Novel Six-Quark Hidden-Color Dibaryon States in QCD

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Abstract

The recent observation of a hadronic resonance \(d^*\) in the proton-neutron system with isospin \(I = 0\) and spin-parity \(J^P = 3^+\) raises the possibility of producing other novel six-quark dibaryon configurations allowed by QCD. A dramatic example of an exotic six-quark color-singlet system is the charge \(Q = +4\), isospin \(I = 3\), \(J^P = +3\) state which couples strongly to \(\Delta^{++} + \Delta^{++}\). The width and decay properties of such six-quark resonances could be regarded as manifestations of "hidden-color" six-quark configurations, a first-principle prediction of QCD – SU(3)-color gauge theory for the deuteron distribution amplitude. Other implications and possible future experiments are discussed.

Keywords: exotic hadrons; hidden color, hexaquark states

1. Introduction

Because of color confinement, one expects that virtually any color-singlet hadronic configuration of quarks and gluons can form either bound states or resonances. In addition to the familiar \(q\bar{q}\) mesons, \(qqq\) baryons, the \(gg\) and \(ggg\) glueball states \cite{1}, as well as nuclei, color confinement can lead to \(q\bar{q}qq\) "tetraquark" systems \cite{2} such as the charged \(Z_c(c\bar{c}ud)\) \cite{3} \cite{4} and possibly \(qqq\bar{q}\) "pentaquark" states \cite{5}. Mesonic nuclei \cite{6} \cite{7} \cite{8} \cite{9} \cite{10} \cite{11} \cite{12} and nuclear-bound quarkonium \cite{13} \cite{14} are also possible. Resonances in the \(q\bar{q}qqq\) channel just below the \(BB\) threshold could explain the anomalously large rates \cite{15} seen in \(e^+e^- \to pp, nn, \Lambda\Lambda\) at threshold. The anomalously large transverse spin-spin correlation \(A_{NN}\) observed in large-angle proton-proton elastic scattering near the strangeness and charm thresholds \cite{16} could be explained by the effects of \(|uuududQQ\rangle\) baryon number \(B = 2\) resonances in the \(J = L = 1 pp s\)-channel \cite{17} \cite{18}. Understanding the mechanisms underlying confinement in QCD is among the most fundamental questions in hadron physics. In the case of heavy quarks, the potential evidently can be identified with gluon exchange, in analogy with the Coulomb forces which bind atoms. The potential underlying light-quark interactions is however much more complex – such as flux-tube exchange \cite{19} and other string-like forces \cite{20} built from multi-gluon exchange. It has recently been shown that the effective confining \(q\bar{q}\) potential in the frame-independent QCD light-front (LF) Hamiltonian has a unique form \cite{21} if one maintains conformal symmetry of the QCD action. The resulting meson eigensolutions of the resulting light-front Schrodinger equation include a zero-mass pion in the chiral \(m_q \to 0\) limit, and linear Regge trajectories \(M^2(n, L) \propto n + L\) with the same slope in the radial quantum number \(n\) and orbital angular momentum \(L\). In the case of light baryons, the confining potential could mimic the \(q\bar{q}\) form as a two-body quark-diquark interaction in a light-front Dirac equation \cite{22} \cite{23} or take the form of a three-body force such as a \(V\) junction \cite{24} between the valence quarks. The LF Dirac equation based on quark-diquark interactions with the same potential as \(q\bar{q}\) accounts well for the measured light baryon spectrum \cite{22}

The possible mechanisms underlying confinement multiply as the number of quarks and gluon constituents in a hadronic system increase. A key question is whether such states bound by fundamental QCD interactions or do the constituents always cluster as color-singlet subsystems? In the case of nuclei, the quark constituents evidently cluster as color-singlet nucleons bound by virtual meson exchange, the analog of covalent binding in molecular physics due to quark interchange or exchange. When there are no covalence quarks in common, QCD also predicts attractive multigluonic van der Waals forces which are dual to glueball exchange. The attractive QCD van der Waals potential leads to the prediction of bound states of heavy quarkonium to heavy nuclei \cite{13} \cite{14} \cite{25}. However, there are also rare configurations in which other multiquark color configurations ("hidden color" \cite{26}) can enter.

There are several possible interpretations \cite{27} for the dominant internal structure of the positively charged \(Z_c(4025)\), which can be identified as a \(|c\bar{c}ud\rangle > color\)-singlet tetraquark bound state. The \(Z_c\) could be considered an example of a bound state of \(cc\) quarkonium with a light \(ud\) meson bound by gluon exchange, corresponding to "disconnected contributions" in lattice gauge theory simulations \cite{28}; or a \(D^*\bar{D}^*\) hadronic molecule \cite{29} \cite{30} \cite{31} such as \(D^*(c\bar{u})\bar{D}^*(\bar{c}\bar{d})\) clusters bound by meson exchange. Other color-confining interactions between higher-color multiquark representations may also dominate \cite{31} \cite{32}.

The possibility of exotic six-quark \(qqqqqq\) dibaryonic "hex-
resonance decay as an enhancement in the rate of the exclusive

...states. A typical example is the study of isotopic-spin-zero

...configurations. When one probes the light-front wavefunc-

...states may well be possible in the near future.

...configurations of six color triplets $3C$ can form a color singlet

...function where all of the six quarks have small

...transverse momentum, the five \"hidden-color\" configurations of

...solution denotes a \"hidden color\" six-quark configuration. The

...amplitude in the hard-scattering fixed

...method or in photodisintegration $yd \rightarrow np$ at high

...function of the deuteron form factor at high moment-

...and 2 quarks in the P-shell). The quark structure with the

...states were first proposed by F. J. Dyson and N.

...singlet states of the deuteron wavefunction also cou-

...baryon states; e.g. the $\pi^+\pi^−\Delta^0$ resonance. This is more

...second, we do not expect major Coulombic corrections to its dibaryon properties from

...charge-related effects in $nn → pp$ or in $Δ^+Δ^−$ systems.

...peak in the $\pi^+\pi^−\Delta^+$ channel measurement $pp \rightarrow \pi^+\pi^−\Delta^+\Delta^+$. The enhancement could appear below the nominal two-isobar mass, indicating a possible $ΔΔ$ bound state phenomenon.

2. Recent Experimental Evidence for a $Δ − Δ$ Resonance

A pronounced resonance structure has recently been observed in $pp$ collisions leading to two-pion production in the reactions $pp \rightarrow d\pi^0\pi^0 \hspace{1em} [50, 51]$, $pp \rightarrow d\pi^+\pi^−\hspace{1em} [52]$, $pp \rightarrow pπ^+π^−\hspace{1em} [53]$ and possibly also in $pn$ elastic scattering, in particular in the total cross section and in the analyzing power $[54]$. For the not yet measured reactions $pp \rightarrow pπ^+π^−$ and $pn \rightarrow pπ^+\pi^−$ exist predictions for the size of the expected resonance effect $[55, 56]$.

The measured parameters for this resonance structure, called henceforth $d^*$, are $I(J^P) = 0(3^+)$ with mass $M = 237$ GeV and width $Γ = 70$ MeV $[51, 52, 53]$. Dalitz plots indicate that $d^*$ dominantly decays via an intermediate $Δ − Δ$ system. However, the mass of this resonance is about 90 MeV below the nominal mass 2$\sqrt{s}$ of a $ΔΔ$ system, and its width is about three times smaller than that of a $ΔΔ$ system formed by conventional $t$-channel meson exchange or quark interchange arising within the NN collision processes. The interchange of quarks of the same flavor $[57]$ has been shown to dominate hadron-hadron elastic scattering amplitudes in the hard-scattering fixed $θ_{CM}$ scattering domain $[58]$.

We conclude from such observations that $d^*$ must be of an unconventional origin, possibly indicating a genuine six-quark nature. With the predominant decay of $d^*$ being $d^* \rightarrow ΔΔ$ ($BR(d^* \rightarrow ΔΔ)/BR(d^* \rightarrow pn) = 9:1$), one could naively expect $d^*$ to be a so-called \"deltaron\" denoting a deuteron-like bound state of two $Δ$s. However, the narrow width of $d^*$ contradicts this simple assumption. A deltaron would need to have 90 MeV binding energy, i.e. 45 MeV per $Δ$, which would lead to a reduction of width from $Γ_{ΔΔ} = 230$ MeV to $Γ_{ΔΔ} = 160$ MeV, using the known momentum dependence of the width of the $Δ$ resonance. This is more than twice what is observed.

On the other hand, if $d^*$ is a genuine six-quark dibaryon state, we need to understand its large coupling $d^* \rightarrow ΔΔ$. This can be explained if one assumes the $d^*$ is dominated by a \"hidden-color\" six-quark state. Hidden-color six-quark states are a rigorous first-principle prediction of SU(3) color gauge theory. Six quark color-triplets $3C$ combine to five different color-singlets in QCD, and as shown in Ref. $[26]$, will significantly decay to $ΔΔ$.

According to M. Harvey $[59]$ there are only two possible quark structures for an $I(J^P) = 0(3^+)$ resonance in the two-

...potential $\Psi_{d^*}$ is $\Psi_{d^*} = \sqrt{\frac{1}{2}}\Psi_{ΔΔ} - \sqrt{\frac{1}{6}}\Psi_{6Q}$. Here $ΔΔ$ means the asymptotic $ΔΔ$ configuration and $6Q$ is the genuine \"hidden color\" six-quark configuration. The first solution denotes a $S^0$ quark structure (all six quarks in the S-shell), the second one a $S^1P^0$ configuration (4 quarks in the S-shell and 2 quarks in the P-shell). The quark structure with the
large $\Delta\Lambda$ coupling would correspond to a deltaron and can be excluded. Thus it is natural to assign the observed $d'^*$ resonance to the $S^6$ six-quark predominantly "hidden color" state, thus providing an explanation for its narrow decay width.

Due to its quantum numbers, the $d'$ state must be fully symmetric in spin, color, and angular momentum as well as fully antisymmetric in isospin. Due to this particular feature, Ref. [69] claims that any model based on confinement and effective one-gluon exchange leads to the prediction of the existence of a non-strange dibaryon with $I(J^P) = 0(3^+)$, the "inevitable non-strange dibaryon". In fact, many groups [33, 60, 61, 63, 65, 64] predicted such a state at similar mass. It is remarkable that the first such calculation published by Dyson and Xuong [33] appears now to be quite precise in the prediction of the $d'$ mass. In the nomenclature of Ref. [33], the $d'$ has the notation $D_{03}$, where the indices (03) denote the isospin $I = 0$ and spin $J = 3$ of the dibaryon. To predict the mass of the $D_{03}$ Dyson and Xuong identified the $D_{03}$ state with the $^3S_1$ deuteron ground state and the $D_{03}$ with the $^1S_0$ virtual state (unbound by 66 keV only [65]), which is known to contribute to the nucleon-nucleon final-state interaction. These two states are also currently being used to check the reliability of lattice calculations for the H-dibaryon [43, 66, 67, 69, 41].

Most quark models predict [60, 61, 63, 62, 33] that in addition to $d'$ one should have also a state with mirrored quantum numbers for spin and isospin, i.e. $I(J^P) = 3(0^+)$ at a similar mass. Such a state, which in the notation of Ref. [33] is $D_{01}$, would be symmetric in isospin, color, angular momentum and antisymmetric in spin. Due to its isospin $I = 3$, it cannot decay into $NN$ or $NN\pi$, but only into the $NN\pi\pi$ channel. Thus if such a state has a mass close to that of $d'$, its width must be even smaller than that of $d'$. According to Ref. [33], both $d'$ and $D_{03}$ belong to multiplets of dibaryons, the first one is assigned to an antidecuplet and the second one to a 28-plet. Thus, given the existence of the $d'$, one should expect a number of strange dibaryons. The three corners of the possible 28-plet look truly exotic: 6u quarks, 6d quarks, 6s quarks. In each of these cases the quarks occupy all possible states. The 6s quark state can be considered as a strange droplet and could play an important role in astrophysics regarding the nuclear equation of matter in the core of neutron stars. Recent calculations on $\Omega\Omega$ (6s quark state) [68, 69, 71] display a range of results — from 100 MeV binding to an unbound state.

3. Experimental Strategies

The existence of novel dibaryon states still awaits definitive experimental confirmation or exclusion. Thus we will discuss in the following a number of possible experiments and strategies for producing the charge-1 $d'$ and charge-4 $D_{03}$ such as photo- or electro-production on a deuteron $yd \rightarrow d' \rightarrow dd'\pi^0$. A suitable place to perform such an experiment appears to be MAMI at Mainz due to its high beam intensity and good neutral particles detection capabilities of the Crystal Ball experiment. Such a reaction should preferably go via photon coupling to the deuteron’s six-quark component and will allow to fix the transition from the six-quark component in the deuteron to the one of $d'$. The reaction $yd \rightarrow d' \rightarrow dd'\pi^0$ is less favorable due much higher background rates [71].

With the knowledge of the $dd'\gamma$ coupling one can estimate possible cross sections for the production of other antidecuplet members in reactions like $yd \rightarrow d', K^+ \rightarrow \Delta\Sigma^+ + K^+$. Such reactions could be measured at JLab. Another possibility to produce the strange partners of $d'$ would be the study of kaon-induced reactions of the kind $K^-d \rightarrow d', \Delta\Sigma^+ \rightarrow K^+\pi\pi\pi^0$ as could be conducted at JPARC.

Accessing the members of the 28-plet appears to be much more complex. Most prominent here is $D_{03}$ with charge $Q = +4$ (six u-quarks). The dedicated decay channel of such a state is $D_{03} \rightarrow pp\pi^+\pi^*$ which can be triggered with high selectivity. However, the production of such a state is challenging. One may be able to produce it in $pp$ collisions; however, in order to reach the $I = 3$ state, one needs to produce in addition two associated negative pions $pp \rightarrow D_{03}\pi^- \rightarrow (pp\pi^+\pi^*)\pi^-\pi^*$. To perform such a reaction in the energy region of interest, one needs a rather high beam energy of $T_p = 1.7-2$ GeV which is available at COSY and JPARC. However, the $pp\pi^+\pi^-\pi^*$ channel will be highly contaminated by conventional $N^*$ and $\Delta$ excitations.

Another important way to identify the $D_{03}$ is its production in nuclei, e.g. on carbon by the reaction $\gamma C^{12} \rightarrow pp\pi^+\pi^* X$ below the $4\pi$ threshold at JLab, or similarly using proton or pion beams in reactions such as $p^{12}C \rightarrow pp\pi^+\pi^* X$ and $\pi^{12}C \rightarrow pp\pi^+\pi^* X$. In all such reactions the conventional background due to associated meson production production needs to be effectively suppressed.

The detection of the $Q = +4 D_{03}$ resonance would help to constrain the properties of the "strange droplets", the $\Omega\Omega$ states, and thus simplify its search in heavy-ion collisions.

Another place to look for both the $D_{03}$ ($d'$) and $D_{03}$ resonances is to search in quarkonium decays. The high mass of dibaryonic resonances excludes charmonium decays; however, bottomium decays measured at B-factories appear to be promising. The observation of the $d'$ looks particularly straightforward: due to its isospin $I = 0$ one does not necessarily need to search for $Y \rightarrow d'd'$; the search for $Y \rightarrow dd'$ would be sufficient. The branching ratio of $BR(Y \rightarrow d'd') = 2.86 \times 10^{-5}$ [72] appears to be large enough to search for the reaction $Y \rightarrow dd'$ or $d'd \rightarrow dd(\pi\pi)_{\pi=0}$. This simple possibility is forbidden for the $D_{03}$ because of its isospin. One could produce the $D_{03}$ paired with $D_{03}$ having in minimal configuration $Y \rightarrow D_{30} \rightarrow (\bar d\bar p\pi^+\pi^-)(pp\pi^+\pi^-)$. Unfortunately, this channel will contain large contamination from the production of conventional $N^*$ and $\Delta$ resonances and their antimatter analogs. However, one can extract not only the mass and width of resonances in this way, but also its time-like form-factor. The extraction of the space-like form-factor for such a state appears to be impossibly at the present level of experimental capabilities, so distinguishing between molecular-type and genuine dibaryon will be challenging.

To our knowledge dibaryon channels have not yet been looked for at $e^+e^-$ colliders; however, the statistics of data already collected at BaBar and Belle should be large enough to search for such resonances. Recent publications on the search
4. Summary

The recent observation of a narrow hadronic proton-neutron resonance \( d^* \) with \( I(J^P) = (3^+) \) and mass \( M = 2.37 \) GeV raises the possibility of producing other novel color-singlet six-quark dibaryon configurations allowed by QCD. A dramatic example would be the discovery of an exotic six-quark \( [uuuuuu] > \) color-singlet system with charge \( Q = +4 \), isospin \( I = 3 \), and \( F = +3 \), a state which couples strongly to \( \Delta^+ + \Delta^+ \). The width and decay properties of such six-quark resonances could be regarded as a manifestation of either a “hidden-color” six-quark configuration, versus a more conventional interpretation as a \( \Delta - \Delta \) (deltaron) resonance. We have discussed a number of possible experiments where such a state could be observed.

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