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Observation of a Narrow Meson Decaying to $D_s^+\pi^0$ at a Mass of 2.32 GeV/c^2

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We have observed a narrow state near 2.32 GeV/c^2 in the inclusive $D_s^+\pi^0$ invariant mass distribution from e^+e^- annihilation data at energies near 10.6 GeV. The observed width is consistent with the experimental resolution. The small intrinsic width and the quantum numbers of the final state indicate that the decay violates isospin conservation. The state has natural spin-parity and the low mass suggests a $J^P = 0^+$ assignment. The data sample corresponds to an integrated luminosity of 91 fb^{-1} recorded by the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- storage ring.

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We have found a narrow state decaying to $D_s^+\pi^0$ at a mass near 2.32 GeV/c^2. This result is obtained from a 91 fb^{-1} data sample recorded both on and off the $\Upsilon(4S)$ resonance by the *BABAR* detector at the PEP-II

asymmetric-energy e^+e^- storage ring.

Experimental information on the spectrum of the $c\overline{s}$ meson states is limited. The $^1S_0$ ground state, the D_s^+ meson, is well-established, as is the $^3S_1$ ground state, the $D_s^*(2112)^+$. Only two other $c\overline{s}$ states have been observed thus far [1]. The $D_{s1}(2536)^+$ has been detected in its D^*K decay mode and analysis of the D^* decay angular distribution prefers $J^P = 1^+$ [2]. The $D_{sJ}^*(2573)^+$ was discovered in its D^0K^+ decay mode and so has natural spin-parity. The assignment $J^P = 2^+$ is consistent with the data, but is not established [3].

The spectroscopy of $c\overline{s}$ states is simple in the limit of large charm-quark mass [4, 5]. In that limit, the total angular momentum $\vec{j} = \vec{l} + \vec{s}$ of the light quark, obtained by summing its orbital and spin angular momenta, is conserved. The P-wave states, all of which have positive parity, then have $j = 3/2$ or $j = 1/2$. Combined with the spin of the heavy quark, the former gives total angular momentum $J = 2$ and $J = 1$, while the latter gives $J = 1$ and $J = 0$. The $J^P = 2^+$ and $J^P = 1^+$ members of the $j = 3/2$ doublet are expected to have small width [6], and are identified with the $D_{sJ}^*(2573)^+$ and $D_{s1}(2536)^+$, respectively, although the latter may include a small admixture of the $j = 1/2$, $J^P = 1^+$ state. Theoretical models typically predict masses between 2.4 and 2.6 GeV/c^2 for the remaining two states [6–8], both of which should decay by kaon emission. They would be expected to have large widths [6, 8] and hence should be difficult to detect.

The experimental and theoretical status of the P-wave $c\overline{s}$ states thus can be summarized by stating that experiment has provided good candidates for the two states that theory predicts should be readily observable, but has no candidates for the two states that should be difficult to observe because of their large predicted widths.

The *BABAR* detector is a general purpose, solenoidal, magnetic spectrometer, which is described in detail elsewhere [9]. The detector components employed in this analysis are discussed briefly here. Charged particles are detected and their momenta measured by a combination of a cylindrical drift chamber (DCH) and a silicon vertex tracker (SVT), both operating within a 1.5-T solenoidal magnetic field. A ring-imaging Cherenkov detector (DIRC) is used for charged-particle identification. Electrons are identified and photons measured with a CsI electromagnetic calorimeter (EMC).

The objective of this analysis is to investigate the inclusively-produced $D_s^+\pi^0$ mass spectrum by combining charged particles corresponding to the decay $D_s^+ \to K^+K^-\pi^+$ [12] with π^0 candidates reconstructed from a pair of photons. Events of interest are required to contain at least three reconstructed tracks yielding a net charge of ± 1 and at least two photons each of which must have energy greater than 100 MeV, and to have a ratio of the second to the zeroth Fox-Wolfram moment [10] less than 0.9. Charged-kaon candidates are selected based on the Cherenkov-photon information from the DIRC together with the measured energy loss in the SVT and DCH.

A K^+K^- candidate pair is combined with a third track that fails the kaon criteria (and so is treated as a pion) in a geometrical fit to a common vertex. An acceptable $K^+K^-\pi^+$ candidate must have a fit probability greater than 0.1% and a trajectory consistent with originating from the e^+e^- luminous region. Background from $D^0 \to K^+K^-$, which is evident from the corresponding K^+K^- mass distribution, is removed by requiring that the K^+K^- mass be less than 1.84 GeV/c^2.

A candidate π^0 is formed by constraining a photon pair to emanate from the intersection of the $K^+K^-\pi^+$ candidate trajectory and the beam envelope, performing a one-constraint fit to the π^0 mass, and requiring a fit probability greater than 1%. A given event may yield several acceptable π^0 candidates. We retain only those candidates for which neither photon belongs to another acceptable π^0 candidate.

Finally, to reduce combinatorial background from the continuum and eliminate background from B-meson decay, each $K^+K^-\pi^+\pi^0$ candidate must have a momentum p^* in the e^+e^- center-of-mass frame greater than 2.5 GeV/c.

The upper histogram in Fig. 1(a) shows the $K^+K^-\pi^+$ mass distribution for all candidates. Clear peaks corresponding to D^+ and D_s^+ mesons are seen. To reduce the background further, only those candidates with K^+K^- mass within 10 MeV/c^2 of the $\phi(1020)$ mass or with $K^-\pi^+$ mass within 50 MeV/c^2 of the $\overline{K}^*(892)$ mass are retained; these densely populated regions in the D_s^+ Dalitz plot do not overlap. The decay products of the vector particles $\phi(1020)$ and $\overline{K}^*(892)$ exhibit the expected $\cos^2\theta_h$ behavior required by conservation of angular momentum, where θ_h is the helicity angle. The signal-to-background ratio is further improved by requiring $|\cos\theta_h| > 0.5$. The lower histogram of Fig. 1(a) shows the net effect of these additional selection criteria. The D_s^+ signal ($1.955 < m(K^+K^-\pi^+) < 1.979$ GeV/c^2) and sideband ($1.912 < m(K^+K^-\pi^+) < 1.934$ GeV/c^2 and $1.998 < m(K^+K^-\pi^+) < 2.020$ GeV/c^2) regions are shaded. The D_s^+ signal peak, consisting of approximately 80,000 events, is centered at a mass of (1967.20 ± 0.03) MeV/c^2 (statistical error only).

Figure 1(b) shows the mass distribution for all two-photon combinations associated with the selected events. The π^0 signal ($122 < m(\gamma\gamma) < 148$ MeV/c^2) and sideband ($90 < m(\gamma\gamma) < 110$ MeV/c^2 and $160 < m(\gamma\gamma) < 180$ MeV/c^2) regions are shaded. Candidates in the D_s^+ signal region of Fig. 1(a) are combined with the mass-constrained π^0 candidates to yield the mass distribution of Fig. 1(c). A clear, narrow signal at a mass near 2.32 GeV/c^2 is seen. The shaded histogram represents the events in the $D_s^+ \to K^+K^-\pi^+$ mass sidebands combined with the π^0 candidates. In Fig. 1(d) the mass distributions result from the combination of the D_s^+ candi-

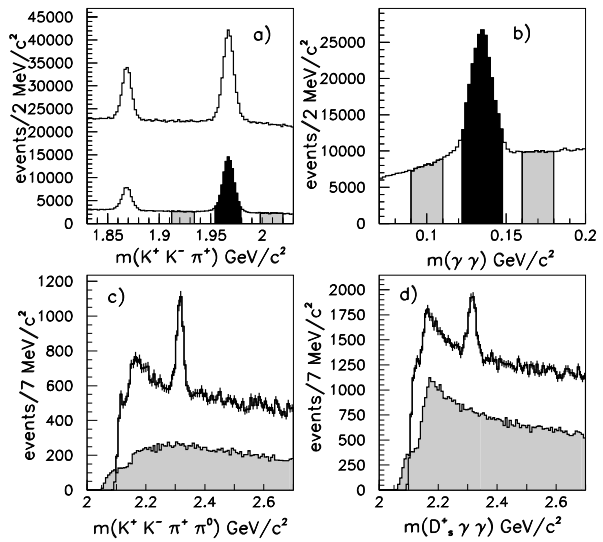

FIG. 1: (a) The distribution of $K^+K^-\pi^+$ mass for all candidate events. Additional selection criteria, described in the text, have been used to produce the lower histogram. (b) The two-photon mass distribution from $D_s^+\pi^0$ candidate events. D_s^+ and π^0 signal and sideband regions are shaded. (c) The $D_s^+\pi^0$ mass distribution for candidates in the D_s^+ signal (top histogram) and $K^+K^-\pi^+$ sideband regions (shaded histogram) of (a). (d) The $D_s^+\gamma\gamma$ mass distribution for signal D_s^+ candidates and a photon pair from the π^0 signal region of (b) (top histogram) and the sideband regions of (b) (shaded histogram).

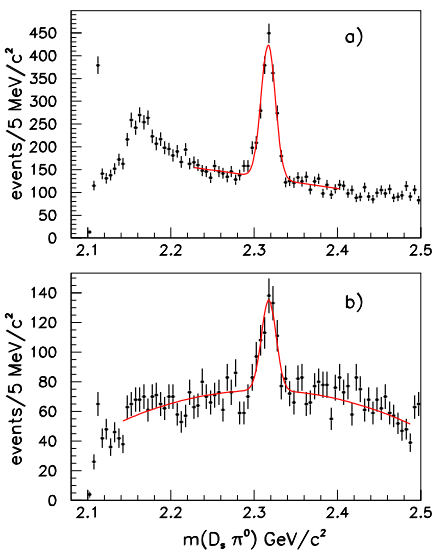

FIG. 2: The $D_s^+\pi^0$ mass distribution for (a) the decay $D_s^+ \to K^+K^-\pi^+$ and (b) the decay $D_s^+ \to K^+K^-\pi^+\pi^0$. The fits to the mass distributions as described in the text are indicated by the curves.

dates with the photon pairs from the π^0 signal and sideband regions of Fig. 1(b) (the sideband distribution is again shaded). In this case, all photon pairs in the signal region of Fig. 1(b) are used. In Figs. 1(c) and 1(d) the 2.32 GeV/c^2 signal is absent from the sideband distributions indicating quite clearly that the peak is associated with the $D_s^+\pi^0$ system. No other signal in the region up to 2.7 GeV/c^2 is evident in these plots, except for a small $D_s^*(2112)^+ \to D_s^+\pi^0$ signal in Fig. 1(c).

In order to improve mass resolution, the nominal D_s^+ mass [1] has been used to calculate the D_s^+ energy for the distributions of Fig. 1(d), for the D_s^+ signal distribution of Fig. 1(c), and for all subsequent mass distributions involving D_s^+ candidates.

The $D_s^+\pi^0$ mass distribution for $p^*(D_s^+\pi^0) > 3.5$ GeV/c is shown in Fig. 2(a). Similar distributions produced for p^* values ranging from 2.5 to 4.5 GeV/c show the same prominent peak at the same mass value. The fit function drawn on Fig. 2(a) comprises a Gaussian function describing the 2.32 GeV/c^2 signal and a third-order polynomial background distribution function. The fit yields 1267 ± 53 candidates in the signal Gaussian with mass (2316.8 ± 0.4) MeV/c^2 and standard deviation (8.6 ± 0.4) MeV/c^2 (statistical errors only). The systematic uncertainty in the mass is conservatively estimated to be less than 3 MeV/c^2. The broad peak in Fig. 2(a) centered at 2.16 GeV/c^2 is due to random $D_s^*(2112)^+\gamma$ combinations where $D_s^*(2112)^+ \to D_s^+\gamma$.

The signal, which we label $D_{sJ}^*(2317)^+$, is observed in both the $\phi\pi^+$ and $\overline{K}^{*0}K^+$ decay modes of the D_s^+. In addition, a sample of $D_s^+ \to K^+K^-\pi^+\pi^0$ decays is selected by adding π^0 candidates (refit to the $K^+K^-\pi^+$ vertex) to each $K^+K^-\pi^+$ candidate. The purity of this D_s^+ sample is enhanced by requiring a π^0 fit probability of at least 10% and selecting the $K^{*\pm}$, $\overline{K}^{*0}$, ϕ, or ρ^+ mass regions for the relevant two-body subsystems. Each resulting D_s^+ candidate is combined with a second π^0 candidate with lab momentum greater than 300 MeV/c. A clear $D_{sJ}^*(2317)^+$ signal is observed as shown in Fig. 2(b). A Gaussian fit yields 273 ± 33 events with a mean of (2317.6 ± 1.3) MeV/c^2 and width (8.8 ± 1.1) MeV/c^2 (statistical errors only). The mean and width are consistent with the values obtained for the $D_s^+ \to K^+K^-\pi^+$ decay mode. The mass distribution of the $D_s^+ \to K^+K^-\pi^+\pi^0$ sample (not shown) peaks at (1967.4 ± 0.2) MeV/c^2 (statistical error only).

We use a Monte Carlo simulation to investigate the possibility that the $D_{sJ}^*(2317)^+$ signal could be due to reflection from other charmed states. This simulation includes $e^+e^- \to c\bar{c}$ events and all known charm states and decays. The generated events were processed by a detailed detector simulation and subjected to the same reconstruction and event-selection procedure as that used for the data. No peak is found in the 2.32 GeV/c^2 $D_s^+\pi^0$ signal region. In addition, no signal peak is produced when the $K^\pm$ and $\pi^\pm$ identities are deliberately

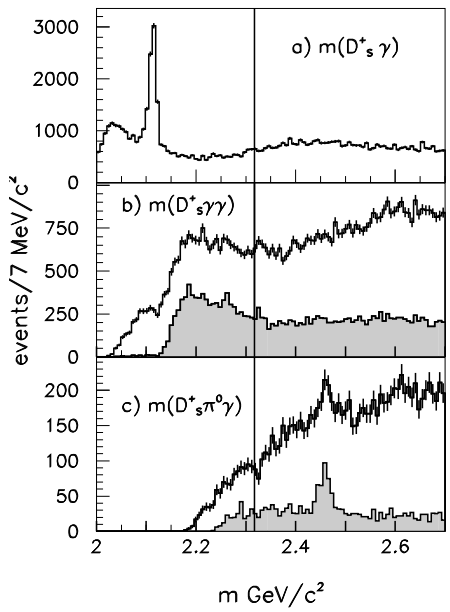

FIG. 3: The mass distribution for (a) $D_s^+\gamma$ and (b) $D_s^+\gamma\gamma$ after excluding photons from the signal region of Fig. 1(b). (c) The $D_s^+\pi^0\gamma$ mass distribution. The lower histograms of (b) and (c) correspond to $D_s^+\gamma$ masses that fall in the $D_s^*(2112)^+$ signal region as described in the text. The vertical line indicates the $D_{sJ}^*(2317)^+$ mass.

exchanged.

Mass resolution estimates for the $K^+K^-\pi^+\pi^0$ system are obtained directly from the data using a fit to the mass distribution $D_s^+ \to K^+K^-\pi^+\pi^0$. The measured width from this mode is consistent with that of the $D_{sJ}^*(2317)^+$ signal. A simulation of the $D_{sJ}^*(2317)^+$ decay to $K^+K^-\pi^+\pi^0$ yields a similar mass resolution after event reconstruction and selection criteria have been satisfied. We conclude that the intrinsic width of the $D_{sJ}^*(2317)^+$ is small ($\Gamma \lesssim 10$ MeV).

The $\cos\theta_h$ distribution of the $D_{sJ}^*(2317)^+$ decay with respect to its direction in the e^+e^- center-of-mass frame has been investigated. The efficiency-corrected distribution is consistent with being flat, as expected for a spin-zero particle, or for a particle of higher spin that is produced unpolarized.

We have also performed a search for the decay $D_{sJ}^*(2317)^+ \to D_s^+\gamma$. Shown in Fig. 3(a) is the $D_s^+\gamma$ mass distribution obtained by combining a D_s^+ candidate in the signal region of Fig. 1(a) with a photon with an energy of at least 150 MeV that does not belong to a $\gamma\gamma$ combination in the signal region of Fig. 1(b). The requirement that the p^* of the $D_s^+\gamma$ system be greater than 3.5 GeV/c is also imposed. There is a clear $D_s^*(2112)^+$ signal, but no indication of $D_{sJ}^*(2317)^+$ production.

The $D_s^+\gamma\gamma$ mass distribution for $p^*(D_s^+\gamma\gamma) > 3.5$ GeV/c, excluding any photon that belongs to the π^0 signal region of Fig. 1(b), is shown as the upper histogram of Fig. 3(b). No signal is observed near 2.32 GeV/c^2. The shaded histogram corresponds to the subset of combinations for which either $D_s^+\gamma$ combination lies in the $D_s^*(2112)^+$ region, defined as $2.096 < m(D_s^+\gamma) < 2.128$ GeV/c^2. Again, no $D_{sJ}^*(2317)^+$ signal is evident, thus demonstrating the absence of a $D_s^*(2112)^+\gamma$ decay mode at the present level of statistics.

The $D_s^+\pi^0\gamma$ mass distribution, excluding any photon that belongs to any π^0 candidate, is shown as the upper histogram of Fig. 3(c). The shaded histogram corresponds to the subset of combinations in which the $D_s^+\gamma$ mass falls in the $D_s^*(2112)^+$ region. No signal is observed near 2.32 GeV/c^2 in either case. A small peak, however, is visible near a mass of 2.46 GeV/c^2. This mass corresponds to the overlap region of the $D_s^*(2112)^+ \to D_s^+\gamma$ and $D_{sJ}^*(2317)^+ \to D_s^+\pi^0$ signal bands that, because of the small widths of both the $D_s^*(2112)^+$ and $D_{sJ}^*(2317)^+$ mesons, produces a narrow peak in the $D_s^+\pi^0\gamma$ mass distribution that survives a $D_s^*(2112)^+$ selection.

If the peak in the $D_s^+\pi^0\gamma$ mass distribution of Fig. 3(c) were due to the production of a narrow state with mass near 2.46 GeV/c^2 decaying to $D_s^*(2112)^+\pi^0$, the kinematics are such that a peak would be produced in the $D_s^+\pi^0$ mass distribution at a mass near 2.32 GeV/c^2. Such a $D_s^+\pi^0$ mass peak, however, would have a root-mean-square of ~ 15 MeV/c^2, which is significantly larger than that obtained for the $D_{sJ}^*(2317)^+$ signal. In addition, Monte Carlo studies indicate that if the apparent signal at 2.46 GeV/c^2 were due to a state that decays entirely to $D_s^*(2112)^+\pi^0$, it would produce only one-sixth the signal we observe at 2.32 GeV/c^2.

Although we rule out the decay of a state of mass 2.46 GeV/c^2 as the sole source of the $D_s^+\pi^0$ mass peak corresponding to the $D_{sJ}^*(2317)^+$, such a state may be produced in addition to the $D_{sJ}^*(2317)^+$. However, the complexity of the overlapping kinematics of the $D_s^*(2112)^+ \to D_s^+\gamma$ and $D_{sJ}^*(2317)^+ \to D_s^+\pi^0$ decays requires more detailed study, currently underway, in order to arrive at a definitive conclusion.

The decay of any $c\overline{s}$ state to $D_s^+\pi^0$ violates isospin conservation, thus guaranteeing a small width. It is possible that the decay proceeds via $\eta - \pi^0$ mixing, as discussed by Cho and Wise [11]. For a parity-conserving decay only a spin-parity assignment in the natural J^P series $\{0^+, 1^-, 2^+, \dots\}$ is allowed. The low mass compared to those of the $D_{s1}(2536)^+$ and the $D_{sJ}^*(2573)^+$ favors $J^P = 0^+$. In this case, decay to $D_s^+\gamma$ is excluded. However, decay of the $D_{sJ}^*(2317)^+$ to $D_s^*(2112)^+\gamma$ is allowed and might compete with decay by pion emission. The shaded mass distribution of Fig. 3(b) suggests that this mode is absent, at least at the present level of statistics. This may simply indicate that decay by pion emission is favored over radiative decay.

Further studies are under way. If, however, the tentative $J^P = 0^+$ assignment is confirmed, the low mass, small width, and decay mode of the $D_{sJ}^*(2317)^+$ are quite different from those predicted by potential models [6–8].

In summary, in 91 fb^{-1} of data collected by the *BABAR* experiment we have observed a narrow state in the inclusive $D_s^+\pi^0$ mass distribution near 2.32 GeV/c^2. We find no evidence for the decay of this state to $D_s^+\gamma$, $D_s^*(2112)^+\gamma$, or $D_s^+\gamma\gamma$. Since a $c\bar{s}$ meson of this mass contradicts current models of charm meson spectroscopy [6–8], either these models need modification or the observed state is of a different type altogether, such as a four-quark state.

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