First exotic hadron with open heavy flavor: $cs\bar{u}\,\bar{d}$ tetraquark

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The LHCb Collaboration has reported resonant activity in the channel D^+K^-, identifying two components: $X_0(2900)$ with $J^P = 0^+$ at 2866 ± 7 MeV, $\Gamma_0 = 57 \pm 13$ MeV and $X_1(2900)$ with $J^P = 1^-$ at 2904 ± 7 MeV, $\Gamma_1 = 110 \pm 12$ MeV. We interpret the $X_0(2900)$ component as a $cs\bar{u}\,\bar{d}$ isosinglet compact tetraquark, calculating its mass to be 2863 ± 12 MeV. This is the first exotic hadron with open heavy flavor. The analogous $bs\bar{u}\,\bar{d}$ tetraquark is predicted at 6213 ± 12 MeV. We discuss possible interpretations of the heavier and wider $X_1(2900)$ state and examine potential implications for other systems with two heavy quarks.

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Very recently, the LHCb Collaboration reported a narrow peak in the D^+K^- (+ charge conjugate) (c.c.) channel as seen in the decay $B^\pm \to D^+D^-K^\pm$. The peak has been parametrized in terms of two Breit-Wigner resonances:

$$X_0(2900): \quad J^P = 0^+, \quad M = 2866 \pm 7\ \text{MeV}, \quad \Gamma_0 = 57 \pm 13\ \text{MeV}; \quad (1)$$

$$X_1(2900): \quad J^P = 1^-, \quad M = 2904 \pm 5\ \text{MeV}, \quad \Gamma_1 = 110 \pm 12\ \text{MeV}. \quad (2)$$

The statistical significance is $\gg 5\sigma$. This is the first exotic hadron with open heavy flavor [1]. An obvious question is the interpretation of these states and whether their structure and properties can be elucidated with our current understanding of nonperturbative QCD.

We believe that, regarding the lighter and narrower 0^+ component, the answer is likely affirmative. We interpret this state as a $cs\bar{u}\,\bar{d}$ compact S-wave tetraquark, with structure completely analogous to the stable, deeply bound $bb\bar{u}\,\bar{d}$ tetraquark expected well below BB^* threshold. The $I = 0$ and $J^P = 0^+$ isospin, spin, and parity quantum numbers are robust consequences of this structure. That said, the c and s quarks being significantly lighter than the b quark results in a significant shift of the tetraquark mass vs the two-meson threshold.

We have approached this problem using two different methods, both based on constituent quarks. In the first, we note that different quark masses are needed to describe mesons and baryons [2], with baryonic quarks approximately 55 MeV heavier than mesonic ones. We used this method to successfully anticipate [3] the mass of the doubly charmed baryon Ξ_{cc} discovered by the LHCb experiment [4,5] and to predict the existence of a $bb\bar{u}\,\bar{d}$ tetraquark below threshold for weak or electromagnetic decay [6]. (See also Ref. [7].)

A second method, permitting the use of universal quark masses to describe mesons and baryons, is to ascribe a mass contribution S to each QCD string junction [8,9], of which a meson has none, a baryon has one, and a tetraquark has two, as illustrated in Fig. 1.

This method was used to predict masses of tetraquarks containing only heavy quarks c or b [10,11].

In the present article, we compare the predictions of the string-junction picture with the baryonic-quark picture for the mass of a ground state $J^P = 0^+$ tetraquark composed of $cs\bar{u}\,\bar{d}$, finding preference for the former in light of the new LHCb result [1]. The preferred string-junction method is also applied to obtain the ground state mass of the exotic tetraquark $bs\bar{u}\,\bar{d}$. The two methods are then compared for $bb\bar{u}\,\bar{d}$, $cc\bar{u}\,\bar{d}$, and $bc\bar{u}\,\bar{d}$ ground states and for $M(\Xi_{cc})$ originally calculated using baryonic quark masses [3].

The LHCb Collaboration has reported two resonances in the D^+K^- (+c.c.) channel around 2.9 GeV [1]: one with $J^P = 0^+$ and the other broader one with $J^P = 1^-$ [see Eqs. (1) and (2).] We can attempt to describe the 0^+ state in either the baryonic-quark picture or the string-junction (universal quark mass) picture, treating the strange quark as heavy.

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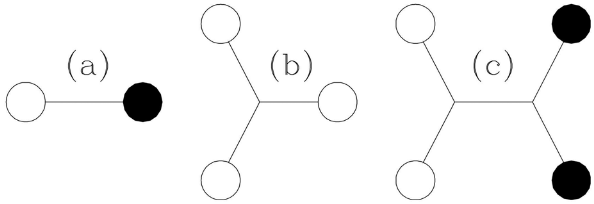

FIG. 1. QCD strings connecting quarks (open circles) and antiquarks (filled circles). (a) Quark-antiquark meson with one string and no junctions, (b) three-quark baryon with three strings and one junction, and (c) baryonium (tetraquark) with five strings and two junctions.

In a scheme with baryonic quarks, whose masses are labeled by superscripts b, we follow the approach and the notation of Ref. [6] to obtain

$$M[T(cs\bar{u}\,\bar{d},\mathrm{bar})] = m_c^b + m_s^b + m_{[ud]}^b + B(cs) + \Delta E_{HF}(cs), \quad (3)$$

where $m_c^b = 1710.5$ MeV, $m_s^b = 538$ MeV, the mass of the $I = J = 0$ diquark is $m_{[ud]}^b = 576$ MeV, the binding energy of a cs pair is $B(cs) = -35.0$ MeV, and the cs hyperfine interaction accounts for $\Delta E_{HF}(cs) = -35.4$ MeV (the last being taken from the footnote of Table IV of Ref. [3]). The result is $M[T(cs\bar{u}\bar{d},\mathrm{bar})] = 2754.1 \pm 12$ MeV, where the theoretical error is that encountered in Ref. [3].

In the string-junction picture, with universal-mass quarks, the relevant parameters are $S = 165.1$ MeV, $m_s = 482.2$ MeV, and $m_c = 1655.6$ MeV. One can combine $m_c^{(b)} + m_{[ud]}^{(b)} = M(\Lambda_c)$ in either calculation, so the only difference between the two calculations is one string-junction term [a second is contained in $M(\Lambda_c)$] and the difference in strange quark masses,

$$\begin{aligned} M[T(cs\bar{u}\,\bar{d},\mathrm{str})] - M[T(cs\bar{u}\,\bar{d},\mathrm{bar})] &= S + m_s - m_s^b \\ &= (165.1 + 482.2 - 538)\ \mathrm{MeV} = 109.3\ \mathrm{MeV}, \quad (4) \end{aligned}$$

or

$$M[T(cs\bar{u}\,\bar{d},\mathrm{str})] = (2863.4 \pm 12)\ \mathrm{MeV}. \quad (5)$$

where the theoretical error is that encountered in fits to light-quark hadrons [10]. This is within 3 MeV of the experimental central value of the 0^+ mass (1). A clear preference for the string-junction (universal quark mass) picture emerges.

The state 0^+ state in Eq. (5) has a hyperfine $J^P = 1^+$ partner in which the cs 0^+ pair is replaced by a 1^+, with $\Delta E_{HF}(cs) = +17.7$ MeV. The mass of the state is 2916.5 MeV. As it is of unnatural parity, it cannot decay into DK and so cannot account for the state (2). The activity in the Dalitz plot giving rise to that state must be due to another source. One possibility is a consequence of rescattering $DK \to D^*K^*$ (e.g., via pion exchange), whose threshold is at 2.9 GeV [1].

The string-junction picture may also be applied to the exotic configuration $bs\bar{u}\,\bar{d}$. The terms contributing to its mass are m_b plus an $I = J = 0$ $\bar{u}\,\bar{d}$ "good quark" mass $m_{[ud]}$ lumped into $M(\Lambda_b) = 5619.5$ MeV; a strange quark mass $m_s = 482.2$ MeV; a string junction term $S = 165.1$ MeV; and a binding energy $B(bs) = -41.8$ MeV and bs hyperfine term of -12 MeV, both taken from [3]. The result is the prediction

$$M[T(bs\bar{u}\,\bar{d},0^+)] = (6213 \pm 12)\ \mathrm{MeV}. \quad (6)$$

It is interesting that this is very close to the B^*K^* threshold at 6216 MeV, while the 0^+ $(cs\bar{u}\,\bar{d})$ state in the charm sector at 2866 MeV is close to the D^*K^* threshold at 2902 MeV. $T(bs\bar{u}\,\bar{d})$ is approximately 440 MeV above the BK threshold. It should be seen in

$$T(bs\bar{u}\,\bar{d}) \to \bar{B}^0K^- \quad (7)$$

and

$$T(bs\bar{u}\,\bar{d}) \to B^-K^0. \quad (8)$$

The first mode is preferable because it avoids the s vs $\bar{s}$ ambiguity associated with neutral kaons. In principle, it should be possible to observe this state in LHCb and perhaps in other LHC experiments.

The contributions to the mass of the lightest tetraquark $T(bb\bar{u}\,\bar{d})$ with two bottom quarks and $J^P = 1^+$ are listed in Table I. The notation and the numerical values of the parameters are the same as in Tables VI and IX of Ref. [3]. Theoretical errors reflect deviations from experiment of fits to light-quark states.

The mass of the ground $bb\bar{u}\,\bar{d}$ $J^P = 1^+$ state is 125.5 higher for universal quarks with two string junctions but is

TABLE I. Contributions to the mass of the lightest tetraquark $T(bb\bar{u}\,\bar{d})$ with two bottom quarks and $J^P = 1^+$. Baryonic quarks as used in Ref. [6] (with superscript b); universal quarks as used in Ref. [10] (no superscript). q denotes u or d quark; isospin breaking is ignored.

Baryonic quarks		Universal quarks	
Contribution	Value (MeV)	Contribution	Value (MeV)
...	...	$2S$	330.2
$2m_b^b$	10087.0	$2m_b$	9977.2
$2m_q^b$	726.0	$2m_q$	617.0
$a_{bb}/(m_b^b)^2$	7.8	$a_{bb}/(m_b)^2$	7.8
$-3a/(m_q^b)^2$	−150.0	$-3a/(m_q)^2$	−151.2
bb binding	−281.4	bb binding	−266.1
Total	10389.4 ± 12	Total	10514.9 ± 12

TABLE II. Contributions to the mass of the lightest tetraquark $T(cc\bar{u}\,\bar{d})$ with two charmed quarks and $J^P = 1^+$.

Baryonic quarks		Universal quarks	
Contribution	Value (MeV)	Contribution	Value (MeV)
$\cdots$	$\cdots$	$2S$	330.2
$2m_c^b$	3421.0	$2m_c$	3311.2
$2m_q^b$	726.0	$2m_q$	617.0
$a_{cc}/(m_c^b)^2$	14.2	$a_{cc}/(m_c)^2$	14.2
$-3a/(m_q^b)^2$	−150.0	$-3a/(m_q)^2$	−151.2
cc binding	−129.0	cc binding	−121.3
Total	3882.2 ± 12	Total	4000.1 ± 12

still 89 MeV below the $B^-\bar{B}^{*0}$ threshold and 44 MeV below threshold for decay to $B^-\bar{B}^0\gamma$.

The calculation of the masses of the lightest $cc\bar{u}\,\bar{d}$ tetraquark masses proceeds analogously to $bb\bar{u}\,\bar{d}$. In Table II, we provide the corresponding contributions to the $cc\bar{u}\,\bar{d}$ mass.

The mass of $T(cc\bar{u}\,\bar{d})$ with universal quarks and two string junctions is 117.8 MeV higher than that with baryonic quarks, well above threshold for decay to a DD^* pair.

In Table III, we provide the corresponding contributions to the $bc\bar{u}\,\bar{d}$ tetraquark mass. The mass of $T(bc\bar{u}\,\bar{d})$ with universal quarks and two string junctions is 121.6 MeV higher than that with baryonic quarks. Whereas in the baryonic-quark picture this value was just below $\bar{B}D$ threshold, the value in the universal-quark picture is well above threshold.

We compare in Table IV the predictions for $M(\Xi_{cc})$ in the baryonic and universal quark mass schemes. The predictions of the two schemes are almost the same and both compatible with the observed value of $(3621.55 \pm 0.23 \pm 0.30)$ MeV [12]. The shift of three quark masses each by about 55 MeV is compensated by the S term, and the only remaining difference is about 8 MeV in the cc binding term. Hence, it is really only when one gets to configurations with two or more string junctions that a distinction emerges.

TABLE III. Contributions to the mass of the lightest tetraquark $T(bc\bar{u}\,\bar{d})$ with one bottom and one charmed quark and $J^P = 0^+$.

Baryonic quarks		Universal quarks	
Contribution	Value (MeV)	Contribution	Value (MeV)
$\cdots$	$\cdots$	$2S$	330.2
$m_b^b + m_c^b$	6754.0	$m_b + m_c$	6644.2
$2m_q^b$	726.0	$2m_q$	617.0
$-3a_{bc}/(m_b^b m_c^b)$	−25.5	$-3a_{bc}/(m_b m_c)$	−25.5
$-3a/(m_q^b)^2$	−150.0	$-3a/(m_q)^2$	−151.2
bc binding	−170.8	bc binding	−159.4
Total	7133.7 ± 13	Total	7255.3 ± 13

TABLE IV. Contributions to the mass of Ξ_{cc}, the spin-1/2 ground state of ccq ($q = u,\ d$); isospin breaking is ignored.

Baryonic quarks		Universal quarks	
Contribution	Value (MeV)	Contribution	Value (MeV)
$\cdots$	$\cdots$	S	165.1
$2m_c^b + m_q^b$	3783.9	$2m_c + m_q$	3619.7
$a_{cc}/(m_c^b)^2$	14.2	$a_{cc}/(m_c)^2$	14.2
$-3a/(m_q^b m_c^b))$	−42.4	$-3a/(m_q m_c)$	−42.4
cc binding	−129.0	cc binding	−121.3
Total	3627 ± 12	Total	3635 ± 12

To summarize, the exotic tetraquark reported by LHCb [1] weighs in favor of the string-junction picture with universal quark masses for mesons and baryons. The observed 0^+ mass is 2866 ± 5 MeV, while we predict 2754 ± 12 MeV in the baryonic-quark scheme and 2863 ± 12 MeV in the string-junction (universal quark mass) picture.

The compact tetraquark picture makes a clear prediction that $X_0(2900)$ is an isoscalar. This prediction can be tested, e.g., by looking for its charged partner in the D^0K^- invariant mass in $B^- \to \bar{D}^0 D^0 K^-$.

The bottom analog of $X_0(2900)$, with quark content $(bs\bar{u}\,\bar{d})$, is predicted at 6213 ± 12 MeV.

There remains the question of how to interpret the broader 1^- peak (2). One possibility, as mentioned, is an artifact due to rescattering at and above the D^*K^* threshold. While the current LHCb analysis [1] prefers a 1^- assignment, it is worth mentioning that if this peak is really due to a $J^P = 2^+$ resonance, it would also populate the Dalitz plot band at 2.9 GeV nonuniformly along its length. Such a state could be a D^*K^* molecule, very close to the threshold at 2902 MeV, with pion exchange providing a major part of the attraction. On the other hand, the lighter and narrower 0^+ state is 36 MeV below the D^*K^* threshold, which is much too large for binding energy in a hadronic molecule.

The predictions for masses of the $bb\bar{u}\,\bar{d}$, $cc\bar{u}\,\bar{d}$, and $bc\bar{u}\,\bar{d}$ masses are shifted upward in the string-junction picture by 126, 118, and 122 MeV, respectively. The $bb\bar{u}\,\bar{d}$ state is still stable with respect to strong and EM interactions, as its mass is predicted to lie 89 MeV below threshold for strong decay and 44 MeV below that for radiative decay, while the $cc\bar{u}\,\bar{d}$ and $bc\bar{u}\,\bar{d}$ masses lie well above strong decay thresholds.

The prediction of the doubly charmed baryon mass [3] based on baryonic quarks, $M(\Xi_{cc}) = 3627 \pm 12$ MeV, is only raised by 8 MeV in the string-junction picture with universal quark masses, still compatible with the experimental value of $(3621.55 \pm 0.23 \pm 0.30)$ MeV.

Further tests of the physical picture discussed here will become possible when additional tetraquark states are observed experimentally. We hope that this will be possible in the foreseeable future.

In particular, since the doubly charmed baryon $\Xi_{cc}^{++}(ccu)$ has been observed by LHCb [4,12], the data accumulated so far might make it possible to observe the $T(cc\bar{u}\,\bar{d})$ tetraquark decaying into D^0D^{*+} and D^+D^{*0}. The measured mass will then tell us whether the string-junction description applies to this state as well or if the physical picture of Ref. [6] is more appropriate for a tetraquark with two truly heavy quarks.

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Note added.—Recently, it was pointed out to us that a prediction was made [13] using coupled-channel unitarity of a $D^{*+}K^{*-}$ bound state with $C = 1$, $S = -1$, $J^P = 0^+$, with pole mass of 2848 MeV (i.e., binding energy of 54 MeV) and width between 23 and 59 MeV, depending on the value of a cutoff parameter.

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