# Chapter 14

* 1. By conservation of momentum the photons must have the same energy. For each one $E = hf = mc^2$ and

$$f = \frac{mc^2}{h} = \frac{938.27 \times 10^6 \text{ eV}}{4.136 \times 10^{-15} \text{ eV} \cdot \text{s}} = 2.27 \times 10^{23} \text{ Hz}$$

* 2. As in the text let $mc^2 = \hbar c/R$, so

$$R = \frac{\hbar c}{mc^2} = \frac{197.3 \text{ eV} \cdot \text{nm}}{140 \times 10^6 \text{ eV}} = 1.41 \times 10^{-6} \text{ nm} = 1.41 \text{ fm}$$

3. We will use a small nucleus (helium. diameter 3.8 fm) and a large nucleus (uranium, diameter 14.9 fm) to obtain a range of values. For helium:

$$\Delta t = \frac{3.8 \times 10^{-15} \text{ m}}{2.998 \times 10^8 \text{ m/s}} = 1.27 \times 10^{-23} \text{ s}$$

For uranium:

$$\Delta t = \frac{14.9 \times 10^{-15} \text{ m}}{2.998 \times 10^8 \text{ m/s}} = 4.97 \times 10^{-23} \text{ s}$$

* 4. We know that $\lambda \leq D$ and the problem says specifically to choose $\lambda = 0.1D$ with the diameter $D = 0.15\,\text{fm}$. Therefore $\lambda = 0.1(1.5\,\text{fm}) = 0.15\,\text{fm}$. We know from de Broglie's relationship that $p = h/\lambda$ and we can determine the kinetic energy from this momentum as follows:

$$E^2 = \left(K + mc^2\right)^2 = (pc)^2 + \left(mc^2\right)^2$$

$$K = \sqrt{(pc)^2 + (mc^2)^2} - mc^2 = \sqrt{\left(\frac{hc}{0.15\,\text{fm}}\right)^2 + (mc^2)^2} - mc^2$$

$$\text{electron: } K = \sqrt{\left(\frac{1239.8\,\text{eV} \cdot \text{nm}}{0.15\,\text{fm}\frac{10^{-6}\,\text{nm}}{1\,\text{fm}}}\right)^2 + (0.511 \times 10^6\,\text{eV})^2} - 0.511 \times 10^6\,\text{eV} = 8.26\,\text{GeV}$$

$$\text{proton: } K = \sqrt{\left(\frac{1239.8\,\text{eV} \cdot \text{nm}}{0.15\,\text{fm}\frac{10^{-6}\,\text{nm}}{1\,\text{fm}}}\right)^2 + (938.27 \times 10^6\,\text{eV})^2} - 938.27 \times 10^6\,\text{eV} = 7.38\,\text{GeV}$$

5. As in the previous problem. we know that $p = h/\lambda$ and

$$K = \sqrt{(pc)^2 + (mc^2)^2} - mc^2 = \sqrt{\left(\frac{hc}{1 \times 10^{-18}\,\text{m}}\right)^2 + (mc^2)^2} - mc^2$$

$$\text{electron: } K = \sqrt{\left(\frac{1239.8\,\text{eV} \cdot \text{nm}}{1 \times 10^{-9}\,\text{nm}}\right)^2 + (0.511 \times 10^6\,\text{eV})^2} - 0.511 \times 10^6\,\text{eV} = 1.24\,\text{TeV}$$

$$\text{proton: } K = \sqrt{\left(\frac{1239.8\,\text{eV} \cdot \text{nm}}{1 \times 10^{-9}\,\text{nm}}\right)^2 + (938.27 \times 10^6\,\text{eV})^2} - 938.27 \times 10^6\,\text{eV} = 1.24\,\text{TeV}$$

The kinetic energies are so large that the rest energies do not affect our answer.

6. We use Equation (14.4) to estimate the range of the force.

$$R = \frac{\hbar c}{2mc^2} = \frac{197.33\,\text{eV}\cdot\text{nm}}{2\,(782 \times 10^6\,\text{eV})} = 1.26 \times 10^{-7}\,\text{nm} = 1.26 \times 10^{-16}\,\text{m}$$

7. We use Equation (14.4) to estimate the range of the force.

$$R = \frac{\hbar c}{2mc^2} = \frac{197.33\,\text{eV}\cdot\text{nm}}{2\,(150 \times 10^9\,\text{eV})} = 6.58 \times 10^{-10}\,\text{nm} = 6.58 \times 10^{-19}\,\text{m}$$

8. a) $\overline{\nu}_\mu$ and $\nu_e$  b) $\overline{\nu}_e$  c) $\overline{\nu}_\mu$  d) $\overline{\nu}_\mu$  e) $\nu_\mu$

9. Assuming roughly an equal number of protons and neutrons, we can use the average of their masses per baryon, or $1.674 \times 10^{-27}$ kg. The mass of the earth is $5.98 \times 10^{24}$ kg, so the baryon number is

$$\frac{5.98 \times 10^{24}\,\text{kg}}{1.674 \times 10^{-27}\,\text{kg}} = 3.57 \times 10^{51}$$

10. a) We use Equation (14.6) to determine the width $\Gamma$ from the mean lifetime.

$$\Gamma = \frac{\hbar}{\tau} = \frac{6.5821 \times 10^{-16}\,\text{eV}\cdot\text{s}}{0.821 \times 10^{-10}\,\text{s}} = 8.02 \times 10^{-6}\,\text{eV}$$

b) This value of $\Gamma$ is much smaller than the experimental uncertainty of the measurement.

11. We use Equation (14.6) to determine the mean lifetime from the width $\Gamma$.

$$\tau = \frac{\hbar}{\Gamma} = \frac{6.5821 \times 10^{-16}\,\text{eV}\cdot\text{s}}{91 \times 10^3\,\text{eV}} = 7.2 \times 10^{-21}\,\text{s}$$

$$\tau = \frac{\hbar}{\Gamma} = \frac{6.5821 \times 10^{-16}\,\text{eV}\cdot\text{s}}{53 \times 10^3\,\text{eV}} = 1.24 \times 10^{-20}\,\text{s}$$

12. In the first reaction strangeness is violated ($+1 \rightarrow -1$). The second reaction is allowed. The fact that the $K^0$ has strangeness $+1$ and $\overline{K}^0$ has strangeness $-1$ is consistent with the idea that it is not its own antiparticle. However, M. Gell-Mann and A. Pais found that $K^0 \rightarrow \pi^+ + \pi^- \rightarrow \overline{K}^0$ (and the reverse operation $\overline{K}^0 \rightarrow \pi^+ + \pi^- \rightarrow K^0$) can occur by the laws of quantum mechanics (see Feynman Lectures in Physics vol. 3 p. 11-16). So in this case the $K^0$ does act as its own antiparticle.

13. In both (a) and (b) the baryon number is not conserved.

14. a) $\mu$ and $e$ lepton numbers are not conserved

b) charge is not conserved

c) momentum-energy is not conserved

* 15. Let subscript 1 refer to the $\Sigma$, subscript 2 to the $\Lambda$, and no subscript to the photon. From conservation of momentum $|\,p\,| = |\,p_2\,| = E/c$. From conservation of energy

$$m_1c^2 = \sqrt{p_2^2c^2 + (m_2c^2)^2} + E = \sqrt{E^2 + (m_2c^2)^2} + E$$

$$E = \frac{(m_1c^2)^2 - (m_2c^2)^2}{2m_1c^2} = \frac{(1193\ \text{MeV})^2 - (1116\ \text{MeV})^2}{2\,(1193\ \text{MeV})} = 74.5\ \text{MeV}$$

16. The $\pi^0$ begins with energy $E = K + E_0 = 735$ MeV. Because the photon energies are equal, we know by conservation of momentum that the two photons make equal angles $\theta$ above and below the original line of motion for the $\pi^0$. Let each photon energy be $E'$. The conservation of energy and momentum give:

$$E' = \frac{E}{2} = \frac{735}{2}\text{ MeV} = 367.5\text{ MeV}$$

$$p = \frac{2E'}{c}\cos\theta = \frac{\sqrt{E^2 - E_0^2}}{c} = \frac{\sqrt{(735\text{ MeV})^2 - (135\text{ MeV})^2}}{c} = 722.5\text{ MeV}/c$$

$$\cos\theta = \frac{pc}{2E'} = \frac{722.5\text{ MeV}}{2(367.5\text{ MeV})} = 0.9830$$

from which we find $\theta = 10.6°$.

17. a) $\nu_\mu$ is needed to conserve lepton number

b) a kaon is needed to conserve strangeness, and to conserve charge too it must be a $K^+$

* 18. $n$ $(udd)$: $q = \frac{2e}{3} - \frac{e}{3} - \frac{e}{3} = 0$; $B = 3\left(\frac{1}{3}\right) = 1$; $S = 3(0) = 0$

$\Sigma^+$ $(uus)$: $q = \frac{2e}{3} + \frac{2e}{3} - \frac{e}{3} = e$; $B = 3\left(\frac{1}{3}\right) = 1$; $S = 0 + 0 - 1 = -1$

$\Lambda_C^+$ $(udc)$: $q = \frac{2e}{3} - \frac{e}{3} + \frac{2e}{3} = e$; $B = 3\left(\frac{1}{3}\right) = 1$; $S = 0 + 0 + 0 = 0$

19. $\pi^+(u\bar{d})$: $q = \frac{2e}{3} + \frac{e}{3} = e$; $B = \frac{1}{3} - \frac{1}{3} = 0$; $S = 0 + 0 = 0$

$K^+(u\bar{s})$: $q = \frac{2e}{3} + \frac{e}{3} = e$; $B = \frac{1}{3} - \frac{1}{3} = 0$; $S = 0 + 1 = 1$

$D^0$:$(c\bar{u})$: $q = \frac{2e}{3} - \frac{2e}{3} = e$: $B = \frac{1}{3} - \frac{1}{3} = 0$; $S = 0 + 0 = 0$

20. $D^0$: $c\bar{u}$ $D^+$: $c\bar{d}$

21. The $B^+$ and $B^-$ have zero strangeness and zero charm, but they have masses greater than 5000 MeV/$c^2$ and charge +1 and −1 respectively. This leads one to conclude that the quark configuration should be $\bar{b}u$ for the $B^+$ and $b\bar{u}$ for the $B^-$. The $B^0$ has zero charge, so it should be either $b\bar{d}$ or $\bar{b}d$. The only way to distinguish between these two possibilities is by looking at the conservation laws in the appropriate decay reactions. it turns out that the $B^0$ is $\bar{b}d$ and the antiparticle $\overline{B}^0$ is $b\bar{d}$.

22. Charge, baryon number, strangeness, topness, and bottomness are zero. Charm = −1. From the table in the text $D^0$ has configuration $c\bar{u}$, so $\bar{c}u$ must be $\overline{D^0}$.

23. a) The $\Omega^-$, $\Lambda^0$, and the $K^-$ have mean lifetimes on the order of $10^{-10}$ s, which indicates the decays are due to the weak interaction. Remember that there can be quark transformations in weak interactions.

b) $\Omega^- \to \Lambda^0 + K^-$, $sss \to uds + \bar{u}s$; an $s$ quark transformed into a $d$ quark and a $u\bar{u}$ quark-antiquark pair was created. $\Lambda^0 \to p + \pi^-$, $uds \to uud + \bar{u}d$; the $s$ quark transformed into a $d$ quark and a $u\bar{u}$ quark-antiquark pair was created. $K^- \to \mu^- + \bar{\nu}_\mu$, $\bar{u}s \to$ no quarks; the $s$ quark transformed into a $u$ quark and the $\bar{u}u$ quark-antiquark pair annihilates. There are no quarks in the final decay products.

* 24. We use Table 14.5 for quark properties and Table 14.4 or Table 14.6 to identify the hadrons. The spin of all quarks and antiquarks is 1/2.

a) $c\bar{d}$; spin is 0 or 1; charge is 1; baryon number is 0; $C = 1$; $S, B, T = 0$. This is a $D^+$ meson.

b) $uds$; spin is 1/2 or 3/2; charge is 0; baryon number is 1; $S = -1$; $C, B, T = 0$. This could be a $\Sigma^0$ or a $\Lambda$ baryon.

c) $\overline{sss}$: spin is 1/2 or 3/2: baryon number is -1; charge is 1: $S = 3$: $C, B, T = 0$. This is a $\Omega^+$ baryon.

d) $\bar{c}d$; spin is 0 or 1; charge is -1; baryon number is 0: $C = -1$; $S, B, T = 0$. This is a $D^-$ meson.

25. Assuming an average nucleon mass of $1.674 \times 10^{-27}$ kg and noting that 10 out of 18 nucleons in water are protons, we have

$$\left(10^5 \text{ gal}\right) \frac{3.786\,\ell}{\text{gal}} \frac{10^{-3}\text{ m}^3}{\ell} \frac{1000\text{ kg}}{\text{m}^3} \frac{1}{1.674 \times 10^{-27}\text{ kg}} \frac{10}{18} = 1.26 \times 10^{32} \text{ protons}$$

Then if one half of the protons decay in $10^{33}$ years,

$$\left(1.26 \times 10^{32}\right) \frac{0.5}{10^{33}\text{ y}} = 0.063\text{ y}^{-1}$$

26. Baryon number is not conserved in any of the three. This is a common problem in proton decay schemes, because there are no lighter baryons. In addition, (a) violates electron lepton number, (b) violates muon lepton number, and (c) violates strangeness.

27.

$$\frac{25\text{ kg}}{1.673 \times 10^{-27}\text{ kg}} \frac{\ln 2\text{ decays}}{10^{32}\text{ y}} \frac{1\text{ y}}{365.25\text{ d}} = 2.84 \times 10^{-7}\text{ decays/d}$$

28. The lifetime of the $\Sigma^+$ is $8.0 \times 10^{-11}$ s. Due to relativity it travels farther then one might expect.

$$\gamma = \frac{K + E_0}{E_0} = \frac{3\text{ GeV} + 1.189\text{ GeV}}{1.189\text{ GeV}} = 3.523 = \frac{1}{\sqrt{1 - v^2/c^2}}$$

$$v = c\sqrt{1 - 1/\gamma^2} = c\sqrt{1 - 1/(3.523)^2} = 0.9588\,c$$

$$d = vt' = \gamma vt = (3.523)\,(0.9588)\,\left(2.998 \times 10^8\text{ m/s}\right)\left(8.0 \times 10^{-11}\text{ s}\right) = 8.10\,\text{cm}$$

* 29. We begin with Equation (14.10). Since $K \gg mc^2$, this simplifies to $E_{\text{cm}} = \sqrt{2mc^2 K_{\text{lab}}}$. From the problem we know that $E_{\text{cm}} = 2K$ so $E_{\text{cm}} = 2K = \sqrt{2mc^2 K_{\text{lab}}}$. This can be rearranged to find $4K^2 = 2mc^2 K_{\text{lab}}$ or

$$K_{\text{lab}} = \frac{2K^2}{mc^2}$$

30. From the preceding problem, we know that

$$K_{\text{lab}} = \frac{2K^2}{mc^2} = \frac{2\,(31\text{ GeV})^2}{0.938\text{ GeV}} = 2050\,\text{GeV}$$

31.

$$\gamma = \frac{K + E_0}{E_0} = \frac{7000 \text{ GeV } + 0.938 \text{ GeV}}{0.938 \text{ GeV}} = 7464 = \frac{1}{\sqrt{1 - v^2/c^2}}$$

$$v = c\sqrt{1 - 1/\gamma^2} = c\sqrt{1 - 1/7464^2} = 0.999\,999\,991\, c$$

32. The maximum energies result from a head-on collision. Before the collision the proton has energy $E = K + E_0 = 998.27$ MeV. After the collision the proton has energy and momentum $E_1, p_1$ and the recoiling particle has $E_2, p_2$. From conservation of momentum and energy

$$p = \frac{\sqrt{E^2 - E_0^2}}{c} = \frac{\sqrt{(998.27 \text{ MeV})^2 - (938.27 \text{ MeV})^2}}{c} = 340.87 \text{ MeV}/c = p_1 + p_2$$

$$E + E_0\,(d) = 998.27 \text{ MeV } + 1875.61 \text{ MeV } = 2873.9 \text{ MeV } = E_1 + E_2$$

Using the energy-momentum invariant $E_0^2 = E^2 - p^2c^2$ for both the proton and deuteron. these two equations can be solved to yield $p_1 = -111$ MeV/$c$, $p_2 = 452$ MeV/$c$, $E_1 = 944$ MeV, $E_2 = 1930$ MeV, so the deuteron's kinetic energy is

$$K = 1930 \text{ MeV } - 1876 \text{ MeV } = 54 \text{ MeV}$$

Similarly for the triton ($t$) with $E_0 = 2809$ MeV, we can follow the same procedure:

$$p = \frac{\sqrt{E^2 - E_0^2}}{c} = \frac{\sqrt{(998.27 \text{ MeV})^2 - (938.27 \text{ MeV})^2}}{c} = 340.87 \text{ MeV}/c = p_1 + p_2$$

$$E + E_0\,(t) = 998.27 \text{ MeV } + 2809 \text{ MeV } = 3807 \text{ MeV } = E_1 + E_2$$

Using the energy-momentum invariant $E_0^2 = E^2 - p^2c^2$ for both the proton and triton. these two equations can be solved to yield $p_1 = -166$ MeV/$c$, $p_2 = 507$ MeV/$c$. $E_1 = 953$ MeV, $E_2 = 2854$ MeV. so the triton's kinetic energy is

$$K = 2854 \text{ MeV } - 2809 \text{ MeV } = 45 \text{ MeV}$$

33. To conserve baryon number we must produce both a proton and antiproton, so in the cm system we need $E_{\text{cm}} = 4E_0$. We can use Equation (14.10) and solve for $K$ to find

$$K = \frac{E_{\text{cm}}^2 - \left(m_1c^2 + m_2c^2\right)^2}{2m_2c^2} = \frac{E_{\text{cm}}^2 - 4\left(mc^2\right)^2}{2mc^2}$$

where we have used $m_1 = m_2 = m$. With $E_{\text{cm}} = 4mc^2$ we have

$$K = \frac{\left(4mc^2\right)^2 - 4\left(mc^2\right)^2}{2mc^2} = 6mc^2 = 6\,(938.27 \text{ MeV}) = 5630 \text{ MeV}$$

* 34. a)

$$p = \frac{\sqrt{E^2 - E_0^2}}{c} = \frac{\sqrt{(948.27 \text{ MeV})^2 - (938.27 \text{ MeV})^2}}{c} = 137.35 \text{ MeV}/c$$

$$R = \frac{p}{qB} = \frac{137.35 \text{ MeV}}{(2.998 \times 10^8 \text{ m/s})\,(e)\,(1 \text{ T})} = 0.458 \text{ m}$$

b) From Equation (14.9) we have

$$f = \frac{eB}{2\pi m}\sqrt{1 - v^2/c^2} = \frac{eB}{2\pi m\gamma}$$

$$\gamma = \frac{E}{E_0} = \frac{948.27 \text{ MeV}}{938.27 \text{ MeV}} = 1.0107$$

$$f = \frac{(e)(1\text{ T})}{2\pi\,(938.27\text{ MeV})\,(1.0107)}\left(2.998\times 10^8\text{ m/s}\right)^2 = 1.51\times 10^7\text{ Hz}$$

35. With $p = \gamma m v$ we have

$$f = \frac{v}{2\pi R} = \frac{p}{2\pi\gamma m R}$$

With $p = qBR$ we find

$$f = \frac{qBR}{2\pi\gamma m R} = \frac{qB}{2\pi m\gamma} = \frac{qB}{2\pi m}\sqrt{1 - v^2/c^2}$$

36.

$$E_{\text{lab}} = K + m_1c^2 + m_2c^2$$

$$p_{\text{lab}}c = \sqrt{\left(K + m_1c^2\right)^2 - \left(m_1c^2\right)^2}$$

Using the fact that $E^2 - p^2c^2$ is invariant, so

$$\begin{aligned}
E_{\text{cm}}^2 &= E_{\text{lab}}^2 - \left(p_{\text{lab}}c\right)^2 = \left(K + m_1c^2 + m_2c^2\right)^2 - \left(K + m_1c^2\right)^2 + \left(m_1c^2\right)^2 \\
&= K^2 + \left(m_1c^2 + m_2c^2\right)^2 + 2K\left(m_1c^2 + m_2c^2\right) - K^2 - 2Km_1c^2 - \left(m_1c^2\right)^2 + \left(m_1c^2\right)^2 \\
&= \left(m_1c^2 + m_2c^2\right)^2 + 2Km_2c^2
\end{aligned}$$

For the nonrelativistic limit we have

$$E_{\text{cm}} = \sqrt{\left(m_1c^2 + m_2c^2\right)^2 + 2Km_2c^2} = \left(m_1c^2 + m_2c^2\right)\sqrt{1 + \frac{2Km_2c^2}{\left(m_1c^2 + m_2c^2\right)^2}}$$

With $K << mc^2$ we can look at the binomial expansion of the square root:

$$E_{\text{cm}} \approx \left(m_1c^2 + m_2c^2\right)\left(1 + \frac{Km_2c^2}{\left(m_1c^2 + m_2c^2\right)^2}\right)$$

$$K_{\text{cm}} = E_{\text{cm}} - \left(m_1c^2 + m_2c^2\right) \approx \frac{Km_2c^2}{m_1c^2 + m_2c^2} = \frac{m_2}{m_1 + m_2}K$$

* 37. As in the previous problem

$$E_{\text{cm}} = \sqrt{\left(m_1c^2 + m_2c^2\right)^2 + 2Km_2c^2} = \sqrt{\left(2mc^2\right)^2 + 2Km_2c^2}$$

a) If $K << mc^2$ we neglect $K$, so $E_{\text{cm}} \approx 2mc^2$.

b) If $K >> mc^2$ we neglect the first term and $E_{\text{cm}} \approx \sqrt{2Km_2c^2} = \sqrt{2Kmc^2}$

In (a) we interpret the result to mean that at very low energies there is no extra energy available (beyond the masses of the two original particles). In (b) we see that the available center of mass energy increases only in proportion to $\sqrt{K}$, thus illustrating the great advantage of colliding beam experiments over fixed target experiments.

38.

$$\gamma = \frac{K + E_0}{E_0} = \frac{50000\text{ MeV } + 0.511\text{ MeV}}{0.511\text{ MeV}} = 97848 = \frac{1}{\sqrt{1 - v^2/c^2}}$$

$$v = c\sqrt{1 - 1/\gamma^2} = c\sqrt{1 - 1/97848^2} = c\left(1 - 5.2 \times 10^{-11}\right) = 0.999\,999\,999\,948\,c$$

39. In each case the desired ratio is simply equal to the relativistic factor $\gamma$.

a)

$$\gamma = \frac{K + E_0}{E_0} = \frac{10\text{ MeV } + 938.27\text{ MeV}}{938.27\text{ MeV}} = 1.0107$$

b)

$$\gamma = \frac{K + E_0}{E_0} = \frac{100\text{ MeV } + 938.27\text{ MeV}}{938.27\text{ MeV}} = 1.107$$

c)

$$\gamma = \frac{K + E_0}{E_0} = \frac{1000\text{ MeV } + 938.27\text{ MeV}}{938.27\text{ MeV}} = 2.066$$

40.

$$\gamma = \frac{K + E_0}{E_0} = \frac{33000\text{ MeV } + 938.27\text{ MeV}}{938.27\text{ MeV}} = 36.17$$

Therefore in the lab frame $v \approx c$ and the time for 160,000 revolutions is

$$t = N\frac{2\pi R}{v} \approx (160000)\,\frac{800\text{ m}}{2.998 \times 10^8\text{ m/s}} = 0.427\text{ s}$$

The statement is accurate.

41. a) Charge = 0; baryon number = 0; charm = 0; strangeness = 0; $L_e = +1$; spin = 1/2

b) The unknown can be a single particle. The $\nu_e$ satisfies the requirements.

42. None of the decays are allowed.

a) There is not enough mass-energy in $\Xi^0$ to produce $\pi^-$ and $\Sigma^+$.

b) Strangeness is not conserved.

c) There is not enough mass-energy in $\Xi^0$ to produce $K^-$ and $p$.

* 43. a) For a stationary target the sum of the rest energies of the products equals the total center of mass energy, so

$$\begin{aligned} E_{\text{cm}} &= \sqrt{2E_0\,(2E_0 + K)} = (m_p + m_\Lambda + m_K)\,c^2 \\ &= 938\text{ MeV } + 1116\text{ MeV } + 494\text{ MeV } = 2548\text{ MeV} \end{aligned}$$

Rearranging we have

$$\frac{E_{\text{cm}}^2}{2E_0} = 2E_0 + K$$

$$K = \frac{E_{\text{cm}}^2}{2E_0} - 2E_0 = \frac{(2548\text{ MeV})^2}{2\,(938\text{ MeV})} - 2\,(938\text{ MeV}) = 1585\text{ MeV}$$

b) In a colliding beam experiment the total momentum is zero, and we have by conservation of energy

$$2E_0 + 2K = E_0 + (m_\Lambda + m_K)\,c^2$$

$$K = \frac{-E_0 + (m_\Lambda + m_K)\,c^2}{2} = \frac{-938\text{ MeV } + 1116\text{ MeV } + 494\text{ MeV}}{2} = 336\text{ MeV}$$

44. a) baryon number and $\mu$ lepton number are not conserved

    b) allowed if neutrinos are added to conserve lepton number

    c) strangeness is not conserved

    d) baryon number is not conserved

45. a) allowed

    b) $\nu_e$ should be $\overline{\nu}_e$ to conserve electron lepton number

    c) strangeness is not conserved

    d) strangeness is not conserved in a strong interaction

    e) allowed

* 46. a) baryon number and electron lepton number not conserved

    b) not allowed - charge is not conserved

    c) allowed

    d) allowed

* 47. a) strangeness is not conserved

    b) charge is not conserved

    c) baryon number is not conserved

    d) strangeness is not conserved

48. a) $\lambda = h/p$ and $p = \sqrt{2mK}$, so

$$\lambda = \frac{h}{\sqrt{2mK}}$$

    b) $p \approx E/c \approx K/c$, so

$$\lambda = \frac{hc}{K}$$

49. a) From Equation (14.10) we have

$$E_{\text{cm}} = \sqrt{(m_1c^2 + m_2c^2)^2 + 2Km_2c^2}$$

and with $m_1 = m_2 = m$ and $K >> mc^2$, we have

$$E_{\text{cm}} \approx \sqrt{2Kmc^2} = \sqrt{2\,(0.938\ \text{GeV})\,(7000\ \text{GeV})} = 114.5\ \text{GeV}$$

b) For colliding beams the available energy is the sum of the two beam energies, or 14 TeV. This is an improvement over the fixed-target result by a factor of

$$\frac{14000\ \text{GeV}}{114.5\ \text{GeV}} = 122$$