44

Particle Physics and Cosmology

CHAPTER OUTLINE

44.1 Field Particles for the Fundamental Forces in Nature

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44.12 Problems and Perspectives

* An asterisk indicates a question or problem new to this edition.

ANSWERS TO THINK-SHARE-PAIR ACTIVITIES

***TP44.1** **Conceptualize** In parts (a) and (b), we must verify that the reactions obey the conservation laws. In parts (c) and (d) we have an unknown particle that we must identify from the conservation laws.

Categorize The reactions represent isolated systems for which a number of conservation laws apply. Specifically, the number of each type of quark must be conserved.

Analyze (a) Use Tables 44.4 and 44.5 to represent each of the particles in the reaction in terms of quarks:

$$\pi^+ + \mathrm{p} \;\rightarrow\; \mathrm{K}^+ + \Sigma^+$$

$$\mathrm{u\bar{d}} + \mathrm{uud} \quad\rightarrow\quad \mathrm{\bar{s}u} + \mathrm{uus}$$

Check for up quarks: $1 + 2 \;\rightarrow\; 1 + 2$ or $3 = 3$

Check for down quarks: $-1 + 1 \;\rightarrow\; 0 + 0$ or $0 = 0$

Check for strange quarks: $0 + 0 \;\rightarrow\; -1 + 1$ or $0 = 0$

Therefore, the number of quarks in the system is 3 u, 0 d, and 0 s both before and after the reaction. $\boxed{\text{Each type of quark is conserved.}}$

(b) Use Tables 44.4 and 44.5 to represent each of the particles in the reaction in terms of quarks:

$$\mathrm{K}^- + \mathrm{p} \rightarrow \mathrm{K}^+ + \mathrm{K}^0 + \Omega^-$$

$$\mathrm{\bar{u}s} + \mathrm{uud} \quad\rightarrow\quad \mathrm{\bar{s}u} + \mathrm{\bar{s}d} + \mathrm{sss}$$

Check for up quarks: $-1 + 2 \;\rightarrow\; 1 + 0 + 0$ or $1 = 1$

Check for down quarks: $0 + 1 \;\rightarrow\; 0 + 1 + 0$ or $1 = 1$

Check for strange quarks: $1 + 0 \;\rightarrow\; -1 - 1 + 3$ or $1 = 1$

Therefore, the number of quarks in the system is 1 u, 1 d, and 1 s both before and after the reaction. $\boxed{\text{Each type of quark is conserved.}}$

(c) Use Tables 44.4 and 44.5 to represent each of the particles in the reaction in terms of quarks:

$$\text{p} + \text{p} \quad \rightarrow \quad \text{K}^0 + \text{p} + \pi^+ + ?$$
$$\text{uud} + \text{uud} \quad \rightarrow \quad \bar{\text{s}}\text{d} + \text{uud} + \bar{\text{d}}\text{u} \; + (?)$$

Check for up quarks: $\quad 2 + 2 \;\rightarrow\; 0 + 2 + 1 + n_\text{u} \quad \text{or} \quad n_\text{u} = 1$

Check for down quarks: $\quad 1 + 1 \;\rightarrow\; 1 + 1 - 1 + n_\text{d} \quad \text{or} \quad n_\text{d} = 1$

Check for strange quarks: $\quad 0 + 0 \;\rightarrow\; -1 + 0 + 0 + n_\text{s} \quad \text{or} \quad n_\text{s} = 1$

Therefore, the quark composition of the mystery particle is $\boxed{\text{uds}}$.

(d) Looking at Table 44.5, we see two possibilities for the mystery particle: $\boxed{\Lambda^0}$ or $\boxed{\Sigma^0}$.

Finalize You might be surprised to find that we could not specifically identify the mystery particle in part (d). The particles Λ^0 and Σ^0 have the same quark structure but differ in their symmetry properties. An explanation of this difference is beyond the scope of this text. The two particles also differ markedly in their lifetimes, as seen in Table 44.2.]

Answers: (a) Answers will vary; see solution. (b) Answers will vary; see solution. (c) uds (d) Λ^0 or Σ^0

***TP44.2** **Conceptualize** If we consider conservation of charge and ignore other conservation laws, the mystery particle could be any positively charged particle, such as a positron, another proton, or a pion. But we must obey several conservation laws, so we need to check each one to focus in on a small number of possibilities.

Categorize The reaction represents an *isolated system* for which a number of conservation laws apply.

Analyze From conservation of charge, we have

$$1+1 \;\rightarrow\; q+1 \qquad \text{or} \qquad q=+1$$

From conservation of baryon number, we have

$$0+1 \;\rightarrow\; B+1 \qquad \text{or} \qquad B=0$$

From conservation of any lepton number, we have

$$0+0 \;\rightarrow\; L+0 \qquad \text{or} \qquad L=0$$

From conservation of strangeness, we have

$$1+0 \;\rightarrow\; S+0 \qquad \text{or} \qquad S=+1$$

Therefore, the mystery particle must be a positively-charged meson with a strangeness of +1. The only possibility in Table 44.2 is a $\boxed{K^+}$.

Finalize There is no change in particle in this reaction. The reaction equation represents an elastic collision between a positive kaon and a proton.]

Answer: K^+

***TP44.3** **Conceptualize** If we look at a single conservation law such as conservation of charge, the mystery particle in (a) could be any neutral particle, such as a neutron, a neutrino, or a lambda. But we must obey several conservation laws, so we need to check each one to focus in on a small number of possibilities.

Categorize The reaction represents an *isolated system* for which a number of conservation laws apply.

Analyze (a) From conservation of charge, we have

$$-1 \quad \rightarrow \quad q-1 \qquad \text{or} \qquad q=0$$

From conservation of baryon number, we have

$$1 \quad \rightarrow \quad B+0 \qquad \text{or} \qquad B=1$$

From conservation of any lepton number, we have

$$0 \quad \rightarrow \quad L+0 \qquad \text{or} \qquad L=0$$

From a change of strangeness of one unit, we have

$$-3 \quad \rightarrow \quad S+0 \qquad \text{or} \qquad S=-2 \;\; \text{or} \;\; -4$$

There is no particle with strangeness –4. Therefore, the mystery particle must be a neutral baryon with a strangeness of –2. Table 44.2 tells us that it is $\boxed{\Xi^0}$.

(b) From conservation of charge, we have

$$1 \quad \rightarrow \quad q+1+0 \qquad \text{or} \qquad q=0$$

From conservation of baryon number, we have

$$0 \quad \rightarrow \quad B+0+0 \qquad \text{or} \qquad B=0$$

From conservation of muon lepton number, we have

$$0 \quad \rightarrow \quad L_\mu-1+1 \qquad \text{or} \qquad L_\mu=0$$

From a change of strangeness of one unit, we have

$$1 \quad \rightarrow \quad S+0+0 \qquad \text{or} \qquad S=0 \;\; \text{or} \;\; 2$$

Because B = 0 and L = 0 (and, implicitly, L_e = 0 and L = 0), the particle must be a meson. There is no meson with strangeness 2. Therefore, the mystery particle must be a neutral meson with a strangeness of 0. Table 44.2 tells us that it is $\boxed{\pi^0}$.

Finalize Notice that these are not reaction equations, but rather decay equations. Therefore, we have found the decay products of the omega-minus and the positive kaon.]

Answers: (a) Ξ^0 (b) π^0

***TP44.4** **Conceptualize** Several possible decay schemes are listed. We must test each one according to the conservation laws.

Categorize The reactions represent *isolated systems* for which a number of conservation laws apply.

Analyze (a) Let us test each reaction separately:

(i) Add the masses of the particles on the right side of the reaction:

$$\begin{aligned} m_{K^+} + m_{K^-} + m_{\pi^0} &= 493.7\text{ MeV}/c^2 + 493.7\text{ MeV}/c^2 + 135.0\text{ MeV}/c^2 \\ &= 1\,122\text{ MeV}/c^2 \end{aligned}$$

This total is larger than the mass of the phi meson, so this reaction violates conservation of energy.

(ii) Add the masses of the particles on the right side of the reaction:

$$\begin{aligned} m_{K^+} + m_{K^-} + m_{\pi^0} &= 493.7\text{ MeV}/c^2 + 493.7\text{ MeV}/c^2 \\ &= 987\text{ MeV}/c^2 \end{aligned}$$

This total is smaller than the mass of the phi meson, so this reaction can occur according to *conservation of energy*. Let's look at the quark composition of the particles:

$$\begin{aligned} \phi &\rightarrow \mathrm{K}^+ + \mathrm{K}^- \\ \bar{\mathrm{s}}\mathrm{s} &\rightarrow \bar{\mathrm{s}}\mathrm{u} + \bar{\mathrm{u}}\mathrm{s} \end{aligned}$$

Therefore, we have zero net strange quarks on the left and right, as well as zero net up quarks on the left and right. This reaction can occur according to *quark composition*. There are no baryons, so *conservation of baryon number* is obeyed. There are no leptons, so *conservation of lepton number* is obeyed. We have zero strangeness on both sides of the reaction, so *conservation of strangeness* is obeyed. We see zero electric charge on the left and zero net electric charge on the right, so *conservation of electric charge* is obeyed. It looks like this reaction is good to go!

(iii) Let's look at the proposed reaction:

$$\phi \rightarrow \mathrm{K}^+ + e^-$$

We see a clear problem here. The electron is a lepton. Therefore, conservation of lepton number is violated. This reaction does not occur.

(iv) Let's look at the quark composition of the particles:

$$\begin{array}{ccc} \phi & \rightarrow & \mathrm{K}^+ + \pi^- \\ \bar{\mathrm{s}}\mathrm{s} & \rightarrow & \bar{\mathrm{s}}\mathrm{u} + \bar{\mathrm{u}}\mathrm{d} \end{array}$$

From the quark composition of the reaction, we see that the strange quarks and the down quarks do not balance on the two sides of the reaction. Therefore, this reaction does not occur.

(b) The only reaction that occurs is (ii). The decay energy will be the difference in rest energies before and after the reaction:

$$\begin{aligned} \Delta E &= m_\phi c^2 - m_{\mathrm{K}^+}c^2 - m_{\mathrm{K}^-}c^2 = 1\,019 \text{ MeV} - 93.7 \text{ MeV} - 493.7 \text{ MeV} \\ &= 31.6 \text{ MeV} \end{aligned}$$

Because the phi meson is at rest and both of the decay product particles have the same mass, symmetry tells us that each particle carries off half of the decay energy:

$$K_{K^+} = \boxed{15.8 \text{ MeV}}$$

$$K_{K^-} = \boxed{15.8 \text{ MeV}}$$

Finalize We find only one of the four reactions given is possible, and, indeed, this reaction is observed.]

Answer: (a) Only (ii) is possible. (b) 15.8 MeV

SOLUTIONS TO END-OF-CHAPTER PROBLEMS

Section 44.2 Positrons and Other Antiparticles

P44.1 (a) The minimum energy is released, and hence the minimum frequency photons are produced, when the proton and antiproton are at rest when they annihilate.

That is, $E = E_0$ and $K = 0$. To conserve momentum, each photon must have the same magnitude of momentum, and $p = E/c$, so each photon must carry away one-half the energy.

Thus $E_{\text{min}} = \dfrac{2E_0}{2} = E_0 = 938.3 \text{ MeV} = hf_{\text{min}}$.

Thus, $f_{\text{min}} = \dfrac{(938.3 \text{ MeV})(1.602 \times 10^{-13} \text{ J/MeV})}{6.626 \times 10^{-34} \text{ J} \cdot \text{s}} = \boxed{2.27 \times 10^{23} \text{ Hz}}$.

(b) $\lambda = \dfrac{c}{f_{\text{min}}} = \dfrac{2.998 \times 10^{8} \text{ m/s}}{2.27 \times 10^{23} \text{ Hz}} = \boxed{1.32 \times 10^{-15} \text{ m}}$

***P44.2** **Conceptualize** The half-life of the isotope is a little over 1 minute. The employee met his supervisor 1.0 hour after being injected, which is many half-lives later, so we expect the activity of the isotope to be very small by this time.

Categorize The problem involves a calculation of the activity of an isotope used in a PET scan to provide positrons to the body.

Analyze From Equation 43.7, we can find the activity of the isotope at any time after the injection:

$$R = \lambda N_0 e^{-\lambda t} \qquad (1)$$

Use Equation 43.8 to replace the decay constant:

$$R = \left(\frac{\ln 2}{T_{1/2}}\right) N_0 e^{-\left(\frac{\ln 2}{T_{1/2}}\right)t} \qquad (2)$$

Substitute numerical values:

$$R = \left(\frac{\ln 2}{70.6\text{ s}}\right)\left(1 \times 10^{14}\right) e^{-\left(\frac{\ln 2}{70.6\text{ s}}\right)(1.0\text{ h})\left(\frac{3\,600\text{ s}}{1\text{ h}}\right)}$$
$$= 4.4 \times 10^{-4}\text{ s}^{-1}\left(\frac{3\,600\text{ s}}{1\text{ h}}\right) = \boxed{1.6\text{ h}^{-1}}$$

Finalize Therefore, during a 2-hour dinner meeting, there *might* be about three decays, *possibly* leading to three gamma rays passing through the supervisor's body. The supervisor likely receives more gamma rays than that from the surroundings. The claim by the supervisor of a significant amount of radiation from the employee is not reasonable.]'

Answer: 1.6 h^{-1}

Section 44.3 Mesons and the Beginning of Particle Physics

P44.3 The creation of a virtual Z^0 boson is an energy fluctuation $\Delta E = m_{Z^0}c^2 = 91\times 10^9$ eV. By the uncertainty principle, it can last no longer than $\Delta t = \dfrac{\hbar}{2\Delta E}$ and move no farther than

$$\begin{aligned}
c(\Delta t) &= \frac{hc}{4\pi\,\Delta E} \\
&= \frac{(6.626\times 10^{-34}\ \text{J}\cdot\text{s})(3.00\times 10^{8}\ \text{m/s})}{4\pi(91\times 10^{9}\ \text{eV})}\left(\frac{1\ \text{eV}}{1.60\times 10^{-19}\ \text{J}}\right) \\
&= 1.06\times 10^{-18}\ \text{m} = \boxed{\sim 10^{-18}\ \text{m}}
\end{aligned}$$

P44.4 (a) The particle's rest energy is mc^2. The time interval during which a virtual particle of this mass could exist is at most Δt in $\Delta E\Delta t = \dfrac{\hbar}{2} = mc^2\Delta t$; or $\Delta t = \dfrac{\hbar}{2mc^2}$; so, the distance it could move (traveling at the speed of light) is at most

$$\begin{aligned}
d \approx c\Delta t &= \frac{\hbar c}{2mc^2} = \frac{(6.626\times 10^{-34}\ \text{J}\cdot\text{s})(2.998\times 10^{8}\ \text{m/s})}{4\pi mc^2(1.602\times 10^{-19}\ \text{J/eV})} \\
&= \frac{1.240\times 10^{-6}\ \text{eV}\cdot\text{m}}{4\pi mc^2}\left(\frac{1\ \text{nm}}{10^{-9}\ \text{m}}\right) = \frac{1\ 240\ \text{eV}\cdot\text{nm}}{4\pi mc^2} \\
&= \frac{98.7\ \text{eV}\cdot\text{nm}}{mc^2}
\end{aligned}$$

or $d \approx \dfrac{98.7}{mc^2}$, where d is in nanometers and mc^2 is in electron volts.

According to Yukawa's line of reasoning, this distance is the range of a force that could be associated with the exchange of virtual particles of this mass.

(b) $\boxed{\text{The range is inversely proportional to the mass of the field particle.}}$

(c) The value of mc^2 for the proton in electron volts is 938.3×10^6. The range of the force is then

$$d \approx \frac{98.7}{mc^2} = \frac{98.7}{938.3\times10^6} = \left(1.05\times10^{-7}\text{ nm}\right)\left(\frac{10^{-9}}{1\text{ nm}}\right)$$
$$= 1.05\times10^{-16}\text{ m}\ \boxed{\sim 10^{-16}\text{ m}}$$

Section 44.5 Conservation Laws

P44.5 The time interval for a particle traveling with the speed of light to travel a distance of 3×10^{-15} m is

$$\Delta t = \frac{d}{v} = \frac{3\times10^{-15}\text{ m}}{3.00\times10^{8}\text{ m/s}} = \boxed{\sim 10^{-23}\text{ s}}$$

P44.6 $\boxed{\text{Baryon number conservation allows the first and forbids the second}}$.

P44.7 (a) $p+\bar{p}\to\mu^+ + e^- \qquad L_\mu: 0+0\to -1+0$ and $L_e: 0+0\to 0+1$

$\boxed{\text{muon lepton number and electron lepton number}}$

(b) $\pi^- + p \to p + \pi^+ \qquad \boxed{\text{charge}}: -1+1\to +1+1$

(c) $p+p\to p+p+n \qquad \boxed{\text{baryon number}}: 1+1\to 1+1+1$

(d) $\gamma + p \to n + \pi^0 \qquad \boxed{\text{charge}}: 0+1\to 0+0$

(f) $\nu_e + p \to n + e^+ \qquad L_e: 1+0\to 0-1$

$\boxed{\text{electron lepton number}}$

P44.8 (a) Baryon number and charge are conserved, with respective values of

baryon: $0 + 1 = 0 + 1$

charge: $1 + 1 = 1 + 1$ in both reactions (1) and (2).

(b) The strangeness values for the reactions are

(1) S: $0 + 0 = 1 - 1$

(2) S: $0 + 0 = 0 - 1$

$\boxed{\text{Strangeness is } \textit{not} \text{ conserved in the second reaction.}}$

P44.9 Check that electron, muon, and tau lepton number are conserved.

(a) $\pi^- \to \mu^- + \boxed{\bar{\nu}_\mu}$ $\quad L_\mu\text{:}\ \ 0 \to 1 - 1$

(b) $\mathrm{K}^+ \to \mu^+ + \boxed{\nu_\mu}$ $\quad L_\mu\text{:}\ \ 0 \to -1 + 1$

(c) $\boxed{\bar{\nu}_\mathrm{e}} + \mathrm{p}^+ \to \mathrm{n} + \mathrm{e}^+$ $\quad L_e\text{:}\ \ -1 + 0 \to 0 - 1$

(d) $\boxed{\nu_\mathrm{e}} + \mathrm{n} \to \mathrm{p}^+ + \mathrm{e}^-$ $\quad L_e\text{:}\ \ 1 + 0 \to 0 + 1$

(e) $\boxed{\nu_\mu} + \mathrm{n} \to \mathrm{p}^+ + \mu^-$ $\quad L_\mu\text{:}\ \ 1 + 0 \to 0 + 1$

(f) $\mu^- \to \mathrm{e}^- + \boxed{\bar{\nu}_\mathrm{e}} + \boxed{\nu_\mu}$ $\quad L_\mu\text{:}\ \ 1 \to 0 + 0 + 1$ and $L_e\text{:}\ \ 0 \to 1 - 1 + 0$

P44.10 The relevant conservation laws are $\Delta L_e = 0$, $\Delta L_\mu = 0$, and $\Delta L_\tau = 0$.

(a) $\pi^+ \to \pi^0 + \mathrm{e}^+ + ?$ $\quad L_e\text{:}\ \ 0 \to 0 - 1 + L_e$ implies $L_e = 1$, so the particle is $\boxed{\nu_e}$.

(b) $? + \mathrm{p} \to \mu^- + \mathrm{p} + \pi^+$ $\quad L_\mu\text{:}\ \ L_\mu + 0 \to +1 + 0 + 0$ implies $L_\mu = 1$, so the particle is $\boxed{\nu_\mu}$.

(c) $\Lambda^0 \to p + \mu^- + ?$ L_μ: $0 \to 0 + 1 + L_\mu$ implies $L_\mu = -1$, so the particle is $\boxed{\bar{\nu}_\mu}$.

(d) $\tau^+ \to \mu^+ + ? + ?$ L_μ: $0 \to -1 + L_\mu$ implies $L_\mu = 1$, so one particle is $\boxed{\nu_\mu}$.

Also, L_τ: $-1 \to 0 + L_\tau$ implies $L_\tau = -1$, so the other particle is $\boxed{\bar{\nu}_\tau}$.

P44.11 (a) $p^+ \to \pi^+ + \pi^0$ check baryon number: $1 \to 0 + 0$

$\boxed{\text{It cannot occur because it violates baryon number conservation.}}$

(b) $p^+ + p^+ \to p^+ + p^+ + \pi^0$ $\boxed{\text{It can occur.}}$

(c) $p^+ + p^+ \to p^+ + \pi^+$ check baryon number: $1 + 1 \to 1 + 0$

$\boxed{\text{It cannot occur because it violates baryon number conservation.}}$

(d) $\pi^+ \to \mu^+ + \nu_\mu$ $\boxed{\text{It can occur.}}$

(e) $n^0 \to p^+ + e^- + \bar{\nu}_e$ $\boxed{\text{It can occur.}}$

(f) $\pi^+ \to \mu^+ + n$ check baryon number: $0 \to 0 + 1$

check muon lepton number: $0 \to -1 + 0$

check masses: $m_{\pi^+} < m_{\mu^+} + m_n$

$$\boxed{\begin{array}{l}\text{It cannot occur because it violates baryon number conservation,}\\ \text{muon lepton number conservation, and energy conservation.}\end{array}}$$

P44.12 (a) In the suggested reaction $p \to e^+ + \gamma$.

From Table 44.2, we would have for baryon numbers $+1 \to 0 + 0$; thus $\Delta B \neq 0$, so baryon number conservation would be violated.

(b) From conservation of momentum for the decay: $p_e = p_\gamma$

Then, for the positron,

$$E_e^2 = (p_e c)^2 + (m_e c^2)^2$$

becomes

$$E_e^2 = (p_\gamma c)^2 + (m_e c^2)^2 = E_\gamma^2 + (m_e c^2)^2$$

From conservation of energy for the system: $m_p c^2 = E_e + E_\gamma$

or $\quad E_e = m_p c^2 - E_\gamma$,

so $\quad E_e^2 = (m_p c^2)^2 - 2(m_p c^2)E_\gamma + E_\gamma^2.$

Equating this to the result from above gives

$$\cancel{E_\gamma^2} + (m_e c^2)^2 = (m_p c^2)^2 - 2(m_e c^2)E_\gamma + \cancel{E_\gamma^2}$$

$$E_\gamma = \frac{(m_p c^2)^2 - (m_e c^2)^2}{2m_p c^2}$$
$$= \frac{(938.3\text{ MeV})^2 - (0.511\text{ MeV})^2}{2(938.3\text{ MeV})} = 469\text{ MeV}$$

Also, $E_e = m_p c^2 - E_\gamma = 938.3\text{ MeV} - 469\text{ MeV} = 469\text{ MeV}$,

Thus, $\boxed{E_e = E_\gamma = 469\text{ MeV}}$.

Also, $p_\gamma = \dfrac{E_\gamma}{c} = \dfrac{469\text{ MeV}}{c}$, so $\boxed{p_e = p_\gamma = 469\text{ MeV}/c}$.

(c) The total energy of the positron is $E_e = 469$ MeV,

but $\quad E_e = \gamma m_e c^2 = \dfrac{m_e c^2}{\sqrt{1-(v/c)^2}}$, so $\sqrt{1-\left(\frac{v}{c}\right)^2} = \frac{m_e c^2}{E_e} = \frac{0.511\text{ MeV}}{469\text{ MeV}} = 1.09\times 10^{-3}$,

which yields $\boxed{v = 0.000\ 999\ 4c}$.

P44.13 (a) To conserve charge, the decay reaction is $\Lambda^0 \to \text{p} + \pi^-$.

We look up in the table the rest energy of each particle:

$m_\Lambda c^2 = 1\ 115.6\text{ MeV}$ $m_\text{p}c^2 = 938.3\text{ MeV}$

$m_\pi c^2 = 139.6\text{ MeV}$

The Q value of the reaction, representing the energy output, is the difference between starting rest energy and final rest energy, and is the kinetic energy of the products:

$$Q = 1\ 115.6\text{ MeV} - 938.3\text{ MeV} - 139.6\text{ MeV} = \boxed{37.7\text{ MeV}}$$

(b) The original kinetic energy is zero in the process considered here, so the whole Q becomes the kinetic energy of the products

$$K_\text{p} + K_\pi = \boxed{37.7\text{ MeV}}$$

(c) The lambda particle is at rest. Its momentum is zero. System momentum is conserved in the decay, so the total vector momentum of the proton and the pion must be $\boxed{\text{zero.}}$

(d) The proton and the pion move in precisely opposite directions with precisely equal momentum magnitudes. Because their masses are different, their kinetic energies are not the same.

The mass of the π-meson is much less than that of the proton, so it carries much more kinetic energy. We can find the energy of each. Let

p represent the magnitude of the momentum of each. Then the total energy of each particle is given by $E^2 = (pc)^2 + (mc^2)^2$ and its kinetic energy is $K = E - mc^2$. For the total kinetic energy of the two particles we have

$$\sqrt{m_p^2c^4 + p^2c^2} - m_pc^2 + \sqrt{m_\pi^2c^4 + p^2c^2} - m_\pi c^2$$
$$= Q = m_\Lambda c^2 - m_pc^2 - m_\pi c^2$$

Proceeding to solve for pc, we find

$$m_p^2c^4 + p^2c^2 = m_\Lambda^2c^4 - 2m_\Lambda c^2\sqrt{m_\pi^2c^4 + p^2c^2} + m_\pi^2c^4 + p^2c^2$$

$$\sqrt{m_\pi^2c^4 + p^2c^2} = \frac{m_\Lambda^2c^4 - m_p^2c^4 + m_\pi^2c^4}{2m_\Lambda c^2}$$
$$= \frac{1\,115.6^2 - 938.3^2 + 139.6^2}{2(1\,115.6)}\text{MeV} = 171.9\text{ MeV}$$

$$pc = \sqrt{171.9^2 - 139.6^2}\text{ MeV} = 100.4\text{ MeV}$$

Then the kinetic energies are

$$K_p = \sqrt{938.3^2 + 100.4^2} - 938.3 = 5.35\text{ MeV}$$

and $K_\pi = \sqrt{139.6^2 + 100.4^2} - 139.6 = 32.3\text{ MeV}$

No. The mass of the π^- meson is much less than that of the proton, so it carries much more kinetic energy. The correct analysis using relativistic energy conservation shows that the kinetic energy of the proton is 5.35 MeV, while that of the π^- meson is 32.3 Mev.

Section 44.6 Strange Particles and Strangeness

P44.14 $\boxed{\begin{array}{l}\text{The } \rho^0 \to \pi^+ + \pi^- \text{ decay must occur via the strong interaction.} \\ \text{The } K_S^0 \to \pi^+ + \pi^- \text{ decay must occur via the weak interaction.}\end{array}}$

P44.15 (a) $\pi^- + p \to 2\eta$

Baryon number: $0+1 \to 0$

$\boxed{\text{It is not allowed because baryon number is not conserved.}}$

(b) $K^- + n \to \Lambda^0 + \pi^-$

Baryon number: $0+1 \to 1+0$

Charge: $-1+0 \to 0-1$

Strangeness: $-1+0 \to -1+0$

Lepton number: $0 \to 0$

The interaction may occur via the $\boxed{\text{strong interaction}}$ since all are conserved.

(c) $K^- \to \pi^- + \pi^0$

Strangeness: $-1 \to 0+0$

Baryon number: $0 \to 0$

Lepton number: $0 \to 0$

Charge: $-1 \to -1+0$

Strangeness conservation is violated by one unit, but everything else is conserved. Thus, the reaction can occur via the

$\boxed{\text{weak interaction}}$, but not the strong or electromagnetic interaction.

(d) $\Omega^- \to \Xi^- + \pi^0$

Baryon number: $1 \to 1+0$

Lepton number: $0 \to 0$

Charge: $-1 \to -1+0$

Strangeness: $-3 \to -2+0$

Strangeness conservation is violated by one unit, but everything else is conserved. The reaction may occur by the $\boxed{\text{weak interaction}}$, but not by the strong or electromagnetic interaction.

(e) $\eta \to 2\gamma$

Baryon number: $0 \to 0$

Lepton number: $0 \to 0$

Charge: $0 \to 0$

Strangeness: $0 \to 0$

No conservation laws are violated, but photons are the mediators of the electromagnetic interaction. Also, the lifetime of the η is consistent with the $\boxed{\text{electromagnetic interaction}}$.

P44.16 (a) $\mu^- \to e^- + \gamma$ $\qquad L_e$: $0 \to 1+0$

L_μ: $1 \to 0$

$\boxed{\text{electron and muon lepton numbers}}$

(b) $n \rightarrow p + e^- + \nu_e$ L_e: $0 \rightarrow 0 + 1 + 1$

$\boxed{\text{electron lepton number}}$

(c) $\Lambda^0 \rightarrow p + \pi^0$ Strangeness: $-1 \rightarrow 0 + 0$

Charge: $0 \rightarrow +1 + 0$

$\boxed{\text{charge and strangeness}}$

(d) $p \rightarrow e^+ + \pi^0$ Baryon number: $+1 \rightarrow 0 + 0$

$\boxed{\text{baryon number}}$

(e) $\Xi^0 \rightarrow n + \pi^0$ Strangeness: $-2 \rightarrow 0 + 0$

$\boxed{\text{strangeness}}$

P44.17 (a) $\Lambda^0 \rightarrow p + \pi^-$ Strangeness: $-1 \rightarrow 0 + 0$, so $\Delta S = +1$

$\boxed{\text{Strangeness is not conserved.}}$

(b) $\pi^- + p \rightarrow \Lambda^0 + K^0$ Strangeness: $0 + 0 \rightarrow -1 + 1$, so $\Delta S = 0$

$\boxed{\text{Strangeness is conserved.}}$

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

$\boxed{\text{Strangeness is conserved.}}$

(d) $\pi^- + p \rightarrow \pi^- + \Sigma^+$ Strangeness: $0 + 0 \rightarrow 0 - 1$, so $\Delta S = -1$

$\boxed{\text{Strangeness is not conserved.}}$

(e) $\Xi^- \rightarrow \Lambda^0 + \pi^-$ Strangeness: $-2 \rightarrow -1 + 0$, so $\Delta S = +1$

$\boxed{\text{Strangeness is not conserved.}}$

(f) $\Xi^0 \to p + \pi^-$ Strangeness: $-2 \to 0 + 0$, so $\Delta S = +2$

$\boxed{\text{Strangeness is not conserved.}}$

P44.18 (a) $\Xi^- \to \Lambda^0 + \mu^- + \nu_\mu$

Baryon number: $+1 \to +1 + 0 + 0$ Charge: $-1 \to 0 - 1 + 0$

L_e: $0 \to 0 + 0 + 0$ L_μ: $0 \to 0 + 1 + 1$

L_τ: $0 \to 0 + 0 + 0$ Strangeness: $-2 \to -1 + 0 + 0$

Conserved quantities are $\boxed{B, \text{ charge}, L_e, \text{ and } L_\tau}$.

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

Baryon number: $0 \to 0$ Charge: $0 \to 0$

L_e: $0 \to 0$ L_μ: $0 \to 0$

L_τ: $0 \to 0$ Strangeness: $+1 \to 0$

Conserved quantities are $\boxed{B, \text{ charge}, L_e, L_\mu, \text{ and } L_\tau}$.

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

Baryon number: $0 + 1 \to 1 + 1$ Charge: $-1 + 1 \to 0 + 0$

L_e: $0 + 0 \to 0 + 0$ L_μ: $0 + 0 \to 0 + 0$

L_τ: $0 + 0 \to 0 + 0$ Strangeness: $-1 + 0 \to -1 + 0$

Conserved quantities are $\boxed{S, \text{ charge}, L_e, L_\mu, \text{ and } L_\tau}$.

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

Baryon number: $+1 \to 1 + 0$ Charge: $0 \to 0$

L_e: $0 \to 0 + 0$ L_μ: $0 \to 0 + 0$

L_τ: $0 \to 0+0$ Strangeness: $-1 \to -1+0$

Conserved quantities are $\boxed{B,\ S,\ \text{charge},\ L_e,\ L_\mu,\ \text{and}\ L_\tau}$.

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

Baryon number: $0+0 \to 0+0$ Charge: $+1-1 \to +1-1$

L_e: $-1+1 \to 0+0$ L_μ: $0+0 \to +1-1$

L_τ: $0+0 \to 0+0$ Strangeness: $0+0 \to 0+0$

Conserved quantities are $\boxed{B,\ S,\ \text{charge},\ L_e,\ L_\mu,\ \text{and}\ L_\tau}$.

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

Baryon number: $-1+1 \to -1+1$ Charge: $-1+0 \to 0-1$

L_e: $0+0 \to 0+0$ L_μ: $0+0 \to 0+0$

L_τ: $0+0 \to 0+0$ Strangeness: $0+0 \to +1-1$

Conserved quantities are $\boxed{B,\ S,\ \text{charge},\ L_e,\ L_\mu,\ \text{and}\ L_\tau}$.

P44.19 As a particle travels in a circle, it experiences a centripetal force, and the centripetal force can be related to the momentum of the particle.

$$\sum F = ma: \quad qvB\sin 90° = \frac{mv^2}{r} \quad \to \quad mv = p = qBr$$

(a) Using $p = qBr$ gives momentum in units of kg · m/s. To convert kg

$\cdot$ m/s into units of MeV/c, we multiply and divide by c:

$$\begin{aligned}\left(\frac{\text{kg}\cdot\text{m}}{\text{s}}\right) = \left(\frac{\text{kg}\cdot\text{m}}{\text{s}}\right)\left(\frac{c}{c}\right) &= \left(\frac{\text{kg}\cdot\text{m}}{\text{s}}\right)\left(2.998\times10^{8}\ \text{m/s}\right)\left(\frac{1}{c}\right)\\ &= \left(2.998\times10^{8}\ \frac{\text{kg}\cdot\text{m}^2}{\text{s}^2}\right)\left(\frac{1}{c}\right)\\ &= 2.998\times10^{8}\ \text{J}\left(\frac{1}{c}\right)\left(\frac{1\ \text{MeV}}{1.602\times10^{-13}\ \text{J}}\right)\\ &= 1.871\times10^{21}\ \text{MeV}/c\end{aligned}$$

$$\begin{aligned}p_{\Sigma^+} &= eBr_{\Sigma^+}\\ &= \left(1.602\times10^{-19}\ \text{C}\right)(1.15\ \text{T})(1.99\ \text{m})\frac{1.871\times10^{21}\ \text{MeV}/c}{\text{kg}\cdot\text{m/s}}\\ &= \boxed{686\ \text{MeV}/c}\end{aligned}$$

$$\begin{aligned}p_{\pi^+} &= eBr_{\pi^+}\\ &= \left(1.602\times10^{-19}\ \text{C}\right)(1.15\ \text{T})(0.580\ \text{m})\left(\frac{1.871\times10^{21}\ \text{MeV}/c}{\text{kg}\cdot\text{m/s}}\right)\\ &= \boxed{200\ \text{MeV}/c}\end{aligned}$$

(b) The total momentum equals the momentum of the Σ^+ particle. The momentum of the pion makes an angle of 64.5° with respect to the original momentum of the Σ^+ particle. If we take the direction of the momentum of the Σ^+ particle as an axis of reference, and let ϕ be the angle made by the neutron's path with the path of the Σ^+ at the moment of its decay, by conservation of momentum, we have these components of momentum:

parallel to the original momentum:

$$p_{\Sigma^+} = p_n\cos\phi + p_{\pi^+}\cos 64.5^\circ$$

thus,

$$p_n \cos\phi = p_{\Sigma^+} - p_{\pi^+} \cos 64.5°$$
$$p_n \cos\phi = 686 \text{ MeV}/c - (200 \text{ MeV}/c)\cos 64.5° \qquad \textbf{[1]}$$

perpendicular to the original momentum:

$$0 = p_n \sin\phi - (200 \text{ MeV}/c)\sin 64.5°$$
$$p_n \sin\phi = (200 \text{ MeV}/c)\sin 64.5° \qquad \textbf{[2]}$$

From [1] and [2]:

$$p_n = \sqrt{(p_n \cos\phi)^2 + (p_n \sin\phi)^2} = \boxed{626 \text{ MeV}/c}$$

(c) $$E_{\pi^+} = \sqrt{(p_{\pi^+}c)^2 + (m_{\pi^+}c^2)^2} = \sqrt{(200\text{ MeV})^2 + (139.6\text{ MeV})^2}$$
$$= \boxed{244\text{ MeV}}$$

$$E_n = \sqrt{(p_n c)^2 + (m_n c^2)^2} = \sqrt{(626\text{ MeV})^2 + (939.6\text{ MeV})^2}$$
$$= 1\,129\text{ MeV} = \boxed{1.13\text{ GeV}}$$

(d) $$E_{\Sigma^+} = E_{\pi^+} + E_n = 244\text{ MeV} + 1129\text{ MeV} = 1\,373\text{ MeV} = \boxed{1.37\text{ GeV}}$$

(e) $$m_{\Sigma^+}c^2 = \sqrt{E_{\Sigma^+}^2 - (p_{\Sigma^+}c)^2} = \sqrt{(1\,373\text{ MeV})^2 - (686\text{ MeV})^2} = 1\,189\text{ MeV}$$

$$\therefore m_{\Sigma^+} = 1\,189 \text{ MeV}/c^2 = \boxed{1.19 \text{ GeV}/c^2}$$

(f) From Table 44.2, the mass of the Σ^+ particle is 1 189.4 MeV/c^2. The percentage difference is

$$\frac{\Delta m}{m} = \frac{1.19 \times 10^3 \text{ MeV}/c^2 - 1\,189.4 \text{ MeV}/c^2}{1\,189.4 \text{ MeV}/c^2} \times 100\% = 0.0504\%$$

$\boxed{\text{The result in part (e) is within 0.05\% of the value in Table 44.2.}}$

Section 44.8 Quarks

P44.20 (a)

	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

(b)

	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

P44.21 Compare the given quark states to the entries in Tables 44.4 and 44.5:

(a) uus = $\boxed{\Sigma^+}$

(b) $\bar{u}d = \boxed{\pi^-}$

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

(d) dss = $\boxed{\Xi^-}$

***P44.22** **Conceptualize** A quick look shows that charge is conserved and baryon number is conserved. We must look deeper.

Categorize The reactions represent *isolated systems* for which a number of conservation laws apply. Specifically, the number of each type of quark must be conserved if the reaction proceeds via the strong interaction.

Analyze Use Tables 44.4 and 44.5 to represent each of the particles in the reaction in terms of quarks:

$$\text{(i)}\ \pi^- + \mathrm{p} \;\rightarrow\; \mathrm{K}^0 + \Lambda^0$$

$$\bar{\mathrm{u}}\mathrm{d} + \mathrm{uud} \;\rightarrow\; \bar{\mathrm{s}}\mathrm{d} + \mathrm{uds}$$

Check for up quarks: $-1 + 2 \;\rightarrow\; 0 + 1$ or $1 = 1$

Check for down quarks: $1 + 1 \;\rightarrow\; 1 + 1$ or $2 = 2$

Check for strange quarks: $0 + 0 \;\rightarrow\; -1 + 1$ or $0 = 0$

Therefore, the number of quarks in the system is 1 u, 1 d, and 0 s both before and after the reaction. Each type of quark is conserved, and the reaction can proceed.

$$\text{(ii)}\ \pi^- + \mathrm{p} \;\rightarrow\; \mathrm{K}^0 + \mathrm{n}$$

$$\bar{\mathrm{u}}\mathrm{d} + \mathrm{uud} \;\rightarrow\; \bar{\mathrm{s}}\mathrm{d} + \mathrm{udd}$$

Check for up quarks: $-1 + 2 \;\rightarrow\; 0 + 1$ or $1 = 1$

Check for down quarks: $1 + 1 \;\rightarrow\; 1 + 2$ or $2 \neq 3$

Check for strange quarks: $0 + 0 \;\rightarrow\; -1 + 0$ or $0 \neq -1$

(b) The numbers of down and strange quark are not conserved, so the reaction cannot occur.

Finalize These calculations show *theoretical* analyses of the two reactions. In *practice*, observations agree: reaction (i) is seen often, while reaction (ii) has never been observed.]

Answers: (a) (i) (b) The number of each type of quark is not conserved.

P44.23 $\Sigma^0 + \mathrm{p} \to \Sigma^+ + \gamma + X$

$\mathrm{uds} + \mathrm{uud} \to \mathrm{uus} + 0 + ?$

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

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

Baryon and strangeness numbers are conserved.

Section 44.11 The Cosmic Connection

P44.24 From Equation 38.10,

$$f_{\text{observer}} = f_{\text{source}}\sqrt{\frac{1+v_a/c}{1-v_a/c}}$$

where the velocity of approach, v, is the negative of the velocity of mutual recession: $v_a = -v$.

Thus, $$\frac{c}{\lambda'} = \frac{c}{\lambda}\sqrt{\frac{1-v/c}{1+v/c}} \quad \text{and} \quad \boxed{\lambda' = \lambda\sqrt{\frac{1+v/c}{1-v/c}}}$$

P44.25 (a) From Wien's law,

$$\lambda_{\max}T = 2.898\times10^{-3}\ \mathrm{m\cdot K}$$

Thus,

$$\lambda_{\max} = \frac{2.898 \times 10^{-3}\ \text{m} \cdot \text{K}}{T} = \frac{2.898 \times 10^{-3}\ \text{m} \cdot \text{K}}{2.73\ \text{K}} = 1.06 \times 10^{-3}\ \text{m}$$
$$= \boxed{1.06\ \text{mm}}$$

(b) This is a $\boxed{\text{microwave.}}$

P44.26 (a) The Hubble constant is defined in $v = HR$. The gap R between any two far-separated objects opens at constant speed according to $R = v\Delta t$. Then the time interval Δt since the Big Bang is found from

$$v = H\, v\Delta t \rightarrow \quad \Delta t = \frac{1}{H}$$

(b)
$$\frac{1}{H} = \frac{1}{22 \times 10^{-3}\ \text{m/s} \cdot \text{ly}} \left[\frac{(1\ \text{yr}) \cdot (3 \times 10^{8}\ \text{m/s})}{1\ \text{ly}} \right] = \boxed{1.36 \times 10^{10}\ \text{yr}}$$
$$= 13.6\ \text{billion years}$$

P44.27 (a) The energy is enough to produce a proton-antiproton pair:

$k_{\text{B}}T \approx 2m_p c^2$, so

$$T \approx \frac{2m_p c^2}{k_{\text{B}}} = \frac{2(938.3\ \text{MeV})}{(1.38 \times 10^{-23}\ \text{J/K})} \left(\frac{1.60 \times 10^{-13}\ \text{J}}{1\ \text{MeV}} \right) \boxed{\sim 10^{13}\ \text{K}}$$

(b) The energy is enough to produce an electron-positron pair:

$k_{\text{B}}T \approx 2m_e c^2$, so

$$T \approx \frac{2m_e c^2}{k_{\text{B}}} = \frac{2(0.511\ \text{MeV})}{(1.38 \times 10^{-23}\ \text{J/K})} \left(\frac{1.60 \times 10^{-13}\ \text{J}}{1\ \text{MeV}} \right) \boxed{\sim 10^{10}\ \text{K}}$$

*** P44.28** **Conceptualize** Review the discussion of dark matter in Section 44.11. If it is there, we cannot see it because it is nonluminous.

Categorize We model the dark matter as uniform throughout the region we are investigating.

Analyze Find the total mass of the dark matter using Equation 1.1:

$$m = \rho V \qquad (1)$$

Substitute for the volume of a sphere whose radius is r_{Earth}:

$$m = \rho\left(\tfrac{4}{3}\pi r_{\text{Earth}}^3\right) = \frac{4\rho\pi r_{\text{Earth}}^3}{3} \qquad (2)$$

Substitute numerical values:

$$m = \frac{4\left(5.00 \times 10^{-22}\ \text{kg/ m}^3\right)\pi\left(1.496 \times 10^{11}\ \text{m}\right)^3}{3} = 7.01 \times 10^{12}\ \text{kg}$$

This amount of mass is 17 orders of magnitude smaller than that of the Sun, so any gravitational effect it would have on the Earth is negligible when compared to the gravitational effect of the Sun.

Finalize Notice that we used a gravitational version of Gauss's law here (Chapter 23; see Example 44.6). The only mass affecting the motion of the Earth is that within a sphere whose radius is that of the Earth's orbit. The gravitational effects of all mass outside this sphere cancel. Our result shows that dark matter does not have gravitational effects on solar-system-sized regions of space. Over very large systems of galaxies and groups of galaxies, however, dark matter is theorized to have a large effect.]

Answer: Mass of dark matter is 17 orders of magnitude smaller than the mass of Sun.

P44.29 We assume that the fireball of the Big Bang is a black body. Then,

$$I = e\sigma T^4 = (1)\left(5.67\times10^{-8}\ \text{W/m}^2\cdot\text{K}^4\right)(2.73\ \text{K})^4$$
$$= \boxed{3.15\times10^{-6}\ \text{W/m}^2}$$

P44.30 (a) What we can see is limited by the finite age of the Universe and by the finite speed of light. We can see out only to a look-back time equal to a bit less than the age of the Universe. Every year on your birthday the Universe also gets a year older, and light now in transit arrives at Earth from still more distant objects. So the radius of the visible Universe expands at the speed of light, which is

$$\frac{dr}{dt} = c = 1\ \text{ly/yr}$$

(b) The volume of the visible section of the Universe is $\frac{4}{3}\pi r^3$, where $r = 13.7$ billion light-years. The rate of volume increase is

$$\frac{dV}{dt} = \frac{d}{dt}\left(\tfrac{4}{3}\pi r^3\right) = \tfrac{4}{3}\pi 3r^2\frac{dr}{dt} = 4\pi r^2 c$$
$$= 4\pi\left[\left(13.7\times10^9\ \text{ly}\right)\left(\frac{9.4605\times10^{15}\ \text{m}}{1\ \text{ly}}\right)\right]^2\left(3.00\times10^8\ \frac{\text{m}}{\text{s}}\right)$$
$$= \boxed{6.34\times10^{61}\ \text{m}^3/\text{s}}$$

P44.31 (a) We use primed symbols to represent observed Doppler-shifted values and unprimed symbols to represent values as they would be measured by an observer stationary relative to the source. Doppler-shift equations from Chapter 16 do not apply to electromagnetic waves, because the speed of source or observer relative to some medium cannot be defined for these waves. Instead, we use Equation 38.10, expressing it as

$$f' = \frac{c}{\lambda'} = \sqrt{\frac{1+v/c}{1-v/c}}\, f = \sqrt{\frac{1+v/c}{1-v/c}}\left(\frac{c}{\lambda}\right)$$

where v is the velocity of mutual approach. Then we have

$$\frac{\lambda'}{\lambda} = \sqrt{\frac{1-v/c}{1+v/c}}$$

Squaring both sides, and solving,

$$\left(\frac{\lambda'}{\lambda}\right)^2 = \frac{1-v/c}{1+v/c}$$

$$\left(\frac{\lambda'}{\lambda}\right)^2 + \left(\frac{\lambda'}{\lambda}\right)^2 \frac{v}{c} = 1 - \frac{v}{c}$$

$$\left(\frac{\lambda'}{\lambda}\right)^2 - 1 = -\frac{v}{c}\left[\left(\frac{\lambda'}{\lambda}\right)^2 + 1\right]$$

Solving for v/c then gives

$$\frac{v}{c} = -\frac{(\lambda'/\lambda)^2 - 1}{(\lambda'/\lambda)^2 + 1} = -\frac{(510\text{ nm}/434\text{ nm})^2 - 1}{(510\text{ nm}/434\text{ nm})^2 + 1} = \frac{(1.18)^2 - 1}{(1.18)^2 + 1}$$

$$= -\frac{1.381 - 1}{1.381 + 1} = -0.160$$

The negative sign indicates that the quasar is moving away from us, or us from it. The speed of recession that the problem asks for is then

$$v = \boxed{0.160c} \text{ (or 16.0\% of the speed of light)}$$

(b) Hubble's law asserts that the universe is expanding at a constant rate so that the speeds of galaxies are proportional to their distance R from Earth, as described by $v = HR$.

So, $R = \dfrac{v}{H} = \dfrac{0.160(3.00\times 10^8\text{ m/s})}{2.2\times 10^{-2}\text{ m/s}\cdot\text{ly}} = \boxed{2.18\times 10^9\text{ ly}}$.

P44.32 (a) Applying the result from Problem 37, $\lambda_n' = \lambda_n\sqrt{\dfrac{1+v/c}{1-v/c}}$, to the definition $Z = \dfrac{\lambda_n' - \lambda_n}{\lambda_n}$, we have

$$Z = \frac{\lambda_n' - \lambda_n}{\lambda_n} \quad \rightarrow \quad (Z+1)\lambda_n = \lambda_n' = \lambda_n\sqrt{\frac{1+v/c}{1-v/c}}$$

$$\frac{1+v/c}{1-v/c} = (Z+1)^2$$

$$1+\frac{v}{c} = (Z+1)^2 - \left(\frac{v}{c}\right)(Z+1)^2$$

$$\left(\frac{v}{c}\right)\left(Z^2+2Z+2\right) = Z^2+2Z$$

$$v = \boxed{c\left(\frac{Z^2+2Z}{Z^2+2Z+2}\right)}$$

(b) $R = \dfrac{v}{H} = \boxed{\dfrac{c}{H}\left(\dfrac{Z^2+2Z}{Z^2+2Z+2}\right)}$

Section 44.12 Problems and Perspectives

P44.33 (a) The Planck length is

$$L = \sqrt{\frac{\hbar G}{c^3}} = \sqrt{\frac{(1.054\ 5\times10^{-34}\ \text{J}\cdot\text{s})(6.673\times10^{-11}\ \text{N}\cdot\text{m}^2/\text{kg}^2)}{(2.998\times10^8\ \text{m/s})^3}}$$

$$= \boxed{1.62\times10^{-35}\ \text{m}}$$

(b) The Planck time is given as

$$T = \frac{L}{c} = \frac{1.616\times10^{-35}\ \text{m}}{2.998\times10^8\ \text{m/s}} = \boxed{5.39\times10^{-44}\ \text{s}}$$

of the same order of magnitude as the ultrahot epoch.

Additional Problems

P44.34 In $? + p^{+} \rightarrow n + \mu^{+}$, charge conservation requires the unknown particle to be neutral. Baryon number conservation requires baryon number = 0. The muon-lepton number of ? must be –1. So the unknown particle must be an muon-antineutrino $\boxed{\bar{\nu}_{\mu}}$.

P44.35 (a) $\pi^{-} + p \rightarrow \Sigma^{+} + \pi^{0}$

Total charge is 0 on the left side of the equation, +1 on the right side. $\boxed{\text{Charge is not conserved.}}$

(b) $\mu^{-} \rightarrow \pi^{-} + \nu_{e}$

The rest mass of the pion is larger than the rest mass of the muon. Muon lepton number is +1 on the left side of the equation, 0 on the right side. Electron lepton number is 0 on left side, +1 on right side. $\boxed{\text{Energy, muon lepton number, and electron lepton number are not conserved.}}$

(c) $p \rightarrow \pi^{+} + \pi^{+} + \pi^{-}$

Baryon number is +1 on the left side of the equation, 0 on the right side. $\boxed{\text{Baryon number is not conserved.}}$

P44.36 Let's find the minimum energy necessary for the increase in rest energy to occur.

$$\Delta E_R = (3m_e - m_e)c^2 = 2m_e c^2 = 2(0.511\ \text{eV}) = 1.02\ \text{eV}$$

This calculation may make it look like the reaction is possible. But there is more to the energy picture here than just the increase in rest energy. There is kinetic energy associated with the moving particles.

Let's demand that energy be conserved for the isolated system:

$$E_i = E_f \quad \rightarrow \quad E_\gamma + m_e c^2 = 3\gamma m_e c^2 \qquad \textbf{[1]}$$

Now demand that momentum in the direction of travel of the initial photon be conserved for the isolated system:

$$p_{xi} = p_{xf} \quad \rightarrow \quad \frac{E_\gamma}{c} = 3\gamma m_e u \qquad \textbf{[2]}$$

Divide equation [1] by equation [2]:

$$\frac{E_\gamma + m_e c^2}{E_\gamma / c} = \frac{c^2}{u} \quad \rightarrow \quad \frac{E_\gamma + m_e c^2}{E_\gamma} = \frac{c}{u} = \frac{1}{\beta} \qquad \textbf{[3]}$$

where $\beta = u/c$. Multiply equation [2] by c and subtract it from equation [1]:

$$\begin{aligned} E_\gamma + m_e c^2 - E_\gamma &= 3\gamma m_e c^2 - 3\gamma m_e uc \\ \rightarrow \quad m_e c^2 &= 3\gamma m_e c^2 - 3\gamma m_e uc \\ \rightarrow \quad 1 &= 3\gamma - 3\gamma \frac{u}{c} = 3\gamma(1 - \beta) \end{aligned}$$

Substitute for γ:

$$1 = \frac{3(1-\beta)}{\sqrt{1-u^2/c^2}} = \frac{3(1-\beta)}{\sqrt{1-\beta^2}} = 3\sqrt{\frac{1-\beta}{1+\beta}}$$

$$1+\beta = 9(1-\beta) \quad \rightarrow \quad \beta = \frac{8}{10} = 0.800$$

Substitute this value into equation [3]:

$$\frac{E_\gamma + m_e c^2}{E_\gamma} = \frac{1}{0.800}$$

$$1 + \frac{m_e c^2}{E_\gamma} = 1.25 \rightarrow \quad E_\gamma = 4 m_e c^2 = 2.04 \text{ MeV}$$

Therefore, the photon arriving with 1.05 MeV of energy cannot cause this reaction.

Let's check the assumptions. If the final particles have any velocity component perpendicular to the initial direction of travel of the photon, then they must be moving with a higher speed after the collision and the incoming photon energy would have to be larger. If any one of the particles had a different energy than the other two, then the only way to satisfy both energy and momentum conservation would be for at least two of the particles to have components of velocity perpendicular to the initial direction of motion of the photon, so again the incoming photon energy would have to be larger. Therefore, 2.04 MeV represents the *minimum* energy for the reaction to occur.

P44.37 We find the number N of neutrinos:

$$\begin{aligned}10^{46}\ \text{J} &= N(6\ \text{MeV}) = N\left(6\times 1.60\times 10^{-13}\ \text{J}\right)\\ N &= 1.0\times 10^{58}\ \text{neutrinos}\end{aligned}$$

The intensity at our location is

$$\begin{aligned}\frac{N}{A} &= \frac{N}{4\pi r^2} = \frac{1.0\times 10^{58}}{4\pi\left(1.7\times 10^5\ \text{ly}\right)^2}\left(\frac{1\ \text{ly}}{9.460\ 5\times 10^{15}\ \text{m}}\right)^2\\ &= 3.1\times 10^{14}\ \text{m}^{-2}\end{aligned}$$

The number passing through a body presenting 5 000 cm^2 = 0.50 m^2

is then $\left(3.1\times 10^{14}\ \dfrac{1}{\text{m}^2}\right)\left(0.50\ \text{m}^2\right) = 1.5\times 10^{14}$, or $\boxed{\sim 10^{14}}$.

P44.38 Since the neutrino flux from the Sun reaching the Earth is 0.400 W/m^2, the total energy emitted per second by the Sun in neutrinos in all directions is that which would irradiate the surface of a great sphere around it, with the Earth's orbit as its equator.

$$\left(0.400\ \text{W/m}^2\right)\left(4\pi r^2\right) = \left(0.400\ \text{W/m}^2\right)\left[4\pi\left(1.496\times10^{11}\ \text{m}\right)^2\right]$$
$$= 1.12\times10^{23}\ \text{W}$$

In a period of 10^9 yr, the Sun emits a total energy of $\Delta E = P\Delta t$.

$$E = \left(1.12\times10^{23}\ \text{J/s}\right)\left(10^9\ \text{yr}\right)\left(3.156\times10^7\ \text{s/yr}\right) = 3.55\times10^{39}\ \text{J}$$

carried by neutrinos. This energy corresponds to an annihilated mass according to

$$E = m_v c^2 = 3.55\times10^{39}\ \text{J} \quad \text{or} \quad m_v = 3.94\times10^{22}\ \text{kg}.$$

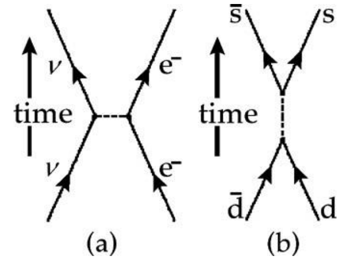
Since the Sun has a mass of 1.989 □ 10^{30} kg, this corresponds to a loss of only about $\boxed{\text{1 part in } 5\times10^7}$ of the Sun's mass over 10^9 yr in the form of neutrinos.

P44.39 In our frame of reference, Hubble's law is exemplified by $\vec{\mathbf{v}}_1 = H\vec{\mathbf{R}}_1$ and $\vec{\mathbf{v}}_2 = H\vec{\mathbf{R}}_2$.

(a) From the first equation $\vec{\mathbf{v}}_1 = H\vec{\mathbf{R}}_1$ we may form the equation $-\vec{\mathbf{v}}_1 = -H\vec{\mathbf{R}}_1$. This equation expresses Hubble's law as seen by the observer in the first galaxy cluster, as she looks at us to find our velocity relative to her (away from her) is $-\vec{\mathbf{v}}_1 = H\left(-\vec{\mathbf{R}}_1\right)$.

(b) From both equations we may form the equation $\vec{\mathbf{v}}_2 - \vec{\mathbf{v}}_1 = H\left(\vec{\mathbf{R}}_2 - \vec{\mathbf{R}}_1\right)$. This equation expresses Hubble's law as seen by the observer in the first galaxy cluster, as she looks at cluster two to find the relative velocity of cluster 2 relative to cluster 1 is $\vec{\mathbf{v}}_2 - \vec{\mathbf{v}}_1 = H\left(\vec{\mathbf{R}}_2 - \vec{\mathbf{R}}_1\right)$.

P44.40 (a) The Feynman diagram in ANS. FIG. P44.40 shows a neutrino scattering off an electron, and the neutrino and electron do not exchange electric charge. The neutrino has no electric charge and interacts through the weak interaction (ignoring gravity). The mediator is a $\boxed{Z^0 \text{ boson.}}$



ANS. FIG. P44.40

(b) The Feynman diagram shows a down quark and its antiparticle annihilating each other. They can produce a particle carrying energy, momentum, and angular momentum, but zero charge, zero baryon number, and, if the quarks have opposite color charges, no color charge. In this case the mediating particle could be a $\boxed{\text{photon or } Z^0 \text{ boson.}}$

Depending on the color charges of the d and $\overline{\text{d}}$ quarks, the ephemeral particle could also be a $\boxed{\text{gluon}}$, as suggested in the discussion of Figure 44.40(b).

For conservation of both energy and momentum in the collision we would expect two mediating particles; but momentum need not be strictly conserved, according to the uncertainty principle, if the particle travels a sufficiently short distance before producing another matter-antimatter pair of particles, as shown in ANS. FIG. P44.40(b).

P44.41 Each particle travels in a circle, so each must experience a centripetal force:

$$\sum F = ma: \quad qvB\sin 90° = \frac{mv^2}{r} \quad \to \quad mv = qBr$$

The proton and the pion have the same momentum because they have the same magnitude of charge and travel in a circle of the same radius:

$$\begin{aligned} p_{\text{p}} = p_\pi = p = qBr &= \left(1.60\times10^{-19}\ \text{C}\right)(0.250\ \text{T})(1.33\ \text{m}) \\ &= 5.32\times10^{-20}\ \text{kg}\cdot\text{m/s} \end{aligned}$$

so

$$\begin{aligned} pc &= \left(3.00\times10^{8}\ \text{m/s}\right)\left(5.32\times10^{-20}\ \text{kg}\cdot\text{m/s}\right)\left(\frac{1\ \text{MeV}}{1.60\times10^{-13}\ \text{J}}\right) \\ &= 99.8\ \text{MeV} \end{aligned}$$

Using masses from Table 44.2, we find the total energy of the proton to be

$$\begin{aligned} E_{\text{p}} &= \sqrt{(pc)^2 + \left(m_{\text{p}}c^2\right)^2} = \sqrt{(99.8\ \text{MeV})^2 + (938.3\ \text{MeV})^2} \\ &= 944\ \text{MeV} \end{aligned}$$

and the total energy of the pion to be

$$\begin{aligned} E_\pi &= \sqrt{(pc)^2 + \left(m_\pi c^2\right)^2} = \sqrt{(99.8\ \text{MeV})^2 + (139.6\ \text{MeV})^2} \\ &= 172\ \text{MeV} \end{aligned}$$

The unknown particle was initially at rest; thus, $E_{\text{total after}} = E_{\text{total before}} =$ rest energy, and the rest energy of unknown particle is

$$mc^2 = 944\ \text{MeV} + 172\ \text{MeV} = 1\ 116\ \text{MeV}$$

$$\text{Mass} = \boxed{1.12\ \text{GeV}/c^2}$$

From Table 44.2, we see this is a Λ^0 particle.

P44.42 Each particle travels in a circle, so each must experience a centripetal force:

$$\sum F = ma: \quad qvB\sin 90° = \frac{mv^2}{r} \quad \rightarrow \quad mv = qBr$$

The particles have the same momentum because they have the same magnitude of charge and travel in a circle of the same radius:

$$p_+ = p_- = p = eBr \quad \rightarrow \quad pc = eBrc$$

We find the total energy of the positively charged particle to be

$$E_{+,\text{ total}} = \sqrt{(pc)^2 + (E_+)^2} = \sqrt{(qBrc)^2 + E_+^2}$$

and the total energy of the negatively charged particle to be

$$E_{+,\text{ total}} = \sqrt{(pc)^2 + (E_-)^2} = \sqrt{(qBrc)^2 + E_-^2}$$

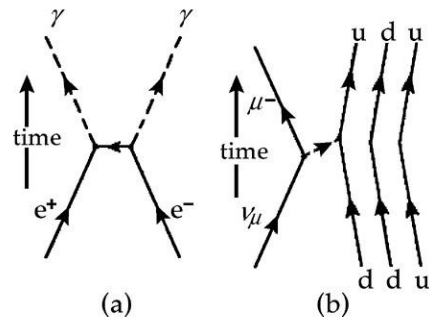
The unknown particle was initially at rest; thus, $E_{\text{total after}} = E_{\text{total before}} =$ rest energy, and the rest energy of the unknown particle is

$$mc^2 = \sqrt{(qBrc)^2 + E_+^2} + \sqrt{(qBrc)^2 + E_-^2}$$

$$\boxed{m = \frac{\sqrt{(qBrc)^2 + E_+^2} + \sqrt{(qBrc)^2 + E_-^2}}{c^2}}$$

P44.43 (a) This diagram represents $\boxed{\text{electron–positron annihilation}}$. From charge and lepton-number conservation at either vertex, the exchanged particle must be an electron, $\boxed{e^-.}$

(b) $\boxed{\text{A neutrino collides with a neutron, producing a proton and a muon.}}$ This is a weak interaction. The exchanged particle has charge +*e* and is a $\boxed{W^+.}$



ANS. FIG. P44.43

***P44.44** **Conceptualize** Imagine the Universe cooling. At higher temperatures, atoms could not form; any atoms that might form were immediately ionized by the collisions of other particles due to the high temperature. At some temperature, the collisions were not sufficiently violent enough to ionize atoms that formed. As a result, electromagnetic radiation could pass through regions of atoms without Compton scattering; only a few wavelengths were absorbed by the atoms, those matching the differences in quantized energy levels: the Universe is transparent!

Categorize We model the Universe as a gas described by the Boltzmann distribution function (Eq. 20.41).

Analyze Find the fraction of particles in the Universe with energy greater than an arbitrary E by integrating the number density (Eq. 20.41) from E to infinity and dividing by the integral from 0 to infinity:

$$f = \frac{\int_E^\infty n_0 e^{-E/k_BT}\,dE}{\int_0^\infty n_0 e^{-E/k_BT}\,dE} = \frac{\left(\dfrac{e^{-E/k_BT}}{-1/k_BT}\right)_E^\infty}{\left(\dfrac{e^{-E/k_BT}}{-1/k_BT}\right)_0^\infty} = \frac{\left(0 - e^{-E/k_BT}\right)}{(0-1)} = e^{-E/k_BT} \tag{1}$$

Your professor asked you to determine the threshold temperature T at which 1.00% of a population of photons has energy greater than 1.00 eV. Solve Equation

(1) for the temperature T:

$$T = -\frac{E}{k_B \ln f} \qquad (2)$$

Substitute numerical values:

$$T = -\frac{1.00 \text{ eV}}{(1.381 \times 10^{-23} \text{ J/K})\ln(0.010\,0)}\left(\frac{1.602 \times 10^{-19} \text{ J}}{1 \text{ eV}}\right) = 2.52 \times 10^3 \text{ K} \boxed{\square\ 10^3 \text{ K}}$$

Finalize Online research on the temperature of the Universe as a function of time shows that this temperature occurs at a time of several hundred thousand years after the Big Bang. This is consistent with the figure of 377 000 years mentioned in Section 44.11.]

Answer: ~10^3 K

P44.45 $\mathrm{p} + \mathrm{p} \to \mathrm{p} + \pi^+ + \mathrm{X}$

The protons each have 70.4 MeV of kinetic energy. In accord with conservation of momentum for the collision, particle X has zero momentum and thus zero kinetic energy. Conservation of system energy then requires

$$m_p c^2 + m_\pi c^2 + m_X c^2 = (m_p c^2 + K_p) + (m_p c^2 + K_p)$$

$$\begin{aligned} m_X c^2 &= m_p c^2 + 2K_p - m_\pi c^2 \\ &= 938.3 \text{ MeV} + 2(70.4 \text{ MeV}) - 139.6 \text{ MeV} \\ &= 939.5 \text{ MeV} \end{aligned}$$

X must be a neutral baryon of rest energy 939.5 MeV. Thus, X is a $\boxed{\text{neutron.}}$

Challenge Problems

P44.46 (a) Let E_{min} be the minimum total energy of the bombarding particle that is needed to induce the reaction. At this energy the product particles all move with the same velocity. The product particles are then equivalent to a single particle having mass equal to the total mass of the product particles, moving with the same velocity as each product particle. By conservation of energy:

$$E_{\text{min}} + m_2c^2 = \sqrt{\left(m_3c^2\right)^2 + \left(p_3c\right)^2} \qquad \textbf{[1]}$$

By conservation of momentum, $p_3 = p_1$, so

$$\left(p_3c\right)^2 = \left(p_1c\right)^2 = E_{\text{min}}^2 - \left(m_1c^2\right)^2 \qquad \textbf{[2]}$$

Substitute [2] into [1]:

$$E_{\text{min}} + m_2c^2 = \sqrt{\left(m_3c^2\right)^2 + E_{\text{min}}^2 - \left(m_1c^2\right)^2}$$

Square both sides:

$$E_{\text{min}}^2 + 2E_{\text{min}}m_2c^2 + \left(m_2c^2\right)^2 = \left(m_3c^2\right)^2 + E_{\text{min}}^2 - \left(m_1c^2\right)^2$$

$$\therefore E_{\text{min}} = \frac{\left(m_3^2 - m_1^2 - m_2^2\right)c^2}{2m_2}$$

$$\therefore K_{\text{min}} = E_{\text{min}} - m_1c^2 = \frac{\left(m_3^2 - m_1^2 - m_2^2 - 2m_1m_2\right)c^2}{2m_2}$$

$$= \frac{\left[m_3^2 - \left(m_1 + m_2\right)^2\right]c^2}{2m_2}$$

Refer to Table 44.2 for the particle masses.

(b) $$K_{\min} = \frac{[4(938.3)]^2\ \text{MeV}^2/c^2 - [2(938.3)]^2\ \text{MeV}^2/c^2}{2\left(938.3\ \text{MeV}/c^2\right)} = \boxed{5.63\ \text{GeV}}$$

(c) $$K_{\min} = \frac{(497.7 + 1\,115.6)^2\ \text{MeV}^2/c^2 - (139.6 + 938.3)^2\ \text{MeV}^2/c^2}{2(938.3)\ \text{MeV}/c^2}$$

$$= \boxed{768\ \text{MeV}}$$

(d) $$K_{\min} = \frac{[2(938.3) + 135]^2\ \text{MeV}^2/c^2 - [2(938.3)]^2\ \text{MeV}^2/c^2}{2(938.3)\ \text{MeV}/c^2}$$

$$= \boxed{280\ \text{MeV}}$$

(e) $$K_{\min} = \frac{\left(91.2 \times 10^3\right)^2 - \left[(938.3 + 938.3)^2\right]\ \text{MeV}^2/c^2}{2(938.3)\ \text{MeV}/c^2} = \boxed{4.43\ \text{TeV}}$$

P44.47 (a) Consider a sphere around us of radius R large compared to the size of galaxy clusters. If the matter M inside the sphere has the critical density, then a galaxy of mass m at the surface of the sphere is moving just at escape speed v according to $K + U_g = 0$,

or $$\frac{1}{2}mv^2 - \frac{GMm}{R} = 0.$$

The energy of the galaxy-sphere system is conserved, so this equation is true throughout the history of the Universe after the Big Bang, where $v = \dfrac{dR}{dt}$. Then,

$$\left(\frac{dR}{dt}\right)^2 = \frac{2GM}{R}$$

or $$\frac{dR}{dt} = R^{-1/2}\sqrt{2GM}.$$

integrating,

$$\int_0^R \sqrt{R}\, dR = \sqrt{2GM}\int_0^T dt$$

$$\left.\frac{R^{3/2}}{3/2}\right|_0^R = \sqrt{2GM}\, t\Big|_0^T \quad \text{gives} \quad \frac{2}{3}R^{3/2} = \sqrt{2GM}\, T$$

or $\quad T = \dfrac{2}{3}\dfrac{R^{3/2}}{\sqrt{2GM}} = \dfrac{2}{3}\dfrac{R}{\sqrt{2GM/R}}.$

From above, $\quad \sqrt{\dfrac{2GM}{R}} = v$

so $\quad T = \dfrac{2}{3}\dfrac{R}{v}.$

Now Hubble's law says $v = HR$, so $T = \dfrac{2}{3}\dfrac{R}{HR} = \dfrac{2}{3H}.$

(b) $\quad T = \dfrac{2}{3\left(22\times10^{-3}\ \text{m/s}\cdot\text{ly}\right)}\left(\dfrac{2.998\times10^{8}\ \text{m/s}}{1\ \text{ly/yr}}\right) = \boxed{9.08\times10^{9}\ \text{yr}}$

$= 9.08$ billion years

P44.48 A photon travels the distance from the Large Magellanic Cloud to us in 170 000 years. The hypothetical massive neutrino travels the same distance in 170 000 years plus 10 seconds:

$$c(170\ 000\ \text{yr}) = v(170\ 000\ \text{yr} + 10\ \text{s})$$

$$\frac{v}{c} = \frac{170\ 000\ \text{yr}}{170\ 000\ \text{yr} + 10\ \text{s}}$$

$$= \frac{1}{1+\left\{10\ \text{s}/\left[\left(1.7\times10^{5}\ \text{yr}\right)\left(3.156\times10^{7}\ \text{s/yr}\right)\right]\right\}}$$

$$= \frac{1}{1+1.86\times10^{-12}}$$

For the neutrino we want to evaluate mc^2 in $E = \gamma mc^2$:

$$mc^2 = \frac{E}{\gamma} = E\sqrt{1-\frac{v^2}{c^2}} = 10\text{ MeV}\sqrt{1-\frac{1}{\left(1+1.86\times10^{-12}\right)^2}}$$

$$= (10\text{ MeV})\sqrt{\frac{\left(1+1.86\times10^{-12}\right)^2-1}{\left(1+1.86\times10^{-12}\right)^2}}$$

$$mc^2 \approx (10\text{ MeV})\sqrt{\frac{2\left(1.86\times10^{-12}\right)}{1}} = (10\text{ MeV})\left(1.93\times10^{-6}\right)$$
$$= 19\text{ eV}$$

Then the upper limit on the mass is

$$m = \boxed{\frac{19\text{ eV}}{c^2}}$$

$$m = \frac{19\text{ eV}}{c^2}\left(\frac{\text{u}}{931.5\times10^6\ \text{eV}/c^2}\right) = 2.1\times10^{-8}\ \text{u}$$

P44.49 (a) If $2N$ particles are annihilated, the energy released is $2Nmc^2$. The resulting photon momentum is $p = \frac{E}{c} = \frac{2Nmc^2}{c} = 2Nmc$. Since the momentum of the system is conserved, the rocket will have momentum $2Nmc$ directed opposite the photon momentum.

$$\boxed{p = 2Nmc}$$

(b) Consider a particle that is annihilated and gives up its rest energy mc^2 to another particle which also has initial rest energy mc^2 (but no momentum initially).

$$E^2 = p^2c^2 + \left(mc^2\right)^2$$

Thus, $(2mc^2)^2 = p^2c^2 + (mc^2)^2$.

Where p is the momentum the second particle acquires as a result of the annihilation of the first particle. Thus

$4(mc^2)^2 = p^2c^2 + (mc^2)^2$, $p^2 = 3(mc^2)^2$. So $p = \sqrt{3}mc$.

This process is repeated N times (annihilate $\frac{N}{2}$ protons and $\frac{N}{2}$ antiprotons). Thus the total momentum acquired by the ejected particles is $\sqrt{3}Nmc$, and this momentum is imparted to the rocket.

$$\boxed{p = \sqrt{3}Nmc}$$

(c) Method (a) produces greater speed since $2Nmc > \sqrt{3}Nmc$.

ANSWERS TO QUICK-QUIZZES

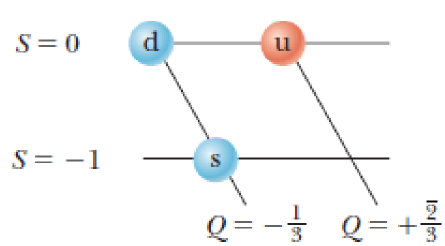
1. (a)

2. (i) (c), (d) **(ii)** (a)

3. (b), (e), (f)

4. (b), (e)

5.



6. false

ANSWERS TO EVEN-NUMBERED PROBLEMS

P44.2 1.6 h^{-1}

P44.4 (a) See ANS. P44.4 for full explanation; (b) $\boxed{\text{The range is inversely proportional to the mass of the field particle}}$; (c) $\sim 10^{-16}$ m

P44.6 Baryon number conservation allows the first reaction and forbids the second.

P44.8 (a) See P44.8 (a) for full explanation; (b) Strangeness is not conserved in the second reaction.

P44.10 (a) ν_e; (b) ν_μ; (c) $\bar{\nu}_\mu$; (d) ν_μ, $\bar{\nu}_\tau$

P44.12 (a) See P44.12 (a) for full explanation;

(b) $E_e = E_\gamma = 469$ MeV, $p_e = p_\gamma = 469$ MeV/c; (c) $v = 0.999\ 999\ 4c$

P44.14 The $\rho^0 \to \pi^+ + \pi^-$ decay must occur via the strong interaction. The $\mathrm{K}_\mathrm{S}^0 \to \pi^+ + \pi^-$ decay must occur via the weak interaction.

P44.16 (a) electron and muon lepton numbers; (b) electron lepton number; (c) charge and strangeness; (d) baryon number; (e) strangeness

P44.18 (a) B, charge, L_e, and L_τ; (b) B, charge, L_e, L_μ, and L_τ;

(c) S, charge, L_e, L_μ, and L_τ; (d) B, S, charge, L_e, L_μ, and L_τ;

(e) B, S, charge, L_e, L_μ, and L_τ; (f) B, S, charge, L_e, L_μ, and L_τ

P44.20 (a) See ANS.Table P44.20(a); (a) See ANS.Table P44.20(b)

P44.22 (a) (i) (b) The number of each type of quark is not conserved.

P44.24 $\lambda' = \lambda\sqrt{\dfrac{1+v/c}{1-v/c}}$

P44.26 1.36×10^{10} yr

P44.28 Mass of dark matter is 17 orders of magnitude smaller than the mass of Sun.

P44.30 (a) See P44.30(a) for full explanation; (b) $6.34 \times 10^{61}\ \text{m}^3/\text{s}$

P44.32 (a) $c\left(\dfrac{Z^2+2Z}{Z^2+2Z+2}\right)$; (b) $\dfrac{c}{H}\left(\dfrac{Z^2+2Z}{Z^2+2Z+2}\right)$

P44.34 $\bar{\nu}_\mu$

P44.36 See P44.36 for full explanation.

P44.38 1 part in 5×10^7

P44.40 (a) Z^0 boson; (b) photon or Z^0 boson, gluon

P44.42 $m = \dfrac{\sqrt{(qBrc)^2 + E_+^2} + \sqrt{(qBrc)^2 + E_-^2}}{c^2}$

P44.44 ~10^3 K

P44.46 (a) See P44.46(a) for full explanation; (b) 5.63 GeV; (c) 768 MeV; (d) 280 MeV; (e) 4.43 TeV

P44.48 19 eV/c^2