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), and the recently discovered particles with five quarks (pentaquark).

Quark	Symbol	Spin	Charge	Baryon Number	S	C	B	T	Mass*
Up	U	1/2	+2/3	1/3	0	0	0	0	360 MeV
Down	D	1/2	-1/3	1/3	0	0	0	0	360 MeV
Charm	C	1/2	+2/3	1/3	0	+1	0	0	1500 MeV
Strange	S	1/2	-1/3	1/3	-1	0	0	0	540 MeV
Top	T	1/2	+2/3	1/3	0	0	0	+1	174 GeV
Bottom	B	1/2	-1/3	1/3	0	0	-1	0	5 GeV

*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 masses quoted for the U and D are about 1/3 the mass of a proton, since we know the proton has three quarks. 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 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.

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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.

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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.

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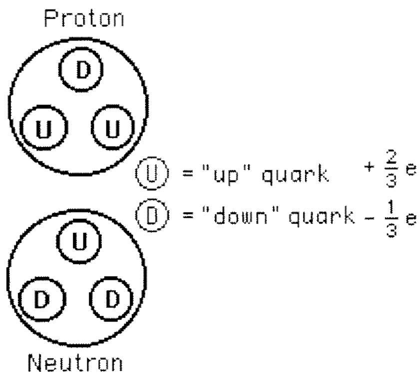
The fact that the free neutron decays

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

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

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

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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.

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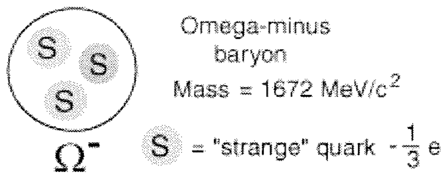

The omega-minus, a baryon composed of three strange quarks, is a classic example of the need for the property called "color" in describing particles. Since quarks are fermions with spin 1/2, they must obey the Pauli exclusion principle and cannot exist in identical states. So with three strange quarks,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

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

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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 Λ^+_c. It has a composition udc and a mass of 2281 MeV/c^2.

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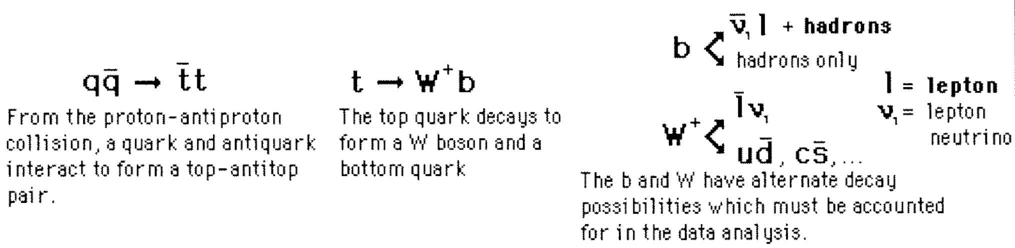
The Top Quark

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:



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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 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.

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Evidence for quarks in deep inelastic scattering

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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 been subsequently studied at other

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accelerators with a detailed investigation of the bound states of the bottom-antibottom meson.

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