Search of D_{sJ}^* mesons in B meson decays

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Introduction

Observation of D^*_{sJ}

- BaBar observed a narrow state with $J^P = 0^+$, denoted by $D^*_{sJ}(2317)$, in the $D_s^+\pi^0$ channel (April 12).

- The mass splitting $m(D_s\pi^0) - m(D_s) = 350.4 \pm 1.6$ MeV. The width $\Gamma < 10$ MeV is narrow, as $D_s(2317) \to D_s\pi^0$ is isospin-violated.

- The observation has been confirmed by CLEO (May 13) and Belle (May 20). Another new state $D^*_{sJ}(2463)$ with $J^P = 1^+$ was found in the $D_s^{*+}\pi^0$ channel.

- BaBar saw a peak in $D_s\pi^0\gamma$ spectrum at 2.46 GeV but didn't claim it as an evidence for a new state.

- The mass splitting $m(D_s^*\pi^0) - m(D_s^*) = 351.6 \pm 2.0$ MeV. The width is narrow, as $D^*_{sJ}(2463) \to D_s^*\pi^0$ is isospin-violated.

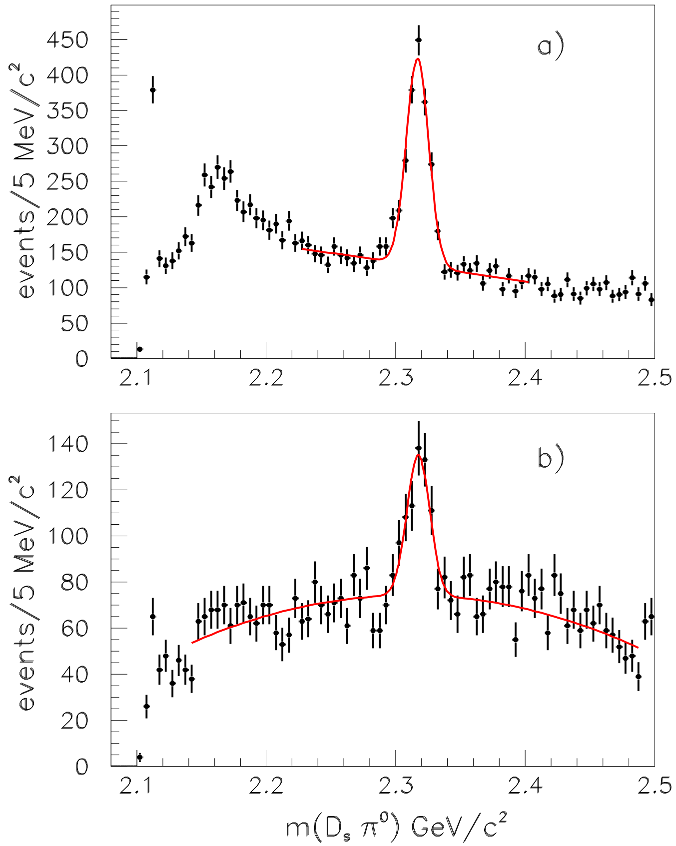

Figure 1: Event number in the $D_s^+\pi^0$ channel through (a) $D_s^+ \to K^+K^-\pi^+$ and (b) $D_s^+ \to K^+K^-\pi^+\pi^0$.

✦ Why D_{sJ}^{*} Interesting?

• Potential model predictions for the mass (in GeV) of $c\bar{s}(0^+)$ state: 2.38 (1995), 2.39 (1995), 2.46 (2000), 2.48 (1991), 2.49 (2001), 2.51 (1998) and width of order 150-300 MeV.

• Lattice (2000): $2499 \pm 13 \pm 5$ MeV (Lewis, Woloshyn).

BaBar: $m(D_s(0^+)) = 2317$ MeV and $\Gamma < 10$ MeV

• Two possibilities:

Theoretical models need modification: including meson-meson scattering, $\cdots$

The new mesons are unconventional bound states: a molecule, a 4-quark state, $\cdots$

Godfrey: "Although it is possible that these models need revision, it seems unlikely that they would disagree with experiment to such a large degree given their success in describing the meson spectrum."

• Many theoretical studies have been made recently.

References

[1] R.N. Cahn and J.D. Jackson, hep-ph/0305012: potential model.

[2] T. Barnes, F.E. Close and H.J. Lipkin, hep-ph/0305025: DK molecule.

[3] E. van Beveren and G. Rupp, hep-ph/0305035: 2-quark.

[4] H.Y. Cheng and W.S. Hou, hep-ph/0305038: 4-quark.

[5] W.A. Bardeen, E.J. Eichten and C.T. Hill, hep-ph/0305049: HQET.

[6] A.P. Szczepaniak, hep-ph/0305060: $D_s\pi$ molecule.

[7] S. Godfrey, hep-ph/0305122: discrimination using D^*_{sJ} radiative decays.

[8] P. Colangelo and F. De Fazio, hep-ph/0305140: same as above.

[9] G.S. Bali, hep-ph/0305209: lattice.

[10] K. Terasaki, hep-ph/0305213: 4-quark.

[11] S. Nussinov, hep-ph/0306187: discrimination using $D\bar{D}$ bound state.

[12] H.J. Lipkin, hep-ph/0306204: against 4-quark.

[13] Y.B. Dai *et al.*, hep-ph/0306274: sum rules.

[14] T. Browder, S. Pakvasa, and A.A. Petrov, hep-ph/0307054: mixed state.

[15] C.H. Chen and H-n. Li, hep-ph/0307075: discrimination using B decays.

[16] Deandrea, hep-ph/0307069: quark-meson model.

[17] Sadzikowski, hep-ph/0307084: bag model.

[18] M.A. Nowak, M. Rho, and I. Zahed, hep-ph/0307102: HQET.

[19] A. Datta and P.J. O'Donnell, hep-ph/0307106: discrimination using B decays.
[20] M. Suzuki, hep-ph/0307118: discrimination using e^+e^- annihilation.

It is not an exhaustive list...

Nature of D_{sJ}^* Meson

- Potential Models
  - The potential between a heavy quark and a light quark,

$$\begin{aligned} \mathcal{V}(r) &= V^{\rm conf} + V^{\rm spin-spin} + V^{\rm spin-orbit} + V^{\rm tensor} \\ V^{\rm conf} &= V + S = a/r + br \\ &= \text{Coulomb potential} + \text{confining potential} \end{aligned}$$

The perturbative terms depend only on V and S.

  - Mass operator for the splittings,

$$\begin{aligned} M &= \lambda \ell \cdot \mathbf{s}_q + 4\tau \ell \cdot \mathbf{s}_Q + \tau T_{12} \\ T_{12} &= 3\sigma_{\mathbf{1}} \cdot \hat{\mathbf{r}}\, \sigma_{\mathbf{2}} \cdot \hat{\mathbf{r}} - \vec{\sigma}_{\mathbf{1}} \cdot \vec{\sigma}_{\mathbf{2}} \end{aligned}$$

  - Two parameters require two inputs.

Cahn, Jackson: For given two mass splittings among three of four states, say $\Delta_2 = M_{2^+} - M_{0^+}$ and $\Delta_1 = M_{1^+} - M_{0^+}$, one has two solutions for τ and λ:

$$\begin{aligned} \tau &= \frac{10}{87}\Delta_2 - \frac{2}{29}\Delta_1 \pm \sqrt{\left(\frac{10}{87}\Delta_2 - \frac{2}{29}\Delta_1\right)^2 + \frac{5}{232}(\Delta_1^2 - \Delta_1\Delta_2)} \\ \lambda &= \frac{2}{3}\Delta_2 - \frac{32}{5}\tau \end{aligned}$$

- Masses (numbers in blue are inputs, numbers in red are predictions)

D Meson (DE=De Pierro, Eichten; GK=Godfrey, Kokoski; CJ=Cahn, Jackson)

State	Expt (MeV)	DE	GK	CJ(A)	CJ(B)
$0^+(^3P_0)$	2290 ± 30(Belle)	2377	2400	2290	2290
$1^+(\approx\ ^1P_1)$	2400 ± 36(Belle)	2490	2470	2400	2385
$1'^+(\approx\ ^3P_1)$	2422(PDG)	2417	2460	2422	2422
$2^+(^3P_2)$	2459(PDG)	2460	2500	2459	2459
$\lambda(\mathrm{MeV})$		-11		39	54
$\tau(\mathrm{MeV})$		11		11	9
θ			$26°$	$48°$	$14°$

D_s Meson

State	Expt (MeV)	DE	GK	CJ(A)	CJ(B)
$0^+(^3P_0)$	2317(BaBar,CLEO)	2487	2480	2317	2317
$1^+(\approx\ ^1P_1)$	2463(BaBar,CLEO)	2605	2560	2480	2408
$1'^+(\approx\ ^3P_1)$	2535(PDG)	2535	2550	2536	2536
$2^+(^3P_2)$	2572(PDG)	2581	2590	2572	2572
$\lambda(\mathrm{MeV})$		-7		43	115
$\tau(\mathrm{MeV})$		11		20	9
θ			$38°$	$69°$	$4°$

Widths

State	Notation	Expt (MeV)	DE	GK	CJ(s-wave)	CJ(d-wave)
$0^+(^3P_0)$	$D_0(2290)$	305 ± 39	127	290	100	
1^+	$D_1(2400)$	380 ± 141	122	250	100	
$1'^+$	$D_1(2422)$	$18.9^{+4.6}_{-3.5}$	11	26	90	10
$2^+(^3P_2)$	$D_2(2459)$	23 ± 5	26	63		25

State	Notation	Expt (MeV)	DE	GK	CJ(s-wave)	CJ(d-wave)
$0^+(^3P_0)$	$D_{s0}(2317)$	< 7	159	310		
1^+	$D_{s1}(2463)$	< 7	151	140		
$1'^+$	$D_{s1}(2535)$	< 2.3	1.5	0.36	100	0.3
$2^+(^3P_2)$	$D_{s2}(2572)$	15^{+5}_{-4}	7	21		10

- $1'^+$ widths prefer nearly pure d-wave decays

$\Rightarrow$ a small mixing angle θ

$\Rightarrow$ solution B.

• $\langle 2\ell \cdot s_q \rangle = j(j+1) - \ell(\ell+1) - 3/4 \Rightarrow \langle 2\ell \cdot s_q \rangle_{1^+(j=1/2)} < \langle 2\ell \cdot s_q \rangle_{1'^+(j=3/2)}$.
$\lambda < 0$ by Di Pierro, Eichten causes inversion: 1^+ is heavier than $1'^+$.

• $\lambda < 0$ means stronger confining potential S. Cahn, Jackson: mass hierarchy of 1^+ and $1'^+ \Rightarrow \lambda > 0$.

• Solution A works spectroscopy, but does not work for decay widths.

• Solution B is OK for describing widths, but cannot accommodate D_s spectrum.

$\Rightarrow$ The conventional potential model has the difficulty to account for the mass spectrum and widths of the D_s system simultaneously.

• Either the assumption of Coulomb potential for V and/or linear potential for S may need modification, or $D_s(2317)$ and $D_s(2463)$ are not 2-quark bound states.

Lattice and Sum Rules

- Bali performed lattice calculations in static limit in quenched approximation with $n_f = 2$.
0^+-0^- mass splitting$=468 \pm 43 \pm 24$ MeV is larger than observed value 350 MeV.

- The above result is consistent with the sum-rule analysis by Y.B. dai *et al.*.
$\Rightarrow$ support the non $q\bar{q}'$ interpretation of D^*_{sJ}.

Molecule

- Also a hint from light mesons:
It has been advocated that $f_0(980)$ and $a_0(980)$ can be regarded as $K\bar{K}$ molecule with binding energy ≈ 20 MeV (Weinstein, Isgur 83).

- Barnes, Close, Lipkin: If scalar D_s state is a DK molecule with binding energy ≈ 40 MeV, its mass $\sim m(DK) - 40$ MeV $\sim (2360 - 40)$ MeV.

- van Beveren, Rupp include the coupling of $D_s(2317)$ to S-wave DK channel in their unitarized quark model $\Rightarrow$ conventional $c\bar{s}$ scalar meson at 2.79 GeV.

- Szczepaniak: $D_s(2317)$ produced as a strong flavor-singlet attraction between π and D_s $\Rightarrow$ conventional $c\bar{s}$ scalar meson at 2.48 GeV with width 17-42 MeV.

❖ 4-quark state

• A hint from the light mesons:

In the 4-quark picture, the scalar 4-quark nonet formed by $\sigma(500)$, $\kappa(800)$, $f_0(980)$ and $a_0(980)$ is much lighter than the conventional $q\bar{q}$ nonet composed of $f_0(1370)$, $a_0(1450)$, $K_0^*(1430)$ and $f_0(1500)/f_0(1710)$ due to (Cheng 03)
(i) a strong attraction between $(qq)_{\mathbf{3}^*}$ and $(\bar{q}\bar{q})_{\mathbf{3}}$
(ii) absence of the orbital angular momentum barrier in the S-wave 4-quark state.

$$\Rightarrow D_{s0}(c\bar{n}n\bar{s}) \text{ is lighter than } D_{s0}(c\bar{s}) \text{ !}$$

• $D_s(2317)$ is identified with $\tilde{D}_{0s}^{+} = c(n\bar{n})_{+}\bar{s}$ by Cheng, Hou, while it is assigned to the isotriplet $\tilde{D}_{Is}^{+} = c(n\bar{n})_{-}\bar{s}$ by Terasaki, $(n\bar{n})_{\pm} = (u\bar{u} \pm d\bar{d})/\sqrt{2}$.

• Browder, S. Pakvasa, and A.A. Petrov proposed that $D_s(2317)$ is a mixing of the conventional P-wave state and the four-quark state.

• Lipkin argued that the charm-strange, and even bottom-strange, four-quark states could not be bound.

• The existence of a new $I = 0$ "$D\bar{D}$ bound state" with a mass less than 3660 MeV would support the four-quark picture (Nussinov 03)— an analogy of $m_{D_s(2317)} < m_{DK}$.

Quark-antiquark vs. Multi-quark

Experimental Discrimination

- Considering the above series of claims and counter claims (most of them are theoretical speculations), it is better to look for an experimental discrimination.

- Whether the D^*_{sJ} meson radiative transition is consistent with the branching ratios of the conventional D^*_{s0} and D_{s1} mesons serves the purpose (Godfrey 03; Colangelo and De Fazio 03).

- We propose that the search of the $B \to D^*_{sJ} M$ decays, $M = D$, π and K, can discriminate the quark-antiquark and multi-quark pictures for the D^*_{sJ} content.

- The ratio of the branching ratios

$$\frac{B(B \to D^*_{sJ} M)}{B(B \to D_s^{(*)} M)} \approx 1(0.1) \; ,$$

supports that the D^*_{sJ} mesons are quark-antiquark (multi-quark) bound states.

- The $B_d(P_1) \to D^{*+}_{sJ}(P_2)\pi^-(P_3)$ decay occurs through the effective Hamiltonian,

$$H_{\rm eff} = \frac{G_F}{\sqrt{2}} V_{ub} V^*_{cs} \left[C_1(\mu) \mathcal{O}_1(\mu) + C_2(\mu) \mathcal{O}_2(\mu) \right] \; ,$$

$$\mathcal{O}_1 = (\bar{s}_i c_j)(\bar{u}_j b_i) \; , \quad \mathcal{O}_2 = (\bar{s}_i c_i)(\bar{u}_j b_j)$$

❖ 2-quark state

• In the 2-quark case the $B \to D_{sJ}^* \pi$ branching ratios are expected to be of the same order of magnitude as the $B \to D_s^{(*)} \pi$ ones.

• The color-allowed amplitude in the factorization assumption (FA),

$$A = i\,\frac{G_F}{\sqrt{2}}\,V_{ub}^* V_{cs}\,(m_B^2 - m_\pi^2)\,f_{D_{sJ}^*}\,F_0^{B\pi}(m_{D_{sJ}^*}^2)\,a_1\ ,$$

$a_1 = C_2 + C_1/N_c$, $f_{D_{sJ}^*} \approx f_{D_s^{(*)}} \approx 240$ MeV as required by heavy quark symmetry.

• Employing $F_0^{B\pi}(m_{D_{sJ}^*}^2) = 0.33$ (Ball 98; Khodjamirian 00) and $a_1 = 1.1$ for a wide range of μ, we have

$$B(B_d \to D_{sJ}^{*+}\pi^-) = 3.0 \times 10^{-5}\ ,$$

close to the Belle and BaBar measurements,

$$B(B_d \to D_s^+ \pi^-) = (2.4^{+1.0}_{-0.8} \pm 0.7,\ 4.6^{+1.2}_{-1.1} \pm 1.3) \times 10^{-5}\ .$$

❖ 4-quark state

• In the 4-quark case the amplitudes contain additional hard scattering the four valence quarks of the D^*_{sJ} meson participate as shown in Figs. 2(a)-2(d).

• The amplitudes are suppressed by α_s, $1/N_c$ and by powers $(m_{D^*_{sJ}}/m_B)^2$.

• The exchanged gluon in Figs. 2(e) and 2(f), being of collinear origin, should be absorbed into the two-parton D^{*+}_{sJ} meson distribution amplitude.

• There are two color configurations,

$$\frac{1}{N_c^2} c^b \bar{s}^b n^c \bar{n}^c \ , \quad \frac{1}{12} f^{ab_1c_1} f^{ab_2c_2} c^{b_1} \bar{s}^{c_1} n^{b_2} \bar{n}^{c_2} \ ,$$

where both the $c\bar{s}$ and $n\bar{n}$ pairs are in the color 1 and color 8 states, respectively.

• The Wilson coefficient for Fig. 2(a) from 11 is largest. Figs. 2(b) and 2(c) are down by $C_1/a_1 \sim -0.2$. Fig. 2(d) is suppressed by $\Lambda_{\rm QCD}/m_{D^*_{sJ}} \sim 0.1$.

configuration	(a)	(b)	(c)	(d)
11	a_1/N_c	C_1/N_c	C_1/N_c	a_1/N_c
88	C_1/N_c	C_1/N_c	C_1/N_c	$C_1(1/N_c - 1)$

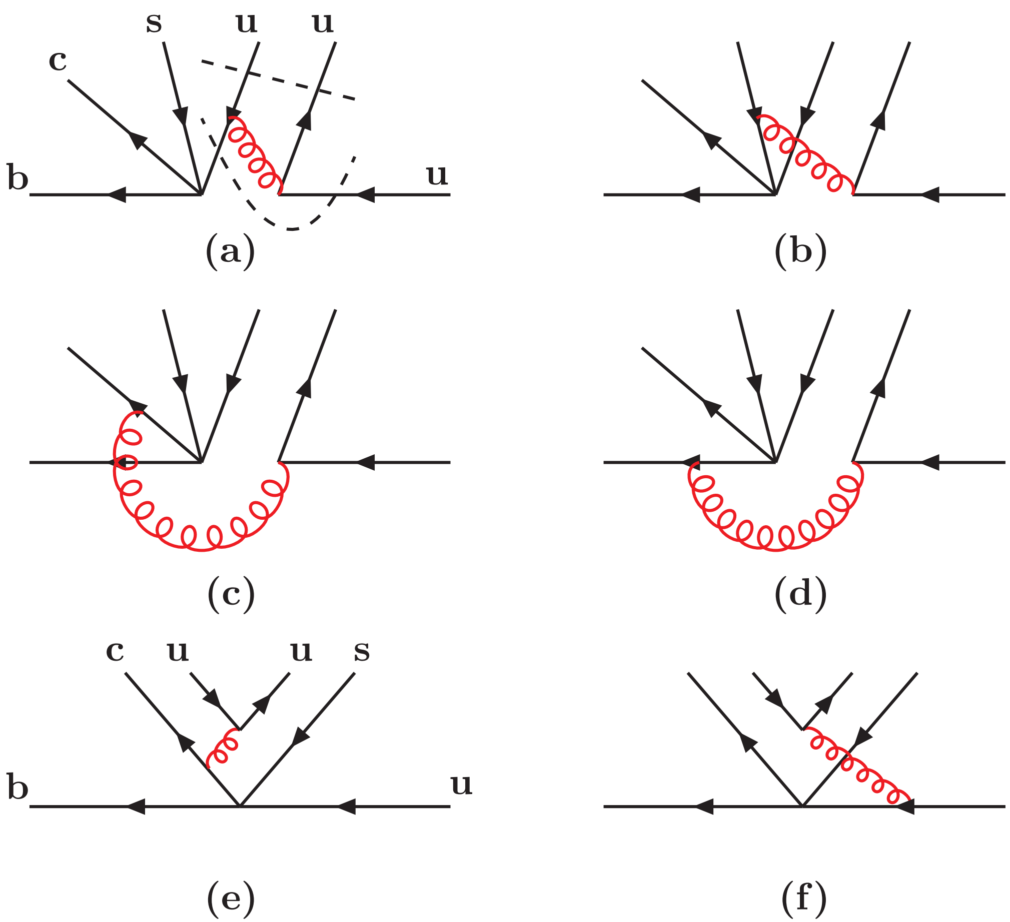

Figure 2: (a)-(d) Diagrams contributing to the $B_d \to D_{sJ}^{*+}\pi^-$ decay in the 4-quark picture for the D_{sJ}^* content. (e) and (f) Diagrams contributing in the 2-quark picture.

Factorization

- Insert the Fierz identity,

$$
\begin{aligned}
1_{ij}1_{lk} &= \frac{1}{8}(1-\gamma_5)_{ik}(1-\gamma_5)_{lj} + \frac{1}{8}(1+\gamma_5)_{ik}(1+\gamma_5)_{lj} \\
&+\frac{1}{8}[\gamma_\nu(1-\gamma_5)]_{ik}[(1-\gamma_5)\gamma^\nu]_{lj} \\
&+\frac{1}{8}[\gamma_\nu(1+\gamma_5)]_{ik}[(1+\gamma_5)\gamma^\nu]_{lj} + \frac{1}{8}(\sigma^{\nu\lambda})_{ik}(\sigma_{\nu\lambda})_{lj} \ ,
\end{aligned}
$$

into Fig. 2(a) to factorize the fermion flows.

- We derive the amplitude in FA,

$$
\begin{aligned}
A &= \frac{G_F}{\sqrt{2}} V_{ub}^* V_{cs} \langle D_{sJ}^{*+} | \bar{c}\gamma_\mu(1-\gamma_5)s\bar{u}\gamma_\nu(1-\gamma_5)u|0\rangle\langle\pi^-|\bar{b}\gamma^\mu(1-\gamma_5)u|B_d\rangle a_1 H^\nu \ , \\
H^\nu &= \frac{g^2}{32\sqrt{2}}\frac{C_F}{N_c}\frac{tr[(1-\gamma_5)\ \not{l}_u\gamma_\beta(1-\gamma_5)\gamma^\nu\gamma^\beta]}{l_u^2 l_g^2} \ .
\end{aligned}
$$

- l_u and l_g are the momenta carried by the internal u quark and gluon, respectively, whose components have the orders of magnitude,

$$
l_u \sim l_g \sim \frac{m_B}{\sqrt{2}}\left(\frac{\Lambda_{\rm QCD}}{m_{D_{sJ}^*}}, \frac{1}{2}, \mathbf{0}_T\right) \ .
$$

• The 4-quark matrix element,

$$\langle D_{sJ}^{*+}(P_2)|\bar{c}\gamma_\mu(1-\gamma_5)s\bar{u}\gamma_\nu(1-\gamma_5)u|0\rangle = i\frac{B}{m_{D_{sJ}^*}}P_{2\mu}P_{2\nu}f_{D_{sJ}^*} \; ,$$

$$B \approx \langle 0|\bar{u}(1-\gamma_5)u|0\rangle = \langle 0|\bar{u}u|0\rangle \approx -0.24 \;\; \mathrm{GeV}^3 \; .$$

• The decay amplitude becomes

$$A \;\; = \;\; i\frac{G_F}{\sqrt{2}}V_{ub}^*V_{cs}\,(m_B^2-m_\pi^2)\,f_{D_{sJ}^*}\,F_0^{B\pi}(m_{D_{sJ}^*}^2)\,a_1\,R \; ,$$

$$R \;\; = \;\; -\sqrt{2}\pi^2\left(\frac{\alpha_s}{\pi}\right)\frac{C_F}{N_c}\frac{B}{m_{D_{sJ}^*}\Lambda_{\mathrm{QCD}}^2}\left(\frac{m_{D_{sJ}^*}}{m_B}\right)^2 \approx 0.275 \; ,$$

for the inputs $\alpha_s/\pi = 0.2$ in $b \to c$ transitions and $\Lambda_{\mathrm{QCD}} \approx 0.3$ GeV.

• The $B_d \to D_{sJ}^{*+}\pi^-$ branching ratio in the 4-quark picture should be smaller than that in the 2-quark one by a suppression factor,

$$\frac{B^{(4)}(B_d \to D_{sJ}^{*+}\pi^-)}{B^{(2)}(B_d \to D_{sJ}^{*+}\pi^-)} = R^2 \approx 0.08 \; .$$

• If the $B_d \to D_{sJ}^{*+}\pi^-$ branching ratio is observed at the 10^{-5} level, the D_{sJ}^{*+} meson is likely to be the conventional 2-quark bound state. If it is observed with the 10^{-6} (around 2.4×10^{-6}) branching ratio, the four-quark picture is preferred.

$B \to D_{sJ}^* M$ Decays

❖ $B \to D_{sJ}^* D$

• There is already a hint from the $B \to D_{sJ}^* D$ decays, to which our analysis can be generalized straightforwardly by substituting F^{BD} for $F^{B\pi}$.

• The Belle measurement,

$$B(B \to D_{sJ}^*(2317)D) \times B(D_{sJ}^*(2317) \to D_s\pi^0) = (9.9^{+2.8}_{-2.5} \pm 3.0) \times 10^{-4}\ ,$$
$$B(B \to D_{sJ}^*(2463)D) \times B(D_{sJ}^*(24603) \to D_s^*\pi^0) = (25.8^{+7.0}_{-6.0} \pm 7.7) \times 10^{-4}\ ,$$
$$B(B \to D_{sJ}^*(2463)D) \times B(D_{sJ}^*(2463) \to D_s\gamma) = (5.3^{+1.4}_{-1.3} \pm 1.6) \times 10^{-4}\ .$$

• The first data imply

$$\frac{B(B \to D_{sJ}^*(2317)D)}{B(B \to D_s D)} \approx 0.07\ ,$$

for $B(B \to D_s D) = (1.3 \pm 0.4)\%$, the 4-quark content of the D_{sJ}^* meson.

• The latter two data lead to $B(B \to D_{sJ}^*(2463)D) \approx 0.3\%$ and $B(B \to D_{sJ}^*(2317)D)/B(B \to D_s D) \approx 0.23$. This ratio, though a bit large, also gives a similar indication.

$B \to D^*_{sJ} K$

• Another ideal mode $B_d \to D^{*-}_{sJ} K^{(*)+}$ serves the purpose. Since it involves only the annihilation topologies, FA does not apply. We estimate its branching ratio in the 2-quark picture using the perturbative QCD approach (Li and Sterman 92; Keum, Li and Sanda, 00).

$B_d \to D^{*-}_{sJ}(2317) K^+$	$B_d \to D^{*-}_{sJ}(2317) K^{*+}$	$B_d \to D^{*-}_{sJ}(2463) K^+$
5.35×10^{-5}	7.79×10^{-5}	7.01×10^{-5}

• The predictions for the $B_d \to D^{*-}_{sJ} K^+$ mode are close the Belle and BaBar measurements,

$$B(B_d \to D_s^- K^+) = (3.2 \pm 0.9 \pm 1.0,\, 3.2 \pm 1.0 \pm 1.0) \times 10^{-5} \; .$$

• In the four-quark picture is similar, the $B_d \to D^{*-}_{sJ} K^+$ branching ratio is expected to be around 4.2×10^{-6}.

Summary

- A measurement of the $B \to D_{sJ}^* M$ branching ratios, $M = D$, π and K, can provide more information on the nature of the new D_{sJ}^* mesons.

- If the D_{sJ}^* mesons are 2-quark states, the $B \to D_{sJ}^* M$ branching ratios will be close to the $B \to D_s^* M$ ones.

- If the D_{sJ}^* mesons are multi-quark states, the branching ratios will be smaller by a factor 10.

- The suppression is a combined effect of α_s, $1/N_c$ and $(m_{D_{sJ}^*}/m_B)^2$, which arise from the additional hard scattering the four valence quarks of the D_{sJ}^* mesons participate.

- Our estimation applies to the other non-quark-anitquark models, such as a molecule, up to order of magnitude. One of the differences is that the 88 color configuration is excluded, which is not essential anyway.

- More precise data are necessary for drawing a conclusion, though the recently measured $B \to D_{sJ}^* D$ branching ratios have indicated an unconventional picture.

- It is unlikely that the dramatically different branching ratios are due to the different decay constants $f_{D_{sJ}^*}$ and f_{D_s} (Datta and O'Donnell 03) from the viewpoint of heavy quark symmetry.