Diquark structures in hadron spectroscopy

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Abstract

The concept of diquark attraction is well grounded in QCD. Yet experimental evidence for diquarks has been at best elusive for many decades. Experimentally, we appear to be on the verge of a tipping point. In the next decade, experiments at hadron and lepton colliders are likely to provide much more unambiguous evidence for exotic hadrons and conventional baryons made out of diquarks. We propose to study experimental and theoretical directions of this now rapidly advancing research field.

The concept of a diquark is almost as old as the quark model, and actually predates QCD [1]. QCD as a gauge theory provides additional motivation for diquarks, since perturbatively the short-distance forces between two quarks in the color-antitriplet configuration are half as attractive as those between a quark and antiquark in the color-singlet combination. Thus, quark (or antiquark) pairs are likely to bind together as colored quasiparticles and play a similar role to that of a single antiquark (quark) in building more complicated hadrons. This

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mechanism can manifest itself as diquark substructure in baryons, or be responsible for the emergence of compact tetra- and penta-quarks, in which all quarks are confined in the same volume and interact via direct color fields. Jaffe developed the diquark concept further, pointing out the preference for $S = 0$, $I = 0$ ("good") ud diquarks, to explain anomalies observed among the lightest scalar mesons [2], though later an alternative explanation for the preference for $f_0(980)$ to decay to $K\bar{K}$ was offered via a "molecular" model, in which $f_0(980)$ is a deuteron-like bound state of $K\bar{K}$ [3]. With the advent of many unexpected states with hidden charm such as $X(3872)$ [4], $Z_c(3900)^{\pm}$ [5, 6], and $Z_c(4020)^{\pm}$ [7], Maiani *et al.* [8] pointed out that "bad" $S = 1$ heavy-light diquarks would not be suppressed, which then allowed these states to be interpreted as diquark-antidiquark compact tetraquarks. A further development, the "dynamical" diquark model [9], preserved the diquark-antidiquark structure but allowed the state to have a greater spatial extent, being held together by a color flux tube between the colored diquark sources. Note however that the proximity of these states to $D^*\bar{D}^{(*)}$ thresholds also motivates molecular models, so these states could be diquark-based, molecule-based, or even a mixture of the two. Nevertheless, many other non-conventional states with hidden charm, like $Z_c(4430)^{\pm} \to \psi(2S)\pi^{\pm}$ [10, 11], or the whole family of states decaying to $J/\psi\,\phi$ [12, 13, 14], do not have simple molecular explanations, nor is it easy to accommodate all the non-conventional charmonium-like vector states as molecules. It is difficult to construct a consistent diquark picture of all these states at the same time, although recent work shows that the basic multiplet structure can be obtained [15].

The very recent LHCb discovery [16] of a significant mass structure near 6.9 GeV in $J/\psi\,J/\psi$ invariant mass offers perhaps the best promise for a clear signature of tetraquarks made out of diquarks, as there are no well-known mechanisms for attractive meson exchanges between two charmonium states [17]. Also very promising is the even more recent discovery by the LHCb of a relatively narrow scalar $X(2900)$ state decaying to D^+K^- [18], which fits diquark-based tetraquark calculations for the ground state of a cs diquark plus a $\bar{u}\bar{d}$ antidiquark [19]. Such calculations, when applied to doubly-heavy diquarks, predict stable tetraquarks, especially using the bb diquark [20]. As noted in some of these references, these models also share several features with the ones used for doubly-heavy baryons. The role of diquarks in conventional baryons is also a rich ground to be further explored [21, 22, 23, 24]. A clear signature of diquarks in Λ_b^0 was shown by LHCb in the lack of $\Lambda_b^0 \to J/\psi\Sigma^0$ events with respect to $\Lambda_b^0 \to J/\psi\Lambda$ [25]. Confirmation of multi-quark hadrons bound via diquarks would provide a solid argument in favor of the color flux confinement, consistent with the linearity of Regge trajectories predating quarks, which was difficult to understand for baryons in the initial quark model [26].

With the upgrade of the LHCb and Belle-II experiments under way, and other programs such as ATLAS, CMS, BESIII, JLab, and eventually EIC and PANDA also contributing to conventional and exotic heavy-quark spectroscopy, the next decade promises to be very exciting. We propose to create a study group between theorists and experimentalists, to survey this dynamic field of research and identify the most promising avenues for more discoveries, obtain more data on the known diquark-based hadron candidates, and develop more advanced theoretical frameworks.

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