The 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 \( cc \bar{q} \bar{q} \) and mass of about 3875 MeV/\( c^2 \), decaying to \( D^0 \bar{D}^0 \pi^+ \) through the intermediate channel \( D^* \bar{D}^0 \). We present a study of its strange companions with the quantum numbers of \( cc \bar{s} \), where \( q = u, d \) and isospin violation is neglected.

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

| Contribution Value (MeV) |
|--------------------------|
| \( 2m_b^c \) | 3421.0 |
| \( 2m_b^s \) | 726.0 |
| \( a_{cc}/(m_b^c)^2 \) | 14.2 |
| \( -3a/(m_b^s)^2 \) | -150.0 |
| \( cc \) binding | -129.0 |
| Total | 3882.2 ± 12 |

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

| Contribution Value (MeV) |
|--------------------------|
| \( 2m_b^c \) | 3421.0 |
| \( m_b^c + m_s \) | 901.0 |
| \( a_{cc}/(m_b^c)^2 \) | 14.2 |
| \( -3a/(m_b^s)^2 \) | -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 Quark | Prospective state | Final state |
|----------------|-------------------|-------------|
| \( T_{cc,s}^+ \) cc\( u \bar{u} \) | \( D^0 D_s^+ \) | \( D^0 D_s^+ \) |
| \( T_{cc,s}^{++} \) cc\( \bar{d} \) | \( D^+ D_s^+ \) | \( D^+ D_s^+ \) |

poses significant challenges. The largest exclusive branching fraction of the \( D_s \) is to \( K^+ K^- \pi^+ \), with \( B = (5.39 \pm 0.15)\% \). 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, 3979 MeV for the singly and doubly charged state \( [5] \) 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 \( T_{cc,s} \) 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 \( [1, 2] \) 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 \( D^0 D^0 \pi^+ \) 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 \( D^0 D^0 \pi^+ \) 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 \( D^0 K^+ \) resonant subsystem in the three-body \( D^0 D^0 K^+ \) system is called \( D^*_s(2700) \) 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 \( \frac{1}{2}^- \) 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 \( M(D^0 D^0 K^+) = 4588 \) MeV which makes it just tangent to the \( D^0 K^+ \) resonance band at 2714 MeV. One is then invited to look for a peak near 4588 MeV in the distribution of \( M(D^0 D^0 K^+) \). If one is seen, it could indicate that the tangency condition helps to generate a three-body resonance with quark content \( cc \bar{q}s \), though probably a broad one in view of the large width of the \( D_s(2714) \). The dot-dashed ovals and straight lines correspond to displacing \( M(D_s) \) by ±Γ/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 $\sim 3.4$ GeV by looking at the corresponding processes for a $b$ quark with mass $\sim 4.2$ GeV [7]. These are described in 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].

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[1] Roel Aaij et al. (LHCb), “Observation of an exotic narrow doubly charmed tetraquark,” (2021), arXiv:2109.01038 [hep-ex].

[2] Roel Aaij et al. (LHCb), “Study of the doubly charmed tetraquark $T^{++}_{c\bar{c}}$,” (2021), arXiv:2109.01056 [hep-ex].

[3] Marek Karliner and Jonathan L. Rosner, “Discovery of doubly-charmed $\Xi_{c\bar{c}}$ baryon implies a stable ($bb\bar{u}\bar{d}$) tetraquark,” Phys. Rev. Lett. 119, 202001 (2017), arXiv:1707.07666 [hep-ph].

[4] Marek Karliner and Jonathan L. Rosner, “Baryons with two heavy quarks: Masses, production, decays, and detection,” Phys. Rev. D 90, 094007 (2014), arXiv:1408.5877 [hep-ph].

[5] Roel Aaij et al. (LHCb), “Observation of the doubly charmed baryon $\Xi_{c\bar{c}}^{++}$,” Phys. Rev. Lett. 119, 112001 (2017) arXiv:1707.01621 [hep-ex].

[6] Anthony Francis, Philippe de Forcrand, Randy Lewis, and Kim Maltman, “Diquark properties from full QCD lattice simulations,” (2021), arXiv:2106.09080 [hep-lat].

[7] P. A. Zyla et al. (Particle Data Group), “Review of Particle Physics,” PTep 2020, 083C01 (2020).

[8] Huimin Ren, Fan Wu, and Rulim Zhu, “Hadronic molecule interpretation of $T^{++}_{c\bar{c}}$ and its beauty-partners,” (2021), arXiv:2109.02531 [hep-ph].

[9] Estia J. Eichten and Chris Quigg, “Heavy-quark symmetry implies stable heavy tetraquark mesons $Q\bar{Q}qq\bar{q}\bar{q}\bar{q}$,” Phys. Rev. Lett. 119, 202002 (2017), arXiv:1707.09575 [hep-ph].

[10] T. Aaltonen et al. (CDF), “Measurement of Ratios of Fragmentation Fractions for Bottom Hadrons in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$-TeV,” Phys. Rev. D 77, 072003 (2008), arXiv:0801.4375 [hep-ex].

[11] Roel Aaij et al. (LHCb), “Measurement of $b$ hadron fractions in 13 TeV $pp$ collisions,” Phys. Rev. D 100, 031102 (2019), arXiv:1902.06794 [hep-ex].

[12] Roel Aaij et al. (LHCb), “Precise measurement of the $f_3/f_4$ ratio of fragmentation fractions and of $B_d^0$ decay branching fractions,” Phys. Rev. D 104, 032005 (2021), arXiv:2103.06810 [hep-ex].