Measurements of the D_{sJ} Resonance Properties

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We report measurements of the properties of the $D_{sJ}^+(2317)$ and $D_{sJ}^+(2457)$ resonances produced in continuum e^+e^- annihilation near $\sqrt{s} = 10.6$ GeV. The analysis is based on an 86.9 fb^{-1} data sample collected with the Belle detector at KEKB. We determine the masses to be $M(D_{sJ}^+(2317)) = 2317.2 \pm 0.5(\text{stat}) \pm 0.9(\text{syst})$ MeV$/c^2$ and $M(D_{sJ}^+(2457)) = 2456.5 \pm 1.3(\text{stat}) \pm 1.3(\text{syst})$ MeV$/c^2$. We observe the radiative decay mode $D_{sJ}^+(2457) \to D_s^+\gamma$ and the dipion decay mode $D_{sJ}^+(2457) \to D_s^+\pi^+\pi^-$ and determine their branching fractions. No corresponding decays are observed for the $D_{sJ}(2317)$ state. These results are consistent with the spin-parity assignments of 0^+ for the $D_{sJ}(2317)$ and 1^+ for the $D_{sJ}(2457)$.

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The narrow $D_s\pi^0$ resonance at 2317 MeV$/c^2$, recently observed by the BaBar Collaboration [1], is naturally interpreted as a p-wave excitation of the $c\bar{s}$ system. The observation of a nearby and narrow $D_s^*\pi^0$ resonance by the CLEO Collaboration [2] supports this view, since the mass difference of the two observed states is consistent with the expected hyperfine splitting for a p-wave doublet with total light-quark angular momentum $j = 1/2$ [3,4]. The observed masses are, however, considerably lower than potential model predictions [6] and similar to those of the $c\bar{u}$ $j = 1/2$ doublet states recently reported by Belle [7]. This has led to speculation that the new $D_s^{(*)}\pi^0$ resonances, which we denote D_{sJ}, may be exotic mesons [8–13]. Measurements of the D_{sJ} quantum numbers and branching fractions (particularly those for radiative decays) will play an important role in determining the nature of these states.

In this Letter we report measurements of the D_{sJ} masses, widths, and branching fractions using a sample of $e^+e^- \to c\bar{c}$ events collected with the Belle detector [14] at the KEKB collider [15].

We reconstruct D_s^+ mesons using the decay chain $D_s^+ \to \phi\pi^+$ and $\phi \to K^+K^-$. To identify kaons or pions, we form a likelihood for each track, $\mathcal{L}_{K(\pi)}$, from dE/dx measurements in a 50-layer central drift chamber, the responses from aerogel threshold Čerenkov counters, and time-of-flight scintillation counters. The kaon likelihood ratio, $P(K/\pi) = \mathcal{L}_K/(\mathcal{L}_K + \mathcal{L}_\pi)$, has values between 0 (likely to be a pion) and 1 (likely to be a kaon).

For $\phi \to K^+K^-$ candidates we use oppositely charged track pairs where one track has $P(K/\pi) > 0.5$ and the other has $P(K/\pi) > 0.2$, and with a K^+K^- invariant mass that is within 10 MeV$/c^2$($\sim 2.5\sigma$) of the nominal ϕ mass. We define the ϕ helicity angle θ_H to be the angle between the direction of the K^+ and the D_s^+ in the ϕ rest frame. For signal events this has a $\cos^2\theta_H$ distribution, while for background it is flat; we require $|\cos\theta_H| > 0.35$.

We reconstruct D_s^+ candidates by combining a ϕ candidate with a π^+ candidate, which is a charged track with $P(K/\pi) < 0.9$, and requiring $M(\phi\pi^+)$ to be within 10 MeV$/c^2$($\sim 2\sigma$) of the nominal D_s^+ mass. We use the D_s^+ sideband regions $1920 < M(\phi\pi^+) < 1940$ MeV$/c^2$ and $1998 < M(\phi\pi^+) < 2018$ MeV$/c^2$ for background studies.

For π^0 reconstruction, we use photons with e^+e^- rest frame (c.m.) energies greater than 100 MeV and select $\gamma\gamma$ pairs that have an invariant mass $M(\gamma\gamma)$ within 10 MeV$/c^2$($\sim 2\sigma$) of the π^0 mass. For background studies we use the π^0 sideband regions $105 \le M_{\gamma\gamma} \le 115$ MeV$/c^2$ and $155 \le M_{\gamma\gamma} \le 165$ MeV$/c^2$.

We reconstruct D_s^{*+} in the $D_s^+\gamma$ final state. We use photons with c.m. energies greater than 100 MeV and require D_s^{*+} candidates to satisfy $127 \le \Delta M(D_s^+\gamma) \le 157$ MeV$/c^2$($\sim 3\sigma$), where $\Delta M(D_s^+\gamma) = M(D_s^+\gamma) - M_{D_s^+}$. The D_s^{*+} sideband regions are defined as $87 \le \Delta M(D_s^+\gamma) \le 117$ MeV$/c^2$ and $167 \le \Delta M(D_s^+\gamma) \le 197$ MeV$/c^2$. The sideband yield is defined as an average of the two regions.

The $\Delta M(D_s^+\pi^0) = M(D_s^+\pi^0) - M_{D_s^+}$ mass-difference distribution for $D_s^+\pi^0$ combinations with $p^*(D_s^+\pi^0) > 3.5$ GeV/c is shown in Fig. 1(a). Here, and in analyses of other D_{sJ} states and modes, we require the c.m. momentum to satisfy $p^*(D_{sJ}) > 3.5$ GeV/c to remove contributions from $B\bar{B}$ events. We do not remove multiple candidates in the subsequent analysis. Also shown are the distributions for the D_s^+ (solid line) and π^0 (dashed line) sideband regions. The prominent peak in the figure corresponds to the $D_{sJ}(2317) \to D_s^+\pi^0$ signal; the peak at small ΔM values is due to $D_s^{*+}(2112) \to D_s^+\pi^0$. No peak is seen in the sideband distributions.

Figure 1(b) shows the $\Delta M(D_s^{*+}\pi^0) = M(D_s^{*+}\pi^0) - M_{D_s^{*+}}$ distribution for $p^*(D_s^{*+}\pi^0) > 3.5$ GeV/c, where a peak corresponding to $D_{sJ}(2457) \to D_s^{*+}\pi^0$ is evident. Also shown is the distribution for the D_s^{*+} sideband region, where we notice the presence of a wider peak in the $D_{sJ}(2457)$ region. The $\Delta M(D_s^{*+}\pi^0)$ distributions for the D_s^+ and π^0 sideband regions show no such peak.

To study the expected signal shape and detection efficiencies, and to determine the level of cross-feed between the two states, we use a Monte Carlo (MC) simulation that treats the $D_{sJ}(2317)$ as a scalar particle with mass 2317 MeV/c^2 decaying to $D_s^+\pi^0$ and the $D_{sJ}(2457)$ as an axial-vector particle with mass 2457 MeV/c^2 decaying to $D_s^{*+}\pi^0$. Zero intrinsic width is assigned to both states. We find that the $D_{sJ}(2317)$ produces a peak of width 7.1 ± 0.2 MeV/c^2 in the $\Delta M(D_s^+\pi^0)$ distribution at its nominal mass, and a broader reflection peak (of width 12.3 ± 1.8 MeV/c^2) at a mass of 8 MeV/c^2 above the $D_{sJ}(2457)$ peak. This latter peak corresponds to a D_s^+ and π^0 from a $D_{sJ}(2317)$ decay that are combined with a random photon that passes the $|M(D_s^+\gamma) - M_{D_s^{*+}}| < 15$ MeV/c^2 requirement. (We refer to this as "feed-up background.") The $D_{sJ}(2457)$ produces a peak of width 6.0 ± 0.2 MeV/c^2 at its nominal mass and a broader peak (of width 19.5 ± 3.6 MeV/c^2), also at its nominal mass. The latter peak is due to events in which the photon from $D_s^{*+} \to D_s^+\gamma$ is missed, and a random photon is reconstructed in its place (referred to as the "broken-signal background"). In addition, the $D_{sJ}(2457)$ produces a reflection in the $D_s^+\pi^0$ mass distribution with width 14.9 ± 0.8 MeV/c^2 at a mass of 4 MeV/c^2 below the $D_{sJ}(2317)$ peak (referred to as "feed-down background").

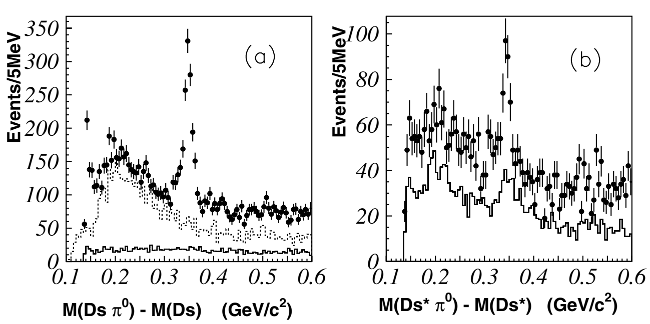

FIG. 1. (a) The $\Delta M(D_s^+\pi^0)$ distribution. Data from the D_s^+ (solid line) and π^0 (dashed line) sideband regions are also shown. (b) The $\Delta M(D_s^{*+}\pi^0)$ distribution. Data from the D_s^* sideband (histogram) region are also shown.

While we must depend on the MC for separating the signal peak and the feed-down background in the $D_{sJ}(2317)$ region, the feed-up and broken-signal backgrounds for the $D_{sJ}(2457)$ region occur when $D_s^{*+}\pi^0$ combinations are formed from candidates in the D_s^{*+} mass sideband. This is evident in Fig. 1(b).

Figure 2(b) shows the sideband-subtracted $\Delta M(D_s^{*+}\pi^0)$ distribution together with the results of a fit that uses a Gaussian to represent the $D_{sJ}(2457)$ signal and a second-order polynomial for the background. The fit gives a signal yield of 126 ± 25 events with a peak value of $\Delta M = 344.1 \pm 1.3$ MeV/c^2 (corresponding to $M = 2456.5 \pm 1.3$ MeV/c^2). The width from the fit, $\sigma = 5.8 \pm 1.3$ MeV/c^2, is consistent with MC expectations for a zero intrinsic width particle.

Figure 2(a) shows the fit result for the $D_{sJ}(2317)$. Here both the signal and the feed-down background are represented as Gaussian shapes modeled from the MC. The mean and σ of the feed-down component are fixed according to the MC and normalized by the measured $D_{sJ}(2457)$ yield. A third-order polynomial is used to represent the non-feed-down background. The fit gives a yield of 761 ± 44 events and a peak ΔM value of 348.7 ± 0.5 MeV/c^2 (corresponding to $M = 2317.2 \pm 0.5$ MeV/c^2). Here again, the width from the fit, $\sigma = 7.6 \pm 0.5$ MeV/c^2, is consistent with MC expectations for a zero intrinsic width particle.

There are systematic errors in the measurements due to uncertainties in the (i) π^0 energy calibration, (ii) parametrization of the cross-feed backgrounds, (iii) parametrization for the non-cross-feed backgrounds, (iv) possible discrepancies between the input and the output seen in the MC simulations, and (v) the uncertainty in the world average value for $M_{D_s^+}$ and $M_{D_s^{*+}}$.

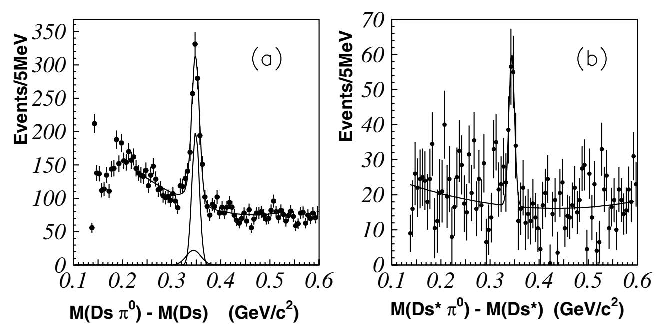

FIG. 2. (a) The $\Delta M(D_s^+\pi^0)$ distribution. The narrow Gaussian peak is the fitted $D_{sJ}(2317)$ signal, whereas the wider Gaussian peak is the feed-down background. (b) The $\Delta M(D_s^{*+}\pi^0)$ distribution after bin-by-bin subtraction of the D_s^{*+} sideband from the D_s^{*+} signal distribution. The curve is the fit result.

The π^0 energy calibration is studied using $D_s^{*+}(2112) \to D_s^+ \pi^0$ events in the same data sample. We measure $\Delta M = 144.3 \pm 0.1$ MeV$/c^2$ and $\sigma = 1.0 \pm 0.1$ MeV$/c^2$, which agrees well with the Particle Data Group (PDG) value of $\Delta M = 143.8 \pm 0.4$ MeV$/c^2$. The MC, which uses the PDG value as an input, gives $\Delta M = 143.9 \pm 0.1$ MeV$/c^2$ and $\sigma = 1.0 \pm 0.1$ MeV$/c^2$. (The errors quoted here are statistical only.) We attribute the difference to the π^0 energy calibration uncertainty and conservatively assign a ± 0.6 MeV$/c^2$ error to this effect. This error contributes only to the mass measurements.

For the cross-feed background to the $D_{sJ}(2317)$ signal, we vary the feed-down background parameters and the $D_{sJ}(2457)$ yield by $\pm 1\sigma$ and assign the variation in output values as errors. For the $D_{sJ}(2457)$, we determine the uncertainty of the feed-up fraction from the difference between the D_s^* signal region and the sideband region using the MC. For the non-cross-feed background, we repeat the fit using a second-order polynomial for the $D_{sJ}(2317)$ and a linear function for the $D_{sJ}(2457)$ and assign the difference as errors. Shifts between the MC input and output masses for the D_{sJ} can reflect possible errors arising from the choice of signal shape and other factors in the analysis. We observe a 0.3 MeV$/c^2$ shift for the $D_{sJ}(2317)$ and a 0.9 MeV$/c^2$ shift for the $D_{sJ}(2457)$. We assign these shifts as errors.

The final results for the masses are

$$M(D_{sJ}(2317)) = 2317.2 \pm 0.5(\text{stat}) \pm 0.9(\text{syst}) \text{ MeV}/c^2,$$

$$M(D_{sJ}(2457)) = 2456.5 \pm 1.3(\text{stat}) \pm 1.3(\text{syst}) \text{ MeV}/c^2.$$

The $M(D_{sJ}(2317))$ result is consistent with BaBar [1] and CLEO results [2]. Our $M(D_{sJ}(2457))$ value is consistent with BaBar [16] but significantly lower than that from CLEO [2]. We set upper limits for the natural widths of $\Gamma(D_{sJ}(2317)) \leq 4.6$ MeV$/c^2$ and $\Gamma(D_{sJ}(2457)) \leq 5.5$ MeV$/c^2$ (90% C.L.), respectively.

Using the observed signal yields of $761 \pm 44(\text{stat}) \pm 30(\text{syst})$ and $126 \pm 25(\text{stat}) \pm 12(\text{syst})$ for the $D_{sJ}(2317)$ and $D_{sJ}(2457)$, and the detection efficiencies of 8.2% and 4.7% for the $D_{sJ}(2317)$ and $D_{sJ}(2457)$, we determine the ratio

$$\frac{\sigma(D_{sJ}(2457))\mathcal{B}(D_{sJ}^+(2457) \to D_s^{*+}\pi^0)}{\sigma(D_{sJ}(2317))\mathcal{B}(D_{sJ}^+(2317) \to D_s^+\pi^0)} = 0.29 \pm 0.06(\text{stat}) \pm 0.03(\text{syst}).$$

The detection efficiencies are determined from the MC assuming the same fragmentation function for the two states. The dominant source of systematic error is the systematic uncertainty in the $D_{sJ}(2457)$ yield.

In the $D_{sJ}(2457)$ region of the $\Delta M(D_s^+\pi^0)$ distribution, we find 22 ± 22 events from a fit to a possible $D_{sJ}(2457)$ signal. From this, we obtain the upper limit

$$\frac{\mathcal{B}(D_{sJ}^+(2457) \to D_s^+\pi^0)}{\mathcal{B}(D_{sJ}^+(2457) \to D_s^{*+}\pi^0)} \leq 0.21 \text{ (90\% C.L.)}.$$

The decay to a pseudoscalar pair is allowed for a state with a parity of $(-1)^J$. Thus, absence of such a decay disfavors $D_{sJ}(2457)$ having J^P of 0^+ or 1^-.

Figure 3(a) shows the $\Delta M(D_s^+\gamma) = M(D_s^+\gamma) - M_{D_s^+}$ distribution. Here photons are required to have energies greater than 600 MeV in the c.m. and those that form a π^0 when combined with another photon in the event are not used. A clear peak near $\Delta M(D_s^+\gamma) \sim 490$ MeV$/c^2$, corresponding to the $D_{sJ}(2457)$, is observed. No peak is found in the $D_{sJ}(2317)$ region. The D_s^+ sideband distribution, shown as a histogram, shows no structure. We fit the distribution with a double Gaussian for the signal, which is determined from the MC, and a third-order polynomial for the background. The fit yields 152 ± 18 (stat) events and a ΔM peak at $491.0 \pm 1.3(\text{stat}) \pm 1.9(\text{syst})$ MeV$/c^2$ (corresponding to $M = 2459.5 \pm 1.3(\text{stat}) \pm 2.0(\text{syst})$ MeV$/c^2$). The $D_{sJ}(2457)$ mass determined here is consistent with the value determined from $D_s^*\pi^0$ decays.

Using the detection efficiency of 10.2% for the $D_s^+\gamma$ decay mode, we determine the branching fraction ratio

$$\frac{\mathcal{B}(D_{sJ}^+(2457) \to D_s^+\gamma)}{\mathcal{B}(D_{sJ}^+(2457) \to D_s^{*+}\pi^0)} = 0.55 \pm 0.13(\text{stat}) \pm 0.08(\text{syst}).$$

This result, which has a statistical significance of 10σ, is consistent with the first measurement by Belle [17] $0.38 \pm 0.11(\text{stat}) \pm 0.04(\text{syst})$ with $B \to \bar{D}D_{sJ}(2457)$ decays, and with the theoretical predictions [3,13]. The existence of the $D_{sJ}(2457) \to D_s\gamma$ mode rules out the $0^\pm$ quantum number assignments for the $D_{sJ}(2457)$ state. For the $D_{sJ}(2317)$, we obtain the upper limit

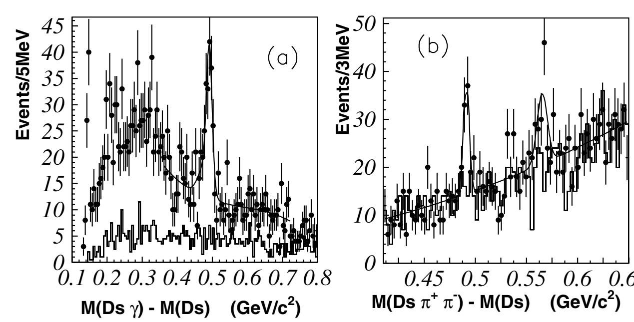

FIG. 3. (a) The $\Delta M(D_s^+\gamma)$ distribution. The curve is a fit using a double Gaussian for the signal and a third-order polynomial for the background. (b) The $\Delta M(D_s^+\pi^+\pi^-)$ distribution. The curve is a fit using Gaussian for the signals and a third-order polynomial for the background.

$$\frac{\mathcal{B}(D_{sJ}^+(2317) \to D_s^+ \gamma)}{\mathcal{B}(D_{sJ}^+(2317) \to D_s \pi^0)} \leq 0.05 \text{ (90\% C.L.)}.$$

From the $M(D_s^{*+}\gamma) = M(D_s^{*+}\gamma) - M_{D_s^{*+}}$ distribution, we determine the upper limits

$$\frac{\mathcal{B}(D_{sJ}^+(2317) \to D_s^{*+} \gamma)}{\mathcal{B}(D_{sJ}^+(2317) \to D_s \pi^0)} \leq 0.18 \text{ (90\% C.L.)} \quad \text{and}$$

$$\frac{\mathcal{B}(D_{sJ}^+(2457) \to D_s^{*+} \gamma)}{\mathcal{B}(D_{sJ}^+(2457) \to D_s^{*+} \pi^0)} \leq 0.31 \text{ (90\% C.L.)}.$$

Figure 3(b) shows the $\Delta M(D_s^+\pi^+\pi^-) = M(D_s^+\pi^+\pi^-) - M_{D_s^+}$ distribution. For additional pions, we require at least one of them to have one momentum greater than 300 MeV$/c$ in the c.m., one with $P(K/\pi) < 0.1$ and another with $P(K/\pi) < 0.9$, and $|M(\pi^+\pi^-) - M_{K_S}| \geq 15$ MeV$/c^2$. A clear peak near $\Delta M(D_s^+\pi^+\pi^-) \sim 490$ MeV$/c^2$, corresponding to the $D_{sJ}(2457)$, is observed. Evidence of an additional peak near $\Delta M(D_s^+\pi^+\pi^-) \sim 570$ MeV$/c^2$ corresponding to $D_{s1}(2536)$ is also visible. No peak is found in the $D_{sJ}(2317)$ region. The D_s^+ sideband distribution, shown as a histogram, shows no structure. We fit the distribution with Gaussians for the signals, which are determined from the MC, and a third-order polynomial for the background. The fit yields 59.7 ± 11.5(stat) events and a ΔM peak at 491.4 ± 0.9(stat) ± 1.5(syst) MeV$/c^2$ [corresponding to $M = 2459.9 \pm 0.9$(stat) ± 1.6(syst) MeV$/c^2$] for $D_{sJ}(2457)$, and 56.5 ± 13.4(stat) events for $D_{s1}(2536)$. The statistical significance is 5.7σ for $D_{sJ}(2457)$, and 4.5σ for $D_{s1}(2536)$. This is the first observation of the $D_{sJ}(2457) \to D_s^+\pi^+\pi^-$ decay mode.

The existence of the $D_{sJ}(2457) \to D_s\pi^+\pi^-$ mode also rules out the 0^+ assignment for $D_{sJ}(2457)$. Using the detection efficiency of 15.8% for the $D_s\pi^+\pi^-$ decay mode which is determined assuming a phase space distribution for the $\pi^+\pi^-$ invariant mass, we determine the branching fraction ratio

$$\frac{\mathcal{B}(D_{sJ}^+(2457) \to D_s^+ \pi^+\pi^-)}{\mathcal{B}(D_{sJ}^+(2457) \to D_s^{*+} \pi^0)} = 0.14 \pm 0.04(\text{stat}) \pm 0.02(\text{syst}),$$

where the systematic error is dominated by the systematic uncertainty of the $D_{sJ}(2457) \to D_s^{*+}\pi^0$ yield. We establish the upper limit

$$\frac{\mathcal{B}(D_{sJ}^+(2317) \to D_s^+ \pi^+\pi^-)}{\mathcal{B}(D_{sJ}^+(2317) \to D_s^+ \pi^0)} \leq 4 \times 10^{-3} \text{ (90\% C.L.)}.$$

Using the detection efficiency of 14.3% for the $D_{s1}(2536) \to D_s\pi^+\pi^-$ decay mode which assumes the same fragmentation function for the $D_{s1}(2536)$ and $D_{sJ}(2457)$, we establish the cross section times branching fraction ratio

$$\frac{\sigma(D_{s1}(2536))\mathcal{B}(D_{s1}^+(2536) \to D_s^+ \pi^+\pi^-)}{\sigma(D_{sJ}(2457))\mathcal{B}(D_{sJ}^+(2457) \to D_s^+ \pi^+\pi^-)} = 1.05 \pm 0.32(\text{stat}) \pm 0.06(\text{syst}).$$

In summary, we observe radiative and dipion decays of the $D_{sJ}(2457)$ and set upper limits on the corresponding decays of the $D_{sJ}(2317)$. We determine the $D_{sJ}(2317)$ and $D_{sJ}(2457)$ masses from their decays to $D_s^+\pi^0$ and $D_s^{*+}\pi^0$, respectively, and set upper limits for their natural widths. We set an upper limit on the decay of $D_{sJ}(2457)$ to $D_s^+\pi^0$. These results are consistent with the spin-parity assignments for the $D_{sJ}(2317)$ and $D_{sJ}(2457)$ of 0^+ and 1^+, respectively.

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