The possible tetraquark states $cc\bar{c}\bar{c}$ observed by the LHCb experiment

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We give a brief comment on the possible tetraquark states $cc\bar{c}\bar{c}$ observed by the LHCb experiment.

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The molecular positronium (sometimes also denoted as di-positronium) was the multi-electron bound state composed of $e^+e^-e^+e^-$, where the electromagnetic interaction is the underlying driving force. Although its existence was predicted as early as in 1947 [1], it remained elusive until it was produced experimentally in 2007 [2]. One may wonder whether there exists the analogue of the di-positronium in Quantum Chromodynamics, which is the tetraquark state with the flavor configurations $q\bar{q}q\bar{q}$. Very recently, the LHCb Collaboration observed distinct structures with the $cc\bar{c}\bar{c}$ (two charm quarks and two anti-charm quarks) in the J/ψ-pair mass spectrum [3]. They reported a broad structure ranging from 6.2 to 6.8 GeV and a narrow structure at around 6.9 GeV with a global significance of more than 5σ. Let's denote it as T_{4c}.

When Gell-Mann [4] and Zweig [5] proposed the quark model, they also speculated the possible existence of the multiquark states beyond conventional mesons and baryons. Later, the low-lying scalar meson nonet below 1 GeV was suggested as possible candidates of the tetraquark states composed of four light quarks due to their unusual mass ordering [6, 7]. Since the discovery of X(3872) in 2003, more and more candidates of multiquark states were reported over the past decades, including dozens of charmonium-like XYZ states [8] and the hidden-charm pentaquarks $P_c(4312)$ and $P_c(4450)$ [9, 10].

The hidden-charm pentaquark P_c states and many XYZ states such as X(3872) and $Z_c(3900)$ lie very close to the di-hadron threshold. For example, the strong couple-channel effect between the $c\bar{c}$ core and the $\bar{D}D^*$ continuum may play a pivotal role in the formation of the X(3872) state [11]. Without the $\bar{D}D^*$ components, it will be difficult to explain its isospin violating decay mode $J/\psi\pi\pi$. Similarly, the $Z_c(3900)$ signal may also arise from the multiple channel scattering.

On the other hand, the P_c states are very good candidates of the loosely bound $\Sigma_c^{(*)}\bar{D}^{(*)}$ molecular states [12–16]. The same chiral dynamics associated with the light quarks is responsible for the existence of both the deuteron and P_c states. In the framework of the meson exchange model, the pseudoscalar meson, scalar meson and vector meson exchange forces provide the attraction. In the chiral effective field theory, the long-range one-pion, medium-range di-pion exchange force and contact interactions contribute to the formation of the hadronic molecules.

Either the light quark degree of freedom or the channel coupling (or both) is crucial to the existence of the P_c and many XYZ states. In contrast, the observed T_{4c} structures lie well above the $\eta_c\eta_c$ threshold (and the narrow structure around 6.9 GeV is even higher than the $J/\psi J/\psi$ threshold by 700 MeV), and they do not contain any light quarks. The molecular states composed of a pair of the doubly-charm baryon and anti-baryon lie above (or around) 7.2 GeV [17]. Therefore, the T_{4c} structures are unlikely to be the hadronic molecules, which are usually formed by light meson exchanges with small binding energies. Namely, the T_{4c} structures do not suffer any complications from the channel coupling and chiral dynamics. These signals may be good candidates of the ”genuine” compact tetraquark states arising from the quark-gluon interaction in QCD [18–35] .

The T_{4c} structure provides a new platform to investigate the low-energy dynamics of QCD. The color configurations of the traditional $q\bar{q}$ meson and qqq baryon are uniquely determined. However, the color wave function of di-charm quarks may be $\bar{3}_c$ or 6_c. In other words, there are two possible color configurations $\bar{3}_c \times 3_c$ and $\bar{6}_c \times 6_c$. One may wonder which configuration leads to the T_{4c} structure with lower energy. The answer is deeply rooted in the confinement mechanism. Moreover, these two color configurations may mix due to the chromo-magnetic interactions.

In the traditional quark model, in addition to the long-ranged confining force, one generally considers the two-body short-ranged interaction from the gluon exchange, which follows the similar formalism in atomic physics. However, the non-Abelian SU(3) gauge group of QCD differs from the U(1) of QED greatly. There exist the triple-gluon and quartic-gluon interactions in QCD. Very luckily, these non-Abelian interactions vanish and do not contribute to the traditional meson and baryon spectrum due to their unique color configuration in quark model. However, the situation is very different for the T_{4c}. The color wave function of any three quarks within the T_{4c} is $\bar{3}_c$ or 3_c. Now the genuine three-body interaction from the triple-gluon or quartic-gluon interaction does not vanish. This effect has never been investigated in the literature. Moreover, it is also important to understand the long-ranged confining force within the T_{4c} states.

In summary, the structures observed by the LHCb experiment in the J/ψ-pair mass spectrum may open up a new testing ground for the ”genuine” compact tetraquark states arising from the quark-gluon interaction in QCD, aside from the hadronic molecules that are loosely bound by light meson exchanges. This significant signal found by LHCb clearly awaits the confirmation of other experiments. Determining the quantum numbers of these structures, and finding structures with other charmonium pairs than the J/ψ-pair are all very helpful. With more progress of the T_{4c}, T_{4b} and T_{2c2b} investigation in the future, we may gain new insight on the confinement mechanism and the non-Abelian low-energy dynamics of QCD.

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