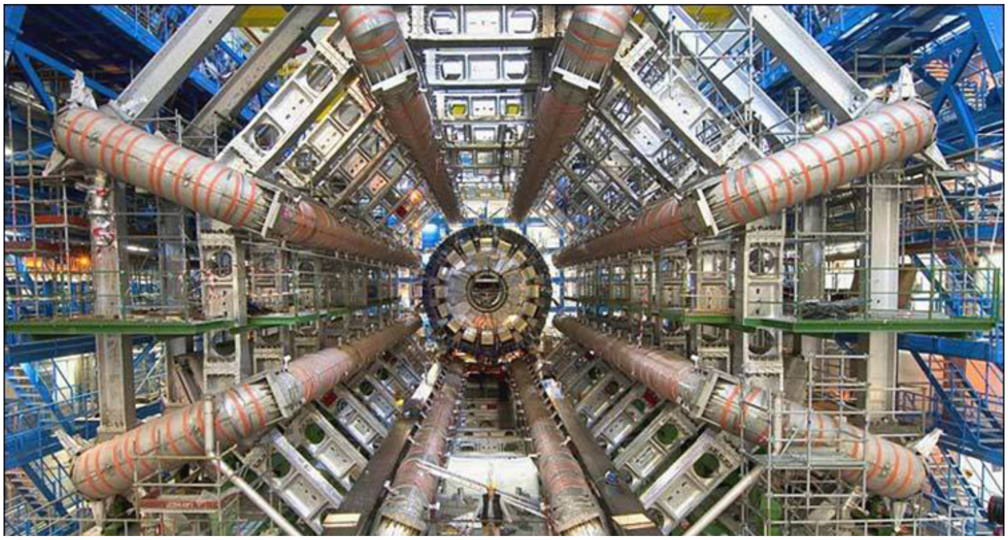
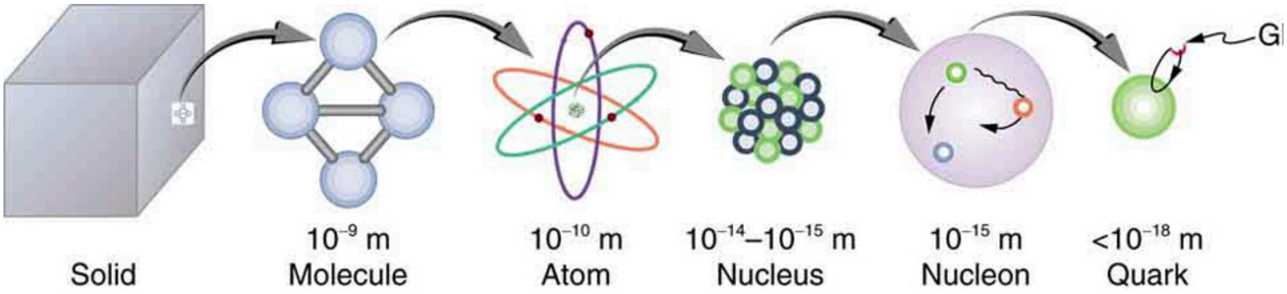
Introduction to Particle Physics

- Explore the substructures of matter.
- Define particle physics.



Part of the Large Hadron Collider at CERN, on the border of Switzerland and France. The LHC is a particle accelerator, designed to study fundamental particles. (credit: Image Editor, Flickr)

Following ideas remarkably similar to those of the ancient Greeks, we continue to look for smaller and smaller structures in nature, hoping ultimately to find and understand the most fundamental building blocks that exist. Atomic physics deals with the smallest units of elements and compounds. In its study, we have found a relatively small number of atoms with systematic properties that explained a tremendous range of phenomena. Nuclear physics is concerned with the nuclei of atoms and their substructures. Here, a smaller number of components—the proton and neutron—make up all nuclei. Exploring the systematic behavior of their interactions has revealed even more about matter, forces, and energy. **Particle physics** deals with the substructures of atoms and nuclei and is particularly aimed at finding those truly fundamental particles that have no further substructure. Just as in atomic and nuclear physics, we have found a complex array of particles and properties with systematic characteristics analogous to the periodic table and the chart of nuclides. An underlying structure is apparent, and there is some reason to think that we *are* finding particles that have no substructure. Of course, we have been in similar situations before. For example, atoms were once thought to be the ultimate substructure. Perhaps we will find deeper and deeper structures and never come to an ultimate substructure. We may never really know, as indicated in [Figure 2].



The properties of matter are based on substructures called molecules and atoms. Atoms have the substructure of a nucleus with orbiting electrons, the interactions of which explain atomic properties. Protons and neutrons, the interactions of which explain the stability and abundance of elements, form the substructure of nuclei. Protons and neutrons are not fundamental—they are composed of quarks. Like electrons and a few other particles, quarks may be the fundamental building blocks of all there is, lacking any further substructure. But the story is not complete, because quarks and electrons may have substructure smaller than details that are presently observable.

This chapter covers the basics of particle physics as we know it today. An amazing convergence of topics is evolving in particle physics. We find that some particles are intimately related to forces, and that nature on the smallest scale may have its greatest influence on the large-scale character of the universe. It is an adventure exceeding the best science fiction because it is not only fantastic, it is real.

Summary

- Particle physics is the study of and the quest for those truly fundamental particles having no substructure.

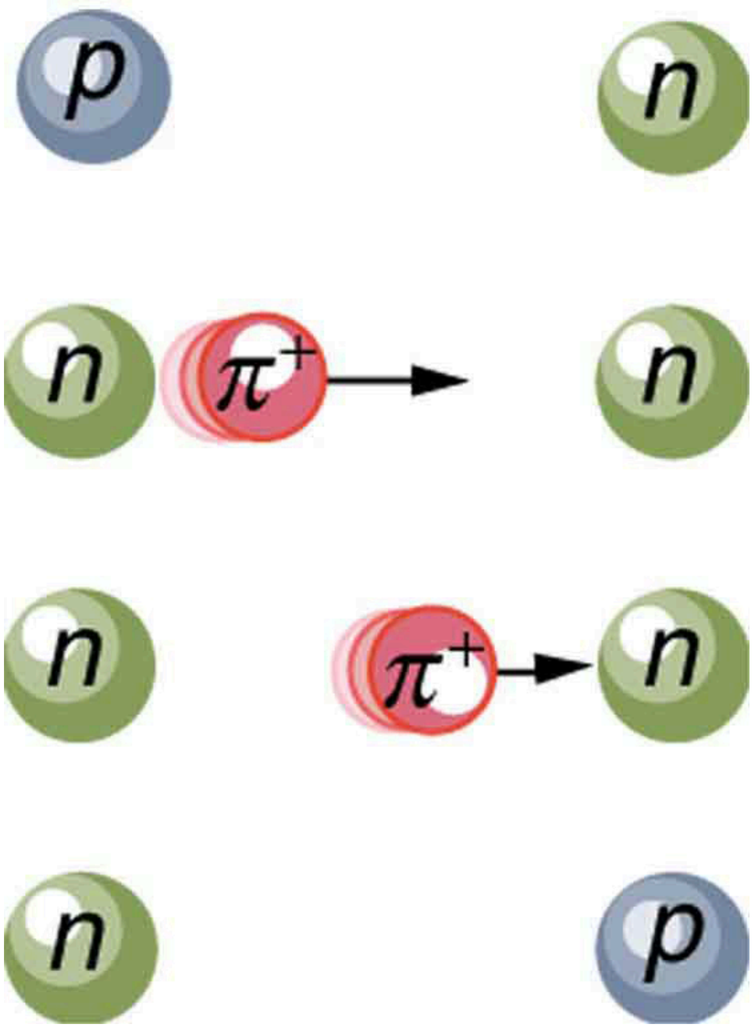
Glossary

particle physics
: the study of and the quest for those truly fundamental particles having no substructure

The Yukawa Particle and the Heisenberg Uncertainty Principle Revisited

- Define Yukawa particle.
- State the Heisenberg uncertainty principle.
- Describe pion.
- Estimate the mass of a pion.
- Explain meson.

Particle physics as we know it today began with the ideas of Hideki Yukawa in 1935. Physicists had long been concerned with how forces are transmitted, finding the concept of fields, such as electric and magnetic fields to be very useful. A field surrounds an object and carries the force exerted by the object through space. Yukawa was interested in the strong nuclear force in particular and found an ingenious way to explain its short range. His idea is a blend of particles, forces, relativity, and quantum mechanics that is applicable to all forces. Yukawa proposed that force is transmitted by the exchange of particles (called carrier particles). The field consists of these carrier particles.



The strong nuclear force is transmitted between a proton and neutron by the creation and exchange of a pion. The pion is created through a temporary violation of conservation of mass-energy and travels from the proton to the neutron and is recaptured. It is not directly observable and is called a virtual particle. Note that the proton and neutron change identity in the process. The range of the force is limited by the fact that the pion can only exist for the short time allowed by the Heisenberg uncertainty principle. Yukawa used the finite range of the strong nuclear force to estimate the mass of the pion; the shorter the range, the larger the mass of the carrier particle.

Specifically for the strong nuclear force, Yukawa proposed that a previously unknown particle, now called a **pion**, is exchanged between nucleons, transmitting the force between them. [Figure 1] illustrates how a pion would carry a force between a proton and a neutron. The pion has mass and can only be created by violating the conservation of mass-energy. This is allowed by the Heisenberg uncertainty principle if it occurs for a sufficiently short period of time. As discussed in Probability: The Heisenberg Uncertainty Principle the Heisenberg uncertainty principle relates the uncertainties ΔE in energy and Δt in time by

$$\Delta E \Delta t \geq \frac{h}{4\pi},$$

where h is Planck's constant. Therefore, conservation of mass-energy can be violated by an amount ΔE for a time $\Delta t \approx \frac{h}{4\pi\Delta E}$ in which time no process can detect the violation. This allows the temporary creation of a particle of mass m, where $\Delta E = mc^2$. The larger the mass and the greater the ΔE, the shorter is the time it can exist. This means the range of the force is limited, because the particle can only travel a limited distance in a finite amount of time. In fact, the maximum distance is $d \approx c\Delta t$, where *c* is the speed of light. The pion must then be captured and, thus, cannot be directly observed because that would amount to a permanent violation of mass-energy conservation. Such particles (like the pion above) are called **virtual particles**, because they cannot be directly observed but their *effects* can be directly observed. Realizing all this, Yukawa used the information on the range of the strong nuclear force to estimate the mass of the pion, the particle that carries it. The steps of his reasoning are approximately retraced in the following worked example:

Calculating the Mass of a Pion

Taking the range of the strong nuclear force to be about 1 fermi (10^{-15}m), calculate the approximate mass of the pion carrying the force, assuming it moves at nearly the speed of light.

Strategy

The calculation is approximate because of the assumptions made about the range of the force and the speed of the pion, but also because a more accurate calculation would require the sophisticated mathematics of quantum mechanics. Here, we use the Heisenberg uncertainty principle in the simple form stated above, as developed in [Probability: The Heisenberg Uncertainty Principle](). First, we must calculate the time Δt that the pion exists, given that the distance it travels at nearly the speed of light is about 1 fermi. Then, the Heisenberg uncertainty principle can be solved for the energy ΔE, and from that the mass of the pion can be determined. We will use the units of MeV/c^2 for mass, which are convenient since we are often considering converting mass to energy and vice versa.

Solution

The distance the pion travels is $d \approx c\Delta t$, and so the time during which it exists is approximately

$$\Delta t \approx \frac{d}{c} = \frac{10^{-15}\text{m}}{3.0\times10^{8}\text{m/s}} \approx 3.3\times10^{-24}\text{s}.$$

Now, solving the Heisenberg uncertainty principle for ΔE gives

$$\Delta E \approx \frac{h}{4\pi\Delta t} \approx \frac{6.63\times10^{-34}\text{J}\cdot\text{s}}{4\pi(3.3\times10^{-24}\text{s})}.$$

Solving this and converting the energy to MeV gives

$$\Delta E \approx (1.6\times10^{-11}\text{J})\frac{1\text{MeV}}{1.6\times10^{-13}\text{J}} = 100\text{MeV}.$$

Mass is related to energy by $\Delta E = mc^2$, so that the mass of the pion is $m = \Delta E/c^2$, or

$$m \approx 100\text{MeV}/c^2.$$

Discussion

This is about 200 times the mass of an electron and about one-tenth the mass of a nucleon. No such particles were known at the time Yukawa made his bold proposal.

Yukawa's proposal of particle exchange as the method of force transfer is intriguing. But how can we verify his proposal if we cannot observe the virtual pion directly? If sufficient energy is in a nucleus, it would be possible to free the pion—that is, to create its mass from external energy input. This can be accomplished by collisions of energetic particles with nuclei, but energies greater than 100 MeV are required to conserve both energy and momentum. In 1947, pions were observed in cosmic-ray experiments, which were designed to supply a small flux of high-energy protons that may collide with nuclei. Soon afterward, accelerators of sufficient energy were creating pions in the laboratory under controlled conditions. Three pions were discovered, two with charge and one neutral, and given the symbols $\pi^+, \pi^-, \text{and}\, \pi^0$, respectively. The masses of π^+ and π^- are identical at $139.6\text{MeV}/c^2$, whereas π^0 has a mass of $135.0\text{MeV}/c^2$. These masses are close to the predicted value of $100\text{MeV}/c^2$ and, since they are intermediate between electron and nucleon masses, the particles are given the name **meson** (now an entire class of particles, as we shall see in [Particles, Patterns, and Conservation Laws]()).

The pions, or π -mesons as they are also called, have masses close to those predicted and feel the strong nuclear force. Another previously unknown particle, now called the muon, was discovered during cosmic-ray experiments in 1936 (one of its discoverers, Seth Neddermeyer, also originated the idea of implosion for plutonium bombs). Since the mass of a muon is around $106\text{MeV}/c^2$, at first it was thought to be the particle predicted by Yukawa. But it was soon realized that muons do not feel the strong nuclear force and could not be Yukawa's particle. Their role was unknown, causing the respected physicist I. I. Rabi to comment, "Who ordered that?" This remains a valid question today. We have discovered hundreds of subatomic particles; the roles of some are only partially understood. But there are various patterns and relations to forces that have led to profound insights into nature's secrets.

Summary

- Yukawa's idea of virtual particle exchange as the carrier of forces is crucial, with virtual particles being formed in temporary violation of the conservation of mass-energy as allowed by the Heisenberg uncertainty principle.

Problems & Exercises

A virtual particle having an approximate mass of $10^{14}\text{GeV}/c^2$ may be associated with the unification of the strong and electroweak forces. For what length of time could this virtual particle exist (in temporary violation of the conservation of mass-energy as allowed by the Heisenberg uncertainty principle)?

Show Solution

$3 \times 10^{-39}\text{s}$

Calculate the mass in GeV/c^2 of a virtual carrier particle that has a range limited to 10^{-30} m by the Heisenberg uncertainty principle. Such a particle might be involved in the unification of the strong and electroweak forces.

Show Solution

Strategy

The approach is similar to the worked example in this section. We'll use the Heisenberg uncertainty principle to find the energy uncertainty ΔE based on the time uncertainty Δt during which the virtual particle can exist. The range of the particle is related to the distance it can travel at approximately the speed of light during this time: $d \approx c\Delta t$. Once we find ΔE, we can determine the mass using $\Delta E = mc^2$.

Solution

First, calculate the time the virtual particle can exist from the range and speed of light:

$$\Delta t \approx \frac{d}{c} = \frac{10^{-30}\text{ m}}{3.0\times10^{8}\text{ m/s}} = 3.33\times10^{-39}\text{ s}$$

Using the Heisenberg uncertainty principle $\Delta E \Delta t \geq \frac{h}{4\pi}$, solve for ΔE:

$$\Delta E \approx \frac{h}{4\pi \Delta t} = \frac{6.63\times10^{-34}\text{ J}\cdot\text{s}}{4\pi(3.33\times10^{-39}\text{ s})} = 1.58\times10^{-5}\text{ J}$$

Convert this energy to GeV:

$$\Delta E = (1.58\times10^{-5}\text{ J})\times\frac{1\text{ GeV}}{1.6\times10^{-10}\text{ J}} = 9.9\times10^{4}\text{ GeV} \approx 10^{5}\text{ GeV} = 100\text{ TeV}$$

The mass of the particle is:

$$m = \frac{\Delta E}{c^2} \approx 10^{5}\text{ GeV}/c^2 = 100\text{ TeV}/c^2$$

Discussion

This mass is extraordinarily large—about 100,000 times the mass of a proton (0.938 GeV/c^2). Such particles would require energies far beyond what any conceivable accelerator could produce. This is why grand unified theories that predict these particles cannot be directly tested in the laboratory. The very short range (10^{-30} m) corresponds to extremely high energy scales, characteristic of conditions that may have existed only in the very early universe, fractions of a second after the Big Bang. This illustrates why cosmology and particle physics are intimately connected in exploring grand unification.

Another component of the strong nuclear force is transmitted by the exchange of virtual *K*-mesons. Taking *K*-mesons to have an average mass of $495\text{MeV}/c^2$, what is the approximate range of this component of the strong force?

Show Solution

$1.99 \times 10^{-16}\text{m}(0.2\text{fm})$

Glossary

pion
: particle exchanged between nucleons, transmitting the force between them

virtual particles
: particles which cannot be directly observed but their effects can be directly observed

meson
: particle whose mass is intermediate between the electron and nucleon masses

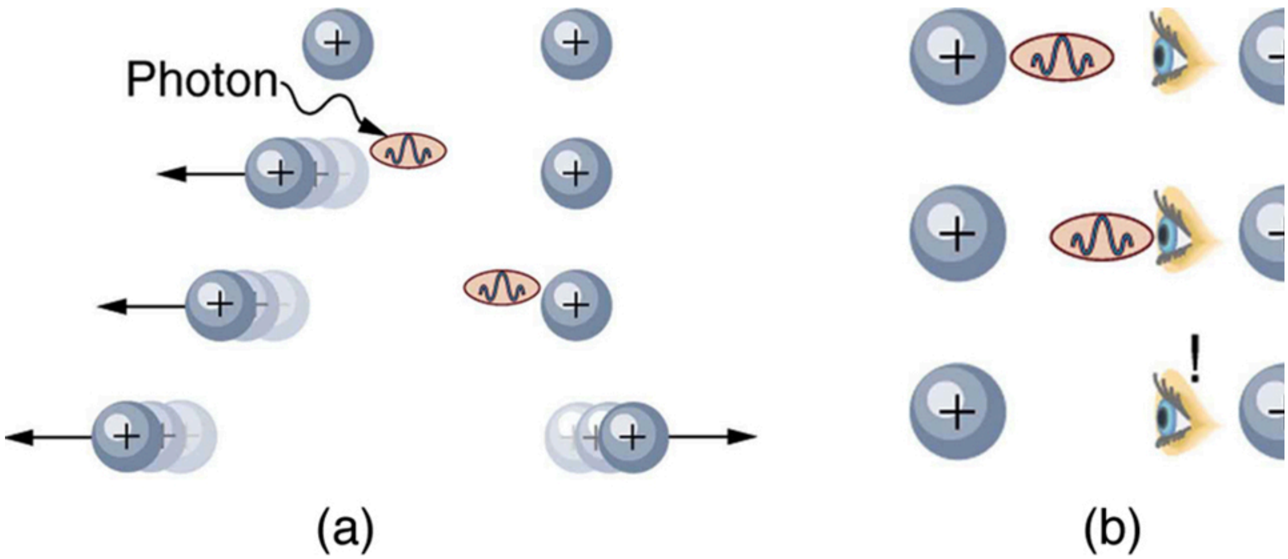
The Four Basic Forces

- State the four basic forces.
- Explain the Feynman diagram for the exchange of a virtual photon between two positive charges.
- Define QED.
- Describe the Feynman diagram for the exchange of a between a proton and a neutron.

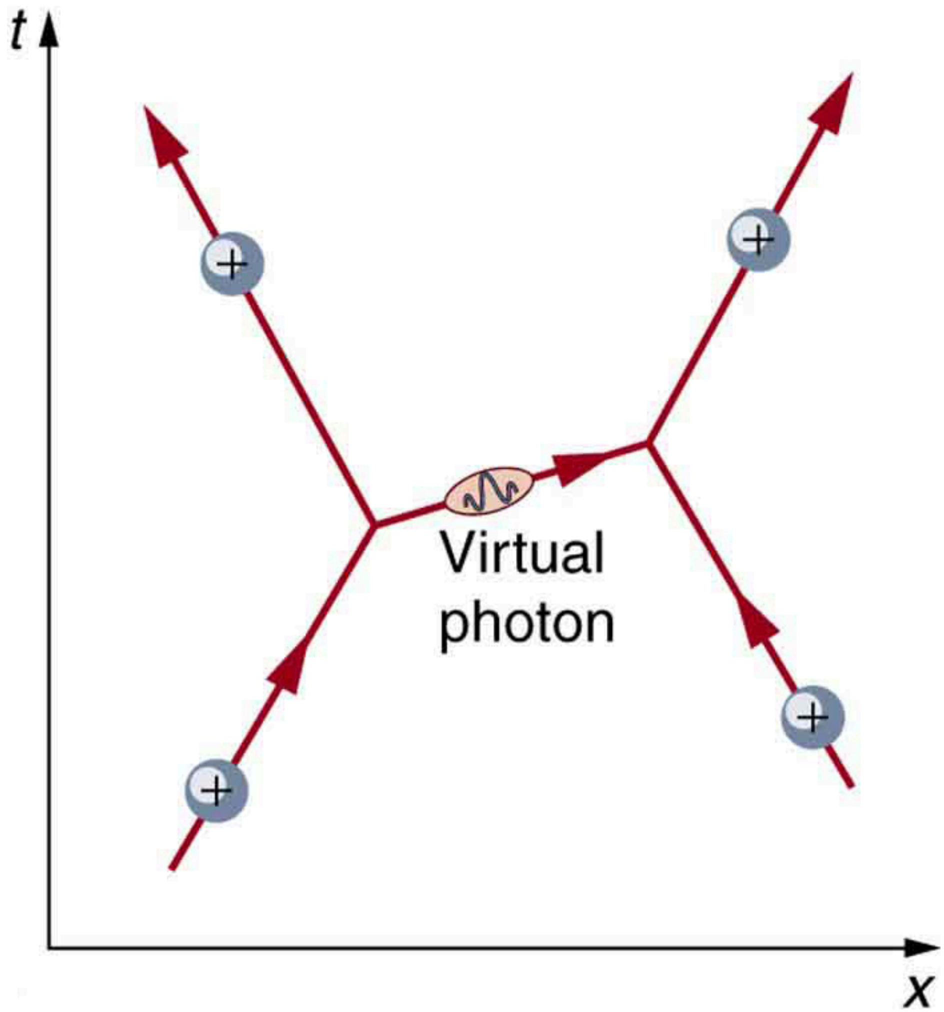
There are only four distinct basic forces in all of nature. This is a remarkably small number considering the myriad phenomena they explain. Particle physics is intimately tied to these four forces. Certain fundamental particles, called carrier particles, carry these forces, and all particles can be classified according to which of the four forces they feel. The table given below summarizes important characteristics of the four basic forces.

Properties of the Four Basic Forces

Force	Approximate relative strength	Range	+/−[1]	Carrier particle
Gravity	10^{-38}	∞	+ only	Graviton (conjectured)
Electromagnetic	10^{-2}	∞	+/−	Photon (observed)
Weak force	10^{-13}	$<10^{-18}$m	+/−	W^+, W^-, Z^0 (observed[2])
Strong force	1	$<10^{-15}$m	+/−	Gluons (conjectured[3])



The first image shows the exchange of a virtual photon transmitting the electromagnetic force between charges, just as virtual pion exchange carries the strong nuclear force between nucleons. The second image shows that the photon cannot be directly observed in its passage, because this would disrupt it and alter the force. In this case it does not get to the other charge.



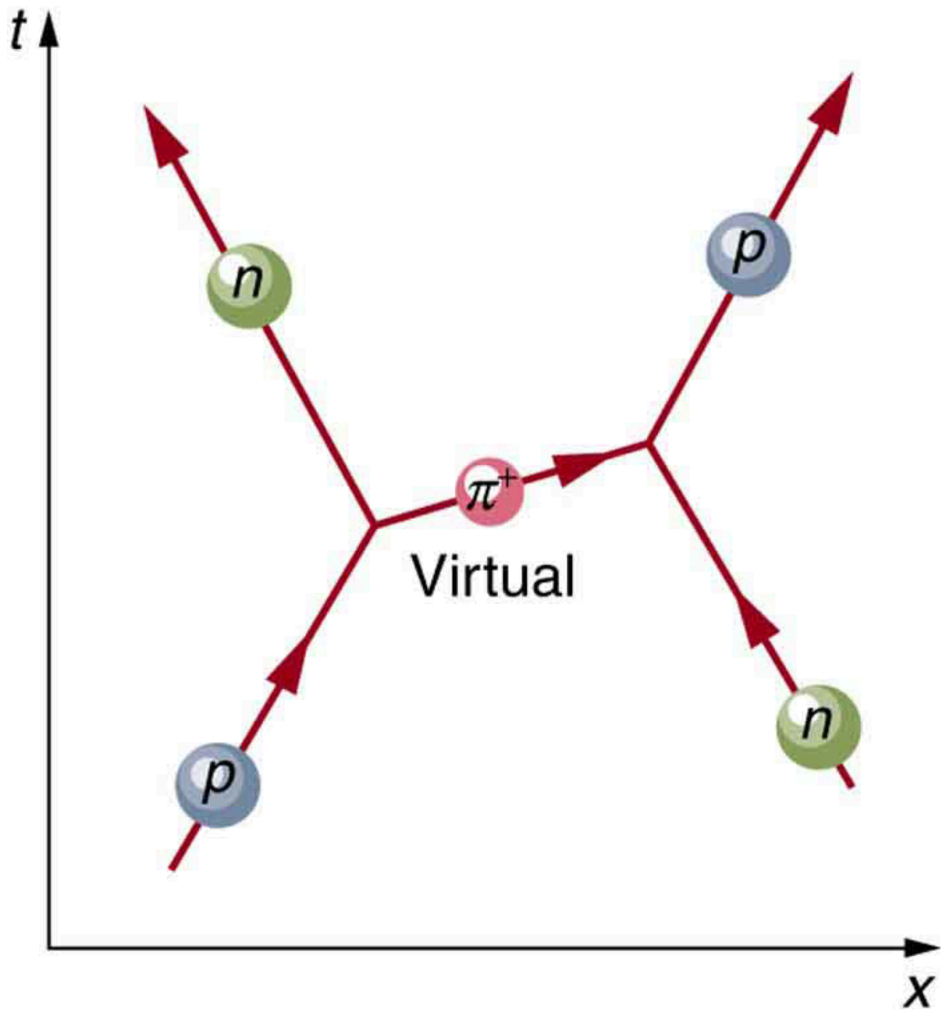
The Feynman diagram for the exchange of a virtual photon between two positive charges illustrates how the electromagnetic force is transmitted on a quantum mechanical scale. Time is graphed vertically while the distance is graphed horizontally. The two positive charges are seen to be repelled by the photon exchange.

Although these four forces are distinct and differ greatly from one another under all but the most extreme circumstances, we can see similarities among them. (In GUTs: the Unification of Forces, we will discuss how the four forces may be different manifestations of a single unified force.) Perhaps the most important characteristic among the forces is that they are all transmitted by the exchange of a carrier particle, exactly like what Yukawa had in mind for the strong nuclear force. Each carrier particle is a virtual particle—it cannot be directly observed while transmitting the force. [Figure 1] shows the exchange of a virtual photon between two positive charges. The photon cannot be directly observed in its passage, because this would disrupt it and alter the force.

[Figure 2] shows a way of graphing the exchange of a virtual photon between two positive charges. This graph of time versus position is called a ** Feynman diagram**, after the brilliant American physicist Richard Feynman (1918–1988) who developed it.

[Figure 3] is a Feynman diagram for the exchange of a virtual pion between a proton and a neutron representing the same interaction as in [The Yukawa Particle and the Heisenberg Uncertainty Principle Revisited]. Feynman diagrams are not only a useful tool for visualizing interactions at the quantum mechanical level, they are also used to calculate details of interactions, such as their strengths and probability of occurring. Feynman was one of the theorists who developed the field of **quantum electrodynamics** (QED), which is the quantum mechanics of electromagnetism. QED has been spectacularly successful in describing electromagnetic interactions on the submicroscopic scale. Feynman was an inspiring teacher, had a colorful personality, and made a profound impact on generations of physicists. He shared the 1965 Nobel Prize with Julian Schwinger and S. I. Tomonaga for work in QED with its deep implications for particle physics.

Why is it that particles called gluons are listed as the carrier particles for the strong nuclear force when, in The Yukawa Particle and the Heisenberg Uncertainty Principle Revisited , we saw that pions apparently carry that force? The answer is that pions are exchanged but they have a substructure and, as we explore it, we find that the strong force is actually related to the indirectly observed but more fundamental **gluons**. In fact, all the carrier particles are thought to be fundamental in the sense that they have no substructure. Another similarity among carrier particles is that they are all bosons (first mentioned in Patterns in Spectra Reveal More Quantization), having integral intrinsic spins.



The image shows a Feynman diagram for the exchange of a π^+ between a proton and a neutron, carrying the strong nuclear force between them. This diagram represents the situation shown more pictorially in [link].

There is a relationship between the mass of the carrier particle and the range of the force. The photon is massless and has energy. So, the existence of (virtual) photons is possible only by virtue of the Heisenberg uncertainty principle and can travel an unlimited distance. Thus, the range of the electromagnetic force is infinite. This is also true for gravity. It is infinite in range because its carrier particle, the graviton, has zero rest mass. (Gravity is the most difficult of the four forces to understand on a quantum scale because it affects the space and time in which the others act. But gravity is so weak that its effects are extremely difficult to observe quantum mechanically. We shall explore it further in General Relativity and Quantum Gravity). The W^+, W^-, and Z^0 particles that carry the weak nuclear force have mass, accounting for the very short range of this force. In fact, the W^+, W^-, and Z^0 are about 1000 times more massive than pions, consistent with the fact that the range of the weak nuclear force is about 1/1000 that of the strong nuclear force. Gluons are actually massless, but since they act inside massive carrier particles like pions, the strong nuclear force is also short ranged.

The relative strengths of the forces given in the [Table 1] are those for the most common situations. When particles are brought very close together, the relative strengths change, and they may become identical at extremely close range. As we shall see in GUTs: the Unification of Forces, carrier particles may be altered by the energy required to bring particles very close together—in such a manner that they become identical.

Summary

- The four basic forces and their carrier particles are summarized in the [Table 1].
- Feynman diagrams are graphs of time versus position and are highly useful pictorial representations of particle processes.
- The theory of electromagnetism on the particle scale is called quantum electrodynamics (QED).

Problems & Exercises

(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?

Show Solution

(a) 10^{-11} to 1, weak to EM

(b) 1 to 1

The ratio of the strong to the weak force and the ratio of the strong force to the electromagnetic force become 1 under circumstances where they are unified. What are the ratios of the strong force to those two forces under normal circumstances?

Show Solution

Strategy

From [Table 1], we can find the approximate relative strengths of the four basic forces under ordinary circumstances. The strong force has a relative strength of 1, the electromagnetic force has a relative strength of 10^{-2}, and the weak force has a relative strength of 10^{-13}. We need to calculate the ratios of the strong force to each of the other two forces.

Solution

The ratio of the strong force to the weak force is:

$$\text{strongweak}=110^{-13}=10^{13} \text{ to } 1$$

The ratio of the strong force to the electromagnetic force is:

$$\text{strongEM}=110^{-2}=10^{2}=100 \text{ to } 1$$

Discussion

These ratios show the dramatic differences in strength between the forces under normal circumstances. The strong force is 10^{13} (ten trillion) times stronger than the weak force and 100 times stronger than the electromagnetic force. These enormous differences explain why the forces appear so distinct in everyday physics and why their unification only occurs at extremely high energies or very small distances. At the unification scale, these ratios all become 1:1, meaning the forces become indistinguishable. The weak force is much weaker than the strong force, which is why weak interactions (like beta decay) proceed much more slowly than strong force interactions. Similarly, the electromagnetic force being 100 times weaker than the strong force explains why electrostatic repulsion between protons in a nucleus is overwhelmed by the strong force at nuclear distances.

Footnotes

- 1 + attractive; - repulsive; $+/-$ both.
- 2 Predicted by theory and first observed in 1983.
- 3 Eight proposed—indirect evidence of existence. Underlie meson exchange. { data-list-type="bulleted" data-bullet-style="none"}

Glossary

Feynman diagram
: a graph of time versus position that describes the exchange of virtual particles between subatomic particles

gluons
: exchange particles, analogous to the exchange of photons that gives rise to the electromagnetic force between two charged particles

quantum electrodynamics
: the theory of electromagnetism on the particle scale

Accelerators Create Matter from Energy

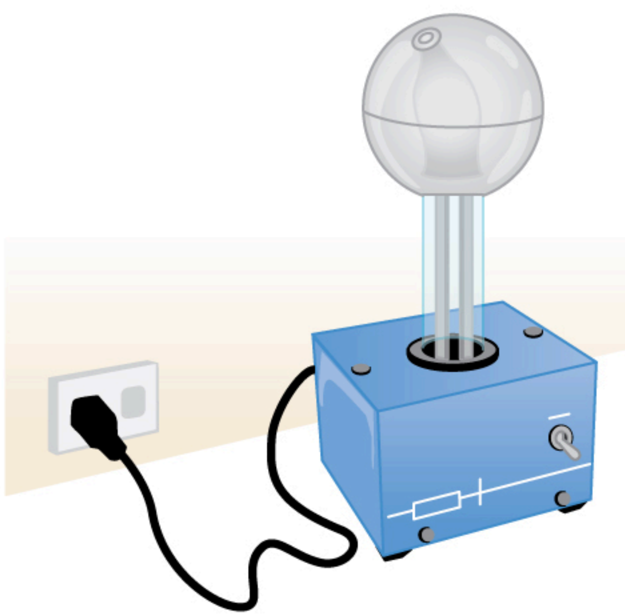
- State the principle of a cyclotron.
- Explain the principle of a synchrotron.
- Describe the voltage needed by an accelerator between accelerating tubes.
- State Fermilab's accelerator principle.

Before looking at all the particles we now know about, let us examine some of the machines that created them. The fundamental process in creating previously unknown particles is to accelerate known particles, such as protons or electrons, and direct a beam of them toward a target. Collisions with target nuclei provide a wealth of information, such as information obtained by Rutherford using energetic helium nuclei from natural α radiation. But if the energy of the incoming particles is large enough, new matter is sometimes created in the collision. The more energy input or ΔE , the more matter m can be created, since $m = \Delta E / c^2$. Limitations are placed on what can occur by known conservation laws, such as conservation of mass-energy, momentum, and charge. Even more interesting are the unknown limitations provided by nature. Some expected reactions do occur, while others do not, and still other unexpected reactions may appear. New laws are revealed, and the vast majority of what we know about particle physics has come from accelerator laboratories. It is the particle physicist's favorite indoor sport, which is partly inspired by theory.

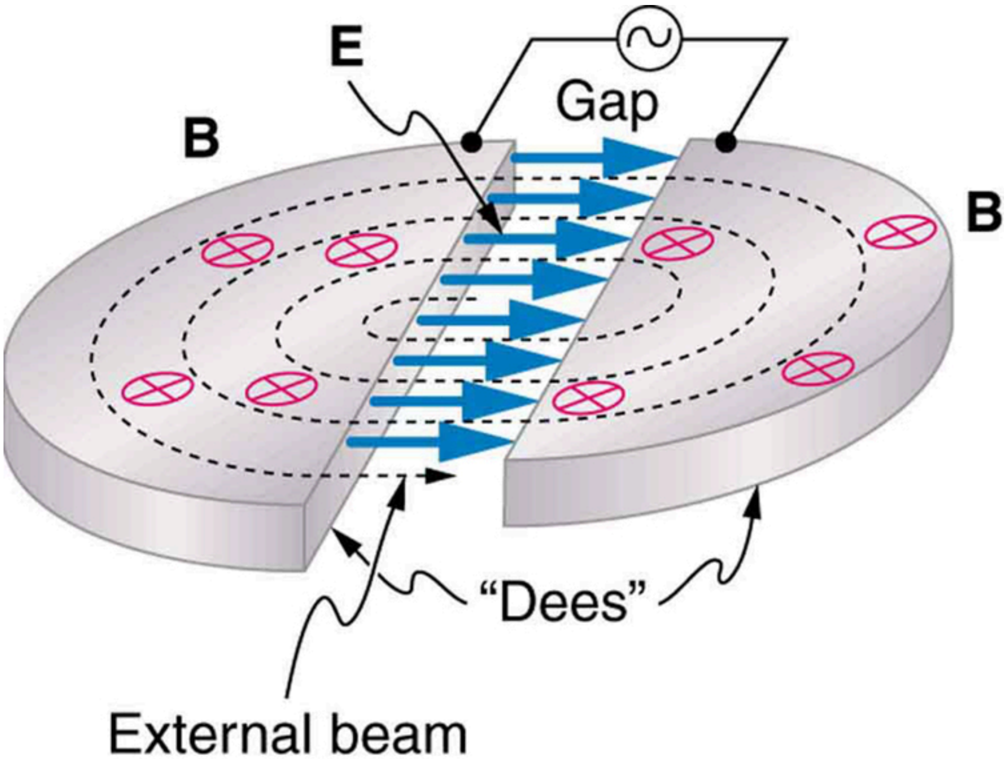
Early Accelerators

An early accelerator is a relatively simple, large-scale version of the electron gun. The **Van de Graaff** (named after the Dutch physicist), which you have likely seen in physics demonstrations, is a small version of the ones used for nuclear research since their invention for that purpose in 1932. For more, see [Figure 1]. These machines are electrostatic, creating potentials as great as 50 MV, and are used to accelerate a variety of nuclei for a range of experiments. Energies produced by Van de Graaffs are insufficient to produce new particles, but they have been instrumental in exploring several aspects of the nucleus. Another, equally famous, early accelerator is the **cyclotron**, invented in 1930 by the American physicist, E. O. Lawrence (1901–1958). For a visual representation with more detail, see [Figure 2]. Cyclotrons use fixed-frequency alternating electric fields to accelerate particles. The particles spiral outward in a magnetic field, making increasingly larger radius orbits during acceleration. This clever arrangement allows the successive addition of electric potential energy and so greater particle energies are possible than in a Van de Graaff. Lawrence was involved in many early discoveries and in the promotion of physics programs in American universities. He was awarded the 1939 Nobel Prize in Physics for the cyclotron and nuclear activations, and he has an element and two major laboratories named for him.

A **synchrotron** is a version of a cyclotron in which the frequency of the alternating voltage and the magnetic field strength are increased as the beam particles are accelerated. Particles are made to travel the same distance in a shorter time with each cycle in fixed-radius orbits. A ring of magnets and accelerating tubes, as shown in [Figure 3], are the major components of synchrotrons. Accelerating voltages are synchronized (i.e., occur at the same time) with the particles to accelerate them, hence the name. Magnetic field strength is increased to keep the orbital radius constant as energy increases. High-energy particles require strong magnetic fields to steer them, so superconducting magnets are commonly employed. Still limited by achievable magnetic field strengths, synchrotrons need to be very large at very high energies, since the radius of a high-energy particle's orbit is very large. Radiation caused by a magnetic field accelerating a charged particle perpendicular to its velocity is called **synchrotron radiation** in honor of its importance in these machines. Synchrotron radiation has a characteristic spectrum and polarization, and can be recognized in cosmic rays, implying large-scale magnetic fields acting on energetic and charged particles in deep space. Synchrotron radiation produced by accelerators is sometimes used as a source of intense energetic electromagnetic radiation for research purposes.



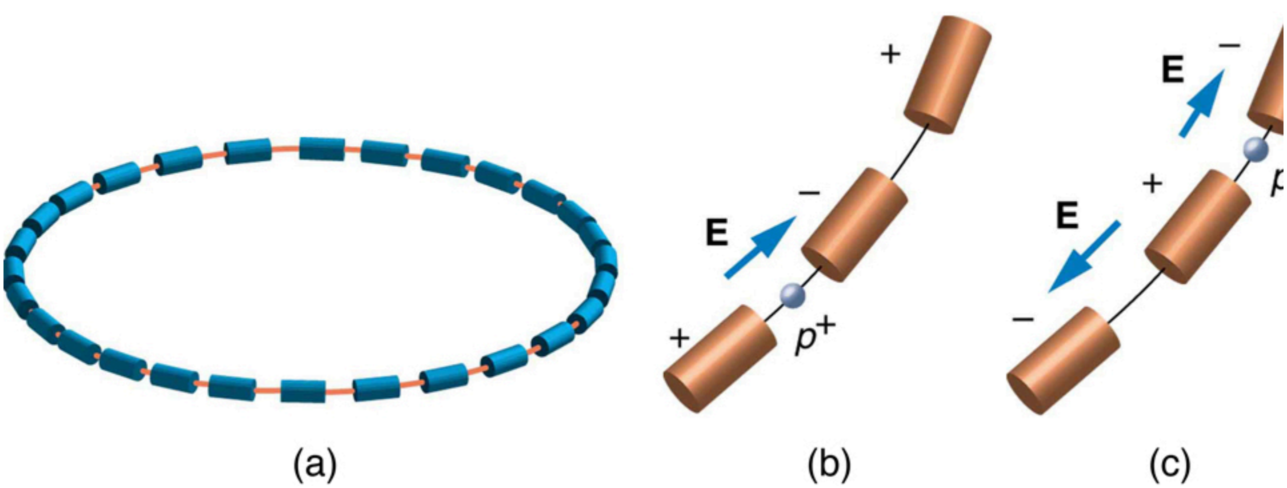
An artist's rendition of a Van de Graaff generator.



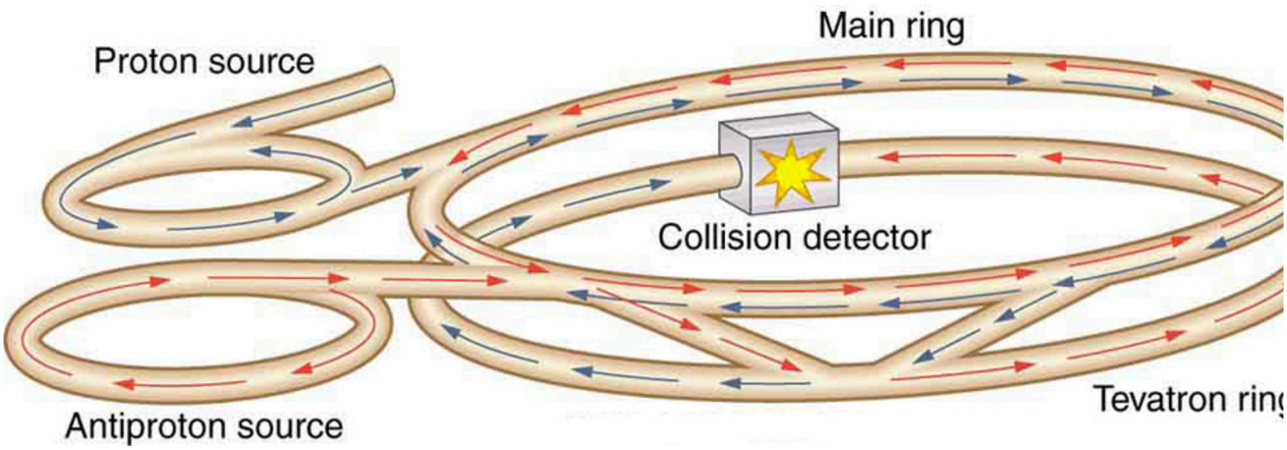
Cyclotrons use a magnetic field to cause particles to move in circular orbits. As the particles pass between the plates of the Ds, the voltage across the gap is oscillated to accelerate them twice in each orbit.

Modern Behemoths and Colliding Beams

Physicists have built ever-larger machines, first to reduce the wavelength of the probe and obtain greater detail, then to put greater energy into collisions to create new particles. Each major energy increase brought new information, sometimes producing spectacular progress, motivating the next step. One major innovation was driven by the desire to create more massive particles. Since momentum needs to be conserved in a collision, the particles created by a beam hitting a stationary target should recoil. This means that part of the energy input goes into recoil kinetic energy, significantly limiting the fraction of the beam energy that can be converted into new particles. One solution to this problem is to have head-on collisions between particles moving in opposite directions. **Colliding beams** are made to meet head-on at points where massive detectors are located. Since the total incoming momentum is zero, it is possible to create particles with momenta and kinetic energies near zero. Particles with masses equivalent to twice the beam energy can thus be created. Another innovation is to create the antimatter counterpart of the beam particle, which thus has the opposite charge and circulates in the opposite direction in the same beam pipe. For a schematic representation, see [Figure 4].



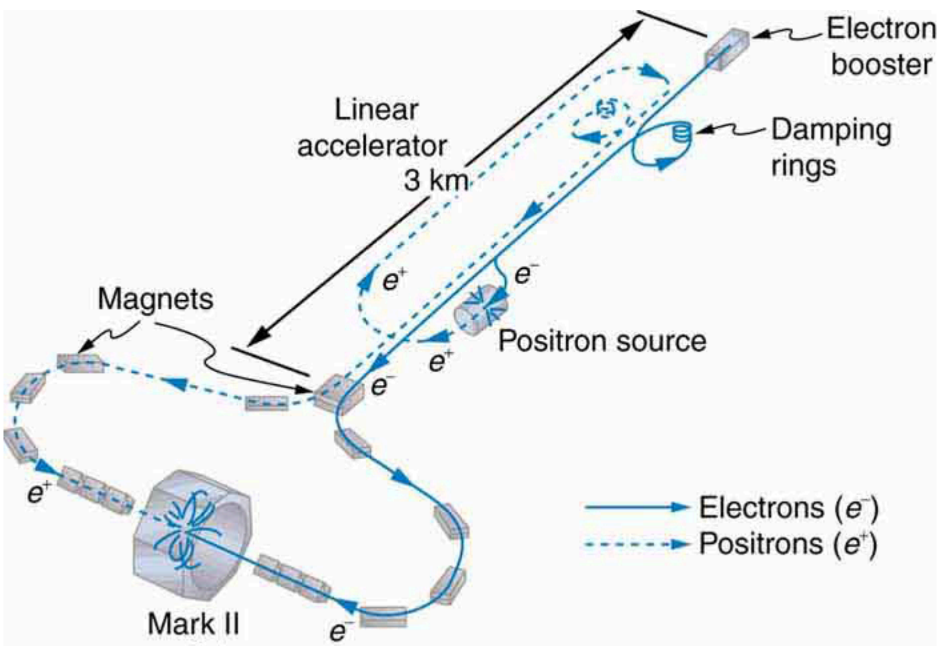
(a) A synchrotron has a ring of magnets and accelerating tubes. The frequency of the accelerating voltages is increased to cause the beam particles to travel the same distance in shorter time. The magnetic field should also be increased to keep each beam burst traveling in a fixed-radius path. Limits on magnetic field strength require these machines to be very large in order to accelerate particles to very high energies. (b) A positive particle is shown in the gap between accelerating tubes. (c) While the particle passes through the tube, the potentials are reversed so that there is another acceleration at the next gap. The frequency of the reversals needs to be varied as the particle is accelerated to achieve successive accelerations in each gap.



This schematic shows the two rings of Fermilab's accelerator and the scheme for colliding protons and antiprotons (not to scale).

Detectors capable of finding the new particles in the spray of material that emerges from colliding beams are as impressive as the accelerators. While the Fermilab Tevatron had proton and antiproton beam energies of about 1 TeV, so that it can create particles up to $2\text{TeV}/c^2$, the Large Hadron Collider (LHC) at the European Center for Nuclear Research (CERN) has achieved beam energies of 3.5 TeV, so that it has a 7-TeV collision energy; CERN hopes to double the beam energy in 2014. The now-canceled Superconducting Super Collider was being constructed in Texas with a design energy of 20 TeV to give a 40-TeV collision energy. It was to be an oval 30 km in diameter. Its cost as well as the politics of international research funding led to its demise.

In addition to the large synchrotrons that produce colliding beams of protons and antiprotons, there are other large electron-positron accelerators. The oldest of these was a straight-line or **linear accelerator**, called the Stanford Linear Accelerator (SLAC), which accelerated particles up to 50 GeV as seen in [Figure 5]. Positrons created by the accelerator were brought to the same energy and collided with electrons in specially designed detectors. Linear accelerators use accelerating tubes similar to those in synchrotrons, but aligned in a straight line. This helps eliminate synchrotron radiation losses, which are particularly severe for electrons made to follow curved paths. CERN had an electron-positron collider appropriately called the Large Electron-Positron Collider (LEP), which accelerated particles to 100 GeV and created a collision energy of 200 GeV. It was 8.5 km in diameter, while the SLAC machine was 3.2 km long.



The Stanford Linear Accelerator was 3.2 km long and had the capability of colliding electron and positron beams. SLAC was also used to probe nucleons by scattering extremely short wavelength electrons from them. This produced the first convincing evidence of a quark structure inside nucleons in an experiment analogous to those performed by Rutherford long ago.

Calculating the Voltage Needed by the Accelerator Between Accelerating Tubes

A linear accelerator designed to produce a beam of 800-MeV protons has 2000 accelerating tubes. What average voltage must be applied between tubes (such as in the gaps in [Figure 3]) to achieve the desired energy?

Strategy

The energy given to the proton in each gap between tubes is $PE_{elec} = qV$ where q is the proton's charge and V is the potential difference (voltage) across the gap. Since $q = q_e = 1.6 \times 10^{-19} C$ and $1 eV = (1 V)(1.6 \times 10^{-19} C)$, the proton gains 1 eV in energy for each volt across the gap that it passes through. The AC voltage applied to the tubes is timed so that it adds to the energy in each gap. The effective voltage is the sum of the gap voltages and equals 800 MV to give each proton an energy of 800 MeV.

Solution

There are 2000 gaps and the sum of the voltages across them is 800 MV; thus,

$$V_{gap} = \frac{800 MV}{2000} = 400 kV.$$

Discussion

A voltage of this magnitude is not difficult to achieve in a vacuum. Much larger gap voltages would be required for higher energy, such as those at the 50-GeV SLAC facility. Synchrotrons are aided by the circular path of the accelerated particles, which can orbit many times, effectively multiplying the number of accelerations by the number of orbits. This makes it possible to reach energies greater than 1 TeV.

Summary

- A variety of particle accelerators have been used to explore the nature of subatomic particles and to test predictions of particle theories.
- Modern accelerators used in particle physics are either large synchrotrons or linear accelerators.
- The use of colliding beams makes much greater energy available for the creation of particles, and collisions between matter and antimatter allow a greater range of final products.

Conceptual Questions

The total energy in the beam of an accelerator is far greater than the energy of the individual beam particles. Why isn't this total energy available to create a single extremely massive particle?

Synchrotron radiation takes energy from an accelerator beam and is related to acceleration. Why would you expect the problem to be more severe for electron accelerators than proton accelerators?

What two major limitations prevent us from building high-energy accelerators that are physically small?

What are the advantages of colliding-beam accelerators? What are the disadvantages?

Problems & Exercises

At full energy, protons in the 2.00-km-diameter Fermilab synchrotron travel at nearly the speed of light, since their energy is about 1000 times their rest mass energy.

(a) How long does it take for a proton to complete one trip around?

(b) How many times per second will it pass through the target area?

Show Solution

(a) $2.09 \times 10^{-5} s$ (b) $4.77 \times 10^{4} Hz$

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 0.900 *c*? 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.

Show Solution

Strategy

The distance traveled by a particle is simply the product of its velocity and time: $d = vt$. We are given that the W^- travels at $0.900c$ for a time of 5.00×10^{-25} s.

Solution

Calculate the distance:

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

Discussion

This distance is incredibly small—only 0.135 femtometers, which is about one-seventh the diameter of a proton (approximately 1 fm). This is far too short to produce a visible track in a bubble chamber, which typically requires distances of micrometers or more. Therefore, the existence of the W^- particle must be inferred indirectly from its decay products rather than from direct observation of its track. The short lifetime and high speed of the W^- are characteristic of particles that mediate the weak nuclear force. The fact that the particle lives for 5.00×10^{-25} s (longer than its rest lifetime of 1.6×10^{-25} s from the particle tables) can be explained by time dilation—at $0.900c$, the relativistic γ factor extends the observed lifetime in the laboratory frame.

What length track does a π^+ traveling at 0.100 *c* leave in a bubble chamber if it is created there and lives for 2.60×10^{-8}s ? (Those moving faster or living longer may escape the detector before decaying.)

Show Solution

78.0 cm

The 3.20-km-long SLAC produces a beam of 50.0-GeV electrons. If there are 15 000 accelerating tubes, what average voltage must be across the gaps between them to achieve this energy?

Show Solution

Strategy

This problem is analogous to the worked example in this section. Each gap provides an energy boost equal to qV, where q is the charge of the electron and V is the voltage across the gap. Since $1\text{ eV}=(1\text{ V})(1.6\times10^{-19}\text{ C})$, an electron gains 1 eV for each volt it passes through. The total energy equals the number of gaps times the voltage per gap.

Solution

The total energy is 50.0 GeV, which must equal the sum of energies gained across all gaps. There are 15,000 gaps (between 15,000 tubes), so:

$$V_{\text{gap}}=\frac{\text{Total Energy}}{\text{Number of gaps}}=\frac{50.0\text{ GeV}}{15{,}000}$$
$$V_{\text{gap}}=\frac{50.0\times10^{9}\text{ eV}}{15{,}000}=3.33\times10^{6}\text{ eV}=3.33\text{ MV}$$

Discussion

An average voltage of 3.33 million volts per gap is required. This is a substantial voltage but achievable in a vacuum environment. The advantage of using many accelerating tubes is that the voltage per gap can be kept at a manageable level while still achieving very high total energies. In SLAC's linear design, particles make a single pass through all the gaps, unlike in circular accelerators where particles can orbit many times. The 3.20-km length of SLAC was specifically chosen to accommodate the number of accelerating structures needed to reach 50 GeV with practically achievable gap voltages. Modern linear accelerators continue to use this principle, balancing the length of the machine against the voltage gradients that can be sustained in each accelerating structure.

Because of energy loss due to synchrotron radiation in the LHC at CERN, only 5.00 MeV is added to the energy of each proton during each revolution around the main ring. How many revolutions are needed to produce 7.00-TeV (7000 GeV) protons, if they are injected with an initial energy of 8.00 GeV?

Show Solution

1.40×10^{6}

A proton and an antiproton collide head-on, with each having a kinetic energy of 7.00 TeV (such as in the LHC at CERN). How much collision energy is available, taking into account the annihilation of the two masses? (Note that this is not significantly greater than the extremely relativistic kinetic energy.)

Show Solution

Strategy

The total collision energy available includes the kinetic energy of both particles plus their rest mass energies. When a proton and antiproton annihilate, both their masses are converted to energy according to $E=mc^2$. The rest mass energy of a proton (or antiproton) is 938.3 MeV or 0.9383 GeV.

Solution

The total collision energy is the sum of:

- Kinetic energy of the proton: 7.00 TeV = 7000 GeV
- Kinetic energy of the antiproton: 7.00 TeV = 7000 GeV
- Rest mass energy of the proton: 0.938 GeV
- Rest mass energy of the antiproton: 0.938 GeV

$$E_{\text{total}}=KE_p+KE_{\bar{p}}+m_pc^2+m_{\bar{p}}c^2$$
$$E_{\text{total}}=7000\text{ GeV}+7000\text{ GeV}+0.938\text{ GeV}+0.938\text{ GeV}$$

E_{total}=14,001.876 GeV≈14.0 TeV

Discussion

The total collision energy is approximately 14.0 TeV, which is essentially just twice the kinetic energy (14.0 TeV versus 14.00 TeV). The rest mass energies of the proton and antiproton contribute only about 1.88 GeV out of 14,000 GeV total—less than 0.014% of the total energy. This confirms the note in the problem that the annihilation energy is not significantly greater than the extremely relativistic kinetic energy. At these ultra-high energies, the particles are moving at speeds extremely close to the speed of light, and their kinetic energies vastly exceed their rest mass energies. This is characteristic of the ultra-relativistic regime. The advantage of colliding beams is evident here: all 14 TeV is available for particle creation, whereas if a 7 TeV proton struck a stationary target, much of the energy would go into recoil momentum rather than particle creation.

When an electron and positron collide at the SLAC facility, they each have 50.0 GeV kinetic energies. What is the total collision energy available, taking into account the annihilation energy? Note that the annihilation energy is insignificant, because the electrons are highly relativistic.

Show Solution

100 GeV

Glossary

colliding beams
: head-on collisions between particles moving in opposite directions

cyclotron
: accelerator that uses fixed-frequency alternating electric fields and fixed magnets to accelerate particles in a circular spiral path

linear accelerator
: accelerator that accelerates particles in a straight line

synchrotron
: a version of a cyclotron in which the frequency of the alternating voltage and the magnetic field strength are increased as the beam particles are accelerated

synchrotron radiation
: radiation caused by a magnetic field accelerating a charged particle perpendicular to its velocity

Van de Graaff
: early accelerator: simple, large-scale version of the electron gun

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Particles, Patterns, and Conservation Laws

- Define matter and antimatter.
- Outline the differences between hadrons and leptons.
- State the differences between mesons and baryons.

In the early 1930s only a small number of subatomic particles were known to exist—the proton, neutron, electron, photon and, indirectly, the neutrino. Nature seemed relatively simple in some ways, but mysterious in others. Why, for example, should the particle that carries positive charge be almost 2000 times as massive as the one carrying negative charge? Why does a neutral particle like the neutron have a magnetic moment? Does this imply an internal structure with a distribution of moving charges? Why is it that the electron seems to have no size other than its wavelength, while the proton and neutron are about 1 fermi in size? So, while the number of known particles was small and they explained a great deal of atomic and nuclear phenomena, there were many unexplained phenomena and hints of further substructures.

Things soon became more complicated, both in theory and in the prediction and discovery of new particles. In 1928, the British physicist P.A.M. Dirac (see [Figure 1]) developed a highly successful relativistic quantum theory that laid the foundations of quantum electrodynamics (QED). His theory, for example, explained electron spin and magnetic moment in a natural way. But Dirac's theory also predicted negative energy states for free electrons. By 1931, Dirac, along with Oppenheimer, realized this was a prediction of positively charged electrons (or positrons). In 1932, American physicist Carl Anderson discovered the positron in cosmic ray studies. The positron, or e^+, is the same particle as emitted in β^+ decay and was the first antimatter that was discovered. In 1935, Yukawa predicted pions as the carriers of the strong nuclear force, and they were eventually discovered. Muons were discovered in cosmic ray experiments in 1937, and they seemed to be heavy, unstable versions of electrons and positrons. After World War II, accelerators energetic enough to create these particles were built. Not only were predicted and known particles created, but many unexpected particles were observed. Initially called elementary particles, their numbers proliferated to dozens and then hundreds, and the term "particle zoo" became the physicist's lament at the lack of simplicity. But patterns were observed in the particle zoo that led to simplifying ideas such as quarks, as we shall soon see.

P.A.M. Dirac's theory of relativistic quantum mechanics not only explained a great deal of what was known, it also predicted antimatter. (credit: Cambridge University, Cavendish Laboratory)

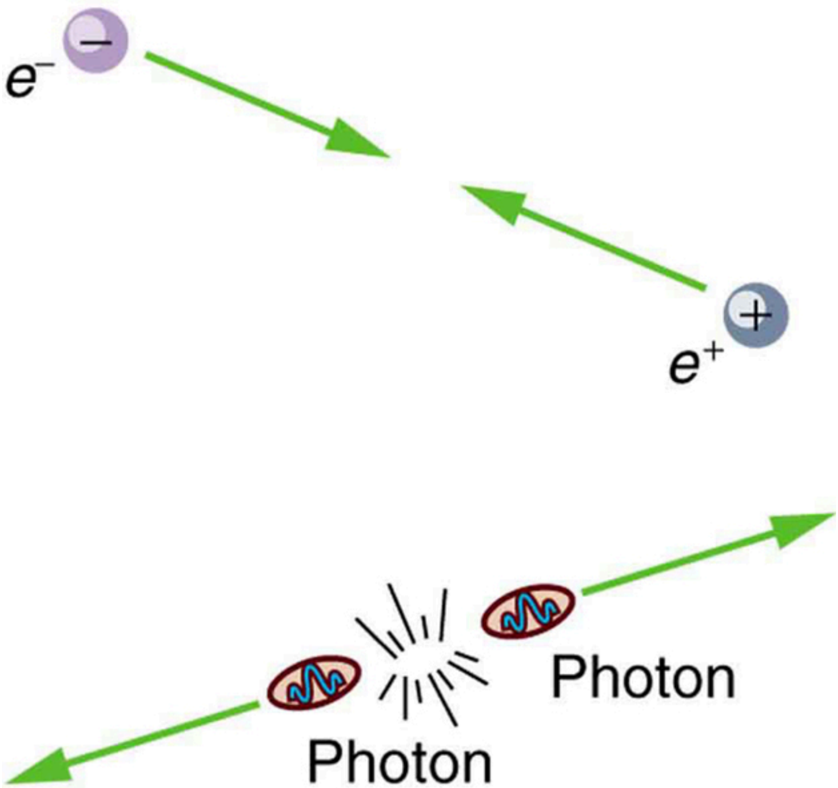
Matter and Antimatter

The positron was only the first example of antimatter. Every particle in nature has an antimatter counterpart, although some particles, like the photon, are their own antiparticles. Antimatter has charge opposite to that of matter (for example, the positron is positive while the electron is negative) but is nearly identical otherwise, having the same mass, intrinsic spin, half-life, and so on. When a particle and its antimatter counterpart interact, they annihilate one another, usually totally converting their masses to pure energy in the form of photons as seen in [Figure 2]. Neutral particles, such as neutrons, have neutral antimatter counterparts, which also annihilate when they interact. Certain neutral particles are their own antiparticle and live correspondingly short lives. For example, the neutral pion π^0 is its own antiparticle and has a half-life about 10^{-8} shorter than π^+ and π^-, which are each other's antiparticles. Without exception, nature is symmetric—all particles have antimatter counterparts. For example, antiprotons and antineutrons were first created in accelerator experiments in 1956 and the antiproton is negative. Antihydrogen atoms, consisting of an antiproton and antielectron, were observed in 1995 at CERN, too. It is possible to contain large-scale antimatter particles such as antiprotons by using electromagnetic traps that confine the particles within a magnetic field so that they don't annihilate with other particles. However, particles of the same charge repel each other, so the more particles that are contained in a trap, the more energy is needed to power the magnetic field that contains them. It is not currently possible to store a significant quantity of antiprotons. At any rate, we now see that negative charge is associated with both low-mass (electrons) and high-mass particles (antiprotons) and the apparent asymmetry is not there. But this knowledge does raise another question—why is there such a predominance of matter and so little antimatter? Possible explanations emerge later in this and the next chapter.

Hadrons and Leptons

Particles can also be revealingly grouped according to what forces they feel between them. All particles (even those that are massless) are affected by gravity, since gravity affects the space and time in which particles exist. All charged particles are affected by the electromagnetic force, as are neutral particles that have an internal distribution of charge (such as the neutron with its magnetic moment). Special names are given to particles that feel the strong and weak nuclear forces. **Hadrons** are particles that feel the strong nuclear force, whereas **leptons** are particles that do not. The proton, neutron, and the pions are examples of hadrons. The electron, positron, muons, and neutrinos are examples of leptons, the name meaning low mass. Leptons feel the weak nuclear force. In fact, all particles feel the weak nuclear force. This means that hadrons are distinguished by being able to feel both the strong and weak nuclear forces.

[Table 1] lists the characteristics of some of the most important subatomic particles, including the directly observed carrier particles for the electromagnetic and weak nuclear forces, all leptons, and some hadrons. Several hints related to an underlying substructure emerge from an examination of these particle characteristics. Note that the carrier particles are called **gauge bosons**. First mentioned in Patterns in Spectra Reveal More Quantization, a **boson** is a particle with zero or an integer value of intrinsic spin (such as $s = 0, 1, 2, \ldots$), whereas a **fermion** is a particle with a half-integer value of intrinsic spin ($s = 1/2, 3/2, \ldots$). Fermions obey the Pauli exclusion principle whereas bosons do not. All the known and conjectured carrier particles are bosons.



When a particle encounters its antiparticle, they annihilate, often producing pure energy in the form of photons. In this case, an electron and a positron convert all their mass into two identical energy rays, which move away in opposite directions to keep total momentum zero as it was before. Similar annihilations occur for other combinations of a particle with its antiparticle, sometimes producing more particles while obeying all conservation laws.

Selected Particle Characteristics[1]

Category	Particle name	Symbol	Antiparticle	Rest mass (MeV/c^2)	B	L_e	L_μ	L_τ	S	Lifetime[2] (s)
Gauge	Photon	γ	Self	0	0	0	0	0	0	Stable
Bosons	W	W^+	W^-	80.39×10^3	0	0	0	0	0	1.6×10^{-25}
	Z	Z^0	Self	91.19×10^3	0	0	0	0	0	1.32×10^{-25}
Leptons	Electron	e^-	e^+	0.511	0	±1	0	0	0	Stable
	Neutrino (*e*)	ν_e	$-\nu_e$	0(7.0eV)[3]	0	±1	0	0	0	Stable
	Muon	μ^-	μ^+	105.7	0	0	±1	0	0	2.20×10^{-6}
	Neutrino (μ)	ν_μ	$-\nu_\mu$	0(<0.27)	0	0	±1	0	0	Stable
	Tau	τ^-	τ^+	1777	0	0	0	±1	0	2.91×10^{-13}
	Neutrino (τ)	ν_τ	$-\nu_\tau$	0(<31)	0	0	0	±1	0	Stable
Hadrons (selected)										

Category	Particle name	Symbol	Antiparticle	Rest mass (MeV/c^2)	B	L_e	L_μ	L_τ	S	Lifetime[2] (s)
Mesons	Pion	π^+	π^-	139.6	0	0	0	0	0	2.60×10^{-8}
		π^0	Self	135.0	0	0	0	0	0	8.4×10^{-17}
	Kaon	K^+	K^-	493.7	0	0	0	0	± 1	1.24×10^{-8}
		K^0	$\bar{K}^0$	497.6	0	0	0	0	± 1	0.90×10^{-10}
	Eta	η^0	Self	547.9	0	0	0	0	0	2.53×10^{-19}
(many other mesons known)										
Baryons	Proton	p	$\bar{p}$	938.3	± 1	0	0	0	0	Stable[4]
	Neutron	n	$\bar{n}$	939.6	± 1	0	0	0	0	882
	Lambda	Λ^0	$\bar{\Lambda}^0$	1115.7	± 1	0	0	0	∓ 1	2.63×10^{-10}
	Sigma	Σ^+	$\bar{\Sigma}^-$	1189.4	± 1	0	0	0	∓ 1	0.80×10^{-10}
		Σ^0	$\bar{\Sigma}^0$	1192.6	± 1	0	0	0	∓ 1	7.4×10^{-20}
		Σ^-	$\bar{\Sigma}^+$	1197.4	± 1	0	0	0	∓ 1	1.48×10^{-10}
	Xi	Ξ^0	$\bar{\Xi}^0$	1314.9	± 1	0	0	0	∓ 2	2.90×10^{-10}
		Ξ^-	Ξ^+	1321.7	± 1	0	0	0	∓ 2	1.64×10^{-10}
	Omega	Ω^-	Ω^+	1672.5	± 1	0	0	0	∓ 3	0.82×10^{-10}
(many other baryons known)										

All known leptons are listed in the table given above. There are only six leptons (and their antiparticles), and they seem to be fundamental in that they have no apparent underlying structure. Leptons have no discernible size other than their wavelength, so that we know they are pointlike down to about $10^{-18}\mathrm{m}$. The leptons fall into three families, implying three conservation laws for three quantum numbers. One of these was known from β decay, where the existence of the electron's neutrino implied that a new quantum number, called the **electron family number** L_e is conserved. Thus, in β decay, an antielectron's neutrino $\bar{\nu}_e$ must be created with $L_e = -1$ when an electron with $L_e = +1$ is created, so that the total remains 0 as it was before decay.

Once the muon was discovered in cosmic rays, its decay mode was found to be

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu,$$

which implied another "family" and associated conservation principle. The particle ν_μ is a muon's neutrino, and it is created to conserve **muon family number** L_μ . So muons are leptons with a family of their own, and **conservation of total L_μ ** also seems to be obeyed in many experiments.

More recently, a third lepton family was discovered when τ particles were created and observed to decay in a manner similar to muons. One principal decay mode is

$$\tau^- \rightarrow \mu^- + \bar{\nu}_\mu + \nu_\tau.$$

Conservation of total L_τ seems to be another law obeyed in many experiments. In fact, particle experiments have found that lepton family number is not universally conserved, due to neutrino "oscillations," or transformations of neutrinos from one family type to another.

Mesons and Baryons

Now, note that the hadrons in the table given above are divided into two subgroups, called mesons (originally for medium mass) and baryons (the name originally meaning large mass). The division between mesons and baryons is actually based on their observed decay modes and is not strictly associated with their masses. **Mesons** are hadrons that can decay to leptons and leave no hadrons, which implies that mesons are not conserved in number. **Baryons** are hadrons that always decay to another baryon. A new physical quantity called **baryon number** B seems to always be conserved in nature and is listed for the various particles in the table given above. Mesons and leptons have $B = 0$ so that they can decay to other particles with $B = 0$. But baryons have $B = +1$ if they are matter, and $B = -1$ if they are antimatter. The **conservation of total baryon number** is a more general rule than first noted in nuclear physics, where it was observed that the total number of nucleons was always conserved in nuclear reactions and decays. That rule in nuclear physics is just one consequence of the conservation of the total baryon number.

Forces, Reactions, and Reaction Rates

The forces that act between particles regulate how they interact with other particles. For example, pions feel the strong force and do not penetrate as far in matter as do muons, which do not feel the strong force. (This was the way those who discovered the muon knew it could not be the particle that carries the strong force—its penetration or range was too great for it to be feeling the strong force.) Similarly, reactions that create other particles, like cosmic rays interacting with nuclei in the atmosphere, have greater probability if they are caused by the strong force than if they are caused by the weak force. Such knowledge has been useful to physicists while analyzing the particles produced by various accelerators.

The forces experienced by particles also govern how particles interact with themselves if they are unstable and decay. For example, the stronger the force, the faster they decay and the shorter is their lifetime. An example of a nuclear decay via the strong force is $^{8}\text{Be} \rightarrow \alpha + \alpha$ with a lifetime of about 10^{-16}s . The neutron is a good example of decay via the weak force. The process $n \rightarrow p + e^{-} + -\nu_e$ has a longer lifetime of 882 s. The weak force causes this decay, as it does all β decay. An important clue that the weak force is responsible for β decay is the creation of leptons, such as e^{-} and $-\nu_e$. None would be created if the strong force was responsible, just as no leptons are created in the decay of ^{8}Be . The systematics of particle lifetimes is a little simpler than nuclear lifetimes when hundreds of particles are examined (not just the ones in the table given above). Particles that decay via the weak force have lifetimes mostly in the range of 10^{-16} to 10^{-12} s, whereas those that decay via the strong force have lifetimes mostly in the range of 10^{-16} to 10^{-23} s. Turning this around, if we measure the lifetime of a particle, we can tell if it decays via the weak or strong force.

Yet another quantum number emerges from decay lifetimes and patterns. Note that the particles Λ, Σ, Ξ , and Ω decay with lifetimes on the order of 10^{-10} s (the exception is Σ^{0} , whose short lifetime is explained by its particular quark substructure.), implying that their decay is caused by the weak force alone, although they are hadrons and feel the strong force. The decay modes of these particles also show patterns—in particular, certain decays that should be possible within all the known conservation laws do not occur. Whenever something is possible in physics, it will happen. If something does not happen, it is forbidden by a rule. All this seemed strange to those studying these particles when they were first discovered, so they named a new quantum number **strangeness**, given the symbol S in the table given above. The values of strangeness assigned to various particles are based on the decay systematics. It is found that **strangeness is conserved by the strong force**, which governs the production of most of these particles in accelerator experiments. However, **strangeness is *not conserved* by the weak force**. This conclusion is reached from the fact that particles that have long lifetimes decay via the weak force and do not conserve strangeness. All of this also has implications for the carrier particles, since they transmit forces and are thus involved in these decays.

Calculating Quantum Numbers in Two Decays

(a) The most common decay mode of the Ξ^{-} particle is $\Xi^{-} \rightarrow \Lambda^{0} + \pi^{-}$. Using the quantum numbers in the table given above, show that strangeness changes by 1, baryon number and charge are conserved, and lepton family numbers are unaffected.

(b) Is the decay $K^{+} \rightarrow \mu^{+} + \nu_{\mu}$ allowed, given the quantum numbers in the table given above?

Strategy

In part (a), the conservation laws can be examined by adding the quantum numbers of the decay products and comparing them with the parent particle. In part (b), the same procedure can reveal if a conservation law is broken or not.

Solution for (a)

Before the decay, the Ξ^{-} has strangeness $S = -2$. After the decay, the total strangeness is –1 for the Λ^{0} , plus 0 for the π^{-} . Thus, total strangeness has gone from –2 to –1 or a change of +1. Baryon number for the Ξ^{-} is $B = +1$ before the decay, and after the decay the Λ^{0} has $B = +1$ and the π^{-} has $B = 0$ so that the total baryon number remains +1. Charge is –1 before the decay, and the total charge after is also $0 - 1 = -1$. Lepton numbers for all the particles are zero, and so lepton numbers are conserved.

Discussion for (a)

The Ξ^{-} decay is caused by the weak interaction, since strangeness changes, and it is consistent with the relatively long 1.64×10^{-10}-s lifetime of the Ξ^{-}.

Solution for (b)

The decay $K^{+} \rightarrow \mu^{+} + \nu_{\mu}$ is allowed if charge, baryon number, mass-energy, and lepton numbers are conserved. Strangeness can change due to the weak interaction. Charge is conserved as $s \rightarrow d$. Baryon number is conserved, since all particles have $B = 0$. Mass-energy is conserved in the sense that the K^{+} has a greater mass than the products, so that the decay can be spontaneous. Lepton family numbers are conserved at 0 for the electron and tau family for all particles. The muon family number is $L_{\mu} = 0$ before and $L_{\mu} = -1 + 1 = 0$ after. Strangeness changes from +1 before to 0 + 0 after, for an allowed change of 1. The decay is allowed by all these measures.

Discussion for (b)

This decay is not only allowed by our reckoning, it is, in fact, the primary decay mode of the K^+ meson and is caused by the weak force, consistent with the long 1.24×10^{-8}-s lifetime.

There are hundreds of particles, all hadrons, not listed in [Table 1] , most of which have shorter lifetimes. The systematics of those particle lifetimes, their production probabilities, and decay products are completely consistent with the conservation laws noted for lepton families, baryon number, and strangeness, but they also imply other quantum numbers and conservation laws. There are a finite, and in fact relatively small, number of these conserved quantities, however, implying a finite set of substructures. Additionally, some of these short-lived particles resemble the excited states of other particles, implying an internal structure. All of this jigsaw puzzle can be tied together and explained relatively simply by the existence of fundamental substructures. Leptons seem to be fundamental structures. Hadrons seem to have a substructure called quarks. Quarks: Is That All There Is? explores the basics of the underlying quark building blocks.

Murray Gell-Mann (b. 1929) proposed quarks as a substructure of hadrons in 1963 and was already known for his work on the concept of strangeness. Although quarks have never been directly observed, several predictions of the quark model were quickly confirmed, and their properties explain all known hadron characteristics. Gell-Mann was awarded the Nobel Prize in 1969. (credit: Luboš Motl)

Summary

- All particles of matter have an antimatter counterpart that has the opposite charge and certain other quantum numbers as seen in [Table 1]. These matter-antimatter pairs are otherwise very similar but will annihilate when brought together. Known particles can be divided into three major groups—leptons, hadrons, and carrier particles (gauge bosons).
- Leptons do not feel the strong nuclear force and are further divided into three groups—electron family designated by electron family number L_e ; muon family designated by muon family number L_μ ; and tau family designated by tau family number L_τ . The family numbers are not universally conserved due to neutrino oscillations.
- Hadrons are particles that feel the strong nuclear force and are divided into baryons, with the baryon family number B being conserved, and mesons.

Conceptual Questions

Large quantities of antimatter isolated from normal matter should behave exactly like normal matter. An antiatom, for example, composed of positrons, antiprotons, and antineutrons should have the same atomic spectrum as its matter counterpart. Would you be able to tell it is antimatter by its emission of antiphotons? Explain briefly.

Massless particles are not only neutral, they are chargeless (unlike the neutron). Why is this so?

Massless particles must travel at the speed of light, while others cannot reach this speed. Why are all massless particles stable? If evidence is found that neutrinos spontaneously decay into other particles, would this imply they have mass?

When a star erupts in a supernova explosion, huge numbers of electron neutrinos are formed in nuclear reactions. Such neutrinos from the 1987A supernova in the relatively nearby Magellanic Cloud were observed within hours of the initial brightening, indicating they traveled to earth at approximately the speed of light. Explain how this data can be used to set an upper limit on the mass of the neutrino, noting that if the mass is small the neutrinos could travel very close to the speed of light and have a reasonable energy (on the order of MeV).

Theorists have had spectacular success in predicting previously unknown particles. Considering past theoretical triumphs, why should we bother to perform experiments?

What lifetime do you expect for an antineutron isolated from normal matter?

Why does the η^0 meson have such a short lifetime compared to most other mesons?

(a) Is a hadron always a baryon?

(b) Is a baryon always a hadron?

(c) Can an unstable baryon decay into a meson, leaving no other baryon?

Explain how conservation of baryon number is responsible for conservation of total atomic mass (total number of nucleons) in nuclear decay and reactions.

Problems & Exercises

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

Show Solution

67.5 MeV

The primary decay mode for the negative pion is $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$. What is the energy release in MeV in this decay?

Show Solution

Strategy

The energy released in a decay is the difference between the initial mass energy and the final mass energies. From the particle tables, we need the masses of the π^- and μ^-. The muon antineutrino $\bar{\nu}_\mu$ is essentially massless. Using [Table 1], the π^- has a mass of 139.6 MeV/c^2 and the μ^- has a mass of 105.7 MeV/c^2.

Solution

The energy release is:

$$Q=(m_{\pi^-}-m_{\mu^-}-m_{\bar{\nu}_\mu})c^2$$
$$Q=(139.6-105.7-0)\text{ MeV}=33.9\text{ MeV}$$

Discussion

The decay releases 33.9 MeV of energy, which is shared between the kinetic energy of the muon and the energy carried away by the massless muon antineutrino. This represents about 24% of the pion's rest mass energy being converted into kinetic energy of the decay products. The fact that this decay is energetically favorable (positive Q-value) means it can occur spontaneously. This is the dominant decay mode of the π^-, occurring about 99.99% of the time. The energy is shared unequally between the products due to momentum conservation—since the neutrino is massless and the muon is massive, the neutrino carries away most of the energy while the muon carries most of the momentum. The muon itself is unstable and will subsequently decay via $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$, but with a much longer lifetime (2.20×10^{-6} s compared to the pion's 2.60×10^{-8} s).

The mass of a theoretical particle that may be associated with the unification of the electroweak and strong forces is $10^{14}\text{GeV}/c^2$.

(a) How many proton masses is this?

(b) How many electron masses is this? (This indicates how extremely relativistic the accelerator would have to be in order to make the particle, and how large the relativistic quantity γ would have to be.)

Show Solution

(a) 1×10^{14} (b) 2×10^{17}

The decay mode of the negative muon is $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$.

(a) Find the energy released in MeV.

(b) Verify that charge and lepton family numbers are conserved.

Show Solution

Strategy

For part (a), we need to find the mass difference between the initial and final particles. The muon mass is 105.7 MeV/c^2 and the electron mass is 0.511 MeV/c^2. Both neutrinos are essentially massless. For part (b), we check conservation of charge and the three lepton family numbers (L_e, L_μ, L_τ).

Solution

(a) The energy released is:

$$Q=(m_{\mu^-}-m_{e^-}-m_{\bar{\nu}_e}-m_{\nu_\mu})c^2$$
$$Q=(105.7-0.511-0-0)\text{ MeV}=105.2\text{ MeV}$$

(b) **Charge conservation:**

- Before: $Q=-1$ (from μ^-)
- After: $Q=-1+0+0=-1$ (from $e^-, \bar{\nu}_e, \nu_\mu$)
- Charge is conserved: $-1=-1$ ✓

Electron family number (L_e):

- Before: $L_e=0$ (muon is not in electron family)
- After: $L_e=+1-1+0=0$ (from $e^-, \bar{\nu}_e, \nu_\mu$)
- Electron family number is conserved: $0=0$ ✓

Muon family number (L_μ):

- Before: $L_\mu=+1$ (from μ^-)
- After: $L_\mu=0+0+1=+1$ (from $e^-, \bar{\nu}_e, \nu_\mu$)
- Muon family number is conserved: $+1=+1$ ✓

Tau family number (L_τ):

- Before and after: $L_\tau=0$ (no tau particles involved)
- Tau family number is conserved: $0=0$ ✓

Discussion

Nearly all of the muon's rest mass energy (105.2 out of 105.7 MeV, or 99.5%) is released in this decay, shared among the three decay products. The electron receives some kinetic energy, while the two neutrinos carry away the rest. This decay demonstrates the weak force in action—the creation of leptons and the relatively long lifetime (2.20×10^{-6} s) are characteristic of weak interactions. The conservation of lepton family numbers is a fundamental principle: the electron antineutrino is created to balance the electron family number when an electron is created, and the muon neutrino preserves the muon family number from the original muon. This decay mode has been studied extensively and provides precise tests of the Standard Model of particle physics.

The decay mode of the positive tau is $\tau^+\rightarrow\mu^++\nu_\mu+\bar{\nu}_\tau$.

(a) What energy is released?

(b) Verify that charge and lepton family numbers are conserved.

(c) The τ^+ is the antiparticle of the τ^-. Verify that all the decay products of the τ^+ are the antiparticles of those in the decay of the τ^- given in the text.

Show Solution

(a) 1671MeV (b) $Q=1, Q'=1+0+0=1. L_\tau=-1; L'_\tau=-1; L_\mu=0; L'_\mu=-1+1=0$ (c) $\tau^-\rightarrow\mu^-+\nu_\mu+\bar{\nu}_\tau \quad \Rightarrow \mu^-$ antiparticle of μ^+; ν_μ of $\bar{\nu}_\mu$; $\bar{\nu}_\tau$ of ν_τ

The principal decay mode of the sigma zero is $\Sigma^0\rightarrow\Lambda^0+\gamma$.

(a) What energy is released?

(b) Considering the quark structure of the two baryons, does it appear that the Σ^0 is an excited state of the Λ^0?

(c) Verify that strangeness, charge, and baryon number are conserved in the decay.

(d) Considering the preceding and the short lifetime, can the weak force be responsible? State why or why not.

Show Solution

Strategy

For part (a), we use the masses from [Table 1]: Σ^0 has mass 1192.6 MeV/c^2 and Λ^0 has mass 1115.7 MeV/c^2. For parts (b)-(d), we examine quark structure, conservation laws, and force characteristics.

Solution

(a) The energy released is the mass difference:

$$Q=(m_{\Sigma^0}-m_{\Lambda^0}-m_\gamma)c^2=(1192.6-1115.7-0)\text{ MeV}=76.9\text{ MeV}$$

(b) From quark tables, both Σ^0 and Λ^0 have the quark composition *uds* (one up, one down, one strange quark). Since they have identical quark content but different masses and spins, **yes, the $\boldsymbol{\Sigma^0}$ appears to be an excited state of the $\boldsymbol{\Lambda^0}$**. The extra 76.9 MeV represents the excitation energy.

(c) **Conservation checks:**

- **Strangeness:** $S=-1$ before (Σ^0), $S=-1+0=-1$ after ($\Lambda^0+\gamma$) ✓
- **Charge:** $Q=0$ before, $Q=0+0=0$ after ✓
- **Baryon number:** $B=+1$ before, $B=+1+0=+1$ after ✓

All three quantum numbers are conserved.

(d) **No, the weak force cannot be responsible** for this decay. The evidence:

1. **Strangeness is conserved**, which indicates the strong or electromagnetic force (the weak force violates strangeness conservation)
2. **The lifetime is extremely short** (7.4×10^{-20} s), characteristic of electromagnetic decay, not weak decay which typically has lifetimes of 10^{-10} s or longer
3. **A photon is emitted**, which is characteristic of an electromagnetic transition

This is an electromagnetic decay of an excited baryon state, analogous to an atomic electron transitioning to a lower energy level and emitting a photon.

Discussion

This decay is a beautiful example of how particle physics mirrors atomic physics. Just as atoms have excited states that decay by photon emission, baryons can also exist in excited states. The Σ^0 is essentially a Λ^0 with its quarks in an excited configuration—perhaps with different relative spins or orbital angular momenta. The electromagnetic force mediates the transition, conserving strangeness (unlike weak decays), and the process is very rapid (unlike weak decays). The photon carries away the 76.9 MeV excitation energy. After this electromagnetic decay, the Λ^0 itself will eventually decay via the weak force (which can change strangeness) with its much longer lifetime of 2.63×10^{-10} s.

(a) What is the uncertainty in the energy released in the decay of a π^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 π^0 mass is destroyed)?

Show Solution

(a) 3.9 eV

(b) 2.9×10^{-8}

(a) What is the uncertainty in the energy released in the decay of a τ^- due to its short lifetime?

(b) Is the uncertainty in this energy greater than or less than the uncertainty in the mass of the tau neutrino? Discuss the source of the uncertainty.

Show Solution

Strategy

For part (a), we use the Heisenberg uncertainty principle $\Delta E\Delta t\geq h4\pi$ with the lifetime of the tau from [Table 1]: $\tau=2.91\times10^{-13}$ s. For part (b), we compare this energy uncertainty to the experimental upper limit on the tau neutrino mass.

Solution

(a) Using the Heisenberg uncertainty principle:

$$\Delta E\approx h4\pi\Delta t=6.63\times10^{-34}\text{ J}\cdot\text{s}4\pi(2.91\times10^{-13}\text{ s})$$

$\Delta E \approx 6.63 \times 10^{-34} 3.66 \times 10^{-12}$ J$=1.81 \times 10^{-22}$ J

Converting to eV:

$\Delta E = 1.81 \times 10^{-22}$ J1.60×10^{-19} J/eV$= 1.13 \times 10^{-3}$ eV≈ 1.1 meV

(b) From [Table 1], the experimental upper limit on the tau neutrino mass is less than 31 MeV/c^2 = 31,000,000 eV. The uncertainty in the tau decay energy ($\sim 1.1 \times 10^{-3}$ eV) is **vastly smaller** than the uncertainty in the neutrino mass.

The ratio is:

$\Delta E_{\tau} \Delta m_{\nu_{\tau}} c^2 = 1.1 \times 10^{-3}$ eV3.1×10^{7} eV$\approx 3.5 \times 10^{-11}$

Discussion

The energy uncertainty from the tau's finite lifetime is about 1.1 millielectronvolts (meV), which is incredibly small—ten billion times smaller than the upper limit on the tau neutrino mass. This demonstrates two different sources of uncertainty:

1. **Quantum uncertainty from finite lifetime**: The tau's lifetime of 2.91×10^{-13} s leads to an intrinsic energy uncertainty via the Heisenberg principle. This is a fundamental quantum mechanical effect—short-lived particles have broader energy distributions.
2. **Experimental uncertainty in neutrino mass**: The much larger uncertainty in the neutrino mass (< 31 MeV) comes from experimental limitations in measuring such tiny masses. Neutrinos interact so weakly that determining their masses precisely is extremely challenging.

The fact that the lifetime-induced uncertainty is negligible compared to the neutrino mass uncertainty means that the tau's finite lifetime doesn't significantly hamper our ability to measure the neutrino mass—the limitation is purely experimental. Recent experiments suggest the tau neutrino mass is actually much smaller than 31 MeV, possibly even zero like its counterparts, but this remains an area of active research.

Footnotes

- 1 The lower of the $\mp$ or ± symbols are the values for antiparticles.
- 2 Lifetimes are traditionally given as $t_{1/2}/0.693$ (which is $1/\lambda$, the inverse of the decay constant).
- 3 Neutrino masses may be zero. Experimental upper limits are given in parentheses.
- 4 Experimental lower limit is $>5 \times 10^{32}$ for proposed mode of decay. { data-list-type="bulleted" data-bullet-style="none"}

Glossary

boson
: particle with zero or an integer value of intrinsic spin

baryons
: hadrons that always decay to another baryon

baryon number
: a conserved physical quantity that is zero for mesons and leptons and ± 1 for baryons and antibaryons, respectively

conservation of total baryon number
: a general rule based on the observation that the total number of nucleons was always conserved in nuclear reactions and decays

conservation of total electron family number
: a general rule stating that the total electron family number stays the same through an interaction

conservation of total muon family number
: a general rule stating that the total muon family number stays the same through an interaction

electron family number
: the number ± 1 that is assigned to all members of the electron family, or the number 0 that is assigned to all particles not in the electron family

fermion
: particle with a half-integer value of intrinsic spin

gauge boson
: particle that carries one of the four forces

hadrons
: particles that feel the strong nuclear force

leptons
: particles that do not feel the strong nuclear force

meson
: hadrons that can decay to leptons and leave no hadrons

muon family number
: the number ± 1 that is assigned to all members of the muon family, or the number 0 that is assigned to all particles not in the muon family

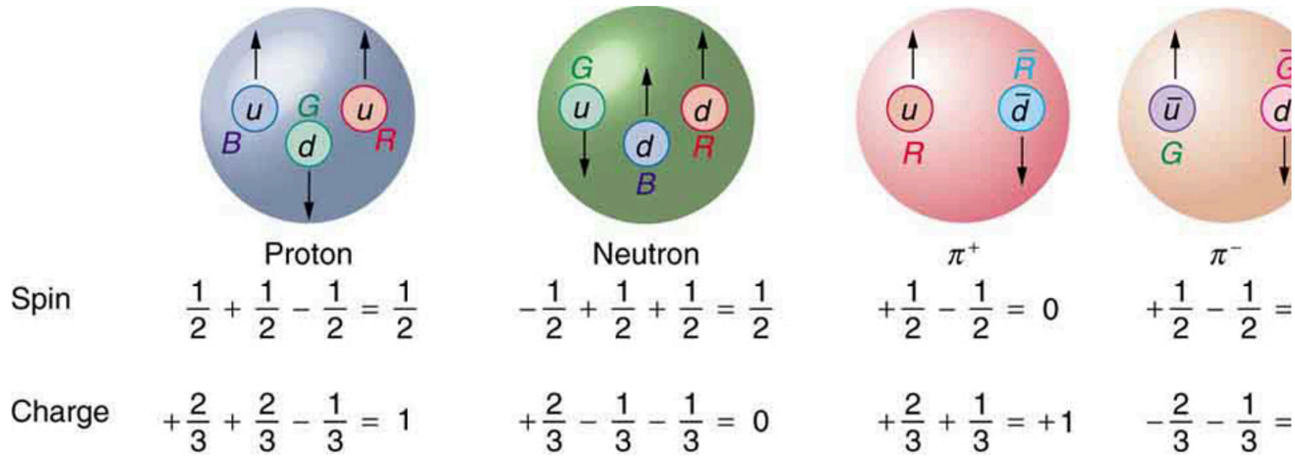
strangeness
: a physical quantity assigned to various particles based on decay systematics

tau family number
: the number ± 1 that is assigned to all members of the tau family, or the number 0 that is assigned to all particles not in the tau family

Quarks: Is That All There Is?

- Define fundamental particle.
- Describe quark and antiquark.
- List the flavors of quark.
- Outline the quark composition of hadrons.
- Determine quantum numbers from quark composition.

Quarks have been mentioned at various points in this text as fundamental building blocks and members of the exclusive club of truly elementary particles. Note that an elementary or **fundamental particle** has no substructure (it is not made of other particles) and has no finite size other than its wavelength. This does not mean that fundamental particles are stable—some decay, while others do not. Keep in mind that *all* leptons seem to be fundamental, whereas *no* hadrons are fundamental. There is strong evidence that **quarks** are the fundamental building blocks of hadrons as seen in [Figure 1]. Quarks are the second group of fundamental particles (leptons are the first). The third and perhaps final group of fundamental particles is the carrier particles for the four basic forces. Leptons, quarks, and carrier particles may be all there is. In this module we will discuss the quark substructure of hadrons and its relationship to forces as well as indicate some remaining questions and problems.



All baryons, such as the proton and neutron shown here, are composed of three quarks. All mesons, such as the pions shown here, are composed of a quark-antiquark pair. Arrows represent the spins of the quarks, which, as we shall see, are also colored. The colors are such that they need to add to white for any possible combination of quarks.

Conception of Quarks

Quarks were first proposed independently by American physicists Murray Gell-Mann and George Zweig in 1963. Their quaint name was taken by Gell-Mann from a James Joyce novel—Gell-Mann was also largely responsible for the concept and name of strangeness. (Whimsical names are common in particle physics, reflecting the personalities of modern physicists.) Originally, three quark types—or **flavors**—were proposed to account for the then-known mesons and baryons. These quark flavors are named **up** (*u*), **down** (*d*), and **strange** (*s*). All quarks have half-integral spin and are thus fermions. All mesons have integral spin while all baryons have half-integral spin. Therefore, mesons should be made up of an even number of quarks while baryons need to be made up of an odd number of quarks. [Figure 1] shows the quark substructure of the proton, neutron, and two pions. The most radical proposal by Gell-Mann and Zweig is the fractional charges of quarks, which are $\pm(23)q_e$ and $(13)q_e$, whereas all directly observed particles have charges that are integral multiples of q_e. Note that the fractional value of the quark does not violate the fact that the *e* is the smallest unit of charge that is observed, because a free quark cannot exist. [Table 1] lists characteristics of the six quark flavors that are now thought to exist. Discoveries made since 1963 have required extra quark flavors, which are divided into three families quite analogous to leptons.

How Does it Work?

To understand how these quark substructures work, let us specifically examine the proton, neutron, and the two pions pictured in [Figure 1] before moving on to more general considerations. First, the proton *p* is composed of the three quarks *uud*, so that its total charge is +(23) {q}*{e}+\left(\frac{2}{3}\right)* *{q}*{e}-\left(\frac{1}{3}\right){q}*{e}={q}*{e}

, as expected. With the spins aligned as in the figure, the proton's intrinsic spin is +(12) +(12) −(12) =(12) , also as expected. Note that the spins of the up quarks are aligned, so that they would be in the same state except that they have different colors (another quantum number to be elaborated upon a little later). Quarks obey the Pauli exclusion principle. Similar comments apply to the neutron *n*, which is composed of the three quarks *udd*. Note also that the neutron is made of charges that add to zero but move internally, producing its well-known magnetic moment. When the neutron β^- decays, it does so by changing the flavor of one of its quarks. Writing neutron β^- decay in terms of quarks,

$$n\rightarrow p+\beta^-+-\nu_e \text{ becomes } \mathrm{udd}\rightarrow \mathrm{uud}+\beta^-+-\nu_e.$$

We see that this is equivalent to a down quark changing flavor to become an up quark:

$$d\rightarrow u+\beta^-+-\nu_e$$

Quarks and Antiquarks[1]

Name	Symbol	Antiparticle	Spin	Charge	B [2]	S	c	b	t	Mass (GeV/c^2)[3]
Up	u	$-u$	1/2	$\pm 23 q_e$	± 13	0	0	0	0	0.005
Down	d	$-d$	1/2	$\mp 13 q_e$	± 13	0	0	0	0	0.008
Strange	s	$-s$	1/2	$\mp 13 q_e$	± 13	∓ 1	0	0	0	0.50
Charmed	c	$-c$	1/2	$\pm 23 q_e$	± 13	0	± 1	0	0	1.6
Bottom	b	$-b$	1/2	$\mp 13 q_e$	± 13	0	0	∓ 1	0	5
Top	t	$-t$	1/2	$\pm 23 q_e$	± 13	0	0	0	± 1	173

Quark Composition of Selected Hadrons[4]

Particle	Quark Composition
Mesons	
π^+	$u-d$
π^-	$-ud$
π^0	$u-u$, $d-d$ mixture[5]
η^0	$u-u$, $d-d$ mixture[6]
K^0	$d-s$
$-K^0$	$-ds$
K^+	$u-s$
K^-	$-us$
J/ψ	$c-c$
Υ	$b-b$
***Baryons*[7], [8]**	
p	uud
n	udd
Δ^0	udd
Δ^+	uud
Δ^-	ddd
Δ^{++}	uuu
Λ^0	uds
Σ^0	uds
Σ^+	uus
Σ^-	dds
Ξ^0	uss
Ξ^-	dss
Ω^-	sss

This is an example of the general fact that **the weak nuclear force can change the flavor of a quark**. By general, we mean that any quark can be converted to any other (change flavor) by the weak nuclear force. Not only can we get $d \rightarrow u$, we can also get $u \rightarrow d$. Furthermore, the strange quark can be changed by the weak force, too, making $s \rightarrow u$ and $s \rightarrow d$ possible. This explains the violation of the conservation of strangeness by the weak force noted in the preceding section. Another general fact is that **the strong nuclear force cannot change the flavor of a quark.**

Again, from [Figure 1], we see that the π^+ meson (one of the three pions) is composed of an up quark plus an antidown quark, or $u-d$. Its total charge is thus $+(23)q_e + (13)q_e = q_e$, as expected. Its baryon number is 0, since it has a quark and an antiquark with baryon numbers $+(13) - (13) = 0$.

The π^+ half-life is relatively long since, although it is composed of matter and antimatter, the quarks are different flavors and the weak force should cause the decay by changing the flavor of one into that of the other. The spins of the u and $-d$ quarks are antiparallel, enabling the pion to have spin zero, as observed experimentally. Finally, the π^- meson shown in [Figure 1] is the antiparticle of the π^+ meson, and it is composed of the corresponding quark antiparticles. That is, the π^+ meson is $u - d$, while the π^- meson is $-ud$. These two pions annihilate each other quickly, because their constituent quarks are each other's antiparticles.

Two general rules for combining quarks to form hadrons are:

1. Baryons are composed of three quarks, and antibaryons are composed of three antiquarks.
2. Mesons are combinations of a quark and an antiquark.

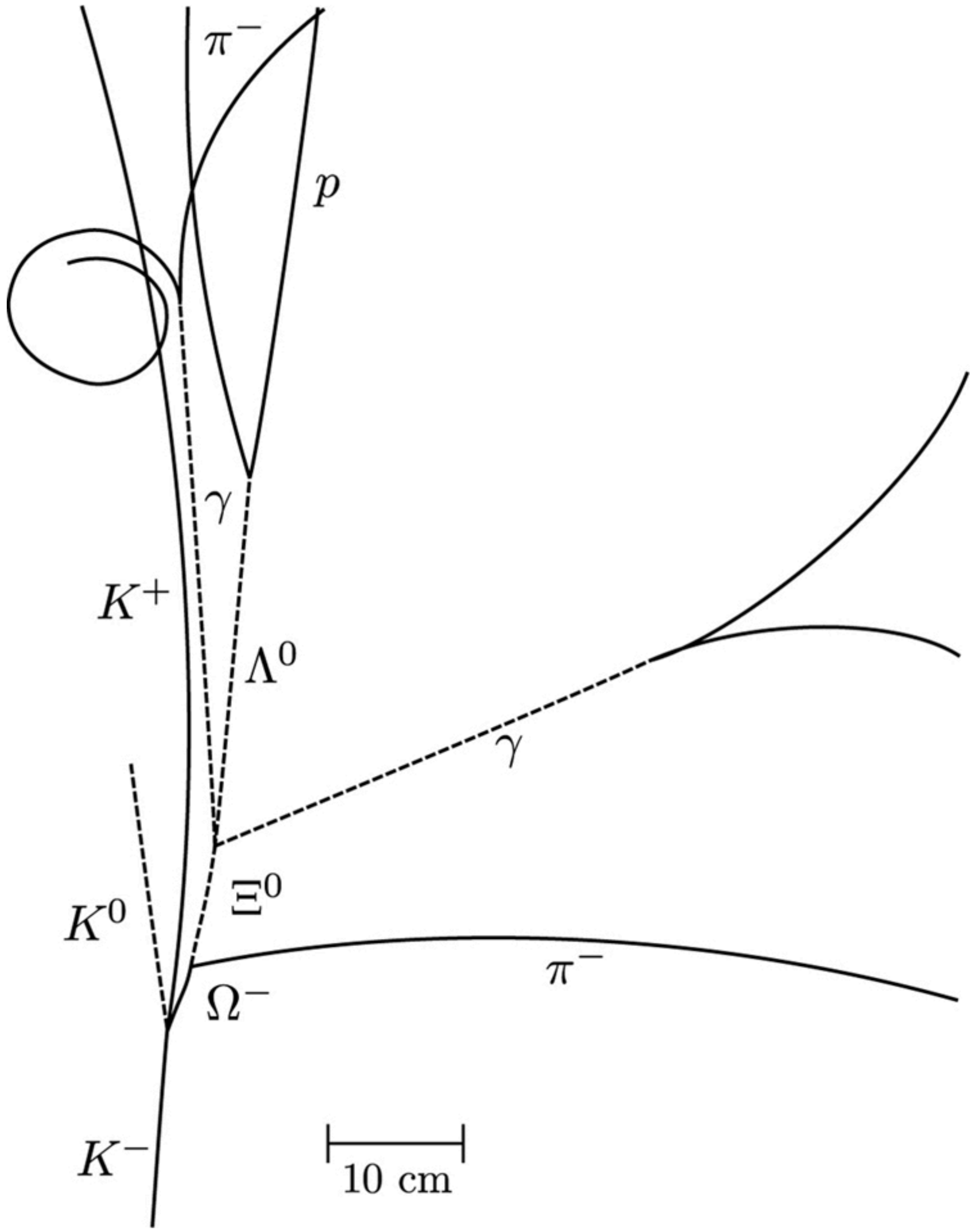
One of the clever things about this scheme is that only integral charges result, even though the quarks have fractional charge.

All Combinations are Possible

All quark combinations are possible. [Table 2] lists some of these combinations. When Gell-Mann and Zweig proposed the original three quark flavors, particles corresponding to all combinations of those three had not been observed. The pattern was there, but it was incomplete—much as had been the case in the periodic table of the elements and the chart of nuclides. The Ω^- particle, in particular, had not been discovered but was predicted by quark theory. Its combination of three strange quarks, sss , gives it a strangeness of -3 (see [Table 2]) and other predictable characteristics, such as spin, charge, approximate mass, and lifetime. If the quark picture is complete, the Ω^- should exist. It was first observed in 1964 at Brookhaven National Laboratory and had the predicted characteristics as seen in [Figure 2]. The discovery of the Ω^- was convincing indirect evidence for the existence of the three original quark flavors and boosted theoretical and experimental efforts to further explore particle physics in terms of quarks.

Patterns and Puzzles: Atoms, Nuclei, and Quarks

Patterns in the properties of atoms allowed the periodic table to be developed. From it, previously unknown elements were predicted and observed. Similarly, patterns were observed in the properties of nuclei, leading to the chart of nuclides and successful predictions of previously unknown nuclides. Now with particle physics, patterns imply a quark substructure that, if taken literally, predicts previously unknown particles. These have now been observed in another triumph of underlying unity.



The image relates to the discovery of the Ω^{-} . It is a secondary reaction in which an accelerator-produced K^{-} collides with a proton via the strong force and conserves strangeness to produce the Ω^{-} with characteristics predicted by the quark model. As with other predictions of previously unobserved particles, this gave a tremendous boost to quark theory. (credit: Brookhaven National Laboratory)

Quantum Numbers From Quark Composition

Verify the quantum numbers given for the Ξ^{0} particle in [Table 2] by adding the quantum numbers for its quark composition as given in [Table 2].

Strategy

The composition of the Ξ^{0} is given as uss in [Table 2]. The quantum numbers for the constituent quarks are given in [Table 1]. We will not consider spin, because that is not given for the Ξ^{0} . But we can check on charge and the other quantum numbers given for the quarks.

Solution

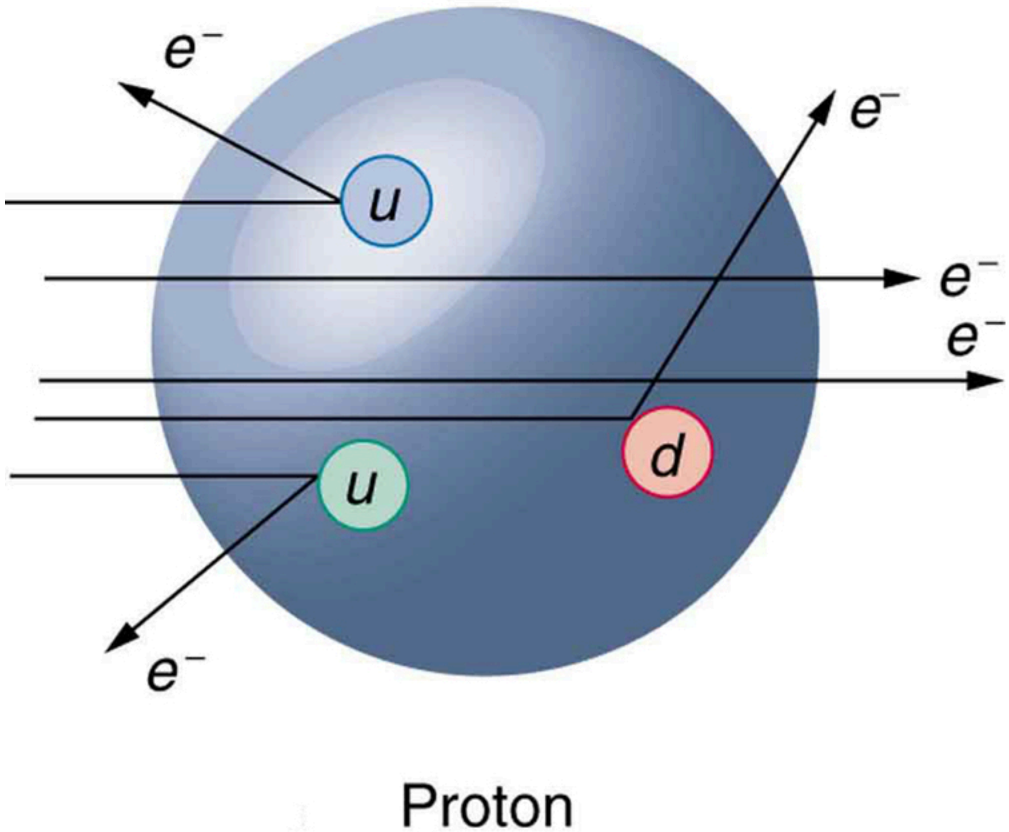
The total charge of *uss* is $+(23)q_e -(13)q_e -(13)q_e =0$, which is correct for the Ξ^{0} . The baryon number is $+(13) +(13) +(13) =1$, also correct since the Ξ^{0} is a matter baryon and has $B =1$, as listed in [Table 2]. Its strangeness is $S =0 -1 -1 =-2$, also as expected from [Table 2]. Its charm, bottomness, and topness are 0, as are its lepton family numbers (it is not a lepton).

Discussion

This procedure is similar to what the inventors of the quark hypothesis did when checking to see if their solution to the puzzle of particle patterns was correct. They also checked to see if all combinations were known, thereby predicting the previously unobserved Ω^{-} as the completion of a pattern.

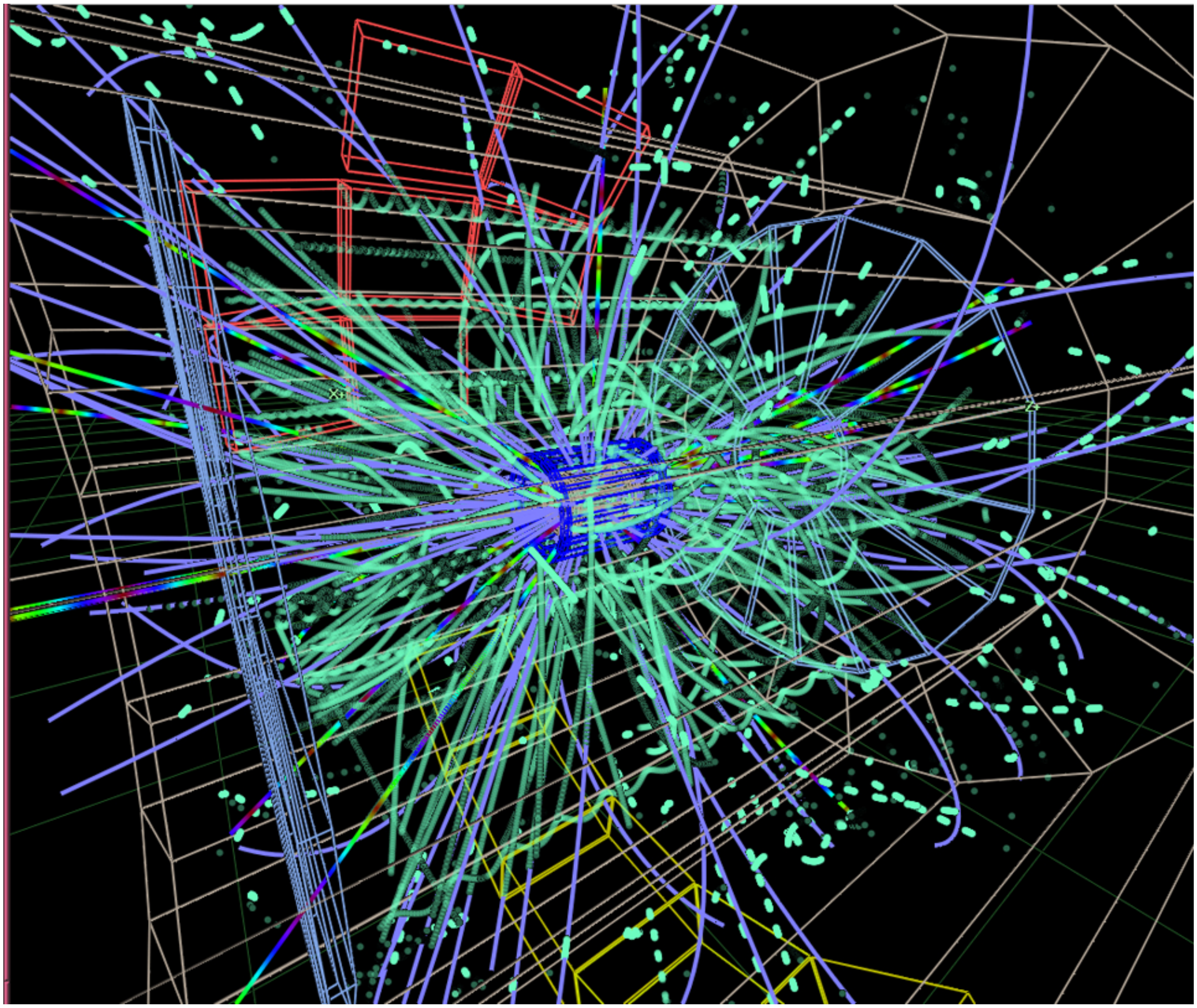
Now, Let Us Talk About Direct Evidence

At first, physicists expected that, with sufficient energy, we should be able to free quarks and observe them directly. This has not proved possible. There is still no direct observation of a fractional charge or any isolated quark. When large energies are put into collisions, other particles are created—but no quarks emerge. There is nearly direct evidence for quarks that is quite compelling. By 1967, experiments at SLAC scattering 20-GeV electrons from protons had produced results like Rutherford had obtained for the nucleus nearly 60 years earlier. The SLAC scattering experiments showed unambiguously that there were three pointlike (meaning they had sizes considerably smaller than the probe's wavelength) charges inside the proton as seen in [Figure 3]. This evidence made all but the most skeptical admit that there was validity to the quark substructure of hadrons.



Scattering of high-energy electrons from protons at facilities like SLAC produces evidence of three point-like charges consistent with proposed quark properties. This experiment is analogous to Rutherford's discovery of the small size of the nucleus by scattering \(\alpha \); particles. High-energy electrons are used so that the probe wavelength is small enough to see details smaller than the proton.

More recent and higher-energy experiments have produced jets of particles in collisions, highly suggestive of three quarks in a nucleon. Since the quarks are very tightly bound, energy put into separating them pulls them only so far apart before it starts being converted into other particles. More energy produces more particles, not a separation of quarks. Conservation of momentum requires that the particles come out in jets along the three paths in which the quarks were being pulled. Note that there are only three jets, and that other characteristics of the particles are consistent with the three-quark substructure.



Simulation of a proton-proton collision at 14-TeV center-of-mass energy in the ALICE detector at CERN LHC. The lines follow particle trajectories and the cyan dots represent the energy depositions in the sensitive detector elements. (credit: Matevž Tadel)

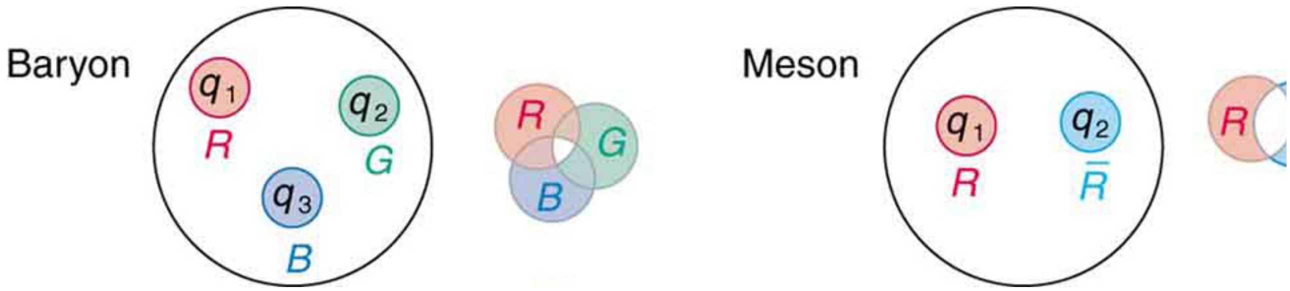
Quarks Have Their Ups and Downs

The quark model actually lost some of its early popularity because the original model with three quarks had to be modified. The up and down quarks seemed to compose normal matter as seen in [Table 2], while the single strange quark explained strangeness. Why didn't it have a counterpart? A fourth quark flavor called **charm** (*c*) was proposed as the counterpart of the strange quark to make things symmetric—there would be two normal quarks (*u* and *d*) and two exotic quarks (*s* and *c*). Furthermore, at that time only four leptons were known, two normal and two exotic. It was attractive that there would be four quarks and four leptons. The problem was that no known particles contained a charmed quark. Suddenly, in November of 1974, two groups (one headed by C. C. Ting at Brookhaven National Laboratory and the other by Burton Richter at SLAC) independently and nearly simultaneously discovered a new meson with characteristics that made it clear that its substructure is $c-c$. It was called *J* by one group and psi (ψ) by the other and now is known as the J/ψ meson. Since then, numerous particles have been discovered containing the charmed quark, consistent in every way with the quark model. The discovery of the J/ψ meson had such a rejuvenating effect on quark theory that it is now called the November Revolution. Ting and Richter shared the 1976 Nobel Prize.

History quickly repeated itself. In 1975, the tau (τ) was discovered, and a third family of leptons emerged as seen in [Table 2]). Theorists quickly proposed two more quark flavors called **top** (*t*) or truth and **bottom** (*b*) or beauty to keep the number of quarks the same as the number of leptons. And in 1976, the upsilon (Υ) meson was discovered and shown to be composed of a bottom and an antibottom quark or $b-b$, quite analogous to the J/ψ being $c-c$ as seen in [Table 2]. Being a single flavor, these mesons are sometimes called bare charm and bare bottom and reveal the characteristics of their quarks most clearly. Other mesons containing bottom quarks have since been observed. In 1995, two groups at Fermilab confirmed the top quark's existence, completing the picture of six quarks listed in [Table 1]. Each successive quark discovery—first c , then b , and finally t —has required higher energy because each has higher mass. Quark masses in [Table 1] are only approximately known, because they are not directly observed. They must be inferred from the masses of the particles they combine to form.

What's Color got to do with it?—A Whiter Shade of Pale

As mentioned and shown in [Figure 1], quarks carry another quantum number, which we call **color**. Of course, it is not the color we sense with visible light, but its properties are analogous to those of three primary and three secondary colors. Specifically, a quark can have one of three color values we call **red** (R), **green** (G), and **blue** (B) in analogy to those primary visible colors. Antiquarks have three values we call **antired or cyan** $(-R)$, **antigreen or magenta** $(-G)$, and **antiblue or yellow** $(-B)$ in analogy to those secondary visible colors. The reason for these names is that when certain visual colors are combined, the eye sees white. The analogy of the colors combining to white is used to explain why baryons are made of three quarks, why mesons are a quark and an antiquark, and why we cannot isolate a single quark. The force between the quarks is such that their combined colors produce white. This is illustrated in [Figure 5]. A baryon must have one of each primary color or RGB, which produces white. A meson must have a primary color and its anticolor, also producing white.



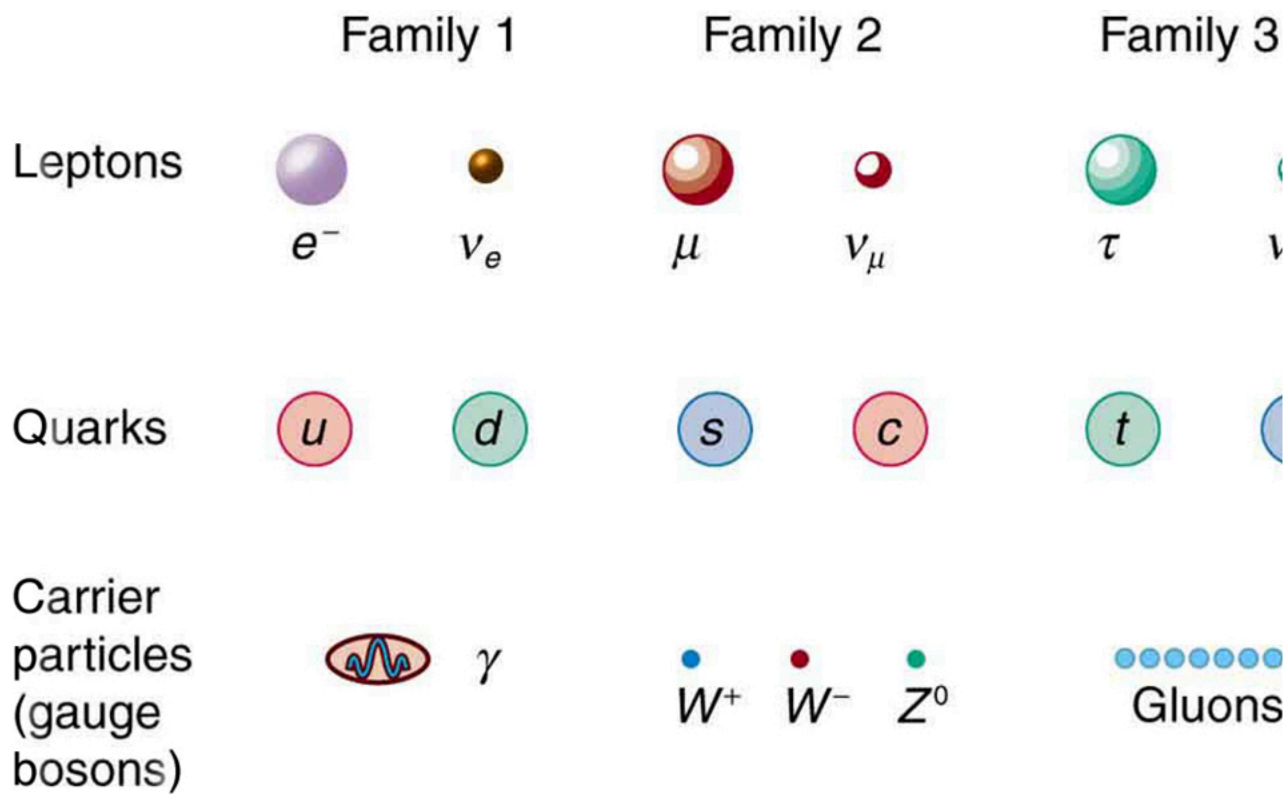
The three quarks composing a baryon must be RGB, which add to white. The quark and antiquark composing a meson must be a color and anticolor, here \(R \overline{R} \) also adding to white. The force between systems that have color is so great that they can neither be separated nor exist as colored.

Why must hadrons be white? The color scheme is intentionally devised to explain why baryons have three quarks and mesons have a quark and an antiquark. Quark color is thought to be similar to charge, but with more values. An ion, by analogy, exerts much stronger forces than a neutral molecule. When the color of a combination of quarks is white, it is like a neutral atom. The forces a white particle exerts are like the polarization forces in molecules, but in hadrons these leftovers are the strong nuclear force. When a combination of quarks has color other than white, it exerts *extremely* large forces—even larger than the strong force—and perhaps cannot be stable or permanently separated. This is part of the **theory of quark confinement**, which explains how quarks can exist and yet never be isolated or directly observed. Finally, an extra quantum number with three values (like those we assign to color) is necessary for quarks to obey the Pauli exclusion principle. Particles such as the Ω^- , which is composed of three strange quarks, sss , and the Δ^{++} , which is three up quarks, *uuu*, can exist because the quarks have different colors and do not have the same quantum numbers. Color is consistent with all observations and is now widely accepted. Quark theory including color is called **quantum chromodynamics** (QCD), also named by Gell-Mann.

The Three Families

Fundamental particles are thought to be one of three types—leptons, quarks, or carrier particles. Each of those three types is further divided into three analogous families as illustrated in [Figure 5]. We have examined leptons and quarks in some detail. Each has six members (and their six antiparticles) divided into three analogous families. The first family is normal matter, of which most things are composed. The second is exotic, and the third more exotic and more massive than the second. The only stable particles are in the first family, which also has unstable members.

Always searching for symmetry and similarity, physicists have also divided the carrier particles into three families, omitting the graviton. Gravity is special among the four forces in that it affects the space and time in which the other forces exist and is proving most difficult to include in a Theory of Everything or TOE (to stub the pretension of such a theory). Gravity is thus often set apart. It is not certain that there is meaning in the groupings shown in [Figure 6], but the analogies are tempting. In the past, we have been able to make significant advances by looking for analogies and patterns, and this is an example of one under current scrutiny. There are connections between the families of leptons, in that the τ decays into the μ and the μ into the *e*. Similarly for quarks, the higher families eventually decay into the lowest, leaving only *u* and *d* quarks. We have long sought connections between the forces in nature. Since these are carried by particles, we will explore connections between gluons, $W^{\pm}$ and Z^0 , and photons as part of the search for unification of forces discussed in GUTs: The Unification of Forces.



The three types of particles are leptons, quarks, and carrier particles. Each of those types is divided into three analogous families, with the graviton left out.

Summary

- Hadrons are thought to be composed of quarks, with baryons having three quarks and mesons having a quark and an antiquark.
- The characteristics of the six quarks and their antiquark counterparts are given in [Table 1], and the quark compositions of certain hadrons are given in [Table 2].
- Indirect evidence for quarks is very strong, explaining all known hadrons and their quantum numbers, such as strangeness, charm, topness, and bottomness.
- Quarks come in six flavors and three colors and occur only in combinations that produce white.
- Fundamental particles have no further substructure, not even a size beyond their de Broglie wavelength.
- There are three types of fundamental particles—leptons, quarks, and carrier particles. Each type is divided into three analogous families as indicated in [Figure 6].

Conceptual Questions

The quark flavor change $d \rightarrow u$ takes place in β^- decay. Does this mean that the reverse quark flavor change $u \rightarrow d$ takes place in β^+ decay? Justify your response by writing the decay in terms of the quark constituents, noting that it looks as if a proton is converted into a neutron in β^+ decay.

Explain how the weak force can change strangeness by changing quark flavor.

Beta decay is caused by the weak force, as are all reactions in which strangeness changes. Does this imply that the weak force can change quark flavor? Explain.

Why is it easier to see the properties of the *c*, *b*, and *t* quarks in mesons having composition W^- or $t - t$ rather than in baryons having a mixture of quarks, such as *udb*?

How can quarks, which are fermions, combine to form bosons? Why must an even number combine to form a boson? Give one example by stating the quark substructure of a boson.

What evidence is cited to support the contention that the gluon force between quarks is greater than the strong nuclear force between hadrons? How is this related to color? Is it also related to quark confinement?

Discuss how we know that π-mesons (π^+, π, π^0) are not fundamental particles and are not the basic carriers of the strong force.

An antibaryon has three antiquarks with colors $-R-G-B$. What is its color?

Suppose leptons are created in a reaction. Does this imply the weak force is acting? (for example, consider β decay.)

How can the lifetime of a particle indicate that its decay is caused by the strong nuclear force? How can a change in strangeness imply which force is responsible for a reaction? What does a change in quark flavor imply about the force that is responsible?

(a) Do all particles having strangeness also have at least one strange quark in them?

(b) Do all hadrons with a strange quark also have nonzero strangeness?

The sigma-zero particle decays mostly via the reaction $\Sigma^0 \to \Lambda^0 + \gamma$. Explain how this decay and the respective quark compositions imply that the Σ^0 is an excited state of the Λ^0.

What do the quark compositions and other quantum numbers imply about the relationships between the Δ^+ and the proton? The Δ^0 and the neutron?

Discuss the similarities and differences between the photon and the Z^0 in terms of particle properties, including forces felt.

Identify evidence for electroweak unification.

The quarks in a particle are confined, meaning individual quarks cannot be directly observed. Are gluons confined as well? Explain

Problems & Exercises

(a) Verify from its quark composition that the Δ^+ particle could be an excited state of the proton.

(b) There is a spread of about 100 MeV in the decay energy of the Δ^+ , interpreted as uncertainty due to its short lifetime. What is its approximate lifetime?

(c) Does its decay proceed via the strong or weak force?

Show Solution

(a) The uud composition is the same as for a proton.

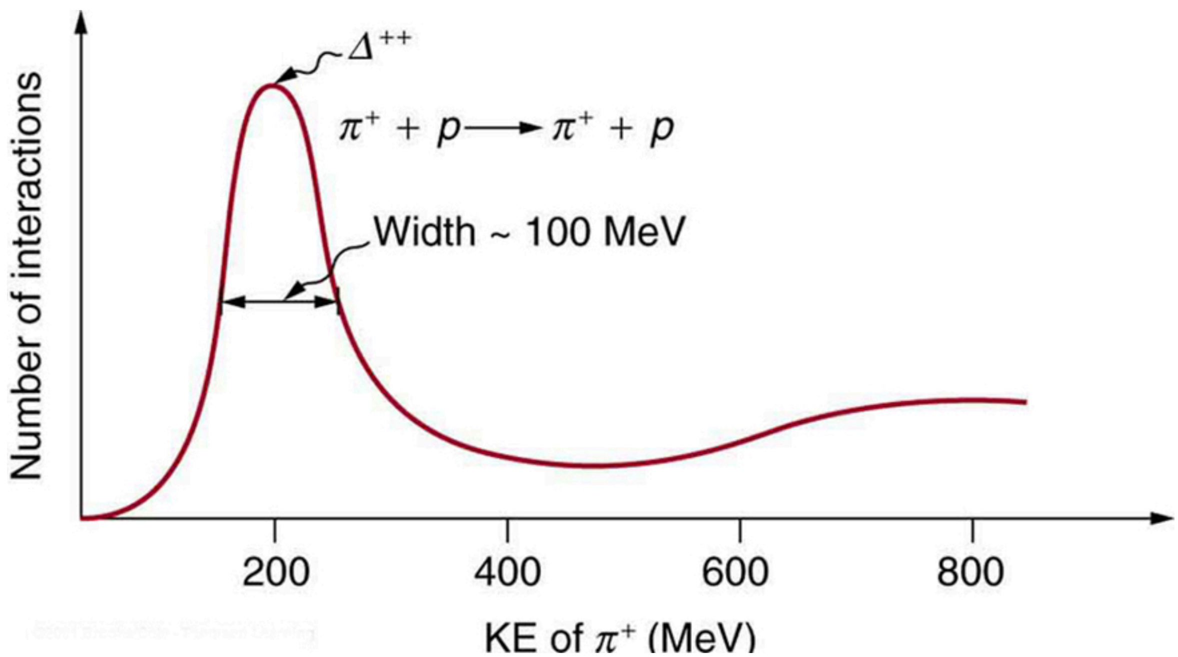
(b) $3.3 \times 10^{-24}\,\mathrm{s}$ (c) Strong (short lifetime)

Accelerators such as the Triangle Universities Meson Facility (TRIUMF) in British Columbia produce secondary beams of pions by having an intense primary proton beam strike a target. Such “meson factories” have been used for many years to study the interaction of pions with nuclei and, hence, the strong nuclear force. One reaction that occurs is $\pi^+ + p \to \Delta^{++} \to \pi^+ + p$, where the Δ^{++} is a very short-lived particle. The graph in [Figure 6] shows the probability of this reaction as a function of energy. The width of the bump is the uncertainty in energy due to the short lifetime of the Δ^{++}.

(a) Find this lifetime.

(b) Verify from the quark composition of the particles that this reaction annihilates and then re-creates a *d* quark and a $-d$ antiquark by writing the reaction and decay in terms of quarks.

(c) Draw a Feynman diagram of the production and decay of the Δ^{++} showing the individual quarks involved.



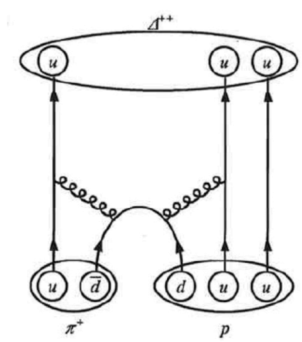
This graph shows the probability of an interaction between a \(\pi^{+} \) and a proton as a function of energy. The bump is interpreted as a very short lived particle called a \(\Delta^{++} \). The approximately 100-MeV width of the bump is due to the short lifetime of the \(\Delta^{++} \).;

The reaction $\pi^+ + p \rightarrow \Delta^{++}$ (described in the preceding problem) takes place via the strong force. (a) What is the baryon number of the Δ^{++} particle?

(b) Draw a Feynman diagram of the reaction showing the individual quarks involved.

Show Solution

a) Δ^{++}(uuu); $B = 13 + 13 + 13 = 1$ b)



One of the decay modes of the omega minus is $\Omega^- \rightarrow \Xi^0 + \pi^-$.

(a) What is the change in strangeness?

(b) Verify that baryon number and charge are conserved, while lepton numbers are unaffected.

(c) Write the equation in terms of the constituent quarks, indicating that the weak force is responsible.

Show Solution

Strategy

We'll use the quantum numbers from the particle tables and quark compositions. From [Table 2], Ω^- has $S = -3$, Ξ^0 has $S = -2$, and π^- has $S = 0$. The quark compositions are: Ω^- is *sss*, Ξ^0 is *uss*, and π^- is $\bar{u}d$.

Solution

(a) The change in strangeness is:

$\Delta S = S_{\text{final}} - S_{\text{initial}} = (S_{\Xi^0} + S_{\pi^-}) - S_{\Omega^-} = (-2+0) - (-3) = +1$

(b) **Baryon number:**

- Before: $B = +1$ (Ω^- is a baryon)
- After: $B = +1 + 0 = +1$ (Ξ^0 is a baryon, π^- is a meson)
- Baryon number is conserved ✓

Charge:

- Before: $Q = -1$ (Ω^-)
- After: $Q = 0 + (-1) = -1$ ($\Xi^0 + \pi^-$)
- Charge is conserved ✓

Lepton numbers:

- All lepton numbers (L_e, L_μ, L_τ) are zero before and after (no leptons involved)
- Lepton numbers are unaffected ✓

(c) In terms of quark constituents:

$\text{sss} \to \text{uss} + \bar{u}d$

This can be rewritten to show the quark flavor change:

$\text{sss} \to \text{us(s)} + \bar{u}d \Rightarrow s \to u + \bar{u} + d$

The weak force is responsible because strangeness changes by 1, indicating a quark flavor change from strange to up and down quarks.

Discussion

This decay clearly demonstrates the weak force at work. The change in strangeness ($\Delta S = +1$) is a signature of the weak interaction—neither the strong nor electromagnetic forces can change strangeness. At the quark level, one of the three strange quarks in the Ω^- transforms into an up quark (creating the Ξ^0), while simultaneously creating an up-antiup quark-antiquark pair along with a down quark (forming the π^-). The relatively long lifetime of the Ω^- (0.82×10^{-10} s) is also consistent with weak decay, being many orders of magnitude longer than strong force decays (typically 10^{-23} to 10^{-16} s). This decay mode occurs about 68% of the time, making it one of the dominant decay channels for the omega minus.

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

Show Solution

(a) +1 (b) $B = 1 = 1 + 0, Z = 0 + (-1)$, all lepton numbers are 0 before and after

(c) $(\text{sss}) \to (\text{uds}) + (\stackrel{-}{u}s)$

One decay mode for the eta-zero meson is $\eta^0 \to \gamma + \gamma$. (a) Find the energy released.

(b) What is the uncertainty in the energy due to the short lifetime?

(c) Write the decay in terms of the constituent quarks.

(d) Verify that baryon number, lepton numbers, and charge are conserved.

Show Solution

Strategy

From [Table 1], the η^0 has mass 547.9 MeV/c^2 and lifetime 2.53×10^{-19} s. The photons are massless. For part (b), we'll use the Heisenberg uncertainty principle.

Solution

(a) Since the η^0 decays completely into two photons, all its rest mass energy is released:

$$E = m_{\eta^0} c^2 = 547.9 \text{ MeV}$$

Each photon carries half the energy (by momentum conservation, since the η^0 is at rest):

E_γ=547.92=274.0 MeV per photon

(b) Using the Heisenberg uncertainty principle:

$\Delta E \approx h 4\pi \Delta t$=6.63×10^{-34} J·s4$\pi$(2.53×10^{-19} s)=2.09×10^{-16} J

Converting to eV:

ΔE=2.09×10^{-16} J1.60×10^{-19} J/eV=1.31×10^{3} eV=1.31 keV

(c) From [Table 2], the η^0 is a mixture of u—u and d—d. The decay in terms of quarks is:

$(u—u+d—d) \to \gamma+\gamma$

The quark-antiquark pairs annihilate to produce the two photons.

(d) **Conservation checks:**

- **Baryon number:** $B=0$ before and after (mesons and photons have $B=0$) ✓
- **Lepton numbers:** All lepton numbers are zero before and after ✓
- **Charge:** $Q=0$ before and after ✓

Discussion

This two-photon decay is characteristic of the η^0 being its own antiparticle. The particle-antiparticle pair (quark and antiquark) annihilate completely, converting all the rest mass into electromagnetic energy. The energy uncertainty of 1.31 keV is tiny compared to the total energy of 547.9 MeV (about 0.0002%), showing that the short lifetime introduces only a small uncertainty in the energy. This decay proceeds via the electromagnetic force, as evidenced by the photon production and the relatively short (but not extremely short) lifetime of 2.53×10^{-19} s. Compare this to $\pi^0 \to \gamma + \gamma$ with an even shorter lifetime of 8.4×10^{-17} s—both are electromagnetic decays of neutral mesons that are their own antiparticles.

One decay mode for the eta-zero meson is $\eta^0 \to \pi^0 + \pi^0$.

(a) Write the decay in terms of the quark constituents.

(b) How much energy is released?

(c) What is the ultimate release of energy, given the decay mode for the pi zero is $\pi^0 \to \gamma + \gamma$?

Show Solution

(a) $(u-u+d—d) \to (u-u+d—d) + (u-u+d—d)$ (b) 277.9 MeV

(c) 547.9 MeV

Is the decay $n \to e^+ + e^-$ possible considering the appropriate conservation laws? State why or why not.

Show Solution

Strategy

We need to check all relevant conservation laws: charge, baryon number, lepton family numbers, and energy.

Solution

No, this decay is not possible. It violates multiple conservation laws:

Charge conservation:

- Before: $Q=0$ (neutron is neutral)
- After: $Q=+1+(-1)=0$
- Charge is conserved ✓ (but this alone isn't sufficient)

Baryon number conservation:

- Before: $B=+1$ (neutron is a baryon)
- After: $B=0+0=0$ (electrons are leptons, not baryons)
- **Baryon number is NOT conserved ✗**

Electron family number (L_e):

- Before: $L_e = 0$ (neutron is not a lepton)
- After: $L_e = -1 + 1 = 0$ (positron has $L_e = -1$, electron has $L_e = +1$)
- Electron family number is conserved ✓ (but not enough)

Discussion

This decay violates baryon number conservation, which is one of the most fundamental conservation laws in particle physics. **Baryon number has never been observed to be violated in any experiment.** The neutron is a baryon ($B = +1$), and this quantum number must be preserved in any decay. Electrons and positrons are leptons ($B = 0$), so the final state has zero baryon number. This means a baryon would simply disappear, which is forbidden.

The actual decay mode of a free neutron is $n \to p + e^- + \overline{\nu}_e$, which conserves baryon number (both neutron and proton have $B = +1$). Grand Unified Theories (GUTs) do predict extremely rare baryon number violation in processes like proton decay ($p \to \pi^0 + e^+$), but with lifetimes exceeding 10^{31} years—far longer than the age of the universe. No such violation has ever been observed experimentally. The conservation of baryon number is why the total number of nucleons (protons plus neutrons) remains constant in nuclear reactions, a fact that was discovered long before the concept of baryon number was formulated.

Is the decay $\mu^- \to e^- + \nu_e + \nu_\mu$ possible considering the appropriate conservation laws? State why or why not.

Show Solution

No. $\text{Charge} = -1$ is conserved. $L_{e_\text{i}} = 0 \neq L_{e_\text{f}} = 2$ is not conserved. $L_\mu = 1$ is conserved.

(a) Is the decay $\Lambda^0 \to n + \pi^0$ possible considering the appropriate conservation laws? State why or why not.

(b) Write the decay in terms of the quark constituents of the particles.

Show Solution

Strategy

We'll check all relevant conservation laws and examine the quark compositions. From the tables: Λ^0 is *uds*, neutron *n* is *udd*, and π^0 is $u\overline{u} + d\overline{d}$.

Solution

(a) **Yes, this decay is possible.** Let's verify all conservation laws:

Charge:

- Before: $Q = 0$ (Λ^0 is neutral)
- After: $Q = 0 + 0 = 0$ (neutron and π^0 are both neutral)
- Charge is conserved ✓

Baryon number:

- Before: $B = +1$ (Λ^0 is a baryon)
- After: $B = +1 + 0 = +1$ (neutron is a baryon, pion is a meson)
- Baryon number is conserved ✓

Strangeness:

- Before: $S = -1$ (Λ^0 has one strange quark)
- After: $S = 0 + 0 = 0$ (neither neutron nor π^0 have strangeness)
- **Strangeness changes by +1**, indicating weak force

Lepton numbers:

- All lepton family numbers are zero before and after ✓

Energy:

- $m_{\Lambda^0} = 1115.7\ \text{MeV}/c^2$, $m_n = 939.6\ \text{MeV}/c^2$, $m_{\pi^0} = 135.0\ \text{MeV}/c^2$
- Total final mass: $939.6 + 135.0 = 1074.6\ \text{MeV}/c^2 < 1115.7\ \text{MeV}/c^2$
- Energy is conserved (spontaneous decay, releases 41.1 MeV) ✓

(b) In terms of quark constituents:

uds $\rightarrow$ udd+(u—u+d—d)

This shows that the strange quark changes to a down quark, consistent with the weak force: $s \rightarrow d$.

Discussion

This decay is allowed and does occur in nature, proceeding via the weak force. The key signature is the change in strangeness (ΔS =+1), which can only occur through weak interactions. The quark-level process involves the strange quark transforming into a down quark via emission of a W^+ boson (the carrier of the weak force), which then creates quark-antiquark pairs that form the π^0. The relatively long lifetime of the Λ^0 (2.63×10^{-10} s) is characteristic of weak decay—much longer than strong force decays but shorter than typical beta decay. This is actually one of the dominant decay modes of the Λ^0, occurring about 36% of the time. The energy release of 41.1 MeV is shared between the kinetic energies of the neutron and pion.

(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.

Show Solution

(a)Yes. $Z = -1 = 0 + (-1)$, $B = 1 = 1 + 0$, all lepton family numbers are 0 before and after, spontaneous since mass greater before reaction.

(b) dds $\rightarrow$ udd+$-ud$

The only combination of quark colors that produces a white baryon is *RGB*. Identify all the color combinations that can produce a white meson.

Show Solution

Strategy

Mesons consist of a quark-antiquark pair. For a meson to be “white” (color neutral), the antiquark must carry the anticolor of the quark’s color. This is analogous to how a color and its complement make white in the RGB color model.

Solution

The color combinations that produce a white meson are:

1. **Red quark + Antired antiquark:** R—R
2. **Green quark + Antigreen antiquark:** G—G
3. **Blue quark + Antiblue antiquark:** B—B

Discussion

In quantum chromodynamics (QCD), color charge works differently than regular electric charge. While baryons require all three colors (RGB) to be colorless (white), mesons achieve color neutrality through color-anticolor pairs. This is similar to how a particle and its antiparticle have opposite charges that cancel. The three combinations listed above are the only ways to make a colorless meson.

It’s important to note that “color” in QCD is just a label for a type of charge—quarks don’t actually have visible color. The terminology comes from the mathematical similarity to how red, green, and blue light combine to make white light. Just as RGB combine to white, the three color charges in a baryon combine to be colorless. And just as red light plus “anti-red” (cyan) makes white, a red quark plus an antired antiquark makes a colorless meson.

This color neutrality requirement is fundamental to quark confinement—all observable hadrons must be color neutral (“white”). Individual colored quarks or gluons cannot exist in isolation, which is why we never observe free quarks despite their being the fundamental constituents of matter. Any meson in nature will be in one of these three color states (though quantum mechanically, it’s actually a superposition of all three), ensuring it remains colorless and observable.

(a) Three quarks form a baryon. How many combinations of the six known quarks are there if all combinations are possible?

(b) This number is less than the number of known baryons. Explain why.

Show Solution

(a) 216

(b) There are more baryons observed because we have the 6 antiquarks and various mixtures of quarks (as for the π-meson) as well.

(a) Show that the conjectured decay of the proton, $p \rightarrow \pi^0 + e^+$, violates conservation of baryon number and conservation of lepton number.

(b) What is the analogous decay process for the antiproton?

Show Solution

Strategy

We’ll check baryon number and lepton family number conservation for this conjectured decay predicted by Grand Unified Theories (GUTs).

Solution

(a) **Baryon number violation:**

- Before: $B = +1$ (proton is a baryon)
- After: $B = 0 + 0 = 0$ (π^0 is a meson, e^+ is a lepton)
- **Baryon number changes from +1 to 0** (violated by 1 unit) ✗

Electron family number violation:

- Before: $L_e = 0$ (proton is not a lepton)
- After: $L_e = -1 + 0 = -1$ (positron has $L_e = -1$, π^0 has $L_e = 0$)
- **Electron family number changes from 0 to -1** (violated by 1 unit) ✗

Note that charge IS conserved: $Q = +1$ before and $Q = 0 + 1 = +1$ after.

(b) For the antiproton, the analogous decay would be:

$$—p \rightarrow \pi^0 + e^-$$

In this case:

- Baryon number: $B = -1 \rightarrow 0$ (violation)
- Electron family number: $L_e = 0 \rightarrow +1$ (violation)
- Charge: $Q = -1 \rightarrow 0 + (-1) = -1$ (conserved)

Discussion

This hypothetical proton decay is forbidden by the conservation laws that have been observed to hold in all experiments to date. However, **Grand Unified Theories predict that baryon and lepton number conservation are not absolute** at extremely high energies where the forces unify. GUTs predict proton lifetimes of about 10^{31} years or longer—far exceeding the age of the universe ($\sim 10^{10}$ years).

Extensive experiments have searched for proton decay using huge tanks of water instrumented with detectors. Despite monitoring trillions of protons for years, no confirmed proton decay has been observed, placing the experimental lower limit on the proton lifetime at greater than 5×10^{32} years. This doesn't disprove GUTs but does constrain their parameters.

If protons could decay rapidly, all matter would be unstable—atoms would disintegrate, and the universe as we know it couldn't exist. The extraordinary stability of the proton (and hence all atomic nuclei) is one of the most important facts about our universe. The search for proton decay continues, as observing it would be revolutionary evidence for grand unification and would fundamentally change our understanding of matter's ultimate fate.

Verify the quantum numbers given for the Ω^+ in [Table 2] by adding the quantum numbers for its quark constituents as inferred from [Table 2].

Show Solution

$$\Omega^+(-s-s-s) \quad B=-13-13-13=-1, \quad L_{e,\mu,\tau}=0+0+0=0, \quad Q=13+13+13=1, \quad S=1+1+1=3.$$

Verify the quantum numbers given for the proton and neutron in [Table 2] by adding the quantum numbers for their quark constituents as given in [Table 2].

Show Solution

Strategy

We'll add the quantum numbers (charge Q, baryon number B, and strangeness S) for the constituent quarks of the proton (*uud*) and neutron (*udd*), using values from [Table 1] in this section.

Solution

Proton (p = uud):

From [Table 1], for each quark:

- Up quark (u): $Q = +23q_e$, $B = +13$, $S = 0$
- Down quark (d): $Q = -13q_e$, $B = +13$, $S = 0$

For the proton (two up quarks, one down quark):

$$Q_p=23+23-13=33=+1 \text{ (in units of } q_e)$$
$$B_p=13+13+13=+1$$

$S_p = 0+0+0 = 0$

Lepton numbers: $L_e = L_\mu = L_\tau = 0$ (quarks are not leptons)

These match the values in the particle tables: $Q = +1$, $B = +1$, $S = 0$ ✓

Neutron (n = udd):

For the neutron (one up quark, two down quarks):

$Q_n = 23 - 13 - 13 = 0$
$B_n = 13 + 13 + 13 = +1$
$S_n = 0+0+0 = 0$

Lepton numbers: $L_e = L_\mu = L_\tau = 0$

These match the values in the particle tables: $Q = 0$, $B = +1$, $S = 0$ ✓

Discussion

This verification demonstrates the power of the quark model. The quantum numbers of composite particles (hadrons) are simply the sums of their constituent quark quantum numbers. The fractional charges of quarks ($\pm 23 q_e$ and $\mp 13 q_e$) combine to give integral charges for all observable particles—this was initially a radical proposal by Gell-Mann and Zweig, but it has been completely vindicated by experiment.

The difference between a proton and neutron is simply one quark: swapping one up quark for a down quark changes the charge from +1 to 0, converting a proton into a neutron. This is exactly what happens in beta-minus decay at the quark level: $d \rightarrow u + e^- + \bar{\nu}_e$. The fact that both have $B = +1$ explains why baryon number is conserved in nuclear reactions—at the quark level, the number of quarks minus antiquarks remains constant. This beautifully explains the empirical observation that the total number of nucleons is conserved in nuclear reactions and decays.

(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 π^0 decays to two γ 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)?

Show Solution

(a)803 MeV

(b) 938.8 MeV

(c) The annihilation energy of an extra electron is included in the total energy.

(a) Find the charge, baryon number, strangeness, charm, and bottomness of the J/Ψ particle from its quark composition.

(b) Do the same for the Υ particle.

Show Solution

Strategy

From [Table 2], the J/Ψ has quark composition $c\bar{c}$ (charm-anticharm) and the Υ has composition $b\bar{b}$ (bottom-antibottom). We'll add the quantum numbers from [Table 1].

Solution

(a) **J/Ψ particle ($c\bar{c}$):**

From [Table 1]:

- Charm quark (c): $Q = +23 q_e$, $B = +13$, $S = 0$, $c = +1$, $b = 0$
- Anticharm quark ($\bar{c}$): $Q = -23 q_e$, $B = -13$, $S = 0$, $c = -1$, $b = 0$

For J/Ψ:

- **Charge:** $Q = +23 - 23 = 0$
- **Baryon number:** $B = +13 - 13 = 0$
- **Strangeness:** $S = 0 + 0 = 0$
- **Charm:** $c = +1 - 1 = 0$

- **Bottomness:** $b = 0 + 0 = 0$

(b) **Υ particle (b—b):**

From [Table 1]:

- Bottom quark (b): $Q = -13q_e$, $B = +13$, $S = 0$, $c = 0$, $b = -1$
- Antibottom quark (—b): $Q = +13q_e$, $B = -13$, $S = 0$, $c = 0$, $b = +1$

For Υ:

- **Charge:** $Q = -13 + 13 = 0$
- **Baryon number:** $B = +13 - 13 = 0$
- **Strangeness:** $S = 0 + 0 = 0$
- **Charm:** $c = 0 + 0 = 0$
- **Bottomness:** $b = -1 + 1 = 0$

Discussion

Both the J/Ψ and Υ are examples of **hidden flavor mesons**—they contain a heavy quark and its own antiquark, so the net flavor quantum number is zero. Despite being made of charmed quarks, the J/Ψ has zero net charm; similarly, the Υ has zero net bottomness.

These particles are particularly important in particle physics history. The J/Ψ (discovered independently by two teams in 1974, hence the double name) was the first particle containing charm quarks to be discovered, providing crucial evidence for the quark model and specifically for the existence of the charm quark. Its discovery is known as the “November Revolution” in particle physics and led to Nobel Prizes for Burton Richter and Samuel Ting in 1976.

The Υ (discovered in 1977) similarly provided the first evidence for the existence of the bottom quark. Both particles are relatively long-lived for their masses because their decay requires the annihilation of the heavy quark-antiquark pair or a flavor-changing weak interaction. These particles and their excited states have been extensively studied and provide a testing ground for quantum chromodynamics (QCD), analogous to how hydrogen atom spectroscopy tested quantum electrodynamics (QED).

There are particles called *D*-mesons. One of them is the D^+ meson, which has a single positive charge and a baryon number of zero, also the value of its strangeness, topness, and bottomness. It has a charm of $+1$. What is its quark configuration?

Show Solution

c—d

There are particles called bottom mesons or *B*-mesons. One of them is the B^- meson, which has a single negative charge; its baryon number is zero, as are its strangeness, charm, and topness. It has a bottomness of -1. What is its quark configuration?

Show Solution

Strategy

We need to find a quark-antiquark combination (since it’s a meson with $B = 0$) that gives $Q = -1$, $S = 0$, $c = 0$, $t = 0$, and $b = -1$. From [Table 1], the bottom quark has $b = -1$.

Solution

Since the B^- has bottomness $b = -1$, it must contain one bottom quark. From [Table 1], the bottom quark has:

- $Q = -13q_e$
- $b = -1$

To make a meson with total charge $Q = -1$, we need an antiquark with charge $-23q_e$. The only antiquark with this charge is the anti-up quark (—u), which has:

- $Q = -23q_e$
- $S = 0$, $c = 0$, $b = 0$, $t = 0$

The quark configuration is:

$B^- = b$—u

Verification:

- Charge: $Q = -13 - 23 = -1$ ✓
- Baryon number: $B = +13 - 13 = 0$ ✓
- Strangeness: $S = 0 + 0 = 0$ ✓
- Charm: $c = 0 + 0 = 0$ ✓
- Topness: $t = 0 + 0 = 0$ ✓
- Bottomness: $b = -1 + 0 = -1$ ✓

Discussion

The B^{-} meson consists of a bottom quark and an anti-up antiquark. This is an example of an “open flavor” meson, where the heavy quark (bottom) is paired with a light antiquark rather than with its own antiparticle. Unlike the Υ particle (b—b) which has hidden bottom, the B^{-} has explicit bottomness of -1.

B-mesons are particularly important in modern particle physics research. They are produced copiously in particle colliders and are extensively studied in dedicated “B-factory” experiments like BaBar and Belle. These experiments have made precise measurements of CP violation (matter-antimatter asymmetry) in B-meson decays, helping to explain why our universe contains more matter than antimatter. The 2008 Nobel Prize in Physics was awarded to Kobayashi and Maskawa for their work predicting CP violation in systems with three or more generations of quarks, which was confirmed through B-meson studies.

The B^{-} meson has a relatively long lifetime for a particle containing a heavy quark (about 1.6×10^{-12} s) because its decay requires a flavor-changing weak interaction where the bottom quark transforms into a charm or up quark. This long lifetime allows B-mesons to travel measurable distances before decaying, enabling detailed study of their decay properties.

(a) What particle has the quark composition $-u-u-d$?

(b) What should its decay mode be?

Show Solution

a)The antiproton

b) $-p \rightarrow \pi^{0} + e^{-}$

(a) Show that all combinations of three quarks produce integral charges. Thus baryons must have integral charge.

(b) Show that all combinations of a quark and an antiquark produce only integral charges. Thus mesons must have integral charge.

Show Solution

Strategy

Quarks have charges of $+23q_e$ (up-type: u, c, t) or $-13q_e$ (down-type: d, s, b). Antiquarks have opposite charges. We’ll show that all possible combinations yield integral multiples of q_e.

Solution

(a) **Baryons (three quarks):**

For three quarks, we can have different combinations of up-type ($Q = +23$) and down-type ($Q = -13$) quarks:

Case 1: Three up-type quarks

$$Q = +23 + 23 + 23 = +63 = +2$$

Example: Δ^{++} = uuu has charge +2 ✓

Case 2: Two up-type, one down-type

$$Q = +23 + 23 - 13 = +33 = +1$$

Example: proton = uud has charge +1 ✓

Case 3: One up-type, two down-type

$$Q = +23 - 13 - 13 = 0$$

Example: neutron = udd has charge 0 ✓

Case 4: Three down-type quarks

$$Q = -13 - 13 - 13 = -33 = -1$$

Example: Ω^- = sss has charge -1 ✓

All combinations give integral charges: +2, +1, 0, or -1.

(b) **Mesons (quark-antiquark pair):**

Antiquarks have charges $-23q_e$ (anti-up-type) or $+13q_e$ (anti-down-type).

Case 1: Up-type quark + anti-up-type antiquark

Q=+23−23=0

Example: $J/\Psi = c—c$ has charge 0 ✓

Case 2: Up-type quark + anti-down-type antiquark

Q=+23+13=+33=+1

Example: $\pi^+ = u—d$ has charge +1 ✓

Case 3: Down-type quark + anti-up-type antiquark

Q=−13−23=−33=−1

Example: $\pi^- = —ud$ has charge -1 ✓

Case 4: Down-type quark + anti-down-type antiquark

Q=−13+13=0

Example: $\pi^0 = d—d$ (partial composition) has charge 0 ✓

All combinations give integral charges: +1, 0, or -1.

Discussion

This elegant result shows that despite quarks having fractional electric charges ($\pm 13q_e$ and $\pm 23q_e$), all observable composite particles—baryons and mesons—must have integral charges. This is a consequence of:

1. **Color confinement:** Only color-neutral ("white") combinations can exist as free particles
2. **Baryons must have three quarks** (to combine RGB colors)
3. **Mesons must have quark-antiquark pairs** (color-anticolor)

The fact that we only observe integral charges in nature was originally one of the objections to the quark model when it was first proposed. How could particles with fractional charges combine to make only integral charges? The answer is that fractional charges are confined—free quarks cannot exist in isolation. The combinations that CAN exist (three quarks or quark-antiquark) automatically produce integral charges.

This also explains why we've never observed a particle with charge $+13q_e$ or $+23q_e$—such charges would require an isolated quark, which is forbidden by confinement. The elementary charge q_e remains the smallest observed unit of charge, even though quarks have smaller fractional charges. This beautiful consistency of the quark model with observed phenomena is one of many pieces of evidence supporting it.

Footnotes

- 1 The lower of the ± symbols are the values for antiquarks.
- 2 B is baryon number, S is strangeness, c is charm, b is bottomness, t is topness.
- 3 Values are approximate, are not directly observable, and vary with model.
- 4 These two mesons are different mixtures, but each is its own antiparticle, as indicated by its quark composition.
- 5 These two mesons are different mixtures, but each is its own antiparticle, as indicated by its quark composition.
- 6 These two mesons are different mixtures, but each is its own antiparticle, as indicated by its quark composition.
- 7 Antibaryons have the antiquarks of their counterparts. The antiproton $-p$ is $-u-u-d$, for example.
- 8 Baryons composed of the same quarks are different states of the same particle. For example, the Δ^+ is an excited state of the proton. { data-list-type="bulleted" data-bullet-style="none"}

Glossary

bottom
: a quark flavor

charm
: a quark flavor, which is the counterpart of the strange quark

color

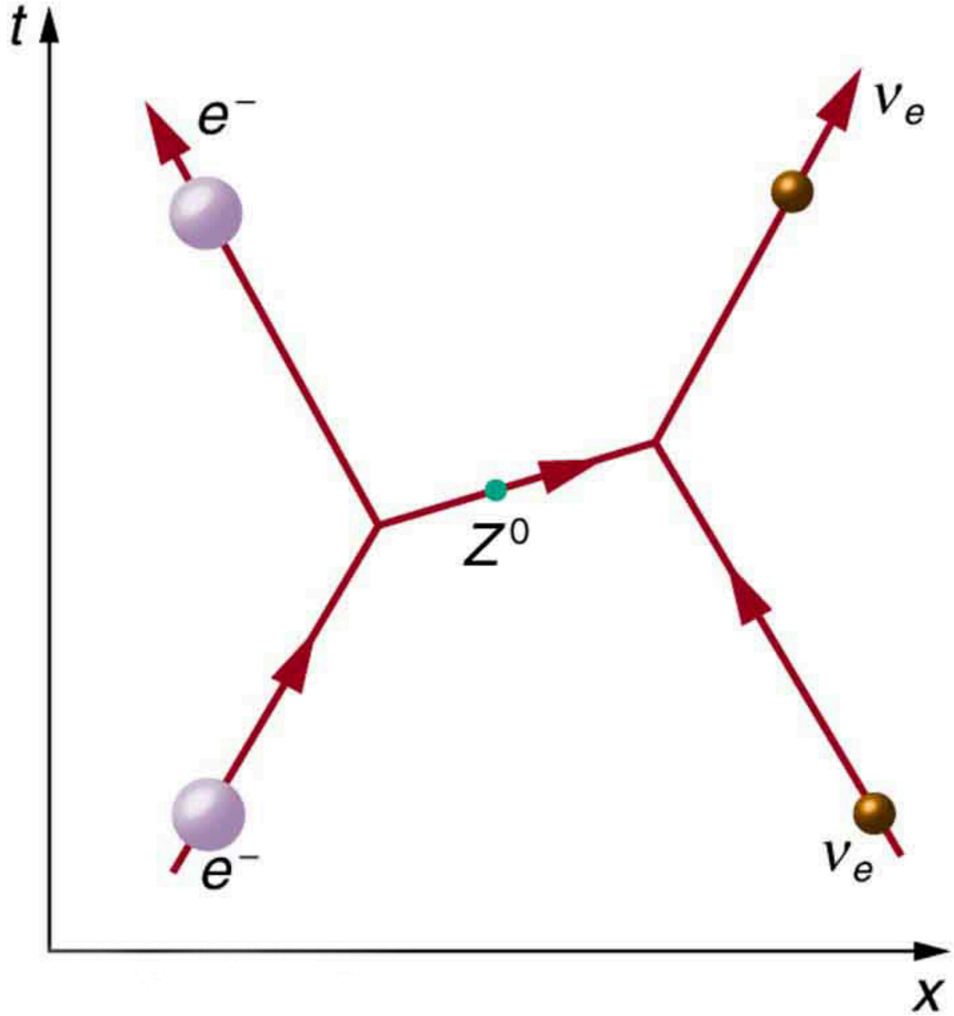
a quark flavor
down
the second-lightest of all quarks
flavors
quark type
fundamental particle
particle with no substructure
quantum chromodynamics
quark theory including color
quark
an elementary particle and a fundamental constituent of matter
strange
the third lightest of all quarks
theory of quark confinement
explains how quarks can exist and yet never be isolated or directly observed
top
a quark flavor
up
the lightest of all quarks

GUTs: The Unification of Forces

- State the grand unified theory.
- Explain the electroweak theory.
- Define gluons.
- Describe the principle of quantum chromodynamics.
- Define the standard model.

Present quests to show that the four basic forces are different manifestations of a single unified force follow a long tradition. In the 19th century, the distinct electric and magnetic forces were shown to be intimately connected and are now collectively called the electromagnetic force. More recently, the weak nuclear force has been shown to be connected to the electromagnetic force in a manner suggesting that a theory may be constructed in which all four forces are unified. Certainly, there are similarities in how forces are transmitted by the exchange of carrier particles, and the carrier particles themselves (the gauge bosons in [Table 1]) are also similar in important ways. The analogy to the unification of electric and magnetic forces is quite good—the four forces are distinct under normal circumstances, but there are hints of connections even on the atomic scale, and there may be conditions under which the forces are intimately related and even indistinguishable. The search for a correct theory linking the forces, called the **Grand Unified Theory (GUT)**, is explored in this section in the realm of particle physics. Frontiers of Physics expands the story in making a connection with cosmology, on the opposite end of the distance scale.

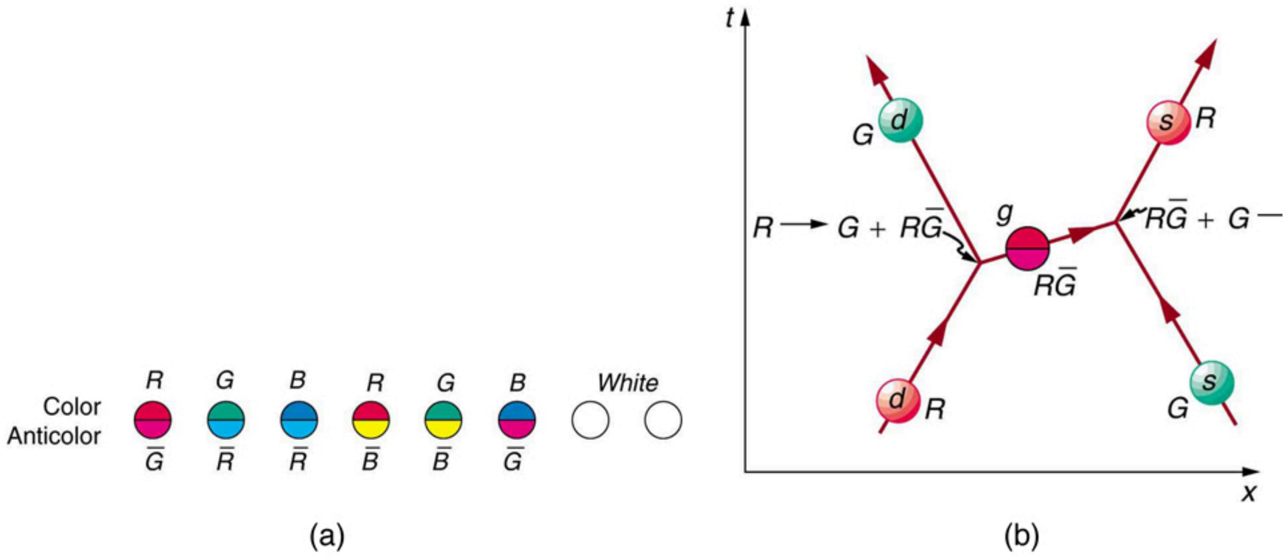
[Figure 1] is a Feynman diagram showing how the weak nuclear force is transmitted by the carrier particle Z^0, similar to the diagrams in [Figure 2] and [Figure 3] for the electromagnetic and strong nuclear forces. In the 1960s, a gauge theory, called **electroweak theory**, was developed by Steven Weinberg, Sheldon Glashow, and Abdus Salam and proposed that the electromagnetic and weak forces are identical at sufficiently high energies. One of its predictions, in addition to describing both electromagnetic and weak force phenomena, was the existence of the W^+, W^-, and Z^0 carrier particles. Not only were three particles having spin 1 predicted, the mass of the W^+ and W^- was predicted to be $81\text{GeV}/c^2$, and that of the Z^0 was predicted to be $90\text{GeV}/c^2$. (Their masses had to be about 1000 times that of the pion, or about $100\text{GeV}/c^2$, since the range of the weak force is about 1000 times less than the strong force carried by virtual pions.) In 1983, these carrier particles were observed at CERN with the predicted characteristics, including masses having the predicted values as seen in [Table 1]. This was another triumph of particle theory and experimental effort, resulting in the 1984 Nobel Prize to the experiment's group leaders Carlo Rubbia and Simon van der Meer. Theorists Weinberg, Glashow, and Salam had already been honored with the 1979 Nobel Prize for other aspects of electroweak theory.



The exchange of a virtual Z^0 carries the weak nuclear force between an electron and a neutrino in this Feynman diagram. The Z^0 is one of the carrier particles for the weak nuclear force that has now been created in the laboratory with characteristics predicted by electroweak theory.

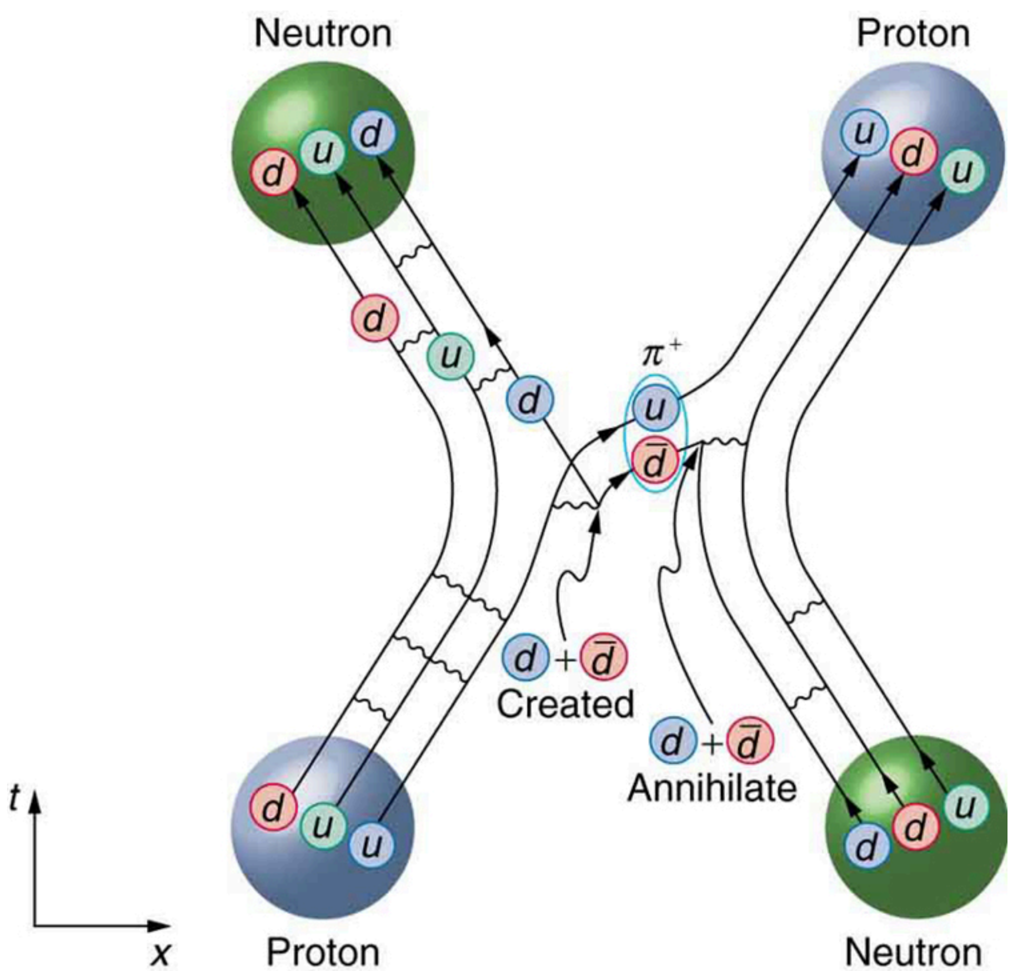
Although the weak nuclear force is very short ranged ($<10^{-18}\text{m}$, as indicated in [Table 1]), its effects on atomic levels can be measured given the extreme precision of modern techniques. Since electrons spend some time in the nucleus, their energies are affected, and spectra can even indicate new aspects of the weak force, such as the possibility of other carrier particles. So systems many orders of magnitude larger than the range of the weak force supply evidence of electroweak unification in addition to evidence found at the particle scale.

Gluons (g) are the proposed carrier particles for the strong nuclear force, although they are not directly observed. Like quarks, gluons may be confined to systems having a total color of white. Less is known about gluons than the fact that they are the carriers of the weak and certainly of the electromagnetic force. QCD theory calls for eight gluons, all massless and all spin 1. Six of the gluons carry a color and an anticolor, while two do not carry color, as illustrated in [Figure 2](a). There is indirect evidence of the existence of gluons in nucleons. When high-energy electrons are scattered from nucleons and evidence of quarks is seen, the momenta of the quarks are smaller than they would be if there were no gluons. That means that the gluons carrying force between quarks also carry some momentum, inferred by the already indirect quark momentum measurements. At any rate, the gluons carry color charge and can change the colors of quarks when exchanged, as seen in [Figure 2](b). In the figure, a red down quark interacts with a green strange quark by sending it a gluon. That gluon carries red away from the down quark and leaves it green, because it is an $R-G$ (red-antigreen) gluon. (Taking antigreen away leaves you green.) Its antigreenness kills the green in the strange quark, and its redness turns the quark red.



In figure (a), the eight types of gluons that carry the strong nuclear force are divided into a group of six that carry color and a group of two that do not. Figure (b) shows that the exchange of gluons between quarks carries the strong force and may change the color of a quark.

The strong force is complicated, since observable particles that feel the strong force (hadrons) contain multiple quarks. [Figure 3] shows the quark and gluon details of pion exchange between a proton and a neutron as illustrated earlier in [Figure 1] and [Figure 3]. The quarks within the proton and neutron move along together exchanging gluons, until the proton and neutron get close together. As the u quark leaves the proton, a gluon creates a pair of virtual particles, a d quark and a $-d$ antiquark. The d quark stays behind and the proton turns into a neutron, while the u and $-d$ move together as a π^+ ([Table 2] confirms the $u-d$ composition for the π^+ .) The $-d$ annihilates a d quark in the neutron, the u joins the neutron, and the neutron becomes a proton. A pion is exchanged and a force is transmitted.



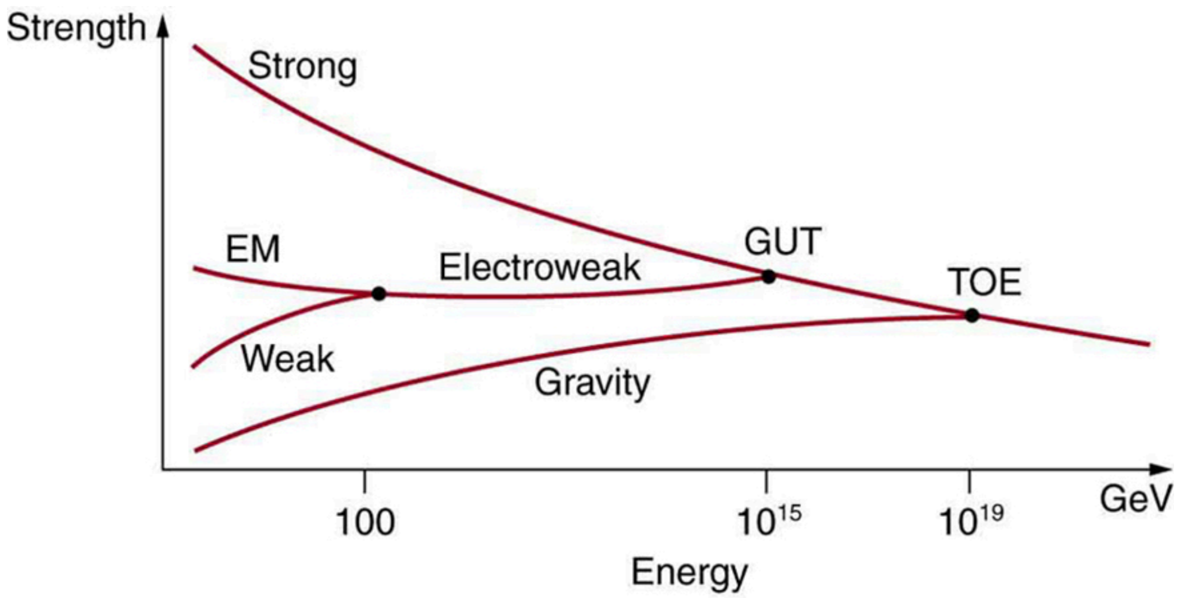
This Feynman diagram is the same interaction as shown in [[Figure 3]](../contents/ch33TheFourBasicForces#Figure3) of the four basic forces, but it shows the quark and gluon details of the strong force interaction.

It is beyond the scope of this text to go into more detail on the types of quark and gluon interactions that underlie the observable particles, but the theory (**quantum chromodynamics** or QCD) is very self-consistent. So successful have QCD and the electroweak theory been that, taken together, they are called the **Standard Model**. Advances in knowledge are expected to modify, but not overthrow, the Standard Model of particle physics and forces.

Making Connections: Unification of Forces

Grand Unified Theory (GUT) is successful in describing the four forces as distinct under normal circumstances, but connected in fundamental ways. Experiments have verified that the weak and electromagnetic forces become identical at very small distances and provide the GUT description of the carrier particles for the forces. GUT predicts that the other forces become identical under conditions so extreme that they cannot be tested in the laboratory, although there may be lingering evidence of them in the evolution of the universe. GUT is also successful in describing a system of carrier particles for all four forces, but there is much to be done, particularly in the realm of gravity.

How can forces be unified? They are definitely distinct under most circumstances, for example, being carried by different particles and having greatly different strengths. But experiments show that at extremely small distances, the strengths of the forces begin to become more similar. In fact, electroweak theory's prediction of the W^+, W^-, and Z^0 carrier particles was based on the strengths of the two forces being identical at extremely small distances as seen in [Figure 4]. As discussed in case of the creation of virtual particles for extremely short times, the small distances or short ranges correspond to the large masses of the carrier particles and the correspondingly large energies needed to create them. Thus, the energy scale on the horizontal axis of [Figure 4] corresponds to smaller and smaller distances, with 100 GeV corresponding to approximately, 10^{-18}m for example. At that distance, the strengths of the EM and weak forces are the same. To test physics at that distance, energies of about 100 GeV must be put into the system, and that is sufficient to create and release the W^+, W^-, and Z^0 carrier particles. At those and higher energies, the masses of the carrier particles becomes less and less relevant, and the Z^0 in particular resembles the massless, chargeless, spin 1 photon. In fact, there is enough energy when things are pushed to even smaller distances to transform the W^+, W^-, and Z^0 into massless carrier particles more similar to photons and gluons. These have not been observed experimentally, but there is a prediction of an associated particle called the **Higgs boson**. The mass of this particle is not predicted with nearly the certainty with which the mass of the W^+,W^-, and Z^0 particles were predicted, but it was hoped that the Higgs boson could be observed at the now-canceled Superconducting Super Collider (SSC). Ongoing experiments at the Large Hadron Collider at CERN have presented some evidence for a Higgs boson with a mass of 125 GeV, and there is a possibility of a direct discovery during 2012. The existence of this more massive particle would give validity to the theory that the carrier particles are identical under certain circumstances.



The relative strengths of the four basic forces vary with distance and, hence, energy is needed to probe small distances. At ordinary energies (a few eV or less), the forces differ greatly as indicated in [[Table 1]](../contents/ch33TheFourBasicForces#Table1) from The Four Basic Forces. However, at energies available at accelerators, the weak and EM forces become identical, or unified. Unfortunately, the energies at which the strong and electroweak forces become the same are unreachable even in principle at any conceivable accelerator. The universe may provide a laboratory, and nature may show effects at ordinary energies that give us clues about the validity of this graph.

The small distances and high energies at which the electroweak force becomes identical with the strong nuclear force are not reachable with any conceivable human-built accelerator. At energies of about 10^{14}GeV (16 000 J per particle), distances of about 10^{-30}m can be probed. Such energies are needed to test theory directly, but these are about

10^{10} *highertheproposedgiantSSCwouldhavehad,andthedistancesareabout* 10^{-12}
smallerthananystructurewehavedirectknowledgeof.ThiswouldbetherealmofvariousGUTs,
10^{12}
),*youfindtheunexpected.Evenmoreextremearetheenergiesanddistancesatwhichgravityisth*

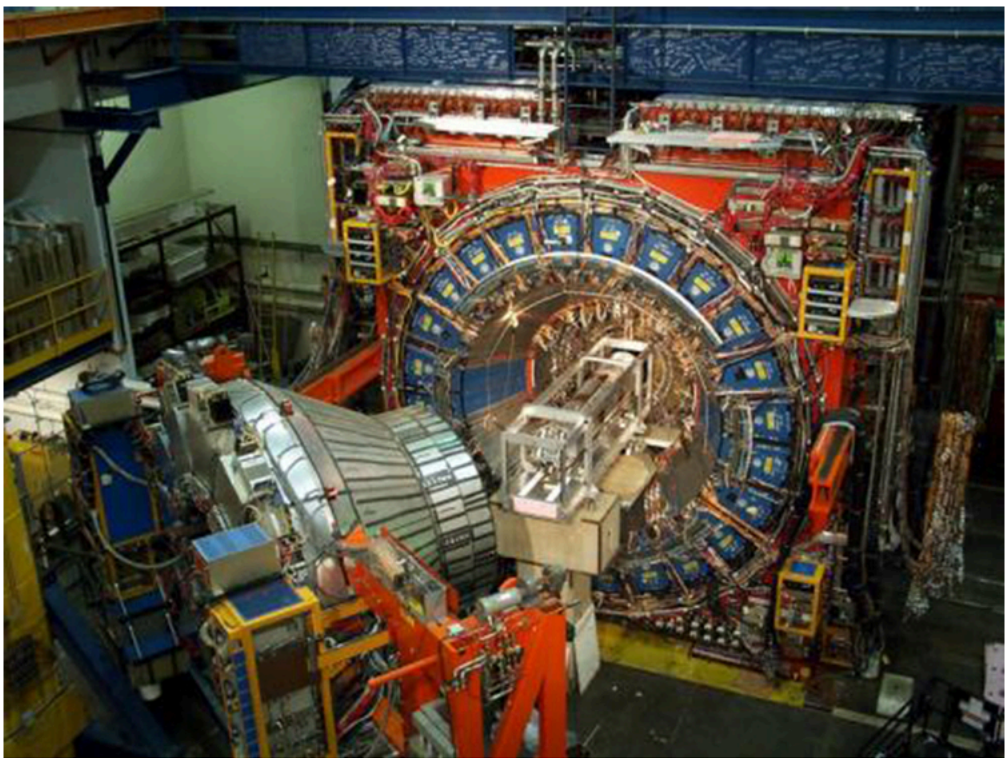
Superstring theory. Superstrings are entities that are $10^{-35}\ \text{m}$ in scale and act like one-dimensional oscillating strings and are also proposed to underlie all particles, forces, and space itself.

At the energy of GUTs, the carrier particles of the weak force would become massless and identical to gluons. If that happens, then both lepton and baryon conservation would be violated. We do not see such violations, because we do not encounter such energies. However, there is a tiny probability that, at ordinary energies, the virtual particles that violate the conservation of baryon number may exist for extremely small amounts of time (corresponding to very small ranges). All GUTs thus predict that the proton should be unstable, but would decay with an extremely long lifetime of about 10^{31}y . The predicted decay mode is

$$p \rightarrow \pi^0 + e^+, \text{ (proposed proton decay)}$$

which violates both conservation of baryon number and electron family number. Although 10^{31}y is an extremely long time (about 10^{21} times the age of the universe), there are a lot of protons, and detectors have been constructed to look for the proposed decay mode as seen in [Figure 5]. It is somewhat comforting that proton decay has not been detected, and its experimental lifetime is now greater than $5 \times 10^{32}\text{y}$. This does not prove GUTs wrong, but it does place greater constraints on the theories, benefiting theorists in many ways.

From looking increasingly inward at smaller details for direct evidence of electroweak theory and GUTs, we turn around and look to the universe for evidence of the unification of forces. In the 1920s, the expansion of the universe was discovered. Thinking backward in time, the universe must once have been very small, dense, and extremely hot. At a tiny fraction of a second after the fabled Big Bang, forces would have been unified and may have left their fingerprint on the existing universe. This, one of the most exciting forefronts of physics, is the subject of Frontiers of Physics.



In the Tevatron accelerator at Fermilab, protons and antiprotons collide at high energies, and some of those collisions could result in the production of a Higgs boson in association with a W boson. When the W boson decays to a high-energy lepton and a neutrino, the detector triggers on the lepton, whether it is an electron or a muon. (credit: D. J. Miller)

Summary

- Attempts to show unification of the four forces are called Grand Unified Theories (GUTs) and have been partially successful, with connections proven between EM and weak forces in electroweak theory.
- The strong force is carried by eight proposed particles called gluons, which are intimately connected to a quantum number called color—their governing theory is thus called quantum chromodynamics (QCD). Taken together, QCD and the electroweak theory are widely accepted as the Standard Model of particle physics.
- Unification of the strong force is expected at such high energies that it cannot be directly tested, but it may have observable consequences in the as-yet unobserved decay of the proton and topics to be discussed in the next chapter. Although unification of forces is generally anticipated, much remains to be done to prove its validity.

Conceptual Questions

If a GUT is proven, and the four forces are unified, it will still be correct to say that the orbit of the moon is determined by the gravitational force. Explain why.

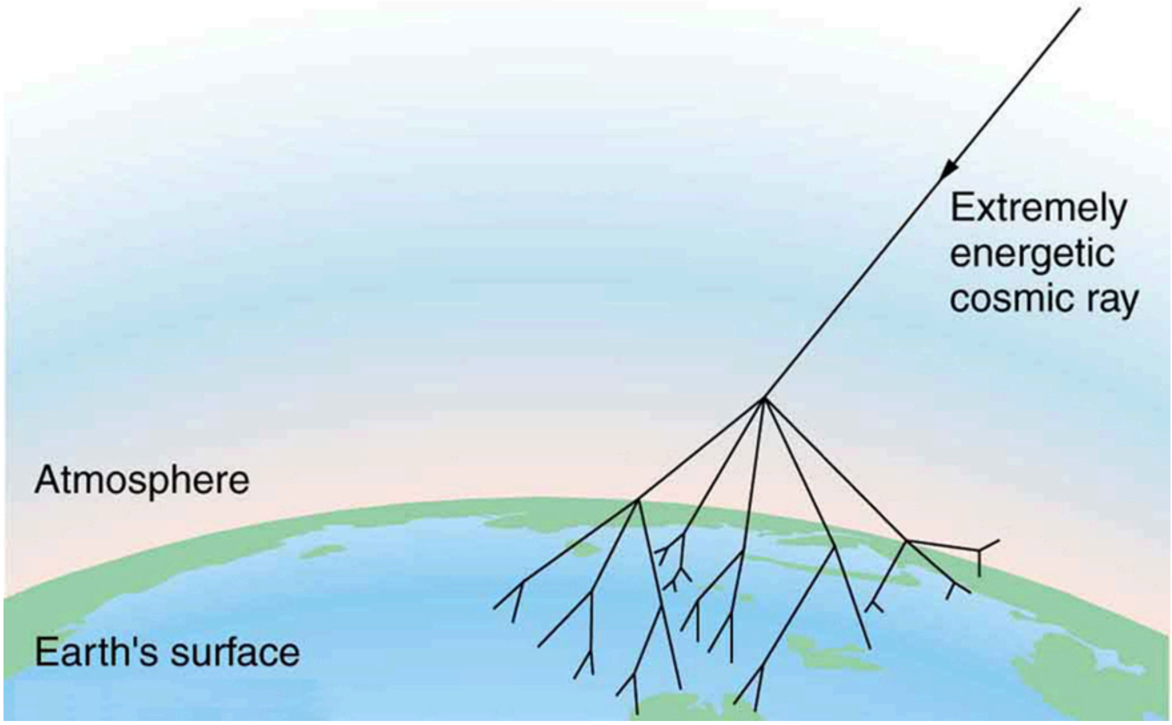
If the Higgs boson is discovered and found to have mass, will it be considered the ultimate carrier of the weak force? Explain your response.

Gluons and the photon are massless. Does this imply that the W^+, W^-, and Z^0 are the ultimate carriers of the weak force?

Problems & Exercises

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-km^2 area, how many particles are there per square meter?



An extremely energetic cosmic ray creates a shower of particles on earth. The energy of these rare cosmic rays can approach a joule (about 10^{10}GeV) and, after multiple collisions, huge numbers of particles are created from this energy. Cosmic ray showers have been observed to extend over many square kilometers.

Show Solution

(a) 5×10^{10} (b) $5 \times 10^4 \text{particles/m}^2$

Integrated Concepts

Assuming conservation of momentum, what is the energy of each γ ray produced in the decay of a neutral at rest pion, in the reaction $\pi^0 \rightarrow \gamma + \gamma$?

Show Solution

Strategy

Since the π^0 is at rest, its initial momentum is zero. By conservation of momentum, the two photons must move in opposite directions with equal and opposite momenta. Since photons have $E = pc$ and equal magnitudes of momentum, they must have equal energies. The total energy equals the rest mass energy of the π^0, which is 135.0 MeV.

Solution

The rest mass energy of the π^0 is completely converted to photon energies:

$$E_{\text{total}} = m_{\pi^0} c^2 = 135.0 \text{ MeV}$$

By conservation of momentum, the two photons must have equal and opposite momenta. Since $E = pc$ for photons, equal momenta means equal energies. Therefore:

$$E_\gamma = \frac{E_{\text{total}}}{2} = \frac{135.0 \text{ MeV}}{2} = 67.5 \text{ MeV}$$

Each photon has an energy of 67.5 MeV.

Discussion

This symmetric two-photon decay is characteristic of neutral particles that are their own antiparticles, like the π^0. The decay proceeds via the electromagnetic force—the quark-antiquark pair in the pion ($u\text{—}u$ or $d\text{—}d$) annihilates to produce two photons. The extremely short lifetime of the π^0 (8.4×10^{-17} s) is consistent with electromagnetic decay.

The equal energy sharing between the two photons is a direct consequence of momentum conservation and the symmetry of the decay. In the pion's rest frame, there is no preferred direction, so the photons must emerge back-to-back with equal energies. If the pion were moving, the photon energies would be different in the lab frame due to Doppler shifting, but in the pion's rest frame they would still be equal.

This decay mode occurs nearly 99% of the time for the π^0. The photons produced have energies in the gamma-ray range (67.5 MeV is much higher than typical atomic transition energies). These high-energy photons can be detected in particle detectors, and their back-to-back emission pattern is a signature of π^0 decay. This process is important in high-energy physics experiments and also occurs in cosmic ray showers when high-energy protons strike atmospheric nuclei, producing pions that quickly decay into photons.

Integrated Concepts

What is the wavelength of a 50-GeV electron, which is produced at SLAC? This provides an idea of the limit to the detail it can probe.

Show Solution

2.5×10^{-17} m

Integrated Concepts

(a) Calculate the relativistic quantity $\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$ for 1.00-TeV protons produced at Fermilab. (b) If such a proton created a π^+ having the same speed, how long would its life be in the laboratory? (c) How far could it travel in this time?

Show Solution

Strategy

For part (a), we'll use the relativistic energy relation $E = \gamma mc^2$ to find γ. For parts (b) and (c), we'll use time dilation: the pion's lifetime in the lab frame is $\tau_{\text{lab}} = \gamma \tau_0$, where $\tau_0 = 2.60 \times 10^{-8}$ s is the pion's rest lifetime.

Solution

(a) The total energy of the proton is its kinetic energy plus rest mass energy:

$$E = KE + m_p c^2 = 1.00 \text{ TeV} + 0.938 \text{ GeV} = 1000.938 \text{ GeV}$$

Using $E = \gamma m_p c^2$:

$$\gamma = \frac{E}{m_p c^2} = \frac{1000.938 \text{ GeV}}{0.938 \text{ GeV}} = 1067 \approx 1.07 \times 10^3$$

(b) The π^+ rest lifetime is $\tau_0 = 2.60 \times 10^{-8}$ s. In the laboratory frame, time dilation gives:

$$\tau_{\text{lab}} = \gamma \tau_0 = (1067)(2.60 \times 10^{-8} \text{ s}) = 2.77 \times 10^{-5} \text{ s} = 27.7\ \mu\text{s}$$

(c) The distance traveled is:

$$d = v\tau_{\text{lab}} \approx c\tau_{\text{lab}} = (3.00 \times 10^8 \text{ m/s})(2.77 \times 10^{-5} \text{ s})$$
$$d = 8.31 \times 10^3 \text{ m} = 8.31 \text{ km}$$

Discussion

The γ factor of 1067 indicates the proton is traveling at extremely relativistic speeds, very close to the speed of light. At this speed, $v/c = \sqrt{1 - 1/\gamma^2} \approx 0.999999560$ or 99.999956% the speed of light.

Time dilation dramatically extends the observed lifetime of the pion from 26 nanoseconds in its rest frame to 27.7 microseconds in the lab frame—over 1000 times longer. This allows the pion to travel 8.31 km before decaying, compared to only about 7.8 meters it would travel without time dilation.

This effect is crucial for particle physics experiments. High-energy particles created in accelerators travel macroscopic distances before decaying, allowing physicists to track and study them. Without time dilation, many particles would decay too quickly to be detected. The observation of such effects provides direct experimental confirmation of special relativity. Similar time dilation effects are observed with cosmic ray muons, which can reach Earth's surface only because their lifetimes are extended by their high speeds, providing one of the most accessible demonstrations of relativistic time dilation in nature.

Integrated Concepts

The primary decay mode for the negative pion is $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$. (a) What is the energy release in MeV in this decay? (b) Using conservation of momentum, how much energy does each of the decay products receive, given the π^- is at rest when it decays? You may assume the muon antineutrino is massless and has momentum $p = E/c$, just like a photon.

Show Solution

(a) 33.9 MeV

(b) Muon antineutrino 29.8 MeV, muon 4.1 MeV (kinetic energy)

Integrated Concepts

Plans for an accelerator that produces a secondary beam of *K*-mesons to scatter from nuclei, for the purpose of studying the strong force, call for them to have a kinetic energy of 500 MeV. (a) What would the relativistic quantity $\gamma = \frac{1}{\sqrt{1-v^2/c^2}}$ be for these particles? (b) How long would their average lifetime be in the laboratory? (c) How far could they travel in this time?

Show Solution

Strategy

We'll use the charged kaon K^+ (or K^-) with mass 493.7 MeV/c^2 and rest lifetime 1.24×10^{-8} s. For part (a), use $KE = (\gamma - 1)mc^2$. For parts (b) and (c), apply time dilation.

Solution

(a) The kinetic energy is related to γ by:

$$KE = (\gamma - 1)m_K c^2$$

Solving for γ:

$$\gamma = 1 + \frac{KE}{m_K c^2} = 1 + \frac{500\text{ MeV}}{493.7\text{ MeV}} = 1 + 1.013 = 2.013 \approx 2.01$$

(b) The K-meson's rest lifetime is $\tau_0 = 1.24 \times 10^{-8}$ s. In the laboratory:

$$\tau_{\text{lab}} = \gamma \tau_0 = (2.01)(1.24 \times 10^{-8}\text{ s}) = 2.49 \times 10^{-8}\text{ s}$$

(c) First, find the velocity from γ:

$$v = c\sqrt{1 - \frac{1}{\gamma^2}} = c\sqrt{1 - \frac{1}{(2.01)^2}} = c\sqrt{1 - 0.247} = 0.868c$$

The distance traveled is:

$$d = v\tau_{\text{lab}} = (0.868)(3.00 \times 10^8\text{ m/s})(2.49 \times 10^{-8}\text{ s})$$
$$d = 6.49\text{ m}$$

Discussion

With a γ factor of 2.01, the K-mesons are moderately relativistic, traveling at about 87% the speed of light. This is significantly slower than the 1-TeV protons in the previous problem, but still fast enough that relativistic effects are important.

Time dilation approximately doubles the K-meson's lifetime from 12.4 ns to 24.9 ns, allowing it to travel about 6.5 meters before decaying. This is a manageable distance for experimental setups—K-meson beams can be transported through beam lines to experimental targets where they scatter from nuclei.

K-mesons are particularly useful for studying the strong force because they contain a strange quark, which interacts via the strong force but isn't present in ordinary matter (protons and neutrons contain only up and down quarks). The kinetic energy of 500 MeV is chosen to be high enough to probe nuclear structure effectively but low enough that the beam can be produced and controlled with reasonable accelerator technology. K-meson scattering experiments have provided important information about the strong nuclear force and the structure of nucleons, complementing electron scattering experiments which probe electromagnetic properties.

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?

Show Solution

(a) $7.2\times10^{5}\text{kg}$ (b) $7.2\times10^{2}\text{m}^{3}$ (c) 100months

Integrated Concepts

In supernovas, neutrinos are produced in huge amounts. They were detected from the 1987A supernova in the Magellanic Cloud, which is about 120 000 light years away from the Earth (relatively close to our Milky Way galaxy). If neutrinos have a mass, they cannot travel at the speed of light, but if their mass is small, they can get close. (a) Suppose a neutrino with a $7\text{-eV}/c^2$ mass has a kinetic energy of 700 keV. Find the relativistic quantity $\gamma=\frac{1}{\sqrt{1-v^2/c^2}}$ for it. (b) If the neutrino leaves the 1987A supernova at the same time as a photon and both travel to Earth, how much sooner does the photon arrive? This is not a large time difference, given that it is impossible to know which neutrino left with which photon and the poor efficiency of the neutrino detectors. Thus, the fact that neutrinos were observed within hours of the brightening of the supernova only places an upper limit on the neutrino's mass. (Hint: You may need to use a series expansion to find *v* for the neutrino, since its γ is so large.)

Show Solution

Strategy

For part (a), use $KE=(\gamma-1)mc^2$ with $m=7\ \text{eV}/c^2$ and $KE=700\ \text{keV}=7\times10^5\ \text{eV}$. For part (b), find the neutrino's velocity, calculate travel times for both neutrino and photon, and find the difference.

Solution

(a) Using the kinetic energy relation:

$$\gamma=1+\frac{KE}{mc^2}=1+\frac{700{,}000\ \text{eV}}{7\ \text{eV}}=1+100{,}000=100{,}001\approx1.0\times10^5$$

(b) To find the neutrino's velocity, use:

$$v=c\sqrt{1-\frac{1}{\gamma^2}}$$

Since γ is very large (10^5), use the approximation $\sqrt{1-x}\approx1-\frac{x}{2}$ for small x:

$$v\approx c\left(1-\frac{1}{2\gamma^2}\right)=c\left(1-\frac{1}{2(10^5)^2}\right)=c(1-5\times10^{-11})$$

The distance is $d=120{,}000$ light years. Travel times are:

- Photon: $t_\gamma=\frac{d}{c}=120{,}000$ years
- Neutrino: $t_\nu=\frac{d}{v}=\frac{d}{c(1-5\times10^{-11})}\approx\frac{120{,}000}{1-5\times10^{-11}}$ years

Using $\frac{1}{1-x}\approx1+x$ for small x:

$$t_\nu\approx120{,}000(1+5\times10^{-11})\ \text{years}$$

The time difference is:

$$\Delta t=t_\nu-t_\gamma=120{,}000\times5\times10^{-11}\ \text{years}=6.0\times10^{-6}\ \text{years}$$

Converting to seconds:

$$\Delta t=6.0\times10^{-6}\ \text{years}\times3.16\times10^{7}\ \text{s/year}\approx190\ \text{s}\approx3.2\ \text{minutes}$$

Discussion

The enormous γ factor of 10^5 shows that despite having a tiny mass (7 eV/c^2, about 70,000 times smaller than an electron), the neutrino with 700 keV kinetic energy travels at 99.99999999995% the speed of light—extraordinarily close to c.

The photon arrives only about 3 minutes sooner after a journey of 120,000 years! This tiny difference is completely negligible compared to the uncertainties in when specific neutrinos and photons were emitted and the detection efficiency. The fact that neutrinos from SN 1987A were detected within hours of the optical brightening places strong constraints on the neutrino mass but cannot determine it precisely.

This observation was historic—it was the first time neutrinos were detected from a supernova, confirming theoretical predictions about stellar collapse and supernova mechanisms. The near-simultaneous arrival of neutrinos and photons after traveling 120,000 light years demonstrates that neutrinos have very small (possibly zero) mass and travel at speeds indistinguishable from light speed over astronomical distances. Modern experiments suggest neutrino masses are even smaller than 7 eV/c^2, possibly less than 0.1 eV/c^2.

Construct Your Own Problem

Consider an ultrahigh-energy cosmic ray entering the Earth's atmosphere (some have energies approaching a joule). Construct a problem in which you calculate the energy of the particle based on the number of particles in an observed cosmic ray shower. Among the things to consider are the average mass of the shower particles, the average number per square meter, and the extent (number of square meters covered) of the shower. Express the energy in eV and joules.

Show Solution

Strategy

To construct a problem about ultrahigh-energy cosmic rays, we need to specify realistic parameters for the cosmic ray shower and use energy conservation principles. The primary cosmic ray converts its energy into a shower of secondary particles.

Sample Problem Construction

Problem: A cosmic ray proton strikes Earth's atmosphere and creates an extensive air shower. Ground detectors observe approximately 2.5×10^5 particles per square meter over a circular area of radius 500 meters. If the average particle mass is 200 MeV/c^2 (mostly pions, muons, and electrons/positrons), estimate the energy of the primary cosmic ray.

Solution Approach:

1. **Calculate total shower area:**

$$A = \pi r^2 = \pi (500\text{ m})^2 = 7.85 \times 10^5\text{ m}^2$$

1. **Calculate total number of particles:**

$$N = (2.5 \times 10^5\text{ particles/m}^2)(7.85 \times 10^5\text{ m}^2) = 1.96 \times 10^{11}\text{ particles}$$

1. **Calculate total energy (assuming most energy goes into particle rest masses):**

$$E \approx N \times m_{\text{avg}} c^2 = (1.96 \times 10^{11})(200\text{ MeV}) = 3.92 \times 10^{13}\text{ MeV}$$

1. **Convert to eV and joules:**

$$E = 3.92 \times 10^{19}\text{ eV} = 3.92 \times 10^{10}\text{ GeV} = 39.2\text{ EeV (exaelectronvolts)}$$
$$E = (3.92 \times 10^{19}\text{ eV})(1.6 \times 10^{-19}\text{ J/eV}) = 6.3\text{ J}$$

Discussion

This constructed problem illustrates the extraordinary energies of ultrahigh-energy cosmic rays. An energy of 6.3 joules may seem small macroscopically (enough to lift a 1-kg mass about 60 cm), but concentrated in a single subatomic particle, it represents an astounding 10^{10} GeV—far beyond anything achievable in human-made accelerators like the LHC (maximum 14 TeV = 14,000 GeV).

Key considerations for constructing similar problems:

1. **Particle density:** Realistic values range from 10^4 to 10^6 particles/m^2 depending on primary energy
2. **Shower extent:** Can range from hundreds of meters (10^{18} eV) to several kilometers (10^{20} eV)
3. **Average particle mass:** Most shower particles are pions (140 MeV), muons (106 MeV), and electrons (0.5 MeV); 200 MeV/c^2 is reasonable
4. **Energy distribution:** Most energy goes into particle production, though some is lost to neutrinos and undetected particles

Such cosmic rays pose fundamental questions: What accelerates particles to these energies? Candidates include supermassive black holes, active galactic nuclei, or exotic physics. The GZK cutoff (Greisen-Zatsepin-Kuzmin limit) predicts cosmic rays above $\sim 5 \times 10^{19}$ eV should be rare due to interactions with cosmic microwave background radiation, yet some ultra-high-energy events above this limit have been observed, making them among the most mysterious phenomena in astrophysics.

Construct Your Own Problem

Consider a detector needed to observe the proposed, but extremely rare, decay of an electron. Construct a problem in which you calculate the amount of matter needed in the detector to be able to observe the decay, assuming that it has a signature that is clearly identifiable. Among the things to consider are the estimated half life (long for rare events), and the number of decays per unit time that you wish to observe, as well as the number of electrons in the detector substance.

Show Solution

Strategy

Electron decay is not observed in nature and would violate charge conservation (unless it decays into something with the same charge). However, some extensions of the Standard Model predict extremely rare processes. We'll construct a problem based on detecting such hypothetical decays using realistic detector parameters.

Sample Problem Construction

Problem: Suppose a theoretical extension of the Standard Model predicts that electrons might decay via a process with a half-life of 10^{35} years (far longer than the proton decay lifetime). You want to design a detector to observe at least one electron decay per year. Assuming your detector uses water (H_2O) and has 80% detection efficiency, how many kilograms of water are needed?

Solution Approach:

1. **Determine the number of electrons needed:**

The decay rate is given by $R = \ln 2 t_{1/2} N$, where N is the number of electrons.

To observe 1 decay per year with 80% efficiency, we need:

$$R_{\text{detected}} = 0.80 \times R = 1 \text{ decay/year}$$
$$R_{\text{actual}} = 10.80 = 1.25 \text{ decays/year}$$

Converting to decays per second:

$$R = 1.25 \text{ decays/year} 3.16 \times 10^{7} \text{ s/year} = 3.96 \times 10^{-8} \text{ decays/s}$$

1. **Calculate number of electrons needed:**

The half-life in seconds:

$$t_{1/2} = 10^{35} \text{ years} \times 3.16 \times 10^{7} \text{ s/year} = 3.16 \times 10^{42} \text{ s}$$

From $R = \ln 2 t_{1/2} N$:

$$N = R \times t_{1/2} \ln 2 = (3.96 \times 10^{-8})(3.16 \times 10^{42}) 0.693 = 1.81 \times 10^{35} \text{ electrons}$$

1. **Calculate mass of water needed:**

Water (H_2O) has 10 electrons per molecule (8 from oxygen + 1 from each hydrogen).

Molar mass of water = 18 g/mol, and Avogadro's number = 6.02×10^{23} molecules/mol.

Electrons per mole of water:

$$N_e/\text{mol} = 10 \times 6.02 \times 10^{23} = 6.02 \times 10^{24} \text{ electrons/mol}$$

Moles needed:

$$n = 1.81 \times 10^{35} 6.02 \times 10^{24} = 3.01 \times 10^{10} \text{ moles}$$

Mass of water:

$$m = (3.01 \times 10^{10} \text{ mol})(18 \text{ g/mol}) = 5.42 \times 10^{11} \text{ g} = 5.42 \times 10^{8} \text{ kg}$$

This requires approximately 540 million kilograms (540,000 metric tons) of water.

Discussion

This constructed problem demonstrates the enormous challenge of detecting extremely rare decays. A detector containing 540,000 tons of water is comparable to large neutrino detectors like Super-Kamiokande (50,000 tons) but would need to be an order of magnitude larger. The detector would need to be deep underground to shield from cosmic rays and equipped with thousands of photomultiplier tubes to detect decay products.

Key considerations for constructing similar problems:

1. **Half-life estimates:** For electron decay, theoretical predictions range from 10^{30} to beyond 10^{50} years
2. **Detection efficiency:** Realistic values are 50-90% depending on decay mode and detector type
3. **Detector material:** Water, liquid scintillator, or pure metals; each has different electron densities
4. **Background noise:** Real detectors must distinguish signal from cosmic rays, radioactivity, and other backgrounds
5. **Observation time:** Longer observation times allow smaller detectors

Fundamental implications: Electron decay would violate both charge conservation and lepton number conservation, fundamental principles never observed to be violated. Its observation would revolutionize physics, suggesting new physics beyond the Standard Model. The fact that no electron decay has been observed despite sensitive searches places experimental lower limits on the electron lifetime exceeding 10^{28} years, making the electron one of the most stable particles known—possibly absolutely stable. This stability is deeply connected to charge conservation, one of the most fundamental symmetries in nature.

Glossary

electroweak theory
: theory showing connections between EM and weak forces

grand unified theory
: theory that shows unification of the strong and electroweak forces

gluons
: eight proposed particles which carry the strong force

Higgs boson
: a massive particle that, if observed, would give validity to the theory that carrier particles are identical under certain circumstances

quantum chromodynamics
: the governing theory of connecting quantum number color to gluons

standard model
: combination of quantum chromodynamics and electroweak theory

superstring theory
: a theory of everything based on vibrating strings some 10^{-35}m in length

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