

$D_{sJ}^+(2632)$: An excellent candidate of tetraquarks

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We analyze various possible interpretations of the narrow state $D_{sJ}(2632)$ which lies 100 MeV above threshold. This interesting state decays mainly into $D_s\eta$ instead of D^0K^+ . If this relative branching ratio is further confirmed by other experimental groups, we point out that the identification of $D_{sJ}(2632)$ either as a $c\bar{s}$ state or more generally as a $\bar{\mathbf{3}}$ state in the $SU(3)_F$ representation is probably problematic. Instead, such an anomalous decay pattern strongly indicates $D_{sJ}(2632)$ is a four-quark state in the $SU(3)_F$ $\mathbf{15}$ representation with the quark content $\frac{1}{2\sqrt{2}}(ds\bar{d} + sd\bar{d} + su\bar{u} + us\bar{u} - 2ss\bar{s})\bar{c}$. We discuss its partners in the same multiplet and the similar four-quark states composed of a bottom quark $B_{sJ}^0(5832)$. Experimental searches of other members especially those exotic ones are strongly called for.

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I. INTRODUCTION

The experimental discovery of the low-lying narrow charm mesons $D_{sJ}(2317)$ and $D_{sJ}(2457)$ [1–4] has attracted much attention. Since their masses in the constituent quark model are roughly 160 MeV higher than the experimental values, some people postulated these states could be four-quark states [5,6]. However, there is no compelling evidence that $D_{sJ}(2317)$ and $D_{sJ}(2457)$ are nonconventional meson states. It is still possible to interpret them as $c\bar{s}$ states [7,8]. Instead, the large electromagnetic branching ratio of $D_{sJ}(2457)$ favors such a picture [3,4]. Interested readers may consult Ref. [9] for a review of this topic.

Very recently the SELEX Collaboration observed another exotic charm-strange meson $D_{sJ}(2632)$ with a significance of 7.2σ in the $D_s\eta$ channel and 5.3σ in the D^0K^+ channel [10], which has created some excitement [11–15]. The decay width of this narrow resonance is less than 17 MeV at a 90% confidence level.

At present there are three puzzles concerning this state. First, this state lies 274 MeV above the D^0K^+ threshold and 116 MeV above the $D_s\eta$ threshold. One would naively expect its strong decay width to be around (100–200) MeV. Both particles in the final states are pseudoscalar mesons, thus $D_{sJ}^+(2632)$ has $J = L$, $P = (-)^L$ with L being the decay angular momentum. Because the final states D_s^+ and η are both isoscalar, $D_{sJ}^+(2632)$ is probably an isoscalar.

Second, the ground state charm-strange mesons with $L = 0$ are $D_s(1968)$ and $D_s^*(2112)$. According to the heavy quark effective field theory, there exist two heavy doublets with positive parity and $L = 1$. We denote them as $l^P = \frac{1}{2}^+$ and $l^P = \frac{3}{2}^+$ where l is the angular momentum

of the light quark. The $l^P = \frac{1}{2}^+$ doublets are $D_{sJ}(2317)$ and $D_{sJ}(2457)$. The $l^P = \frac{3}{2}^+$ doublets are $D_{sJ}(2536)$ and $D_{sJ}(2573)$ [16]. One may be tempted to interpret $D_{sJ}(2632)$ either as a member of the $l^P = \frac{5}{2}^-$ doublet with $J = 3$, $L = 2$ or as a member of the $l^P = \frac{3}{2}^-$ doublet with $J = 1$, $L = 2$. Especially the identification of $D_{sJ}(2632)$ as a $J = 3$, $L = 2$ state may seem attractive at first sight since the presence of the high angular momentum may lead to a small decay width. But apparently $D_{sJ}(2632)$ is too low for $L = 2$. Another possibility is that $D_{sJ}(2632)$ is the first radial excitation of the ground state charm-strange meson [14].

The most demanding issue is the unusual decay pattern. This state decays mainly into the $D_s\eta$ mode. Recall that $SU(3)$ flavor symmetry breaking is at most around 20% and the physical eta meson is mainly an octet. One may perform a more refined analysis taking into account the mixing between η_8 and η_1 or the $SU(3)$ symmetry breaking effects. But the following result will not change dramatically. We may write an effective Lagrangian for $D_{sJ}(2632)$ decay processes if it is a $c\bar{s}$ state. The decay width reads

$$\Gamma = \lambda^2 g^2 \frac{k^{2L+1}}{m^{2L}}, \quad (1)$$

where λ is the Clebsch-Gordan (CG) coefficient, g is the universal and dimensionless effective coupling constant, and L is the angular momentum for decay. m is the parent mass and k is the decay momentum in the center of mass frame

$$k = \frac{1}{2m} \{[m^2 - (m_1 + m_2)^2][m^2 - (m_1 - m_2)^2]\}^{1/2}, \quad (2)$$

where m_1 and m_2 are the masses of final mesons. The ratio of decay widths of these two channels is

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$$\frac{\Gamma(D^0 K^+)}{\Gamma(D_s \eta)} = \left(\frac{\lambda_{D^0 K^+}}{\lambda_{D_s \eta}} \right)^2 \left(\frac{k_{D^0 K^+}}{k_{D_s \eta}} \right)^{2L+1}. \quad (3)$$

Using $\lambda_{D^0 K^+}/\lambda_{D_s \eta} = \sqrt{3/2}$, $k_{D^0 K^+} = 499$ MeV, and $k_{D_s \eta} = 325$ MeV, we get

$$\frac{\Gamma(D^0 K^+)}{\Gamma(D_s \eta)} = 2.3 * (1.54)^{2L} \geq 2.3, \quad (4)$$

which is nearly 15 times larger than the experimental value [10]

$$\frac{\Gamma(D^0 K^+)}{\Gamma(D_s \eta)} = 0.16 \pm 0.06. \quad (5)$$

If this relative branching ratio is confirmed by other experimental groups, we conclude that the identification of $D_{sJ}(2632)$ either as a $c\bar{s}$ state or more generally as a $\bar{3}$ state in the $SU(3)_F$ representation is very problematic. We must seek other interpretations.

$D_{sJ}(2632)$ decays mainly into $D_s \eta$. η is a mixture of η_8 and η_1 . η_1 is a $SU(3)$ singlet which mixes strongly with $G\tilde{C}$. One may think $D_{sJ}(2632)$ is a good candidate of a heavy hybrid meson with the content $cG\bar{s}$ [17]. If it is the lowest hybrid state, one should expect that it is composed of c , \bar{s} and a gluon of magnetic field type (all in S state) so that it has spin parity 1^- . For decay of this state to D_s and η , the quark should emit a gluon of an electric field type in the S state so that the gluon component has total spin parity 0^- . However, in this transition the quark component must jump to the excited state due to a selection rule contrary to the experiment observation. If the initial state is not the lowest hybrid state, its mass should be heavier than the observed mass. The hybrid state with two explicit gluons $G\tilde{C}$ also seems to be too heavy. However, the gluon is a flavor singlet. So the hybrid assumption cannot explain the unusual decay pattern.

Since $D_{sJ}(2632)$ is above threshold, it cannot be a hadron molecule state. Molecules are bound states of color singlet hadrons. They should lie near or below threshold. However, it could be a bound state of two color nonsinglet clusters like a diquark and antidiquark. That is what we will advocate below: $D_{sJ}(2632)$ is a four-quark state which provides a simple and natural explanation of the unusual decay pattern.

II. TETRAQUARK MULTIPLETS

In this section, we consider a tetraquark state $qq\bar{q}\bar{c}$ with $q = u, d, s$. We present the wave functions and the decay modes of the tetraquark states with one anticharm quark.

Under the transformation of $SU(3)_F$, the charm quark is singlet. There are four multiplets according to

$$3 \otimes 3 \otimes \bar{3} \otimes 1 = 3 \oplus 3 \oplus \bar{6} \oplus 15. \quad (6)$$

In these tetraquark multiplets, all states have a charm number of $C = -1$. We denote the states with strangeness $S = 1$ as $D_{\bar{s}}$, with $S = 0$ as D , with $S = -1$ as D_s , and with $S = -2$ as D_{ss} . The weight diagrams are shown in Fig. 1.

We present all the tetraquark flavor wave functions in Tables I, II, and III. These expressions are obtained by operating U_- and I_- operators on the highest weight state.

As we have pointed out, $D_{sJ}(2632)$ cannot be a member of the $\bar{3}$ representation. From now on, we focus on the $\bar{6}$ and 15 representations. We can get the decay modes of these tetraquark states by expanding the following effective Lagrangian:

$$L_{\text{eff}} = g_6 T^{\dagger ij} M_i^a T^b \epsilon_{abj} + g_{15} T_{jm}^{\dagger i} M_i^j T^m, \quad (7)$$

where the triplet T^i reads

$$(T^i) = \begin{pmatrix} \bar{c}u \\ \bar{c}d \\ \bar{c}s \end{pmatrix} = \begin{pmatrix} \bar{D}^0 \\ D^- \\ D_s^- \end{pmatrix}. \quad (8)$$

The tensor representation for the antisextet is

$$(T_{ij}) = \begin{pmatrix} D_{s,\bar{6}}^{--} & -\frac{1}{\sqrt{2}} D_{s,\bar{6}}^- & \frac{1}{\sqrt{2}} D_{\bar{6}}^- \\ -\frac{1}{\sqrt{2}} D_{s,\bar{6}}^- & D_{s,\bar{6}}^0 & -\frac{1}{\sqrt{2}} D_{\bar{6}}^0 \\ \frac{1}{\sqrt{2}} D_{\bar{6}}^- & -\frac{1}{\sqrt{2}} D_{\bar{6}}^0 & D_{s,\bar{6}}^0 \end{pmatrix}. \quad (9)$$

The members of the 15 representation are

(i) $Y = \frac{4}{3}, I = 1$:

$$\begin{aligned} T_3^{11} &= D_{s,15}^+, & T_3^{12} &= \frac{1}{\sqrt{2}} D_{s,15}^0, \\ T_3^{22} &= D_{s,15}^-. \end{aligned} \quad (10)$$

(ii) $Y = \frac{1}{3}, I = 3/2, 1/2$:

$$\begin{aligned} T_2^{11} &= -D_{15}^+, & T_1^{11} &= \frac{1}{\sqrt{3}} D_{15}^0 - \frac{1}{\sqrt{6}} D_{15}^{0'}, \\ T_2^{12} &= -\frac{1}{\sqrt{3}} D_{15}^0 - \frac{1}{2\sqrt{6}} D_{15}^{0'}, & T_3^{13} &= \frac{\sqrt{6}}{4} D_{15}^{0'}, \end{aligned} \quad (11)$$

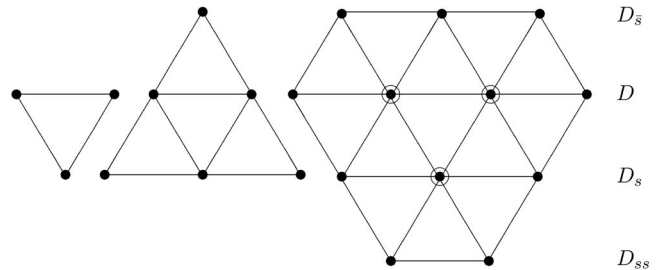


FIG. 1. Weight diagrams of heavy flavor tetraquark multiplets.

TABLE I. The flavor wave functions of the heavy tetraquarks in the two triplets.

	States	Flavor wave functions	States	Flavor wave functions
$I = \frac{1}{2}, S = 0$	\bar{D}_3^0	$\frac{1}{2}(su\bar{s} - us\bar{s} - ud\bar{d} + du\bar{d})\bar{c}$	$\bar{D}_3^{0'}$	$\frac{1}{2\sqrt{2}}(su\bar{s} + us\bar{s} + ud\bar{d} + du\bar{d} + 2uu\bar{u})\bar{c}$
	D_3^-	$\frac{1}{2}(ud\bar{u} - du\bar{u} - ds\bar{s} + sd\bar{s})\bar{c}$	$D_3^{-'}$	$\frac{1}{2\sqrt{2}}(ud\bar{u} + du\bar{u} + ds\bar{s} + sd\bar{s} + 2dd\bar{d})\bar{c}$
$I = 0, S = -1$	$D_{s,3}^-$	$\frac{1}{2}(ds\bar{d} - sd\bar{d} - su\bar{u} + us\bar{u})\bar{c}$	$D_{s,3}^{-'}$	$\frac{1}{2\sqrt{2}}(ds\bar{d} + sd\bar{d} + su\bar{u} + us\bar{u} + 2ss\bar{s})\bar{c}$

$$T_1^{12} = \frac{1}{\sqrt{3}}D_{15}^- - \frac{1}{2\sqrt{6}}D_{15}^{-'}, \quad \text{reads}$$

$$T_2^{22} = -\frac{1}{\sqrt{3}}D_{15}^- - \frac{1}{\sqrt{6}}D_{15}^{-'}, \quad T_3^{23} = \frac{\sqrt{6}}{4}D_{15}^{-'}, \quad \frac{\Gamma(D_{s,15}^{-'} \rightarrow \bar{D}^0 K^-)}{\Gamma(D_{s,15}^{-'} \rightarrow D_s^- \eta)} = 0.25 * (1.54)^{2L} \quad (15)$$

$$T_1^{22} = D_{15}^{--}. \quad (12)$$

(iii) $Y = -\frac{2}{3}, I = 1, 0$:

$$T_2^{13} = -\frac{1}{\sqrt{2}}D_{s,15}^0, \quad T_1^{13} = \frac{1}{2}D_{s,15}^- - \frac{\sqrt{2}}{4}D_{s,15}^{-'}$$

$$T_2^{23} = -\frac{1}{2}D_{s,15}^- - \frac{\sqrt{2}}{4}D_{s,15}^{-'}, \quad T_3^{33} = \frac{1}{\sqrt{2}}D_{s,15}^{-'}$$

$$T_1^{23} = \frac{1}{\sqrt{2}}D_{s,15}^{--}. \quad (13)$$

(iv) $Y = -\frac{5}{3}, I = 1/2$:

$$T_2^{33} = -D_{ss}^-, \quad T_1^{33} = D_{ss}^{--}. \quad (14)$$

These expressions can also be obtained by using the isospin and U spin lowering operators.

We present the CG coefficient of each interaction term in Tables IV and V. With these CG coefficients, it is easy to derive the relative branching ratio.

It is important to note that there is no isoscalar state with valence quark content $\bar{c}s$ in the anti-sextet. However, in the 15 tetraquark multiplet, there is an isoscalar $D_{s,15}^{-'}$. From Table V, we find that the ratio of CG coefficients for the $\bar{D}^0 K^-$ channel and the $D_s^- \eta_8$ channel is $\frac{1}{\sqrt{6}}$. Now the relative branching ratio

TABLE II. The flavor wave functions of the heavy tetraquarks in the antisextet T_{ij} .

	States	Flavor wave functions
$I = 0, S = 1$	$D_{\bar{s},6}^0$	$\frac{1}{\sqrt{2}}(ud\bar{s} - du\bar{s})\bar{c}$
$I = \frac{1}{2}, S = 0$	D_6^0	$\frac{1}{2}(us\bar{s} - su\bar{s} - ud\bar{d} + du\bar{d})\bar{c}$
	D_6^-	$\frac{1}{2}(ds\bar{s} - sd\bar{s} + ud\bar{u} - du\bar{u})\bar{c}$
$I = 1, S = -1$	$D_{s,6}^0$	$\frac{1}{\sqrt{2}}(su\bar{d} - us\bar{d})\bar{c}$
	$D_{s,6}^-$	$\frac{1}{2}(sd\bar{d} - ds\bar{d} - su\bar{u} + us\bar{u})\bar{c}$
	$D_{s,6}^{--}$	$\frac{1}{\sqrt{2}}(ds\bar{u} - sd\bar{u})\bar{c}$

if we roughly assume $\eta \approx \eta_8$. This ratio is around 0.25 if $D_{s,15}^{-'}$ decays via the S wave, which is consistent with the experimental result 0.16 ± 0.06 . With P wave decay the relative ratio is about 0.59.

The above derivation of the ratio of the SU(3) Clebsch-Gordan coefficients is rather tedious. A straightforward way is to find these coefficients from available tables in literature. An exhaustive compilation of them is presented in Ref. [18]. When a particle A in the SU(3) representation R with hypercharge Y , isospin I, I_3 couples to particle B r, y, i, i_3 and particle C r', y', i', i'_3 , the SU(3) Clebsch-Gordan coefficient can be decomposed into the product of an isoscalar part and SU(2) Clebsch-Gordan coefficient [18]:

TABLE III. The flavor wave functions of the heavy tetraquarks in 15-plet T_k^{ij} .

	States	Flavor wave functions
$I = 1, S = 1$	$D_{s,15}^+$	$uu\bar{s}\bar{c}$
	$D_{s,15}^0$	$\frac{1}{\sqrt{2}}(ud\bar{s} + du\bar{s})\bar{c}$
	$D_{s,15}^-$	$dd\bar{s}\bar{c}$
$I = \frac{3}{2}, S = 0$	D_{15}^+	$-uu\bar{d}\bar{c}$
	D_{15}^0	$-\frac{1}{\sqrt{3}}(ud\bar{d} + du\bar{d} - uu\bar{u})\bar{c}$
	D_{15}^-	$\frac{1}{\sqrt{3}}(ud\bar{u} + du\bar{u} - dd\bar{d})\bar{c}$
	D_{15}^{--}	$dd\bar{u}\bar{c}$
$I = \frac{1}{2}, S = 0$	$D_{15}^{0'}$	$\frac{1}{2\sqrt{6}}[3us\bar{s} + 3su\bar{s} - ud\bar{d} - du\bar{d} - 2uu\bar{u}]\bar{c}$
	$D_{15}^{-'}$	$\frac{1}{2\sqrt{6}}[3ds\bar{s} + 3sd\bar{s} - ud\bar{u} - du\bar{u} - 2dd\bar{d}]\bar{c}$
$I = 1, S = -1$	$D_{s,15}^0$	$-\frac{1}{\sqrt{2}}(su\bar{d} + us\bar{d})\bar{c}$
	$D_{s,15}^-$	$-\frac{1}{2}(ds\bar{d} + sd\bar{d} - su\bar{u} - us\bar{u})\bar{c}$
$I = 0, S = -1$	$D_{s,15}^{--}$	$\frac{1}{\sqrt{2}}(ds\bar{u} + sd\bar{u})\bar{c}$
	$D_{s,15}^{-'}$	$-\frac{1}{2\sqrt{2}}(ds\bar{d} + sd\bar{d} + su\bar{u} + us\bar{u} - 2ss\bar{s})\bar{c}$
$I = \frac{1}{2}, S = 0$	D_{ss}^-	$-ss\bar{d}\bar{c}$
	D_{ss}^{--}	$ss\bar{u}\bar{c}$

TABLE IV. Couplings of the heavy tetraquark antisextet T_{ij} with the heavy meson triplet T^i and pseudoscalar meson octet M_j^i . The universal coupling constant is omitted.

$D_{s,\bar{6}}^{--}$		$D_{s,\bar{6}}^-$		$D_{s,\bar{6}}^0$	
$K^- D^-$	-1	$K^- \bar{D}^0$	$-\frac{1}{\sqrt{2}}$	$\pi^+ D_s^-$	-1
$\pi^- D_s^-$	1	$\bar{K}^0 D^-$	$\frac{1}{\sqrt{2}}$	$\bar{K}^0 \bar{D}^0$	1
		$\pi^0 D_s^-$	1		
D_6^-		D_6^0		$D_{s,\bar{6}}^0$	
$\pi^- \bar{D}^0$	$-\frac{1}{\sqrt{2}}$	$\pi^0 \bar{D}^0$	$-\frac{1}{2}$	$K^0 \bar{D}^0$	-1
$\pi^0 D^-$	$\frac{1}{2}$	$\eta_8 \bar{D}^0$	$\frac{\sqrt{3}}{2}$	$K^+ D^-$	1
$\eta_8 D^-$	$\frac{\sqrt{3}}{2}$	$\pi^+ D^-$	$-\frac{1}{\sqrt{2}}$		
$K^0 D_s^-$	$\frac{1}{\sqrt{2}}$	$K^+ D_s^-$	$\frac{1}{\sqrt{2}}$		

$$\langle \mathbf{R} Y I_3 | \mathbf{r} y i i_3 \mathbf{r}' y' i' i'_3 \rangle = F(\mathbf{R}, Y, I; \mathbf{r}, y, i, \mathbf{r}', y', i') \times \langle I I_3 | i i_3 i' i'_3 \rangle. \quad (16)$$

$F(\mathbf{R}, Y, I; \mathbf{r}, y, i, \mathbf{r}', y', i')$ is the isoscalar function which can be found in the tables of Ref. [18]. For example, from Table 10 in Ref. [18] we get

$$F(D_{s,15}^- \rightarrow D_s \eta) = \frac{\sqrt{3}}{2}, \quad (17)$$

$$F(D_{s,15}^- \rightarrow K^- \bar{D}^0) = -\frac{1}{2}. \quad (18)$$

The SU(2) Clebsch-Gordan coefficient is 1 for $D_{s,15}^- \rightarrow D_s \eta$ and $\frac{1}{\sqrt{2}}$ for $D_{s,15}^- \rightarrow K^- \bar{D}^0$. Putting everything together we obtain the relative ratio of the decay CG

TABLE V. Couplings of the heavy tetraquark 15-plet T_k^{ij} with the usual meson octet M_j^i and the heavy meson triplet T^i . The universal coupling constant is omitted.

D_{15}^+	D_{15}^0	D_{15}^-	D_{15}^{--}	$D_{15}^{0'}$	
$\pi^+ \bar{D}^0$	-1	$\pi^0 \bar{D}^0$	$\frac{2}{\sqrt{6}}$	$\pi^0 D^-$	$\frac{2}{\sqrt{6}}$
		$\pi^+ D^-$	$-\frac{1}{\sqrt{3}}$	$\pi^- \bar{D}^0$	$\frac{1}{\sqrt{3}}$
				$\pi^- D^-$	1
				$K^+ D_s^-$	$\frac{3}{2\sqrt{6}}$
				$\pi^+ D^-$	$-\frac{1}{2\sqrt{6}}$
				$\pi^0 \bar{D}^0$	$-\frac{1}{4\sqrt{3}}$
				$\eta_8 \bar{D}^0$	$-\frac{3}{4}$
D_{15}^-	$D_{s,15}^0$	$D_{s,15}^-$	$D_{s,15}^{--}$	$D_{s,15}^{-'}$	
$K^0 D_s^-$	$\frac{3}{2\sqrt{6}}$	$\pi^+ D_s^-$	$-\frac{1}{\sqrt{2}}$	$\pi^0 D_s^-$	$\frac{1}{\sqrt{2}}$
$\eta_8 D^-$	$-\frac{3}{4}$	$\bar{K}^0 \bar{D}^0$	$-\frac{1}{\sqrt{2}}$	$K^- \bar{D}^0$	$\frac{1}{2}$
$\pi^0 D^-$	$\frac{1}{4\sqrt{3}}$	$\bar{K}^0 D^-$	$-\frac{1}{2}$	$K^- D^-$	$\frac{1}{\sqrt{2}}$
$\pi^- \bar{D}^0$	$-\frac{1}{2\sqrt{6}}$			$K^- \bar{D}^0$	$-\frac{1}{2\sqrt{2}}$
				$\bar{K}^0 D^-$	$-\frac{1}{2\sqrt{2}}$
$D_{s,15}^+$	$D_{s,15}^0$	$D_{s,15}^-$	D_{ss}^-	D_{ss}^{--}	
$K^+ \bar{D}^0$	1	$K^+ D^-$	$\frac{1}{\sqrt{2}}$	$K^- D_s^-$	1
		$K^0 \bar{D}^0$	$\frac{1}{\sqrt{2}}$	$\bar{K}^0 D_s^-$	-1

coefficients again as

$$\left| \frac{\lambda(D_{s,15}^- \rightarrow K^- \bar{D}^0)}{\lambda(D_{s,15}^- \rightarrow D_s \eta)} \right| = \frac{1}{\sqrt{6}}. \quad (19)$$

In fact, an even more transparent derivation of the relative ratio of the decay coupling constants is possible if we assume the ‘‘fall-apart’’ decay mechanism for tetraquarks. With the flavor wave function of $D_{s,15}^-$ in Table III, only the first two terms contribute to the $K^- \bar{D}^0$ decay mode while every piece contributes to the $D_s \eta$ mode. The ratio of their coupling constants is simply

$$\begin{aligned} & |\lambda(D_{s,15}^- \rightarrow K^- \bar{D}^0) : \lambda(D_{s,15}^- \rightarrow D_s \eta)| \\ &= (1+1) : \frac{1}{\sqrt{6}} [1+1+1+1+(-2)*(-2)*2] \\ &= 1 : \sqrt{6}. \end{aligned} \quad (20)$$

The last factor 2 arises because there are two possible ways to get an $s\bar{s}$ from $ss\bar{s}$. Once again we reproduce this ratio.

Based on the above argument, we propose that $D_{sJ}^+(2632)$ is very probably a tetraquark state in the $SU(3)_F$ 15 representation with the quantum number $I=0, J^P=0^+$.

III. DISCUSSIONS

We may also perform a rough estimate of the mass of $D_{s,15}^-$ with the flavor wave function. If we use constituent quark masses: $m_u = m_d = 310$ MeV, $m_s = 450$ MeV, and $m_c = 1430$ MeV, we have

$$\begin{aligned} M_{D_{s,15}^-} &= \frac{1}{8} [4(m_u + m_u + m_s) + 4(m_s + m_s + m_s)] + m_c \\ &= m_u + 2m_s + m_c = 2640 \text{ MeV}. \end{aligned} \quad (21)$$

Using the well-known Gell-Mann-Okubo formula, it is easy to derive the mass relations between the tetraquark states within the same multiplet:

$$M = a + b[I(I+1) - \frac{1}{4}Y^2] + cY. \quad (22)$$

For the heavy tetraquark antisextet,

$$M_{D_{s,\bar{6}}} - M_{D_{\bar{6}}} = M_{D_6} - M_{D_{ss}}. \quad (23)$$

For the heavy tetraquark 15-plet, we find

$$M_{D_{s,15}} - M_{D_{15}'} = M_{D_{15}'} - M_{D_{s,15}'}, \quad (24a)$$

$$M_{D_{15}} - M_{D_{s,15}} = M_{D_{s,15}} - M_{D_{ss}}, \quad (24b)$$

$$M_{D_{s,15}} + 3M_{D_{15}} = 2(M_{D_{15}} + M_{D_{s,15}'}). \quad (24c)$$

It is very interesting to note that there are three manifestly exotic four-quark states: $D_{s,\bar{6}}^0$, $D_{s,\bar{6}}^0$, and $D_{s,\bar{6}}^{--}$. There are nine manifestly exotic four-quark states: $D_{s,15}^+$, $D_{s,15}^0$, $D_{s,15}^-$, D_{15}^+ , D_{15}^- , $D_{s,15}^0$, $D_{s,15}^{--}$, D_{ss}^- , and D_{ss}^{--} .

If $D_{sJ}(2632)$ is really a member of the tetraquark states in the 15 representation, these exotic states should appear as partners of $D_{sJ}(2632)$. We strongly call for an experimental search of these interesting states. Some of them have a unique decay channel such as $D_{15}^+ \rightarrow \bar{D}^0 \pi^+$, $D_{15}^- \rightarrow D^- \pi^-$, etc.

Replacing the charm quark in $D_{sJ}^+(2632)$ by the bottom quark, we get bottom tetraquark state $B_{sJ}^0(5832)$ where we have assumed the mass difference between $D_{sJ}^+(2632)$ and $B_{sJ}^0(5832)$ is simply $m_b - m_c = 3200$ MeV. $B_{sJ}^0(5832)$ is also expected to be a narrow resonance above threshold with a dominant decay mode $B_s \eta$.

In Ref. [11] Maiani *et al.* suggested that $D_{sJ}^+(2632)$ is a $cd\bar{d}\bar{s}$ state to a good extent while its anomalous decay ratio is caused by isospin breaking. In Ref. [13] it was also suggested that $D_{sJ}^+(2632)$ is a cryptoexotic tetraquark baryonium state $cd\bar{d}\bar{s}$ [13]. Reference [12] tried to identify all three narrow charm-strange mesons $D_{sJ}(2137)$, $D_{sJ}(2457)$, and $D_{sJ}^+(2632)$ as four-quark states. Reference [14] suggested that $D_{sJ}^+(2632)$ could be the first radial excitation of the $D_s^*(2112)$ state and the unusual decay pattern might be explained by the node structure of the wave function. Reference [14] also dealt with the

possibility of interpreting $D_{sJ}^+(2632)$ as a diquark and antidiquark bound state. Reference [15] suggested the same scheme for the narrow width of $D_{sJ}^+(2632)$. However it was pointed out that the relative branching ratio of such an assignment still disagrees with the SELEX experiment [15].

We have inferred from the unusual decay pattern that the narrow resonance observed by the SELEX Collaboration is very probably a four-quark state with the quark content $\frac{1}{2\sqrt{2}}(ds\bar{d} + sdd + su\bar{u} + us\bar{u} - 2ss\bar{s})\bar{c}$. We have made a systematic analysis of the charm tetraquark states and have explicitly demonstrated how this unusual decay pattern occurs.

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