Just as the electromagnetic force can be said to be due to an exchange of photons, the strong nuclear force is carried by massless **gluons**. The W and Z particles carry the weak force. These fundamental force carriers (photon, W and Z, gluons) are called **gauge bosons**.

Other particles can be classified as either *leptons* or *hadrons*. **Leptons** participate only in gravity, the weak, and the electromagnetic interactions. **Hadrons**, which today are considered **composite** particles, are made up of **quarks**, and participate in all four interactions, including the strong interaction. The hadrons can be classified as **mesons**, with baryon number zero, and **baryons**, with nonzero baryon number.

Most particles, except for the photon, electron, neutrinos, and proton, decay with measurable mean lives varying from 10^{-25} s to 10^3 s. The mean life depends on which force is predominant. Weak decays usually have mean lives greater than about 10^{-13} s. Electromagnetic decays typically have mean lives on the order of 10^{-16} to 10^{-19} s. The shortest lived particles, called **resonances**, decay via the strong interaction and live typically for only about 10^{-23} s.

Today's **Standard Model** of elementary particles considers **quarks** as the basic building blocks of the hadrons. The six quark "flavors" are called **up**, **down**, **strange**, **charm**, **bottom**, and **top**. It is expected that there are the same number of quarks as leptons (six of each), and that quarks and leptons are truly fundamental particles along with the gauge bosons (γ, W, Z, gluons) and the Higgs boson.

Quarks are said to have **color**, and, according to **quantum chromodynamics** (QCD), the strong color force acts between their color charges and is transmitted by **gluons**. **Electroweak theory** views the weak and electromagnetic forces as two aspects of a single underlying interaction. QCD plus the electroweak theory are referred to as the *Standard Model* of the fundamental particles.

Grand unified theories of forces suggest that at very short distance $\left(10^{-31}\text{ m}\right)$ and very high energy, the weak, electromagnetic, and strong forces would appear as a single force, and the fundamental difference between quarks and leptons would disappear.

According to **string theory**, the fundamental particles may be tiny strings, 10^{-35} m long, distinguished by their standing wave pattern. **Supersymmetry** predicts that each fermion (or boson) has a corresponding boson (or fermion) partner.

Questions

1. Give a reaction between two nucleons, similar to Eq. 32–4, that could produce a π^-.

2. If a proton is moving at very high speed, so that its kinetic energy is much greater than its rest energy $\left(mc^2\right)$, can it then decay via $\mathrm{p} \rightarrow \mathrm{n} + \pi^+$?

3. What would an "antiatom," made up of the antiparticles to the constituents of normal atoms, consist of? What might happen if *antimatter*, made of such antiatoms, came in contact with our normal world of matter?

4. What particle in a decay signals the electromagnetic interaction?

5. (*a*) Does the presence of a neutrino among the decay products of a particle necessarily mean that the decay occurs via the weak interaction? (*b*) Do all decays via the weak interaction produce a neutrino? Explain.

6. Why is it that a neutron decays via the weak interaction even though the neutron and one of its decay products (proton) are strongly interacting?

7. Which of the four interactions (strong, electromagnetic, weak, gravitational) does an electron take part in? A neutrino? A proton?

8. Verify that charge and baryon number are conserved in each of the decays shown in Table 32–2.

9. Which of the particle decays listed in Table 32–2 occur via the electromagnetic interaction?

10. Which of the particle decays listed in Table 32–2 occur by the weak interaction?

11. The Δ baryon has spin $\frac{3}{2}$, baryon number 1, and charge $Q = +2, +1, 0,$ or -1. Why is there no charge state $Q = -2$?

12. Which of the particle decays in Table 32–4 occur via the electromagnetic interaction?

13. Which of the particle decays in Table 32–4 occur by the weak interaction?

14. Quarks have spin $\frac{1}{2}$. How do you account for the fact that baryons have spin $\frac{1}{2}$ or $\frac{3}{2}$, and mesons have spin 0 or 1?

15. Suppose there were a kind of "neutrinolet" that was massless, had no color charge or electrical charge, and did not feel the weak force. Could you say that this particle even exists?

16. Is it possible for a particle to be both (*a*) a lepton and a baryon? (*b*) a baryon and a hadron? (*c*) a meson and a quark? (*d*) a hadron and a lepton? Explain.

17. Using the ideas of quantum chromodynamics, would it be possible to find particles made up of two quarks and no antiquarks? What about two quarks and two antiquarks?

18. Why can neutrons decay when they are free, but not when they are inside a stable nucleus?

19. Is the reaction $\mathrm{e}^- + \mathrm{p} \rightarrow \mathrm{n} + \bar{\nu}_\mathrm{e}$ possible? Explain.

20. Occasionally, the Λ will decay by the following reaction: $\Lambda^0 \rightarrow \mathrm{p}^+ + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$. Which of the four forces in nature is responsible for this decay? How do you know?

MisConceptual Questions

1. There are six kinds (= flavors) of quarks: up, down, strange, charm, bottom, and top. Which flavors make up most of the known matter in the universe?
(*a*) Up and down quarks.
(*b*) Strange and charm quarks.
(*c*) Bottom and top quarks.
(*d*) All of the above.

2. Which of the following particles can not be composed of quarks?
(*a*) Proton.
(*b*) Electron.
(*c*) π meson.
(*d*) Neutron.
(*e*) Higgs boson.

3. If gravity is the weakest force, why is it the one we notice most?
   (*a*) Our bodies are not sensitive to the other forces.
   (*b*) The other forces act only within atoms and therefore have no effect on us.
   (*c*) Gravity may be "very weak" but always attractive, and the Earth has enormous mass. The strong and weak nuclear forces have very short range. The electromagnetic force has a long range, but most matter is electrically neutral.
   (*d*) At long distances, the gravitational force is actually stronger than the other forces.
   (*e*) The other forces act only on elementary particles, not on objects our size.
4. Is it possible for a tau lepton (whose mass is almost twice that of a proton) to decay into only hadrons?
   (*a*) Yes, because it is so massive it could decay into a proton and pions.
   (*b*) Yes, it could decay into pions and nothing else.
   (*c*) No, such a decay would violate lepton number; all of its decay products must be leptons.
   (*d*) No, its decay products must include a tau neutrino but could include hadrons such as pions.
   (*e*) No, the tau lepton is too massive to decay.
5. Many particle accelerators are circular because:
   (*a*) particles accelerate faster around circles.
   (*b*) in order to move in a circle, acceleration is required.
   (*c*) a circular accelerator has a shorter length than a square one.
   (*d*) the particles can be accelerated through the same potential difference many times, making the accelerator more compact.
   (*e*) a particle moving in a circle needs more energy than a particle moving in a straight line.
6. Which of the following are today considered fundamental particles (that is, not composed of smaller components)? Choose as many as apply.
   (*a*) Atoms. (*b*) Electrons. (*c*) Protons. (*d*) Neutrons.
   (*e*) Quarks. (*f*) Photon. (*g*) Higgs boson.
7. The electron's antiparticle is called the positron. Which of the following properties, if any, are the same for electrons and positrons?
   (*a*) Mass.
   (*b*) Charge.
   (*c*) Lepton number.
   (*d*) None of the above.
8. The strong nuclear force between a neutron and a proton is due to
   (*a*) the exchange of π mesons between the neutron and the proton.
   (*b*) the conservation of baryon number.
   (*c*) the beta decay of the neutron into the proton.
   (*d*) the exchange of gluons between the quarks within the neutron and the proton.
   (*e*) Both (*a*) and (*d*) at different scales.
9. Electrons are still considered fundamental particles (in the group called leptons). But protons and neutrons are no longer considered fundamental; they have substructure and are made up of
   (*a*) pions. (*b*) leptons. (*c*) quarks. (*d*) bosons. (*e*) photons.
10. Which of the following will interact via the weak nuclear force *only*?
   (*a*) Quarks. (*b*) Gluons. (*c*) Neutrons. (*d*) Neutrinos.
   (*e*) Electrons. (*f*) Muons. (*g*) Higgs boson.

For assigned homework and other learning materials, go to the MasteringPhysics website.

Problems

32–1 Particles and Accelerators

1. (I) What is the total energy of a proton whose kinetic energy is 4.65 GeV?

2. (I) Calculate the wavelength of 28-GeV electrons.

3. (I) If α particles are accelerated by the cyclotron of Example 32–2, what must be the frequency of the voltage applied to the dees?

4. (I) What is the time for one complete revolution for a very high-energy proton in the 1.0-km-radius Fermilab accelerator?

5. (II) What strength of magnetic field is used in a cyclotron in which protons make 3.1×10^7 revolutions per second?

6. (II) (*a*) If the cyclotron of Example 32–2 accelerated α particles, what maximum energy could they attain? What would their speed be? (*b*) Repeat for deuterons $\left({}^2_1\mathrm{H}\right)$. (*c*) In each case, what frequency of voltage is required?

7. (II) Which is better for resolving details of the nucleus: 25-MeV alpha particles or 25-MeV protons? Compare each of their wavelengths with the size of a nucleon in a nucleus.

8. (II) What is the wavelength (= minimum resolvable size) of 7.0-TeV protons at the LHC?

9. (II) The 1.0-km radius Fermilab Tevatron took about 20 seconds to bring the energies of the stored protons from 150 GeV to 1.0 TeV. The acceleration was done once per turn. Estimate the energy given to the protons on each turn. (You can assume that the speed of the protons is essentially c the whole time.)

10. (II) A cyclotron with a radius of 1.0 m is to accelerate deuterons $\left({}^2_1\mathrm{H}\right)$ to an energy of 12 MeV. (*a*) What is the required magnetic field? (*b*) What frequency is needed for the voltage between the dees? (*c*) If the potential difference between the dees averages 22 kV, how many revolutions will the particles make before exiting? (*d*) How much time does it take for one deuteron to go from start to exit? (*e*) Estimate how far it travels during this time.

11. (III) Show that the energy of a particle (charge e) in a synchrotron, in the relativistic limit $(v \approx c)$, is given by E (in eV) $= Brc$, where B is the magnetic field and r is the radius of the orbit (SI units).

32–2 to 32–6 Particle Interactions, Particle Exchange

12. (I) About how much energy is released when a Λ^0 decays to $\mathrm{n} + \pi^0$? (See Table 32–2.)

13. (I) How much energy is released in the decay

$$\pi^+ \rightarrow \mu^+ + \nu_\mu?$$

See Table 32–2.