum requires the two photons go in opposite directions and have equal magnitude momenta. The energy of each photon is then

$$E_\gamma = \frac{\left(E_R\right)_{\pi^0}}{2} = \frac{135\text{ MeV}}{2} = \boxed{67.5\text{ MeV}}$$

30.23

	Reaction	Conservation Law Violated
(a)	$p+\overline{p}\to\mu^{+}+e$	$L_e:(0+0\to0+1)$; and $L_\mu:(0+0\to-1+0)$
(b)	$\pi^{-}+p\to p+\pi^{+}$	Charge, Q: $(-1+1\to+1+1)$
(c)	$p+p\to p+\pi^{+}$	Baryon Number, B: $(1+1\to1+0)$
(d)	$p+p\to p+p+n$	Baryon Number, B: $(1+1\to1+1+1)$
(e)	$\gamma+p\to n+\pi^{0}$	Charge, Q: $(0+1\to0+0)$

30.24 (a) $\pi^+ + p \to K^+ + \Sigma^+$ Baryon number, B: $0+1 \to 0+1$ $\boxed{\Delta B = 0}$

Charge, Q: $1+1 \to 1+1$ $\boxed{\Delta Q = 0}$

$\pi^+ + p \to \pi^+ + \Sigma^+$ Baryon number, B: $0+1 \to 0+1$ $\boxed{\Delta B = 0}$

Charge, Q: $1+1 \to 1+1$ $\boxed{\Delta Q = 0}$

(b) Strangeness is conserved in the first reaction:

S: $0+0 \to 1-1$ $\boxed{\Delta S = 0}$

The second reaction does not conserve strangeness:

S: $0+0 \to 0-1$ $\boxed{\Delta S = -1}$

This reaction $\boxed{\text{cannot occur via the strong or electromagnetic interactions}}$

30.25 $? + p \to n + \mu^+$

Conservation of charge $\Rightarrow Q + e \to 0 + e$ or $\Rightarrow Q = 0$

Conservation of Baryon number $\Rightarrow B + 1 \to 1 + 0$ or $\Rightarrow B = 0$

Conservation of electron-lepton number $\Rightarrow L_e + 0 \to 0 + 0$ or $\Rightarrow L_e = 0$

Conservation of muon-lepton number $\Rightarrow L_\mu + 0 \to 0 - 1$ or $\Rightarrow L_\mu = -1$

Conservation of tau-lepton number $\Rightarrow L_\tau + 0 \to 0 + 0$ or $\Rightarrow L_\tau = 0$

The particle having these properties is a neutral, antimuon lepton. It is the $\boxed{\bar{\nu}_\mu}$.

30.26 The relevant conservation laws are $\Delta L_e = 0$, $\Delta L_\mu = 0$, and $\Delta L_\tau = 0$.

(a) $\pi^+ \to \pi^0 + e^+ + ?$ $\Delta L_e = 0 \Rightarrow 0 \to 0 - 1 + L_e$, so $L_e = +1$ $\Rightarrow \boxed{\nu_e}$

(b) $? + p \to \mu^- + p + \pi^+$ $\Delta L_\mu = 0 \Rightarrow L_\mu + 0 \to 1 + 0 + 0$, so $L_\mu = +1$ $\Rightarrow \boxed{\nu_\mu}$

(c) $\Lambda^0 \to p + \mu^- + ?$ $\Delta L_\mu = 0 \Rightarrow 0 \to 0 + 1 + L_\mu$, so $L_\mu = -1$ $\Rightarrow \boxed{\bar{\nu}_\mu}$

(d) $\tau^{+} \to \mu^{+} + ? + ?$ $\Delta L_{\mu} = 0 \Rightarrow 0 \to -1 + L_{\mu}$, so $L_{\mu} = +1$

$\Delta L_{\tau} = 0 \Rightarrow -1 \to 0 + L_{\tau}$, so $L_{\tau} = -1$

One particle must be $\boxed{\nu_{\mu}}$ with $L_{\mu} = +1$,

while the other is $\boxed{\bar{\nu}_{\tau}}$ with $L_{\tau} = -1$

30.27 The relevant conservation laws are $\Delta L_e = 0$, $\Delta L_{\mu} = 0$, and $\Delta L_{\tau} = 0$.

(a) $\pi^{+} \to \mu^{-} + ?$ $\Delta L_{\mu} = 0 \Rightarrow 0 \to 1 + L_{\mu}$, so $L_{\mu} = -1$ $\Rightarrow \boxed{\bar{\nu}_{\mu}}$

(b) $K^{+} \to \mu^{+} + ?$ $\Delta L_{\mu} = 0 \Rightarrow 0 \to -1 + L_{\mu}$, so $L_{\mu} = +1$ $\Rightarrow \boxed{\nu_{\mu}}$

(c) $? + p \to n + e^{+}$ $\Delta L_e = 0 \Rightarrow L_e + 0 \to 0 - 1$, so $L_e = -1$ $\Rightarrow \boxed{\bar{\nu}_e}$

(d) $? + n \to p + e^{-}$ $\Delta L_e = 0 \Rightarrow L_e + 0 \to 0 + 1$, so $L_e = +1$ $\Rightarrow \boxed{\nu_e}$

(e) $? + n \to p + \mu^{-}$ $\Delta L_{\mu} = 0 \Rightarrow L_{\mu} + 0 \to 0 + 1$, so $L_{\mu} = +1$ $\Rightarrow \boxed{\nu_{\mu}}$

(f) $\mu^{-} \to e^{-} + ? + ?$ $\Delta L_{\mu} = 0 \Rightarrow 1 \to 0 + L_{\mu}$, so $L_{\mu} = +1$

$\Delta L_e = 0 \Rightarrow 0 \to +1 + L_e$, so $L_e = -1$

One particle must be $\boxed{\nu_{\mu}}$ with $L_{\mu} = +1$, while the other is $\boxed{\bar{\nu}_e}$ with $L_e = -1$.

30.28 (a) $p \to \pi^{+} + \pi^{0}$ $\boxed{\text{violates Baryon number}}$ $1 \to 0 + 0$ $\Rightarrow \Delta B \neq 0$

(b) $p + p \to p + p + \pi^{0}$ $\boxed{\text{Can occur - all conservation laws obeyed}}$

(c) $p + p \to p + \pi^{+}$ $\boxed{\text{violates Baryon number}}$ $1 + 1 \to 1 + 0$ $\Rightarrow \Delta B \neq 0$

(d) $\pi^{+} \to \mu^{+} + \nu_{\mu}$ $\boxed{\text{Can occur - all conservation laws obeyed}}$

(e) $n \to p + e^{-} + \bar{\nu}_e$ $\boxed{\text{Can occur - all conservation laws obeyed}}$

(f) $\pi^{+} \to \pi^{+} + n$ $\boxed{\text{violates Baryon number}}$ $0 \to 0 + 1$ $\Rightarrow \Delta B \neq 0$

30.29 (a) $\pi^{-} + p \to 2\eta^{0}$ $\boxed{\text{not allowed - violates Baryon number}}$

(b) $K^- + n \to \Lambda^0 + \pi^+$ $\boxed{\text{strong interaction}}$ - obeys all conservation laws

(c) $K^- \to \pi^- + \pi^0$ $\Delta S = +1$, all other conservation laws obeyed – may occur via $\boxed{\text{weak interaction}}$ but not strong or electromagnetic interactions

(d) $\Omega^- \to \Xi^- + \pi^0$ $\Delta S = +1$, all other conservation laws obeyed – may occur via $\boxed{\text{weak interaction}}$ but not strong or electromagnetic interactions

(e) $\eta^0 \to 2\gamma$ All conservation laws are obeyed. Photons are the mediators of the electromagnetic interaction. Also, the lifetime of the η^0 is consistent with the electromagnetic interaction. May occur via $\boxed{\text{electromagnetic interaction}}$.

30.30 With zero momentum before the decay, conservation of momentum requires the two pions go in opposite directions with equal magnitude momenta. Since the pions have the same rest energy and momentum, they also have the same kinetic energy, $KE = Q/2$, where

$$Q = (\Delta m)c^2 = \left[m_{K^0} - 2m_\pi\right]c^2 = \left[497.7\text{ MeV} - 2(139.6\text{ MeV})\right] = 218.5\text{ MeV}$$

The total energy of each pion is

$$E = E_R + KE = 139.6\text{ MeV} + \frac{218.5\text{ MeV}}{2} = 248.9\text{ MeV},$$

so $$\gamma = \frac{E}{E_R} = \frac{248.9\text{ MeV}}{139.6\text{ MeV}} = 1.783 = \frac{1}{\sqrt{1-(v/c)^2}}$$

The speed is then $$v = c\sqrt{1-1/\gamma^2} = c\sqrt{1-1/(1.783)^2} = \boxed{0.8278c}$$

30.31 (a) $\Lambda^0 \to p + \pi^-$ Strangeness: $-1 \to 0 + 0$ $\boxed{\Delta S \neq 0}$

(b) $\pi^- + p \to \Lambda^0 + K^0$ Strangeness: $0+0 \to -1+1$ $\boxed{\Delta S = 0}$

(c) $\bar{p} + p \to \bar{\Lambda}^0 + \Lambda^0$ Strangeness: $0+0 \to +1-1$ $\boxed{\Delta S = 0}$

(d) $\pi^- + p \to \pi^- + \Sigma^+$ Strangeness: $0+0 \to 0-1$ $\boxed{\Delta S \neq 0}$

(e) $\Xi^- \to \Lambda^0 + \pi^-$ Strangeness: $-2 \to -1+0$ $\boxed{\Delta S \neq 0}$

(f) $\Xi^0 \to p + \pi^-$ Strangeness: $-2 \to 0+0$ $\boxed{\Delta S \neq 0}$

30.32 (a) $K^+ + p \to \underline{?} + p$ The strong interaction obeys all conservation laws.

Charge:	$+1+1 \to Q+1$	$\Rightarrow Q = +1e$
Baryon number:	$0+1 \to B+1$	$\Rightarrow B = 0$
Lepton numbers:	$0+0 \to L+0$	$\Rightarrow L_e = L_\mu = L_\tau = 0$
Strangeness:	$+1+0 \to S+0$	$\Rightarrow S = +1$

The missing particle is a positive meson $\left(B = 0 \text{ and } L_e = L_\mu = L_\tau = 0\right)$ with strangeness $S = +1$. This must be the $\boxed{K^+}$, so this is an elastic scattering process.

(b) $\Omega^- \to \underline{?} + \pi^-$ Weak interactions obey all conservation laws except conservation of strangeness. For it, $\Delta S = 0, \pm 1$.

Charge:	$-1 \to Q-1$	$\Rightarrow Q = 0$
Baryon number:	$+1 \to B+0$	$\Rightarrow B = +1$
Lepton numbers:	$0 \to L+0$	$\Rightarrow L_e = L_\mu = L_\tau = 0$
Strangeness:	$-3 \to S+0$	so $\Delta S = 0, \pm 1 \Rightarrow S = -2, -3, \text{or } -4$

The missing particle is a neutral baryon $\left(B = +1\right)$ with strangeness $S = -2, -3,$ or -4. From Table 30.2, the only particle with these properties is the $\boxed{\Xi^0}$.

(c) $K^+ \to \underline{?} + \mu^+ + \nu_\mu$ Weak interactions obey all conservation laws except conservation of strangeness. For it, $\Delta S = 0, \pm 1$.

Charge:	$+1 \to Q+1+0$	$\Rightarrow Q = 0$
Baryon number:	$0 \to B+0+0$	$\Rightarrow B = 0$
Lepton numbers:	$0 \to L_e+0+0$	$\Rightarrow L_e = 0$
	$0 \to L_\mu - 1 + 1$	$\Rightarrow L_\mu = 0$
	$0 \to L_\tau + 0 + 0$	$\Rightarrow L_\tau = 0$
Strangeness:	$+1 \to S+0+0$	so $\Delta S = 0, \pm 1 \Rightarrow S = 0, +1, \text{or } +2$

The missing particle is a neutral meson $\left(B = 0 \text{ and } L_e = L_\mu = L_\tau = 0\right)$ less massive than the K^+ (to conserve energy). This must be the $\boxed{\pi^0}$.

30.33 (a) $\Xi^- \to \Lambda^0 + \mu^- + \nu_\mu$

Charge:		$-1 \to 0 - 1 + 0$	$\Rightarrow \boxed{\Delta Q = 0}$
Baryon number:		$+1 \to +1 + 0 + 0$	$\Rightarrow \boxed{\Delta B = 0}$
Lepton numbers,	L_e:	$0 \to 0 + 0 + 0$	$\Rightarrow \boxed{\Delta L_e = 0}$
	L_μ:	$0 \to 0 + 1 + 1$	$\Rightarrow \Delta L_\mu \neq 0$
	L_τ:	$0 \to 0 + 0 + 0$	$\Rightarrow \boxed{\Delta L_\tau = 0}$
Strangeness:		$-2 \to -1 + 0 + 0$	$\Rightarrow \Delta S \neq 0$

(b) $K^0 \to 2\pi^0$

Charge:		$0 \to 0 + 0$	$\Rightarrow \boxed{\Delta Q = 0}$
Baryon number:		$0 \to 0 + 0$	$\Rightarrow \boxed{\Delta B = 0}$
Lepton numbers,	L_e:	$0 \to 0 + 0$	$\Rightarrow \boxed{\Delta L_e = 0}$
	L_μ:	$0 \to 0 + 0$	$\Rightarrow \boxed{\Delta L_\mu = 0}$
	L_τ:	$0 \to 0 + 0$	$\Rightarrow \boxed{\Delta L_\tau = 0}$
Strangeness:		$+1 \to 0 + 0$	$\Rightarrow \Delta S \neq 0$

(c) $K^- + p \to \Sigma^0 + n$

Charge:	$-1 + 1 \to 0 + 0$	$\Rightarrow \boxed{\Delta Q = 0}$
Baryon number:	$0 + 1 \to 1 + 1$	$\Rightarrow \Delta B \neq 0$

Lepton numbers, L_e: $0+0 \to 0+0$ $\Rightarrow$ $\boxed{\Delta L_e = 0}$

L_μ: $0+0 \to 0+0$ $\Rightarrow$ $\boxed{\Delta L_\mu = 0}$

L_τ: $0+0 \to 0+0$ $\Rightarrow$ $\boxed{\Delta L_\tau = 0}$

Strangeness: $-1+0 \to -1+0$ $\Rightarrow$ $\boxed{\Delta S = 0}$

(d) $\Sigma^0 \to \Lambda^0 + \gamma$

Charge: $0 \to 0+0$ $\Rightarrow$ $\boxed{\Delta Q = 0}$

Baryon number: $1 \to 1+0$ $\Rightarrow$ $\boxed{\Delta B = 0}$

Lepton numbers, L_e: $0 \to 0+0$ $\Rightarrow$ $\boxed{\Delta L_e = 0}$

L_μ: $0 \to 0+0$ $\Rightarrow$ $\boxed{\Delta L_\mu = 0}$

L_τ: $0 \to 0+0$ $\Rightarrow$ $\boxed{\Delta L_\tau = 0}$

Strangeness: $-1 \to -1+0$ $\Rightarrow$ $\boxed{\Delta S = 0}$

(e) $e^+ + e^- \to \mu^+ + \mu^-$

Charge: $1-1 \to 1-1$ $\Rightarrow$ $\boxed{\Delta Q = 0}$

Baryon number: $0+0 \to 0+0$ $\Rightarrow$ $\boxed{\Delta B = 0}$

Lepton numbers, L_e: $-1+1 \to 0+0$ $\Rightarrow$ $\boxed{\Delta L_e = 0}$

L_μ: $0+0 \to 1-1$ $\Rightarrow$ $\boxed{\Delta L_\mu = 0}$

L_τ: $0+0 \to 0+0$ $\Rightarrow$ $\boxed{\Delta L_\tau = 0}$

Strangeness: $0+0 \to 0+0$ $\Rightarrow$ $\boxed{\Delta S = 0}$

(f) $\bar{p}+n \to \bar{\Lambda}^0+\Sigma^-$

Charge:		$-1+0 \to 0-1$	$\Rightarrow$	$\boxed{\Delta Q=0}$
Baryon number:		$-1+1 \to -1+1$	$\Rightarrow$	$\boxed{\Delta B=0}$
Lepton numbers,	L_e:	$0+0 \to 0+0$	$\Rightarrow$	$\boxed{\Delta L_e=0}$
	L_μ:	$0+0 \to 0+0$	$\Rightarrow$	$\boxed{\Delta L_\mu=0}$
	L_τ:	$0+0 \to 0+0$	$\Rightarrow$	$\boxed{\Delta L_\tau=0}$
Strangeness:		$0+0 \to +1-1$	$\Rightarrow$	$\boxed{\Delta S=0}$

30.34

	proton	u	u	d	total
strangeness	0	0	0	0	0
baryon number	1	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	1
charge	e	$2e/3$	$2e/3$	$-e/3$	e

	neutron	u	d	d	total
strangeness	0	0	0	0	0
baryon number	1	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	1
charge	0	$2e/3$	$-e/3$	$-e/3$	0

30.35 The number of water molecules in one liter (mass = 1000 g) of water is

$$N=\left(\frac{1000 \text{ g}}{18.0 \text{ g/mol}}\right)\left(6.02\times10^{23} \text{ molecules/mol}\right)=3.34\times10^{25} \text{ molecules}$$

Each molecule contains 10 protons, 10 electrons, and 8 neutrons. Thus, there are

$$N_e=10N=\boxed{3.34\times10^{26} \text{ electrons}},\ N_p=10N=3.34\times10^{26} \text{ protons},$$

and $N_n=8N=2.68\times10^{26}$ neutrons

Each proton contains 2 up quarks and 1 down quark, while each neutron has 1 up quark and 2 down quarks. Therefore, there are

$$N_u=2N_p+N_n=\boxed{9.36\times10^{26} \text{ up quarks}}, \text{ and}$$

$$N_d=N_p+2N_n=\boxed{8.70\times10^{26} \text{ down quarks}}$$

30.36

K^0 Particle				
	K^0	d	$\bar{s}$	total
strangeness	1	0	1	1
baryon number	0	$1/3$	$-1/3$	0
charge	0	$-e/3$	$e/3$	0

Λ^0 Particle					
	Λ^0	u	d	s	total
strangeness	-1	0	0	-1	-1
baryon number	1	$1/3$	$1/3$	$1/3$	1
charge	0	$2e/3$	$-e/3$	$-e/3$	0

30.37 Compare the given quark states to the entries in Table 30.4:

(a) $suu = \boxed{\Sigma^+}$ (b) $\bar{u}d = \boxed{\pi^-}$

(c) $\bar{s}d = \boxed{K^0}$ (d) $ssd = \boxed{\Xi^-}$

30.38 (a) $\bar{u}\bar{u}\bar{d}$: charge $= \left(-\frac{2}{3}e\right) + \left(-\frac{2}{3}e\right) + \left(+\frac{1}{3}e\right) = \boxed{-e}$. This is the $\boxed{\text{antiproton}}$

(b) $\bar{u}\bar{d}\bar{d}$: charge $= \left(-\frac{2}{3}e\right) + \left(+\frac{1}{3}e\right) + \left(+\frac{1}{3}e\right) = \boxed{0}$. This is the $\boxed{\text{antineutron}}$

30.39

	Reaction	At Quark Level	Net Quarks (Before and After)
(a)	$\pi^- + p \to K^0 + \Lambda^0$	$\bar{u}d + uud \to d\bar{s} + uds$	1 up, 2 down, 0 strange
(b)	$\pi^+ + p \to K^+ + \Sigma^+$	$u\bar{d} + uud \to u\bar{s} + uus$	3 up, 0 down, 0 strange
(c)	$K^- + p \to K^+ + K^0 + \Omega^-$	$\bar{u}s + uud \to u\bar{s} + d\bar{s} + sss$	1 up, 1 down, 1 strange

(d) $p + p \to K^0 + p + \pi^+ + X \quad \Rightarrow \quad uud + uud \to d\bar{s} + uud + u\bar{d} + X$

To conserve the net number of each type quark, the quark composition of particle X must be $1u$, $1d$, and $1s$, or uds. This particle is $\boxed{\text{a } \Lambda^0 \text{ or a } \Sigma^0}$.

30.40 The quark composition of the proton is uud, while that of the neutron is udd. Thus, neglecting binding energy,

$$m_p = 2m_u + m_d \text{ and } m_n = m_u + 2m_d,$$

giving

$$m_u = \frac{2m_p - m_n}{3} = \frac{2\left(938.3 \text{ MeV}/c^2\right) - 939.6 \text{ MeV}/c^2}{3} = \boxed{312.3 \text{ MeV}/c^2}$$

and $$m_d = m_p - 2m_u = 938.3 \text{ MeV}/c^2 - 2\left(312.3 \text{ MeV}/c^2\right) = \boxed{313.7 \text{ MeV}/c^2}$$

30.41 The reaction is $\Sigma^0 + p \rightarrow \Sigma^+ + \gamma + X$, or on the quark level, $uds + uud \rightarrow uus + 0 + ?$.

The left side has a net $3u$, $2d$, and $1s$. The right side has $2u$, $0d$, and $1s$, leaving $1u$ and $2d$ missing.

$\boxed{\text{The unknown particle is a neutron, } udd.}$

Baryon and strangeness numbers are conserved.

30.42 The reaction $\pi^- + p \rightarrow K^0 + \Lambda^0$ is $\bar{u}d + uud \rightarrow d\bar{s} + uds$ at the quark level. There is $\boxed{\text{a net } 1u \text{ and } 2d \text{ quarks both before and after the reaction}}$

For the reaction $\pi^- + p \rightarrow K^0 + n$, or $\bar{u}d + uud \rightarrow d\bar{s} + udd$, there is a net $\boxed{1u \text{ and } 2d \text{ before the reaction and } 1u,\ 3d, \text{ and } 1 \text{ antistrange quark afterwards}}$
This reaction does not conserve the net number of each type quark.

30.43 The total momentum is zero both before and after reaction. For minimum incident kinetic energy, all particles will be left at rest after the reaction. The energy release in the reaction $p + p \rightarrow p + n + \pi^+$ is

$$Q = (\Delta m)c^2 = \left[m_p - m_n - m_{\pi^+}\right]c^2 = (938.3 - 939.6 - 139.6) \text{ MeV} = -140.9 \text{ MeV}$$

Thus, to conserve energy, each incident proton must have kinetic energy

$$KE = \frac{|Q|}{2} = \frac{|-140.9 \text{ MeV}|}{2} = \boxed{70.45 \text{ MeV}}$$

30.44 (a) $\pi^- + p \to \Sigma^+ + \pi^0$ is forbidden by $\boxed{\text{conservation of charge}}$

(b) $\mu^- \to \pi^- + \nu_e$ is forbidden by $\boxed{\text{conservation of electron-lepton number}}$,

$\boxed{\text{conservation of energy}}$, and $\boxed{\text{conservation of muon-lepton number}}$

(c) $p \to \pi^+ + \pi^+ + \pi^-$ is forbidden by $\boxed{\text{conservation of baryon number}}$

30.45 To the reaction for nuclei, ${}^1_1\text{H} + {}^3_2\text{He} \to {}^4_2\text{He} + {}^{\ 0}_{+1}\text{e} + \nu_e$, we add three electrons to both sides to obtain ${}^1_1\text{H atom} + {}^3_2\text{He atom} \to {}^4_2\text{He atom} + {}^{\ 0}_{-1}\text{e} + {}^{\ 0}_{+1}\text{e} + \nu_e$. Then we use the masses of the neutral atoms to compute

$$Q = (\Delta m)c^2 = \left[m_{{}^1\text{H}} + m_{{}^3\text{He}} - m_{{}^4\text{He}} - 2m_e\right]c^2$$

$$= \left[1.007\,825 + 3.016\,029 - 4.002\,602 - 2(0.000\,549)\right]\text{u}(931.5\text{ MeV/u})$$

$$= \boxed{18.8\text{ MeV}}$$

30.46 For the partial reaction, $\mu^+ + e^- \to 2\nu$, the lepton numbers before the event are $L_\mu = -1$ and $L_e = +1$. These values must be conserved by the reaction so one of the emerging neutrinos must have $L_\mu = -1$ while the other has $L_e = +1$. The emerging particle are $\boxed{\bar{\nu}_\mu}$ and $\boxed{\nu_e}$.

30.47 (a) $\mu^- \to e^- + \gamma$ Violates $\boxed{\text{conservation of muon-lepton number}}$

and also $\boxed{\text{conservation of electron-lepton number}}$

(b) $n \to p + e^- + \nu_e$ Violates $\boxed{\text{conservation of electron-lepton number}}$

(c) $\Lambda^0 \to p + \pi^0$ Violates $\boxed{\text{conservation of charge}}$

(d) $p \to e^+ + \pi^0$ Violates $\boxed{\text{conservation of electron-lepton number}}$

and also $\boxed{\text{conservation of baryon number}}$

(e) $\Xi^0 \to n + \pi^0$ Violates $\boxed{\text{conservation of strangeness number by 2 units}}$
Even weak interactions only violate this rule by 1 unit

30.48 Assuming a head-on collision, the total momentum is zero both before and after the reaction $p + p \to p + \pi^+ + X$. Therefore, since the proton and the pion are at rest after reaction, particle *X* must also be left at rest.

Particle *X* must be a neutral baryon in order to conserve charge and baryon number in the reaction. The rest energy this particle is

$$E_{0X} = 2\left(E_{0p} + 70.4\text{ MeV}\right) - E_{0p} - E_{0\pi^+} = E_{0p} - E_{0\pi^+} + 140.8\text{ MeV},$$

or $$E_{0X} = 938.3\text{ MeV} - 139.6\text{ MeV} + 140.8\text{ MeV} = 939.5\text{ MeV}$$

Particle *X* is $\boxed{\text{a neutron}}$

30.49 (a) Suppose each ^{235}U fission releases 208 MeV of energy. Then, the number of nuclei that must have undergone fission is

$$N = \frac{\text{total release}}{\text{energy per fission}} = \frac{5 \times 10^{13}\text{ J}}{(208\text{ MeV})\left(1.60 \times 10^{-13}\text{ J/MeV}\right)} = \boxed{1.5 \times 10^{24}\text{ nuclei}}$$

(b) The mass of this number of ^{235}U atoms is

$$m = \left(1.5 \times 10^{24}\right)\left[(235.044\text{ u})\left(1.66 \times 10^{-27}\text{ kg/u}\right)\right] \approx \boxed{0.6\text{ kg}}$$

30.50 The neutron initially has $KE_i = 2.0 \times 10^6\text{ eV}$ and, after *n* collisions, has final kinetic energy $KE_f = 0.039\text{ eV}$. If one-half of the kinetic energy present before a collision is lost in that collision, then

$$KE_f = \left(\frac{1}{2}\right)^n KE_i, \text{ giving } n = \frac{\ln\left(KE_f/KE_i\right)}{\ln(1/2)} = \frac{\ln\left(KE_i/KE_f\right)}{\ln 2}$$

or $$n = \frac{\ln\left(2.0 \times 10^6\text{ eV}/0.039\text{ eV}\right)}{\ln 2} = 25.6 \text{ or } \boxed{26\text{ collisions}}$$

30.51 (a) The proposed decay $p \to e^+ + \gamma$ has 1 baryon before and zero baryons afterward. $\boxed{\text{Baryon number is not conserved}}$ in this decay.

(b) Since the total momentum is zero both before and after the event, the photon and the positron must travel in opposite directions with equal magnitude momenta.

Therefore, $p_\gamma = p_e$ or $\frac{E_\gamma}{c} = \frac{\sqrt{E_e^2 - E_{Re}^2}}{c}$, giving $E_\gamma^2 = E_e^2 - E_{Re}^2$. (1)

From conservation of energy, $E_{Rp} = E_e + E_\gamma$ or $E_e = E_{Rp} - E_\gamma$. Substituting into equation (1) from above gives $E_\gamma^2 = E_{Rp}^2 - 2E_{Rp}E_\gamma + E_\gamma^2 - E_{Re}^2$, which reduces to

$$E_\gamma = \frac{E_{Rp}^2 - E_{Re}^2}{2E_{Rp}} = \frac{(938.3 \text{ MeV})^2 - (0.511 \text{ MeV})^2}{2(938.3 \text{ MeV})} = \boxed{469 \text{ MeV}}$$

The momentum of the photon is then $p_\gamma = \frac{E_\gamma}{c} = \boxed{469 \text{ MeV}/c}$

(c) The positron energy is $E_e = E_{Rp} - E_\gamma = (938.3 - 469) \text{ MeV} = 469 \text{ MeV}$

Then, $\gamma = \frac{E_e}{E_{Re}}$ and the speed of the positron is

$$v = c\sqrt{1 - \frac{1}{\gamma^2}} = c\sqrt{1 - \left(\frac{E_{Re}}{E_e}\right)^2},$$

or $v = c\sqrt{1 - \left(\frac{0.511 \text{ MeV}}{469 \text{ MeV}}\right)^2} = \boxed{0.999\,999\,4\,c}$

30.52 (a) $L = \sqrt{\frac{(h/2\pi)G}{c^3}} = \sqrt{\frac{hG}{2\pi c^3}} = \sqrt{\frac{(6.63 \times 10^{-34} \text{ J}\cdot\text{s})(6.67 \times 10^{-11} \text{ N}\cdot\text{m}^2/\text{kg}^2)}{2\pi(3.00 \times 10^8 \text{ m/s})^3}}$

$L = \boxed{1.61 \times 10^{-35} \text{ m}}$

(b) $T = \frac{L}{c} = \frac{1.61 \times 10^{-35} \text{ m}}{3.00 \times 10^8 \text{ m/s}} = \boxed{5.38 \times 10^{-44} \text{ s}}$

This is approximately equal to the duration of the ultra-hot epoch.

(c) Yes.

Answers to Even Numbered Conceptual Questions

2. The two factors presenting the most technical difficulties are the requirements of a high plasma density and a high plasma temperature. These two conditions must occur simultaneously.

4. Notice in the fusion reactions discussed in the text that the most commonly formed by-product of the reactions is helium, which is inert and not radioactive.

6. They are hadrons. Such particles decay into other strongly interacting particles such as p, n, and π with very short lifetimes. In fact, they decay so quickly that they cannot be detected directly. Decays which occur via the weak force have lifetimes of 10^{-13} s or longer; particles that decay via the electromagnetic force have times in the range of 10^{-16} s to 10^{-19} s.

8. Each flavor of quark can have three colors, designated as red, green, and blue. Antiquarks are colored antired, antigreen, and antiblue. Baryons consist of three quarks, each having a different color. Mesons consist of a quark of one color and an antiquark with a corresponding anticolor. Thus, baryons and mesons are colorless or white.

10. The decays of the neutral pion, eta, and neutral sigma occur by the electromagnetic interaction. These are the three shortest lifetimes in the table. All produce photons, which are the quanta of the electromagnetic force, and all conserve strangeness.

12. Momentum must be conserved in this annihilation process. If the electron and positron have low speeds, the momentum before annihilation is essentially zero. Production of a single photon of energy 1.02 MeV would leave momentum of $1.02 \text{ MeV}/c$, far greater then any momentum that may have existed before annihilation. The only way to conserve both energy and momentum simultaneously is to produce two photons of equal energy traveling in opposite directions.

14. A neutron inside a nucleus is stable because it is in a lower energy state than a free neutron and lower in energy than it would be if it decayed into a proton (plus electron and antineutrino). The nuclear force gives it this lower energy by binding it inside the nucleus and by favoring pairing between neutrons and protons.

16. A neutron will lose significantly more kinetic energy when it collides with a particle having nearly the same mass than it would in a collision with a very massive particle such as a lead or iron nucleus. Every water molecule contains two hydrogen atoms, each having mass approximately equal to that of the neutron. Therefore, water makes an excellent shield against neutrons or moderator of neutrons.

18. Electrons participate in gravitational, electromagnetic, and weak interactions. As leptons, they do not participate in strong interactions. Protons participate in all four fundamental interactions. Neutrons also participate in all four interactions. While neutrons are electrically neutral, they do have magnetic dipole moments, and are therefore affected by electromagnetic forces.

Answers to Even Numbered Problems

2. 192 MeV

4. ${}^{144}_{54}\mathrm{Xe}$, ${}^{143}_{54}\mathrm{Xe}$, ${}^{142}_{54}\mathrm{Xe}$

6. $2.63\ \mathrm{kg/d}$

8. 0.94 kg

10. 5.49 MeV

12. (a) ${}^{13}_{7}\mathrm{N}$ (b) ${}^{13}_{6}\mathrm{C}$ (c) ${}^{14}_{7}\mathrm{N}$ (d) ${}^{15}_{8}\mathrm{O}$ (e) ${}^{15}_{7}\mathrm{N}$ (f) ${}^{12}_{6}\mathrm{C}$

14. (a) $2.23\times 10^{6}\ \mathrm{m/s}$ (b) $\sim 10^{-8}\ \mathrm{s}$

16. $2.26\times 10^{23}\ \mathrm{Hz}$, 1.32 fm

18. 118 MeV

20. $\sim 10^{-16}\ \mathrm{m}$

22. 67.5 MeV

24. (b) The second reaction violates conservation of strangeness number. It cannot occur via the strong or electromagnetic interactions.

26. (a) ν_e (b) ν_μ (c) $\bar{\nu}_\mu$ (d) ν_μ and $\bar{\nu}_\tau$

28. (a) violates conservation of baryon number (b) can occur
(c) violates conservation of baryon number (d) can occur
(e) can occur (f) violates conservation of baryon number

30. $0.827\,8\,c$

32. (a) K^{+} (b) Ξ^{0} (c) π^{0}

34.

	proton	u	u	d	total
strangeness	0	0	0	0	0
baryon number	1	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	1
charge	e	$2e/3$	$2e/3$	$-e/3$	e

	neutron	u	d	d	total
strangeness	0	0	0	0	0
baryon number	1	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	1
charge	0	$2e/3$	$-e/3$	$-e/3$	0

36.

K^0 Particle				
	K^0	d	$\bar{s}$	total
strangeness	1	0	1	1
baryon number	0	$1/3$	$-1/3$	0
charge	0	$-e/3$	$e/3$	0

Λ^0 Particle					
	Λ^0	u	d	s	total
strangeness	-1	0	0	-1	-1
baryon number	1	$1/3$	$1/3$	$1/3$	1
charge	0	$2e/3$	$-e/3$	$-e/3$	0

38. (a) $-e$, antiproton (b) 0, antineutron

40. $m_{up} = 312.3\ \text{MeV}/c^2$, $m_{down} = 313.7\ \text{MeV}/c^2$ (neglecting binding energies)

42. First reaction: Net of 1 up and 2 down quarks before and after.
Second reaction: Net of 1 up and 2 down quarks before, but 1 up, 3 down, and 1 antistrange quark afterwards.

44. (a) conservation of charge
(b) conservation of electron-lepton number, conservation of energy, and conservation of muon-lepton number
(c) conservation of baryon number

46. $\bar{\nu}_\mu$ and ν_e

48. a neutron

50. 26 collisions

52. (a) 1.61×10^{-35} m (b) 5.38×10^{-44} s (c) Yes