Comprehensive Four-Quark Interpretation of $D_s(2317)$, $D_s(2457)$, and $D_s(2632)$

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(Received 12 July 2004; published 1 December 2004)

The recently observed new member of the charm-strange family $D_s(2632)$, which has a surprisingly narrow width, is challenging our theory. $D_s(2317)$ and $D_s(2457)$, which were observed earlier, have similar behaviors and receive various theoretical explanations. Some authors use the heavy hadron chiral effective theory to evaluate heavy-light quark systems and obtain a reasonable evaluation on the masses of $D_s(2317)$ and $D_s(2457)$. An alternative picture is to interpret them as four-quark or molecular states. In this work, we are following the latter and propose a unitive description for all three new members, $D_s(2632)$, $D_s(2317)$, and $D_s(2457)$, and, at least, so far our picture is consistent with the data.

DOI: 10.1103/PhysRevLett.93.232001 PACS numbers: 14.40.Ev, 13.25.Ft, 14.40.Lb

Introduction.—Recently, the SELEX Collaboration reported a new observation of a narrow resonance $D_s(2632)$ with a mass of $2632 \pm 1.6\ \mathrm{MeV/c^2}$ and total width <17 MeV [1]. This resonance is the heaviest member, so far, of the charm-strange family. $D_s(2632)$ and the other two resonances $D_s(2317)$ and $D_s(2457)$, which were observed earlier [2–4], constitute an exotic group that is obviously distinguished from the ordinary $D_s(1968)$ and $D_s^*(2112)$ by the masses, narrow total widths, and decay modes. The total decay width of the newly observed resonance $D_s(2632)$ seems to be too small to be understood in the regular $c\bar{s}$ structure. If $D_s(2632)$ were of a simple quark structure of $c\bar{s}$, one would expect that the heavier the resonance is, the shorter its lifetime should be. Especially, it would decay into DK with a large decay rate, for it is an Okubo-Zweig-Iizuka allowed process. But the observation seems not to follow this pattern. These unusual features challenge our present theory.

There have been some theoretical models proposed to interpret the structures of $D_s(2317)$ and $D_s(2457)$ which are most likely to possess spin parity as 0^+ and 1^+, respectively [5,6]. For example, Cahn and Jackson [7,8] studied the new forms of the spin-orbit and tensor forces in the heavy-light quark system and applied the technique to the $D_s(2317)$ meson. In the special models, a mass difference was predicted which is close to the experimental data. Especially, two groups independently work on the spectra by using the heavy hadron chiral effective theory [9,10]. In their work, they study the heavy-light quark hadrons where the doublet $[0^+, 1^+]$ stands as a chiral partner of the doublet $[0^-, 1^-]$. Thus the mass difference between the two doublets can be accounted by the Godberg-Trieman relation and is roughly $m_N/3$ where m_N is the mass of nucleon. It is consistent with the present experimental data. Instead, the authors of other theoretical papers suggested that the newly observed $D_s(2317)$ and $D_s(2457)$ are not in the simple $c\bar{s}$ composition, but possibly are four-quark states, or mixtures of four-quark states and $c\bar{s}$ [11–13].

The discovery of $D_s(2632)$ which is 650 MeV heavier than the ground state D_s, indicates that all three, $D_s(2317)$, $D_s(2457)$, and $D_s(2632)$, might constitute a new group which is different from the normal members of the charm-strange family. Thus we are motivated to search for a unitive picture to describe all of the three new resonances. In this work we follow the four-quark picture and see if it can fit the data. Concretely, it is postulated that all the three resonances are four-quark states and have special spin-parity structures with narrow total widths. Since all of the resonances are isospin singlets, and possibly are four-quark states, we would determine their SU(3) quark structures according to the general principle. We stress that in this picture, we postulate that all the quarks are in S waves. Since $c\bar{s}$ is an isosinglet, thus to constitute a four-quark state which is still an isosinglet, the extra $q\bar{q}$ constituent must be an isosinglet. As well known, in the SU(3) framework, an isosinglet can have two independent components, i.e., $u\bar{u} + d\bar{d}$ and $s\bar{s}$. Because the orbital angular momenta for all constituents are zero, the dynamics (which is still not very clear so far) permits one of the two components to dominate in a physical resonance. We propose that in $D_s(2317)$ and $D_s(2457)$, the $u\bar{u} + d\bar{d}$ component dominates, namely, they are of structure $c\bar{s}(u\bar{u} + d\bar{d})$, while for $D_s(2632)$, the $s\bar{s}$ component dominates, so the composition is mainly $c\bar{s}s\bar{s}$ which is exactly an isospin partner of the former one. Of course, QCD dynamics allows reaction $s\bar{s} \to u\bar{u} + d\bar{d}$, which can occur by exchanging only one gluon if they are in color octet, and then might mix the two structures. But generally as the system is in a color octet, the interaction between the quark and antiquark is repulsive and the annihilation process is strongly suppressed by the wave function. Thus the mixing between the two states can be, in general, neglected.

The $D_s(2317)$ and $D_s(2457)$ states.—As proposed, $D_s(2317)$ and $D_s(2457)$ would have the quark structure $c\bar{s}(u\bar{u} + d\bar{d})$ which guarantees the isosinglet requirement. Generally, they can be in either $(c\bar{s})_8(u\bar{u} + d\bar{d})_8$ or

$(c\bar{s})_1(u\bar{u}+d\bar{d})_1$ where the subscripts one and eight refer to the color singlet and octet, respectively, and may also be a mixture of the two states. With a color recombination, the former one can be transformed into a $(c\bar{u}(\bar{d}))_1 \otimes (u(d)\bar{s})_1$ structure, which is a DK molecule. The molecular structure was proposed to interpret some mesons such as $f_0(980)$ and $a_0(980)$ [14], several states of charmonium spectroscopy [15], and $X(3872)$ [16]. Here we show that $D_s(2317)$ and $D_s(2457)$ can be accommodated in the molecular structure. Actually, $D_s(2317)$ may be a molecule of DK mesons, whereas $D_s(2457)$ is a D^*K molecule.

The data support the picture of a molecular structure. The masses of $D_s(2317)$ and $D_s(2457)$ are very close and slightly (about 40–50 MeV) below the thresholds of $M_D + M_K$ and $M_{D^*} + M_K$, respectively. This is consistent with the molecular picture [14]. When the mass is near the threshold, c and $\bar{u}(\bar{d})$ quarks tend to form a D meson while $u(d)$ and $\bar{s}$ quarks tend to form a K meson. The two clusters may be separated by a sizable distance.

Moreover, it is noticed that the mass differences follow the relations

$$M_{D^*} - M_D \approx M_{D_s(2457)} - M_{D_s(2317)} \sim 140 \text{ MeV}. \quad (1)$$

This relation can be understood in the molecular picture, with $D_s(2317)$ and $D_s(2457)$ being the molecular states of DK and D^*K in S wave, respectively. In a system where a heavy flavor is involved, the mass difference arises from spin flip of the charm quark and is suppressed by $1/m_c$ according to the heavy quark effective theory [17]. In the molecular states DK or D^*K the K meson is pseudoscalar which is blind to the charm spin, and the energy difference of $D_s(2317)$ and $D_s(2457)$ should completely come from the mass difference of D and D^*. Thus the relation (1) is nicely understood. However, the explanation of this relation is not unique. It can also be understood in the heavy hadron chiral effective theory as mentioned in the introduction [9,10].

The main decay modes of $D_s(2317)$ is the isospin violation process $D_s(2317) \to D_s\pi$ due to the constraint of the final state phase space. The reaction may be realized via $D_s(2317)$ decay into D_s and a virtual η, followed by a $\eta - \pi$ mixing [13]. Certainly, this process is highly suppressed. This explains why the decay width is so narrow. Similarly, for $D_s(2457)$, its main channel is an isospin violated process $D_s(2457) \to D_s^* + \pi^0$, which suffers from the same suppression as for $D_s(2317) \to D_s^+ + \pi^0$. This argument does not depend on the molecular picture; namely, for a P-wave excitation, a narrow width is still expected.

The experiment [3] has observed the decay channel $D_s(2457) \to D_s + \gamma$ with a small branching ratio. In our picture, this process can happen via $u\bar{u} + d\bar{d}$ annihilating into photons. One-gluon or photon exchange between two constituent quarks is necessary to make this process possible. Therefore, the rate is small.

$D_s(2632)$.—The newly observed resonance raises a challenge to the theory. In our picture, it is the SU(3) partner of $D_s(2317)$, and its peculiar narrow total width can be naturally understood.

$D_s(2632)$ is supposed to be dominated by the $c\bar{s}(s\bar{s})$ structure. Since $s\bar{s}$ can reside only in η, η', ϕ, one might suspect if $D_s(2632)$ could be a $D_s\eta$ molecule; however, it is unlikely because its mass is 100 MeV above the threshold of D_s and η. There is no suitable molecular structure which can fit this quark composition [as long as the spin parity of $D_s(2632)$ is 0^+ in analog to $D_s(2317)$]. Thus we suppose that $D_s(2632)$ is a pure four-quark state.

An intuitive picture of this state could be that the c quark stays in the middle and the three s quarks with gluon clouds move around it. Its mass is $3m_s + m_c + \Delta E_B$ where ΔE_B is the binding energy and can be evaluated only by invoking concrete models. Since the constituent mass of strange quark is about 150 MeV heavier than the constituent mass of u and d quarks, the state of $c\bar{s}(s\bar{s})$ should be roughly 300 MeV heavier than $c\bar{s}(u\bar{u}+d\bar{d})$, and this simple evaluation is consistent with the measurement.

As four quarks (c, $\bar{s}$, s, $\bar{s}$) form a bound state, several color configurations are possible. If two quarks and two antiquarks combine into two clusters, the color configurations can be either $(c\bar{s})_1(s\bar{s})_1$ or $(c\bar{s})_8(s\bar{s})_8$. Likewise, for clusters of quark-quark and antiquark-antiquark, the color configurations can be $(cs)_{\bar{3}}(\bar{s}\,\bar{s})_3$ and $(cs)_6(\bar{s}\,\bar{s})_{\bar{6}}$. Among the configurations, the interaction induced by the one-gluon exchange between the constituents in the clusters of the second and the fourth configurations is repulsive. Thus they are not able to form tight clusters and not physically favored. The molecular picture implies that the four-quark state is dominated by the first configuration with the two clusters being separated by a large distance while the diquark-antidiquark picture corresponds to the third color configuration with the two clusters being separated by a large distance.

Because of the special structure, one can expect the total width of $D_s(2632)$ to be small. The reason is the Pauli exclusive principle. As is well known, the destructive interference between two anti-d quarks in $D^+ \to K\pi$ can remarkably reduce the total width of $D^\pm$ and makes its lifetime to be 2.5 times longer than that of D^0 [18,19]. The same mechanism may apply here. The two anti-strange quarks in the initial state would eventually join the other quarks (c and s) to constitute final mesons, and an interchange of the two anti-s quarks can result in a minus sign or, in other words, a destructive interference.

The most natural decay mode is $D_s(2632) \to D_s\eta$ with the $s\bar{s}$ pair forming an η and $c\bar{s}$ forming a D_s meson. When the $s\bar{s}$ annihilates into a $u\bar{u}+d\bar{d}$ pair, it can also decay to D^+K^0. From the above argument, the $s\bar{s}$ at short distance resides in the color singlet configuration. Thus the annihilation process is dominated by exchanging two gluons. This is a higher order process, so that is suppressed. Moreover, the color matching of the quarks (antiquarks) in the mesons leads to an additional suppression. The reason is that when the produced $u(d)$ combines with $\bar{s}$ and $\bar{u}(\bar{d})$ combines with c to form K meson and D meson of color singlet, respectively, the color match leads to the fact that the amplitude is suppressed by $1/N_c$. Hence the decay width is suppressed by a factor $1/N_c^2$. The experimental data show that the DK decay channel is 6 times smaller than the $D_s\eta$ channel, and it is indeed understandable in our picture.

Predictions.—In this four-quark state picture, one straightforward prediction is the existence of the vector partner of $D_s(2632)$.

By a simple $SU(3)_f$ manipulation, we can guess the mass of a new 1^+ resonance D_{sj}^*. The following relation,

$$M_{D_s(2632)} - M_{D_s(2317)} \approx M_{D_{sj}^*} - M_{D_s(2457)}, \qquad (2)$$

seems to hold, and we can expect the mass of D_{sj}^* to be

$$M_{D_{sj}^*} \approx 2770 \text{ MeV}/c^2. \qquad (3)$$

Since it is not a molecular state [similar to $D_s(2632)$], one cannot expect to make a precise estimate on its mass. Therefore, if a measured mass is 50 MeV deviated from our predicted value, it is not surprising. D_{sj}^* is a 1^+ meson whose total width is small, i.e., a narrow resonance, and is of quantum number of $c\bar{s}$ (or $\bar{c}s$). Its decay modes should be dominated by $D_s^*\eta$ and D^*K. This narrow resonance should be tested in the near future experiments.

We noticed that Maiani [20] proposed a $c\bar{s}(d\bar{d})$ structure for the newly discovered $D_s(2632)$. This $c\bar{s}(d\bar{d})$ structure obviously is not an isospin singlet; therefore the authors of [20] predicted that the decay width of D^+K^0 is much larger than that of D^0K^+. By contrast, in our picture, the four-quark state is an isospin singlet; thus it has the same probability to decay into D^+K^0 and D^0K^+ with $u, \bar{u}$ and $d, \bar{d}$ residing in the respective final states.

Another interesting prediction is that these states possess semileptonic decay modes, in which the light quark pair is annihilated into a e^+e^- pair via a virtue photon exchange. Specifically, we consider $D_s(2632) \to D_s^* e^+e^-$, $D_s(2317) \to D_s^* e^+e^-$, and $D_s(2457) \to D_s e^+e^-$. In the normal $c\bar{s}$ meson, the branching ratios of these decay modes are very tiny. The measurement on these decays will be a crucial test for the four-quark state explanation.

Conclusion.—In this Letter, we propose a simple unitive picture for the three new members of the D_s family which are observed in recent experiments. We consider $D_s(2317)$ and $D_s(2457)$ to be of $c\bar{s}(u\bar{u} + d\bar{d})$ quark composition and moreover motivated by the data; it is supposed that the quarks (antiquarks) are recombined into molecular states. Namely, $D_s(2317)$ is a molecular state of DK while $D_s(2457)$ is a D^*K molecular state. By contrast, the newly observed $D_s(2632)$ is of the $c\bar{s}(s\bar{s})$ structure, and it is exactly the partner of $D_s(2317)$ of 0^+.

In this picture, we have naturally explained the narrowness of the widths of all three resonances and discussed some decay modes. We further predict another narrow resonance which is a 1^+ meson, and its mass is located at about 2770 MeV with a narrow width; we also predict that these states should have relatively large branching ratios for decaying into $D_s^{(*)}$ and a e^+e^- pair.

The four-quark pictures for the three states accommodate the newly observed resonances, $D_s(2317)$, $D_s(2457)$, and $D_s(2632)$, and everything seems to be consistent with all existing experimental data. Once those predictions are confirmed by further experiments, the existence of the four-quark structure can be established. Then it may open a new page in the hadronic physics.

In this Letter, we do not account for any concrete dynamics, but only apply the SU(3) flavor symmetry to analyze the quark structure of all the states $D_s(2317)$, $D_s(2457)$, and $D_s(2632)$ and try to understand their qualitative behaviors, such as the very narrow total widths and some decay modes. Since the dynamics is not involved, some details are missing, as we discussed in last section about our prediction. It is, of course, interesting and compelling to pursue this line by adding the dynamics in the calculations.

One of the authors (Y. Q. C.) thanks C. Liu for bringing this subject to his attention. This work is partially supported by the National Natural Science Foundation of China.

[1] SELEX Collaboration, A. Evdokimov *et al.*, hep-ex/0406045.

[2] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **90**, 242001 (2003).

[3] Belle Collaboration, P. Krokovny *et al.*, Phys. Rev. Lett. **91**, 262002 (2003); Y. Mikami *et al.*, Phys. Rev. Lett. **92**, 012002 (2004).

[4] CLEO Collaboration, D. Besson *et al.*, Phys. Rev. D **68**, 032002 (2003).

[5] A. Pompili, hep-ex/0311036.

[6] F. Porter, Eur. Phys. J. C **33**, S219 (2004).

[7] R. N. Cahn and J. D. Jackson, Phys. Rev. D **68**, 037502 (2003).

[8] M. DiPierro and E. Eichten, Phys. Rev. D **64**, 114004 (2001).

[9] W. A. Bardeen, E. J. Eichten, and C. T. Hill, Phys. Rev. D **68**, 054024 (2003); W. A. Bardeen and C. T. Hill, Phys. Rev. D **49**, 409 (1994).

[10] M. A. Nowak, M. Rho, and I. Zahed, Phys. Rev. D **48**, 4370 (1993); hep-ph/0307102.

[11] T. Barnes, F. Close, and H. Lipkin, Phys. Rev. D **68**, 054006 (2003); A. Szczepaniak, Phys. Lett. B **567**, 23 (2003).

[12] E. Beveren and G. Rupp, Phys. Rev. Lett. **91**, 012003 (2003).

[13] H. Cheng and W. Hou, Phys. Lett. B **566**, 193 (2003).

[14] J. Weinstein and N. Isgur, Phys. Rev. D **41**, 2236 (1990).
[15] A. Rujula, H. Georgi, and S. Glashow, Phys. Rev. Lett. **38**, 317 (1977).
[16] S. F. Tuan, Phys. Lett. B **473**, 136 (2000).
[17] N. Isgur and M. Wise, Phys. Lett. B **232**, 113 (1989); **237**, 527 (1980).
[18] I. Bigi, B. Blok, M. Shifman, N. Uraltsev, and A. Vainstein, in *B Decays*, edited by S. Stone (World Scientific Publishing Co., Singapore, 1994).
[19] W. Dai, X. He, X. Li, and G. Zhao, Phys. Rev. D **60**, 034005 (1999).
[20] L. Maiani *et al.*, Phys. Rev. D **70**, 054009 (2004).