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 at a mass value near 2.32 GeV/c^2 in the $D_s^+\pi^0$ invariant mass distribution. The observed width is consistent with the experimental mass resolution. The narrowness and the quantum numbers of the final state suggest that the decay is isospin violating. The state has natural spin-parity and the low mass value suggests a $J^P = 0^+$ assignment. The absence of any corresponding signal in the $D_s^+\gamma$ mass distribution is consistent with this hypothesis. The data sample corresponds to an integrated luminosity of 91 fb^{-1} recorded by the *BABAR* detector at the PEP-II asymmetric e^+e^- storage ring.

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In this letter we present evidence for a narrow meson decaying to $D_s^+\pi^0$at a mass near 2.32 GeV/c^2. These results are obtained from a 91 fb^{-1} data sample taken both on and off the $\Upsilon(4S)$ resonance by the *BABAR* detector at the PEP-II asymmetric e^+e^- collider.

Knowledge spectrum of $c\overline{s}$ meson states [?] is limited. The $^1S_0$ ground state, the D_s^+ meson, is well-established, as is the $^3S_1$ ground state, the $D_s^*(2112)$, although the spin-parity (J^P) assignment for the latter is still in question. Only two other $c\overline{s}$ states have been observed thus far. The $D_{s1}(2536)$ has been detected in its D^*K decay mode and analysis of the D^* decay angular distribution prefers $J^P = 1^+$ [?]. 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 by no means established [?].

The spectroscopy of $c\overline{s}$ states is simple in the limit in which the charm quark mass is regarded as very large[? ?]. Then the total angular momentum j_l of the light quark, adding its spin and orbital angular momentum, is a good quantum number. The p-wave states, all of which have positive parity, then have $j_l = 3/2$ or $j_l = 1/2$. Combined with the spin of the heavy quark, the former give total angular momentum $J = 2$ and $J = 1$, while the latter give $J = 1$ and $J = 0$. The $D_{sJ}^*(2573)$ is identified then as the $J = 2, j_l = 3/2$ state. The $D_{s1}(2536)(J^P = 1^+, j_l = 3/2)$ state can decay to $D^*(J^P = 1^-, j_l = 1/2)$ by K emission only through d wave because of conservation of the light quark angular momentum. This explains the narrow width of this state. Theoretical predictions typically find the two $j_l = 1/2$ states between 2.4 GeV and 2.6 GeV. These would then decay to the D or D^* by s-wave emission of a K and would thus be much broader than the $j_l = 3/2$ states, and hence difficult to observe. The light quark angular momentum is not rigorously conserved and the two $J = 1$ p-wave states actually mix, but the overall picture survives: experiment has provided good candidates for the two states which theory predicts should be readily observable and has no candidates for the two states which should be difficult to observe because of their predicted large widths.

Our observation of a natural-spin-parity meson with the apparent quark composition $c\overline{s}$ changes this picture since the scalar $j_l = 1/2$ meson has a much lower mass than expected. A similar phenomenon might then be expected in the non-strange charm meson system.

The *BABAR* detector is a general purpose, solenoidal, magnetic spectrometer which is described in detail elsewhere [?]. Those 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 and photons are identified and measured by means of a CsI electromagnetic calorimeter (EMC).

The objective of this analysis is to define candidate charged track combinations corresponding to the decay $D_s^+ \to K^+K^-\pi^+$ [1] and to combine each with a π^0 reconstructed from a pair of photons detected in the EMC in order to investigate the inclusively-produced $D_s^+\pi^0$ mass spectrum. Events of interest must contain at least three reconstructed charged tracks yielding a net charge of ±1 and at least two photons each of which must have greater than 100 MeV in the EMC. Topological requirements designed to reduce background contributions from light-quark jet continuum events must also be satisfied. A charged kaon candidate is selected by means of measured energy-loss in the SVT and DCH together with Cherenkov ring-image information from the DIRC.

A K^+K^- candidate pair is combined with a third charged track which fails the kaon criteria (and so is treated as a pion) in a geometrical fit to a common vertex. An acceptable candidate must have fit probability greater than 0.1%, position consistent with the e^+e^- collision axis, and $K^+K^-\pi^+$ mass less than 2.05 GeV/c^2.

A candidate π^0 is formed by constraining a γ pair to emanate from the $K^+K^-\pi^+$ vertex, 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. However, we retain only those candidates for which neither photon belongs to another acceptable candidate. We find that this requirement leads to a significant reduction of background with little loss of signal in the subsequent analysis.

Finally, in order to eliminate background from B meson decay, each $K^+K^-\pi^+\pi^0$ candidate must have a re-

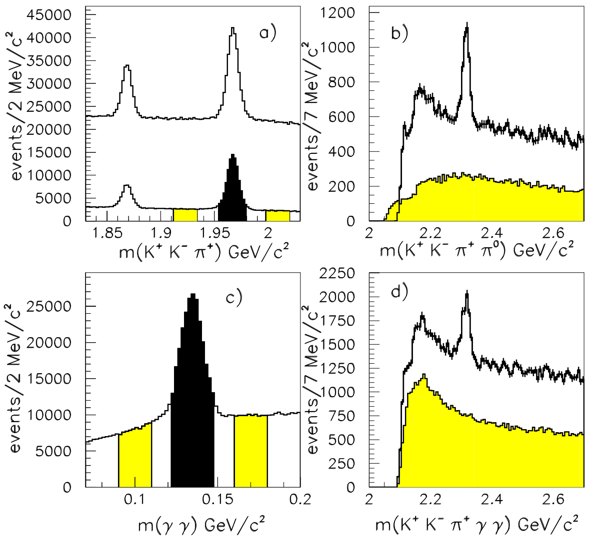

FIG. 1: (a) The distribution of $K^+K^-\pi^+$ mass for all candidate events. The lower histogram has been selected as described in the text. (b) The $D_s^+\pi^0$ mass distribution for candidates in the signal (top histogram) sideband regions (shaded histogram) of (a). (c) The two-photon invariant mass distribution from $D_s^+\pi^0$ candidate events. The shaded regions indicate signal and sideband π^0 regions. (d) The $D_s^+\pi^0$ mass distribution for candidates in the π^0 signal region of (c) (top histogram) and candidates in the sideband regions of (c) (shaded histogram).

sultant momentum p^* in the overall center-of-mass (c.m.) 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 due to D^+ and D_s^+ mesons are seen. The corresponding K^+K^- mass distribution (not shown) produces a clear D^0 signal. This source of background is removed by requiring that the K^+K^- mass be less than 1.84 GeV/c^2. In order to further reduce background, 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 regions do not overlap in the D_s^+ Dalitz plot. Each vector meson has a helicity cosine ($\cos\theta_h$) distribution showing the $\cos^2\theta_h$ dependence expected for helicity-zero production. 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 selection criteria. The D_s^+ signal ($1.955 < m(K^+K^-\pi^+) < 1.979$ GeV/c^2) and sideband ($1.920 < m(K^+K^-\pi^+) < 1.940$ and $2.000 < m(K^+K^-\pi^+) < 2.020$ GeV/c^2) regions are shaded.

Fig. 1(c) shows all two-photon mass combinations associated with the selected events. The π^0 signal ($122 < m(\gamma\gamma) < 148$ MeV/c^2) and sideband ($90 < m(\gamma\gamma) < 110$ and $160 < m(\gamma\gamma) < 180$ MeV/c^2) regions are shaded. Events in the D_s^+ signal region of Fig. 1(a) are combined with π^0 candidates to yield the mass distribution of Fig. 1(b). 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^+ sidebands. In Fig. 1(d) the mass distributions corresponding to the π^0 signal and sideband regions of Fig. 1(c) are compared (the sideband distribution is again shaded). In Figs. 1(b) 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 the plots, except for the small $D_s^*(2112)$ signal in Fig. 1(b).

The $D_s^+\pi^0$ system is examined in various p^* regions in Figs. 2(a)–(c). Clearly, the 2.32 GeV/c^2 signal is present throughout the entire p^* range and is enhanced at large p^*, where combinatoric background is reduced. For $p^* > 3.5$ GeV/c, shown in Fig. 2(d), clear evidence for $D_s^*(2112) \to D_s^+\pi^0$ decay is observed. The fit function drawn on this figure comprises a Gaussian function describing the 2.32 GeV/c^2 signal and a third order polynomial background distribution function. For the signal, the fit gives mass and standard deviation values $m = 2316.8 \pm 0.4$ and $\sigma = 8.6 \pm 0.4$ MeV/c^2, respectively. A fit to the mass difference $\Delta m = m(K^+K^-\pi^+\pi^0) - m(K^+K^-\pi^+)$ in the region of the $D_s^*(2112)$ gives the value $\Delta m = 144.2 \pm 0.1$ MeV/c^2, in agreement with previous experiments [?].

The signal, which we label the $D_s^*(2317)$, is seen separately for the $\phi\pi^+$ and $\overline{K}^{*0}K^+$ decay modes of the D_s^+. As a further check, the $D_s^+\pi^0$ mass distribution is shown in Fig. 2(e) for events corresponding to the $D_s^+ \to K^+K^-\pi^+\pi^0$ decay. The sample of candidates for this decay mode is enhanced by selecting the $K^{*\pm}$, $\overline{K}^{*0}$, ϕ, or ρ^+ regions for the relevant two-body subsystems. A clear $D_s^*(2317)$ signal is observed, and the Gaussian fit yields mass and width values $m = 2317.6 \pm 1.3$ and $\sigma = 8.8 \pm 1.1$ MeV/c^2, respectively, in excellent agreement with the values obtained for the $D_s^+ \to K^+K^-\pi^+$ decay mode.

We use a Monte Carlo simulation to investigate the possibility that the $D_s^*(2317)$ signal could be the result of a reflection from other charmed states. This Monte Carlo includes generic $e^+e^- \to c\bar{c}$ events and their known states and decays. The generated events were processed by a detailed detector simulation and subjected to the same reconstruction and event selection procedure as 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 were deliberately exchanged.

Mass resolution estimates for the $K^+K^-\pi^+\pi^0$ system are obtained directly from the data from fits to the D_s^+ signal region for $D_s^+ \to K^+K^-\pi^+\pi^0$ decay, to the $D^*(2010)$ region for decay to $D^+\pi^0$ with $D^+ \to K^+K^-\pi^+$, and to the $D_s^*(2112)$ region for decay to

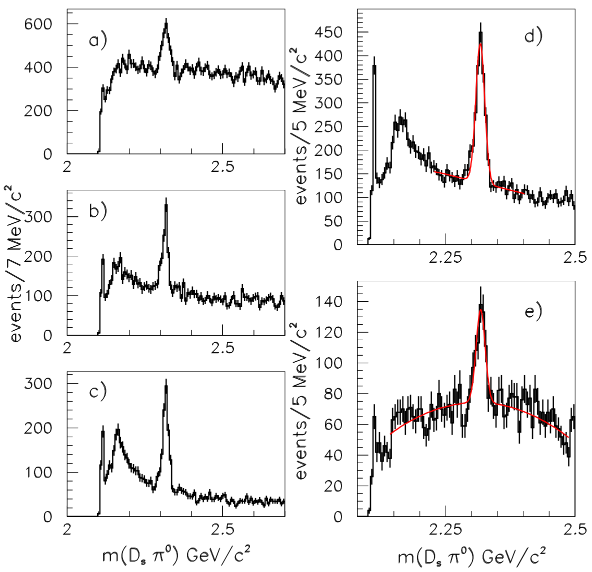

FIG. 2: The $D_s^+\pi^0$ invariant mass distribution for (a) $2.5 < p^* < 3.5$ GeV/c, (b) $3.5 < p^* < 4.5$ GeV/c, (c) $p^* > 4.5$ GeV/c, and (d) for $p^* > 3.5$ GeV/c. e) The $D_s^+\pi^0$ mass distribution for the alternate decay mode $D_s^+ \to K^+K^-\pi^+\pi^0$ for $p^* > 3.5$ GeV/c. The results of the fits to the mass distributions described in the text are indicated by the curves in (d) and (e).

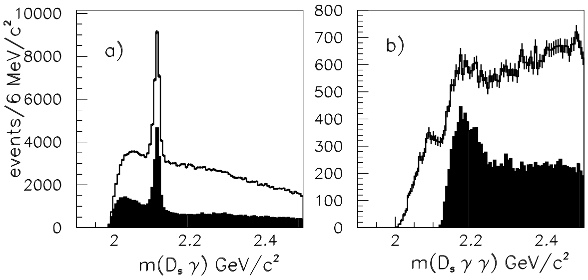

FIG. 3: (a) The invariant mass distribution for all $D_s^+\gamma$ combinations from $D_s^+\pi^0$ candidate events where γs from the signal region of Fig. 2(c) have been excluded. The shaded region represents $D_s^+\gamma$ combinations for which $p^* > 3.5$ GeV/c. (b) The invariant mass distribution for all $D_s^+\gamma\gamma$ combinations from $D_s^+\pi^0$ candidate events where γs from the signal region of Fig. 2(c) have been excluded. The shaded distribution contains events for which either $D_s^+\gamma$ combination has a mass in the $D_s^{*+}(2112)\gamma$ region defined in the text.

$D_s^+\pi^0$ with $D_s^+ \to K^+K^-\pi^+$. The fitted values of the Gaussian signal function width obtained for these samples is consistent within systematic uncertainty with that of the $D_s^*(2317)$ signal. Monte Carlo events simulating $D_s*(2317)$ decay to $K^+K^-\pi^+\pi^0$ yield a similar mass resolution value after event reconstruction and selection criteria have been satisfied. Therefore we conclude that the intrinsic width of the $D_s^*(2317)$ is small ($\Gamma \lesssim 10$ MeV).

We have also performed a search for the decay $D_s^*(2317) \to D_s^+\gamma$. Shown in Fig. 3(a) is the $D_s^+\gamma$ effective mass distribution obtained by combining a D_s^+ candidate in the signal region of Fig. 1(a) with a γ which does not belong to a $\gamma\gamma$ combination in the signal region of Fig. 1(c). For the shaded histogram of Fig. 3(a) there is an additional requirement that the p^* of the $D_s^+\gamma$ system be greater than 3.5 GeV/c. No $D_s^*(2317)$ signal is seen in either histogram.

The $D_s^+\gamma\gamma$ mass distribution corresponding to the upper histogram of Fig. 3(a) is shown as the upper histogram of Fig. 3(b). Any γ which belongs to a $\gamma\gamma$ combination in the signal region of Fig. 1(c) is excluded. 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 $D_s^*(2317)$ signal is evident, thus demonstrating the absence of a $D_s^*(2112)\gamma$ decay mode at the present level of statistics.

A similar investigation of the $D_s^+\pi^0\pi^0$ system reviews no signal near 2.32 GeV/c^2.

Decay of a D_s^* state to a $D_s^+\pi^0$ system violates isospin conservation and so may proceed via a mechanism similar to that discussed by Cho and Wise [?]. It is possible that there is also an electromagnetic component within the decay mechanism. In either case, a width which is comparable to experimental resolution is not surprising. For a parity conserving decay only a spin parity assignment in the series $\{0^+, 1^-, 2^+, \dots\}$ is allowed. For all of these except $J^P = 0^+$, decay to $D_s^+\gamma$ is possible. Consequently, the apparent absence of this decay mode for the $D_s^*(2317)$ is consistent with such a spin-parity assignment. The low mass value compared to those of the $D_{s1}(2536)$ and the $D_{sJ}^*(2573)$ also favors such an assignment, since the relativistic quark potential model predicts a lower mass for the $^3P_0$ state and there is at present no other candidate for this assignment. However, if this interpretation is correct, decay of the $D_s^*(2317)$ to $D_s^*(2112)\gamma$ is allowed and would be expected to occur. The mass distribution of Fig. 3(b) suggests that this mode is absent, at least at the present level of statistics. This seems surprising and it may indicate that a different interpretation of the signal is required. For example, if the signal near 2.32 GeV/c^2 corresponds to a $D_s^+\pi^0$ "molecule," it has no bearing on the $c\overline{s}$ level structure. However, it would then seem difficult to explain the small width for an object so far above threshold. Alternatively, it could be a zero isospin DK bound state analogous to the $f_0(980)$, the $a_0(980)$, or the $\Lambda(1405)$.

Further studies are under way. If, however, the tentative $J^P = 0^+$ assignment is borne out, and if the signal can indeed be considered to correspond to a true $c\bar{s}$ state, then this would constitute the first observation of a charm scalar meson.

In that case, its properties are quite different from those predicted by the potential model [?] and also from the expectations based on HQET. The observed mass is too low by about 140 MeV/c^2, such that it is even below DK threshold. This makes the width very small, whereas the model prediction is that it should be very large. This might call into question the predictive power of such models in the mass region below 2.5 GeV/c^2.

In this regard, it should be noted that the potential model predictions for the P-wave states with $J^P = 0^+$ in the strange and isovector meson sectors exhibit some discrepancies of similar magnitude. The predicted mass of the K_0^* is 1240 MeV/c^2, whereas the observed state is at 1430 MeV/c^2, a difference of approximately 190 MeV/c^2. In the isovector sector, the predicted and observed masses of the $a_2(1320)$, $a_1(1260)$ and $b_1(1235)$ agree very well. However, the related a_0 mass is predicted to be 1090 MeV/c^2, while the observed mass of the $a_0(1450)$ is about 1470 MeV/c^2. Assuming that this is in fact part of the a_2, a_1, and b_1 P-wave multiplet, this represents a discrepancy of approximately 380 MeV/c^2.

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