Observation of a Narrow Meson Decaying to $D_s^+ \pi^0$ at a Mass of 2.32 GeV/c²

We have observed a narrow state near 2.32 GeV/c^2 in the inclusive D^+_s π^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 π^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 Υ(4S) resonance by the BABAR detector at the PEP-II
asymmetric-energy $e^+e^-$ storage ring.

Experimental information on the spectrum of the $c\bar{s}$ meson states is limited. The $^3S_1$ ground state, the $D_1^+$ meson, is well-established, as is the $^3S_1$ ground state, the $D_1^*(2112)^+$. Only two other $c\bar{s}$ 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 $D_{s1}^{*+}(2573)$ 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 $c\bar{s}$ states is simple in the limit of large charm-quark mass [4, 5]. In that limit, the total angular momentum $j = l + s$ 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 $D_{s1}^{*+}(2573)^+$ 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 $c\bar{s}$ 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 $D_s^+ \rightarrow K^+K^-\pi^+$ [12] with $\pi^0$ candidates reconstructed from a pair of photons. Events of interest are required to contain at least three reconstructed tracks yielding a net charge of $\pm 1$ 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 $K^+K^-$ candidates that fail the kaon criteria (and so are 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 $D^0K^+K^-$, 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 $\pi^0$ 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 $\pi^0$ mass, and requiring a fit probability greater than 1%. A given event may yield several acceptable $\pi^0$ candidates. We retain only those candidates for which neither photon belongs to another acceptable $\pi^0$ 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 $K^*(892)$ 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 $K^*(892)$ exhibit the expected $\cos^2\theta_h$ behavior required by conservation of angular momentum, where $\theta_h$ 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 $\pi^0$ 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. In the $D_s^+$ signal region of Fig. 1(a) are combined with the mass-constrained $\pi^0$ candidates to yield the mass distribution of Fig. 1(c). A clear, narrow signal at a mass near 2.82 GeV/$c^2$ is seen. The shaded histogram represents the events in the $D_s^+ \rightarrow K^+K^-\pi^+$ mass sidebands combined with the $\pi^0$ candidates. In Fig. 1(d) the mass distributions result from the combination of the $D_s^+$ candi-
The fit function drawn on Fig. 2(a) comprises a Gaussian combination where $D_s^*(2112)^+ \rightarrow D_s^+ \gamma$. The signal, which we label $D_{sJ}^*(2317)^+$, is observed in both the $\phi \pi^+$ and $K^{*0} K^+$ decay modes of the $D_s^+$. In addition, a sample of $D_s^+ \rightarrow K^+ K^- \pi^+ \pi^0$ decays is selected by adding $\pi^0$ 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 $\pi^0$ fit probability of at least 10% and selecting the $K^{*0}$, $K^{*0}$, $\phi$, or $\rho$ mass regions for the relevant two-body subsystems. Each resulting $D_s^+$ candidate is combined with a second $\pi^0$ 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 $273 \pm 33$ events with a mean of $2317.6 \pm 1.3$ MeV/c$^2$ and width $8.8 \pm 1.1$ MeV/c$^2$ (statistical errors only). The mean and width are consistent with the values obtained for the $D_s^+ \rightarrow K^+ K^- \pi^+$ decay mode. The mass distribution of the $D_s^+ \rightarrow K^+ K^- \pi^+ \pi^0$ sample (not shown) peaks at $1967.4 \pm 0.2$ 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 charm states. This simulation includes $e^+ e^- \rightarrow c \bar{c}$ 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 $K^+$ and $\pi^+$ identities are deliberately
The shaded histogram corresponds to the subset of combinations for which either $D_s^+\gamma\gamma$ combination lies in the $D_s^+(2112)^+$ region, defined as $2.096 < m(D_s^+\gamma\gamma) < 2.128$ GeV/c$^2$. Again, no $D_{sJ}^+(2317)^+$ signal is evident, thus demonstrating the absence of a $D_s^+(2112)^+$ decay mode at the present level of statistics.

The $D_s^+\pi^0\gamma$ mass distribution, excluding any photon that belongs to any $\pi^0$ 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 $D_s^+(2112)^+\rightarrow D_s^+\gamma$ and $D_{sJ}^+(2317)^+\rightarrow D_s^+\pi^0$ 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 $\sim 15$ 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 $D_s^+(2112)^+\rightarrow D_s^+\gamma$ and $D_{sJ}^+(2317)^+\rightarrow D_s^+\pi^0$ decays requires more detailed study, currently underway, in order to arrive at a definitive conclusion.

The decay of any $c\bar{s}$ 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 $\{0^+, 1^-, 2^+, \ldots \}$ is allowed. The low mass compared to those of the $D_{sJ}^+(2536)^+$ 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].

**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.
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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\[1\] Also with Università della Basilicata, Potenza, Italy
\[2\] Also with IFIC, Instituto de Física Corpuscular, CSIC-Universidad de Valencia, Valencia, Spain
\[3\] Deceased

[12] The inclusion of charge-conjugate configurations is implied throughout this letter.

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