# 11.A: Particle Physics and Cosmology (Answers)

## Check Your Understanding

**11.1.** 1

**11.2.** 0

**11.3.** 0

**11.4.** 0

**11.5.** 1 eV

**11.6.** The radius of the track is cut in half.

**11.7.** The colliding particles have identical mass but opposite vector momenta.

**11.8.** blueshifted

**11.9.** about the same

## Conceptual Questions

**1.** Strong nuclear force: interaction between quarks, mediated by gluons. Electromagnetic force: interaction between charge particles, mediated photons. Weak nuclear force: interactions between fermions, mediated by heavy bosons. Gravitational force: interactions between material (massive) particle, mediate by hypothetical gravitons.

**3.** electron, muon, tau; electron neutrino, muon neutrino, tau neutrino; down quark, strange quark, bottom quark; up quark, charm quark, top quark

**5.** Conservation energy, momentum, and charge (familiar to classical and relativistic mechanics). Also, conservation of baryon number, lepton number, and strangeness—numbers that do not change before and after a collision or decay.

**7.** It means that the theory that requires the conservation law is not understood. The failure of a long-established theory often leads to a deeper understanding of nature.

**9.** 3 quarks, 2 quarks (a quark-antiquark pair)

**11.** Baryons with the same quark composition differ in rest energy because this energy depends on the internal energy of the quarks $(m = E/c^2)$. So, a baryon that contains a quark with a large angular momentum is expected to be more massive than the same baryon with less angular momentum.

**13.** the “linac” to accelerate the particles in a straight line, a synchrotron to accelerate and store the moving particles in a circular ring, and a detector to measure the products of the collisions

**15.** In a colliding beam experiment, the energy of the colliding particles goes into the rest mass energy of the new particle. In a fix-target experiment, some of this energy is lost to the momentum of the new particle since the center-of-mass of colliding particles is not fixed.

**17.** The Standard Model is a model of elementary particle interactions. This model contains the electroweak theory and quantum chromodynamics (QCD). It describes the interaction of leptons and quarks though the exchange of photons (electromagnetism) and bosons (weak theory), and the interaction of quark through the exchange of gluons (QCD). This model does not describe gravitational interactions.

**19.** To explain particle interactions that involve the strong nuclear, electromagnetic, and weak nuclear forces in a unified way.

**21.** No, however it will explain why the W and Z bosons are massive (since the Higgs “imparts” mass to these particles), and therefore why the weak force is short ranged.

**23.** Cosmological expansion is an expansion of space. This expansion is different than the explosion of a bomb where particles pass rapidly through space. A plot of the recessional speed of a galaxy is proportional to its distance. This speed is measured using the red shift of distant starlight.

**25.** With distance, the absolute brightness is the same, but the apparent brightness is inversely proportional to the square of its distance (or by Hubble’s law recessional velocity).

**27.** The observed expansion of the universe and the cosmic background radiation spectrum.

**29.** If light slow down, it takes long to reach Earth than expected. We conclude that the object is much closer than it really is. Thus, for every recessional velocity (based on the frequency of light, which we assume is not disturbed by the slowing), the distance is smaller than the "true" value, Hubble's constant is larger than the "true" value, and the age of the universe is smaller than the "true" value.

## Problems

**31.** 1.022 MeV

**33.** 0.511 MeV, $2.73 \times 10^{-22} kg \cdot m/s, 1.23 \times 10^{20} Hz$

**35.** a, b, and c

**37.** a. $\bar{p_e} + \nu e$;

b. $\bar{p}\pi^+$ or $\bar{p}\pi^0$;

c. $\bar{\Xi}^0\pi^0$ or $\bar{\Lambda}^0 K^+$;

d. $\mu - \bar{\nu_\mu}$ or $\pi^-\pi^0$;

e. $\bar{p}\pi^0$ or $\bar{n}\pi^-$

**39.** A proton consists of two up quarks and one down quark. The total charge of a proton is therefore $+\frac{2}{3} + \frac{2}{3} + -\frac{1}{3} = +1$ .

**41.** The $K^+$ meson is composed of an up quark and a strange antiquark ($u\bar{s}$). Since the changes of this quark and antiquark are $2e/3$ and $e/3$, respectively, the net charge of the $K^+$ meson is **e**, in agreement with its known value. Two spin $-1/2$ particles can combine to produce a particle with spin of either 0 or 1, consistent with the $K^+$ meson's spin of 0. The net strangeness of the up quark and strange antiquark is $0+1=1$, in agreement with the measured strangeness of the $K^+$ meson.

**43.** a. color;

b. quark-antiquark

**45.** $d \rightarrow u + e^- + \bar{\nu_e}; u \rightarrow d + e^+ + \nu_e$

**47.** 965 GeV

**49.** According to Example 11.7,

$W = 2E_{beam} = 9.46 GeV$,

$M = 9.46 GeV/c^2$.

This is the mass of the upsilon (1S) meson first observed at Fermi lab in 1977. The upsilon meson consists of a bottom quark and its antiparticle ($b\bar{b}$).

**51.** 0.135 fm; Since this distance is too short to make a track, the presence of the $W^-$ must be inferred from its decay products.

**53.** 3.33 MV

**55.** The graviton is massless, so like the photon is associated with a force of infinite range.

**57.** 67.5 MeV

**59.** a. 33.9 MeV;

b. By conservation of momentum, $|p_\mu| = |p_\nu| = p$. By conservation of energy, $E_\nu = 29.8 MeV, E_\mu = 4.1 MeV$

**61.** $(0.99)(299792 km/s) = ((70\frac{km}{s})/Mpc)(d), d = 4240 Mpc$

**63.** $1.0 \times 10^4 km/s$ away from us.

**65.** $2.26 \times 10^8 y$

**67.** a. $1.5 \times 10^{10} y = 15$ billion years;

b. Greater, since if it was moving slower in the past it would take less more to travel the distance.

**69.** $v = \sqrt{\frac{GM}{r}}$

## Additional Problems

**71.** a. $\bar{n}$;

b. $K^+$;

c. $K^+$;

d. $\pi^-$;

e. $\bar{\nu}_\tau$;

f. $e^+$

**73.** $14.002 TeV \approx 14.0 TeV$

**75.** $964 rev/s$

**77.** a. $H_0 = \frac{30 km/s}{1 Mly} = 30 km/s \cdot Mly$ ;

b. $H_0 = \frac{15 km/s}{1 Mly} = 15 km/s \cdot Mly$

## Challenge Problems

**79.** a. $5 \times 10^{10}$ ;

b. divide the number of particles by the area they hit: $5 \times 10^4 particles/m^2$

**81.** a. 2.01;

b. $2.50 \times 10^{-8} s$;

c. 6.50 m

**83.** $\frac{mv^2}{r} = \frac{GMm}{r^2} \Rightarrow v = (\frac{GM}{r})^{1/2} = [\frac{(6.67 \times 10^{-11} N \cdot m^2/kg^2)(3 \times 10^{41} kg)}{(30,000 ly)(9.46 \times 10^{15} m/ly)}] = 2.7 \times 10^5 m/s$

**85.** a. 938.27 MeV;

b. $1.84 \times 10^3$

**87.** a. $3.29 \times 10^{18} GeV \approx 3 \times 10^{18} GeV$ ;

b. 0.3; Unification of the three forces breaks down shortly after the separation of gravity from the unification force (near the Planck time interval). The uncertainty in time then becomes greater. Hence the energy available becomes less than the needed unification energy.