PHYSICAL REVIEW D **69**, 031101(R) (2004)

Observation of a narrow meson decaying to $D_s^+\pi^0\gamma$ at a mass of 2.458 GeV/c^2

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(Received 24 October 2003; published 25 February 2004)

A narrow state, which we label $D_{sJ}(2458)^+$, with a mass 2458.0 ± 1.0 (stat) ±1.0 (syst) MeV/c^2, is observed in the inclusive $D_s^+\pi^0\gamma$ mass distribution in 91 fb^{-1} of e^+e^- annihilation data recorded by the BABAR detector at the SLAC PEP-II asymmetric-energy e^+e^- storage ring. The observed width is consistent with the experimental resolution. The data favor decay through $D_s^*(2112)^+\pi^0$ rather than through $D_{sJ}^*(2317)^+\gamma$. An analysis of $D_s^+\pi^0$ data accounting for the influence of the $D_{sJ}(2458)^+$ produces a $D_{sJ}^*(2317)^+$ mass of 2317.3 ± 0.4 (stat) ±0.8 (syst) MeV/c^2.

DOI: 10.1103/PhysRevD.69.031101 PACS number(s): 14.40.Lb, 12.40.Yx, 13.25.Ft

Interest in the spectrum of charmed mesons has been heightened by the discovery by this Collaboration [1] of a narrow state, produced in $e^+e^-\to c\bar{c}$ collisions at the SLAC e^+e^- storage ring PEP-II, decaying to $D_s^+\pi^0$ [2], with mass 2317 MeV/c^2, approximately 41 MeV/c^2 below the DK mass threshold. This state, $D_{sJ}^*(2317)^+$ has been confirmed by CLEO [3] and Belle [4,5]. Along with $D_{sJ}^*(2317)^+$, we noted [1] the presence of a narrow peak in the $D_s^+\pi^0\gamma$ mass distribution near 2.46 GeV/c^2. Because this signal is near the kinematic overlap of the $D_{sJ}^*(2317)^+\gamma$ and $D_s^*(2112)^+\pi^0$ systems, special attention is required to remove the associated background and to distinguish between the two possible decay modes. Such an analysis is the subject of this paper.

This state near 2.46 GeV/c^2 has been seen by CLEO [3]

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and Belle [4] in the inclusive $D_s^+\pi^0\gamma$ mass spectrum and by Belle [5] in exclusively reconstructed B decays.

To investigate the $D_s^+\pi^0\gamma$ spectrum, we study D_s^+ candidates from $e^+e^-\to c\bar{c}$ (at a center-of-mass energy near 10.6 GeV) that decay to $K^-K^+\pi^+$. Particle identification is used to provide clean samples of charged K and π candidates, which are combined using a geometric fit to a common vertex. Backgrounds are suppressed by selecting decays to $\bar{K}^{*0}K^+$ and $\phi\pi^+$. A description of this sample and additional details can be found elsewhere [1]. Events with $1.954 < m(K^-K^+\pi^+) < 1.981$ GeV/c^2 are taken as D_s^+ candidates.

A candidate π^0 is formed by constraining a pair of photons each with an energy greater than 100 MeV to emanate from the intersection of the D_s^+ trajectory with the beam envelope, performing a one-constraint fit to the π^0 mass, and requiring a fit probability greater than 5%. A given event may yield several acceptable π^0 candidates. We retain only those candidates for which neither photon belongs to another otherwise acceptable π^0.

Each D_s^+ candidate is combined with all combinations of accompanying π^0 candidates with momentum greater than 300 MeV/c and photon candidates of energy greater than 100 MeV. To suppress background, photons that belong to any π^0 candidate are excluded and we require the momentum p^* of each $D_s^+\pi^0\gamma$ combination in the e^+e^- center-of-mass frame to be greater than 3.5 GeV/c. The last requirement also removes any $D_s^+\pi^0\gamma$ combination from B decay.

The $D_s^+\pi^0\gamma$ invariant mass distribution is shown in Fig. 1(a). A clear enhancement is observed near 2.46 GeV/c^2. The background underneath this peak is from several sources, which can be described in terms of mass differences defined as

$$\Delta m_\gamma \equiv m(D_s^+\gamma) - m(D_s^+), \quad (1)$$

$$\Delta m_{\pi^0} \equiv m(D_s^+\gamma\pi^0) - m(D_s^+\gamma). \quad (2)$$

A scatter plot of the data is shown in Fig. 1(b). Particular background patterns are visible: $D_s^*(2112)^+\to D_s^+\gamma$ decay combined with an unassociated π^0, which appears as a horizontal band, and $D_{sJ}^*(2317)^+\to D_s^+\pi^0$ decay combined with an unassociated γ, which appears as a band that is almost vertical.

To demonstrate the existence of a signal above these backgrounds, the upper histogram of Fig. 1(c) shows $D_s^+\pi^0\gamma$ combinations in the $D_s^*(2112)^+$ signal region, and the gray histogram, scaled to the area of the signal region, corresponds to the two $D_s^*(2112)^+$ sidebands. We conclude that a signal for a state decaying to $D_s^+\pi^0\gamma$ exists over a background resulting from $D_{sJ}^*(2317)^+$ and an unassociated γ. This background peaks at a mass slightly higher than that of the signal. A Gaussian fit to the subtracted mass distribution [Fig. 1(d)] indicates a narrow signal at $\Delta m_{\pi^0} = 346.2 \pm 0.9$ MeV/c^2 (statistical error only).

The state corresponding to this signal, which we label $D_{sJ}(2458)^+$, may decay to $D_s^+\pi^0\gamma$ through $D_s^*(2112)^+\pi^0$ or $D_{sJ}^*(2317)^+\gamma$. To disentangle these modes and reliably extract the parameters of the signal, we apply an unbinned maximum likelihood fit simultaneously to the $D_s^+\pi^0\gamma$, $D_s^+\pi^0$, and $D_s^+\gamma$ invariant masses of all $D_s^+\pi^0\gamma$ combinations using the channel likelihood method [6]. This fit describes the probability density function of the two $D_{sJ}(2458)^+$ decay channels as the product of a Gaussian shape in the $D_s^+\pi^0\gamma$ mass distribution and a Gaussian shape projected into the $D_s^+\pi^0$ or $D_s^+\gamma$ mass axes, as appropriate. Because the daughter resonances are narrow, interference between the two $D_{sJ}(2458)^+$ decay modes cannot be resolved and so is ignored.

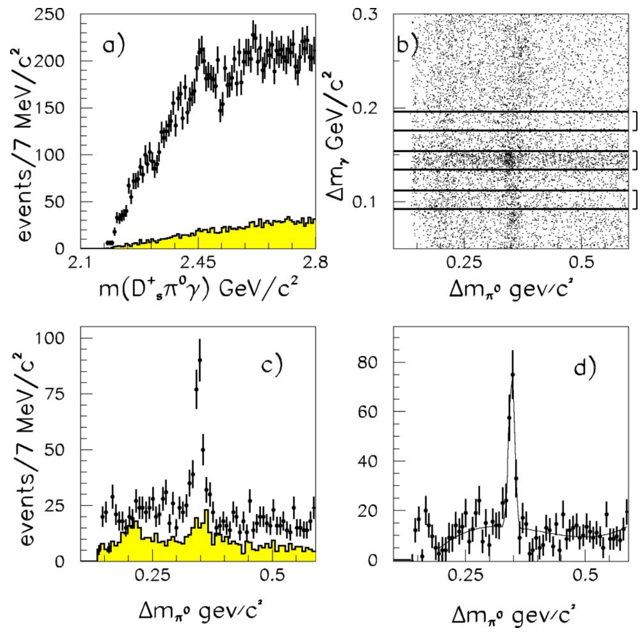

FIG. 1. (a) The mass distribution for all selected $D_s^+\pi^0\gamma$ combinations. The shaded region is from D_s^+ sidebands defined by $1.912 < m(K^-K^+\pi^+) < 1.933$ GeV/c^2 and $1.999 < m(K^-K^+\pi^+) < 2.020$ GeV/c^2. (b) The value of Δm_γ versus Δm_{π^0} for all combinations. The horizontal lines delineate three ranges in Δm_γ. (c) The Δm_{π^0} mass distribution for the middle range of Δm_γ (points) and for the average of the upper and lower ranges (shaded histogram). (d) The difference between the two distributions shown in (c). The curve is the fit described in the text.

Sources of background in the $D_s^+\pi^0\gamma$ spectrum included in the fit are purely combinatorial background (D_s^+ meson combined with an unassociated π^0 and γ), $D_s^*(2112)^+\to D_s^+\gamma$ decay combined with an unassociated π^0 and $D_{sJ}^*(2317)^+\to D_s^+\pi^0$ decay combined with an unassociated γ. The fit also includes a contribution from $D_{sJ}(2458)^+\to D_s^*(2112)^+\pi^0$ decay but with an unassociated γ replacing the γ from $D_s^*(2112)^+$ decay. The fit determines the relative size of the background and signal contributions, the mass and width of the $D_{sJ}(2458)^+$, and the $D_{sJ}^*(2317)^+$ mass.

The likelihood fit is validated using Monte Carlo (MC) simulation. This simulation includes $e^+e^-\to c\bar{c}$ events and all known charm states and decays, including the $D_{sJ}^*(2317)^+$ and the signal under study. The generated

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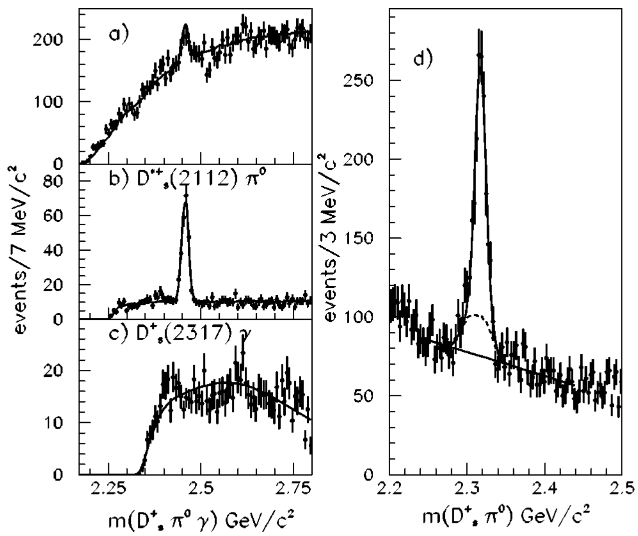

FIG. 2. Maximum likelihood fit results overlaid on the $D_s^+\pi^0\gamma$ mass distribution with (a) no weights and after applying weights corresponding to (b) the decay $D_s^*(2112)^+\pi^0$ and (c) the decay $D_{sJ}^*(2317)^+\gamma$. (d) The mass spectrum of $D_s^+\pi^0$ combinations (with no γ requirement). The solid curve is the fit described in the text. The dashed and lower solid curves are the contributions from $D_{sJ}(2458)^+$ decays and combinatorial background, respectively.

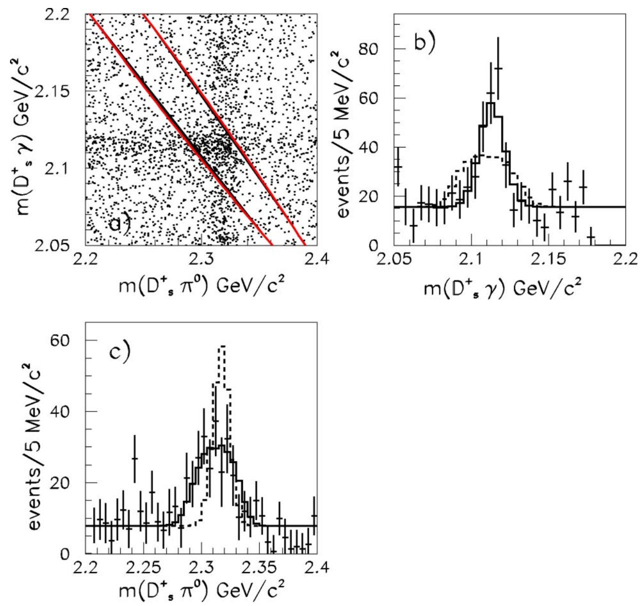

FIG. 3. (a) The $D_s^+\gamma$ versus $D_s^+\pi^0$ mass distribution for all $D_s^+\pi^0\gamma$ combinations. The decay of a zero-width $D_{sJ}(2458)^+$ is kinematically restricted to the region between the two curves. (b) Sideband-subtracted $D_s^+\gamma$ mass distribution with MC simulation for (solid histogram) $D_{sJ}(2458)^+\to D_s^*(2112)^+\pi^0$ and (dashed histogram) $D_{sJ}(2458)^+\to D_{sJ}^*(2317)^+\gamma$. (c) A similar plot for the $D_s^+\pi^0$ mass distribution.

events were processed by a detailed detector simulation [7] and subjected to the same reconstruction and event-selection procedure as the data.

As shown in Fig. 2(a), the fit provides a good description of the $D_s^+\pi^0\gamma$ mass distribution observed in the data. The $D_{sJ}(2458)^+$ signal for a particular decay mode can be isolated by calculating a weight for each $D_s^+\pi^0\gamma$ combination proportional to the relative likelihood contributed by the decay mode of interest. Distributions of events so weighted can be compared to the likelihood function to validate the fit. This is shown in Figs. 2(b) and 2(c). A χ^2 probability calculation gives 22%, 74%, and 11% for Figs. 2(a), 2(b), and 2(c), respectively. The resulting yield of correctly reconstructed $D_{sJ}(2458)^+\to D_s^*(2112)^+\pi^0$ [$D_{sJ}(2458)^+\to D_{sJ}^*(2317)^+\gamma$] decays is 195 ± 26 [0 ± 23], consistent with the fit shown in Fig. 1(d). Excluding the $D_{sJ}(2458)^+$ from the likelihood fit decreases the logarthmic likelihood by approximately 57, corresponding to a significance of more than 10 standard deviations. The fit yields a $D_{sJ}(2458)^+$ mass of 2458.0 ± 1.0 MeV/c^2 with an rms width of 8.5 ± 1.0 MeV/c^2.

The likelihood fit uses the shapes of the $D_s^+\pi^0$ and $D_s^+\gamma$ mass distributions to distinguish between the two possible decay modes $D_{sJ}(2458)^+\to D_s^*(2112)^+\pi^0$ and $D_{sJ}(2458)^+\to D_{sJ}^*(2317)^+\gamma$. These shapes are influenced by the kinematic constraints of $D_{sJ}(2458)^+$ decay shown in Fig. 3(a). Figures 3(b)–3(c) show the sideband-subtracted $D_s^+\pi^0$ and $D_s^+\gamma$ mass projections compared with MC simulations of the two hypotheses (scaled to match the data yield). The $D_{sJ}(2458)^+\to D_s^*(2112)^+\pi^0$ decay mode (solid histograms) produces a narrow $D_s^+\gamma$ mass distribution and a wide $D_s^+\pi^0$ mass distribution. In contrast, the $D_{sJ}(2458)^+\to D_{sJ}^*(2317)^+\gamma$ decay mode (dashed histograms) produces a wide $D_s^+\gamma$ mass distribution and a narrow $D_s^+\pi^0$ mass distribution. Figures 3(b) and 3(c) show that the $D_{sJ}(2458)^+\to D_s^*(2112)^+\pi^0$ hypothesis is in better agreement with the data.

Our previous measurement [1] of the $D_{sJ}^*(2317)^+$ mass using the decay $D_{sJ}^*(2317)^+\to D_s^+\pi^0$ did not explicitly consider background from $D_{sJ}(2458)^+\to D_s^*(2112)^+\pi^0$ decay. This background peaks in the $D_s^+\pi^0$ mass spectrum just below the $D_{sJ}^*(2317)^+$ mass. Shown in Fig. 2(d) is the $D_s^+\pi^0$ invariant mass distribution for a sample of D_s^+ candidates combined with all π^0 candidates, with $p^*>3.5$ GeV/c. Superimposed on this distribution is a binned fit that includes the contribution from the $D_{sJ}(2458)^+$ as estimated from MC simulation and a quadratic background function. The result is a $D_{sJ}^*(2317)^+$ yield of 1022 ± 50 events, a mass of 2317.3 ± 0.4 MeV/c^2, and measured rms width 7.3 ± 0.2 MeV/c^2. These results are an improvement over our earlier measurement [1].

We divide the sources of systematic uncertainty in the $D_{sJ}(2458)^+$ and $D_{sJ}^*(2317)^+$ mass values and production rates into three categories. The first category is associated with the fit procedure. Likelihood fits to MC samples that include samples of $D_{sJ}(2458)^+\to D_s^*(2112)^+\pi^0$ and $D_{sJ}(2458)^+\to D_{sJ}^*(2317)^+\gamma$ decays correctly reproduce the given sample sizes within statistical errors. The average values of the fit results obtained using statistically distinct MC samples corresponding to the measurements in the data are used to place limits on any fit bias.

We obtain the background distribution used in the likelihood from a random selection of D_s^+, π^0, and γ candidates taken from the MC $D_s^+\pi^0\gamma$ sample. To test our sensitivity to this distribution, various selection requirements are altered within reasonable bounds to provide alternate background samples for use in the fit. The resulting changes in yield and mass are used as the second category of systematic uncertainty.

Reconstruction of the decay sequences is the third source of systematic uncertainty. To evaluate the reliability of the MC determination of π^0 efficiency and momentum calibration, we use control samples of $K_S \to \pi^0\pi^0$ and $\tau \to \pi^0 X$. On this basis, we assign a systematic uncertainty of $\pm 5\%$ in π^0 reconstruction efficiency and a relative $\pm 1\%$ in π^0 momentum bias. Similar studies for γ reconstruction reveal a systematic uncertainty of $\pm 3\%$ in γ reconstruction efficiency and $\pm 1\%$ in energy bias. Uncertainties in the D_s^+ and $D_s^*(2112)^+$ masses, taken from world averages [8], also contribute to the systematic uncertainty.

The resulting total systematic uncertainty in the $D_{sJ}(2458)^+$ $[D_{sJ}^*(2317)^+]$ mass is ± 1.0 $[\pm 0.8]$ MeV/c^2.

Using the yields from our fit and correcting for efficiency, we estimate the relative production rate

$$R = \frac{\sigma(D_{sJ}(2458)^+)\mathcal{B}(D_{sJ}(2458)^+ \to D_s^*(2112)^+\pi^0)}{\sigma(D_{sJ}^*(2317)^+)\mathcal{B}(D_{sJ}^*(2317)^+ \to D_s^+\pi^0)} \quad (3)$$

to be 0.25 ± 0.03 (stat) ± 0.03 (syst), requiring $p^* > 3.5$ GeV/c for both states. We also estimate, at 95% C.L.,

$$\frac{\mathcal{B}(D_{sJ}(2458)^+ \to D_{sJ}^*(2317)^+\gamma)}{\mathcal{B}(D_{sJ}(2458)^+ \to D_s^*(2112)^+\pi^0)} < 0.22. \quad (4)$$

The observed rms width of the $D_{sJ}(2458)^+$ is consistent with detector resolution, as determined by Monte Carlo studies. We conclude that the intrinsic width of the $D_{sJ}(2458)^+$ is small ($\Gamma \lesssim 10$ MeV/c^2).

The mass of the $D_{sJ}(2458)^+$ lies above DK and below D^*K thresholds. The narrow width and the isospin-violating decay to $D_s^*(2112)^+\pi^0$ indicate that decay to DK is forbidden and suggest an unnatural spin-parity assignment for the state. Belle has observed the decay $D_{sJ}(2458)^+ \to D_s^+\gamma$ in production from both $c\bar{c}$ continuum [4] and B decay [5]. Such a decay rules out $J=0$ and favors a 1^+ interpretation. Decay distributions studied by Belle further support $J=1$ for $D_{sJ}(2458)^+$ and also $J^P = 0^+$ for $D_{sJ}^*(2317)^+$. The apparent absence of the decay $D_{sJ}(2458)^+ \to D_{sJ}^*(2317)^+\gamma$ may indicate that the electromagnetic decay mechanism cannot compete with $D_s^*(2112)^+\pi^0$, which may be a strong, but isospin-violating, process resulting from η-π^0 mixing, as discussed by Cho and Wise [9].

Our measurement of the $D_{sJ}(2458)^+$ mass (2458.0 ± 1.4 MeV/c^2, with combined statistical and systematic uncertainties) agrees with that obtained by Belle (2456.5 ± 1.7 MeV/c^2) [4], but is two standard deviations smaller than that obtained by CLEO (2463.1 ± 2.1 MeV/c^2) [3]. We obtain a relative yield ($R = 0.25 \pm 0.04$) which agrees with that of Belle (0.26 ± 0.08). Both values are somewhat smaller than that reported by CLEO (0.44 ± 0.13). Our reanalysis of the $D_{sJ}^*(2317)^+ \to D_s^+\pi^0$ sample to account for background from the $D_{sJ}(2458)^+$ gives a mass of 2317.3 ± 0.4 (stat) ± 0.8 (syst) MeV/c^2, which remains consistent with results from CLEO [3] and Belle [4].

In summary, in 91 fb^{-1} of data collected from the BABAR experiment, we have observed a narrow state that decays to $D_s^+\pi^0\gamma$ with a mass of 2458.0 ± 1.0 (stat) ± 1.0 (syst) MeV/c^2. The only significant $D_s^+\pi^0\gamma$ decay mode we observe is through $D_s^*(2112)^+\pi^0$. We measure a mass and yield relative to the $D_{sJ}^*(2317)^+$ similar to those measured by Belle though smaller than those reported by CLEO. The observed width is compatible with our mass resolution. After including the influence of this state, our new measurement of the $D_{sJ}^*(2317)^+$ mass is 2317.3 ± 0.4 (stat) ± 0.8 (syst) MeV/c^2.

We are grateful for the extraordinary contributions of our PEP-II colleagues in achieving the excellent luminosity and machine conditions that have made this work possible. The success of this project also relies critically on the expertise and dedication of the computing organizations that support BABAR. The collaborating institutions wish to thank SLAC for its support and the kind hospitality extended to them. This work is supported by the U.S. Department of Energy and National Science Foundation, the Natural Sciences and Engineering Research Council (Canada), Institute of High Energy Physics (China), the Commissariat à l'Energie Atomique and Institut National de Physique Nucléaire et de Physique des Particules (France), the Bundesministerium für Bildung und Forschung and Deutsche Forschungsgemeinschaft (Germany), the Istituto Nazionale di Fisica Nucleare (Italy), the Foundation for Fundamental Research on Matter (The Netherlands), the Research Council of Norway, the Ministry of Science and Technology of the Russian Federation, and the Particle Physics and Astronomy Research Council (United Kingdom). Individuals have received support from the A. P. Sloan Foundation, the Research Corporation, and the Alexander von Humboldt Foundation.

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