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Doubly charmed strange tetraquark

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The LHCb experiment at CERN has discovered a doubly charmed isoscalar tetraquark T_{cc} with the quantum numbers of $cc\bar{u}\,\bar{d}$ and mass of about $3875~\mathrm{MeV}/c^2$, decaying to $D^0D^0\pi^+$ through the intermediate channel $D^{*+}D^0$. We present a study of its strange companions with the quantum numbers of $cc\bar{q}\,\bar{s}$, where $q = u$, d and isospin violation is neglected.

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The LHCb Experiment at CERN has discovered an exotic meson $T_{cc} = cc\bar{u}\,\bar{d}$ decaying to $D^0D^0\pi^+$ through the channel $D^{*+}D^0$, with a mass around $3875~\mathrm{MeV}/c^2$ [1,2]. This mass is just below that for which the pion can form a D^{*+} resonance with either D^0. It is also within $7~\mathrm{MeV}/c^2$ of the value of $3882 \pm 12~\mathrm{MeV}/c^2$ predicted in Ref. [3] using the same quark-model parameters that led to the successful prediction [4] of the mass of the doubly charmed baryon Ξ_{cc}^{++} [5]. We use the methods of Ref. [3] to predict the masses of the strange companions of the T_{cc} and propose a study of the $D^0D^0K^+$ system to search for excited companions of the doubly charmed strange tetraquark. We comment on production and decay of the $T_{cc,s}$ states.

A generalization of Table II in Ref. [3] gives a spin-1 state at 4106 MeV which can decay to D^*D_s or DD_s^*, composed of a cc diquark with spin 1 and a $\bar{q}\,\bar{s}(q = u, d)$ antidiquark with spin 0. We reproduce the table in Ref. [3], which led to the successful prediction of the T_{cc} mass (Table I), and then indicate the changes that apply to a $T_{cc;s} = cc\bar{q}\,\bar{s}$ (Table II). Here, we have taken $m_q^b = 363$ MeV, $m_s^b = 538$ MeV, and the superscript b denotes values suitable for baryons (and tetraquarks).

There are also states with spin 0, 1, and 2 composed of a cc diquark with spin 1 and a $\bar{q}\,\bar{s}$ with spin 1. The spin-weighted average mass $\bar{M}$ of the corresponding hyperfine multiplet differs from 4106 MeV only in the mass of the light $\bar{q}\,\bar{s}$ diquark. For a nonstrange diquark this "bad-good" difference has long been known to be $200~\mathrm{MeV} = (2/3)[M(\Delta) - M(N)]$, as in Ref. [4] and earlier references therein. It is encouraging that a recent lattice QCD calculation [6] finds this difference to be 198(4) MeV. The corresponding difference for a strange diquark is $(m_q^b/m_s^b)\cdot 200~\mathrm{MeV} = 135~\mathrm{MeV}$, so the spin-weighted average mass of the hyperfine multiplet with two spin-1 cc and $\bar{q}\,\bar{s}$ diquarks is obtained by adding the bad-good $\bar{q}\,\bar{s}$ diquark mass difference to the state in Table II, $\bar{M} = 4106 + 135 = 4241$ MeV.

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

Contribution	Value (MeV)
$2m_c^b$	3421.0
$2m_q^b$	726.0
$a_{cc}/(m_c^b)^2$	14.2
$-3a/(m_q^b)^2$	−150.0
cc binding	−129.0
Total	3882.2 ± 12

TABLE II. Contributions to the mass of the lightest tetraquark $T(cc\bar{q}\,\bar{s})$ with two charmed quarks, $\bar{q}\,\bar{s}$ in a state of spin zero, and $J^P = 1^+$.

Contribution	Value (MeV)
$2m_c^b$	3421.0
$m_q^b + m_s$	901.0
$a_{cc}/(m_c^b)^2$	14.2
$-3a/(m_q^b m_s^b)$	−101.2
cc binding	−129.0
Total	4106 ± 12

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TABLE III. Decay modes of the ground-state singly and doubly charged $T_{cc,s}$ with spin 1 and mass 4106 MeV.

Decaying state	Quark content	Prospective final state
$T^{+}_{cc,s}$	$cc\bar{u}\,\bar{s}$	$D^0 D^{*+}_s$
		$D^{*0} D^{+}_s$
$T^{++}_{cc,s}$	$cc\bar{d}\,\bar{s}$	$D^+ D^{*+}_s$
		$D^{*+} D^{+}_s$

The two spin-1 cc and $\bar{q}\,\bar{s}$ diquarks can form S-wave states with spin (0,1,2). The mass splittings between the members of this multiplet result only from hyperfine, i.e., spin-dependent, interaction between the two diquarks. They scale like $\Delta M = (-2x, -x, x)$ for spin (0,1,2), respectively. The $D^0D^0K^+$ threshold is at 4223 MeV. Depending on the sign of x, at least either the spin-0 or spin-2 three-body resonance should be able to decay to $D^0D^0K^+$. Indeed, we expect the spin-spin interaction to be repulsive, i.e., $x > 0$. In quark-model calculations, whether it is quark-quark or quark-antiquark, we always have that spin-spin interaction is antiferromagnetic; i.e., spin 1 has higher energy than spin 0. This is likely to carry over into interaction of two spin-1 diquarks, since such an interaction presumably can be viewed as the sum of interactions of quarks in one diquark with quarks in the other diquark.

The identification of states decaying to D_s or D_s^* poses significant challenges. The largest exclusive branching fraction of the D_s is to $K^+K^-\pi^+$, with $\mathcal{B} = (5.39 \pm 0.15)\%$ [7]. Furthermore, the soft photon in $D_s^* \to \gamma D_s$ will be very difficult to identify, preventing full reconstruction of the D_s^* decay. Table III lists some prospective final states of the predicted $T_{cc,s}(4106)$. The most promising decay is $T^{++}_{cc,s} \to D^{*+}D_s$, where $D^{*+} \to D^0\pi^+$ (giving an identifiable soft pion) and $D_s \to K^+K^-\pi^+$ (giving a fully reconstructed final state).

Other calculations of $M(T_{cc,s})$ include, e.g., 3975 and 3979 MeV for the singly and doubly charged state [8] based on a molecular picture and 4156 MeV [9] based on heavy-quark symmetry (giving 3978 MeV for the nonstrange state). A comprehensive list of theoretical mass predictions for the T_{cc} states can be found in Refs. [1,2].

The predictions for T_{cc} and $T_{cc,s}$ masses in Tables I and II are based on the same approach. Therefore, if it turns out that the mass of the lightest doubly charmed strange tetraquark $M(T_{cc,s})$ is significantly different from 4106 MeV, it will imply that LHCb's T_{cc} candidate reported in Refs. [1,2] is unlikely to be the state predicted in Ref. [3]. If so, the most probable interpretation will be a molecular state, but one also needs to examine the possibility that it is a kinematic effect, as discussed below.

The LHCb analysis of the $D^0D^0\pi^+$ system via a unitarized Breit-Wigner formalism gives rise to a resonance at a mass of 361 ± 40 keV below $D^{*+}D^0$ threshold, or at approximately $M_0 = 3874.7$ MeV. (We shall use units in which $c = \hbar = 1$.) We show the boundary of the $D^0D^0\pi^+$ Dalitz plot along with the maximum of the two-dimensional distribution in Fig. 1. The proximity of this maximum to the intersection of the two $M(D^{*+})$ dashed straight lines is a cautionary signal of a possible kinematic enhancement.

The lowest-lying D^0K^+ resonant subsystem in the three-body $D^0D^0K^+$ system is called $D^{*+}_{s1}(2700)$ in Ref. [7]. Its mass is 2714 ± 5 MeV, and its width is 122 ± 10 MeV. Henceforth, we shall refer to this resonance as $D_s(2714)$. With its spin-parity 1^- and its mass about 600 MeV above the $D_s^*(2112)$, it is a candidate for a 2S radial excitation of that state.

The boundary of the Dalitz plot in Fig. 2 is for a value of $M(D^0D^0K^+) = 4588$ MeV, which makes it just tangent to the D^0K^+ resonance band at 2714 MeV. One is then invited to look for a peak near 4588 MeV in the distribution of $M(D^0D^0K^+)$. If one is seen, it could indicate that the tangency condition helps to generate a three-body resonance with quark content $cc\bar{q}\,\bar{s}$, though probably a broad one in view of the large width of the $D_{s1}(2714)$. The dot-dashed ovals and straight lines correspond to displacing $M(D_{s1}$ by $\pm\Gamma/2$ from its central value.

We gain some insight into the possible production rate of a $T_{cc,s}$ state by comparison with T_{cc} production. This corresponds to the top $SU(3)$ relation in Fig. 3. One can get a rough idea about the relevant relative fragmentation probabilities of a color antitriplet cc diquark with mass ~3.4 GeV by looking at the corresponding processes for a b quark with mass ~4.2 GeV [7]. These are described in

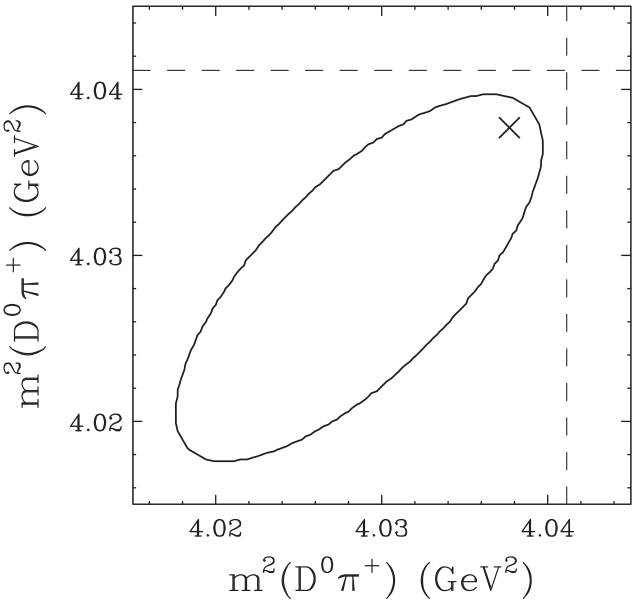

FIG. 1. Solid curve: boundary of $D^0D^0\pi^+$ Dalitz plot for a c.m. energy of $M_0 = 3874.7$ MeV. Dashed straight lines denote central values of $m(D^{*+}) = 2010.26$ MeV. The cross marks the approximate maximum of the two-dimensional distribution. Axis units are in GeV^2.

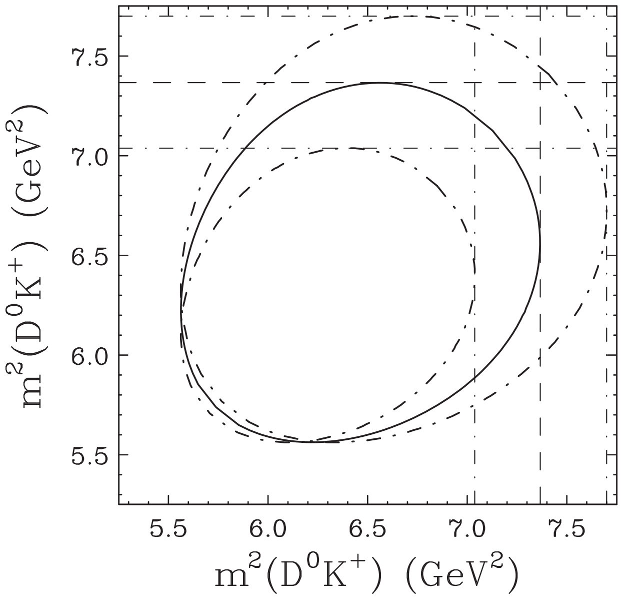

FIG. 2. Boundary of $D^0D^0K^+$ Dalitz plot for c.m. energy of 4588 MeV. Axes denote squared effective masses of the two D^0K^+ combinations. Dashed straight lines correspond to $m(D^0K^+) = 2714$ MeV. Dot-dashed ovals correspond to c.m. energy 4527 and 4649 MeV. Dot-dashed straight lines correspond to $M(D_{s1}) = 2714 \pm 61$ MeV.

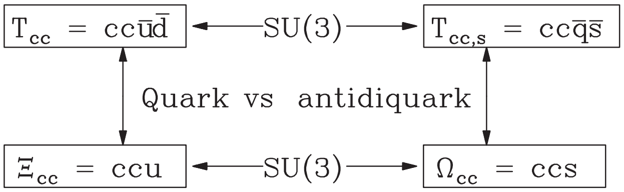

FIG. 3. Relations among processes involving production of states containing two charmed quarks. Columns correspond to nonstrange (left) and strange (right) particles. Rows correspond to fragmentation of the cc diquark into an antidiquark (top) and a quark (bottom). Processes in the left-hand column have been observed.

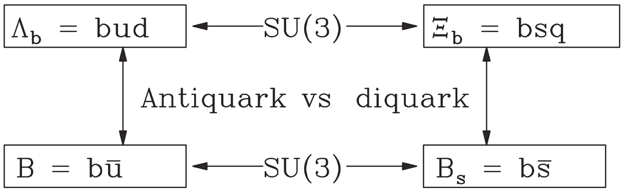

FIG. 4. Relations among processes involving production of states containing one bottom quark. Columns correspond to nonstrange (left) and strange (right) particles. Rows correspond to fragmentation of the b quark into a diquark (top) and an antiquark (bottom). All processes have been observed.

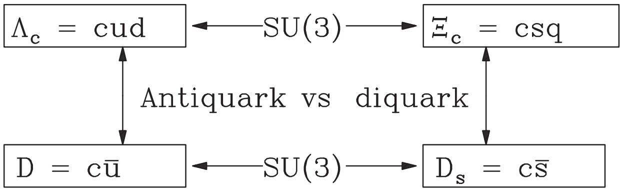

FIG. 5. Relations among processes involving production of states containing one charmed quark. Columns correspond to nonstrange (left) and strange (right) particles. Rows correspond to fragmentation of the c quark into a diquark (top) and an antiquark (bottom). All processes have been observed.

Fig. 4; the corresponding relations involving a charmed quark are shown for comparison in Fig. 5. The fragmentation of a b quark into a strange quark accounts for roughly $1/8$ of b fragmentation into a nonstrange quark [10–12].

In more detail, for b quark fragmentation at 13 TeV, Ref. [11] quotes

$$f_s/(f_u + f_d) = 0.122 \pm 0.006, \tag{1}$$

$$f_{\Lambda_b}/(f_u + f_d) = 0.259 \pm 0.018, \tag{2}$$

where f_q are the fragmentation functions of a b quark to a B_q hadron, and similarly for the Λ_b. The latter relation can be interpreted as describing the relative probability of a heavy color (anti)triplet fragmenting into $[ud]$ (a “good” diquark) vs the sum of probabilities of fragmentation into u or d quarks. So, in this case, we need

$$f_{[ud]}/f_q = 2 \times 0.259 = 0.518 (q = u, d). \tag{3}$$

Further, from $f_s/(f_u + f_d)$, we have

$$f_s/f_q = 2 \times 0.122 = 0.244. \tag{4}$$

We then assume $SU(3)$ breaking is the same in quarks and diquarks:

$$f_{qs}/f_{[ud]} = f_s/f_q = 0.244, \tag{5}$$

$$f_{qs}/f_q = f_{ud}/f_q \times f_{qs}/f_{ud} = 0.518 \times 0.244 = 0.126. \tag{6}$$

The estimate of diquark-quark symmetry could be verified by comparing the production of T_{cc} with that of Ξ_{cc}^{++}, the former being 0.518 of the latter. LHCb can already provide an estimate for this ratio.

One must then take account of differences in branching fractions into observable final states: $K^-\pi^+$ and $K^-\pi^+\pi^-\pi^+$ (about 10%) for D^0 and $K^+K^-\pi^+$ (about 5%) for D_s. All told, one might expect the signal for the lightest strange doubly charmed tetraquark to be about $1/16$ of that for the T_{cc}. Background might be higher because the D_s signal is weaker in the $T_{cc,s}$ than the second D^0 signal in the T_{cc}.

Another estimate of $T_{cc,s}$ production compares the fragmentation of cc into $\bar{q}\,\bar{s}$ with cc fragmentation into u, which gives rise to the observed Ξ_{cc}^{++} [5]. This comparison can involve measurement of the intermediate fragmentation of cc into s and hence observation of the $\Omega_{cc} = ccs$. We have noted prospects for detecting the Ω_{cc} in Ref. [4]. As in the preceding discussion, a rough estimate of the relevant relative fragmentation probabilities can be obtained by comparing the fragmentation of a b quark into $\Xi_b(= bqs)$ and to a B^- meson $(= b\bar{u})$.

The observation by LHCb of a tetraquark T_{cc} implies a rich spectrum of its strange counterpart with quark content $cc\bar{q}\,\bar{s}$. If the observed $D^{*+}D^0$ enhancement is merely due to kinematics, one might expect the prediction of $M(T_{cc,s}) =$ 4106 MeV to fail. A corresponding effect in $M(D^0D^0K^+)$ around threshold would occur at $M(D_s(2714)D^0) =$ 4588 MeV. If, on the other hand, one generalizes the approach of Ref. [3] to systems with quark content $cc\bar{q}\,\bar{s}$, one expects several states decaying to a pair of charmed mesons, one nonstrange and one strange, including one around 4100 MeV decaying to D^*D_s and DD_s^* and one not far from threshold decaying to $D^0D^0K^+$.

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