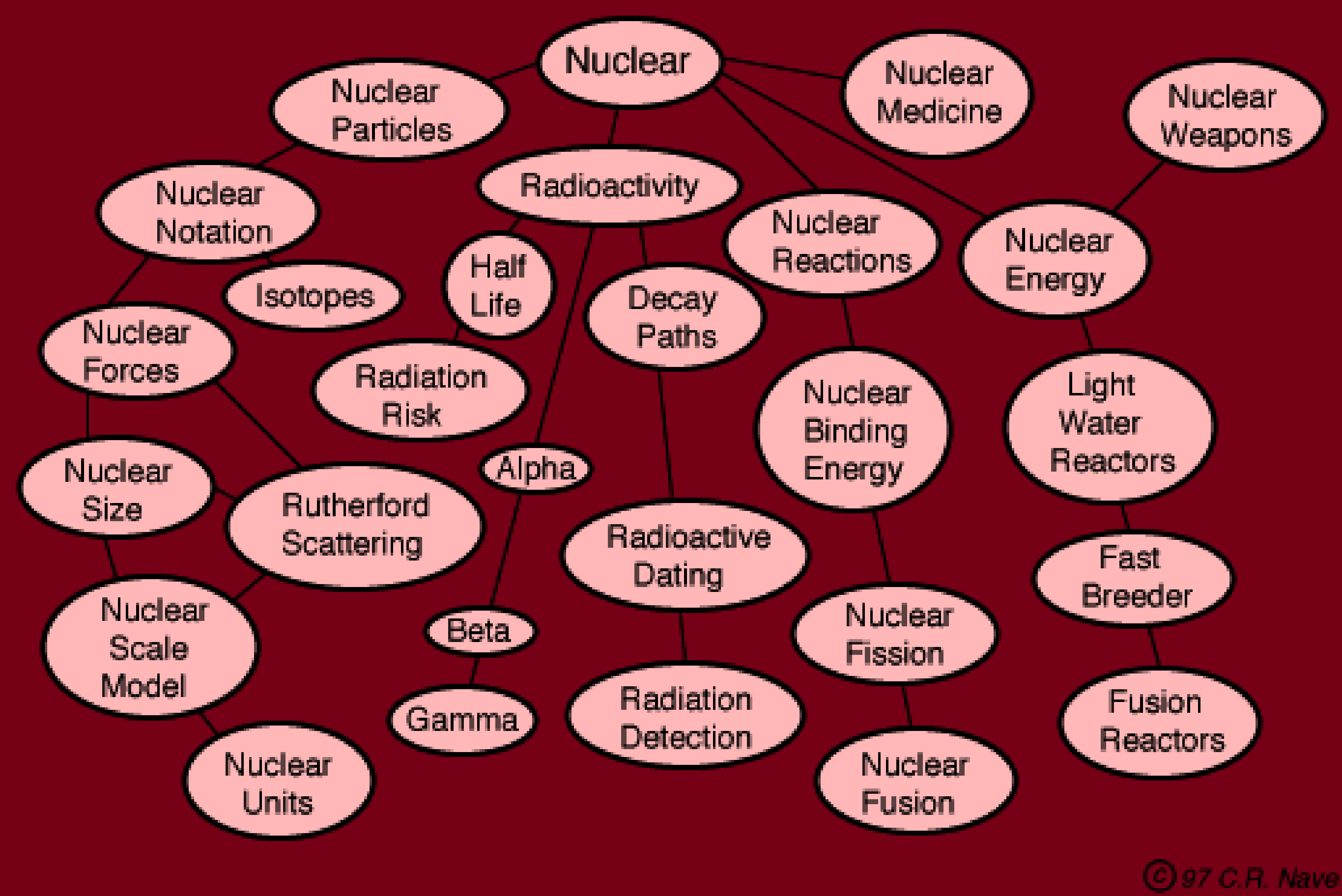
Nuclear
Nuclear Particles
Nuclear Medicine
Nuclear Weapons
Radioactivity
Nuclear Notation
Nuclear Reactions
Nuclear Energy
Isotopes
Half Life
Decay Paths
Nuclear Forces
Radiation Risk
Nuclear Binding Energy
Light Water Reactors
Nuclear Size
Alpha
Rutherford Scattering
Radioactive Dating
Fast Breeder
Nuclear Scale Model
Beta
Nuclear Fission
Gamma
Radiation Detection
Fusion Reactors
Nuclear Units
Nuclear Fusion
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Radioactive Dating

Because the radioactive half-life of a given radioisotope is not affected by temperature, physical or chemical state, or any other influence of the environment outside the nucleus save direct particle interactions with the nucleus, then radioactive samples continue to decay at a predictable rate. That is, any radioactive nucleus acts as a clock. If determinations or reasonable estimates of the original composition of a radioactive sample can be made, then the amounts of the radioisotopes present can provide a measurement of the time elapsed.

One such method is called carbon dating, which is limited to the dating of organic (once living) materials. The longer-lived radioisotopes in minerals provide evidence of long time scales in geological processes. While original compositions cannot be determined with certainty, various combination measurements provide self-consistent values for the the times of formations of certain geologic deposits. These clocks-in-the-rocks methods provide data for modeling the formation of the Earth and solar system.

More detail about dating process

A brief overview of time.

Index

HyperPhysics***** Nuclear

R Nave

Go Back

Radioactive Dating

Because the radioactive half-life of a given radioisotope is not affected by temperature, physical or chemical state, or any other influence of the environment outside the nucleus save direct particle interactions with the nucleus, then radioactive samples continue to decay at a predictable rate and can be used as a clock. This makes several types of radioactive dating feasible. For geologic dating, where the time span is on the order of the age of the earth and the methods use the clocks in the rocks, there are two main uncertainties in the dating process:

1. What was the amount of the daughter element when the rocks were formed?
2. Have any of the parent or daughter atoms been added or removed during the process?

Starting with the simplest case where there are no daughter atoms present and no mass is lost from the sample, the age can be determined by measuring the relative amounts of the isotopes. This can be done by chemical means, but for precise determinations, mass spectrometry can be used. From the radioactive decay equations, an expression for elapsed time can be developed. Using the common nuclear practice of calling the isotopes "parent" and "daughter", we use P and D to indicate the associated numbers of atoms. The requirement of keeping the same number of nuclei gives

$$N_D(t_1) + N_P(t_1) = N_P(t_0)$$

and the radioactive decay relationship is

$$N_P(t_1) = N_P(t_0)e^{-\lambda(t_1 - t_0)}$$

The elapsed time is then

$$\Delta t = t_1 - t_0 = \frac{1}{\lambda}\ln\left[\frac{N_P(t_0)}{N_P(t_1)}\right]$$

but with the use of the first expression above can be expressed in terms of the present concentrations of the parent and daughter isotopes.

$$\Delta t = \frac{1}{\lambda}\ln\left[1 + \frac{N_D(t_1)}{N_P(t_1)}\right]$$

Now suppose that there was an original amount of the daughter element present at the formation time of the sample being studied. This adds an additional unknown in the process, and requires an additional piece of data to permit a solution for elapsed time. The requirement on the populations is now

$$N_D(t_1) + N_P(t_1) = N_D(t_0) + N_P(t_0)$$

Fortunately for radioactive dating processes, additional information is available in the form of other isotopes of the elements involved in the radioactive process. If there is another isotope of the daugther element D' which is presumed to be constant throughout the process, then the population requirement can be expressed in terms of the ratios

$$\frac{N_D(t_1) + N_P(t_1)}{N_{D'}(t_1)} = \frac{N_D(t_0) + N_P(t_0)}{N_{D'}(t_0)}$$

We can be reasonably confident that the isotope D' is contant if it is not radioactive (not part of one of the natural radioactive series). Using the radioactive decay equation as above, this becomes

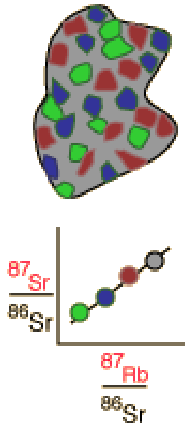
$$\frac{N_D(t_1)}{N_{D'}(t_1)} = \frac{N_P(t_1)}{N_{D'}(t_1)}\left[e^{-\lambda(t_1 - t_0)} - 1\right] + \frac{N_D(t_0)}{N_{D'}(t_0)}$$

We still have too many unknowns to solve directly for the age, but it is a reasonable presumption that all the minerals which crystallize together should show identical ages and identical isotopic ratios $N_D/N_{D'}$. We can then plot the ratio $y = N_D(t_1)/N_{D'}(t_1)$ against $x = N_P(t_1)/N_{D'}(t_1)$ for a number of minerals in a given crystalline sample and take the slope of the line. The age can then be calculated from that slope as follows:

$$y = x\left[e^{-\lambda(t_1 - t_0)} - 1\right] + y_0$$

Index

Reference
Krane
Sec 6.7



$$\frac{dy}{dx} = e^{-\lambda(t_1 - t_0)} - 1 \quad = slope \;\; of \;\; line$$

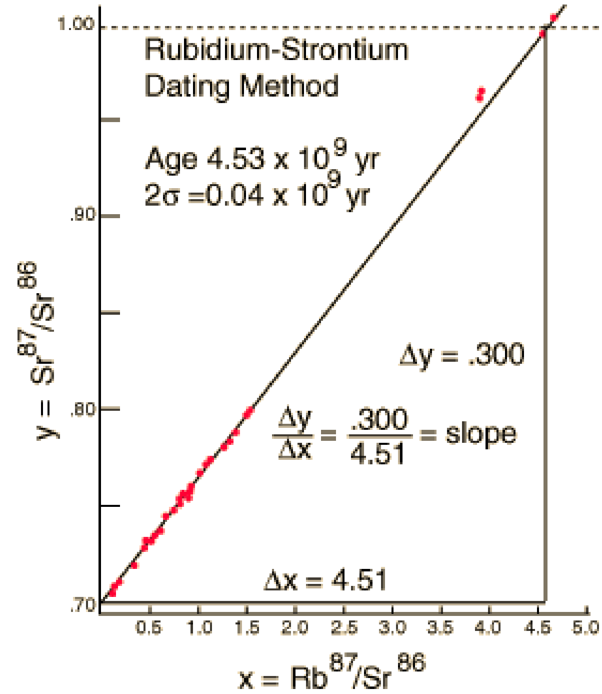
$$\Delta t = \frac{1}{\lambda}\ln\left[1 + \frac{dy}{dx}\right] = calculated\ age$$

This calculation is expressed in terms of the decay constant λ, which is related to the half-life of the isotope.

Example

Rubidium/Strontium Dating Example

For geologic dating, the age calculation must take into account the presence of the radioactive species at the beginning of the time interval. If there is a non-radiogenic isotope of the daughter element present in the mineral, it can be used as a reference and the ratios of the parent and daughter elements plotted as ratios with that reference isotope. The slope of the curve then gives the time interval.



$$\Delta t = \frac{1}{\lambda}\ln\left[1+\frac{\Delta y}{\Delta x}\right] = \textit{calculated age}$$

$$\Delta t = 4.53 \times 10^9 \text{ yrs}$$

$$T_{1/2} = 48.8 \times 10^9 \text{ yrs} \qquad \frac{1}{\lambda} = \frac{T_{1/2}}{0.693}$$

Rubidium/Strontium Radioactive Dating

Reference
Krane
Sec 6.7

HyperPhysics***** Nuclear

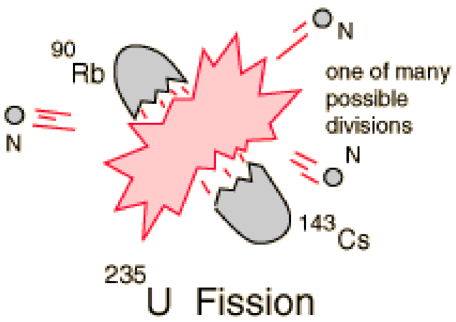
R Nave

Go Back

Nuclear Fission

If a massive nucleus like uranium-235 breaks apart (fissions), then there will be a net yield of energy because the sum of the masses of the fragments will be less than the mass of the uranium nucleus. If the mass of the fragments is equal to or greater than that of iron at the peak of the binding energy curve, then the nuclear particles will be more tightly bound than they were in the uranium nucleus, and that decrease in mass comes off in the form of energy according to the Einstein equation. For elements lighter than iron, fusion will yield energy.

The fission of U-235 in reactors is triggered by the absorption of a low energy neutron, often termed a "slow neutron" or a "thermal neutron". Other fissionable isotopes which can be induced to fission by slow neutrons are plutonium-239, uranium-233, and thorium-232.



Uranium-235 Fission

Index

Fission concepts

HyperPhysics***** Nuclear

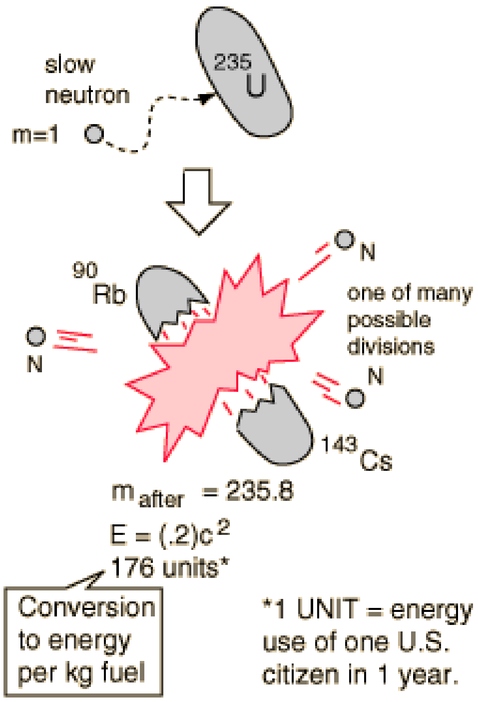
R Nave

Go Back

Uranium-235 Fission

In one of the most remarkable

phenomena in nature, a slow neutron can be captured by a uranium-235 nucleus, rendering it unstable toward nuclear fission. A fast neutron will not be captured, so neutrons must be slowed down by moderation to increase their capture probability in fission reactors. A single fision event can yield over 200 million times the energy of the neutron which triggered it!



Index

Fission concepts

More detailed illustration	Comparison with fusion	Some history.

Detailed energy release calculation

HyperPhysics***** Nuclear

R Nave

Go Back

Uranium Fuel

Natural uranium is composed of 0.72% U-235 (the fissionable isotope), 99.27% U-238, and a trace quantity 0.0055% U-234 . The 0.72% U-235 is not sufficient to produce a self-sustaining critical chain reaction in U.S. style light-water reactors, although it is used in Canadian CANDU reactors. For light-water reactors, the fuel must be enriched to 2.5-3.5% U-235.

Uranium is found as uranium oxide which when purified has a rich yellow color and is called "yellowcake". After reduction, the uranium must go through an

Index

isotope enrichment process. Even with the necessity of enrichment, it still takes only about 3 kg of natural uranium to supply the energy needs of one American for a year.		
HyperPhysics***** Nuclear	*R Nave*	Go Back

Fissionable Isotopes

While uranium-235 is the naturally occuring fissionable isotope, there are other isotopes which can be induced to fission by neutron bombardment. Plutonium-239 is also fissionable by bombardment with slow neutrons, and both it and uranium-235 have been used to make nuclear fission bombs. Plutonium-239 can be produced by "breeding" it from uranium-238. Uranium-238, which makes up 99.3% of natural uranium, is not fissionable by slow neutrons. U-238 has a small probability for spontaneous fission and also a small probability of fission when bombarded with fast neutrons, but it is not useful as a nuclear fuel source. Some of the nuclear reactors at Hanford, Washington and the Savannah-River Plant (SC) are designed for the production of bomb-grade plutonium-239. Thorium-232 is fissionable, so could conceivably be used as a nuclear fuel. The only other isotope which is known to undergo fission upon slow-neutron bombardment is uranium-233.

Nuclear fission

Index

HyperPhysics***** Nuclear	*R Nave*	Go Back

History of U-235 Fission

In the 1930s, German physicists/chemists Otto Hahn and Fritz Strassman attempted to create transuranic elements by bombarding uranium with neutrons. Rather than the heavy elements they expected, they got several unidentified products. When they finally identified one of the products as Barium-141, they were reluctant to publish the finding because it was so unexpected. When they finally published the results in 1939, they came to the attention of Lise Meitner, an Austrian-born physicist who had worked with Hahn on his nuclear experiments. Upon Hitler's invasion of Austria, she had been forced to flee to Sweden where she and Otto Frisch, her nephew, continued to work on the neutron bombardment problem. She was the first to realize that Hahn's barium and other lighter products from the neutron bombardment experiments were coming from the fission of U-235. Frisch and Meitner carried out further experiments which showed that the U-235 fission yielded an enormous amount of energy, and that the fission yielded at least two neutrons per neutron absorbed in the interaction. They realized that this made possible a chain reaction with an unprecedented energy yield.

Index

HyperPhysics***** Nuclear

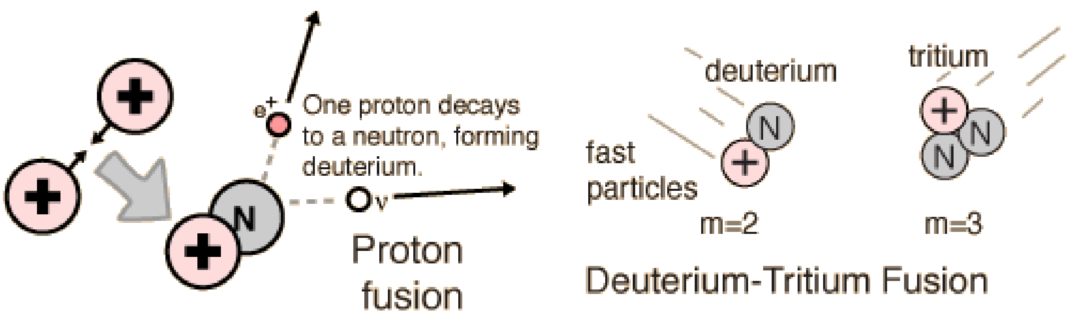
R Nave

Go Back

Nuclear Fusion

If light nuclei are forced together, they will fuse with a yield of energy because the mass of the combination will be less than the sum of the masses of the individual nuclei. If the combined nuclear mass is less than that of iron at the peak of the binding energy curve, then the nuclear particles will be more tightly bound than they were in the lighter nuclei, and that decrease in mass comes off in the form of energy according to the Einstein relationship. For elements heavier than iron, fission will yield energy.

For potential nuclear energy sources for the Earth, the deuterium-tritium fusion reaction contained by some kind of magnetic confinement seems the most likely path. However, for the fueling of the stars, other fusion reactions will dominate.



Fusion reactors	Conditions for fusion

Index

Fusion concepts

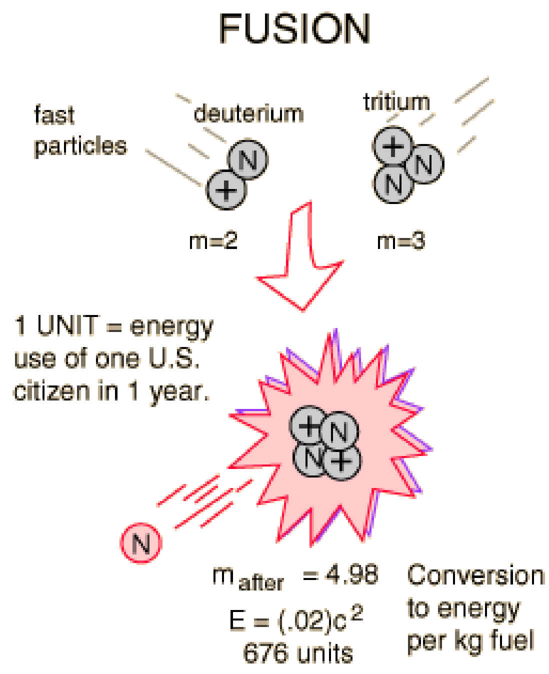
HyperPhysics***** Nuclear

Go Back

R Nave

Deuterium-Tritium Fusion

The most promising of the hydrogen fusion reactions which make up the deuterium cycle is the fusion of deuterium and tritium. The reaction yields 17.6 MeV of



energy but requires a temperature of approximately 40 million Kelvins to overcome the coulomb barrier and ignite it. The deuterium fuel is abundant, but tritium must be either bred from lithium or gotten in the operation of the deuterium cycle.

Compare with fission

Conditions for fusion

Index

Fusion concepts

HyperPhysics***** Nuclear

R Nave

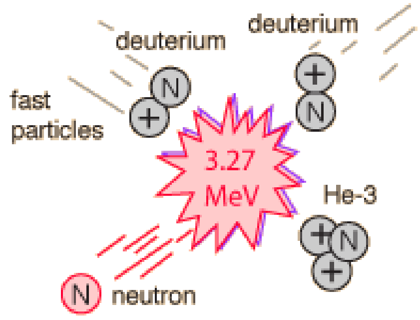
Go Back

Hydrogen Fusion Reactions

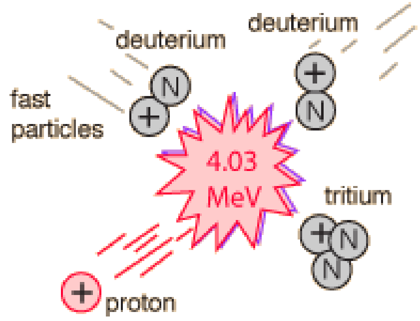
Even though a lot of energy is required to overcome the Coulomb barrier and initiate hydrogen fusion, the energy yields are enough to encourage continued research. Hydrogen fusion on the earth could make use of the reactions:

$$ {}^2_1H + {}^2_1H \rightarrow {}^3_2He + {}^1_0n + 3.27\,MeV $$

Deuterium-deuterium Fusion

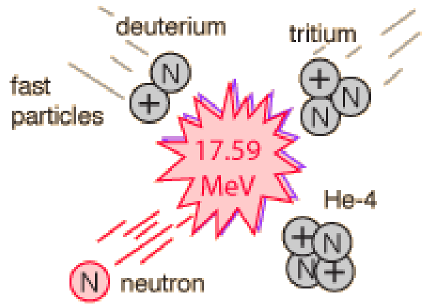


$$ {}^2_1H + {}^2_1H \rightarrow {}^3_1H + {}^1_1H + 4.03\,MeV $$



$$ {}^2_1H + {}^3_1H \rightarrow {}^4_2He + {}^1_0n + 17.59\,MeV $$

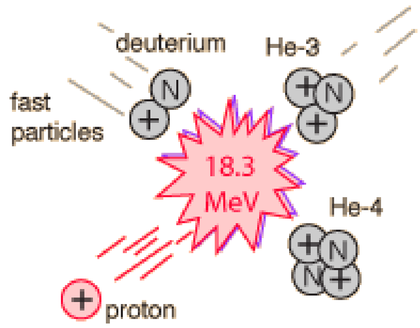
Deuterium-tritium Fusion



These reactions are more promising than the proton-proton fusion of the stars for potential energy sources. Of these the deuterium-tritium fusion appears to be the most promising and has been the subject of most experiments. In a deuterium-deuterium reactor, another reaction could also occur, creating a deuterium cycle:

$$ {}^2_1H + {}^3_2He \rightarrow {}^4_2He + {}^1_1H + 18.3\,MeV $$

Deuterium-helium-3 Fusion



Index

Fusion concepts

HyperPhysics***** Nuclear

Go Back

R Nave

Deuterium Cycle of Fusion

The four fusion reactions which can occur with deuterium can be considered to form a deuterium cycle. The four reactions:

$$^2_1H + ^2_1H \rightarrow ^3_2He + ^1_0n + 3.27MeV$$
$$^2_1H + ^2_1H \rightarrow ^3_1H + ^1_1H + 4.03MeV$$
$$^2_1H + ^3_1H \rightarrow ^4_2He + ^1_0n + 17.59MeV$$
$$^2_1H + ^3_2He \rightarrow ^4_2He + ^1_1H + 18.3MeV$$

can be combined as

$$6^2_1H + ^3_1H + ^3_2He \rightarrow 2^4_2He + ^3_2He + ^3_1H + 2^1_1H + 2^1_0n + 43.2MeV$$

or, omitting those constituents whose concentrations do not change:

$$6^2_1H \rightarrow 2^4_2He + 2^1_1H + 2^1_0n + 43.2MeV$$

Index

Fusion concepts

HyperPhysics***** Nuclear

R Nave

Go Back

Tritium Breeding

Deuterium-Tritium fusion is the most promising of the hydrogen fusion reactions, but no tritium occurs in nature since it has a 10 year half-life. The most promising source of tritium seems to be the breeding of tritium from lithium-6 by neutron bombardment with the reaction

$$^6_3Li + ^1_0n \rightarrow ^4_2He + ^3_1H + 4.8MeV$$

which can be achieved by slow neutrons. This would occur if lithium were used as the coolant and heat transfer medium around

Index

Fusion concepts

the reaction chamber of a fusion reactor. Lithium-6 makes up 7.4% of natural lithium. While this constitutes a sizable supply, it is the limiting resource for the D-T process since the supply of deuterium fuel is virtually unlimited. With fast neutrons, tritium can be bred from the more abundant Li-7:

$$ {}^{1}_{0}n(fast) + {}^{7}_{3}Li \rightarrow {}^{3}_{1}H + {}^{3}_{2}He + {}^{1}_{0}n(slow) $$

HyperPhysics***** Nuclear R Nave Go Back

Deuterium Source

Since the most practical nuclear fusion reaction for power generation seems to be the deuterium-tritium reaction, the sources of these fuels are important. The deuterium part of the fuel does not pose a great problem because about 1 part in 5000 of the hydrogen in seawater is deuterium. This amounts to over 10^{15} tons of deuterium. Viewed as a potential fuel for a fusion reactor, a gallon of seawater could produce as much energy as 300 gallons of gasoline. The tritium part of the fuel is more problematic - there is no sizable natural source since tritium is radioactive with a halflife of about 10 years. It would have to be obtained by breeding the tritium from lithium.

Index

Fusion concepts

HyperPhysics***** Nuclear R Nave Go Back

Nuclear Medicine

There are a number of processes involved in health care that make use of the properties of the nucleus. Nuclear medicine is a broad term encompassing both diagnostic and therapeutic processes. To some extent this is unfortunate, since in the cases where nuclear radiation is involved the doses involved in diagnostic procedures are very small and those in therapeutic applications are very large. It is therefore important to make clear distinctions between the risks involved in diagnostic and therapeutic applications. Still another class of processes include diagnostic procedures such as magnetic resonance imaging which involve nuclear properties but do not involve any exposure to ionizing radiation.

Index

Nuclear Applications to Health

Nuclear Diagnostic Procedures with No Ionizing Radiation

Magnetic Resonance Imaging (MRI)

Nuclear Diagnostic Procedures with Low Dose Radiation

Myocardial Perfusion Imaging | PET Scan

Nuclear Therapeutic Processes

Radiation Therapy for Cancer)

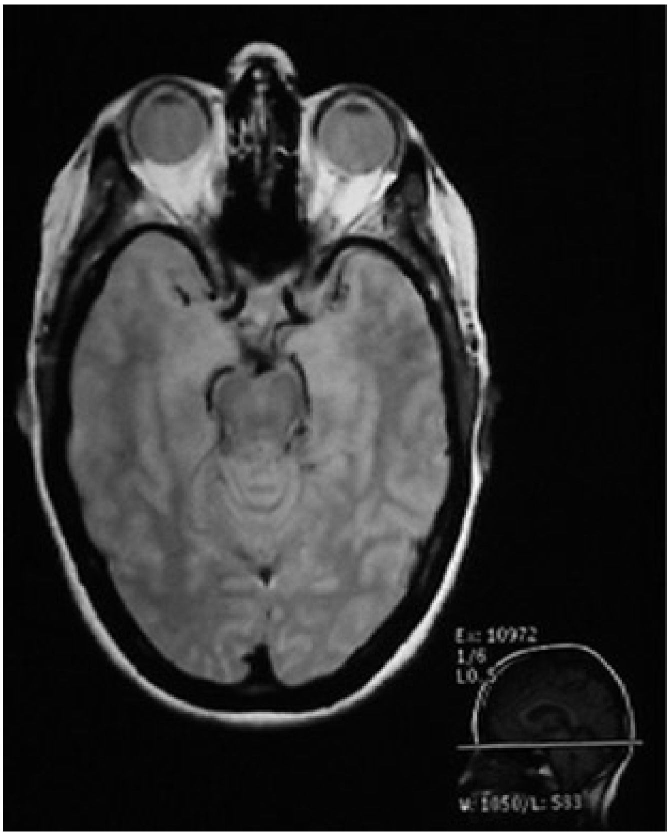
HyperPhysics***** Nuclear

R Nave

Go Back

Magnetic Resonance Imaging

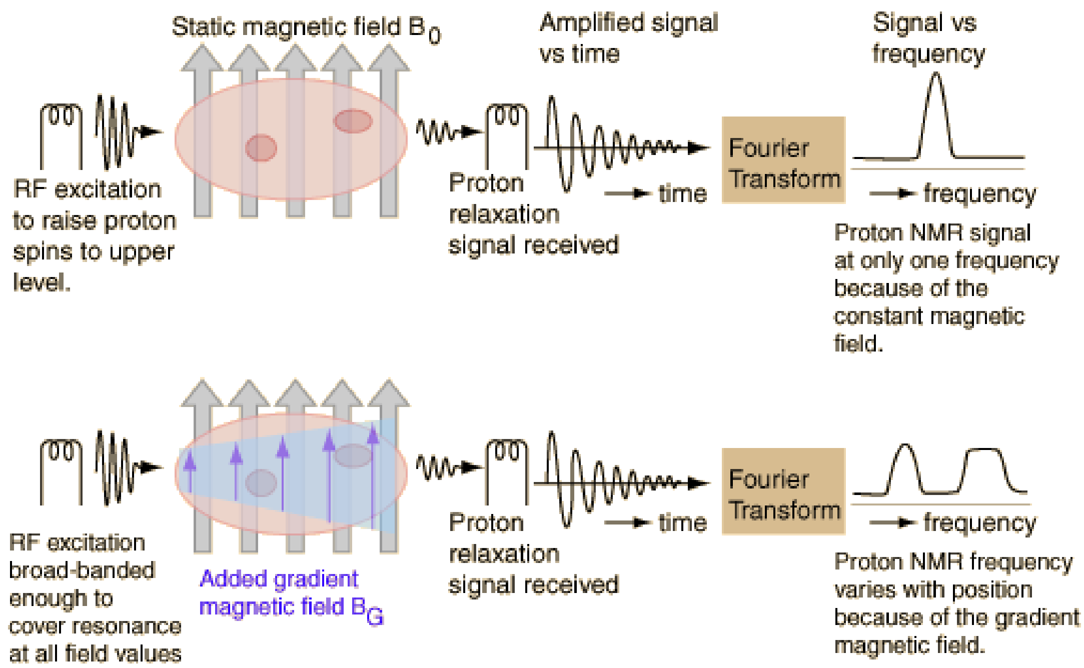
Proton nuclear magnetic resonance (NMR) detects the presence of hydrogens (protons) by subjecting them to a large magnetic field to partially polarize the nuclear spins, then exciting the spins with properly tuned radio frequency (RF) radiation, and then detecting weak radio frequency radiation from them as they "relax" from this magnetic interaction. The frequency of this proton "signal" is proportional to the magnetic field to which they are subjected during this relaxation process. In the medical application known as Magnetic Resonance Imaging (MRI), an image of a cross-section of tissue can be made by producing a well-calibrated magnetic field gradient across the tissue so that a certain value of magnetic field can be associated with a given location in the tissue. Since the proton signal frequency is proportional to that magnetic field, a given proton signal frequency can be assigned to a location in the tissue. This provides the information to map the tissue in terms of the protons present there. Since the proton density varies with the type of tissue, a certain amount of contrast is achieved to image the organs and other tissue variations in the subject tissue.



Since the MRI uses proton NMR, it images the concentration of protons. Many of those protons are the protons in water, so MRI is particularly well suited for the imaging of soft tissue, like the brain, eyes, and other soft tissue structures in the head as shown at left. The bone of the skull doesn't have many protons, so it shows up dark. Also the sinus cavities image as a dark region.

Bushong's assessment is that about 80% of the body's atoms are hydrogen atoms, so most parts of the body have an abundance of sources for the hydrogen NMR signals which make up the magnetic resonance image.

The schematic below may help visualize the imaging process. It is presumed that there are two regions of the sample which contain enough hydrogens to produce a strong NMR signal. The top sketch visualizes an NMR process with a constant magnetic field applied to the entire sample. The hydrogen spin-flip frequency is then the same for all parts of the sample. Once excited by the RF signal, the hydrogens will tend to return to their lower state in a process called "relaxation" and will re-emit RF radiation at their Larmor frequency. This signal is detected as a function of time, and then is converted to signal strength as a function of frequency by means of a [Fourier transformation](). Since the protons in each of the active areas of the sample are subjected to the same magnetic field, they will produce the same frequency of radiation and the Fourier transform of the detected signal will have only one peak. This one peak demonstrates the presence of hydrogen atoms, but gives no information to locate them in the sample.



Information about the location of the hydrogen atoms can be obtained by adding a calibrated gradient field across the region of the sample as shown in the bottom sketch above. With an increasing magnetic field as you move to the right across the sample, the spin-flip energy and therefore the frequency of the emitted signal increases from left to right. When excited by an RF transmitter, the emitted signal contains

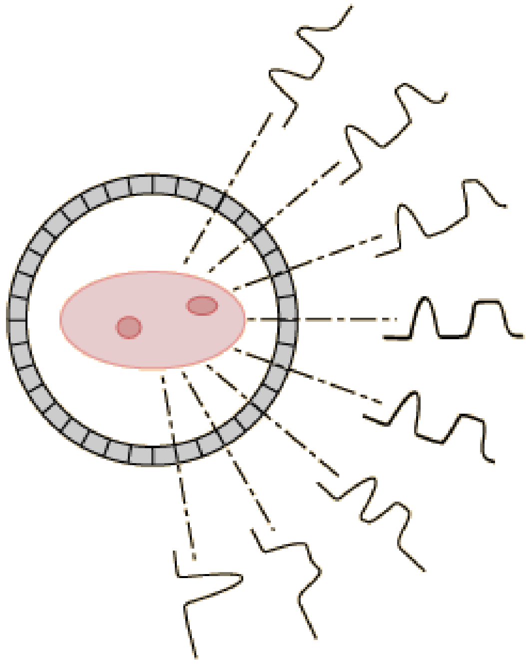
[Index]()

[Nuclear Spectra Concepts]()

References
[Hobbie]()
Ch 17

[Bushong]()
MRI

different frequencies for the two proton concentration areas. These frequencies can be separated by means of the Fourier transform and the example gives two different regions of frequency for the two sample areas. This is the beginning of the process of locating the hydrogen atoms. In the sketch, it only locates them along the horizontal direction, giving no indication that they are at different heights.



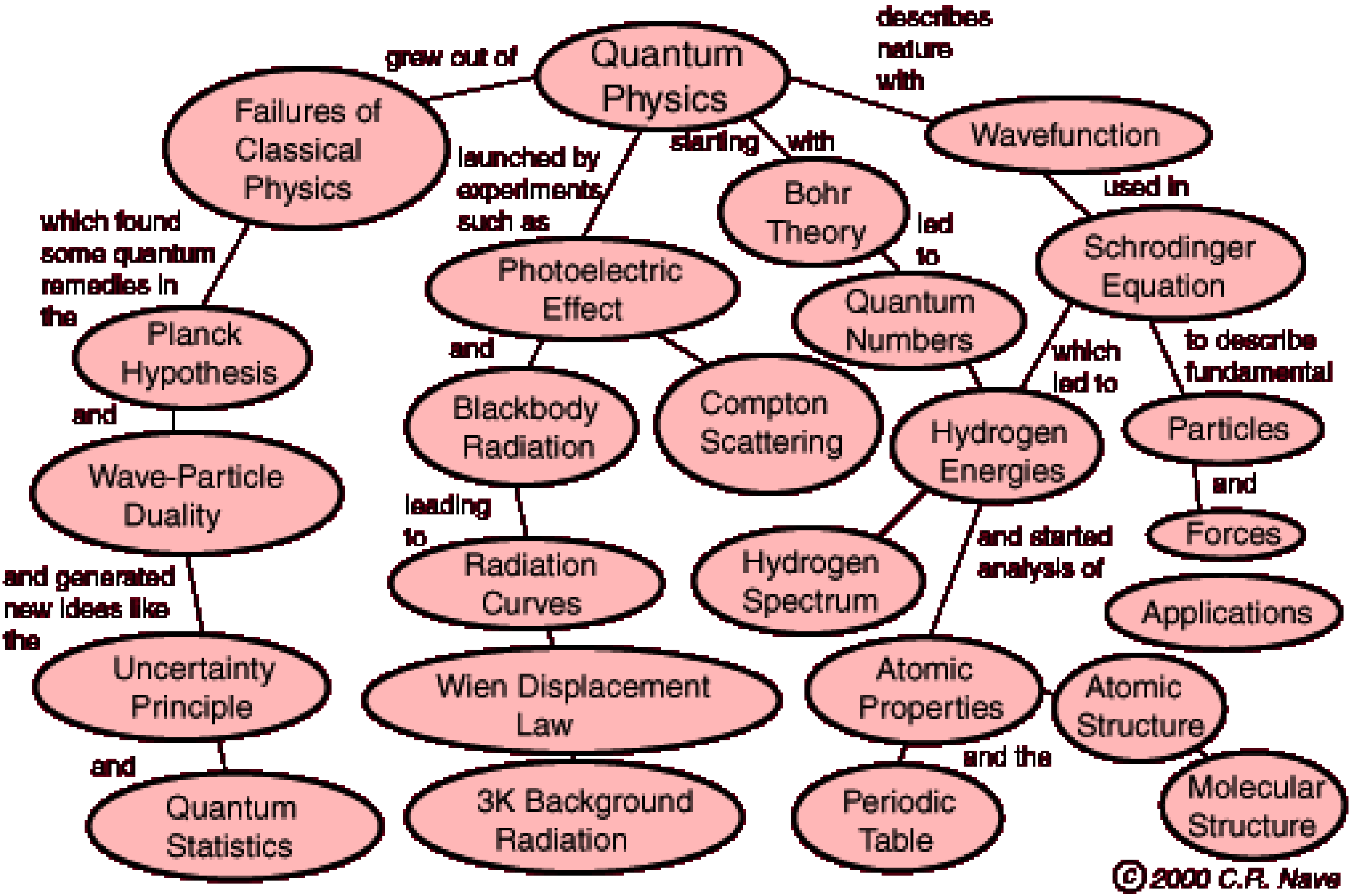
When a rotating field gradient is used, linear positioning information is collected along a number of different directions. That information can be combined to produce a two-dimensional map of the proton densities. The proton NMR signals are quite sensitive to differences in proton content that are characteristic of different kinds of tissue. Even though the spatial resolution of MRI is not as great as a conventional x-ray film, its contrast resolution is much better for tissue. Rapid scanning and computer reconstruction give well-resolved images of organs.

Nuclear Magnetic Resonance (NMR)

HyperPhysics***** Nuclear

R Nave

Go Back


Quantum Physics
grew out of
Failures of Classical Physics
which found some quantum remedies in the
Planck Hypothesis
and
Wave-Particle Duality
and generated new ideas like the
Uncertainty Principle
and
Quantum Statistics
launched by experiments such as
Photoelectric Effect
and
Blackbody Radiation
leading to
Radiation Curves
Wien Displacement Law
3K Background Radiation
Compton Scattering
starting with
Bohr Theory
led to
Quantum Numbers
Hydrogen Energies
Hydrogen Spectrum
and started analysis of
Atomic Properties
and the
Periodic Table
Atomic Structure
Molecular Structure
describes nature with
Wavefunction
used in
Schrodinger Equation
which led to
to describe fundamental
Particles
and
Forces
Applications
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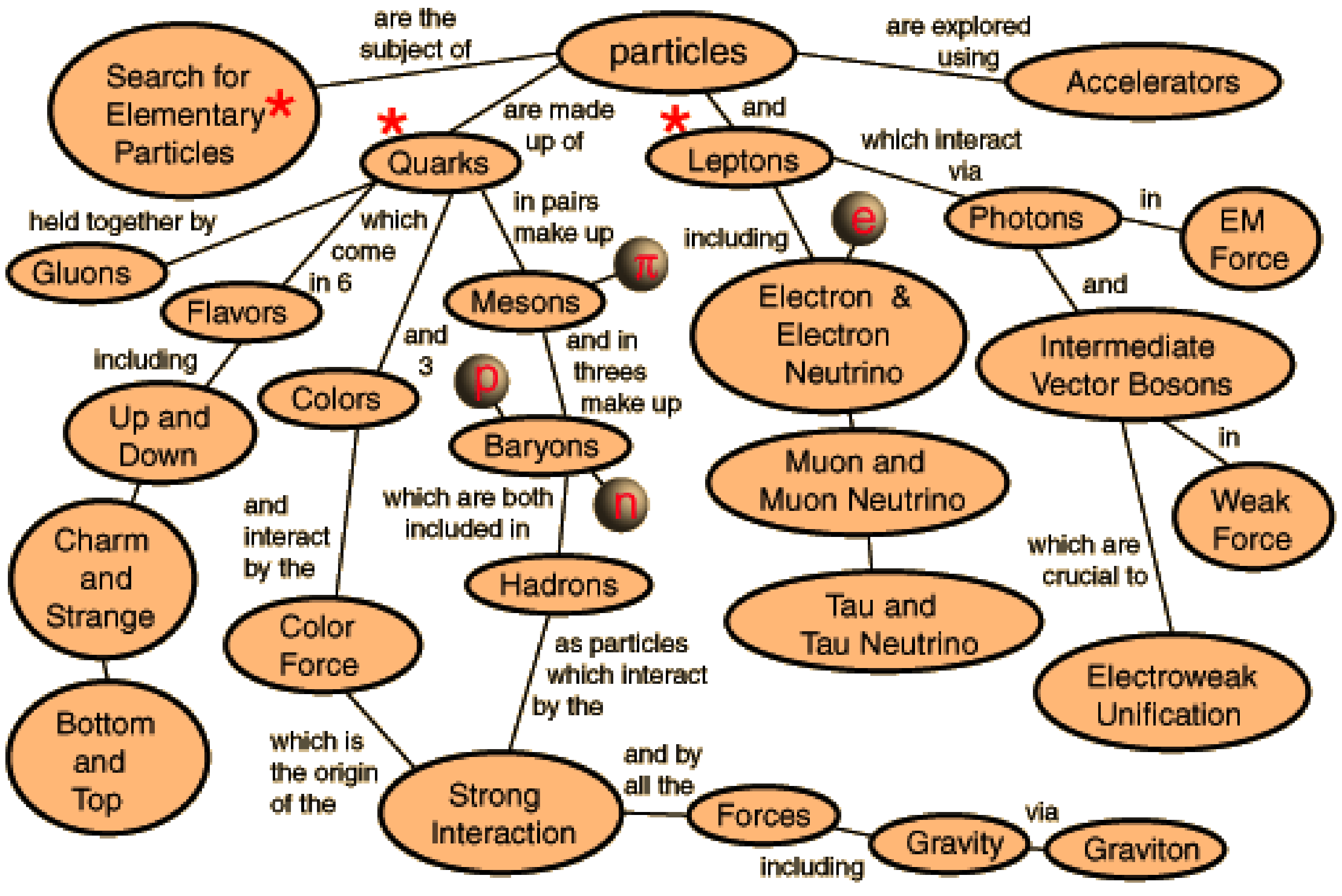

particles
are the subject of
Search for Elementary Particles *
are explored using
Accelerators
are made up of
* Quarks
and
* Leptons
which interact via
Photons
in
EM Force
held together by
Gluons
which come in 6
Flavors
including
Up and Down
Charm and Strange
Bottom and Top
and 3
Colors
and interact by the
Color Force
which is the origin of the
in pairs make up
Mesons
π
and in threes make up
p
Baryons
n
which are both included in
Hadrons
as particles which interact by the
Strong Interaction
and by all the
Forces
including
Gravity
via
Graviton
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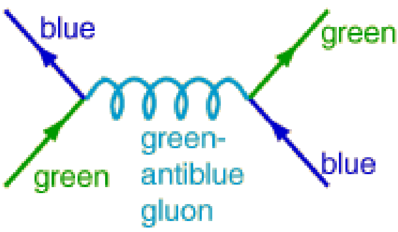
e
Electron & Electron Neutrino
Muon and Muon Neutrino
Tau and Tau Neutrino
and
Intermediate Vector Bosons
in
Weak Force
which are crucial to
Electroweak Unification

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

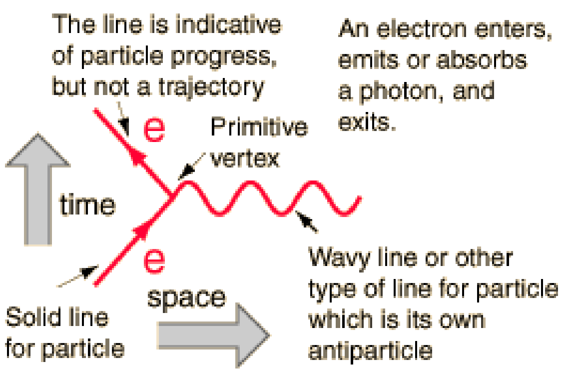
Particle concepts

Reference
Griffiths
Section
2.3

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.



Only lines entering or leaving the

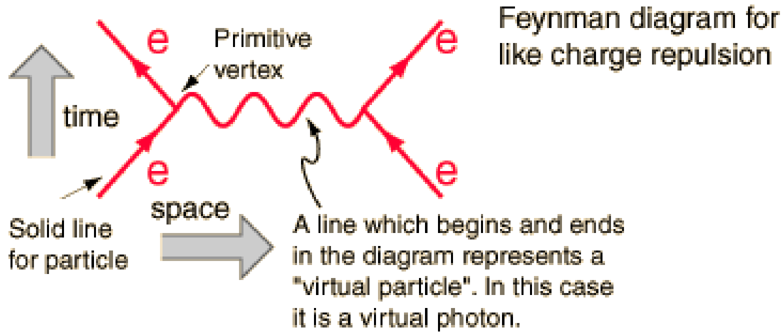


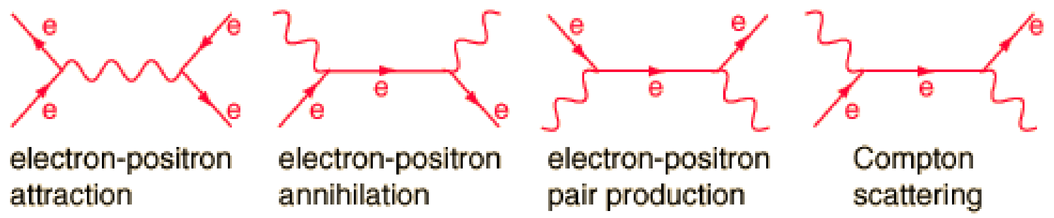
diagram represent observable particles. Here two electrons enter, exchange a photon, and then exit. The time and space axes are usually not indicated. The vertical direction indicates the progress of time upward, but the horizontal spacing does not give the distance between the particles.

[Index](#)

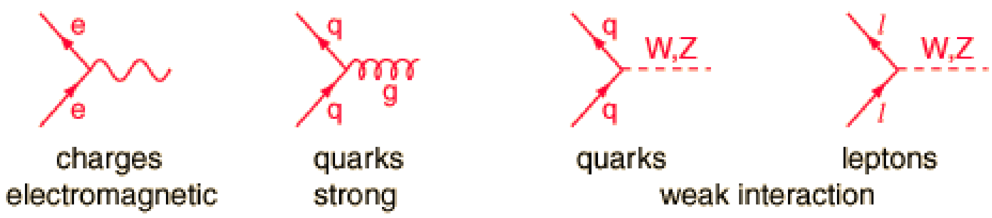
[Particle concepts](#)

References
[Griffiths](#)
Ch 2

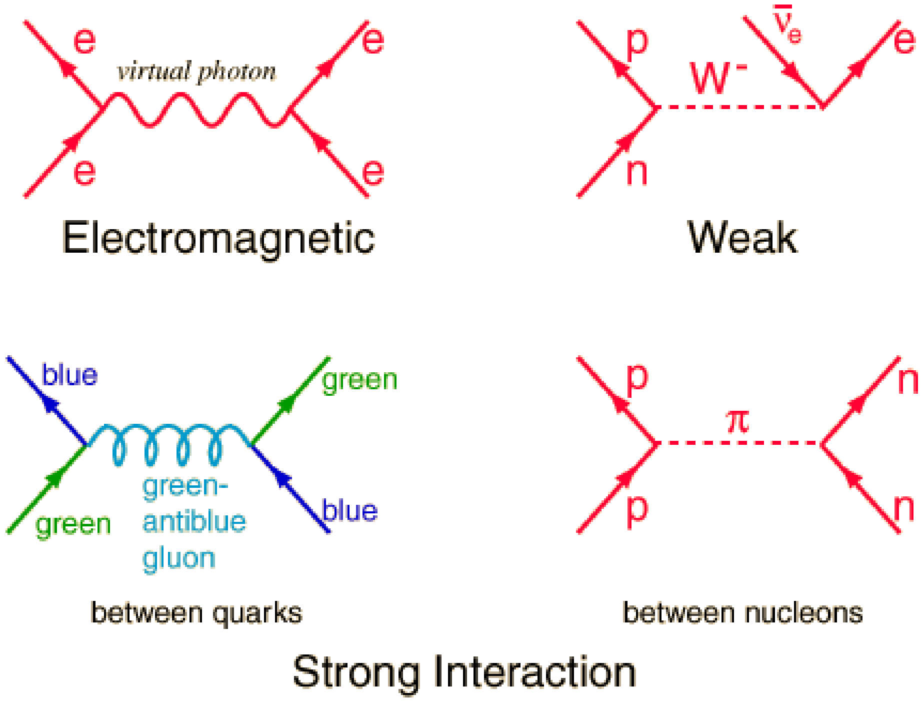
Other electromagnetic process can be represented, as in the examples below. A backward arrow represents the antiparticle, in these cases a positron. Keep in mind that time progresses upward, and that a downward arrow is not a particle progressing downward, but an antiparticle progressing upward (forward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



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



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.



Feynman diagrams for:

Lamb shift	Neutron decay	Weak interaction	Quark decay	Strong interaction

Twisted Feynman diagrams and crossing symmetry

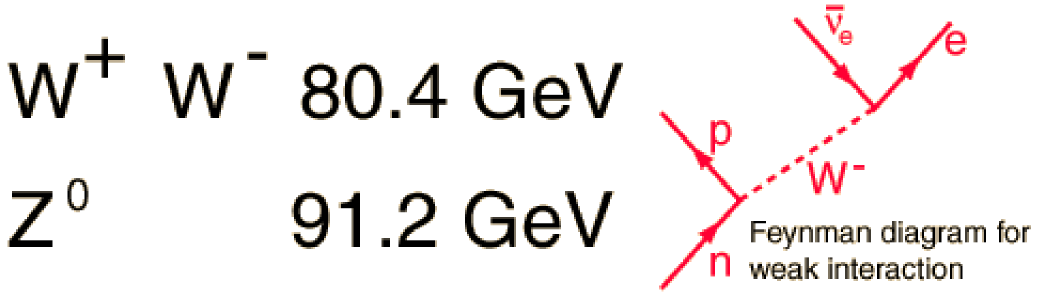
Intermediate Vector Bosons

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.



Feynman diagram for weak interaction involved in beta decay.

The charged W bosons participate in the transformation of quarks in

Index

Particle concepts

Reference
Rohlf

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".

Ch. 18

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

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

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

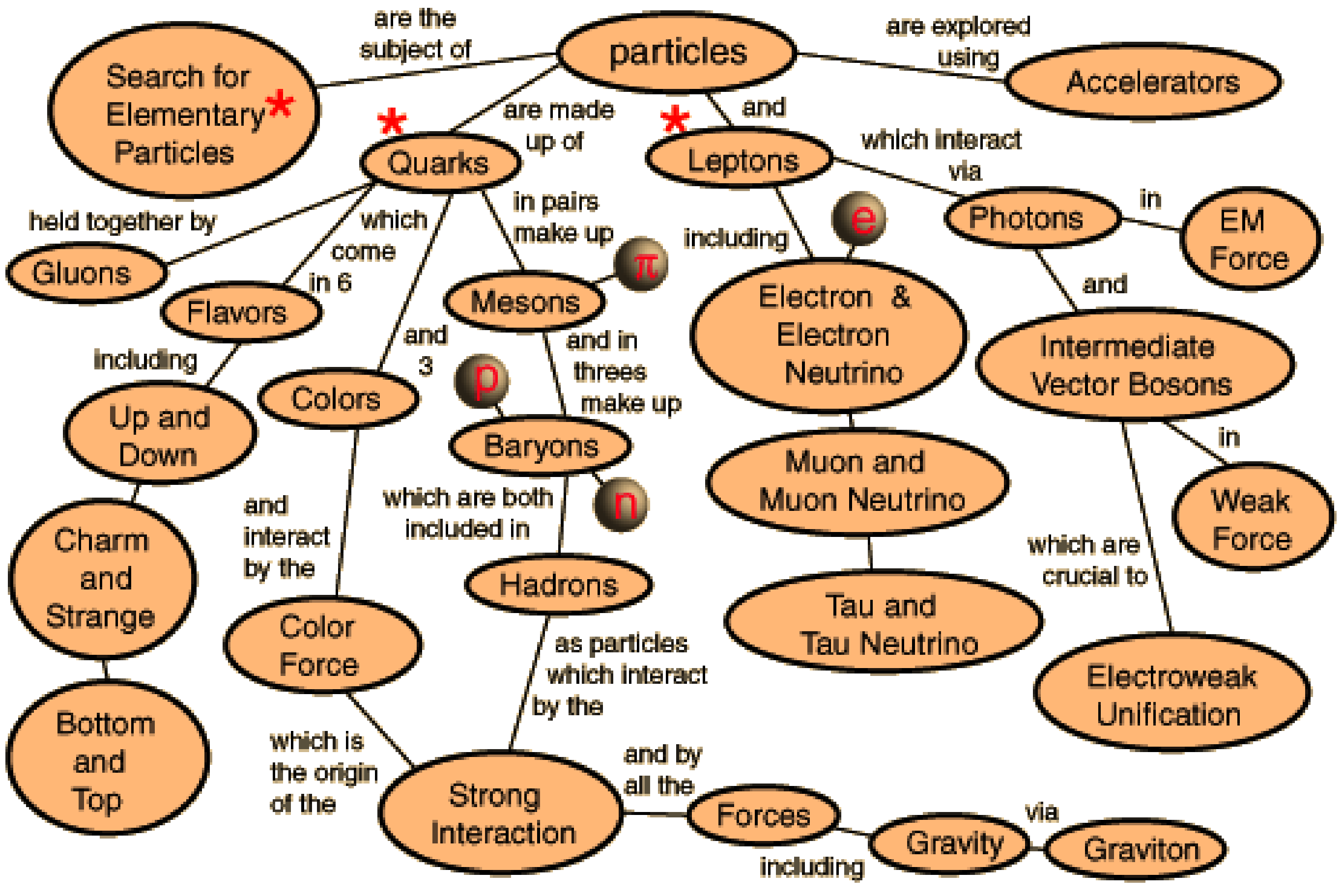
Feynman diagram for the electromagnetic force between two charges.

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. 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



particles
are the subject of
Search for Elementary Particles
are explored using
Accelerators
are made up of
Quarks
and
Leptons
which interact via
Photons
in
EM Force
held together by
Gluons
which come in 6
Flavors
in pairs make up
Mesons
π
including
e
Electron & Electron Neutrino
and
Intermediate Vector Bosons
including
Up and Down
and 3
Colors
and in threes make up
p
Baryons
Muon and Muon Neutrino
in
Weak Force
Charm and Strange
and interact by the
which are both included in
n
Hadrons
which are crucial to
Tau and Tau Neutrino
Color Force
as particles which interact by the
Electroweak Unification
Bottom and Top
which is the origin of the
Strong Interaction
and by all the
Forces
Gravity
via
Graviton
including

Quarks

Quarks and Leptons are the building blocks which build up matter, i.e., they are seen as the "elementary particles". In the present standard model, there are six "flavors" of quarks. They can successfully account for all known mesons and baryons (over 200). The most familiar baryons are the proton and neutron, which are each constructed from up and down quarks. Quarks are observed to occur only in combinations of two quarks (mesons), three quarks (baryons). There was a recent claim of observation of particles with five quarks (pentaquark), but further experimentation has not borne it out.

Quark	Symbol	Spin	Charge	Baryon Number	S	C	B	T	Mass*
Up	U	1/2	+2/3	1/3	0	0	0	0	1.7-3.3 MeV
Down	D	1/2	-1/3	1/3	0	0	0	0	4.1-5.8 MeV
Charm	C	1/2	+2/3	1/3	0	+1	0	0	1270 MeV
Strange	S	1/2	-1/3	1/3	-1	0	0	0	101 MeV
Top	T	1/2	+2/3	1/3	0	0	0	+1	172 GeV
Bottom	B	1/2	-1/3	1/3	0	0	-1	0	4.19 GeV(MS) 4.67 GeV(1S)

*The masses should not be taken too seriously, because the confinement of quarks implies that we cannot isolate them to measure their masses in a direct way. The masses must be implied indirectly from scattering experiments. The numbers in the table are very different from numbers previously quoted and are based on the July 2010 summary in Journal of Physics G, Review of Particle Physics, Particle Data Group. A summary can be found on the LBL site. These masses represent a strong departure from earlier approaches which treated the masses for the U and D as about 1/3 the mass of a proton, since in the quark model the proton has three quarks. The masses quoted are model dependent, and the mass of the bottom quark is quoted for two different models. But in other combinations they contribute different masses. In the pion, an up and an anti-down quark yield a particle of only 139.6 MeV of mass energy, while in the rho vector meson

Index

Particle concepts

References
Serway
Ch. 47

Rohlf
Ch. 17

Griffiths
Ch. 1

the same combination of quarks has a mass of 770 MeV! The masses of C and S are from Serway, and the T and B masses are from descriptions of the experiments in which they were discovered.

Each of the six "flavors" of quarks can have three different "colors". The quark forces are attractive only in "colorless" combinations of three quarks (baryons), quark-antiquark pairs (mesons) and possibly larger combinations such as the pentaquark that could also meet the colorless condition. Quarks undergo transformations by the exchange of W bosons, and those transformations determine the rate and nature of the decay of hadrons by the weak interaction.

Why "quark"? | Has anyone ever seen a quark?

What is the evidence for quarks inside protons?

What is the evidence for six quarks?

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

Why "Quark"?

The name "quark" was taken by Murray Gell-Mann from the book "Finnegan's Wake" by James Joyce. The line "Three quarks for Muster Mark..." appears in the fanciful book. Gell-Mann received the 1969 Nobel Prize for his work in classifying elementary particles.

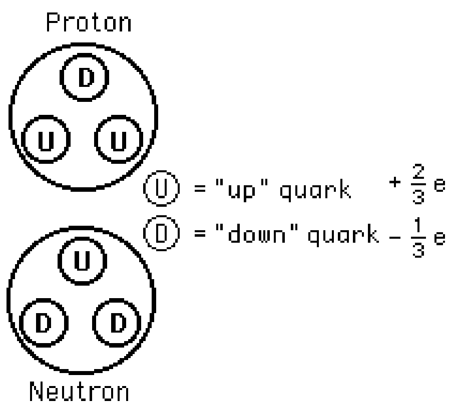
Index

Particle concepts

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

Up and Down Quarks

The up and down quarks are the most common and least massive quarks, being the constituents of protons and neutrons and thus of most ordinary matter.



The fact that the free neutron decays

$$n \rightarrow p + e^- + \bar{\nu}_e$$

and nuclei decay by beta decay in processes like

$$P^{32} \rightarrow S^{32} + e^- + \bar{\nu}_e$$

is thought to be the result of a more fundamental quark process

$$d \rightarrow u + e^- + \bar{\nu}_e$$

Table of quark properties

Index

Particle concepts

HyperPhysics***** Quantum Physics

R Nave

Go Back

The Strange Quark

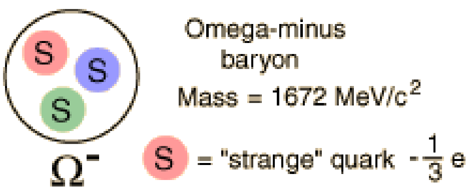
In 1947 during a study of cosmic ray interactions, a product of a proton collision with a nucleus was found to live for much longer time than expected: 10^{-10} seconds instead of the expected 10^{-23} seconds! This particle was named the lambda particle (Λ^0) and the property which caused it to live so long was dubbed "strangeness" and that name stuck to be the name of one of the quarks from which the lambda particle is constructed. The lambda is a baryon which is made up of three quarks: an up, a down and a strange quark.

The shorter lifetime of 10^{-23} seconds was expected because the lambda as a baryon participates in the strong interaction, and that usually leads to such very short lifetimes. The long observed lifetime helped develop a new conservation law for such decays called the "conservation of strangeness". The presence of a strange quark in a particle is denoted by a quantum number S=-1. Particle decay by the strong or electromagnetic interactions preserve the strangeness quantum number. The decay process for the lambda particle must violate that rule, since there is no lighter particle which contains a strange quark - so the strange quark must be transformed to another quark in the process. That can only occur by the weak interaction, and that leads to a much longer lifetime. The decay processes show that strangeness is not conserved:

$$\overset{uds}{\Lambda^0} \rightarrow \overset{uud}{p} + \overset{\bar{u}d}{\pi^-} \qquad \overset{uds}{\Lambda^0} \rightarrow \overset{udd}{n} + \overset{\frac{\bar{u}u+\bar{d}d}{\sqrt{2}}}{\pi^0}$$

$$S = -1 \neq 0 + 0 \qquad S = -1 \neq 0 + 0$$

The quark transformations necessary to accomplish these decay processes can be visualized with the help of Feynmann diagrams.



The omega-minus, a baryon composed of three strange quarks, is a classic example of the need for the property called "color" in describing particles. Since quarks are fermions with spin 1/2, they must obey the Pauli exclusion principle and cannot exist in identical states. So with three strange quarks, the property which distinguishes them must be capable of at least three distinct values.

Conservation of strangeness is not in fact an independent conservation law, but can be viewed as a combination of the conservation of charge, isospin, and baryon number. It is often expressed in terms of hypercharge Y, defined by:

$$Y = S + B = 2(Q - I)$$

S = Strangeness
B = Baryon number
Q = Electric charge
I = Isospin

Index

Particle concepts

Isospin and either hypercharge or strangeness are the quantum numbers often used to draw particle diagrams for the hadrons.

Table of quark properties

The Charm Quark

In 1974 a meson called the J/Psi particle was discovered. With a mass of 3100 MeV, over three times that of the proton, this particle was the first example of another quark, called the charm quark. The J/Psi is made up of a charm-anticharm quark pair.

The lightest meson which contains a charm quark is the D meson. It provides interesting examples of decay since the charm quark must be transformed into a strange quark by the weak interaction in order for it to decay.

One baryon with a charm quark is a called a lambda with symbol $\Lambda^+{}_c$. It has a composition udc and a mass of 2281 MeV/c^2.

Table of quark properties

Index

Particle concepts

The Top Quark

Convincing evidence for the observation of the top quark was reported by Fermilab 's Tevatron facility in April 1995. The evidence was found in the collision products of 0.9 TeV protons with equally energetic antiprotons in the proton-antiproton collider. The evidence involved analysis of trillions of 1.8 TeV proton-antiproton collisions. The Collider Detector Facility group had found 56 top candidates over a predicted background of 23 and the D0 group found 17 events over a predicted background of 3.8. The value for the top quark mass from the combined data of the two groups after the completion of the run was 174.3 +/- 5.1 GeV. This is over 180 times the mass of a proton and about twice the mass of the next heaviest fundamental particle, the Z0 vector boson at about 93 GeV.

The interaction is envisioned as follows:

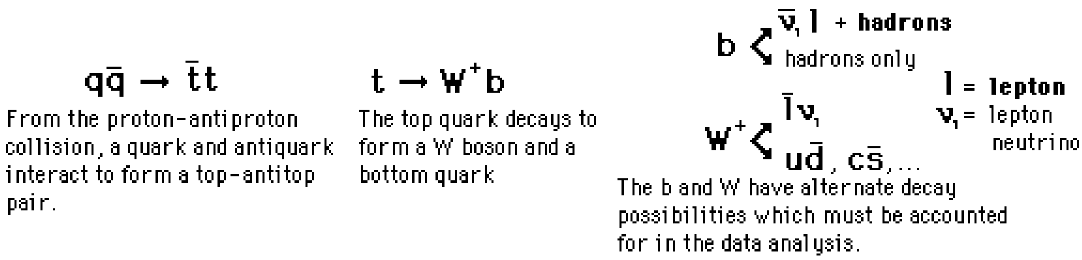


Table of quark properties

Index

Particle concepts

Reference
Ladbury

External Link
D-Zero

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

Confinement of Quarks

How can one be so confident of the quark model when no one has ever seen an isolated quark? There are good reasons for the lack of direct observation. Apparently the color force does not drop off with distance like the other observed forces. It is postutated that it may actually increase with distance at the rate of about 1 GeV per fermi. A free quark is not observed because by the time the separation is on an observable scale, the energy is far above the pair production energy for quark-antiquark pairs. For the U and D quarks the masses are 10s of MeV so pair production would occur for distances much less than a fermi. You would expect a lot of mesons (quark-antiquark pairs) in very high energy collision experiments and that is what is observed.

Basically, you can't see an isolated quark because the color force does not let them go, and the energy required to separate them

Index

produces quark-antiquark pairs long before they are far enough apart to observe separately.

One kind of visualization of quark confinement is called the "bag model". One visualizes the quarks as contained in an elastic bag which allows the quarks to move freely around, as long as you don't try to pull them further apart. But if you try to pull a quark out, the bag stretches and resists.

Another way of looking at quark confinement is expressed by Rohlf. "When we try to pull a quark out of a proton, for example by striking the quark with another energetic particle, the quark experiences a potential energy barrier from the strong interaction that increases with distance." As the example of alpha decay demonstrates, having a barrier higher than the particle energy does not prevent the escape of the particle - quantum mechanical tunneling gives a finite probability for a 6 MeV alpha particle to get through a 30 MeV high energy barrier. But the energy barrier for the alpha particle is thin enough for tunneling to be effective. In the case of the barrier facing the quark, the energy barrier does not drop off with distance, but in fact increases.

Evidence for quarks in deep inelastic scattering

Particle concepts

Reference Rohlf Sec 6-6

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

The Bottom Quark

In 1977, an experimental group at Fermilab led by Leon Lederman discovered a new resonance at 9.4 GeV/c^2 which was interpreted as a bottom-antibottom quark pair and called the Upsilon meson. From this experiment, the mass of the bottom quark is implied to be about 5 GeV/c^2. The reaction being studied was

$$p + N \rightarrow \mu^+ + \mu^- + X$$

where N was a copper or platinum nucleus. The spectrometer had a muon-pair mass resolution of about 2%, which allowed them to measure an excess of events at 9.4 GeV/c^2. This resonance has

Index

Particle concepts

Reference Rohlf Ch. 17

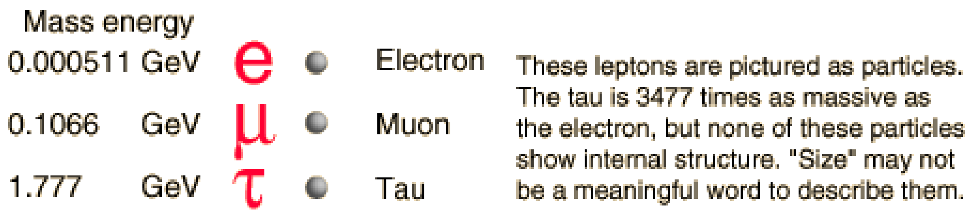
been subsequently studied at other accelerators with a detailed investigation of the bound states of the bottom-antibottom meson.

Table of quark properties

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

Leptons

Leptons and quarks are the basic building blocks of matter, i.e., they are seen as the "elementary particles". There are six leptons in the present structure, the electron, muon, and tau particles and their associated neutrinos. The different varieties of the elementary particles are commonly called "flavors", and the neutrinos here are considered to have distinctly different flavor.



Important principles for all particle interactions are the conservation of lepton number and the the conservation of baryon number.

Now that we have experimental evidence for six leptons, a relevant question is "Are there more?". The present standard model assumes that there are no more than three generations. One of the pieces of experimental evidence for that is the measured hydrogen/helium abundance ratio in the universe. When the process of nucleosynthesis from the big bang is modeled, the number of types of neutrinos affects the abundance of helium. The observed abundance agrees with three types of neutrinos.

Table of lepton properties

Index

Particle concepts

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

Electron and Positron

As one of the leptons, the electron is viewed as one of the fundamental particles. It is a fermion of spin 1/2 and therefore constrained by the Pauli exclusion principle, a fact that has key implications for the building up of the periodic table of elements.

The electron's antiparticle, the positron, is identical in mass but has a positive charge. If an electron and a positron encounter each other,they will annihilate with the production of two gamma-rays. On the other hand, one of the mechanisms for the interaction of radiation with matter is the pair production of an electron-positron pair. Associated with the electron is a the electron neutrino.

Particle	Symbol	Anti-particle	Rest mass MeV/c^2	L(e)	L(muon)	L(tau)	Lifetime (seconds)
Electron	e^-	e^+	0.511	+1	0	0	Stable
Neutrino (Electron)	ν_e	$\bar{\nu}_e$	0(<7 x 10^{-6})	+1	0	0	Stable

Electron spin

Index

Particle concepts

Muon

The muon is a lepton which decays to form an electron or positron.

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

mass = $207m_e$= 105.7 MeV/c^2 of μ

The fact that the above decay is a three-particle decay is an example of the conservation of lepton number; there must be one electron neutrino and one muon neutrino or antineutrino in the decay.

The lifetime of the muon is 2.20 microseconds. The muon is produced in the upper atmosphere by the decay of pions produced by cosmic rays:

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

Index

Particle

Measuring the flux of muons of cosmic ray origin at different heights above the earth is an important time dilation experiment in relativity.

Muons make up more than half of the cosmic radiation at sea level, the remainder being mostly electrons, positrons and photons from cascade events.(Richtmyer) The average sea level muon flux is about 1 muon per square centimeter per minute.

Particle	Symbol	Anti-particle	Rest mass MeV/c^2	L(e)	L(muon)	L(tau)	Lifetime (seconds)
Muon	μ^-	μ^+	105.7	0	+1	0	2.20×10^{-6}
Neutrino (Muon)	ν_μ	$\bar{\nu}_\mu$	0(<0.27)	0	+1	0	Stable

Some history | Atmospheric muons

concepts

Tau

The tau is the most massive of the leptons, having a rest mass some 3490 times the mass of the electron, also a lepton. Its mass is some 17 times that of the muon, the other massive lepton.

Particle	Symbol	Anti-particle	Rest mass MeV/c^2	L(e)	L(muon)	L(tau)	Lifetime (seconds)
Tau	τ^-	τ^+	1777	0	0	+1	2.96×10^{-13}
Neutrino (Tau)	ν_τ	$\bar{\nu}_\tau$	0(<31)	0	0	+1	Stable

Index

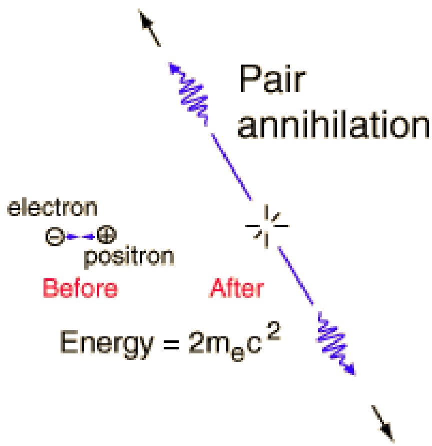
Particle concepts

Positron Annihilation

The positron is the antiparticle of the electron, and when a positron enters any normal matter, it will find an abundant supply of electrons with which to annihilate. The energy released by the annihilation forms two highly energetic gamma rays, and if one assumes that the momenta of the positron and electron before the annihilation, the two gamma ray photons must travel in opposite directions in order to conserve momentum.

Index

Particle concepts



These coincident gamma rays at 180 degrees provide a useful analysis tool. For one thing, eliminating all gamma events which are not coincident at 180 degrees improves the signal-to-noise ratio of experiments using positron annihilation. Another interesting application is the use of the coincident gammas to locate the source by back projecting. This is used in medical PET scans.

HyperPhysics***** Quantum Physics

R Nave

Go Back

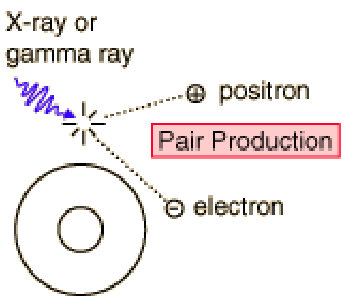
Electron-Positron Pair Production

When a photon has quantum energy higher than the rest mass energy of an electron plus a positron, one of the ways that such a photon interacts with matter is by producing and electron-positron pair.

Index

Particle

The rest mass energy of the electron is



0.511 MeV, so for photon energy above 1.022MeV, pair production is possible. For photon energies far above this threshold, pair production becomes the dominant mode for the interaction of x-rays and gamma-rays with matter.

concepts

More detail in relativity section

HyperPhysics***** Quantum Physics

R Nave

Go Back

Properties of the Leptons

Particle	Symbol	Anti-particle	Rest mass MeV/c^2	L(e)	L(muon)	L(tau)	Lifetime (seconds)
Electron	e^-	e^+	0.511	+1	0	0	Stable
Neutrino (Electron)	ν_e	$\underline{\nu}_e$	0(<7 x 10^{-6})	+1	0	0	Stable
Muon	μ^-	μ^+	105.7	0	+1	0	2.20×10^{-6}
Neutrino (Muon)	ν_μ	$\underline{\nu}_\mu$	0(<0.27)	0	+1	0	Stable
Tau	τ^-	τ^+	1777	0	0	+1	2.96×10^{-13}
Neutrino (Tau)	ν_τ	$\underline{\nu}_\tau$	0(<31)	0	0	+1	Stable

Numerical data from Giancoli

Lepton discussion

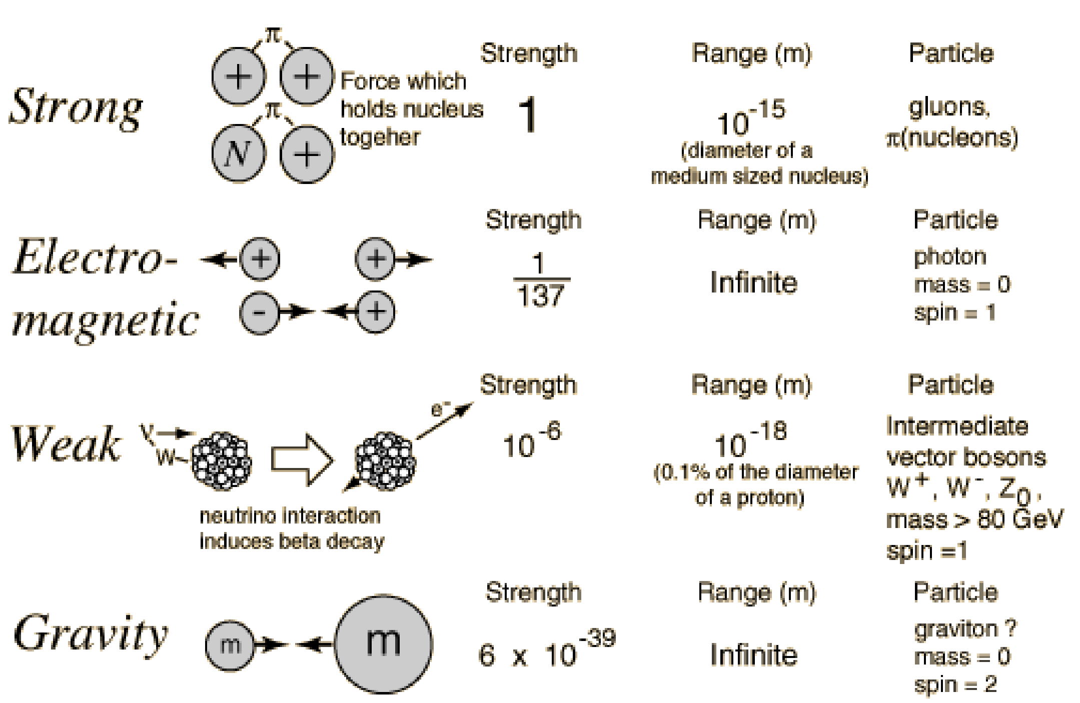
Index

Particle concepts

Reference Giancoli

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

Fundamental Forces



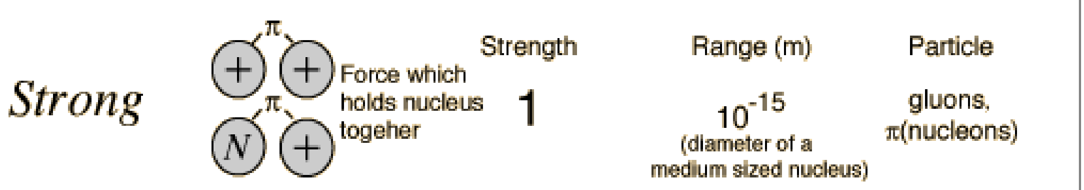
Index

Fundamental force concepts

Coupling constants

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

The Strong Force

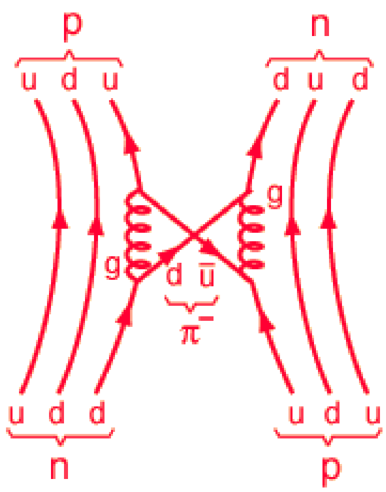


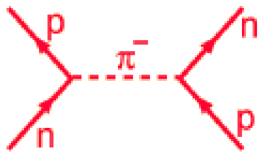
A force which can hold a nucleus together against the enormous forces of repulsion of the protons is strong indeed. However, it is not an inverse square force like the electromagnetic force and it has a very short range. Yukawa modeled the strong force as an exchange force in which the exchange particles 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



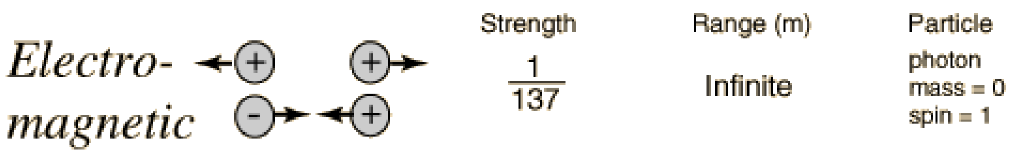


The sketch is an attempt to show one of many forms the gluon interaction between nucleons could take, this one involving up-antiup pair production and annililation and producing a π^- bridging the nucleons.

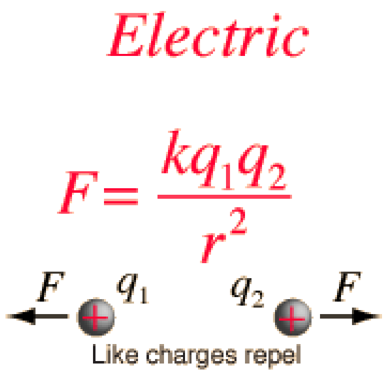
Feynman diagrams and the strong force

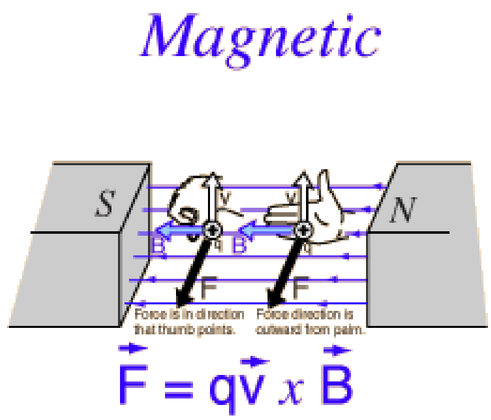
HyperPhysics***** Quantum Physics *R Nave* Go Back

The Electromagnetic Force



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.





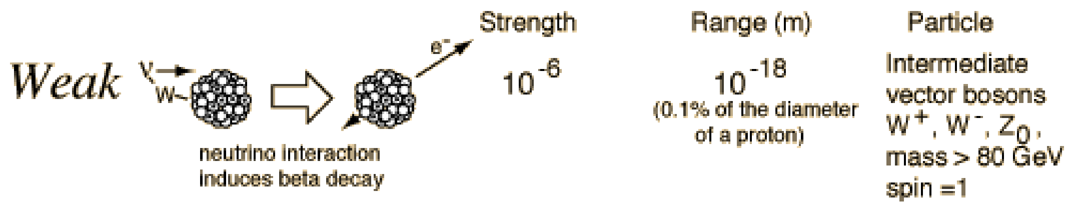
The electromagnetic force holds atoms and molecules together. In fact, the forces of electric attraction and repulsion of electric charges are so dominant over the other three fundamental forces that they can be considered to be negligible as determiners of atomic and molecular structure. Even magnetic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



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 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

Index

Fundamental force concepts

Reference Griffiths Ch 2

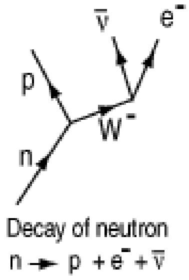
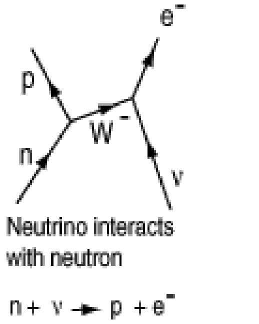
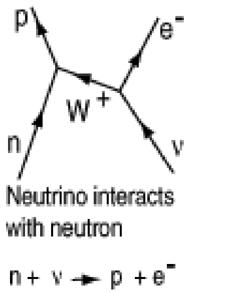
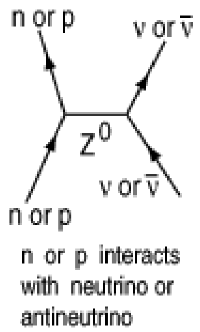
HyperPhysics***** Quantum Physics

R Nave

Go Back

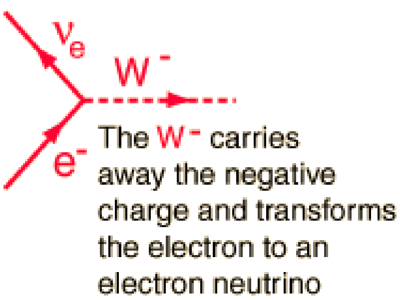
Feynman Diagrams for Weak

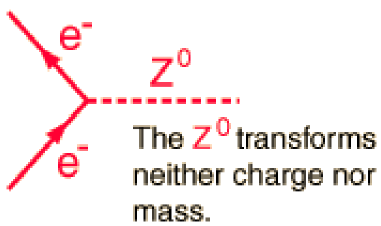
Force

 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.

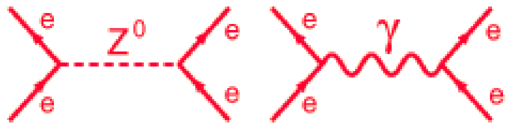
The primitive vertices in the Feynman diagrams for the weak interaction are of two types, charged and neutral. For leptons they take the following form





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.

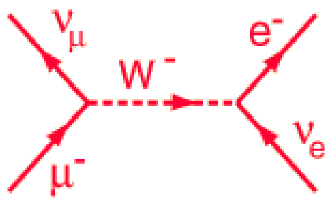
The neutral interaction is simpler to conceive, but rarely observed because it competes with the much stronger electromagnetic interaction and is masked by it.

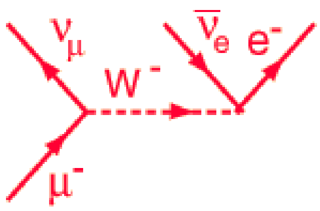


Neutral weak interaction

Electromagnetic interaction

With the charged vertices, one can postulate an interaction like $\mu, \nu_e \to e, \nu_\mu$ 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

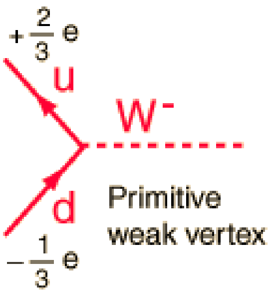
The charged vertices in the weak interaction with quarks take the form

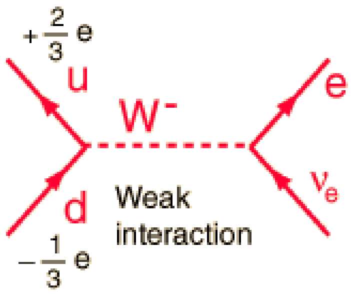
Index

Fundamental force concepts

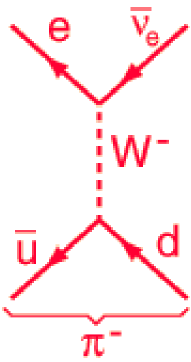
Reference Kaufmann Ch. 29

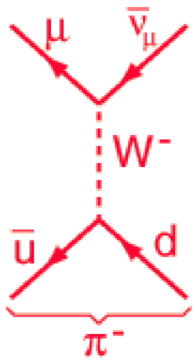
Griffiths Ch 2





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