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$D_{s0}^+(2317)$ as an iso-triplet four-quark meson

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Abstract. Although assigning $D_{s0}^+(2317)$ to the $I_3 = 0$ component $\hat{F}_I^+$ of iso-triplet four-quark mesons is favored by experiments, its neutral and doubly charged partners have not yet been observed. It is discussed why they were not observed in inclusive $e^+e^- \to c\bar{c}$ experiment and that they can be observed in B decays.

PACS. 14.40.Lb Charmed mesons

The charm-strange scalar meson $D_{s0}^+(2317)$ has been observed in inclusive e^+e^- annihilation [1,2]. It is very narrow ($\Gamma < 3.8\,\mathrm{MeV}$ [3]) and it decays dominantly into $D_s^+\pi^0$ while no signal of $D_s^{*+}\gamma$ decay has been observed. Therefore, the CLEO provided a severe constraint [2],

$$R(D_{s0}^+(2317)) < 0.059, \qquad (1)$$

where $R(S) = \Gamma(S \to D_s^{*+}\gamma)/\Gamma(S \to D_s^+\pi^0)$ with $S = D_{s0}^+(2317)$. Similar resonances have been observed in B decays: $B \to \bar{D}\tilde{D}_{s0}^+(2317)[D_s\pi^0, D_s^{*+}\gamma]$ [4], $B \to \bar{D}(\text{or } \bar{D}^*)$ $\tilde{D}_{s0}^+(2317)[D_s\pi^0]$ [5]. Here the new resonances have been denoted by $\tilde{D}_{s0}^+(2317)$ (observed channel(s)) to distinguish them from the above $D_{s0}^+(2317)$. It is because the resonance signals have been observed in the $D_s^{*+}\gamma$ channel in addition to the $D_s^+\pi^0$ [4]. It is quite different from the previous $D_{s0}^+(2317)$.

As will be seen later, assigning $D_{s0}^+(2317)$ to the $I_3 = 0$ component $\hat{F}_I^+$ [6] of scalar $\hat{F}_I \sim [cn][\bar{s}\bar{n}]_{I=1}$, ($n = u, d$), is favored by eq. (1). In this case, its narrow width can be realized by a small overlap between wave functions of the initial and final states of its dominant decay $\hat{F}_I^+ \to D_s^+\pi^0$. Such a small overlap can be seen by decomposing a scalar $|[qq][\bar{q}\bar{q}]\rangle$ with $\mathbf{1}_s \times \mathbf{1}_s$ of spin $SU(2)$ and $\bar{\mathbf{3}}_c \times \mathbf{3}_c$ of color $SU_c(3)$ into a sum of $|\{q\bar{q}\}\{q\bar{q}\}\rangle$ states:

$$\begin{aligned}|[qq]^{\mathbf{1}_s}_{\bar{\mathbf{3}}_c}[\bar{q}\bar{q}]^{\mathbf{1}_s}_{\mathbf{3}_c}\rangle^{\mathbf{1}_s}_{\mathbf{1}_c} &= -\sqrt{1/4}\sqrt{1/3}|\{q\bar{q}\}^{\mathbf{1}_s}_{\mathbf{1}_c}\{q\bar{q}\}\}^{\mathbf{1}_s}_{\mathbf{1}_c}\rangle^{\mathbf{1}_s}_{\mathbf{1}_c}\\ &\quad+\sqrt{3/4}\sqrt{1/3}|\{q\bar{q}\}^{\mathbf{3}_s}_{\mathbf{1}_c}\{q\bar{q}\}\}^{\mathbf{3}_s}_{\mathbf{1}_c}\rangle^{\mathbf{1}_s}_{\mathbf{1}_c} + \cdots\,, \qquad (2)\end{aligned}$$

where the above state is the lowest-lying four-quark state. However, another possible $\mathbf{6}_c \times \bar{\mathbf{6}}_c$ state has been ignored because it is much heavier [7]. The color and spin wave function overlap between $|\hat{F}_I^+\rangle$ and $\langle D_s^+\pi^0|$ is given by the first term of the right-hand side of eq. (2). To see its narrow width more explicitly, it might be better to calculate directly its rate. However, it is difficult because no one knows spatial wave functions of particles included. Therefore, we estimate the rate for $\hat{F}_I^+ \to D_s^+\pi^0$ by comparing it with $\hat{\delta}^{s+} \to \eta\pi^+$. To this aim, we assign the observed $a_0(980)$, $f_0(980)$, $\kappa(800)$ and $f_0(600)$ [8] to scalar $[qq][\bar{q}\bar{q}]$ mesons, $\hat{\delta}^s$, $\hat{\sigma}^s$, $\hat{\kappa}$ and $\hat{\sigma}$ [7], although their assignment is still in controversy. However, the above overlap can be quite different from that of $\langle\eta\pi^+|$ and $|\hat{\delta}^{s+}\rangle$ at the scale of $m_{\hat{\delta}^s} \sim 1\,\mathrm{GeV}$, because a gluon exchange between $\{q\bar{q}\}$ pairs will reshuffle the above decomposition (while such a reshuffling will be rare at the 2 GeV or a higher energy scale, because it is known that the s-quark at the 2 GeV scale is much more slim ($m_s \simeq 90\,\mathrm{MeV}$) [9] than the s-quark in the constituent quark model, *i.e.*, the quark-gluon coupling at 2 GeV scale is much weaker than that at 1 GeV scale). With this in mind, we introduce a parameter β_0 describing the difference between overlaps of color and spin wave functions at the scale of $m_{\hat{\delta}^s}$ and at the scale of $m_{\hat{F}_I^+}$. In the limiting case of full reshuffling around 1 GeV but no reshuffling at the scale of $m_{\hat{F}_I}$, we have $|\beta_0|^2 = 1/12$ as seen in eq. (2). By using a hard-pion technique and the asymptotic $SU_f(4)$ symmetry, which have been reviewed comprehensively in ref. [10], we have

$$\Gamma(\hat{F}_I^+ \to D_s^+\pi^0)_{SU_f(4)} \simeq 5\text{–}10\,\mathrm{MeV}, \qquad (3)$$

where the spatial wave function overlap is in the $SU_f(4)$ symmetry limit at this stage. Here, we have used $\Gamma(a_0(980) \to \eta\pi)_{\mathrm{exp}} = 50\text{–}100\,\mathrm{MeV}$ and the η-η' mixing angle $\theta_P \simeq -20^\circ$ [8] as the input data. Noting that the above $SU_f(4)$ symmetry overestimates by 20–30% the amplitude, we have $\Gamma(\hat{F}_I^+) \simeq \Gamma(\hat{F}_I^+ \to D_s^+\pi^0) \sim 3.5\text{–}7\,\mathrm{MeV}$ [11], which is sufficiently narrow.

Next, we study the radiative decay of $D_{s0}^+(2317)$ to see that its assignment to $\hat{F}_I^+$ is consistent with eq. (1).

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Table 1. Rates for radiative decays of charm-strange mesons under the VMD, where the spatial wave function overlap is in the $SU_f(4)$ symmetry. The input data are taken from ref. [8].

Decay	Pole(s)	Input data	Rate (keV)
$D_s^{*+} \to D_s^+\gamma$	ϕ, ψ	$\Gamma(\omega \to \pi^0\gamma)_{\rm exp}$	0.8
$\hat{F}_I^+ \to D_s^{*+}\gamma$	ρ^0	$\Gamma(\phi \to a_0\gamma)_{\rm exp}$	45
$\hat{F}_0^+ \to D_s^{*+}\gamma$	ω	$\Gamma(\phi \to a_0\gamma)_{\rm exp}$	4.7
$D_{s0}^{*+} \to D_s^{*+}\gamma$	ϕ, ψ	$\Gamma(\chi_{c0} \to \psi\gamma)_{\rm exp}$	35

Table 2. Rates for isospin non-conserving decays, where the spatial wavefunction overlap is in the $SU_f(4)$ symmetry. Input data are taken from ref. [8].

Decay	Input data	Rate (keV)
$D_s^{*+} \to D_s^+\pi^0$	$\Gamma(\rho \to \pi\pi)_{\rm exp}$	0.05
$\hat{F}_0^+ \to D_s^+\pi^0$	$\Gamma(a_0 \to \eta\pi) \simeq 70\,\mathrm{MeV}$	0.7
$D_{s0}^{*+} \to D_s^+\pi^0$	$\Gamma(K_0^{*0} \to K^+\pi^-)_{\rm exp}$	0.6

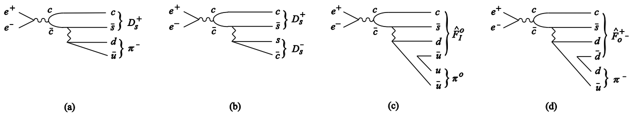

Fig. 1. Production of charm-strange scalar four-quark mesons through $e^+e^- \to c\bar{c}$. (a) and (b) describe the productions $D_s^+\pi^-$, $D_s^{*+}\pi^-$, etc., and $D_s^+D_s^-$, $D_s^{*+}D_s^-$, etc., respectively. The production of $\hat{F}_I^0$, $\hat{F}_I^+$ and $\hat{F}_0^+$ is given by (c) and (d).

For later convenience, we study the typical three cases, $D_{s0}^+(2317)$ as i) the iso-triplet $\hat{F}_I^+$, ii) the iso-singlet $\hat{F}_0^+ \sim [cn][\bar{s}\bar{n}]_{I=0}$ and iii) the conventional scalar $D_{s0}^{*+} \sim \{c\bar{s}\}$, under the vector meson dominance (VMD) hypothesis. To test our approach, we study $D_s^{*+} \to D_s^+\gamma$ in the same way. Here, we take VVP and SVV couplings with spatial wave function overlap in the $SU_f(4)$ symmetry limit, where V, P and S denote a vector, a pseudoscalar and a scalar meson, respectively, and take the overlapping factor $|\beta_1|^2 = 1/4$ between wave functions of a scalar four-quark and two vector-meson states, as seen in eq. (2). The results are listed in table 1, where the input data are taken from ref. [8]. Comparing the rate for $\hat{F}_I^+ \to D_s^{*+}\gamma$ in table 1 with eq. (3), we obtain $R(\hat{F}_I^+) \sim (4.5\text{–}9)\times 10^{-3}$ [11], which is consistent with the constraint eq. (1). It implies that assigning $D_{s0}^+(2317)$ to $\hat{F}_I^+$ is favored by experiments.

In the cases of the above assignments ii) and iii), $D_{s0}^+(2317) \to D_s^+\pi^0$ is isospin non-conserving. The isospin non-conservation is assumed to be caused by the η-π^0 mixing as usual. The mixing parameter ϵ has been estimated [12] as $\epsilon = 0.0105 \pm 0.0013$, *i.e.*, $\epsilon \sim O(\alpha)$ with the fine-structure constant α. It implies that isospin non-conserving decays are much weaker than the radiative ones. By using the hard-pion approximation, the asymptotic $SU_f(4)$ symmetry and the above value of ϵ, the rates for the isospin non-conserving decays can be obtained as listed in table 2. The results on the decays of D_s^{*+} in tables 1 and 2 lead to the ratio of decay rates $R(D_s^{*+})^{-1} \simeq 0.06$. This reproduces well the experimental value [13] $R(D_s^{*+})^{-1}_{\rm BABAR} = 0.062 \pm 0.005 \pm 0.006$. This means that the present approach is sufficiently reliable. The corresponding ratios of the decay rates in the cases ii) and iii) are also obtained as ii) $R(\hat{F}_0^+) \simeq 7$ and iii) $R(D_{s0}^{*+}) \simeq 60$. They are much larger than the experimental upper bound. It should be noted that the isospin non-conserving decays are much weaker than the radiative decays, as expected intuitively above. The assignment of $D_{s0}^+(2317)$ to the iso-singlet DK molecule [14] leads to $R(\{DK\}) \simeq 3$ which is much larger than the experimental upper bound in eq. (1). Hence, such an assignment should be rejected [15]. Thus, assigning $D_{s0}^+(2317)$ to an iso-singlet state ($\hat{F}_0^+$, D_{s0}^{*+} or DK molecule) is disfavored by experiments.

From the above considerations, it is natural to assign $D_{s0}^+(2317)$ to the iso-triplet $\hat{F}_I^+$. However, its neutral and doubly charged partners, $\hat{F}_I^{++}$ and $\hat{F}_I^0$, have not yet been observed [3]. With this in mind, we study the production of charm-strange scalar mesons ($\hat{F}_I^{++,+,0}$ and $\hat{F}_0^+$) by assigning $D_{s0}^+(2317)$ to $\hat{F}_I^+$, and discuss why experiments have observed $D_{s0}^+(2317)$ but not its neutral and doubly charged partners. To this aim, we consider their production through weak interactions as a possible mechanism, because the OZI-rule violating productions of multi-$q\bar{q}$-pairs and their recombinations into four-quark meson states are believed to be strongly suppressed at high energies. First, we recall that color-mismatched decays which include rearrangements of colors in weak-decay processes would be suppressed compared with color favored ones as long as non-factorizable contributions, which are actually small in B decays and are expected to be much smaller at higher energies, are ignored. Next, we draw quark-line diagrams within the minimal $q\bar{q}$-pair creation, noting the OZI rule. Because there is no diagram yielding $\hat{F}_I^{++}$ production in this approximation, as seen in fig. 1, it is easy to understand why no evidence of $\hat{F}_I^{++}$ was found in $e^+e^- \to c\bar{c}$ experiments. As will be seen in productions of $\tilde{D}_{s0}^+(2317)[D_s^+\pi^0]$ in the B decays, their observed rates are comparable with color-mismatched decays, so that rates for $\hat{F}_I^0$ and $\hat{F}_0^+$ productions in $e^+e^- \to c\bar{c}$ annihilation will be expected to be comparable with those through the color-suppressed ones. Therefore, they would be much weaker (possibly by about two orders of magnitude) than productions of $D_s^+\pi^-$, $D_s^{*+}\pi^-$, $D_s^{*+}\rho^-$, etc., and $D_s^+D_s^-$, $D_s^{*+}D_s^-$, $D_s^{*+}D_s^{*-}$, etc., created through the reaction depicted by figs. 1(a) and (b). The $D_s^+\pi^-$ produced through fig. 1(a) obscures the signal $\hat{F}_I^0 \to D_s^+\pi^-$ events. In addition, the D_s^{*+} and γ from $D_s^{*-} \to D_s^-\gamma$ produced through the ordinary $e^+e^- \to c\bar{c} \to D_s^{*+}D_s^{*-}$ (and through fig. 1 (b)) obscure the signal of $\hat{F}_0^+ \to D_s^{*+}\gamma$ events. Therefore, it is understood why the inclusive e^+e^- annihilation experiment found no signal of scalar resonance in the $D_s^+\pi^-$ and $D_s^{*+}\gamma$ channels. In the case of

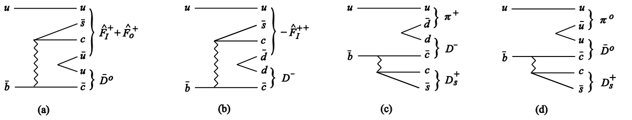

Fig. 2. Production of charm-strange scalar mesons in the B_u^+ decays. (c) and (d) describe the production of backgrounds of $\hat{F}_I^{++}$ and $\hat{F}_I^+$ signals, respectively.

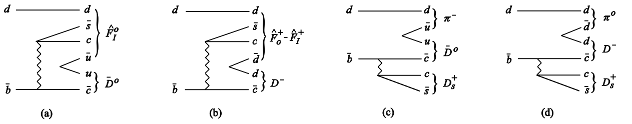

Fig. 3. Production of $\hat{F}_I^+$, $\hat{F}_0^+$ and $\hat{F}_I^0$ in the B_d^0 decays. (c) and (d) depict the production of backgrounds of $\hat{F}_I^0$ and $\hat{F}_I^+$.

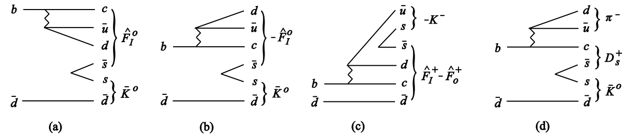

Fig. 4. Production of $\hat{F}_I^+$, $\hat{F}_I^0$ and $\hat{F}_0^+$ in the decays of $\bar{B}_d^0$. (d) describes the production of backgrounds of the $\hat{F}_I^0$ signal.

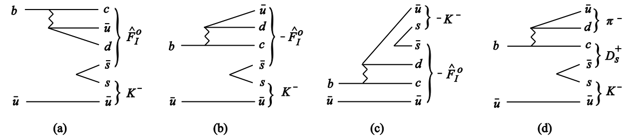

Fig. 5. Production of $\hat{F}_I^0$ in the $\bar{B}_u^-$ decays. (d) describes the production of backgrounds of its signals.

$\hat{F}_I^+$, however, there do not exist large numbers of background events described by figs. 1(a) and (b), because its main decay is $\hat{F}_I^+ \to D_s^+\pi^0$. In fact, $D_{s0}^+(2317)$ has been observed in the $D_s^+\pi^0$ channel. This seems to imply that the production of four-quark mesons in hadronic weak decays plays an essential role [16].

Because it is difficult to observe $\hat{F}_I^{++}$ and $\hat{F}_I^0$ in inclusive $e^+e^- \to c\bar{c}$ experiments, we study their productions in B decays. First, we draw quark-line diagrams in the same way as the above. As expected in figs. 2(a) and 3(b), $\tilde{D}_{s0}^+(2317)[D_s^+\pi^0]$, which can be identified to $\hat{F}_I^+$ because it decays dominantly into $D_s^+\pi^0$ as seen above, has been observed. The production of $\hat{F}_I^{++}$ is given by fig. 2(b) which is of the same type as fig. 2(a). In addition, the production of $\hat{F}_I^0$ is given by fig. 3(a) which is again of the same type as figs. 2(a) and (b), so that their production rates are not very different from each other; $B(B_u^+ \to \hat{F}_I^{++}D^-) \sim B(B_d^+ \to \hat{F}_I^0\bar{D}^0) \sim B(B_u^+ \to \hat{F}_I^+\bar{D}^0)$, where $B(B_u^+ \to \hat{F}_I^+\bar{D}^0)_{\text{exp}} \sim 10^{-3}$ [4, 5]. Besides, BELLE Collaboration observed indications of $\tilde{D}_{s0}^+(2317)[D_s^{*+}\gamma]$ which are conjectured to be signals of $\hat{F}_0^+ \to D_s^{*+}\gamma$ because the production of $\hat{F}_0^+$ and $\hat{F}_I^+$ are depicted by the same diagrams and the $\hat{F}_I^+ \to D_s^{*+}\gamma$ is much weaker than the $\hat{F}_I^+ \to D_s^+\pi^0$ while the $\hat{F}_0^+ \to D_s^{*+}\gamma$ is much stronger than the $\hat{F}_0^+ \to D_s^+\pi^0$, as seen before. As expected in fig. 4(c), BELLE Collaboration [17] observed $\bar{B}_d \to \tilde{D}_{s0}^+(2317)[D_s^+\pi^0]K^-$, and provided $B(\bar{B}_d \to \tilde{D}_{s0}^+(2317)K^-)\cdot B(\tilde{D}_{s0}^+(2317) \to D_s^+\pi^0) = (5.3^{+1.5}_{-1.3} \pm 0.7 \pm 1.4)\times 10^{-5}$. If $\tilde{D}_{s0}^+(2317)[D_s^+\pi^0]$ is identified to $\hat{F}_I^+$ and $B(\tilde{D}_{s0}^+(2317) \to D_s^+\pi^0) \simeq 100\,\%$ is taken, $B(\bar{B}_d^0 \to \hat{F}_I^+K^-) \sim 10^{-5}$–$10^{-4}$ would be obtained. Using it as the input data and noting that figs. 4(c) and 5(c) are of the same type, we could estimate $B(B_u^- \to K^-\hat{F}_I^0) \sim 10^{-5}$–$10^{-4}$, if contributions from the diagrams of figs. 5(a) and (b) cancel each other (because the phases of $\hat{F}_I^0$ in these diagrams have opposite signs arising from the antisymmetry property of its wave function).

In summary, we have seen that assigning $D_{s0}^+(2317)$ to an iso-triplet $\hat{F}_I^+$ is favored by experiments. In addition, we have discussed why inclusive $e^+e^- \to c\bar{c}$ experiments observed no evidence for its neutral and doubly charged partners $\hat{F}_I^0$ and $\hat{F}_I^{++}$. $\tilde{D}_{s0}^+(2317)[D_s^+\pi^0]$ which was observed in B decays has been identified to $D_{s0}^+(2317)$. Indications of $\hat{F}_0^+$ have also been observed as $\tilde{D}_{s0}^+(2317)[D_s^{*+}\gamma]$ in B decays. $\hat{F}_I^0$ and $\hat{F}_I^{++}$ will be observed in B decays.

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