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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 $I = 3$, $I^z = +3$ $|uuuuuu>$ 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 [1], as well as nuclei, color confinement can lead to $q\bar{q}q\bar{q}$ "tetraquark" systems [2] such as the charged $Z_c(c\bar{c}u\bar{d})$[3, 4] and possibly $qqqq\bar{q}$ "pentaquark" states [5]. Mesonic nuclei [6, 7, 8, 9, 10, 11, 12] and nuclear-bound quarkonium [13, 14] are also possible. Resonances in the $\bar{q}\bar{q}\bar{q}qqq$ channel just below the $B\bar{B}$ threshold could explain the anomalously large rates [15] seen in $e^+e^- \to p\bar{p}, n\bar{n}, \bar{\Lambda}\Lambda$ 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 [16] could be explained by the effects of $|uuduudQ\bar{Q}>$ baryon number $B = 2$ resonances in the $J = L = 1$ pp s-channel [17, 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 [19] and other string-like forces [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 [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 [23, 22], or take the form of a three-body force such as a Y junction [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 [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 [13, 14, 25]. However, there are also rare configurations in which other multiquark color configurations ("hidden color" [26]) can enter.

There are several possible interpretations [27] for the dominant internal structure of the positively charged $Z_c^+(4025)$, which can be identified as a $|c\bar{c}u\bar{d}>$ color-singlet tetraquark bound state. The Z_c could be considered an example of a bound state of $c\bar{c}$ quarkonium with a light $u\bar{d}$ meson bound by gluon exchange, corresponding to "disconnected contributions" in lattice gauge theory simulations [28]); or a $D^*\bar{D}^*$ hadronic molecule [29, 2, 30] such as $D^*(c\bar{u})\bar{D}^*(\bar{c}d)$ clusters bound by meson exchange. Other color-confining interactions between higher-color multiquark representations may also dominate [31, 32].

The possibility of exotic six-quark $qqqqqq$ dibaryonic "hex-

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aquark" states was first proposed by F. J. Dyson and N. Xuong [33] in 1964, just a half a year after Gell-Mann's publication of the quark model [34]. However, this topic received intensive attention only after Jaffe's proposal[35] of the so-called "H dibaryon", a $|uuddss>$ state corresponding asymptotically to a bound $\Lambda\Lambda$ system. This hypothesis initiated a worldwide activity of theoretical predictions for dibaryon states with and without strangeness – as well as numerous experimental searches. Despite numerous claims, no established dibaryon candidate has emerged. For a recent report concerning the experimental H dibaryon search see *e.g.* Ref. [36]. However, there has been renewed interest in such states, in part because lattice QCD calculations are now becoming available [37, 38, 39, 40, 41, 42, 43].

As we shall show in this paper, the discovery of six-quark states would provide a novel extension of the domain of hadronic states in QCD, and the experimental verification of such dibaryon states may well be possible in the near future.

The most familiar six-quark state is the isospin-zero $|uudddu>$ deuteron; in fact, the wavefunction of the deuteron has novel properties in QCD. Five distinct color-singlet configurations of six color triplets 3_C can form a color singlet in $SU(3)$ color, only one of which corresponds to the usual pn configuration. When one probes the light-front wavefunctions of the deuteron where all of the six quarks have small relative separation, as in the deuteron form factor at high moment transfer or in photodisintegration $\gamma d \to np$ at high transverse momentum, the five "hidden-color configurations" of the deuteron mix due to gluon exchange and become equal in magnitude at asymptotic $Q^2 \to \infty$ [26]. For example, the observed $Q^{10}F_d(Q^2)$ scaling [44] of the deuteron $\sqrt{A}(Q^2)$ form factor at high Q^2 [45] is dominated by hidden-color configurations. This result can be derived by applying ERBL evolution [46, 47] to the five-component deuteron distribution amplitude $\phi_d(x_i, Q)$. The color-singlet states of the deuteron wavefunction also couple to a virtual $\Delta^+\Delta^0$ state [48].

The most dramatic example of an exotic six-quark color-singlet system is the charge $Q = +4$, isospin $I = 3$, $I^z = +3$ $|uuuuuu>$ state, as originally proposed by Dyson and Xuong [33]. The Fermi-Dirac statistics of the color-triplet $u$quark only allows one color-singlet six-quark configuration with zero orbital angular momentum: $|u_R^\uparrow u_Y^\uparrow u_B^\uparrow u_R^\downarrow u_Y^\downarrow u_B^\downarrow>$. The set of seven $I^z = 3, 2, 1, 0, -1, -2, -3$ states ranging from $Q = +4$ to $Q = -2$ are then obtained by applying the isospin-lowering operator. As a first approximation, one can estimate their masses $\simeq 2.4$ GeV by considering these states as effective $\Delta\Delta$ bound states; e.g. the $|uuuuuu>$ state can be considered as a bound-state of two $I^z = 3/2$ Δ^{++} isobars. We do not expect major Coulombic corrections to its dibaryon properties from the high $Q = +4$ charge since one does not observe significant charge-related effects in $nn - pp$ or in Δ^{++}-Δ^0 systems.

In this paper we will review the present evidence for dibaryon states and discuss future strategies for detecting such six-quark states. A typical example is the study of $pp \to \pi^-\pi^- X$, where the recoil system X could display a charge $Q = +4$ resonance peak in the X missing mass. One can also look for $\Delta^{++}\Delta^{++}$ resonance decay as an enhancement in the rate of the exclusive channel measurement $pp \to \pi^-\pi^-\Delta^{++}\Delta^{++}$. The enhancement could appear below the nominal two-isobar mass, indicating a possible $\Delta\Delta$ bound state phenomenon.

2. Recent Experimental Evidence for a $\Delta - \Delta$ Resonance

A pronounced resonance structure has recently been observed in pn collisions leading to two-pion production in the reactions $pn \to d\pi^0\pi^0$ [50, 51], $pn \to d\pi^+\pi^-$ [52], $pn \to pp\pi^-\pi^0$ [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 $pn \to pn\pi^0\pi^0$ and $pn \to pn\pi^+\pi^-$ 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 $M = 2.37$ GeV and width $\Gamma = 70$ MeV [51, 52, 53]. Dalitz plots indicate that d^* dominantly decays via an intermediate $\Delta - \Delta$ system. However, the mass of this resonance is about 90 MeV below the nominal mass $2m_\Delta$ of a $\Delta\Delta$ system, and its width is about three times smaller than that of a $\Delta\Delta$ 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 $d^* \to \Delta\Delta$ ($BR(d^* \to \Delta\Delta)/BR(d^* \to pn) = 9{:}1$), one could naively expect d^* to be a so-called a "deltaron" denoting a deuteron-like bound state of two Δs. 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 $\Gamma_{\Delta\Delta} = 230$ MeV to $\Gamma_{\Delta\Delta} = 160$ 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 $d^* \to \Delta\Delta$. 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 3_C combine to five different color-singlets in QCD, – and as shown in Ref. [26], will significantly decay to $\Delta\Delta$.

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

$|\Psi_{d^*}\rangle = \sqrt{\frac{1}{5}}|\Delta\Delta\rangle + \sqrt{\frac{4}{5}}|6Q\rangle$ and

$|\Psi_{d^*}\rangle = \sqrt{\frac{4}{5}}|\Delta\Delta\rangle - \sqrt{\frac{1}{5}}|6Q\rangle$.

Here $\Delta\Delta$ means the asymptotic $\Delta\Delta$ configuration and $6Q$ is the genuine "hidden color" six-quark configuration. The first solution denotes a S^6 quark structure (all six quarks in the S-shell), the second one a S^4P^2 configuration (4 quarks in the S-shell and 2 quarks in the P-shell). The quark structure with the large $\Delta\Delta$ 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. [60] 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, 62, 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 D_{03} Dyson and Xuong identified the D_{01} state with the $^3S_1$ deuteron ground-state and the D_{10} 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, 39, 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_{30}, 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_{30} 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, 70] 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_{30} such as photo- or electro-production on a deuteron $\gamma d \to d^* \to d\pi^0\pi^0$. 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 $\gamma d \to d^* \to d\pi^+\pi^-$ 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 $\gamma d \to d_s^* + K^+ \to \Delta\Sigma^* + K^+$. 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 $K^- d \to d_s^* \to \Delta\Sigma^*$ as could be conducted at JPARC.

Accessing the members of the 28-plet appears to be much more complex. Most prominent here is D_{30} with charge $Q = +4$ (six u-quarks). The dedicated decay channel of such a state is $D_{30} \to pp\pi^+\pi^+$ 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 $pp \to D_{30}\pi^-\pi^- \to (pp\pi^+\pi^+)\pi^-\pi^-$. 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 $pp\pi^+\pi^+\pi^-\pi^-$ channel will be highly contaminated by conventional N^* and Δ excitations.

Another important way to identify the D_{30} is its production in nuclei, *e.g.* on carbon by the reaction $\gamma C^{12} \to pp\pi^+\pi^+ X$ below the 4π threshold at JLab, or similarly using proton or pion beams in reactions such as $p^{12}\mathrm{C} \to pp\pi^+\pi^+ X$ and $\pi^{+12}\mathrm{C} \to pp\pi^+\pi^+ X$. 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_{30} 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_{30} 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 $\Upsilon \to \overline{d^*} d^*$; the search for $\Upsilon \to \overline{d} d^*$ would be sufficient. The branching ratio of $BR(\Upsilon \to \overline{d} + X) = 2.86\times10^{-5}$ [72] appears to be large enough to search for the reaction $\Upsilon \to \overline{d} d^*$ or $\overline{d^*} d \to d\overline{d}(\pi\pi)_{I=0}$. This simple possibility is forbidden for the D_{30} because of its isospin. One could produce the D_{30} paired with $\overline{D}_{30}$ having in minimal configuration $\Upsilon \to \overline{D}_{30} D_{30} \to (\overline{p}\overline{p}\pi^-\pi^-)(pp\pi^+\pi^+)$. Unfortunately, this channel will contain large contamination from the production of conventional N^* and Δ 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 impossible 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 for H-dibaryon production in the Υ decays by Belle [36] may be a good starting point for the search of other dibaryon candidates, including the ones discussed here.

Another important experimental option is the photoproduction or electroproduction of a dibaryon state on a nucleon target in combination with associated anti-nucleon production, such as $\gamma p \rightarrow \bar{p}\pi^-\pi^- D_{30} \rightarrow (\bar{p}\pi^-\pi^-)(pp\pi^+\pi^+)$, a reaction which could be investigated at the upcoming 12 GeV electron facility at JLab. The advantage of such reactions is the particularly simple triggering conditions – the essential signal for the dibaryon is provided by the antiproton trigger. Of course, as in the other cases discussed above, one may encounter a high level of conventional backgrounds.

The triggering on antiparticles promises to be even better suited for strange dibaryons. In case of strangeness $S = -1$, the tagging on the $\overline{\Sigma^*}$ allows one to separate antidecuplet from 27-plet states. Only a 27-plet $J = 0$ state can be produced in combination with $\overline{\Sigma^{*-}}$ in the reaction $\gamma p \rightarrow \overline{\Sigma^{*-}} + (\Sigma^{*+}\Delta^+)_{27}$, whereas with $\overline{\Sigma^{*+}}$ both the 27-plet $J = 0$ and antidecuplet $J = 3$ states are possible in the process $\gamma p \rightarrow \overline{\Sigma^{*+}} + (\Sigma^{*-}\Delta^+)_{27,\overline{10}}$. Similarly, one can search for double and triple-strange dibaryons in the reactions $\gamma p \rightarrow \overline{\Xi^{*+}} + (\Xi^{*-}\Delta^+)_{27,\overline{10}}$ and $\gamma p \rightarrow \overline{\Omega} + (\Omega\Delta^+)_{27,\overline{10}}$. in addition, tagging on antiparticles can effectively suppress conventional backgrounds.

4. Summary

The recent observation of a narrow hadronic proton-neutron resonance d^* with $I(J^P) = 0(3^+)$ 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 $I^z = +3$, 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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