Chapter 44

3. The total rest energy of the electron-positron pair is

$$E = m_e c^2 + m_e c^2 = 2m_e c^2 = 2(0.511\text{ MeV}) = 1.022\text{ MeV}.$$

With two gamma-ray photons produced in the annihilation process, the wavelength of each photon is (using $hc = 1240\text{ eV}\cdot\text{nm}$)

$$\lambda = \frac{hc}{E/2} = \frac{1240\text{ eV}\cdot\text{nm}}{0.511\times10^6\text{eV}} = 2.43\times10^{-3}\text{ nm} = 2.43\text{ pm}.$$

4. Conservation of momentum requires that the gamma ray particles move in opposite directions with momenta of the same magnitude. Since the magnitude p of the momentum of a gamma ray particle is related to its energy by $p = E/c$, the particles have the same energy E. Conservation of energy yields $m_\pi c^2 = 2E$, where m_π is the mass of a neutral pion. The rest energy of a neutral pion is $m_\pi c^2 = 135.0$ MeV, according to Table 44-4. Hence, $E = (135.0\text{ MeV})/2 = 67.5$ MeV. We use $hc = 1240\text{ eV}\cdot\text{nm}$ to obtain the wavelength of the gamma rays:

$$\lambda = \frac{1240\text{ eV}\cdot\text{nm}}{67.5\times10^6\text{eV}} = 1.84\times10^{-5}\text{ nm} = 18.4\text{ fm}.$$

5. We establish a ratio, using Eq. 22-4 and Eq. 14-1:

$$\frac{F_{\text{gravity}}}{F_{\text{electric}}} = \frac{Gm_e^2/r^2}{ke^2/r^2} = \frac{4\pi\varepsilon_0 G m_e^2}{e^2} = \frac{\left(6.67\times10^{-11}\text{ N}\cdot\text{m}^2/\text{C}^2\right)\left(9.11\times10^{-31}\text{ kg}\right)^2}{\left(9.0\times10^{9}\text{ N}\cdot\text{m}^2/\text{C}^2\right)\left(1.60\times10^{-19}\text{ C}\right)^2}$$
$$= 2.4\times10^{-43}.$$

Since $F_{\text{gravity}} \ll F_{\text{electric}}$, we can neglect the gravitational force acting between particles in a bubble chamber.

11. (a) The conservation laws considered so far are associated with energy, momentum, angular momentum, charge, baryon number, and the three lepton numbers. The rest energy of the muon is 105.7 MeV, the rest energy of the electron is 0.511 MeV, and the rest energy of the neutrino is zero. Thus, the total rest energy before the decay is greater than the total rest energy after. The excess energy can be carried away as the kinetic energies of the decay products and energy can be conserved. Momentum is conserved if the electron and neutrino move away from the decay in opposite directions with equal

magnitudes of momenta. Since the orbital angular momentum is zero, we consider only spin angular momentum. All the particles have spin $\hbar/2$. The total angular momentum after the decay must be either $\hbar$ (if the spins are aligned) or zero (if the spins are antialigned). Since the spin before the decay is $\hbar/2$, angular momentum cannot be conserved. The muon has charge $-e$, the electron has charge $-e$, and the neutrino has charge zero, so the total charge before the decay is $-e$ and the total charge after is $-e$. Charge is conserved. All particles have baryon number zero, so baryon number is conserved. The muon lepton number of the muon is +1, the muon lepton number of the muon neutrino is +1, and the muon lepton number of the electron is 0. Muon lepton number is conserved. The electron lepton numbers of the muon and muon neutrino are 0 and the electron lepton number of the electron is +1. Electron lepton number is not conserved. The laws of conservation of angular momentum and electron lepton number are not obeyed and this decay does not occur.

(b) We analyze the decay $\mu^- \to e^+ + \nu_e + \bar{\nu}_\mu$ in the same way. We find that charge and the muon lepton number L_μ are not conserved.

(c) For the process $\mu^+ \to \pi^+ + \nu_\mu$, we find that energy cannot be conserved because the mass of muon is less than the mass of a pion. Also, muon lepton number L_μ is not conserved.

33. We apply Eq. 37-36 for the Doppler shift in wavelength:

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

where v is the recessional speed of the galaxy. We use Hubble's law to find the recessional speed: $v = Hr$, where r is the distance to the galaxy and H is the Hubble constant $\left(21.8\times10^{-3}\,\frac{\text{m}}{\text{s}\cdot\text{ly}}\right)$. Thus,

$$v = \left(21.8\times10^{-3}\ \text{m/s}\cdot\text{ly}\right)\left(2.40\times10^{8}\ \text{ly}\right) = 5.23\times10^{6}\ \text{m/s}$$

and

$$\Delta\lambda = \frac{v}{c}\lambda = \left(\frac{5.23\times10^{6}\ \text{m/s}}{3.00\times10^{8}\ \text{m/s}}\right)(656.3\ \text{nm}) = 11.4\ \text{nm}\,.$$

Since the galaxy is receding, the observed wavelength is longer than the wavelength in the rest frame of the galaxy. Its value is

$$656.3\ \text{nm} + 11.4\ \text{nm} = 667.7\ \text{nm} \approx 668\ \text{nm}.$$

$$\Delta t = \frac{12\,\text{m}}{0.993\left(2.998\times10^{8}\ \text{m/s}\right)} = 4.0\times10^{-8}\ \text{s} = 40\,\text{ns}\,.$$