

Exotic particles with four or more quarks

Stephen Lars Olsen

The familiar denizens of the particle zoo are made of two or three quarks, but particle theory allows for states comprising any number of those fundamental particles. Finally, after decades of searching, tetraquarks seem to have been spotted.

Steve Olsen is a research fellow at the Institute for Basic Science in Daejeon, South Korea.

At the beginning of the 20th century, physicists thought the fundamental interactions between particles were two in number: gravitation, which is governed by mass, and electromagnetism, governed by charge. We now recognize two additional fundamental forces. The weak force is responsible for radioactive decay, and the strong force holds the nucleus together despite the Coulomb repulsion that tries to blow it apart. In the standard model of particle physics, the fundamental particles interacting via the strong interaction are fractionally charged quarks—featured prominently in this tutorial—that are held together by electrically neutral, photon-like gluons.

Quarks come in six varieties, or flavors: up (u), down (d), strange (s), charm (c), bottom (b), and top (t); their antiparticles, called antiquarks, are designated $\bar{u}$, $\bar{d}$, $\bar{s}$, $\bar{c}$, $\bar{b}$, and $\bar{t}$. The protons and neutrons that make up the nuclei of ordinary matter are themselves composed of up and down quarks. Each flavored quark carries one of three strong-interaction charges called color charges because the rules for combining them to form the particles observed in nature are reminiscent of rules associated with human color perception. Those color charges are called red, green, and blue; antiquark charges are the corresponding complementary colors: cyan, magenta, and yellow.

Colored quarks form white particles

The theory that describes interactions of quarks and gluons is quantum chromodynamics (QCD); chromo derives from the Greek word for color. According to QCD, particles observed in nature must be built from quark combinations that are white. (Some physicists prefer the term “colorless.”) Colored combinations, including single quarks themselves, cannot exist in isolation and are not directly observable. On the other hand, amalgamations of one red, one green, and one blue quark are allowed, as shown in panel a of the figure. Three-quark combinations, called baryons, include protons and neutrons.

Another way to form a white particle involves a colored quark and an antiquark of the corresponding anticolor. Such quark–antiquark combinations, also shown in panel a, are

found in mesons. Examples that will feature prominently below are the ψ' , made of a charm–anticharm quark pair ($c\bar{c}$), and the π^+ , which is a ($u\bar{d}$) combination.

Although a quark and an antiquark can combine to give a white meson, a combination of two quarks is necessarily colored, or perhaps better, anticolored. For instance, a green and blue quark pair forms a cyan configuration called a “diquark,” as shown in panel b. Since diquarks (and diantiquarks) have color, they cannot exist by themselves as isolated, observable particles. However, they can combine with other colored objects to form white configurations that should be observable particles.

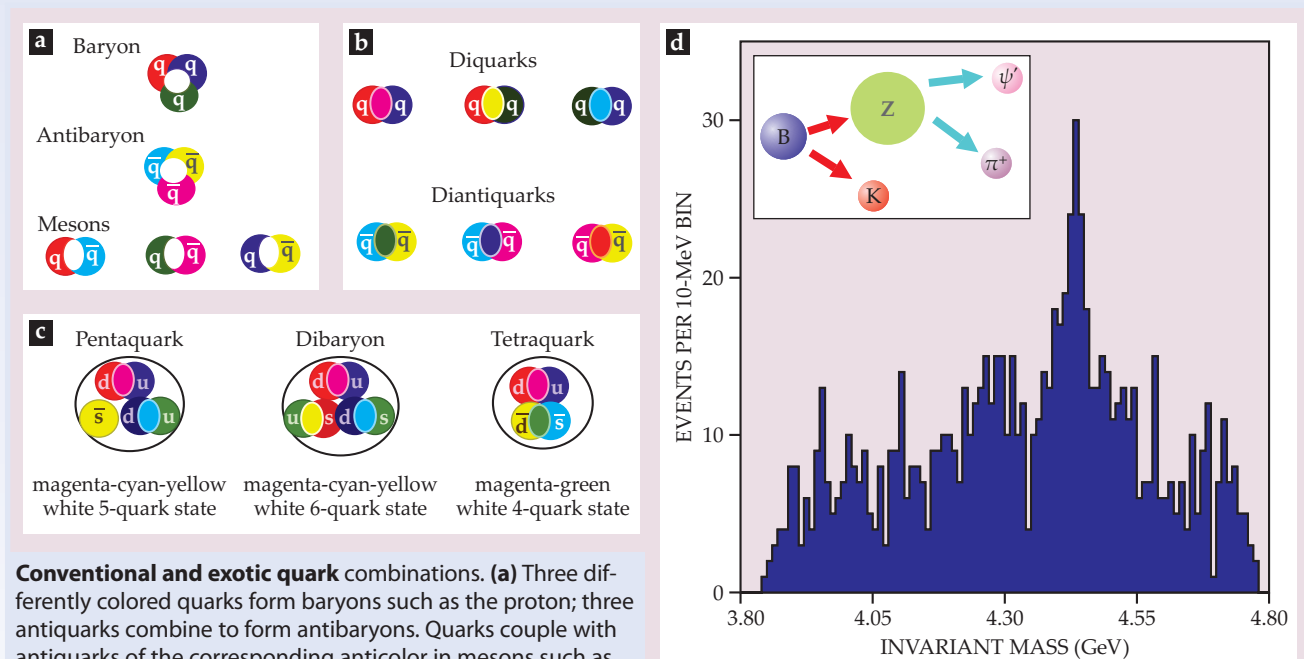
One can thus imagine creating particles with many quarks, as illustrated in panel c. A magenta and a cyan diquark, for example, could combine with a yellow antiquark to form a white five-quark state called a pentaquark baryon. Likewise, three differently colored diquarks could form a six-quark dibaryon, or a colored diquark could combine with a diantiquark of the corresponding anticolor to form a four-quark, or tetraquark, meson. Even before the discovery of color and the formulation of QCD, physicists had anticipated pentaquark baryons and tetraquark mesons: They are first mentioned in Murray Gell-Mann’s 1964 paper that proposed quarks.

Despite the general expectation that states with more than three quarks exist, experimental searches spanning more than three decades failed to uncover any unambiguous smoking-gun candidates. That failure was a major puzzle for particle physicists, though in the past couple of years some strong possibilities have emerged.

In 2003 and 2004, a series of claims of experimental evidence for a pentaquark (called Θ_5^+) generated considerable excitement. Based on the decay products of what they thought was the Θ_5^+ , experimenters concluded that they had spotted a baryon that had to contain an antistrange quark. Given that the Θ_5^+ is a baryon with positive charge and an antistrange quark, the simplest possible white configuration is $uudd\bar{s}$, shown in panel c of the figure. However, several subsequent experiments with higher sensitivity failed to reproduce those claims, which the particle-physics community now considers to have been incorrect. At various times physicists were excited about the possibility of a six-quark H-dibaryon (the dibaryon shown in panel c) and various possible tetraquark mesons, but the H was never observed, and until recently, none of the candidate tetraquark mesons could be confirmed.

A gun, if not quite smoking

The past decade saw a dramatic change in the experimental situation, mainly at B factories at SLAC in the US and KEK in Japan that were designed to study the weak-interaction-induced decays of b quarks. Studies involving charmonium (the generic name for mesons comprising a charm–anticharm quark pair, $c\bar{c}$) and bottomonium ($b\bar{b}$) uncovered a number of meson states that contained a c and a $\bar{c}$ quark but had properties at odds with all the states in the tightly constrained charmonium spectrum.



Conventional and exotic quark combinations. (a) Three differently colored quarks form baryons such as the proton; three antiquarks combine to form antibaryons. Quarks couple with antiquarks of the corresponding anticolor in mesons such as the pion. (b) Combining two quarks of different colors produces anticolored diquarks. (c) Any number of quarks can combine to form a particle as long as the resulting color is white. Examples are pentaquark baryons, dibaryons, and tetraquark mesons. In such cases, “baryon” means that the number of quarks minus the number of antiquarks is three, and “meson” means that quarks and antiquarks appear in equal number. Prefixes like “penta” or “tetra” refer to the total amount of quarks and antiquarks, without distinction. (d) In 2007 the Belle collaboration at KEK studied the reaction $B \rightarrow K\pi^+\psi'$. The plot here shows the invariant mass (defined in the text) of the $\pi^+\psi'$ products; the peak indicates that those products arose from the decay of an intermediate Z meson, as illustrated in the inset, and the nature of the products suggests that the Z is a four-quark state.

Notable among those was the $Z(4430)^+$, first reported in 2007 by the Belle collaboration at KEK. The group had been investigating the B-meson decay process $B \rightarrow K\pi^+\psi'$ to see if the π^+ and ψ' sometimes originated from the decay of an intermediate state, which they initially dubbed Z. The inset to figure panel d shows the imagined process.

If the intermediate Z exists, then its mass m_Z can be determined in terms of its energy E_Z and momentum $\mathbf{p}_Z$ through Einstein’s relation: $m_Zc^2 = (E_Z^2 - p_Z^2c^2)^{1/2}$. The Belle experimenters didn’t directly measure the energy and momentum of a Z; rather, they measured the properties of the π^+ and ψ' . But conservation of energy dictates that if the mesons arise from Z decay, $E_Z = E_{\pi^+} + E_{\psi'}$, and $\mathbf{p}_Z = \mathbf{p}_{\pi^+} + \mathbf{p}_{\psi'}$. When those substitutions are made into Einstein’s relation, one speaks of the invariant mass of the π^+ and ψ' system. Panel d of the figure shows the frequency of measured invariant mass values; its distinct peak was interpreted by the Belle group as evidence for a Z meson that quickly decays to the π^+ and ψ' .

Since the ψ' is a well-established $c\bar{c}$ state, the Z must contain an electrically neutral $c\bar{c}$ pair. However, since the Z decays to a ψ' and a π^+ , it must have a positive electric charge and, therefore, contain additional quarks to provide that charge. The simplest possibility is a $c\bar{c}u\bar{d}$ four-quark system. Since the mass corresponding to the peak in panel d is near 4430 MeV/ c^2 , the name of the positively charged four-quark state was expanded to $Z(4430)^+$. Results from a subsequent study by the BaBar collaboration at SLAC neither confirmed nor contradicted the Belle result, however, so the status of the Z meson remained ambiguous until recently.

In 2012 Belle experiments uncovered two charged mesons whose simplest structure is the four-quark state $b\bar{b}u\bar{d}$ —the $Z_b(10610)^+$ and $Z_b(10650)^+$. Last year the BESIII group at the Beijing Electron Positron Collider spotted two

charged mesons—the $Z_c(3900)^+$ and $Z_c(4020)^+$ —both of which presumably have a $c\bar{c}u\bar{d}$ structure similar to that of the $Z(4430)^+$. The Belle group subsequently confirmed the existence of the $Z_c(3900)^+$ and last year provided additional evidence for the $Z(4430)^+$. The big news of 2014 came from the LHCb collaboration at CERN’s Large Hadron Collider: With 10 times the statistics of either Belle or BaBar, the LHCb group strikingly confirmed Belle’s original claim for the $Z(4430)^+$.

The LHCb result clinches the identification of the $Z(4430)^+$ as a four-quark state and suggests that the other recently discovered charged Z mesons are also made from four quarks. Still, it is not certain they are diquark–diantiquark tetraquark states expected from QCD. Some authors argue that they are, but others suggest that at least some of the new four-quark mesons may be molecule-like states formed from charmed $c\bar{d}$ mesons interacting with anticharmed $\bar{c}u$ mesons via conventional nuclear forces. Unfortunately, QCD prohibits physicists from directly viewing a particle’s underlying color structure, and that makes it difficult to differentiate between competing theoretical interpretations of multiquark states. Hopefully, as more of those states are discovered and their properties measured, patterns will emerge that will enable physicists to distinguish among different explanations.

Additional resources

- M. Gell-Mann, “A schematic model of baryons and mesons,” *Phys. Lett.* **8**, 214 (1964).
- S.-K. Choi et al. (Belle collaboration), “Observation of a resonancelike structure in the $\pi^+\psi'$ mass distribution in exclusive $B \rightarrow K\pi^+\psi'$ decays,” *Phys. Rev. Lett.* **100**, 142001 (2008).
- R. Aaij et al. (LHCb collaboration), “Observation of the resonant character of the $Z(4330)^-$ state,” *Phys. Rev. Lett.* **112**, 222002 (2014), and references therein.