Beyond the Quark Model: Tetraquarks and Pentaquarks

in completion of Drexel University's Physics 502 Final

Tyler Rehak

March 15, 2016

The Standard Model of particle physics is continually being tested by new experimental findings. One of the main components of the model is the quark model. The quark model was introduced in 1964 independently by Murray Gell-Mann and George Zweig as a way to describe the elementary components of hadrons. While most hadrons are composed of either two or three quarks, there is the possibility of exotic hadrons that break the mold. There have been two recent announcements from particle physics laboratories regarding exotic hadrons. The DØ experiment at Fermilab announced in February 2016 the observation of a possible particle containing four types of quarks, a tetraquark. Earlier in July 2015, the LHCb collaboration at CERN announced the observation of a particle composed of five types of quarks, a pentaquark.

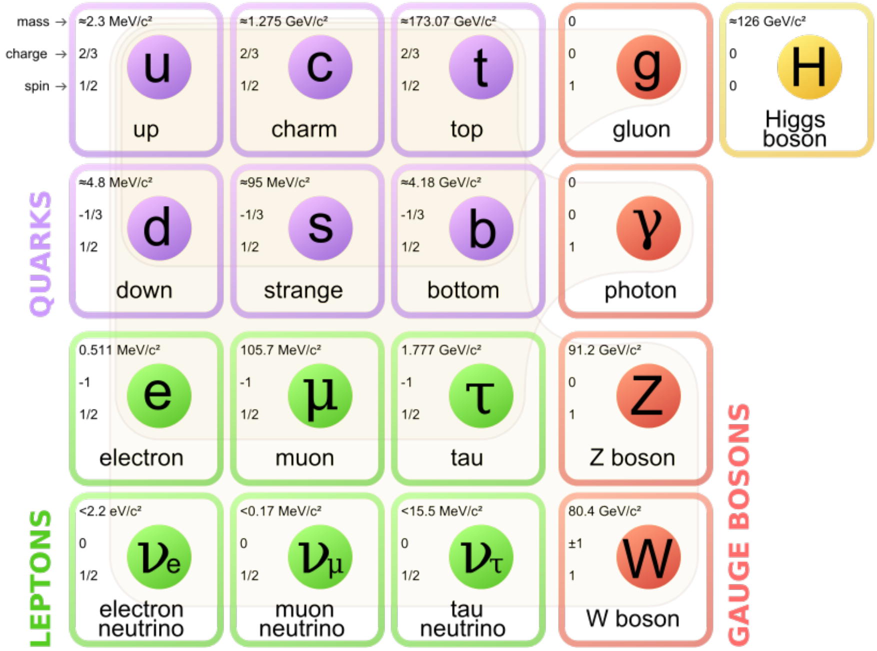

Figure 1 The Standard Model of particle physics (wikimedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg)

The Standard Model (Figure 1) consists of twelve types of fermions and their antiparticles, four gauge bosons, and the Higgs boson. The gauge bosons are the force carriers of the fundamental forces. Photons mediate the electromagnetic force between electrically charged particles. Gluons mediate the strong force between color charged particles, a property of quarks. The W and Z bosons are responsible for the weak force between quarks and leptons of varying flavors.

The fermions are elementary particles with spin ½ and each has a corresponding antiparticle. Six of the types of the fermions are quarks which are the particles interacting via the strong force, and the other six are leptons that do not interact via the strong force. The leptons and quarks are further split into three generations. Each generation consists of a pair of leptons (one with -1 electric charge and one neutral) and a pair of quarks (one with -1/3 charge and one with +2/3 charge). For example, the electron, the electron neutrino, the up quark, and the down quark are all first generation particles. Each higher generation indicates a greater mass of the particles than the previous generation. The increased masses of the higher generations results in the particles of higher generations only existing in high energy environments and then decaying into the first generation. This is evident by the observation that everyday matter is composed of first generation particles. One exception to this is the behavior of neutrinos which rarely interact with other matter and oscillate between the three generations, called flavor oscillation.

There are six types of quarks. In increasing order of generation, up, charm, and top quarks have +2/3 electric charge. Their corresponding -1/3 electrically charged generation partners are the down, strange, and bottom quarks, respectively. For example, a proton is composed of two up quarks and one down quark so its total electric charge is $2*(+2/3)+1*(-1/3)=+1$.

In addition to electric charge, quarks possess an additional property, color charge, which is involved in strong interactions. The current theory behind the strong force mediating interactions between quarks is called quantum chromodynamics. In the theory, quarks may have one of three values of color charge: red, green, or blue. Antiquarks have related anticolor charges of either antired, antigreen, or antiblue.

When groups of quarks and antiquarks are held together by the strong force, they form hadrons. A triplet of quarks is a baryon and a pair of a quark and an antiquark is a meson. The two types can also be classified by the baryon number which is defined as $B=1/3(n-n\_bar)$ where n is the number of quarks in a particle and n_bar is the number of antiquarks. Therefore, a baryon which has 3 quarks has a baryon number of +1 and a meson with one quark and one antiquark has a baryon number of 0. This specific grouping of quarks and antiquarks into baryons and mesons is required so that the resultant hadrons have zero color charge. Color charge adds to zero in two ways. Either three quarks or three antiquarks of three different colors combine, or a quark of a particular color is paired with an antiquark with the corresponding anticolor.

In fact, no particle with a nonzero color charge can be isolated singularly. This is referred to as color confinement. Unlike electric fields that decrease in strength over distance, the strong force acts between a pair of quarks at a constant force regardless of distance. Therefore, when a high energy collision occurs, rather than splitting immediately, two quarks will increase their distance from one another until it becomes energetically favorable for a new quark-antiquark pair to appear from the vacuum. This is called hadronization, and it results in particle detectors observing jets of hadrons rather than individual isolated quarks after a high energy collision.

Since mesons can be defined as being colorless hadrons with a baryon number of zero, there is nothing theoretically limiting mesons to only be composed of a quark and antiquark pair. For example, a meson could be comprised of two quark-antiquark pairs and still have zero color and zero baryon number. This would be an exotic meson called a tetraquark, and it is indeed the type of particle observed by the DØ experiment at Fermilab which they announced in February 2016.

Upon analyzing the invariant mass spectrum of $B^0_s\pi^\pm$, a new state labeled X(5568) was observed with mass equal to $m=5567.8$ MeV/c^2 and width $\Gamma=21.9$ MeV/c^2 with a significance of 5.1σ. Figure 2 shows a representation of the production of X(5568). The sum of the masses of a B_d and a $K^\pm$ meson adds up to about 5773 MeV/c^c, which is much different from the observed state, so the probability that X(5568) is composed of a loosely bound pair of a B_d and a $K^\pm$ meson is low. B^0_s mesons are composed of a strange quark and a bottom antiquark. $\pi^\pm$ mesons are composed of an up quark and a down antiquark (π^+)or an up antiquark and a down quark (π^-). Therefore, the structure of X(5568) must consist of four quark flavors (bottom, strange, up, and down) in a diquark-antidiquark pairing. Such a pairing would indeed result in a colorless particle (for example, anti-red and red paired with anti-blue and blue), so X(5568) does not contradict theory.

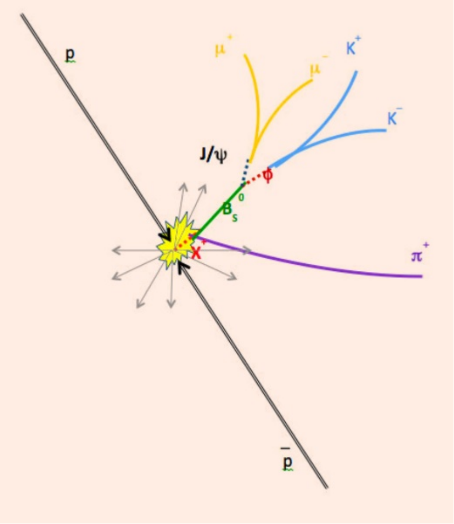

Figure 2 (left) Production of possible textraquark X(5568) and its decay into a Bs meson and a π+ meson. V.M. Abazov et al./Fermilab.

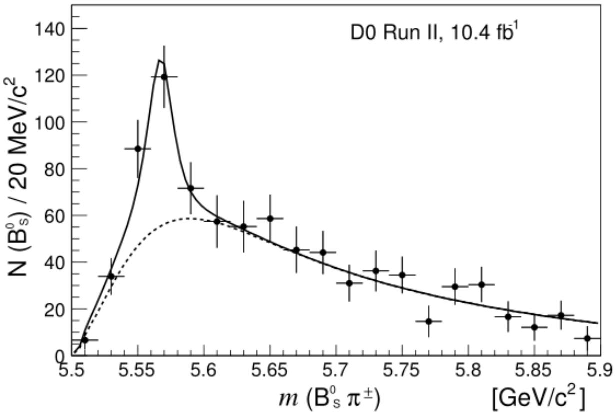

Figure 3 The mass distribution of B0sπ±. The solid line is the result of analysis fitting. The dashed line shows contributions due to B0s background from simulations. V.M. Abazov et al.

Just as mesons are not limited to only a single pair of quarks, baryons are not limited to only a set of three quarks. For example, if a particle consisted of four quarks and one antiquark, the total baryon number would be 1, which would classify it as a baryon, and it would be called a pentaquark. Creating a colorless baryon is a little more involved with five types of quarks, but it is possible. For example, the particle could have a red quark, blue quark, and green quark, plus a repeated color (e.g. red) quark and its corresponding anticolor (anti-red) antiquark. The first three quarks would cancel their color charge and the quark-antiquark pair would also be colorless. In July 2015, the LHCb collaboration at CERN announced the observation of two particles that have the composition of pentaquarks.

The LHCb experiment has been used to measure the lifetime of Λ^0_b. This means the collaboration already had plenty of data on the decay Λ^0_b -> J/ψ K^- p. Upon inspection of the data, there was a significant contribution in the decay structure that could be attributed to pentaquarks. In fact, two states were found with significances of 9σ and 12σ. $P_c(4380)^+$ was observed with a mass of 4380 MeV and a width of 205 MeV, and $P_c(4450)^+$ was observed with a mass of 4449.8 MeV and a width of 39 MeV. Figure 4 shows the Feynman diagram of the decay with the quarks of each particle labelled. The pentaquark states were concluded to consist of two up quarks, a down quark, a charm quark, and an anti-charm quark. The charm quark and antiquark are accounted for due to the pentaquark states decaying strongly to J/ψ p, and J/ψ is a meson composed of a charm quark-antiquark pair. There was no conclusive evidence for the type of structure within the pentaquark. It could possibly be a tightly bounded diquark, diquark, and antiquark, or it could even be a baryon bound weakly to a meson. Further experiments and analysis will be required to reveal the structure of the observed pentaquarks.

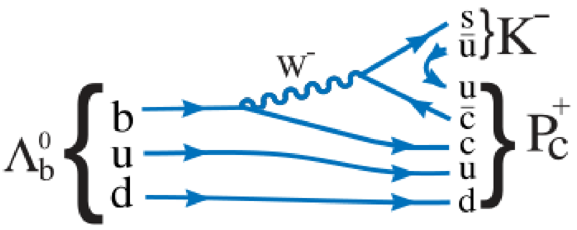

Figure 4 Feynman diagram for the decay Λ0b -> Pc+ K-. LHCb collaboration

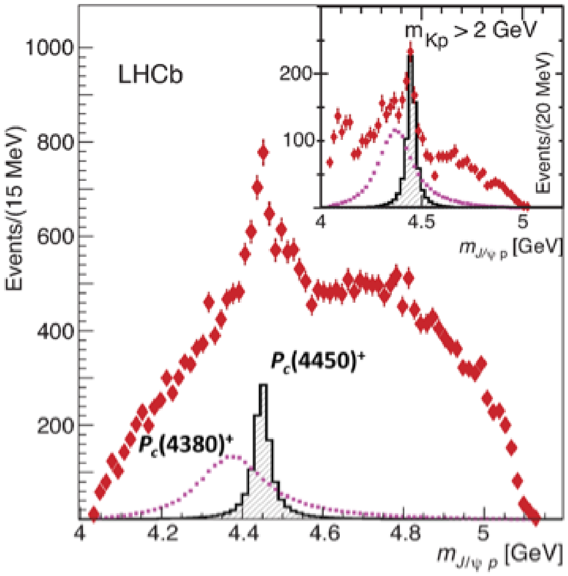

Figure 5 The mass distribution of the decay Λ0b -> J/ψ K- p. Data is red diamonds, with the contributions from the two pentaquark states indicated by the purple and black distributions. CERN / LHCb Collaboration

Since the quark model was introduced in the 1960s, particle physicists have continued to test the model and push deeper into the realm of the smallest particles of the universe. It took thirty years since they were proposed until all six quarks had finally been observed and discovered through experiments. However, there is no sign of slowing down the research. The recent observations by scientists at Fermilab and CERN of particles that go beyond the standard form of baryons and mesons is just one step in understanding the universe. Since tetraquarks and pentaquarks are formed at high energies, their structure may reveal more about the moments soon after the big bang when baryogenesis produced an asymmetry between baryons and antibaryons.

References

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