Possible Interpretations of D+sJ (2632) If It Really Exists (Postprint)

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Abstract

We analyze various possible interpretations of the narrow state D+sJ (2632) observed by SELEX Collaboration recently, which lies above threshold and has abnormal decay pattern. These interpretations include: (1) several versions of tetraquarks; (2) conventional cs¯ meson such as the first radial excitation of Ds(2112) with abnormally large SU(3) symmetry breaking; (3) conventional cs¯ meson with abnormally large 1 coupling; (4) heavy hybrid meson. We discuss the physical implications of each interpretation. For example, if the existence of D +sJ (2632) is confirmed as the first radial excitation of Ds(2112) by other experiments, it will be helpful to look for (1) its SU(3) flavor partners D 0,+J(2530); (2) its B-meson analogues B0,+J(5840), B+sJ (5940); (3) S-wave two pion decaymodes.

Full Text

Preamble

Possible Interpretations of D^+_{sJ}(2632) If It Really Exists

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We analyze various possible interpretations of the narrow state D^+{sJ}(2632) *recently observed by the SELEX Collaboration, which lies above threshold and exhibits an abnormal decay pattern. These interpretations include: (1) several versions of tetraquarks; (2) a conventional $\bar{c}s$ meson such as the first radial excitation of D_s(2112) with abnormally large SU(3) symmetry breaking; (3)*

a conventional $\bar{c}s$ meson with abnormally large $_1$ *coupling; (4) a heavy hybrid meson. We discuss the physical implications of each interpretation. For example, if the existence of* D^+{sJ}(2632) is confirmed as the first radial excitation of D_s(2112) by other experiments, it will be helpful to look for (1) its SU(3) flavor partners D^{0+}{sJ}(5940); (2) its B-meson analogues B^{0+}(5840), B^+{sJ}(2530); (3) S-wave two-pion decay modes.

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I. Difficulty with c̄s Assignment and SU(3) Flavor Symmetry

The experimental discovery of narrow low-lying charm-strange mesons D_{sJ}(2317) and D_{sJ}(2457) represents an important event in heavy meson spectroscopy [?, ?, ?, ?]. Many theoretical interpretations have been proposed [?, ?, ?, ?, ?]. However, the large electromagnetic branching ratio of D_{sJ}(2457) observed by the BELLE Collaboration favors assigning these two states as conventional c̄s mesons [?, ?, ?]. These two states belong to the (0^+, 1^+) doublet with j_l = 1 in heavy quark effective field theory.

Recently, the SELEX Collaboration observed an exotic charm-strange meson D_{sJ}(2632). Its decay width is very narrow, $\Gamma < 17$ MeV at 90% C.L. The decay channels are D_s and D^0K^+ with the unusual relative branching ratio: $\Gamma(D^0K^+)/\Gamma(D\_s\ ) = 0.16 \pm 0.06$ [?]. This observation has inspired numerous theoretical papers [?, ?, ?, ?, ?, ?, ?, ?, ?, ?].

To understand why this relative branching ratio is abnormal, let us first assume (1) SU(3) flavor symmetry and (2) that D^+*{sJ}(2632) is a $\bar{c}s$ state. The charge conjugate state* D^-{sJ}(2632) belongs to an SU(3)_F triplet when the heavy quark transforms as an SU(3)_F singlet. We denote the triplet as (T) = ($\bar{D}^0$_J, D^-*J,* D^-{sJ}(2632)), where $\bar{D}^0$_J and D^-*J are SU(3) flavor partners of* D^-{sJ}(2632).

The decay of the heavy meson triplet T' can be described with the effective Lagrangian in the SU(3)_F symmetry limit:

$$\mathcal{L}_8 = g_8 T'^{\dagger}_i M^i_j T^j + \text{H.c.}$$

where M _j is the matrix of pseudoscalar meson octet and T is the final-state heavy pseudoscalar meson triplet. We have suppressed the Lorentz indices for mesons.

The two-body decay width of a meson reads:

$$\Gamma = \frac{g^2 k^{2L+1}}{8\pi m_0^2}$$

where g is the dimensionless effective coupling constant, L is the angular momentum for the decay, m_0 is the parent mass, and k is the decay momentum in the center-of-mass frame:

$$k = \frac{\sqrt{[m_0^2 - (m_1 + m_2)^2][m_0^2 - (m_1 - m_2)^2]}}{2m_0}$$

where m_1 and m_2 are the masses of the final mesons. The ratio of decay widths of these two channels for D^+_{sJ}(2632) is:

$$\frac{\Gamma(D^{0K^+)}}{\Gamma(D_s\eta)} = \frac{g^2_{D^0K^+}}{g^2_{D_s\eta}} \frac{k^{2L+1}_{D^0K^+}}{k^{2L+1}_{D_s\eta}}$$

Using SU(3) symmetry, we have g_{D^0K^+}^{2}/g_{D_s }^{2} = 2, k_{D^0K^+} = 499 MeV, and k_{D_s } = 325 MeV. We obtain:

$$\frac{\Gamma(D^{0K^+)}}{\Gamma(D_s\eta)} = 2.3 \left(\frac{1.54}{1}\right)^{2L}$$

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

Clearly, either some important physics is missing or one of the above two assumptions—SU(3) symmetry or D_{sJ}(2632) as a c̄s state—is wrong. In the following sections, we analyze four different interpretations of this charming state and the resulting phenomenology.

II. Tetraquarks

One intriguing possibility is that D_s(2632) is a tetraquark [?, ?, ?, ?, ?, ?]. In this case, there should be other tetraquark partners of D_{sJ}(2632). Moreover, its narrow width may require that quarks inside D_{sJ}(2632) form tightly bound clusters like diquarks [?]. We provide a brief review of different versions of tetraquark interpretations.

Tetraquarks with quark content c̄q̄qq form four multiplets: two triplets, one anti-sextet, and one 15-plet:

$$\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{3}_1 \oplus \mathbf{3}_2 \oplus \bar{\mathbf{6}} \oplus \mathbf{15}$$

The wave functions of these states can be found in Ref. [?]. Identifying D_{sJ}(2632) as the J^P = 0^+ isoscalar member of the 15 tetraquarks with quark content (d s̄d + s d̄d + s ūu + u s̄u - 2 s s̄s)c̄ leads to the relative branching ratio [?]:

$$\frac{\Gamma(D^{0K^{+)}}}{\Gamma(D_s\eta)} = 0.25$$

This decay pattern arises very naturally from the SU(3) Clebsch-Gordan coefficients.

Another possibility is that D$^+$_{sJ}(2632) is dominated by c̄s s̄s with J^P = 0$^+$ [?, ?]. The s̄s fluctuates into √3 $_1$ - $_8$. Hence, its decay mode is mainly D$^+$_s . The final states D^{0}K$^+$ and D$^+$K^0 are produced through the annihilation of s̄s into ūu + d̄d, which requires the $_1$ component. Thus this process is OZI suppressed. In this way, the anomalous decay pattern is achieved.

In the diquark correlation configuration [?], D$^+$_{sJ}(2632) is suggested to be a (cs)$_3$* ($\overline{\text{ss}}$)$_3$ state, where the subscript numbers are color representations. With the assumption that (cs)$_3$* has small mixing with (c̄s)$_1$ - (s̄s)$_1$, one can provide a nice interpretation for the narrow width. The mixing between s̄s and ūu + d̄d can lead to the unusual branching ratio.

All three tetraquark interpretations above predict the same production rates for D$^+$K^0 and D^{0}K$^+$ final states. A serious challenge is that the SELEX Collaboration found no signal in the D$^+$K^0 channel [?].

A very different tetraquark version c d̄d̄s is proposed in Refs. [?, ?]. Naively, one would expect D^{0}K$^+$ decay to dominate. Ref. [?] invoked isospin symmetry breaking to explain the relative branching ratio. It was proposed that the mass eigenstate D$^+$_{sJ}(2632) is a mixture between the two flavor eigenstates a$^+$ and f$^+$, where a$^+$ is the I = 1, I$_3$ = 0 state in SU(3)_F 6 representation and f$^+$ is the I = 0 state in $\mathbf{3}_1$ with our notation. With some special mixing scheme, the D^{0}K$^+$ channel is suppressed while D$^+$K^0 and D_s modes are both important. Interestingly, Ref. [?] predicted:

$$\frac{\Gamma(D^{0K^{+)}}}{\Gamma(D_s\eta)} = 0.16$$

At the same time, the authors of Ref. [?] predicted 4 < Γ(D$^+$K^0) < 7.6 and 1.7 < Γ(D_sπ^0) < 6.5.

III. Large SU(3)*F Breaking and D*{sJ}(2632) as a c̄s State

Some authors have suggested that D_{sJ}(2632) might be the first radial excitation of D_s(2112) with J^P = 1$^-$. The nodal structure of the radial wave function of D_s(2632) ensures the narrow width while different decay momenta in the two channels lead to the anomalous decay pattern [?, ?].

We emphasize that two new narrow states D^0*J and D*$^+$J should also exist as flavor partners of D*{sJ}(2632) within this scheme. The mass difference between D*{sJ}(2632) and D^{0+}*J should roughly be the strange quark mass m_s   100 MeV. Therefore, their masses are around 2532 MeV. If D*{sJ}(2632) is interpreted as the first radial excitation of D_s(2112), D^{0+}_J(2532) should be the first radial excitation of D*(2010). Similarly, one expects the following B-meson analogues: B^{0+}*{sJ}(5940). Moreover, the branching ratio of S-wave two-pion decay modes may be significant if D*{sJ}(2632) is the radial excitation.

We point out that the decay momenta of the two channels D^+_s and D^0K^+ are identical in the exact SU(3)_F symmetry limit. Consequently, there would be no anomalous decay pattern. In other words, the origin of this explanation for the anomalous decay pattern can be traced back to SU(3) flavor symmetry breaking effects. In the following, we use the effective Lagrangian formalism to analyze this effect in a model-independent way.

The symmetry breaking is caused by the quark mass matrix m = diag(m̂, m̂, m_s). We assume isospin symmetry. The symmetry-breaking Lagrangian reads:

$$\mathcal{L}_m = \alpha {T'}^{\dagger}_i m^i_j (S_3)^j + \beta {T'}^{\dagger}_i m^l_j (\bar{S}_6)_{lk} \epsilon^{ijk} + \gamma {T'}^{\dagger}_i m^k_j (S_{15})^i_j$$

where:

$$(S_3)^i = M^i_j T^j, \quad (\bar{S}_6)_{ij} = M^a_j T^b \epsilon_{iab} + M^a_i T^b \epsilon_{jab}, \quad (S_{15})^i_j = M^i_k T^k_j + M^k_j T^i_k - \frac{1}{3}\delta^i_j M^a_k T^k_a$$

For D^-_{sJ}(2632), we have:

$$\mathcal{L}_{D_{sJ}} = (g_8 + \alpha m_s) \bar{D}^0_J K^- D^+_s + \frac{1}{\sqrt{2}} (g_8 + \alpha m_s) D^+_J \bar{K}^0 D^+_s + \frac{1}{\sqrt{6}} (g_8 + \alpha m_s) D^+_{sJ} \eta_8 D^-_s$$

$$+ \frac{1}{4}(g_8 + \alpha m_s) D^+_{sJ} \eta_1 D^-_s + \frac{\sqrt{2}}{3} \gamma (m_s - \hat{m}) D^+_{sJ} \eta_8 D^-_s$$

Naively, one would expect |γ(m_s - m̂)/(g_8 + αm_s)| 1. From the relative branching ratio $\Gamma(D^0K^+)/\Gamma$(D_s) = 0.16, we can extract the value γ(m_s - m̂)/(g_8 + αm_s). Numerically, there are two possibilities:

1. If we assume the physical meson is approximately $_8$, we obtain:

$$\left| \frac{\gamma(m_s - \hat{m})}{g_8 + \alpha m_s} \right| = 4.8$$

2. If we assume the physical meson is approximately $_1$, we obtain:

$$\left| \frac{\gamma(m_s - \hat{m})}{g_8 + \alpha m_s} \right| = 1.1$$

Although these numbers seem quite unnatural, anomalously large SU(3)*F breaking can in principle explain the special decay pattern of D*{sJ}(2632).

For D̄^0_J and D^−_J:

$$\mathcal{L}_{D_J} = (g_8 + \alpha\hat{m})D_J^0\pi^0\bar{D}^0 + \frac{1}{\sqrt{2}}(g_8 + \alpha\hat{m})D_J^0\pi^+D^- + \frac{1}{\sqrt{2}}(g_8 + \alpha\hat{m})D_J^+\pi^-\bar{D}^0$$

$$-(g_8+\alpha\hat{m})D_J^+\pi^0D^- + \frac{1}{\sqrt{2}}(\beta+\gamma)(m_s-\hat{m})D_J^0K^+D_s^- + \frac{1}{\sqrt{2}}(\beta+\gamma)(m_s-\hat{m})D_J^+K^0D_s^-$$

$$+\frac{1}{\sqrt{6}}(\beta-\gamma)(m_s-\hat{m})D_J^0\eta_8\bar{D}^0 + \frac{1}{\sqrt{6}}(\beta-\gamma)(m_s-\hat{m})D_J^+\eta_8D^-$$

In general, D^{0+}*J may not have the same decay pattern as D*{sJ}(2632). For example, in the extreme case |γ(m_s - m̂)/(g_8 + αm_s)| 1, we have the following relative branching ratios:

- For the ratio in Eq. (13): Γ(D^0π^+) : Γ(D^+π^0) : Γ(D^+K^0) : Γ(D^+) = 1 : 0.5 : 36.6 : 74.8
- For the ratio in Eq. (14): Γ(D^0π^+) : Γ(D^+π^0) : Γ(D^+K^0) : Γ(D^+) = 1 : 0.5 : 0.4 : 0.1

IV. Large Singlet Coupling and D_{sJ}(2632) as a c̄s State

As in the previous section, we assume D_{sJ}(2632) is a c̄s state with J^P = 1^−. Instead of invoking very large SU(3) breaking effects to account for its decay pattern, we introduce the interaction between the SU(3) singlet $_1$ and D_{sJ}(2632) and consider mixing between $_8$ and $_1$. The effective Lagrangian becomes:

$$\mathcal{L}_{\text{eff}} = g_8 T'^{\dagger}_i M^i_j T^j + g_1\eta_1 T'^{\dagger}_i T^i$$

The physical states and ′ are admixtures of $_8$ and $_1$:

$$\eta = \eta_8\cos\theta - \eta_1\sin\theta$$
$$\eta' = \eta_8\sin\theta + \eta_1\cos\theta$$

with mixing angle = 20° [**?**].

For D_{sJ}:

$$\mathcal{L}_{D_{sJ}} = g_8\left\{\frac{1}{\sqrt{2}}D_{sJ}^+K^-\bar{D}^0 + \frac{1}{\sqrt{2}}D_{sJ}^+\bar{K}^0D^- + \frac{1}{\sqrt{6}}D_{sJ}^+\eta_8D_s^-\right\} + g_1D_{sJ}^+\eta_1D_s^-$$

$$= \frac{g_8}{\sqrt{2}} D_{sJ}^+ K^- \bar{D}^0 + \frac{g_8}{\sqrt{2}} D_{sJ}^+ \bar{K}^0 D^- + \left(\frac{g_8}{\sqrt{6}} \cos\theta + g_1 \sin\theta \right) D_{sJ}^+ \eta D_s^-$$

$$+ \left(-\frac{g_8}{\sqrt{6}} \sin\theta + g_1 \cos\theta \right) D_{sJ}^+ \eta' D_s^-$$

The Lagrangian involving D̄^{0}__J and D$^-$__J reads:

$$\mathcal{L}_{D_J} = g_8 \left\{ \frac{1}{\sqrt{2}} D_J^0 \pi^0 \bar{D}^0 + \frac{1}{\sqrt{2}} D_J^0 \pi^+ D^- + \frac{1}{\sqrt{2}} D_J^+ \pi^- \bar{D}^0 - D_J^+ \pi^0 D^- \right\}$$

$$+ \frac{g_8}{\sqrt{2}} D_J^0 K^+ D_s^- + \frac{g_8}{\sqrt{2}} D_J^+ K^0 D_s^- + \frac{g_8}{\sqrt{6}} (D_J^0 \eta_8 \bar{D}^0 + D_J^+ \eta_8 D^-)$$

$$= g_8 \left\{ \frac{1}{\sqrt{2}} D_J^0 \pi^0 \bar{D}^0 + \frac{1}{\sqrt{2}} D_J^0 \pi^+ D^- + \frac{1}{\sqrt{2}} D_J^+ \pi^- \bar{D}^0 - D_J^+ \pi^0 D^- \right\}$$

$$+ \frac{g_8}{\sqrt{2}} D_J^0 K^+ D_s^- + \frac{g_8}{\sqrt{2}} D_J^+ K^0 D_s^- + \frac{g_8}{\sqrt{6}} \cos\theta (D_J^0 \eta \bar{D}^0 + D_J^+ \eta D^-)$$

$$- \frac{g_8}{\sqrt{6}} \sin\theta (D_J^0 \eta' \bar{D}^0 + D_J^+ \eta' D^-)$$

From the relative decay ratio, we can extract either:

$$\left| \frac{g_1}{g_8} \right| = 16.2$$

or:

$$\left| \frac{g_1}{g_8} \right| = 0.62$$

With these values, we have the following relative branching ratios:

- For the ratio in Eq. (22): $\Gamma(D^0\pi^+) : \Gamma(D^+\pi^0) : \Gamma(D^+\bar{K}^0) : \Gamma(D^+\ ) = 1 : 0.5 : 0.07 : 6.6$
- For the ratio in Eq. (23): $\Gamma(D^0\pi^+) : \Gamma(D^+\pi^0) : \Gamma(D^+\bar{K}^0) : \Gamma(D^+\ ) = 1 : 0.5 : 0.07 : 2.4$

It is interesting to note that $_1$ mixes strongly with G$\tilde{G}$ because of the axial anomaly. The anomalously large coupling between $_1$ and D$^+${*sJ}(2632) may indicate that D*$^+${sJ}(2632) is a heavy hybrid meson containing explicit glue [**?**]. This is the subject of the next section.

V. Large N_c Limit and D^+_{sJ}(2632) as a Heavy Hybrid Meson

The large N_c formalism is a very useful and unique tool applicable across the entire energy regime from zero to infinity. In this section, we explore the possibility of D_s(2632) being a hybrid state containing explicit glue using large N_c expansion. Recall that the normalized interpolating currents for a pure glueball and a conventional meson A in the large N_c limit read:

$$\mathcal{O}_G = g_s^2 G^2$$
$$\mathcal{O}_A = \bar{q}_i \Gamma_A q_i$$

The factor 1/√N_c is introduced to ensure that the creation amplitude by O_A from the vacuum is O(N_c^0) in the large N_c limit. That is, the following matrix elements are order unity when N_c $\to \infty$:

$$\langle 0|\mathcal{O}_A(0)|\text{meson}\rangle \sim O(N_c^0)$$
$$\langle 0|\mathcal{O}_G(0)|\text{glueball}\rangle \sim O(N_c^0)$$

We have depicted q$\bar{q}$ mesons, $\bar{q}$Gq hybrid states, and glueballs in Fig. 1 [Figure 1: see original paper].

To illustrate the formalism, we consider the N_c order of the mixing amplitude between a glueball and a q$\bar{q}$ meson, which can be extracted through the correlation function:

$$\langle T\{\mathcal{O}_A(x)\mathcal{O}_G(y)\}\rangle$$

The Feynman diagram is presented in Fig. 2 [Figure 2: see original paper], along with the double-line representation in the large N_c approach. There are two independent closed color loops that contribute N_c^2, while two vertices contribute g_s^2. Its N_c order reads:

$$\langle T\{\mathcal{O}_A(x)\mathcal{O}_G(y)\}\rangle \sim \frac{N_c^2}{N_c} \sim N_c$$

In other words, glueballs decouple from conventional mesons when N_c $\to \infty$.

We consider two kinds of heavy hybrid mesons:

1. $$\mathcal{O}_{H1} = \bar{s}\gamma_\nu g_s G_{\mu\nu} c$$
   with J^P = 1^- and c$\bar{s}$ in the color octet state
2. $$\mathcal{O}_{H2} = \bar{s} i\gamma_5 c g_s^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$$
   with J^P = 0^+ and c$\bar{s}$ in the color singlet state

The normalized states are:

$$\langle \text{Vector Hybrid State } H_1|\mathcal{O}^{\mu}_{H1}(0)|0\rangle = F_{H1}\epsilon^{\mu}$$
$$\langle \text{Scalar Hybrid State } H_2|\mathcal{O}_{H2}(0)|0\rangle \sim O(N_c^0)$$

For the J^P = 1^- hybrid meson, its decay channels are shown in Fig. 3 [Figure 3: see original paper] using Feynman diagrams and double-line representation. The dominant decay mode in the large N_c limit is for the gluon to split into a color-octet q$\bar{q}$ pair in diagram (a) of Fig. 3. Then the q$\bar{q}$ pair recombines with the c$\bar{s}$ pair to form D^0K^+, D^+K^0, and D_s . The N_c order of this decay amplitude is O(N_c^0). When it decays into two q$\bar{q}$ mesons through color-singlet two-gluon intermediate states in diagram (b), the decay amplitude is O(1/N_c). When it decays into a glueball and a q$\bar{q}$ meson, the decay amplitude is O(1/N_c^2), i.e., diagram (c). In other words, assigning D_{sJ}(2632) as a J^P = 1^- hybrid meson does not lead to the abnormal decay pattern observed by the SELEX Collaboration.

Now we turn to the second case. With this configuration, it is possible to understand the narrowness of D_s(2632). When it decays into a glueball and D_s in diagram (b) of Fig. 4 [Figure 4: see original paper], the amplitude is O(N_c^0) in the large N_c limit. Hence, this would be the most probable decay channel if kinematics allowed. However, it cannot occur because the glueball is too heavy.

The decay mode D_s $_1$ in diagram (c) of Fig. 4 is O(1/N_c) and subleading. However, it is also forbidden by kinematics. Therefore, D_s(2632) is narrow. We note that the meson is a mixture of $_8$ and $_1$. The mixing amplitude is O(1/N_c) arising from SU(3) symmetry breaking effects. Hence, the kinematically allowed decay mode D_s becomes the dominant mode, although it is O(1/N_c) suppressed.

The DK channel can occur only when the color-singlet two gluons annihilate into a pair of light quarks, namely after the hybrid becomes a four-quark state. This hybrid-to-four-quark transition is 1/N_c suppressed in amplitude. The four-quark state can decay to both D_s and DK, and the latter channel is further suppressed compared to the former due to the color mismatch factor, which is 1/N_c in amplitude. The N_c order can be read from diagram (a) in Fig. 4:

$$\frac{\Gamma(D^{0K^{+)}}}{\Gamma(D_s\eta)} \sim \left(\frac{1}{N_c^3}\right)^2 \sim \frac{1}{N_c^6}$$

Naively, there are three closed color loops, so one would expect a factor N_c^3. However, the charm and strange quarks are in a color-singlet state, so their color indices are identical. In other words, there are only two independent color loops. Finally, we obtain:

$$\frac{\Gamma(D^{0K^{+})}}{\Gamma(D_s\eta)} \sim \left(\frac{1}{N_c^3}\right)^2 \sim \frac{1}{N_c^6}$$

where the numerical value arises from using N_c = 3. The assignment of D_{sJ}(2632) as a c̄s g_s^2 G$\tilde{G}$ state explains the decay pattern quite naturally. A dynamical calculation of the mass of such a heavy hybrid meson would be very desirable but is beyond the scope of this note.

VI. Discussions

In this note, we have considered various possible interpretations of D$^+$_{sJ}(2632) and discussed the resulting phenomenology. Future experimental confirmation of this state and discovery of its partners will help unveil the mysterious underlying dynamics of this narrow charm-strange meson.

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Note: Figure translations are in progress. See original paper for figures.