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The new narrow "D_s" states – A minireview

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Abstract. The experimental status concerning the two new narrow states with charm-strange content is reviewed. The states have masses of 2317 and 2460 MeV, widths less than 10 MeV, isospin consistent with zero, and spin-parities consistent with being 0^+ and 1^+, respectively. Although the masses are lower than the conventional expectation, these states appear to be the $j = 1/2$ P-wave levels of the D_s system, where j is the light quark angular momentum; there may be mixing with the $j = 3/2$ level for the 1^+ state.

PACS. 14.40.Lb Charmed mesons – 13.66.Bc Hadron production in e-e+ interactions

1 Introduction

Two new narrow states have been observed with charm and strangeness. The current state of experimental knowledge is summarized, drawing experimental results from BaBar[1], Belle[2], CDF[3], and CLEO[4]. These new states will be referred to here as $D_{sJ}^*(2317)^\pm$ and $D_{sJ}(2460)^\pm$, in accordance with Particle Data Group naming conventions and their presumed quantum numbers in the $q\bar{q}$ model.

2 The $D_{sJ}^*(2317)^\pm$ level

The $D_{sJ}^*(2317)^\pm$ state is observed as a mass peak in the $D_s^\pm \pi^0$ spectrum, Fig. 1. A $p^* > 3.5$ GeV CM momentum cut ensures that the signal observed here is from continuum charm production (not from B decays). The peak width is consistent with experimental resolution, hence the state is narrow, with a width less than several MeV.

The narrow width suggests an isospin violating decay, ie $I \neq 1$. CDF has looked for a peak in the $D_s^\pm \pi^\mp$ and $D_s^\pm \pi^\pm$ spectra, Fig. 2. While they have a large $D_s^\pm$ signal, there is no evidence for a peak in these modes. The CDF sensitivity is estimated using $D_2^* \to D\pi$ decays and the relative $D_s : D$ rates. Further work is underway to quantify the sensitivity using $D_{sJ}(2573) \to DK$, but it presently seems that CDF has the sensitivity to observe isospin partners if they exist. The lack of such a signal leads to the preferred $I = 0$ assignment.

If parity is conserved, then the decay $D_{sJ}^*(2317)^\pm \to D_s^\pm \pi^0$ implies that J_P is natural for the $D_{sJ}^*(2317)^\pm$ (hence, the $*$ in its name). There is some evidence favoring a $J^P = 0^+$ assignment: First the helicity angle distribution for the decay is consistent with uniform, Fig. 3. This is consistent with $J^P = 0^+$, but doesn't rule out other pos-
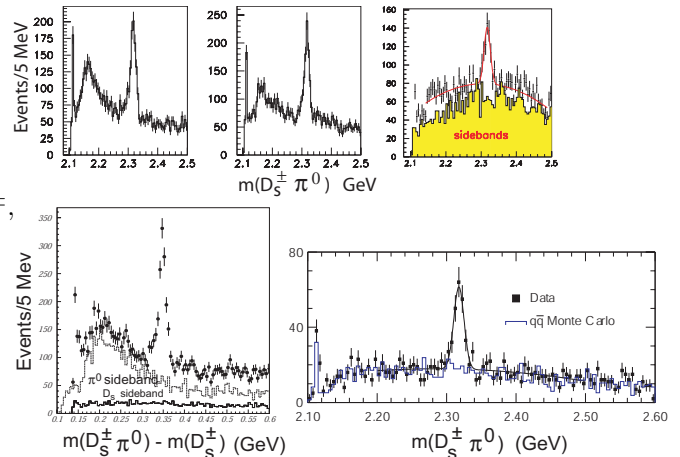

Fig. 1. The $D_s^\pm \pi^0$ mass spectrum, for $p^* > 3.5$ GeV. *Top row:* BaBar, with $D_s^\pm \to \phi\pi^\pm$ (left), $D_s^\pm \to K^{*0}K^\pm$ (*middle*), $D_s^\pm \to K^+K^-\pi^\pm\pi^0$ (right). *Bottom left*: Belle preliminary, with $D_s^\pm \pi^0 - D_s^\pm$ mass difference, where $D_s^\pm \to \phi\pi^\pm$; Bottom right: CLEO, with $D_s^\pm \to \phi\pi^\pm$

sibilities, because it can also result from an isotropic production polarization. Further support for the 0^+ hypothesis is gleaned from the absence of a peak in the $D_s^\pm \pi^+\pi^-$ and $D_s^\pm \pi^0\pi^0$ spectra, Fig. 4, forbidden for 0^+. Furthermore, a spin zero decay to $D_s^\pm \gamma$ is forbidden, and is not observed, Fig. 5. Ultimately, we look forward to an unambiguous spin-parity determination in an angular analysis of $B \to DD_{sJ}^*(2317)^\pm$ decays.

There is hope for such an analysis; the Belle experiment has already observed the $D_{sJ}^*(2317)^\pm$ in exclusive $B \to DD_s\pi^0$ decays, as shown in Fig. 6a and summarized in Table 1. As more data is accumulated, an angular analysis will become possible. Table 2 gives a summary of the other information on the $D_{sJ}^*(2317)^\pm$.
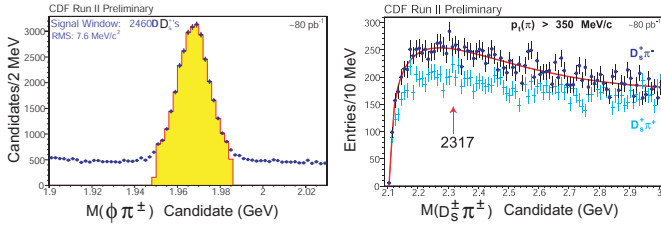
Fig. 2. CDF preliminary. *Left:* The $D_s^\pm$ signal in $\phi\pi^\pm$. *Right:* Search for a peak at 2317 MeV in the $D_s^\pm\pi^\pm$ spectra, dark points are opposite-sign, light points are same sign
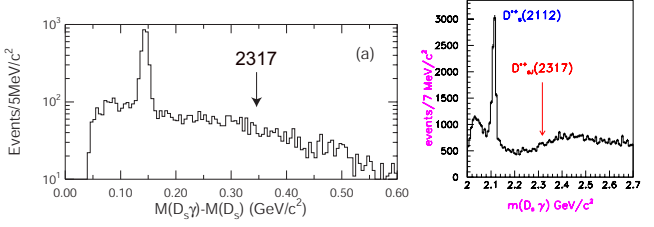

Fig. 3. BaBar helicity angle (θ) analysis of the decay $D_{sJ}^*(2317)^\pm \to D_s^\pm\pi^0$. *Left:* Uncorrected angular distribution. *Center:* Dependence of efficiency on angle. *Right:* Efficiency-corrected angular distribution
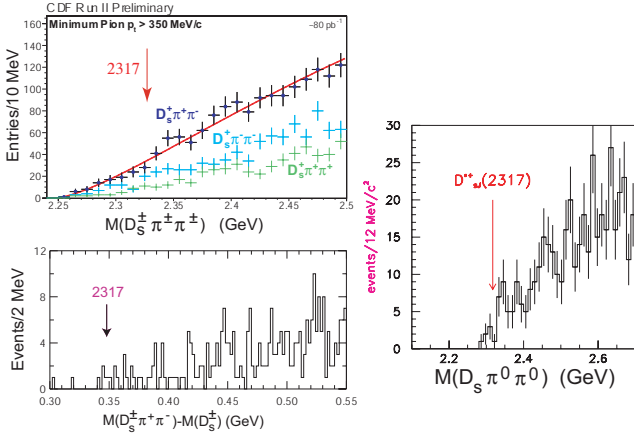
Fig. 4. Search for signals in the $D_s^\pm\pi\pi$ spectra. *Arrows* indicate where a signal for the $D_{sJ}^*(2317)^\pm$ would peak. *Top left:* CDF preliminary, dark points are opposite sign pions, middle points are like sign pions, opposite sign with $D_s^\pm$, and lower points are like sign pions, same sign with $D_s^\pm$. *Bottom left:* CLEO, $D_s^\pm\pi^+\pi^- - D_s^\pm$ mass difference. *Right:* BaBar, $D_s^\pm\pi^0\pi^0$

3 The $D_{sJ}(2460)$ level

The $D_{sJ}(2460)^\pm$ state is observed as a mass peak in the $D_s^\pm\pi^0\gamma$ spectrum, selected on the $D_s^*(2112)^\pm$ region of the $D_s^\pm\gamma$ mass, Fig. 7. A $p^* > 3.5$ GeV CM momentum cut ensures that the signal observed here is not in B decays. The peak width is consistent with experimental resolution, hence the state is narrow, with a width less than several MeV. Again, this is indicative of an isospin-violating decay. This state is not seen in the $D_s^\pm\pi^\pm$ and $D_s^\pm\pi^+\pi^-$

Fig. 5. Search for signals in the $D_s^\pm\gamma$ spectrum. The arrows indicate where a signal for the $D_{sJ}^*(2317)^\pm$ would appear. The peak at lower mass is from $D_s^*(2112)^\pm \to D_s^\pm\gamma$. Left: CLEO, $D_s^\pm\gamma - D_s^\pm$ mass difference. Right: BaBar, $D_s^\pm\gamma$ mass

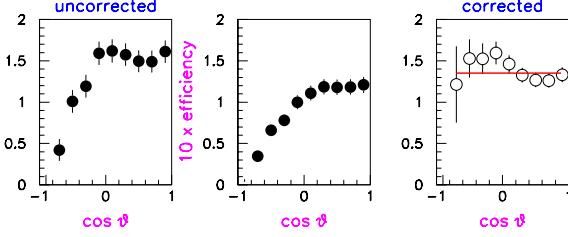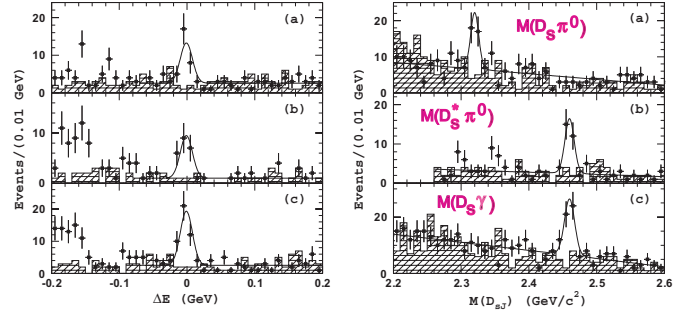**Fig. 6.** Belle preliminary analysis of the channels $B \to DD_s\pi^0$ and $DD_s\gamma$, where $D_s^+ \to \phi\pi^+$, $\bar{K}^{*0}K^+$, and $K_S^0 K^+$ (and charge conjugate modes) and $D \to K\pi, K\pi\pi$, and $K\pi\pi\pi$, in a sample of $124 \times 10^6 \, B\bar{B}$ events. The plots on the left are the $\Delta E \equiv \sum_i \sqrt{m_i^2 + \mathbf{p}_i^{*2}} - E_b^*$ distributions, and on the right the $M_{ES} \equiv \sqrt{E_b^{*2} - |\sum_i \mathbf{p}_i^*|^2}$ distributions, where m_i and $\mathbf{p}_i^*$ are the masses and three-momenta of the candidate B decay products in the $\Upsilon(4S)$ frame, and E_b^* is the beam energy in the $\Upsilon(4S)$ frame

Table 1. Product branching fractions in exclusive B decays to $D_{sJ}^*(2317)^\pm$ or $D_{sJ}(2460)^\pm$ (Belle preliminary). The yields are obtained from fits to the ΔE distributions (Fig. 6, left)

B Decay channel	Yield	$\mathcal{B}(10^{-4})$
$\bar{D}^0 D_{sJ}^*(2317) \to \bar{D}^0 D_s\pi^0$	$13.7^{+5.1}_{-4.5}$	$8.1^{+3.0}_{-2.7} \pm 2.4$
$\bar{D}^- D_{sJ}^*(2317) \to D^- D_s\pi^0$	$10.3^{+3.9}_{-3.1}$	$8.6^{+3.3}_{-2.6} \pm 2.6$
$\bar{D}^0 D_{sJ}^*(2317) \to \bar{D}^0 D_s\gamma$	$3.4^{+2.8}_{-2.2}$	$2.4^{+2.0}_{-1.5}(< 5.7)$
$\bar{D}^- D_{sJ}^*(2317) \to \bar{D}^- D_s\gamma$	$2.3^{+2.5}_{-1.9}$	$2.6^{+2.8}_{-2.2}(< 7.1)$
$\bar{D}^0 D_{sJ}(2460) \to \bar{D}^0 D_s^*\pi^0$	$7.2^{+3.7}_{-3.0}$	$11.9^{+6.1}_{-4.9} \pm 3.6$
$D^- D_{sJ}(2460) \to D^- D_s^*\pi^0$	$11.8^{+3.8}_{-3.2}$	$22.7^{+7.3}_{-6.2} \pm 6.8$
$\bar{D}^0 D_{sJ}(2460) \to \bar{D}^0 D_s\gamma$	$19.1^{+5.6}_{-5.0}$	$5.6^{+1.6}_{-1.5} \pm 1.7$
$D^- D_{sJ}(2460) \to D^- D_s\gamma$	$18.5^{+5.0}_{-4.3}$	$8.4^{+2.4}_{-2.2} \pm 2.5$
$\bar{D}^0 D_{sJ}(2460) \to \bar{D}^0 D_s^*\gamma$	$4.4^{+3.8}_{-3.3}$	$3.1^{+2.7}_{-2.3}(< 7.5)$
$D^- D_{sJ}(2460) \to D^- D_s^*\gamma$	$1.1^{+1.8}_{-1.2}$	$1.3^{+2.0}_{-1.4}(< 4.6)$
$\bar{D}^0 D_{sJ}(2460) \to \bar{D}^0 D_s\pi^0$	< 2.4	< 2.2
$D^- D_{sJ}(2460) \to D^- D_s\pi^0$	< 2.4	< 2.8
$\bar{D}^0 D_{sJ}(2460) \to \bar{D}^0 D_s\pi^+\pi^-$	< 4.0	< 2.4
$D^- D_{sJ}(2460) \to D^- D_s\pi^+\pi^-$	< 2.5	< 2.0

Table 2. Summary of $D_{sJ}^*(2317)^\pm$. Limits are 90% C.L. Masses and widths are in MeV. †The Belle peak has $\sigma = 7.6 \pm 0.5$ MeV, consistent with resolution

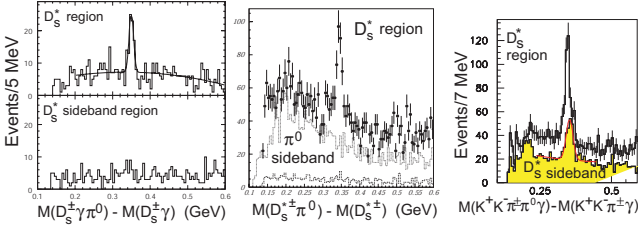| Quantity	BaBar	Belle	CLEO
Dataset (fb^{-1})	91	87	13.5
D_s Modes	$\phi\pi, K^*K$	$\phi\pi$	$\phi\pi$
Mass	$2316.8 \pm 0.4 \pm 3$		$2318.5 \pm 1.2 \pm 1.1$
		$2317.2 \pm 0.5 \pm 0.9$	
$\Delta m(2317 - D_s)$	$348.4 \pm 0.4 \pm 3$		$350.0 \pm 1.2 \pm 1.0$
		$348.7 \pm 0.5 \pm 0.7$	
Width	< 10	†	< 7
$\mathcal{B}(D_s\pi^+\pi^-)/\mathcal{B}(D_s\pi^0)$			< 0.019
$\mathcal{B}(D_s\gamma)/\mathcal{B}(D_s\pi^0)$		< 0.05	< 0.052
$\mathcal{B}(D_s^*\pi^0)/\mathcal{B}(D_s\pi^0)$			< 0.11
$\mathcal{B}(D_s^*\gamma)/\mathcal{B}(D_s\pi^0)$			< 0.059
$\frac{\sigma \cdot \mathcal{B}(D_{sJ}^* \to D_s\pi^0)}{\sigma(D_s)}$ ($p^* > 3.5$ GeV)			$(7.9 \pm 1.2 \pm 0.4) \times 10^{-2}$

Fig. 7. Observation of the $D_{sJ}(2460)^\pm$ in the $D_s^\pm\gamma\pi^0$ mass spectrum. *Left:* CLEO. *Middle:* Belle preliminary. *Right:* BaBar preliminary

Fig. 8. BaBar preliminary study of the cross-feed between $D_{sJ}(2460) \to D_s^*(2112)\pi^0$ and $D_{sJ}(2460) \to D_{sJ}^*(2317)\gamma$. *Top row:* plots of $m(D_s^\pm\gamma)$ vs. $m(D_s^\pm\pi^0)$. *Left:* Kinematic boundary for mass 2460 to $D_s^\pm\pi^0\gamma$. *Middle:* Data. *Right:* Monte Carlo simulation for the $D_{sJ}(2460) \to D_s^*(2112)\pi^0$ hypothesis. Bottom row: Projections from the top-middle scatter plot (points with error bars). A linear background subtraction has been performed using the sidebands indicated with the boxes in the top-middle plot. *Right:* Projections overlaid with histograms according to a simulation of the $D_{sJ}(2460) \to D_s^*(2112)\pi^0$ hypothesis. Left: Projections overlaid with histograms according to a simulation of the $D_{sJ}(2460) \to D_{sJ}^*(2317)\gamma$ hypothesis

spectra, Figs. 2 and 4, nor in the $D_s^\pm\pi^+\pi^-$ spectrum in exclusive B decays against a D from Belle (Table 1).

The $D_{sJ}(2460)$ is above threshold for isospin-allowed decays to DK. The fact that this decay is not observed is suggestive that this level has unnatural J^P quantum numbers (hence, no "*" in the name).

There is a serious difficulty with a cross-feed ambiguity, due to the fact that

$$\Delta m\left[D_{sJ}(2460) - D_s^*(2112)\right] \sim \Delta m\left[D_{sJ}^*(2317) - D_s\right]$$
$$\sim 350\,\text{MeV}.$$

This coincidence has two potential consequences: First, the $D_{sJ}^*(2317)$ signal could feed up to create a peak at ~ 2460 by adding a random photon selected to be consistent with the decay $D_s^*(2112) \to D_s\gamma$. Second, a signal for $D_{sJ}(2460)$ could create a peak at ~ 2317 by neglecting the photon in the $D_s^*(2112) \to D_s\gamma$ transition. There is also an ambiguity in the $D_{sJ}(2460)$ decays: Is it $D_{sJ}(2460) \to D_s^*(2112)\pi^0$, or is it $D_{sJ}(2460) \to D_{sJ}^*(2317)\gamma$? All three experiments which have observed this state correct for the cross-feed between 2317 and 2460 peaks under the $D_{sJ}(2460) \to D_s^*(2112)\pi^0$ hypothesis.

BaBar and CLEO have both attempted to test the hypothesis, with consistent results; we use the BaBar study here to illustrate. Fig. 8 shows the kinematic boundary for a mass 2460 MeV particle in the $m(D_s\gamma)$ vs $m(D_s\pi^0)$ plane. We see the problem immediately: The two hypothe-
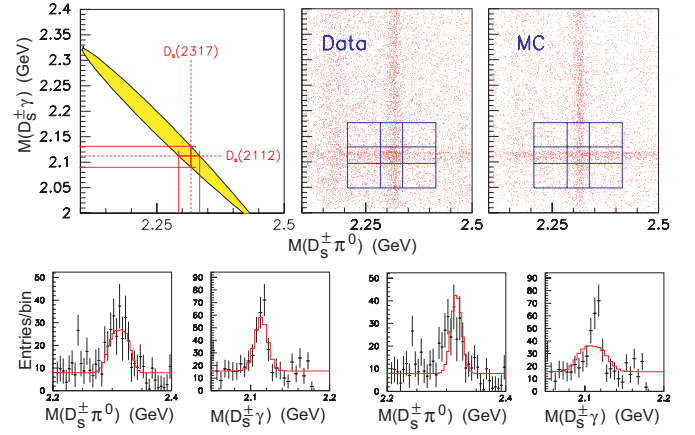
ses correspond to vertical and horizontal lines crossing within the narrow kinematic boundary. The scatter plot of the data is also shown, and for comparison a Monte Carlo sample under the $D_{sJ}(2460) \to D_s^*(2112)\pi^0$ hypothesis. Because of the experimental resolution, the favored hypothesis is not obvious from the scatter plot, although the band in the overlap region perhaps looks more "horizontal." However, we may make projections of this scatterplot, with a background subtraction performed in the linear approximation. The result is shown in Fig. 8, where the projection plots are shown with curves overlain for the two hypotheses. It may be observed that the $D_{sJ}(2460) \to D_s^*(2112)\pi^0$ hypothesis gives a better fit. The data are consistent with being 100% due to this channel, though a significant contribution from the other hypothesis cannot yet be excluded.

The state at 2460 is observed by Belle to decay to $D_s\gamma$, Fig. 9. This rules out $J = 0$ for this state. A BaBar angular analysis of $D_{sJ}(2460)$ decays (not shown) also finds that spin 0 is disfavored. Belle also observes this state in exclusive $B \to DD_{sJ}(2460)$ decays, with $D_{sJ}(2460) \to D_s\gamma$, Fig. 6c. The product branching fraction is $\mathcal{B}\left[B \to DD_{sJ}(2460) \to DD_s\gamma\right] = \left(6.7^{+1.3}_{-1.2} \pm 2.0\right) \times 10^{-4}$. Together with the observation of $D_{sJ}(2460) \to D_s^*\pi^0$, Fig. 6b, a branching ratio of $0.38 \pm 0.11 \pm 0.04$ is obtained for $\mathcal{B}\left[D_{sJ}(2460) \to D_s\gamma\right]/\mathcal{B}\left[D_{sJ}(2460) \to D_s^*\pi^0\right]$. An angular analysis is shown in Fig. 10, finding consistency for $J^P = 1^+$ and ruling out spin 2.

A summary of the $D_{sJ}(2460)^\pm$ as seen in exclusive B decays is included in Table 1, a summary of other properties is shown in Table 3.
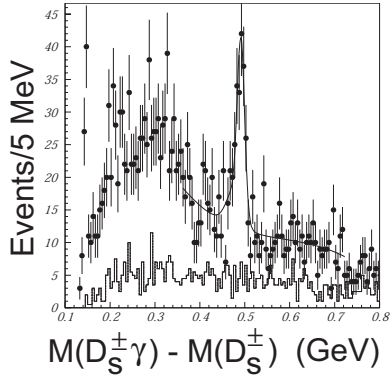
Fig. 9. Belle preliminary observation of $D_{sJ}(2460)^{\pm} \to D_s^{\pm}\gamma$ in continuum e^+e^- annihilation. The fit gives $N\left[D_{sJ}(2460)^{\pm} \to D_s\gamma\right] = 152 \pm 18 \pm 11$ signal events. Note that no signal appears at a mass difference around 350 MeV, which would correspond to the 2317 state, consistent with the favored $J = 0$ hypothesis for the $D_{sJ}^*(2317)^{\pm}$. The histogram shows the $D_s^{\pm}$ sidebands
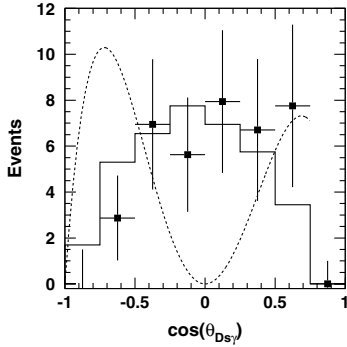

Fig. 10. Cosine of the helicity angle for $D_{sJ}(2460) \to D_s\gamma$ in exclusive $B \to DD_{sJ}(2460)$ decays (Belle preliminary). The data are the points with error bars; the predicton for the spin 1 hypothesis is shown by the histogram, and for the spin two hypothesis by the curve

Table 3. Summary of $D_{sJ}(2460)$. N is the number of events in the peak at 2460 MeV in the $D_s^*(2112)^{\pm}\pi^0$ spectrum, where $D_s^*(2112)^{\pm} \to D_s^{\pm}\gamma$. Limits are 90% C.L. Masses and widths are in MeV. †Width of mass peak is consistent with resolution

Quantity	BaBar	Belle	CLEO
N	127 ± 22	$126 \pm 25 \pm 24$	41 ± 12
Mass	$2457.0 \pm 1.4 \pm 3$		$2463.6 \pm 1.7 \pm 1.2$
		$2456.5 \pm 1.3 \pm 1.1$	
$\Delta m(2460 - D_s^*)$	$344.6 \pm 1.2 \pm 3$		$351.2 \pm 1.7 \pm 1.0$
		$344.1 \pm 1.3 \pm 0.9$	
Width	$\dagger$	$\dagger$	< 7
$\frac{\mathcal{B}(D_s\pi^+\pi^-)}{\mathcal{B}(D_s^*\pi^0)}$			< 0.08
$\frac{\mathcal{B}(D_s\gamma)}{\mathcal{B}(D_s^*\pi^0)}$		$0.63 \pm 0.15 \pm 0.15$	< 0.49
$\frac{\mathcal{B}(D_s^*\gamma)}{\mathcal{B}(D_s^*\pi^0)}$			< 0.16
$\frac{\mathcal{B}(D_{sJ}(2317)^*\gamma)}{\mathcal{B}(D_s^*\pi^0)}$			< 0.58

4 Production rates

For $p^* > 3.5$ GeV, CLEO has measured production (times decay) rates for the 2317 and 2460 states, normalized to $D_s^{\pm}$ production:

$$\frac{\sigma \cdot \mathcal{B}(D_{sJ}^*(2112)^+ \to D_s^+\gamma)}{\sigma(D_s^+)} = 0.59 \pm 0.03 \pm 0.01$$

$$\frac{\sigma \cdot \mathcal{B}(D_{sJ}^*(2317)^+ \to D_s^+\pi^0)}{\sigma(D_s^+)} = (7.9 \pm 1.2 \pm 0.4) \times 10^{-2}$$

$$\frac{\sigma \cdot \mathcal{B}(D_{sJ}(2460)^+ \to D_s^{*+}\pi^0)}{\sigma(D_s^+)} = (3.5 \pm 0.9 \pm 0.2) \times 10^{-2}.$$

Belle (preliminary) has measured the ratio of 2460 to 2317 production (times decay) rates:

$$\frac{\sigma \cdot \mathcal{B}(D_{sJ}(2460)^+ \to D_s^{*+}\pi^0)}{\sigma \cdot \mathcal{B}(D_{sJ}^*(2317)^+ \to D_s^+\pi^0)} = 0.26 \pm 0.05 \pm 0.06$$

$$\frac{\sigma \cdot \mathcal{B}(D_{sJ}(2460)^+ \to D_s^+\pi^0)}{\sigma \cdot \mathcal{B}(D_{sJ}^*(2317)^+ \to D_s^+\pi^0)} < 0.06 \ (90\% \text{ C.L.}).$$

The results from the two experiments are consistent.

5 Conclusions

Two new narrow states with $c\bar{s}$ content, denoted $D_{sJ}^*(2317)^{\pm}$ and $D_{sJ}(2460)^{\pm}$, have been observed in e^+e^- collisions. They are consistent with being 0^+ and 1^+ states, respectively, and isospin singlets. They are candidates for the two heretofore unseen P-wave $j = 1/2$ (light quark angular momentum) states of the D_s system, possibly with some mixing with $j = 3/2$ for the 1^+ state. They are below threshold for isospin-allowed decays to $D^0K^{\pm}$ or $D^{0*}K$, respectively, in contrast to the consensus expectation. The results from the different experiments are generally consistent; a potential concern is the $D_{sJ}(2460)^{\pm}$ mass, for which the combined average mass difference (with the $D_s^*(2112)^{\pm}$) is 346.6 ± 1.2 MeV, with a χ^2 consistency of 2%.

References

1. BaBar: IECHEP Abstract 395; B. Aubert et al.: Phys. Rev. Lett. **90**, 242001 (2003); A. Palano: XXIII Physics In Collision conference, Zeuthen, 2003
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