Physics 228, Lecture 24
Monday, April 25, 2005

Resonances, Quarks, Color. Ch. 44:4

1 Particle Production

As we saw in that event from Fermilab, when particles collide at very high energy, nothing prevents the creation of lots of particles, including unstable particles that don't occur in everyday nature on Earth.

How do we know what constitutes a particle in a world in which 0.1 ns is considered a long lifetime? A particle like the Σ^-, if it is moving at speeds close to the speed of light, can travel many centimeters, and therefore it can leave a track in detectors. So there is not much doubt about it being a particle. Neutral particles like the Λ^0 don't leave tracks, but when a lambda decays $\Lambda^0 \rightarrow p + \pi^-$ the decay products will leave tracks. So we can connect the creation point and the decay point and still visualize a trail.

About the shortest track we can see this way, with microscopic viewing, is one micron, which at the speed of light corresponds to 3×10^{-15} s. How can we measure half-lives shorter than that? Time dilation helps — the lifetime is the proper time, so the time in the lab can be longer by a factor of γ. So a particle moving at .9999 c could leave a one micron track even if its lifetime were 4×10^{-17} s.

But what about the interaction

$$\begin{aligned} \pi^- + p &\longrightarrow \pi^- + \Delta^+ \\ \Delta^+ &\longrightarrow \pi^+ + n \end{aligned}$$

where the Δ^+ is a particle with mass 1232 MeV and half-life 8.2×10^{-24} s. What does such a short lifetime mean? Surely we can't see a track, so how do we distinguish the reactions above from

$$\pi^- + p \longrightarrow \pi^- + \pi^+ + n?$$

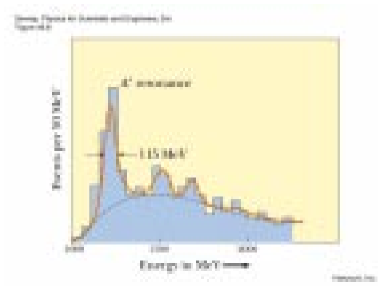
The answer to both questions is in the energy dependence. If the π^+ and n are the results of the decay of a Δ^+ particle, their total momentum and energy much satisfy the equation

$$(E_{\pi^+} + E_n)^2 = (p_{\pi^+} + p_n)^2 c^2 + m_{\Delta^-}^2 c^4,$$

while if the reaction does not proceed by way of making an unstable particle, there is no such constraint.

If we take data for many events from an experiment in which we measure the momentum of the π^+ and n, calculate the mass from the above relation,

$$Mc^2 = \sqrt{(E_{\pi^+} + E_n)^2 - (p_{\pi^+} + p_n)^2 c^2},$$



and plot the number of scatterings in each 50 MeV bin of values of Mc^2, we get the plot of S&B 46.8. It looks like a good fraction of them have roughly the same mass, roughly 1200 MeV/c^2, though not all, so we may say that some of these events come through production of the Δ^-. But why the spread of rest energies? Because if the particle only lives for a mean lifetime of τ, its rest energy must be uncertain by an amount

$$\Delta mc^2 = \frac{\hbar}{2\tau},$$

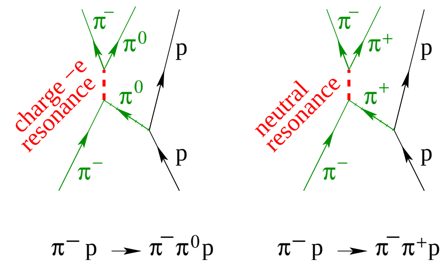
so we can use the observed spread in rest energy, $\Delta mc^2 = 115$ MeV, to **measure** the lifetime,

$$\tau = \frac{\hbar}{2\Delta E} = \frac{\hbar}{115\text{MeV}} = 5.7 \times 10^{-24}\,\text{s}.$$

Particles that are so short-lived that they can't leave tracks are known as resonances, because they can only be detected by these plots which look like the response of an oscillator to a driving frequency near resonance.

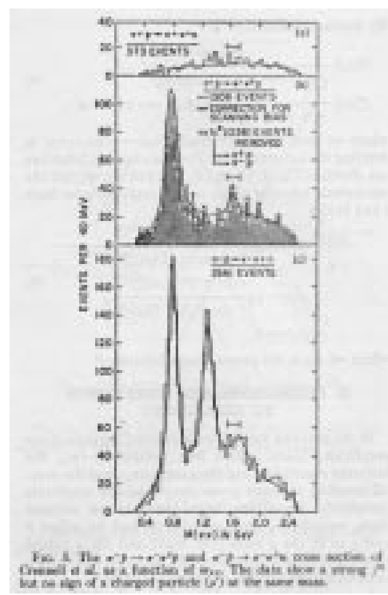
Let me show you another example. If we want to explore the scattering the scattering of mesons, we can't use a meson target, but we can scatter off the virtual mesons given off by a proton. So with a beam of π^- incident on a hydrogen target, we can examine

$$\begin{aligned} \pi^- + p &\longrightarrow \pi^- + \pi^0 + p \\ \pi^- + p &\longrightarrow \pi^- + \pi^+ + n \end{aligned}$$



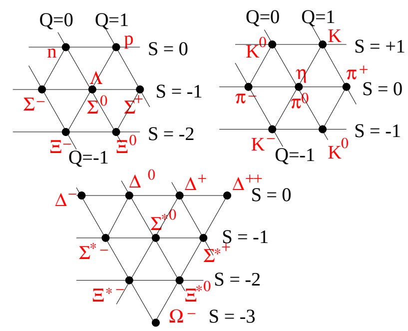
We find that a large part of the scattering can be understood in terms of the diagrams shown, which are known as Feynman diagrams. We see that we have a scattering of two π mesons by means of an intermediate resonance, which in the first case is negatively charged and in the second neutral. If we examine the total energy and momentum of the two emerging pions, we can ask how the scattering depends on the center-of-mass energy of those two pions, and if there is a strong peak at some energy, that says we have a resonance with that mass.

Here is some data from an old paper of Crennel *et al*, showing neutral resonances at 0.8 GeV (ρ^0) and 1.21 Gev (f^0), and a charged resonance at 0.8 GeV (ρ^-), but none at 1.21 GeV. Why do I show you this data?



2 Many Particles, Patterns

In the 1950's and 1960's improvements in accelerator technology resulted in the discovery of hundreds of such resonances and particles. Physicists looked for patterns to describe these particles as families of particles related by some sort of symmetry. For example, the neutron and proton are quite similar, acting almost the same for strong interactions, though of course their different charges cause them to act differently under electromagnetism. As we have seen, there are families of three pions, two kaons, three Σ's. These families are known as **isotopic spin multiplets**.



In 1961 Gell-Mann and Ne'eman independently proposed an abstract symmetry called $SU(3)$ which grouped together several isotopic spin multiplets into a single SU(3) multiplet. I have shown the nucleon multiplet, an octet with 8 particles including the neutron and proton, but also the lambda and sigma particles and another doublet called the xi (Ξ) or cascade particles. They are called that because they decay first into $\Sigma + \pi$ and then the Σ decays, causing a cascade of particles. All these particles have spin 1/2.

Also shown is the spin 0 meson octet, which includes the pions and kaons, and their antiparticles. Finally, there is a decouplet of particles which have spin 3/2, including the Δ^- that we discussed earlier, excited states of the Σ's and Ξ's, and the famous Ω^-. When Gell-Mann proposed SU(3) symmetry[1] in 1962 the Ω^- was not yet discovered. He predicted it must exist in order to fill out this decouplet, and was also able to predict its mass. Of course its spin and charge are also determined by where it lies in this multiplet. When it was found in a bubble chamber photograph in 1964 (S&B 46.10), SU(3) became the hottest fad.

The motivation of the patterns of $SU(3)$ was originally based on the abstract symmetry group, and one needs a course in the field of mathematics known as group theory to understand where these patterns come from. But there is an easier way to understand these patterns, and that is to consider all these particles to be composites of three more fundamental particles called (by Gell-Mann) quarks.

3 Quarks

The multiplets of particles possible in SU(3) can be understood in terms of being built of more fundamental objects, which Gell-Mann called quarks, although he was originally very careful to make clear that he was proposing these only as mnemonics and not as real constituents. But later on it became clear that, in fact, one should view the quarks as the constituents that make up all hadrons. According to Gell-Mann and Zweig, there were three quarks,

[1] Nobel prize, 1969

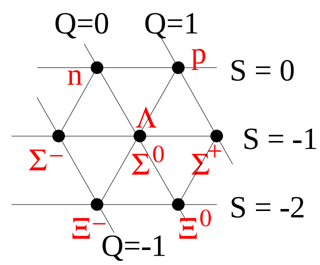
known as up, down, and strange. They are all fermions with spin 1/2, but otherwise they have peculiar quantum numbers:

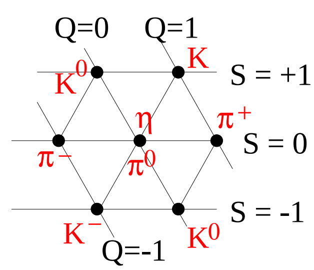
Name	symbol	charge ($\times e$)	baryon number	strangeness
up	u	$+2/3$	$+1/3$	0
down	d	$-1/3$	$+1/3$	0
strange	s	$-1/3$	$+1/3$	-1

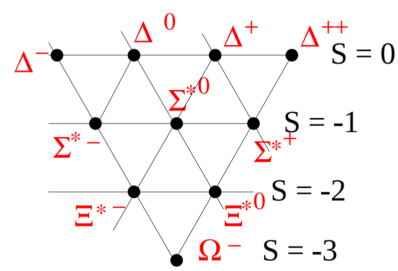
Of course they each have an antiparticle, $\bar{u}$, $\bar{d}$, $\bar{s}$, with baryon number $-1/3$, and with charges $-2/3$, $+1/3$, and $+1/3$ respectively. The baryons and mesons are made up of these. The baryons have three quarks, while the mesons have one quark and one antiquark. Here is how the nucleon octet, the meson octet, and the spin 3/2 decouplet are made of quarks:

Nucleon		meson		$J = 3/2$	
				Δ^{++}	uuu
p	uud	K^+	$u\bar{s}$	Δ^+	uud
n	udd	K^0	$d\bar{s}$	Δ^0	udd
Σ^+	uus	π^+	$u\bar{d}$	Δ^-	ddd
Σ^0	uds	π^0	$u\bar{u}$ †	Σ^{*+}	uus
Σ^-	dds	π^-	$u\bar{d}$	Σ^{*0}	uds
Λ	uds	η	$d\bar{d}$ †	Σ^{*-}	dds
Ξ^0	uss	$\bar{K}^0$	$s\bar{d}$	Ξ^{*0}	uss
Ξ^-	dss	K^-	$s\bar{u}$	Ξ^{*-}	dss
				Ω^-	sss

†: actually these are mixtures of $u\bar{u}$, $d\bar{d}$, and some $s\bar{s}$.







For 6 years the SU(3) symmetry, which can be considered the consequence of all three quarks interacting identically, was the hot thing in particle physics. Of course they are not exactly identical, as can be seen by the fact that the masses of the particles in the multiplets are not all the same, and of course the different charges mean they interact differently with electromagnetism, but as an approximate symmetry it seems quite useful. But then two strange things happened to the quark model. In the first place, the combinations of quarks described above seem to fit better with the quarks being bosons than fermions, and that can't be, because spin 1/2 particles must be fermions. In particular, an Ω^- with spin $S_z = 3\hbar/2$ in the z direction is composed of three s quarks all with spin up, so how can that be consistent with the Pauli exclusion principle? Something apparently is missing in our description. Secondly, in 1974 we suddenly found ourselves with a fourth quark! Several people had proposed more quarks, usually for a total of six, but the discovery of the J/ψ particle[2] in 1974, was the first convincing evidence that more than three were needed, and also the event which convinced those who had remained sceptical that quarks had a real existence. The fourth quark was called the **charmed** quark, and the other two quarks were found, **bottom** in 1977 and finally **top**, in 1995, by a group of about 400 physicists at Fermilab, one of whom was Prof. Devlin.

While you might think these additions would make for a much bigger and better (SU(6)) symmetry, that is not really the case, because the first three quarks were all light and could be thought of as having nearly equal masses, while the charm quark has three times the mass of the heaviest of the three, the bottom three times that, and the top 30 times heavier than the bottom. So there is no useful symmetry in interchanging these quarks with the light ones.

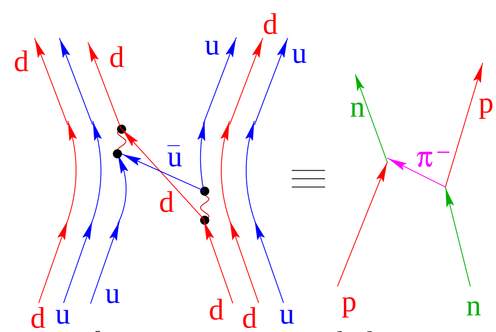
quark:	up	down	strange	charm	bottom	top
mass:	360 MeV	360 MeV	540 MeV	1.5 GeV	5.0 GeV	173 GeV

The first problem was resolved by finding that the quarks come not only in 6 "flavors", u, d, s, c, b, and t, but also in three colors. These names aren't to be taken seriously — the colors of quarks have nothing to do with ordinary colors, but there are three types of each quark, which we may call red, green, and blue. With the correct dependence of the wave function of the baryons on the color values of the quarks, the quark model now works with fermionic quarks, as it should. That is why color was first proposed. Now the three quarks in the Ω^- are in different states, one red, one blue, and one green.

[2]It was discovered independently by two groups, and the world could never determine which name to use, J or ψ.

But it turned out that color was a much more powerful idea than its original purpose would indicate. The three colors enter with a symmetry which is mathematically identical to the SU(3) of Gell-Mann, but used in physics in a different way. The "rotations" of this symmetry are changes in color, for example changing a red quark into a green one. These "rotations" are associated with spin one bosons, called gluons, which are the carriers of strong force[3]. There are eight of these, characterized by one color and one anticolor, with eight combinations, because the symmetric totally white combination (red $\overline{\text{red}}$ + blue $\overline{\text{blue}}$ + green $\overline{\text{green}}$) is excluded from the list of gluons. These gluons act very much like the photons do in quantum electrodynamics (QED)[4], though the fact that there are eight of them, and that they are colored, does make some profound differences. The photon does not have any charge, so photons do not directly interact with each other, but gluons interact with all things colored, including other gluons.

Because these new kinds of charges are called colors, the theory that has gluons playing the role of photons is called **quantum chromodynamics**, or QCD.



If we consider pion exchange between nucleons in the language of QCD, the incident neutron and proton are each a collection of three quarks. Say one of the d quarks in the neutron emits a virtual gluon and recoils to the left. The virtual gluon pair produces a $u\bar{u}$ pair, with the u joining up with the two "spectator" quarks, d and u, from the neutron to form a proton, and the $\bar{u}$ pairing up with the recoiling d to form a π^-. They travel until they are in the

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[3]Earlier we spoke of the pion as the particle exchanged in strong nuclear interactions. But the pion is now viewed as a composite, and pion exchange is a phenomenological discription at low energies of a much more complex strong interaction carried by the gluons.

[4]There is a wrong statement in the book on page 1534, lines 11-12, which states "This property is similar in many respects to electric charge except that it occurs in three varieties rather than two." This is wrong — the two signs of charge are not different varieties in the sense that green and red quarks are, and redness occurs with both signs (an antired antiquark is analogous to a negatively charged particle). Thus the statement should have read "... rather than one."

incoming proton, where the $\bar{u}$ from the π^- annihilates with one of the u's in the incoming proton, producing a gluon which can then be absorbed by one of the quarks. The d from the π^- joins up with the spectator u and d quarks from the incoming proton to form a neutron. Thus we have "charge exchange" scattering of a proton and neutron.

Quantum chromodynamics is now understood as the theory of the strong interaction. It is an example of a **gauge field theory**, which means that its carriers are massless spin 1 particles associated with a symmetry. Electromagnetism is also a gauge theory, though it has only one carrier, the photon, which is uncharged. Such a theory is called Abelian, while theories, like QCD, in which the carriers carry the charges they interact with are called non-Abelian or Yang-Mills theories.

One of the strange consequences of the carriers interacting with themselves is that the forces may not fall off like $1/r^2$. We saw that that force was the consequence of exchange of one massless particle, but if the field particles interact with each other that force may be overwhelmed by more complicated balls of interacting gluons. In fact, the coupling constant for QCD, analogous to e^2 in electromagnetism, is thought to vary with distance, becoming weak at very short distances and strong at large distances. This has two very important consequences. At high energy and short distances, the strong interactions are less strong and can be calculated with approximation techniques which don't work when the interactions are strong. Detailed calculations in QCD aren't possible at medium energies because of this, but it had been observed that simple calculations which should work only if the interactions are small did work at very high energies. This is called asymptotic or ultraviolet freedom. At the other extreme, we now believe that the force between two colored objects in QCD doesn't fall off with distance at all, for large distances. That means two colored objects can never get free from each other, for to get infinitely far apart would require an infinite amount of work against the force which is holding them together. Thus all observable particles are color neutral, white if you will, either a mixture of red, blue and green or a red-antired combination. This is why baryons and mesons are observable as free particles, but free quarks or gluons *have never been directly observed*. This is called infrared slavery.

Despite the fact that quarks and gluons never exist as independent particles, they provide an excellent understanding of the strong interactions, especially at high energies, where the interactions grow weaker and easier to understand. That ultraviolet freedom is what QCD theory predicts was discovered (calculated) in 1973 by these three gentlemen, Gross, Politzer and Wilczek, for which they received the Nobel Prize in Physics last October.