

## CHAPTER 33: PARTICLE PHYSICS

### 33.2 THE FOUR BASIC FORCES

4. (a) Find the ratio of the strengths of the weak and electromagnetic forces under ordinary circumstances. (b) What does that ratio become under circumstances in which the forces are unified?

**Solution** (a) From Table 33.1, we know that the ratio of the weak force to the electromagnetic force is  $\frac{\text{Weak}}{\text{Electromagnetic}} = \frac{10^{-13}}{10^{-2}} = 10^{-11}$ . In other words, the weak force is 11 orders of magnitude weaker than the electromagnetic force.

(b) When the forces are unified, the idea is that the four forces are just different manifestations of the same force, so under circumstances in which the forces are unified, the ratio becomes 1 to 1. (See Section 33.6.)

### 33.3 ACCELERATORS CREATE MATTER FROM ENERGY

7. Suppose a  $W^-$  created in a bubble chamber lives for  $5.00 \times 10^{-25}$  s. What distance does it move in this time if it is traveling at  $0.900c$ ? Since this distance is too short to make a track, the presence of the  $W^-$  must be inferred from its decay products. Note that the time is longer than the given  $W^-$  lifetime, which can be due to the statistical nature of decay or time dilation.

**Solution** Using the definition of velocity, we can determine the distance traveled by the  $W^-$  in a bubble chamber:

$$d = vt = (0.900)(3.00 \times 10^8 \text{ m/s})(5.00 \times 10^{-25} \text{ s}) = 1.35 \times 10^{-16} \text{ m} = \underline{0.135 \text{ fm}}$$

### 33.4 PARTICLES, PATTERNS, AND CONSERVATION LAWS

13. The  $\pi^0$  is its own antiparticle and decays in the following manner:  $\pi^0 \rightarrow \gamma + \gamma$ . What is the energy of each  $\gamma$  ray if the  $\pi^0$  is at rest when it decays?

**Solution** If the  $\pi^0$  is at rest when it decays, its total energy is just  $E = mc^2$ . Since its initial momentum is zero, each  $\gamma$  ray will have equal but opposite momentum i.e.

$$p_i = 0 = p_f, \text{ so that } p_{y_1} + p_{y_2} = 0, \text{ or } p_{y_1} = -p_{y_2}. \text{ Since a } \gamma \text{ ray is a photon: } E_\gamma = |p_\gamma|c.$$

Therefore, since the momenta are equal in magnitude the energies of the  $\gamma$  rays are equal:  $E_1 = E_2$ . Then, by conservation of energy, the initial energy of the  $\pi^0$  equals twice the energy of one of the  $\gamma$  rays:  $m_{\pi^0}c^2 = 2E$ . Finally, from Table 33.2, we can determine the rest mass energy of the  $\pi^0$ , and the energy of each  $\gamma$  ray is:

$$E = \frac{m_{\pi^0}c^2}{2} = \frac{(135 \text{ MeV}/c^2)c^2}{2} = \underline{67.5 \text{ MeV}}$$

19. (a) What is the uncertainty in the energy released in the decay of a  $\pi^0$  due to its short lifetime? (b) What fraction of the decay energy is this, noting that the decay mode is  $\pi^0 \rightarrow \gamma + \gamma$  (so that all the  $\pi^0$  mass is destroyed)?

**Solution** (a) Using  $\Delta E \Delta t \approx \frac{h}{4\pi}$ , we can calculate the uncertainty in the energy, given the

lifetime of the  $\pi^0$  from Table 33.2:

$$\Delta E = \frac{h}{4\pi\Delta t} = \frac{6.63 \times 10^{-34} \text{ J}\cdot\text{s}}{4\pi(8.4 \times 10^{-17} \text{ s})} = 6.28 \times 10^{-19} \text{ J} \times \frac{1 \text{ eV}}{1.60 \times 10^{-19} \text{ J}} = \underline{3.9 \text{ eV}}$$

(b) The fraction of the decay energy is determined by dividing this uncertainty in the energy by the rest mass energy of the  $\pi^0$  found in Table 33.2:

$$\frac{\Delta E}{m_{\pi^0} c^2} = \frac{3.9256 \text{ eV}}{(135.0 \times 10^6 \text{ eV}/c^2) c^2} = 2.9 \times 10^{-8}$$

So the uncertainty is approximately  $2.9 \times 10^{-6}$  percent of the rest mass energy.

### 33.5 QUARKS: IS THAT ALL THERE IS?

25. Repeat the previous problem for the decay mode  $\Omega^- \rightarrow \Lambda^0 + K^-$ .

**Solution** (a) From Table 33.4, we know the quark composition of each of the particles involved in this decay:  $\Omega^- (sss) \rightarrow \Lambda^0 (uds) + K^- (\bar{u}s)$ . Then, to determine the change in strangeness, we need to subtract the initial from the final strangeness, remembering that a strange quark has a strangeness of -1:

$$\Delta S = S_f - S_i = [-1 + (-1)] - (-3) = +1$$

- (b) Using Table 33.3, we know that  $B_i = \left(\frac{1}{3} + \frac{1}{3} + \frac{1}{3}\right) = 1$ ,

$$B_f = \left(\frac{1}{3} + \frac{1}{3} + \frac{1}{3}\right) + \left(\frac{1}{3} - \frac{1}{3}\right) = 1, \text{ so the baryon number is indeed conserved. Again,}$$

using Table 33.3, the charge is:

$$Q_i = \left(-\frac{1}{3} - \frac{1}{3} - \frac{1}{3}\right) q_e = -q_e, \text{ and } Q_f = \left(+\frac{2}{3} - \frac{1}{3} - \frac{1}{3}\right) q_e + \left(-\frac{2}{3} - \frac{1}{3}\right) q_e = -q_e, \text{ so}$$

charge is indeed conserved. This decay does not involve any electrons or neutrinos, so all lepton numbers are zero before and after, and the lepton numbers are unaffected by the decay.

- (c) Using Table 33.4, we can write the equation in terms of its constituent quarks:  $(sss) \rightarrow (uds) + (\bar{u}s)$  or  $s \rightarrow u + \bar{u} + d$ . Since there is a change in quark flavor, the weak nuclear force is responsible for the decay.

31. (a) Is the decay  $\Sigma^- \rightarrow n + \pi^-$  possible considering the appropriate conservation laws? State why or why not. (b) Write the decay in terms of the quark constituents of the

particles.

**Solution** (a) From Table 33.4, we know the quark composition of each of the particles involved in the decay:  $\Sigma^- (dds) \rightarrow n(udd) + \pi^- (\bar{u}d)$ . The charge is conserved at -1. The baryon number is conserved at B=1. All lepton numbers are conserved at zero, and finally the mass initially is larger than the final mass:  $m_{\Sigma^-} > (m_n + m_{\pi^-})$ , so, yes, this decay is possible by the conservation laws.

(b) Using Table 33.4, we can write the equation in terms of its constituent quarks:

$$dds \rightarrow udd + \bar{u}d \text{ or } s \rightarrow u + \bar{u} + d$$

37. (a) How much energy would be released if the proton did decay via the conjectured reaction  $p \rightarrow \pi^0 + e^+$ ? (b) Given that the  $\pi^0$  decays to two  $\gamma$ s and that the  $e^+$  will find an electron to annihilate, what total energy is ultimately produced in proton decay? (c) Why is this energy greater than the proton's total mass (converted to energy)?

**Solution** (a) The energy released from the reaction is determined by the change in the rest mass energies:  $\Delta E = (mc^2)_i - \Sigma(mc^2)_f = (m_p - m_{\pi^0} - m_{e^+})c^2$

Using Table 33.2, we can then determine this difference in rest mass energies:

$$\Delta E = (938.3 \text{ MeV}/c^2 - 135.0 \text{ MeV}/c^2 - 0.511 \text{ MeV}/c^2)c^2 = \underline{802.8 \text{ MeV}} = 803 \text{ MeV}$$

(b) The two  $\gamma$  rays will carry a total energy of the rest mass energy of the  $\pi^0$ :

$$\pi^0 \rightarrow 2\gamma \Rightarrow \Delta E_{\pi^0} = m_{\pi^0}c^2 = 135.0 \text{ MeV}$$

The positron/electron annihilation will give off the rest mass energies of the positron and the electron:

$$e^- + e^+ \rightarrow 2\gamma \Rightarrow \Delta E_{e^+} = 2m_e c^2 = 2(0.511 \text{ MeV}) = 1.022 \text{ MeV}$$

So, the total energy would be the sum of all these energies:

$$\Delta E_{\text{tot}} = \Delta E + \Delta E_{\pi^0} + \Delta E_{e^+} = \underline{938.8 \text{ MeV}}$$

- (c) Because the total energy includes the annihilation energy of an extra electron. So the full reaction should be  $p + e \rightarrow (\pi^0 + e^+) + e \rightarrow 4\gamma$ .

### 33.6 GUTS: THE UNIFICATION OF FORCES

43. **Integrated Concepts** The intensity of cosmic ray radiation decreases rapidly with increasing energy, but there are occasionally extremely energetic cosmic rays that create a shower of radiation from all the particles they create by striking a nucleus in the atmosphere as seen in the figure given below. Suppose a cosmic ray particle having an energy of  $10^{10}$  GeV converts its energy into particles with masses averaging  $200 \text{ MeV}/c^2$ . (a) How many particles are created? (b) If the particles rain down on a  $1.00\text{-km}^2$  area, how many particles are there per square meter?

**Solution** (a) To determine the number of particles created, divide the cosmic ray particle energy by the average energy of each particle created:

$$\# \text{ of particles created} = \frac{\text{cosmic ray energy}}{\text{energy/particle created}} = \frac{10^{10} \text{ GeV}}{(0.200 \text{ GeV}/c^2)c^2} = \underline{5 \times 10^{10}}$$

(b) Divide the number of particles by the area they hit:

$$\text{particles}/\text{m}^2 = \frac{5 \times 10^{10} \text{ particles}}{(1000 \text{ m})^2} = \underline{5 \times 10^4 \text{ particles}/\text{m}^2}$$

49. **Integrated Concepts** Suppose you are designing a proton decay experiment and you can detect 50 percent of the proton decays in a tank of water. (a) How many kilograms of water would you need to see one decay per month, assuming a lifetime of  $10^{31}$  y? (b) How many cubic meters of water is this? (c) If the actual lifetime is  $10^{33}$  y, how long would you have to wait on an average to see a single proton decay?

**Solution** (a) On average, one proton decays every  $10^{31} \text{ y} = 12 \times 10^{31} \text{ months}$ . So for one decay every month, you would need:

$$N \left( \frac{1}{12 \times 10^{31} \text{ months/decay}} \right) = \frac{1 \text{ decay}}{\text{month}} \Rightarrow N = 12 \times 10^{31} \text{ protons}$$

Since you detect only 50% of the actual decays, you need twice this number of protons to observe one decay per month, or  $N = 24 \times 10^{31}$  protons. Now, we know that one  $\text{H}_2\text{O}$  molecule has 10 protons (1 from each hydrogen plus 8 from the oxygen), so we need  $24 \times 10^{30}$   $\text{H}_2\text{O}$ . Finally, since we know how many molecules we need, and we know the molar mass of water, we can determine the number of kilograms of water we need.

$$(24 \times 10^{30} \text{ molecules}) \left( \frac{1 \text{ mole}}{6.02 \times 10^{23} \text{ molecules}} \right) \left( \frac{0.018 \text{ kg}}{\text{mole}} \right) = \underline{7.2 \times 10^5 \text{ kg of water}}$$

(b) Now, we know the density of water,  $\rho = 1000 \text{ kg/m}^3$ , so we can determine the

$$\text{volume of water we need: } V = m\rho = (7.2 \times 10^5 \text{ kg}) \left( \frac{1 \text{ m}^3}{1000 \text{ kg}} \right) = \underline{7.2 \times 10^2 \text{ m}^3}$$

(c) If we had  $7.2 \times 10^2 \text{ m}^3$  of water, and the actual decay rate was  $10^{33} \text{ y}$ , rather than  $10^{31} \text{ y}$ , a decay would occur 100 times less often, and we would have to wait on average 100 months to see a decay.