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Observation of a New D_s Meson Decaying to DK at a Mass of 2.86 GeV/c^2

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We observe a new D_s meson with mass $(2856.6 \pm 1.5_{stat.} \pm 5.0_{syst.})$ MeV/c^2 and width $(48 \pm 7_{stat.} \pm 10_{syst.})$ MeV/c^2 decaying into D^0K^+ and $D^+K^0_S$. In the same mass distributions we also observe a broad structure with mass $(2688 \pm 4_{stat.} \pm 3_{syst.})$ MeV/c^2 and width $(112 \pm 7_{stat.} \pm 36_{syst.})$ MeV/c^2. To obtain this result we use 240 fb^{-1} of data recorded by the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- storage rings at the Stanford Linear Accelerator Center running at center-of-mass energies near 10.6 GeV.

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The spectrum of known $c\bar{s}$ states can be described economically as two s-wave states (D_s^+, D_s^{*+}) with $J^P = 0^-, 1^-$, and four p-wave states ($D_{s0}^*(2317)^+$, $D_{s1}(2460)^+$, $D_{s1}(2536)^+$, $D_{s2}(2573)^+$) with $J^P = 0^+, 1^+, 1^+, 2^+$, though the last two spin-parity assignments are not firmly established. Whether this picture is correct remains controversial because the states at 2317 MeV/c^2 and 2460 MeV/c^2 [1] had been expected to lie at much higher masses [2].

We report here on a new $c\bar{s}$ state and a broad structure observed in the decay channels D^0K^+ and $D^+K^0_S$. This analysis is based on a 240 fb^{-1} data sample recorded near the $\Upsilon(4S)$ resonance by the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- storage rings.

The *BABAR* detector is described in detail elsewhere [3]. 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. Photon energies are measured with a CsI electromagnetic calorimeter. We use information from the DIRC and energy-loss measurements in the SVT and DCH to identify charged kaon and pion candidates.

We observe three inclusive processes [4]:

$$e^+e^- \rightarrow D^0K^+X, D^0 \rightarrow K^-\pi^+ \quad (1)$$
$$e^+e^- \rightarrow D^0K^+X, D^0 \rightarrow K^-\pi^+\pi^0 \quad (2)$$
$$e^+e^- \rightarrow D^+K^0_SX, D^+ \rightarrow K^-\pi^+\pi^+, K^0_S \rightarrow \pi^+\pi^- \quad (3)$$

For channels (1) and (2) we perform a vertex fit for the $K^-\pi^+$ and require a χ^2 probability greater than 0.1%. For the π^0 in channel (2), we consider the photons that emanate from the $K^-\pi^+$ vertex, perform a fit with the π^0 mass constraint, and require a χ^2 probability greater than 1%. The combinatorial background is reduced by requiring the π^0 laboratory momentum to be greater than 350 MeV/c.

To purify the D^0 sample in channel (2), its quasi-two body decays [5] $K^*\pi$ and $K\rho$ are used, allowing ranges of ± 50 MeV/c^2 around the K^* mass for $K\pi$ and ± 100 MeV/c^2 around the ρ mass for $\pi\pi$.

For channel (3), we fit two pions with the same charge and a kaon of the opposite charge to a common vertex to form the D^+ candidate, and require a χ^2 probability greater than 0.1%. We obtain the K^0_S sample with a fit that constrains the mass and require a χ^2 probability greater than 2%. K^0_S candidates are retained only if their decay lengths are greater than 0.5 cm.

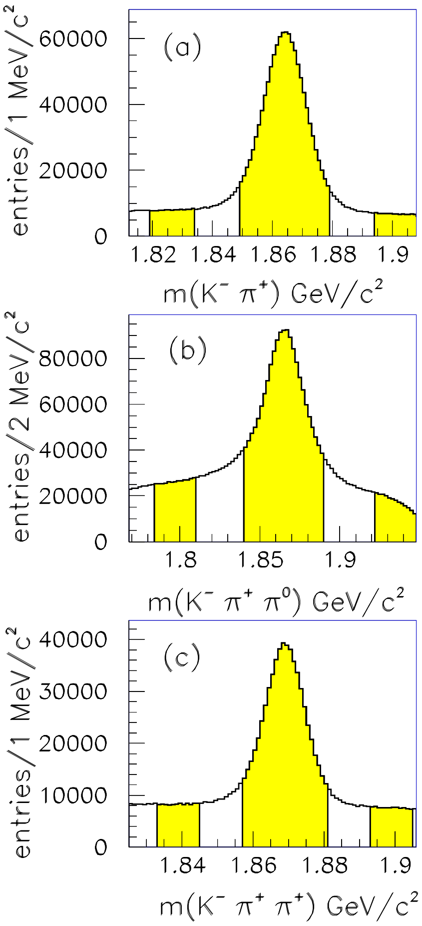

FIG. 1: (a) $K^-\pi^+$, (b) $K^-\pi^+\pi^0$ and (c) $K^-\pi^+\pi^+$ mass distributions for all candidate events to channels (1), (2) and (3) respectively. The shaded regions indicate the definition of signal and sidebands regions.

For all three channels, the D candidate is combined with an identified K, requiring a vertex fit χ^2 probability greater than 0.1%, and constraining the vertex to be in the e^+e^- luminous region. To reduce combinatorial background from the continuum ($e^+e^- \rightarrow q\bar{q}, q = u, d, s, c$) and B-meson decays, each DK candidate must have a

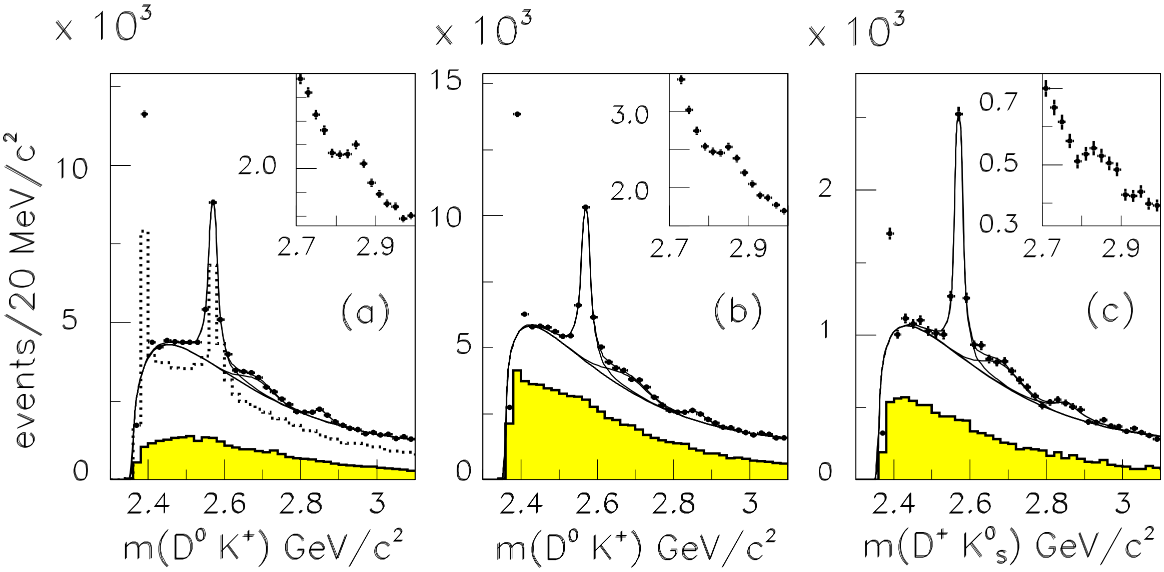

FIG. 2: The DK invariant mass distributions for (a) $D^0_{K^-\pi^+}K^+$, (b) $D^0_{K^-\pi^+\pi^0}K^+$ and (c) $D^+_{K^-\pi^+\pi^+}K^0_s$. The shaded histograms are for the D-mass sideband regions. The dotted histogram in (a) is from $e^+e^- \to c\bar{c}$ Monte Carlo simulations incorporating previously known D_s states with an arbitrary normalization. The insets show an expanded view of the 2.86 GeV/c^2 region. The solid curves are the fitted background threshold functions from the three separate fits described in the text.

momentum p^* in the e^+e^- center-of-mass frame greater than 3.5 GeV/c.

Figs. 1(a), (b) and (c) show the $K^-\pi^+$, $K^-\pi^+\pi^0$, and $K^-\pi^+\pi^+$ invariant mass distributions, respectively. All distributions show pronounced peaks at the D mass, with signal yields of about 950,000, 790,000, and 430,000 events. Fits using a polynomial and a single Gaussian give $\sigma = 7.6, 12.6, 6.0$ MeV/c^2 for the three widths. We define the signal region by $\pm 2\sigma$ from the fitted D mass and establish sidebands at $(-6\sigma, -4\sigma)$ and $(4\sigma, 6\sigma)$. In the signal regions, the signal-to-background ratios are 4.1, 1.2, and 2.2 respectively.

Selecting events in the D signal regions, Fig. 2 shows the D^0K^+ invariant mass distributions for channels (1) and (2), and the $D^+K^0_S$ invariant mass distribution for channel (3). To improve mass resolution, the nominal D mass and the reconstructed 3-momentum are used to calculate the D energy for channels (1) and (3). Since channel (2) has a poorer D^0 resolution, each $K^-\pi^+\pi^0$ candidate is kinematically fit with a D^0 mass constraint and we require a χ^2 probability greater than 0.1%.

We find that the fraction of events having more than one DK combination per event is 0.9% for channels (1) and (3) and 3.4% for channel (2). In the rest of the paper, we use the term reflection to describe enhancements produced by two or three body decays of narrow resonances where one of the decay products is missed.

The three mass spectra in Fig. 2 present similar features.

- A single bin peak at 2.4 GeV/c^2 due to a reflection from the decays of the $D_{s1}(2536)^+$ to $D^{*0}K^+$ or $D^{*+}K^0_S$ in which the π^0 or γ from the D^* decay is missed. This state, if $J^P = 1^+$, cannot decay to DK.
- A prominent narrow signal due to the $D_{s2}(2573)^+$.
- A broad structure peaking at a mass of approximately 2.7 GeV/c^2.
- An enhancement around 2.86 GeV/c^2. This can be seen better in the expanded views shown in the insets of Fig. 2.

In the following we examine different background sources: combinatorial, possible reflections from D^* decays, and particle misidentification.

Backgrounds come both from events in which the candidate D meson is correctly identified and from events in which it is not. The first case can be studied combining a reconstructed D meson with a kaon from another $\bar{D}$ meson in the same event, using data with fully reconstructed $D\bar{D}$ pairs or Monte Carlo simulations. No signal near 2.7 or 2.86 GeV/c^2 is seen in the DK mass plots for these events. The second case can be studied using the D mass sidebands. The shaded regions in Fig. 2 show the DK mass spectra for events in the D sideband regions normalized to the estimated background in the signal region. No prominent structure is visible in the sideband mass spectra.

We examined the possibility that the features at 2.7 and 2.86 GeV/c^2 could be a reflection from D^* or other higher mass resonances. Candidate DK pairs where the D is a D^*-decay product are identified by forming $D\pi$ and $D\gamma$ combinations and requiring the invariant-mass difference between one of those combinations and the D to be within $\pm 2\sigma$ of the known $D^* - D$ mass difference. No signal near 2.7 or 2.86 GeV/c^2 is seen in the DK mass plots for these events. Events belonging to these possible reflections (except for the $D^{*0} \to D^0\gamma$ events, which could not be isolated cleanly) have been removed from the mass distributions shown in Fig. 2 (corresponding to $\approx$8% of the final sample).

We use a Monte Carlo simulation to investigate the possibility that the 2.7 or 2.86 GeV/c^2 signals could be due to reflections from other charmed states. This simulation includes $e^+e^- \to c\bar{c}$ events and all known charmed states and decays. The Monte Carlo events were generated using a detailed detector simulation and subjected to the same reconstruction and event-selection procedure as was used for the data. The D^0K^+ effective mass distribution for these Monte Carlo events is shown (dotted) in Fig. 2(a) for channel (1). The normalization is arbitrary. No peak is found in the 2.7 and 2.86 GeV/c^2 D^0K^+ signal regions. We note that the simulation underestimates the size of the $D_{s1}(2536)^+$ reflection and the $D_{s2}(2573)^+$ signal relative to the background. No such discrepancy is found in the study of the $D^0\pi^+$ final state, therefore we attribute this effect to a poor knowledge of the strange-charmed meson cross sections. In order to improve the data-Monte Carlo comparison, the events having a $D_{s1}(2536)^+$ and $D_{s2}(2573)^+$ in the final state have been scaled up by factors 5 and 2 respectively.

We checked the possibility that the structures at 2.7 and 2.86 GeV/c^2 are due to misidentifying pions as kaons by assigning the kaon mass to the pion in $D^0\pi^+$ data events. We observe no structure near 2.7 or 2.86 GeV/c^2 in the resulting D^0K^+ invariant mass distribution. Monte Carlo simulations and tests using the data show that these structures also do not originate from protons misidentified as kaons from high mass charmed baryon decays.

Wrong sign D^0K^- mass distributions for channels (1) and (2) have also been examined and we find no signal in either mass spectrum.

A more detailed study in channel (1) of the 2.7 GeV/c^2 structure shows a broad structure in this mass region for events from the D^0 sidebands in which the DK candidate has a very low p^* ($p^* < 3$ GeV/c). This is not seen in channels (2) or (3) however. We conclude that the assignment of the 2.7 GeV/c^2 structure to a reflection remains inconclusive.

By comparing the reconstructed mass distributions for the DK system with those generated with Monte Carlo simulations, we obtain the mass resolutions. The resolutions are similar in the three channels, increasing linearly from 1.7 MeV/c^2 at a mass of 2.5 GeV/c^2, to 3.5 MeV/c^2 at a mass of 2.86 GeV/c^2.

In the following discussion we label as $D_{sJ}(2860)^+$ the structure in the 2.86 GeV/c^2 mass region and as $X(2690)^+$ the structure observed in the 2.7 GeV/c^2 mass region. We fit to the three DK mass spectra shown in Fig. 2 from 2.42 GeV/c^2 to 3.1 GeV/c^2 (excluding the $D_{s1}(2536)^+$ reflection) using a binned χ^2 minimization. The background for the three DK mass distributions is described by a threshold function: $(m - m_{\rm th})^\alpha \; e^{-\beta m - \gamma m^2 - \delta m^3}$ where $m_{\rm th} = m_D + m_K$. A fit to the Monte Carlo distribution shown in Fig. 2(a) using this background expression and one spin-2 relativistic Breit-Wigner for the $D_{s2}(2573)^+$ gives a good fit with 32 % χ^2 probability. In the fit to the data, the $D_{s2}(2573)^+$ and $D_{sJ}(2860)^+$ peaks are described with relativistic Breit-Wigner lineshapes where spin-2 is assumed for the $D_{s2}(2573)^+$ and spin 0 is used for the $D_{sJ}(2860)^+$. We find that the $D_{sJ}(2860)^+$ parameters are insensitive to the choice of the spin. The best description of the $X(2690)^+$ structure is obtained using a Gaussian distribution. The results from the fits are summarized in Table I. Table II summarizes the χ^2 probabilities, the number of $D_{sJ}(2860)^+$ events (with statistical and systematic errors) and the $D_{sJ}(2860)^+$ statistical significances from the three separate fits to the DK mass spectra.

The fits give consistent values for the parameters of the three structures. We notice a smaller width of the $D_{s2}(2573)^+$ in the $D^+_{K^-\pi^+\pi^+}K^0_s$ channel which we attribute to the uncertainty in the description of the background. We compute also the ratios of the yields of $D_{sJ}(2860)^+$ with respect to $D_{s2}(2573)^+$ finding agreement, within statistical errors, between the three channels.

The presence of resonant structures can be visually enhanced by subtracting the fitted background threshold function from the data. Fig. 3 shows the background-subtracted $D^0_{K^-\pi^+}K^+$, $D^0_{K^-\pi^+\pi^0}K^+$, and $D^+_{K^-\pi^+\pi^+}K^0_s$ invariant mass distributions in the 2.86 GeV/c^2 mass region. Fig. 3(d) shows the sum of the three mass spectra.

We also fit to the three distributions simultaneously. The parameters from this fit are labelled DK_A in Table I. If we remove the $D_{sJ}(2860)^+$, the χ^2 increases by 108 units while the number of degrees of freedom increases by five.

As a systematic test, we repeated the fits varying the lower p^* cut on the DK system from 3.50 to 3.75 and to 4.00 GeV/c. We also restricted the fit to the $D_{sJ}(2860)^+$ only and replaced the threshold function which represents the background with a polynomial. Fits have also been performed without removing the events associated to D^* reflections and modifying the spin of $D_{s2}(2573)^+$. The systematic uncertainties take into account the variation of the resonance parameters among the three different final states and the resonance parameterizations. The

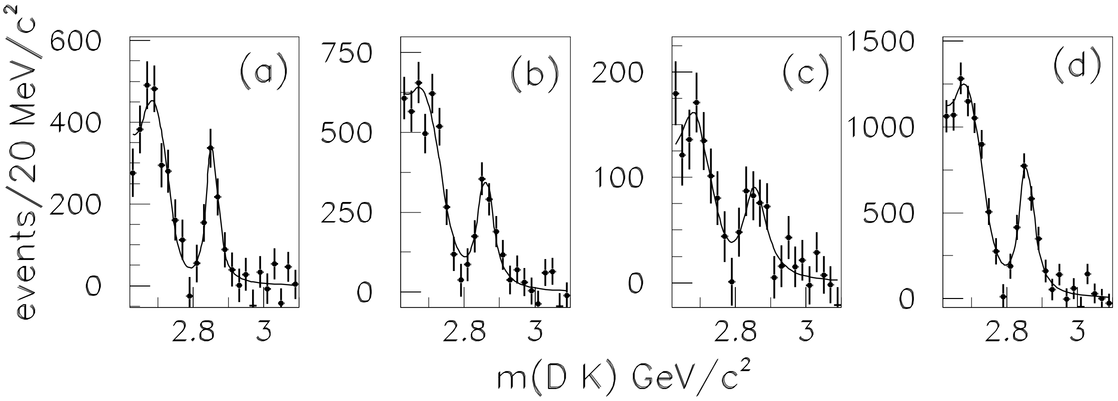

FIG. 3: Fitted background-subtracted DK invariant mass distributions for (a) $D^0_{K^-\pi^+}K^+$, (b) $D^0_{K^-\pi^+\pi^0}K^+$, (c) $D^+_{K^-\pi^+\pi^+}K^0_s$, and (d) the sum of all modes in the 2.86 GeV/c^2 mass region. The curves are the fitted functions described in the text.

TABLE I: Results from the fits to the total DK mass spectra of Fig. 2. Quantities are in units of MeV/c^2. Errors are statistical only. Simultaneous fits of the three mass spectra are labelled with DK_A and DK_B.

Fit	$m(D_{s2}(2573)^+)$	$\Gamma(D_{s2}(2573)^+)$	$m(X(2690)^+)$	$\sigma(X(2690)^+)$	$m(D_{sJ}(2860)^+)$	$\Gamma(D_{sJ}(2860)^+)$	χ^2/NDF
$D^0_{K^-\pi^+}K^+$	2572.4 ± 0.4	27.6 ± 0.5	2687 ± 4	41 ± 5	2855.4 ± 2.0	37 ± 8	26/20
$D^0_{K^-\pi^+\pi^0}K^+$	2572.3 ± 0.5	28.4 ± 0.9	2682 ± 5	52 ± 5	2860.8 ± 4.0	52 ± 14	33/20
$D^+_{K^-\pi^+\pi^+}K^0_s$	2572.6 ± 0.9	21.9 ± 1.1	2684 ± 7	50 ± 7	2856.6 ± 8.0	81 ± 25	26/21
DK_A	2572.3 ± 0.3	27.1 ± 0.6	2684 ± 3	48 ± 2	2856.6 ± 1.5	47 ± 7	100/72
Fit	$m(D_{s2}(2573)^+)$	$\Gamma(D_{s2}(2573)^+)$	$m(X(2690)^+)$	$\Gamma(X(2690)^+)$	$m(D_{sJ}(2860)^+)$	$\Gamma(D_{sJ}(2860)^+)$	χ^2/NDF
DK_B	2572.3 ± 0.3	27.0 ± 0.5	2688 ± 4	112 ± 7	2857.6 ± 1.9	38 ± 7	112/72

TABLE II: χ^2 probabilities, $D_{sJ}(2860)^+$ event yields and statistical significances from the three separate fits to the total DK mass spectra of Fig. 2.

Channel	χ^2 probability (%)	$D_{sJ}(2860)^+$ events	Statistical significance
$D^0_{K^-\pi^+}K^+$	17	886 ± 134 ± 49	6.2 σ
$D^0_{K^-\pi^+\pi^0}K^+$	3	1146 ± 157 ± 78	6.5 σ
$D^+_{K^-\pi^+\pi^+}K^0_s$	21	371 ± 84 ± 53	3.7 σ
DK_A	1.6	2717 ± 262 ± 190	8.4 σ
DK_B	0.2	2161 ± 238 ± 151	7.7 σ

uncertainty on the mass scale is estimated to be of the order of 1 MeV/c^2.

We obtain the mass and width of $D_{s2}(2573)^+$:

$$m(D_{s2}(2573)^+) = (2572.2 \pm 0.3 \pm 1.0)\ \text{MeV}/c^2$$
$$\Gamma(D_{s2}(2573)^+) = (27.1 \pm 0.6 \pm 5.6)\ \text{MeV}/c^2,$$

where the first errors are statistical and the second systematic. For the new state we find

$$m(D_{sJ}(2860)^+) = (2856.6 \pm 1.5 \pm 5.0)\ \text{MeV}/c^2$$
$$\Gamma(D_{sJ}(2860)^+) = (47 \pm 7 \pm 10)\ \text{MeV}/c^2.$$

Since the assignment of the $X(2690)^+$ as a reflection is inconclusive, the three mass spectra have also been fit including the $X(2690)^+$ as an additional resonance (Breit-Wigner, rather than Gaussian shape). This gives fit DK_B shown in Table I. The resulting resonance parameters are:

$$m(X(2690)^+) = (2688 \pm 4 \pm 3)\ \text{MeV}/c^2$$
$$\Gamma(X(2690)^+) = (112 \pm 7 \pm 36)\ \text{MeV}/c^2.$$

In summary, in 240 fb^{-1} of data collected by the *BABAR* experiment, we observe a new D_s^+ state in the inclusive DK mass distribution near 2.86 GeV/c^2 in three independent channels. The decay to two pseudoscalar mesons implies a natural spin-parity for this state: $J^P = 0^+, 1^-, \ldots$. It has been suggested that this new state could be a radial excitation of $D^*_{sJ}(2317)$ [6] although other possibilities cannot be ruled out. In the same mass distributions we also observe a broad enhancement around 2.69 GeV/c^2 which it is not possible to associate to any known reflection or background.

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