Particle Interactions and Conservation Laws

In developing the standard model for particles, certain types of interactions and decays are observed to be common and others seem to be forbidden. The study of interactions has led to a number of conservation laws which govern them. These conservation laws are in addition to the classical conservation laws such as conservation of energy, charge, etc., which still apply in the realm of particle interactions. Strong overall conservation laws are the conservation of baryon number and the conservation of lepton number. Specific quantum numbers have been assigned to the different fundamental particles, and other conservation laws are associated with those quantum numbers.

From another point of view, it would seem that any localized particle of finite mass should be unstable, since the decay into several smaller particles provides many more ways to distribute the energy, and thus would have higher entropy. This idea is even stated as a principle called the "totalitarian principle" which might be stated as "every process that is not forbidden must occur". From this point of view, any decay process which is expected but not observed must be prevented from occuring by some conservation law. This approach has been fruitful in helping to determine the rules for particle decay.

Conservation laws for parity, isospin, and strangeness have been developed by detailed observation of particle interactions. The combination of charge conjugation (C), parity (P) and time reversal (T) is considered to be a fundamental symmetry operation - all physical particles and interactions appear to be invariant under this combination. Called CPT invariance, this symmetry plumbs the depths of our understanding of nature.

Another part of the high energy physicist's toolkit in anticipating what interactions can be expected is "crossing symmetry". Any interaction which is observed can be used to predict other related interactions by "crossing" any particle across the reason symbol and turning it into it's antiparticle.

Some allowed and forbidden transitions

Index

Particle concepts

References
Blatt
Ch. 17

HyperPhysics***** Quantum Physics

R Nave

Go Back

Conservation of Baryon Number

Nature has specific rules for particle interactions and decays, and these rules have been summarized in terms of conservation laws. One of the most important of these is the conservation of baryon number. Each of the baryons is assigned a baryon number B=1. This can be considered to be equivalent to assigning each quark a baryon number of 1/3. This implies that the mesons, with one quark and one antiquark, have a baryon number B=0. No known decay process or interaction in nature changes the net baryon number.

The neutron and all heavier baryons decay directly to protons or eventually form protons, the proton being the least massive baryon. This implies that the proton has nowhere to go without violating the conservation of baryon number, so if the conservation of baryon number holds exactly, the proton is completely stable against decay. One prediction of grand unification of forces is that the proton would have the possibility of decay, so that possibility is being investigated experimentally.

Conservation of baryon number prohibits a decay of the type

$$p + n \rightarrow p + \mu^+ + \mu^-$$
$$B = 1 + 1 \neq 1 + 0 + 0$$

but with sufficient energy permits pair production in the reaction

$$p + n \rightarrow p + n + p + \bar{p}$$
$$B = 1 + 1 = 1 + 1 + 1 - 1$$

The fact that the decay

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

is observed implied that there is no corresponding principle of conservation of meson number. The pion is a meson composed of a quark and an antiquark, and on the right side of the equation there are only leptons. (Equivalently, you could assign a baryon number of 0 to the meson.)

Index

Particle concepts

HyperPhysics***** Quantum Physics

R Nave

Go Back

Conservation of Lepton Number

Nature has specific rules for particle interactions and decays, and these rules have been summarized in terms of conservation laws. One of the most important of these is the conservation of lepton number. This rule is a little more complicated than the conservation of baryon number because there is a separate requirement for each of the three sets of leptons, the electron, muon and tau and their associated neutrinos.

The first significant example was found in the decay of the neutron. When the decay of the neutron into a proton and an electron was observed, it did not fit the pattern of two-particle decay. That is, the electron emitted does not have a definite energy as is required by conservation of energy and momentum for a two-body decay. This implied the emission of a third particle, which we now identify as the electron antineutrino.

$$n \not\rightarrow p^+ + e^-$$
$$n \rightarrow p^+ + e^- + \bar{\nu}_e$$

The assignment of a lepton number of 1 to the electron and -1 to the electron antineutrino keeps the lepton number equal to zero on both sides of the second reacton above, while the first reaction does not conserve lepton number.

The observation of the following two decay processes leads to the conclusion that there is a separate lepton number for muons which must also be conserved.

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

The first reaction above (decay of the pion) is known to be a two-body decay by the fact that a well-defined muon energy is observed from the decay. However, the decay of the muon into an electron produces a distribution of electron energies, showing that it is at least a three-body decay. In order for both electron lepton number and muon lepton number to be conserved, then the other particles must be an electron anti-neutrino and a muon neutrino.

Table of lepton properties

Index

Particle concepts

R

Go Back

HyperPhysics***** Quantum Physics Nave

Parity

One of the conservation laws which applies to particle interactions is associated with parity.

Quarks have an intrinsic parity which is defined to be +1 and for an antiquark parity = -1. Nucleons are defined to have intrinsic parity +1. For a meson with quark and antiquark with antiparallel spins (s=0), then the parity is given by

$$P = P_q P_{\bar{q}}(-1)^{\ell} \quad \text{where } \ell = \text{orbital angular momentum}$$

The meson parity is given by

$$P = -(-1)^{\ell} = (-1)^{\ell+1}$$

The lowest energy states for quark-antiquark pairs (mesons) will have zero spin and negative parity and are called pseudoscalar mesons. The nine pseudoscalar mesons can be shown on a meson diagram. One kind of notation for these states indicates their angular momentum and parity

$$j^P = 0^-$$

Excited states of the mesons occur in which the quark spins are aligned, which with zero orbital angular momentum gives j=1. Such states are called vector mesons.

$$j^P = 1^-$$

The vector mesons have the same spin and parity as photons.

All neutrinos are found to be "left-handed", with an intrinsic parity of -1 while antineutrinos are right-handed, parity =+1.

Non-conservation of Parity

Index

Particle concepts

References
Rohlf
Ch. 17

HyperPhysics***** Quantum Physics R Nave

Go Back

Isospin

Isospin is a term introduced to describe groups of particles which have nearly the same mass, such as the proton and neutron. This doublet of particles is said to have isospin 1/2, with projection +1/2 for the proton and -1/2 for the neutron. The three pions compose a triplet, suggesting isospin 1. The projections are +1 for the positive, 0 and -1 for the neutral and negative pions.

Isospin is associated with the fact that the strong interaction is independent of electric charge. Any two members of the proton-neutron isospin doublet experience the same strong interaction: proton-proton, proton-neutron, neutron-neutron have the same strong force attraction.

At the quark level, the up and down quarks form an isospin doublet (I=1/2) and the projection +1/2 is assigned to the up quark and -1/2 to the down. The strange quark is in a class by itself and has isospin I=0. Isospin is related to other quantum numbers for the particles by

$$\frac{q}{e} = m_I + \frac{S+B}{2}$$

m_I = projection of isospin
S = strangeness
B = baryon number

Isospin is associated with a conservation law, as illustrated by the process

$$\Sigma^+ \rightarrow p + \eta^0$$
$$I = 1 \neq 1/2 + 0 \quad \text{Isospin}$$

which has never been observed even though it conserves charge, angular momentum and baryon number. It is forbidden by the fact that it does not conserve isospin.

Index

Particle concepts

References
Rohlf
Ch. 17

Blatt
Ch. 17

HyperPhysics***** Quantum Physics

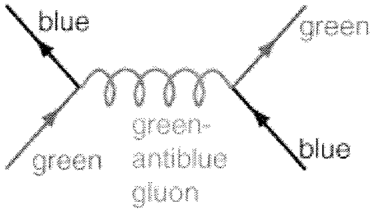
R Nave

Go Back

Gluons

Gluons are the exchange particles for the color force between quarks, analogous to the exchange of photons in the electromagnetic force between two charged particles. The gluon can be considered to be the fundamental exchange particle underlying the strong interaction between protons and neutrons in a nucleus. That short-range nucleon-nucleon interaction can be considered to be a residual color force extending outside the boundary of the proton or neutron. That strong interaction was modeled by Yukawa as involving an exchange of pions, and indeed the pion range calculation was helpful in developing our understanding of the strong force.

Gluon interactions are often represented by a Feynman diagram. Note that the gluon generates a color change for the quarks. The gluons are in fact considered to be bi-colored, carrying a unit of color and a unit of anti-color as suggested in the diagram at right. The gluon exchange picture there converts a blue quark to a green one and vice versa. The range of the strong force is limited by the fact that the gluons interact with each other as well as with quarks in the context of quark confinement. These properties contrast them with photons, which are massless and of infinite range. The photon does not carry electric charge with it, while the gluons do carry the "color charge".



Feynman diagram for an interaction between quarks generated by a gluon.

Within their range of about a fermi, the gluons can interact with each other, and can produce virtual quark-antiquark pairs. The property of interaction with each other is very different from the other exchange particles, and raises the possibility of gluon collections referred to as "glueballs". The internal state of a hadron is viewed as composed of a fixed net number of quarks, but with a dynamic cloud of gluons and quark-antiquark pairs in equilibrium.

Index

Particle concepts

Reference
Griffiths
Section
2.3

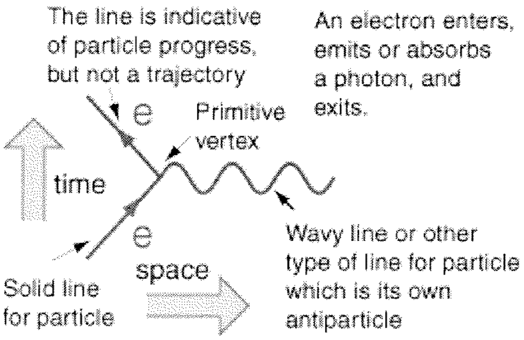
HyperPhysics***** Quantum Physics *R Nave*

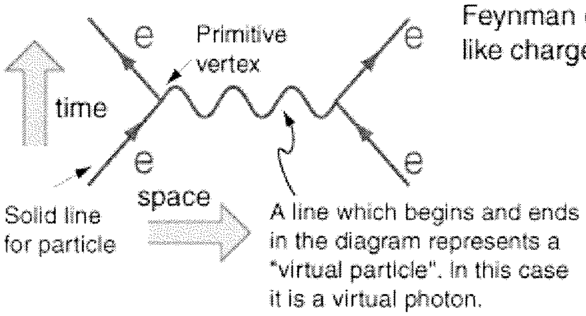
Go Back

Feynman Diagrams

Feynman diagrams are graphical ways to represent exchange forces. Each point at which lines come together is called a vertex, and at each vertex one may examine the conservation laws which govern particle interactions. Each vertex must conserve charge, baryon number and lepton number.

Developed by Feynman to decribe the interactions in quantum electrodynamics (QED), the diagrams have found use in describing a variety of particle interactions. They are spacetime diagrams, ct vs x. The time axis points upward and the space axis to the right. (Particle physicists often reverse that orientation.) Particles are represented by lines with arrows to denote the direction of their travel, with antiparticles having their arrows reversed. Virtual particles are represented by wavy or broken lines and have no arrows. All electromagnetic interactions can be described with combinations of primitive diagrams like this one.





Feynman diagram for like charge repulsion

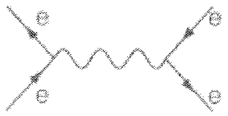
Only lines entering or leaving the diagram represent observable particles. Here two electrons enter, exchange a photon, and then exit. The time and space axes are usually not indicated. The vertical direction indicates the progress of time upward, but the horizontal spacing does not give the distance between the particles.

Other electromagnetic process can be represented, as in the examples below. A backward arrow represents the antiparticle, in these cases a positron. Keep in mind that time progresses upward, and that a downward arrow is not a particle progressing downward, but an antiparticle progressing upward (forward in time).

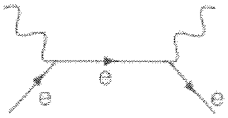
Index

Particle concepts

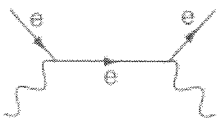
References
Griffiths
Ch 2



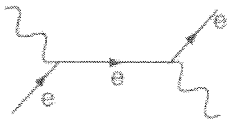
electron-positron attraction



electron-positron annihilation

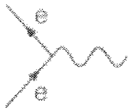


electron-positron pair production

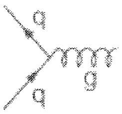


Compton scattering

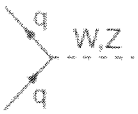
After being introduced for electromagnetic processes, Feynman diagrams were developed for the weak and strong interactions as well. Forms of primitive vertices for these three interactions are



charges
electromagnetic



quarks
strong

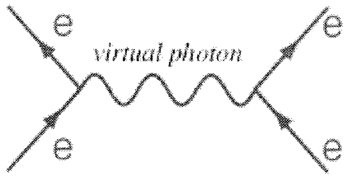


quarks

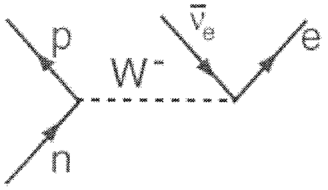
leptons

weak interaction

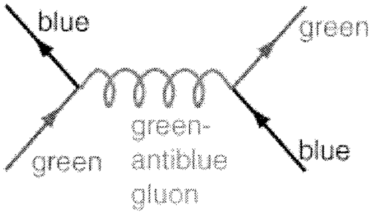
Particle interactions can be represented by diagrams with at least two vertices. They can be drawn for protons, neutrons, etc. even though they are composite objects and the interaction can be visualized as being between their constituent quarks.



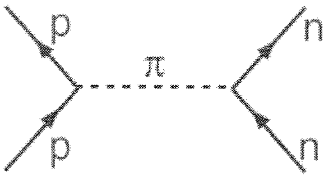
Electromagnetic



Weak



between quarks



between nucleons

Strong Interaction

Feynman diagrams for:

Lamb shift | Neutron decay | Weak interaction | Quark decay | Strong interaction

Twisted Feynman diagrams and crossing symmetry

Go Back

HyperPhysics***** Quantum Physics R Nave

Intermediate Vector Bosons

The W and Z particles are the massive exchange particles which are involved in the nuclear weak interaction, the weak force between electrons and neutrinos. They were predicted by Weinberg, Salam, and Glashow in 1979 and measured at CERN in 1982. The prediction included a prediction of the masses of these particles as a part of the unified theory of the electromagnetic and weak forces, the electroweak unification. "If the weak and electromagnetic forces are essentially the same, then they must also have the same strength. The fact that the experimentally observed strengths seem quite different is attributed to the masses of the W and Z particles- under certain conditions a force of large strength can have the appearance of a force of small strength if the particle that carries the force is very massive. Theoretical calculations show that at a fundamental level the weak and electromagnetic forces have the same strength if the W and Z particles have masses of 80 and 90 GeV respectively." The masses measured at CERN were 82 and 93 GeV, a brilliant confirmation of the electroweak unification.

The experiments at CERN detected a total of 10 W bosons and 4 Z bosons. In the extended experiment at Fermilab's Tevatron known as "Run 1" (1992-96), the D0 detector facility measured over 100,000 W particles. The D0 value for the mass of the W is 80.482 +/- 0.091 GeV. Current values combining the experiments at the Tevatron and at CERN's LEP electron-positron collider are $M_W = 80.41$ +/- 0.18 GeV and $M_Z = 91.1884$ +/- 0.0022 GeV.

Index

Particle concepts

Reference Ohanian Sec 46.5

HyperPhysics***** Quantum Physics R Nave

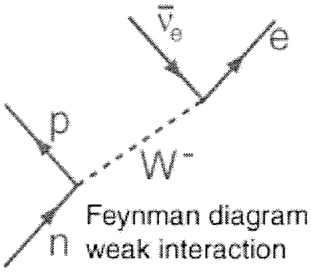
Go Back

Properties of W and Z

The W and Z particles are called intermediate vector bosons and are the exchange particles for the weak interaction. The weak interaction visualized in the Feynman diagram below is responsible for the decay of the neutron and for beta decay.

W^+ W^- 80.4 GeV

Z^0 91.2 GeV



Feynman diagram for weak interaction involved in beta decay.

The charged W bosons participate in the transformation of quarks in which the flavor of the quark is changed. The neutron Z boson does not participate in changing the flavor of quarks, so its interactions are harder to detect. It interacts by influencing the scattering cross sections for neutrinos in what are called "neutral currents".

$$W^{*+} \rightarrow e^+ + \nu_e$$
$$W^{*+} \rightarrow \mu^+ + \nu_\mu$$
$$W^{*+} \rightarrow \tau^+ + \nu_\tau$$
$$W^{*+} \rightarrow u\bar{d}$$
$$W^{*+} \rightarrow c\bar{s}$$

The W bosons can decay by a number of processes, and this provides a variety of decay paths for those particles which decay by the weak interaction. An interesting example is the decay of the D meson.

Feynman diagrams of quark transformations

Index

Particle concepts

Reference Rohlf Ch. 18

HyperPhysics***** Quantum Physics *R Nave*

Go Back

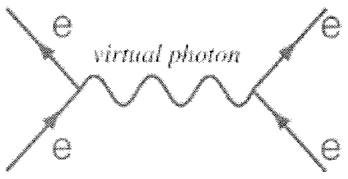
Photon

Photon is the name given to a quantum of light or other electromagnetic radiation. The photon energy is given in the Planck relationship. The photon is the exchange particle responsible for the electromagnetic force. The force between two electrons can be visualized in terms of a Feynman diagram as shown below. The infinite range of the electromagnetic force is owed to the zero rest mass of the photon. While the photon has zero rest mass, it has finite momentum, exhibits deflection by a gravity field, and can exert a force.

The photon has an intrinsic angular momentum or "spin" of 1, so that the electron transitions which emit a photon must result in a net change of 1 in the angular momentum of the system.

Index

Particle concepts



Feynman diagram for the electromagnetic force between two charges.

This is one of the "selection rules" for electron transitions.

HyperPhysics***** Quantum Physics

R Nave

Go Back

Graviton

The graviton is the exchange particle for the gravity force. Although it has not been directly observed, a number of its properties can be implied from the nature of the force. Since gravity is an inverse square force of apparently infinite range, it can be implied that the rest mass of the graviton is zero.

Index

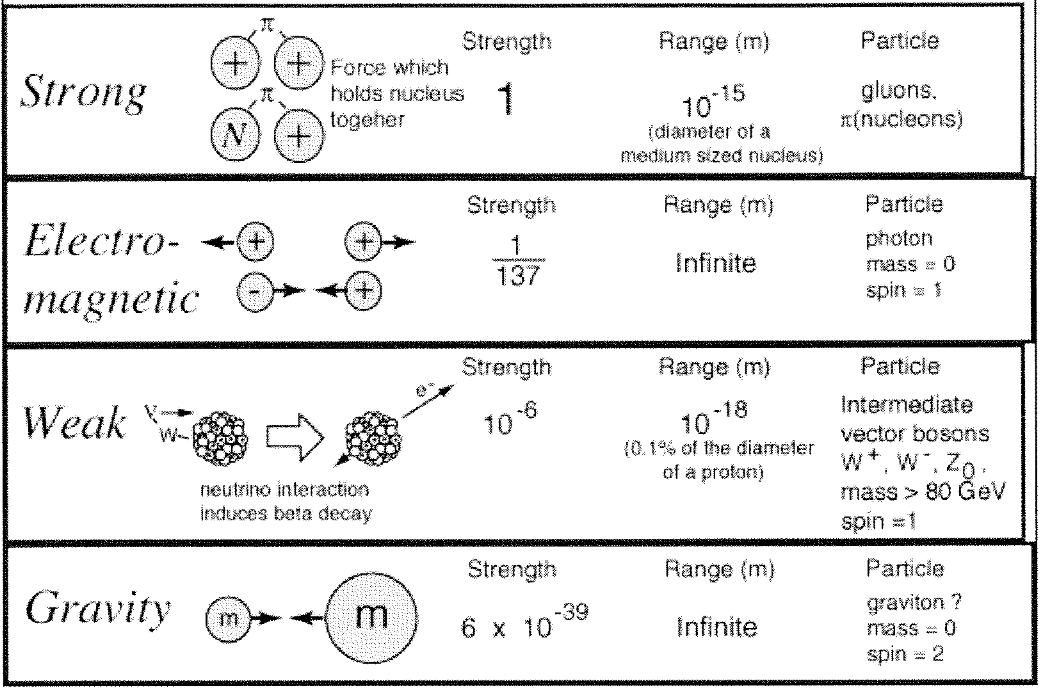
Particle concepts

HyperPhysics***** Quantum Physics

R Nave

Go Back

Fundamental Forces



		Strength	Range (m)	Particle
Strong	Force which holds nucleus togeher	1	10^{-15} (diameter of a medium sized nucleus)	gluons, π(nucleons)
Electro-magnetic		$\frac{1}{137}$	Infinite	photon mass = 0 spin = 1
Weak	neutrino interaction induces beta decay	10^{-6}	10^{-18} (0.1% of the diameter of a proton)	Intermediate vector bosons W^+, W^-, Z_0, mass > 80 GeV spin =1
Gravity		6×10^{-39}	Infinite	graviton ? mass = 0 spin = 2

Index

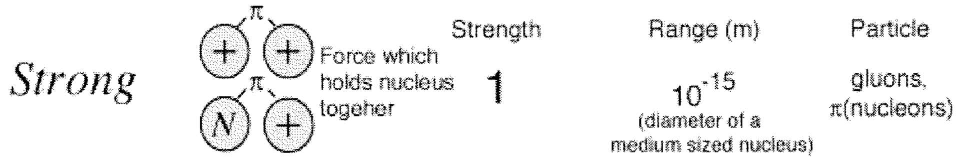
Fundamental force concepts

Coupling constants

HyperPhysics***** Quantum Physics *R Nave*

Go Back

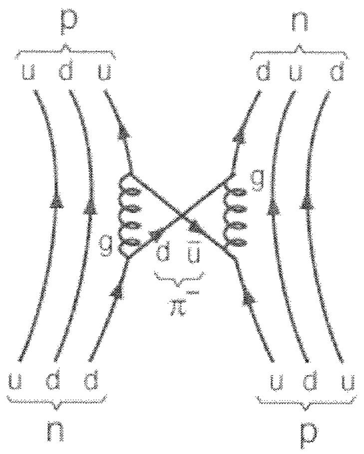
The Strong Force

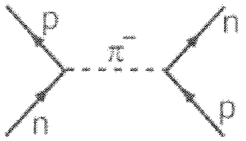


		Strength	Range (m)	Particle
Strong	Force which holds nucleus togeher	1	10^{-15} (diameter of a medium sized nucleus)	gluons, π(nucleons)

A force which can hold a nucleus together against the enormous forces of repulsion of the protons is strong indeed. However, it is not an inverse square force like the electromagnetic force and it has a very short range. Yukawa modeled the strong force as an exchange force in which the exchange particles are pions and other heavier particles. The range of a particle exchange force is limited by the uncertainty principle. It is the strongest of the four fundamental forces

Since the protons and neutrons which make up the nucleus are themselves considered to be made up of quarks, and the quarks are considered to be held together by the color force, the strong force between nucleons may be considered to be a residual color force. In the standard model, therefore, the basic exchange particle is the gluon which mediates the forces between quarks. Since the individual gluons and quarks are contained within the proton or neutron, the masses attributed to them cannot be used in the range relationship to predict the range of the force. When something is viewed as emerging from a proton or neutron, then it must be at least a quark-antiquark pair, so it is then plausible that the pion as the lightest meson should serve as a predictor of the maximum range of the strong force between nucleons.





Index

Fundamental force concepts

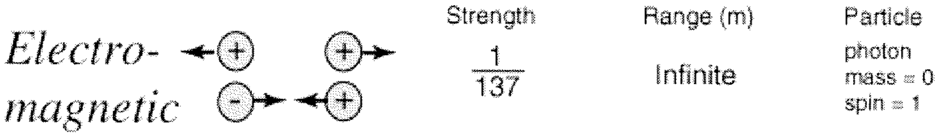
The sketch is an attempt to show one of many forms the gluon interaction between nucleons could take, this one involving up-antiup pair production and annililation and producing a π^- bridging the nucleons.

Feynman diagrams and the strong force

HyperPhysics***** Quantum Physics *R Nave*

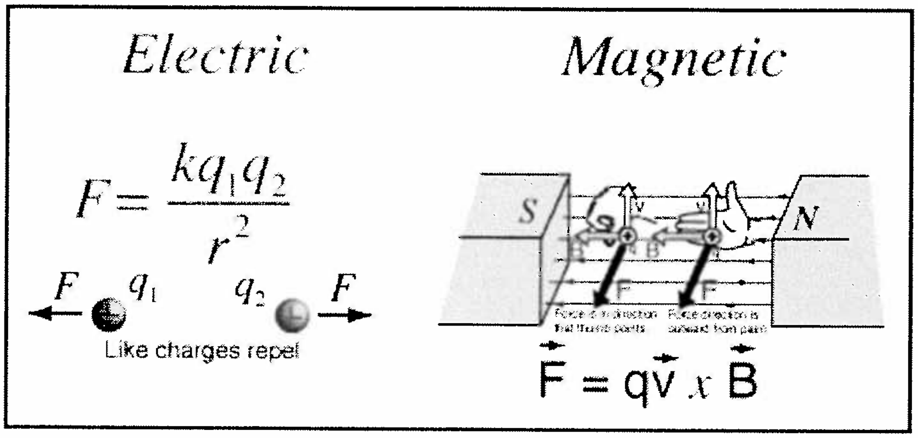
Go Back

The Electromagnetic Force



	Strength	Range (m)	Particle
Electro-magnetic	$\frac{1}{137}$	Infinite	photon mass = 0 spin = 1

One of the four fundamental forces, the electromagnetic force manifests itself through the forces between charges (Coulomb's Law) and the magnetic force, both of which are summarized in the Lorentz force law. Fundamentally, both magnetic and electric forces are manifestations of an exchange force involving the exchange of photons . The quantum approach to the electromagnetic force is called quantum electrodynamics or QED. The electromagnetic force is a force of infinite range which obeys the inverse square law, and is of the same form as the gravity force.



The electromagnetic force holds atoms and molecules together. In fact, the forces of electric attraction and repulsion of electric charges are so dominant over the other three fundamental forces that they can be considered to be negligible as determiners of atomic and molecular structure. Even magnetic effects are usually apparent only at high resolutions, and as small corrections.

Index

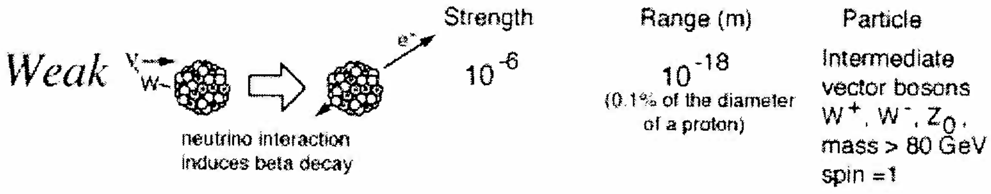
Fundamental force concepts

HyperPhysics***** Quantum Physics

R Nave

Go Back

The Weak Force



Strength	Range (m)	Particle
10^{-6}	10^{-18} (0.1% of the diameter of a proton)	Intermediate vector bosons W^+, W^-, Z_0, mass > 80 GeV spin =1

One of the four fundamental forces, the weak interaction involves the exchange of the intermediate vector bosons, the W and the Z. Since the mass of these particles is on the order of 80 GeV, the uncertainty principle dictates a range of about 10^{-18} meters which is about 0.1% of the diameter of a proton.

The weak interaction changes one flavor of quark into another. It is crucial to the structure of the universe in that

1. The sun would not burn without it since the weak interaction causes the

Index

transmutation p -> n so that deuterium can form and deuterium fusion can take place.

2. It is necessary for the buildup of heavy nuclei.

The role of the weak force in the transmutation of quarks makes it the interaction involved in many decays of nuclear particles which require a change of a quark from one flavor to another. It was in radioactive decay such as beta decay that the existence of the weak interaction was first revealed. The weak interaction is the only process in which a quark can change to another quark, or a lepton to another lepton - the so-called "flavor changes".

The discovery of the W and Z particles in 1983 was hailed as a confirmation of the theories which connect the weak force to the electromagnetic force in electroweak unification.

The weak interaction acts between both quarks and leptons, whereas the strong force does not act between leptons. "Leptons have no color, so they do not participate in the strong interactions; neutrinos have no charge, so they experience no electromagnetic forces; but *all* of them join in the weak interactions."(Griffiths)

Show Feynmann diagrams

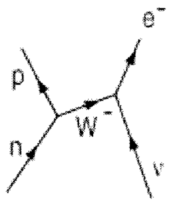
Fundamental force concepts

Reference Griffiths Ch 2

HyperPhysics***** Quantum Physics *R Nave*

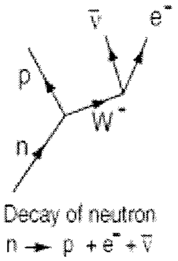
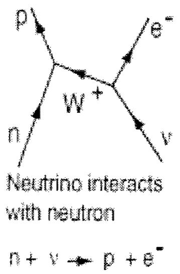
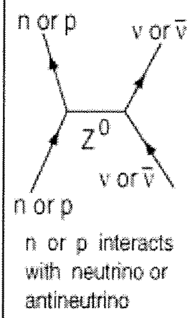
Go Back

Feynman Diagrams for Weak Force



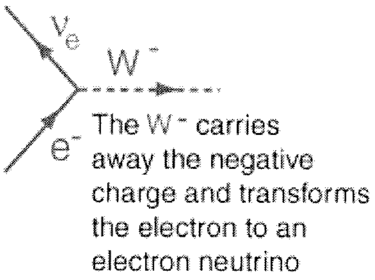
Neutrino interacts with neutron

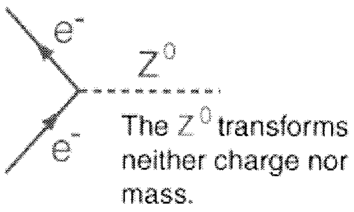
$n + \nu \rightarrow p + e^-$

 A free neutron will decay by emitting a W^-, which produces an electron and an antineutrino.	When a neutrino interacts with a neutron, a W^- can be exchanged, transforming the neutron into a proton and producing an electron.	 This interaction is the same as the one at left since a W^+ going right to left is equivalent to a W^- going left to right.	 A neutron or proton can interact with a neutrino or antineutrino by the exchange of a Z^0.

One of the four fundamental forces, the weak interaction involves the exchange of the intermediate vector bosons, the W and the Z. Since the mass of these particles is on the order of 80 GeV, the uncertainty principle dictates a range of about 10^{-18} meters which is about .1% of the diameter of a proton. The weak interaction changes one flavor of quark into another. For example, in the neutron decay depicted by the Feynman diagram at left above, one down quark is changed to an up quark, transforming the neutron into a proton.

The primitive vertices in the Feynman diagrams for the weak interaction are of two types, charged and neutral. For leptons they take the following form





The electron is used as an example in these diagrams, but any lepton can be substituted on the incoming side. The exit side (top) will be the same for the neutral vertex, but determined by the charge of the W in the charged vertex. Besides conserving charge, the vertex must conserve lepton number, so the process with the electron can produce an electron neutrino but not a muon neutrino.

The neutral interaction is simpler to conceive, but rarely observed because it competes with the much stronger

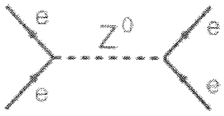
Index

Fundamental force concepts

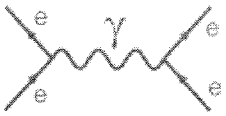
Reference Kaufmann Ch. 29

Griffiths

electromagnetic interaction and is masked by it.

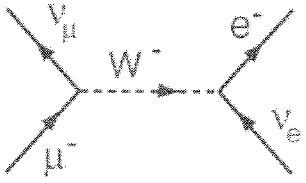


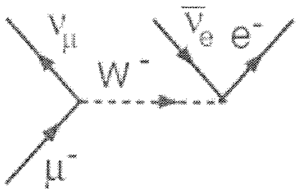
Neutral weak interaction



Electromagnetic interaction

With the charged vertices, one can postulate an interaction like $\mu, \nu_e \rightarrow e, \nu_\mu$ and draw a Feynman diagram for it. This interaction is not likely to be oberved because of the incredible difficulty of observing the scattering of neutrinos, but it suggests other interactions which may be obtained by rotating or twisting the diagram.

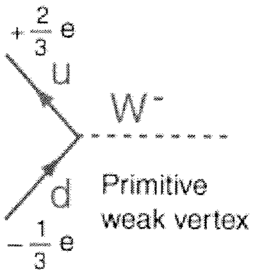


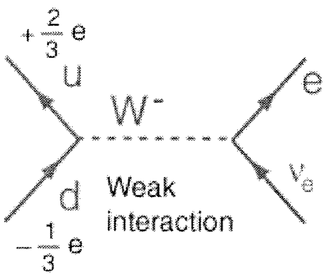


With a twist of the Feynman diagram above, one can arrive at the interaction responsible for the decay of the muon, so the structures obtained from the primitive vertices can be used to build up a family of interactions. The transformation between the two Feynman diagrams can also be seen as an example of crossing symmetry.

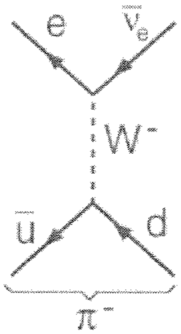
Twisted Feynman diagrams and crossing symmetry

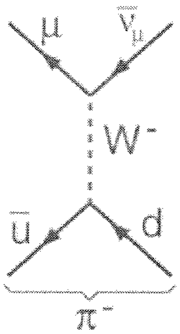
The charged vertices in the weak interaction with quarks take the form





So it is seen that the quark changes its flavor when interacting via the W^- or W^+. As drawn, this interaction cannot be observed because it implies the isolation of an up quark. Because of quark confinement, isolated quarks are not observed. But rotating the Feynman diagram gives an alternative interaction, shown below for both electron and muon products.





This suggests the weak interaction mechanism for the decay of the pion, which is observed to happen by the muon pathway.

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

The weak interaction in the electron form at left above is responsible for the decay of the neutron and for beta decay in general.

Discussion of weak force

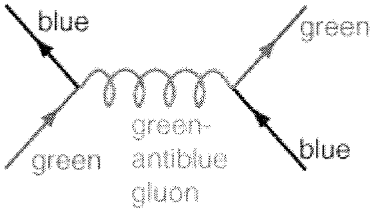
HyperPhysics***** Quantum Physics *R Nave*

Go Back

Gluons

Gluons are the exchange particles for the color force between quarks, analogous to the exchange of photons in the electromagnetic force between two charged particles. The gluon can be considered to be the fundamental exchange particle underlying the strong interaction between protons and neutrons in a nucleus. That short-range nucleon-nucleon interaction can be considered to be a residual color force extending outside the boundary of the proton or neutron. That strong interaction was modeled by Yukawa as involving an exchange of pions, and indeed the pion range calculation was helpful in developing our understanding of the strong force.

Gluon interactions are often represented by a Feynman diagram. Note that the gluon generates a color change for the quarks. The gluons are in fact considered to be bi-colored, carrying a unit of color and a unit of anti-color as suggested in the diagram at right. The gluon exchange picture there converts a blue quark to a green one and vice versa. The range of the strong force is limited by the fact that the gluons interact with each other as well as with quarks in the context of quark confinement. These properties contrast them with photons, which are massless and of infinite range. The photon does not carry electric charge with it, while the gluons do carry the "color charge".



Feynman diagram for an interaction between quarks generated by a gluon.

Within their range of about a fermi, the gluons can interact with each other, and can produce virtual quark-antiquark pairs. The property of interaction with each other is very different from the other exchange particles, and raises the possibility of gluon collections referred to as "glueballs". The internal state of a hadron is viewed as composed of a fixed net number of quarks, but with a dynamic cloud of gluons and quark-antiquark pairs in equilibrium.

Index

Particle concepts

Reference Griffiths Section 2.3

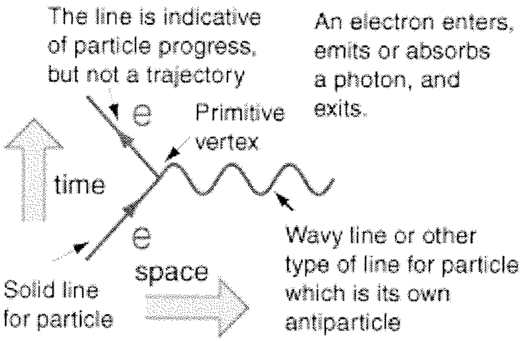
HyperPhysics***** Quantum Physics *R Nave*

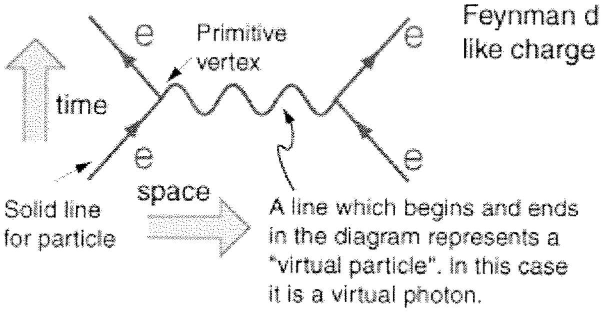
Go Back

Feynman Diagrams

Feynman diagrams are graphical ways to represent exchange forces. Each point at which lines come together is called a vertex, and at each vertex one may examine the conservation laws which govern particle interactions. Each vertex must conserve charge, baryon number and lepton number.

Developed by Feynman to decribe the interactions in quantum electrodynamics (QED), the diagrams have found use in describing a variety of particle interactions. They are spacetime diagrams, ct vs x. The time axis points upward and the space axis to the right. (Particle physicists often reverse that orientation.) Particles are represented by lines with arrows to denote the direction of their travel, with antiparticles having their arrows reversed. Virtual particles are represented by wavy or broken lines and have no arrows. All electromagnetic interactions can be described with combinations of primitive diagrams like this one.





Feynman diagram for like charge repulsion

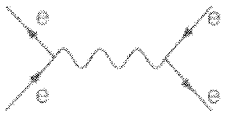
Only lines entering or leaving the diagram represent observable particles. Here two electrons enter, exchange a photon, and then exit. The time and space axes are usually not indicated. The vertical direction indicates the progress of time upward, but the horizontal spacing does not give the distance between the particles.

Other electromagnetic process can be represented, as in the examples below. A backward arrow represents the antiparticle, in these cases a positron. Keep in mind that time progresses upward, and that a downward arrow is not a particle progressing downward, but an antiparticle progressing upward (forward in time).

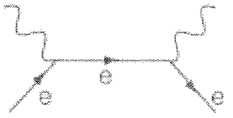
Index

Particle concepts

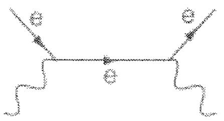
References
Griffiths
Ch 2



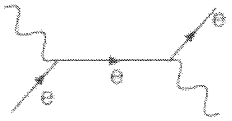
electron-positron attraction



electron-positron annihilation

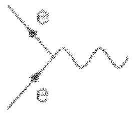


electron-positron pair production

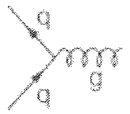


Compton scattering

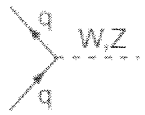
After being introduced for electromagnetic processes, Feynman diagrams were developed for the weak and strong interactions as well. Forms of primitive vertices for these three interactions are



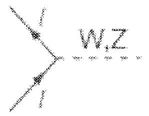
charges
electromagnetic



quarks
strong



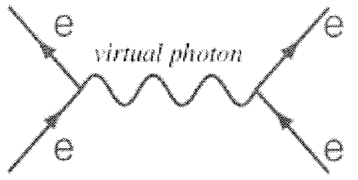
quarks



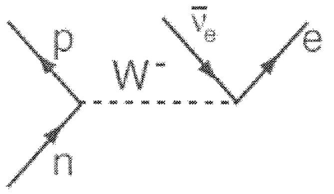
leptons

weak interaction

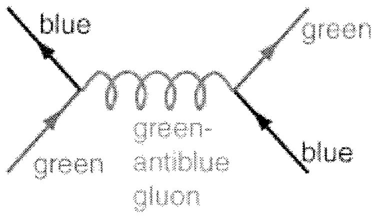
Particle interactions can be represented by diagrams with at least two vertices. They can be drawn for protons, neutrons, etc. even though they are composite objects and the interaction can be visualized as being between their constituent quarks.



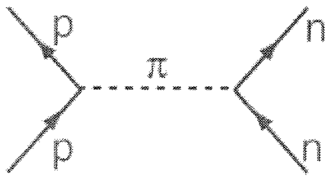
Electromagnetic



Weak



between quarks



between nucleons

Strong Interaction

Feynman diagrams for:

Lamb shift | Neutron decay | Weak interaction | Quark decay | Strong interaction

Twisted Feynman diagrams and crossing symmetry

Go Back

HyperPhysics***** Quantum Physics *R Nave*

Intermediate Vector Bosons

The W and Z particles are the massive exchange particles which are involved in the nuclear weak interaction, the weak force between electrons and neutrinos. They were predicted by Weinberg, Salam, and Glashow in 1979 and measured at CERN in 1982. The prediction included a prediction of the masses of these particles as a part of the unified theory of the electromagnetic and weak forces, the electroweak unification. "If the weak and electromagnetic forces are essentially the same, then they must also have the same strength. The fact that the experimentally observed strengths seem quite different is attributed to the masses of the W and Z particles- under certain conditions a force of large strength can have the appearance of a force of small strength if the particle that carries the force is very massive. Theoretical calculations show that at a fundamental level the weak and electromagnetic forces have the same strength if the W and Z particles have masses of 80 and 90 GeV respectively." The masses measured at CERN were 82 and 93 GeV, a brilliant confirmation of the electroweak unification.

The experiments at CERN detected a total of 10 W bosons and 4 Z bosons. In the extended experiment at Fermilab's Tevatron known as "Run 1" (1992-96), the D0 detector facility measured over 100,000 W particles. The D0 value for the mass of the W is 80.482 +/- 0.091 GeV. Current values combining the experiments at the Tevatron and at CERN's LEP electron-positron collider are M_W = 80.41 +/- 0.18 GeV and M_Z = 91.1884 +/- 0.0022 GeV.

Index

Particle concepts

Reference Ohanian Sec 46.5

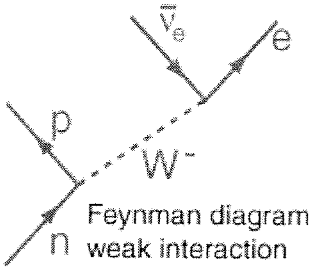
HyperPhysics***** Quantum Physics *R Nave* Go Back

Properties of W and Z

The W and Z particles are called intermediate vector bosons and are the exchange particles for the weak interaction. The weak interaction visualized in the Feynman diagram below is responsible for the decay of the neutron and for beta decay.

W^+ W^- 80.4 GeV

Z^0 91.2 GeV



Feynman diagram for weak interaction involved in beta decay.

The charged W bosons participate in the transformation of quarks in which the flavor of the quark is changed. The neutron Z boson does not participate in changing the flavor of quarks, so its interactions are harder to detect. It interacts by influencing the scattering cross sections for neutrinos in what are called "neutral currents".

$$W^{*+} \rightarrow e^+ + \nu_e$$
$$W^{*+} \rightarrow \mu^+ + \nu_\mu$$
$$W^{*+} \rightarrow \tau^+ + \nu_\tau$$
$$W^{*+} \rightarrow u\bar{d}$$
$$W^{*+} \rightarrow c\bar{s}$$

The W bosons can decay by a number of processes, and this provides a variety of decay paths for those particles which decay by the weak interaction. An interesting example is the decay of the D meson.

Feynman diagrams of quark transformations

Index

Particle concepts

Reference
Rohlf
Ch. 18

HyperPhysics***** Quantum Physics *R Nave*

Go Back

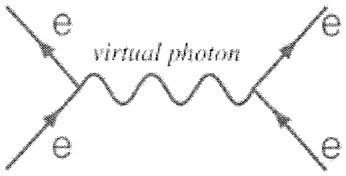
Photon

Photon is the name given to a quantum of light or other electromagnetic radiation. The photon energy is given in the Planck relationship. The photon is the exchange particle responsible for the electromagnetic force. The force between two electrons can be visualized in terms of a Feynman diagram as shown below. The infinite range of the electromagnetic force is owed to the zero rest mass of the photon. While the photon has zero rest mass, it has finite momentum, exhibits deflection by a gravity field, and can exert a force.

Index

Particle concepts

The photon has an intrinsic angular momentum or "spin" of 1, so that the electron transitions which emit a photon must result in a net change of 1 in the angular momentum of the system.



Feynman diagram for the electromagnetic force between two charges.

This is one of the "selection rules" for electron transitions.

HyperPhysics***** Quantum Physics *R Nave*

Go Back

Graviton

The graviton is the exchange particle for the gravity force. Although it has not been directly observed, a number of its properties can be implied from the nature of the force. Since gravity is an inverse square force of apparently infinite range, it can be implied that the rest mass of the graviton is zero.

Index

Particle concepts

HyperPhysics***** Quantum Physics *R Nave*

Go Back