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First Observation of a Narrow Charm-Strange Meson $D^+_{sJ}(2632) \to D^+_s \eta$ and D^0K^+

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We report the first observation of a charm-strange meson $D^+_{sJ}(2632)$ at a mass of $2632.6 \pm 1.6\,\mathrm{MeV/c^2}$ in data from SELEX, the charm hadro-production experiment E781 at Fermilab. This state is seen in two decay modes, $D^+_s\eta$ and D^0K^+. In the $D^+_s\eta$ decay mode we observe an excess of 49.3 events with a significance of 7.2 σ at a mass of $2635.9 \pm 2.9\,\mathrm{MeV/c^2}$. There is a corresponding peak of 14 events with a significance of 5.3 σ at $2631.5 \pm 1.9\,\mathrm{MeV/c^2}$ in the decay mode D^0K^+. The decay width of this state is $< 17\,\mathrm{MeV/c^2}$ at 90% confidence level. The relative branching ratio $\Gamma(D^0K^+)/\Gamma(D^+_s\eta)$ is 0.16 ± 0.06. The mechanism which keeps this state narrow is unclear. Its decay pattern is also unusual, being dominated by the $D^+_s\eta$ decay mode.

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In 2003 the BaBar collaboration reported the first observation of a massive, narrow charm-strange meson $D^+_{sJ}(2317)$ below the DK threshold [1]. Confirmation quickly followed from CLEO [2] and BELLE [3]. The CLEO collaboration showed that a higher-lying state, suggested by BaBar, existed and was a partner to the $D^+_{sJ}(2317)$. A number of theory papers suggested different explanations for the unexpectedly low mass of the state, which had been thought to lie above the DK threshold. Among them were updates by two groups who had independently proposed chiral models that predicted such states a decade earlier [4–9]. These models predicted parity-doublet sets of states with increasing internal angular excitation. The ground state doublet [$\mathrm{D_s}(1969)$, $\mathrm{D_s}^*(2112)$] of $[0^-, 1^-]$ states would have a parity-partner $[0^+, 1^+]$ pair at an excitation of approximately $\mathrm{m_N}/3 \sim 310$ MeV/c^2 , very close to what is observed. An interesting prediction for this experiment was that the pattern of parity-doubled states is expected to continue to higher excitations with similar splittings [10].

The SELEX experiment used the Fermilab charged hyperon beam at 600 GeV/c to produce charmed particles in a set of thin foil targets of Cu or diamond. The negative beam composition was approximately half Σ^- and half π^-. The three-stage magnetic spectrometer is shown elsewhere [11, 12]. The most important features are the high-precision, highly redundant, vertex detector that provides an average proper time resolution of 20 fs for charm decays, a 10 m long Ring-Imaging Cerenkov (RICH) detector that separates π from K up to 165 GeV/c [13], and a high-resolution tracking system that has momentum resolution of $\sigma_p/p < 1\%$ for a 150 GeV/c track. Photons are detected in 3 lead glass photon detectors, one following each spectrometer magnet. The photon angular coverage in the center of mass of a production collision exceeds 2π. For this analysis the photon energy threshold was 2 GeV.

The experiment selected charm candidate events using an online secondary vertex algorithm. A scintillator trigger demanded an inelastic collision with at least four charged tracks in the interaction scintillators and at least two hits in the positive particle hodoscope after the second analyzing magnet. Event selection in the online filter required full track reconstruction for measured fast tracks ($p \gtrsim 15\,\mathrm{GeV}/c$). These tracks were extrapolated back into the vertex silicon planes and linked to silicon hits. The beam track was measured in upstream silicon detectors. A full three-dimensional vertex fit was then performed. An event was written to tape if it was *inconsistent* with having come from a single primary vertex. This filter passed 1/8 of all interaction triggers and had about 50% efficiency for otherwise accepted charm decays. The experiment recorded data from 15.2×10^9 inelastic interactions and wrote 1×10^9 events to tape using both positive and negative beams. The data set had 65% of the events induced by the Σ^- beam with the balance split roughly equally between π^- and protons. Previous SELEX $\mathrm{D_s}$ studies showed that most of the signal came from the Σ^- beam [14]. We restrict ourselves in this analysis to the 9.9×10^9 Σ^--induced interactions.

The analysis selected charm candidates by a topological identification procedure. Only charged tracks with reconstructed momenta were used. Tracks which traversed the RICH ($p \gtrsim 22\,\mathrm{GeV}/c$) were identified as protons or kaons if those hypotheses were more likely than the pion hypothesis. All other tracks were assumed to be pions. The primary vertex was refit using all found tracks. For those events which were inconsistent with having come from a single primary vertex, secondary vertices were formed geometrically. Candidate vertices were tested against a set of charge, RICH-identification and mass conditions to identify the different single charm states.

In this study we began with the SELEX $\mathrm{D_s^\pm} \to \mathrm{K^+K^-}\pi^\pm$ sample used in lifetime and hadroproduction studies [14, 15]. Charged conjugate final states are included here and throughout this paper. The sample-defining cuts are defined in the references. The $\mathrm{D_s}$ meson momentum vector had to point back to the primary vertex with $\chi^2 < 8$ and its decay point must have a vertex separation significance of at least 8 from the primary. The K mesons were identified by the RICH detector. The pion was required to be RICH-identified if it went into its acceptance. There are 544 ± 29 Σ^- induced signal events with these cuts when the photon detectors were operating.

Due to high multiplicity, photon detection in an open charm trigger is challenging. SELEX has 3 lead glass calorimeters covering much of the forward solid angle. The energy scale for the detector was set first by using electron beam scans for transition radiation detector identified electrons in the charged beam. Then π^o decays were reconstructed from exclusive trigger data and used to refine the energy calibration. The exclusive trigger selected low-multiplicity final states and was used in the measurement of a variety of radiative states: ($\eta \to \gamma\gamma$ and $\pi^+\pi^-\pi^0$, $\omega \to \pi^+\pi^-\pi^0$) as well as $\pi^+\pi^-\eta$ combinations to reconstruct the η' and the f(1285) mesons. The final corrections to the energy scale were developed by studying the π^o decays from the charm trigger data. Further checks were made on single photon decays, e.g., $\Sigma^0 \to \Lambda\gamma$. The uncertainty in the photon energy scale is less than 2%. Details can be found in Ref. [16].

We selected $\eta \to \gamma\gamma$ candidates in the $\gamma\gamma$ mass range 400-800 MeV/c^2. Each photon of the pair has $E_\gamma > 2$ GeV. The photon pair has $\mathrm{E}_{\gamma\gamma} > 10$ GeV, and the total number of η candidates in the event $N_\eta \leq 10$. The $\gamma\gamma$ mass distribution from 10^6 charm-trigger events (0.1% of the data) is shown in Fig. 1. An η signal over a large combinatoric background is seen. A fit to a Gaussian plus an exponentially falling background yields an η mass of 544.8 ± 2.9 MeV/c^2 , 0.9 σ below the PDG value [17] and consistent with it. The mass uncertainty for this and all subsequent states is only statistical.

The resolution is 27.8 ± 4.3 MeV/c^2 , consistent with the SELEX simulation result, 30.2 MeV/c^2. The simulation includes all the material in the spectrometer and also reproduces the observed π° width as a function of energy [16].

We searched for high-mass charm-strange decays that

Fig.	state	events	ΔM MeV/c^2	Mass MeV/c^2	Significance $(S-B)/\sqrt{B}$	σ MeV/c^2	Γ MeV/c^2	χ^2/n_d
1	$\eta(548) \to \gamma\gamma$	5087 ± 863		544.8 ± 2.9	13.9 σ	27.8 ± 4.3		1.17
2	$D_s^+(2632) \to D_s^+\eta$	45 ± 9.3	667.4 ± 2.9	2635.9 ± 2.9	7.2 σ	10.7		0.95
3	$D_s^+(2573) \to D^0K^+$	25 ± 9	705.4 ± 4.3	2569.9 ± 4.3	5.4 σ	4.9	14^{+9}_{-6}	0.77
3	$D_s^+(2632) \to D^0K^+$	14 ± 4.5	767.0 ± 1.9	2631.5 ± 1.9	5.3 σ	4.9	$< 17(90\%CL)$	

TABLE I: Fit results for Figures 1-3.

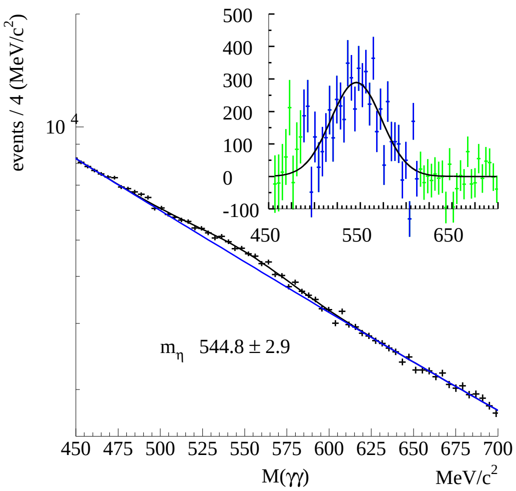

FIG. 1: M($\gamma\gamma$) distribution for photon pairs in the η mass region. Results for the fit shown are in Table I. The inset shows the background subtracted η signal. The dark points indicate the η signal region.

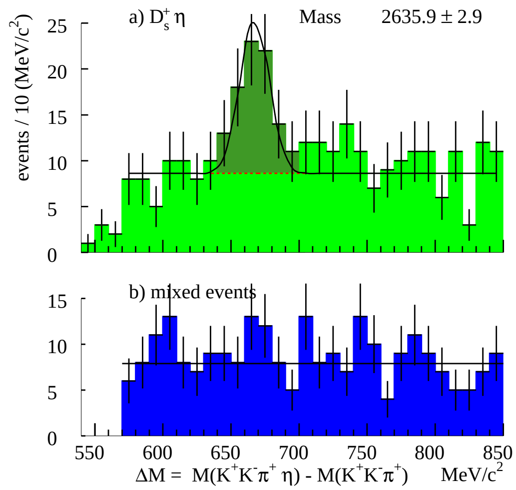

FIG. 2: (a) M(KK$\pi^\pm$ η) - M(KK$\pi^\pm$) mass difference distribution. Charged conjugates are included. The shaded region is the event excess used in the estimation of signal significance. Results for the fit shown are in Table I. (b) Mass difference distribution for mixed events as described in the text.

followed the pattern $\mathrm{D_s}$ plus pseudoscalar meson. We had good acceptance and efficiency for the $\mathrm{D_s}$ η channel. Event selection required that each photon in the $\eta \to \gamma\gamma$ decay have E $>$ 2 GeV and that $E_\eta > 15$ GeV. The $\mathrm{D_s}$ momenta are typically 150 GeV/c in the SELEX data set, so this η energy cut is very loose. We rejected events in which there were more than 5 η candidates. The η signal region is shown in Fig. 1.

The results of our search are shown in the M(KK$\pi^\pm$ η) - M(KK$\pi^\pm$) mass difference distribution in Fig. 2(a). In this plot we fixed the η mass at the PDG value [17] by defining an η 4-vector with the measured η momentum and the PDG η mass. A clear peak is seen for a mass difference of 667.4 $\pm$ 2.9 MeV/c^2. To estimate the combinatoric background, we took the $\mathrm{D_s}$ candidate from one event and the η candidates from a previous event to form a event-mixed sample representing the combinatoric background of true single charm production and real η candidates. As can be seen in Fig. 2(b), the event-mixed background models the background shape in (a) quite well, but produces no signal peak. After the initial sharp rise at threshold, the event-mixed background is fit well by a constant. Therefore we fit the signal channel with a Gaussian plus a constant in this mass difference interval. The width of the Gaussian was fixed at the simulation value of 10.7 MeV/c^2. We did not convolve the resolution function with a Breit-Wigner for this fit because the $\mathrm{D^0K^+}$ width, to be discussed below, is consistent with a 4.9 MeV/c^2 Gaussian, while this peak has Gaussian resolution of 10.7 MeV/c^2. The reduced χ^2 for the fit is 0.95. There is an excess of 49.3 events over an expected background of 51.7 events with a significance of 7.2 σ at a mass of 2635.9 $\pm$ 2.9 MeV/c^2. The yield and the statistical significance are stable as we vary the fit's starting point.The signal does not change with variations of $\pm$ 2% in the photon energy scale. We also studied combinations of events in the D_s mass sidebands with η candidates and candidates in the D_s mass peak with events in the η mass sidebands. In all cases only smooth combinatoric backgrounds, as in Fig. 2(b), were observed.

A GEANT simulation was also used to determine the overall acceptance for these signals. If we detected the

D_s from a $D_{sJ}^+(2632) \to D_s^+\eta$ decay, then 35 ± 2% of the time we also detected the $\eta \to \gamma\gamma$. This acceptance was obtained by embedding $D_{sJ}^+(2632) \to D_s^+\eta$ decay events in existing events from the real data. The photon multiplicity problem is slightly worse in the simulation than in the real data. The acceptance is underestimated, but the effect is small. About 55% of the D_s decays in SELEX come through this high mass state.

The decay $D_{sJ}^+(2632) \to D^0K^+$ is kinematically allowed. After finding the $D_{sJ}^+(2632) \to D_s^+\eta$ signal we searched for this second decay mode as confirmation. The D^0 sample is the Σ^- induced $D^0 \to K^-\pi^+$ subset of the sample used in our measurement of the D^0 lifetime [18] with tight D^0 cuts ($L/\sigma > 6$, point-back $\chi^2 < 5$, and a good fit to the secondary vertex; $\chi^2/n_d < 3$). The K^+ track is > 46 GeV/c (RICH kaon threshold) and is strongly identified by the RICH as ≥ 10 times more likely to be a kaon than any other hypothesis.

The results are shown in Fig. 3(a). We see the known $D_{sJ}^+(2573)$ state clearly. There is another peak above the $D_{sJ}^+(2573)$. We fit each peak with a Breit-Wigner convolved with a fixed width Gaussian and use a constant background term as suggested from the wrong-sign data discussed below. The Gaussian resolution is set to the simulation value of 4.9 MeV/c^2. The mass difference and width of the $D_{sJ}^+(2573)$ returned by the fit, ΔM = 705.4± 4.3 MeV/c^2 and $\Gamma = 14^{+9}_{-6}$ MeV/c^2 , respectively, agree well with the PDG values [17] of ΔM = 707.9 ± 1.5 MeV/c^2 and $\Gamma = 15^{+5}_{-4}$MeV/c^2. The fitted mass difference of the second Breit-Wigner is 767.0 ± 1.9 MeV/c^2, leading to a mass for the new peak of 2631.5 ± 1.9 MeV/c^2. The yield is 14 events, obtained by counting events above the constant background level in three bins. The signal spread is consistent with the Gaussian resolution, even when plotted in 2.5 MeV/c^2 bins. That limits the possible natural width. For the Breit-Wigner fit we find that it is < 17 MeV/c^2 at 90% confidence level. This signal has a significance of 5.3 σ . The mass difference between this signal and the one seen in the $D_s^+\eta$ mode is 3.2 ± 3.5 MeV/c^2 , statistically consistent with being the same mass. Unlike the D_s case, the D^0K^+ decay contributes a small fraction to the SELEX D^0 sample.

Combinatoric background will be equally likely to produce a D^0K^- combination (wrong-sign kaon) as a D^0K^+. The wrong-sign combinations are shown in Fig. 3(b). There is no structure in these data, which fits well to a constant background. We conclude that the peak at 2631.5 MeV/c^2 is real and confirms the observation in the $D_s^+\eta$ mode. We note that a one-bin excess at 2636 MeV/c^2 can be seen in the original CLEO observation of the $D_s(2573)$ [19].

The relative branching ratio $\Gamma(D^0K^+)/\Gamma(D_s^+\eta$) must be corrected for the relative acceptances of D^0, D_s, η, and K^+ mesons, for the η, D^0 and D_s^+ branching ratios, the relative acceptances of the $D_{sJ}^+(2632)$ final states, and phase space. We estimate the relative acceptance ratio from simulation as 73 ± 3%. The relative phase space ratio is 2.35:1. We correct the number of $D_s^+\eta$ events for the restriction to valid photon detector operation compared to all runs (71%). Our result for the relative branching ratio is $\Gamma(D^0K^+)/\Gamma(D_s^+\eta$) = 0.16 ± 0.06.

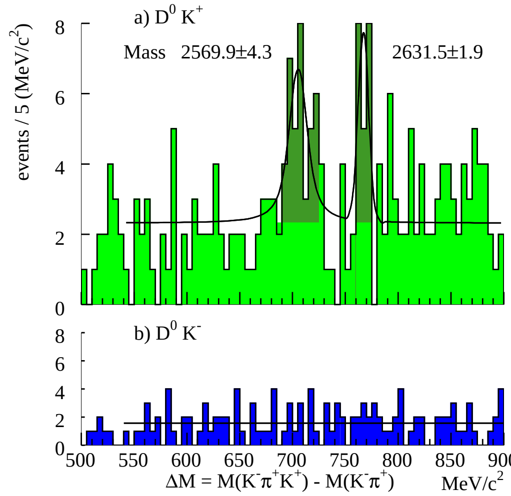

FIG. 3: (a) D_s (2632) → D^0K^+ mass difference distribution. Charged conjugates are included. The shaded regions are the event excesses used in the estimation of signal significances. Results for the fit shown are in Table I. (b) Wrong sign background D^0 K^- events, as described in the text.

In conclusion we combined our clean sample of D_s mesons with additional photon pairs which made η candidates to study the $D_s\eta$ mass spectrum. We observe a clear peak of 45 ± 9.3 events with a significance of 7.2 σ at a mass difference of 667.4 ± 2.9 MeV/c^2 above the ground state D_s. The background shape is well-represented by combinatoric background from event-mixing, as discussed above. A corresponding mass peak is also seen in the D^0K^+channel with a significance of 5.3 σ at the same mass. The combined measurement of the mass of this state is 2632.6 ± 1.6 MeV/c^2. The state is very narrow, consistent with a width due only to resolution in the D^0K^+decay mode. The 90% confidence level upper limit for the width is < 17 MeV/c^2.

SELEX reports these peaks as the first observation of yet another narrow, high-mass D_s state decaying strongly to a ground state charm plus a pseudoscalar meson. The mechanism which keeps this state narrow is unclear. The D^0K^+ channel is well above threshold, with a Q value ∼ 275 MeV. The branching ratios for this state are also unusual. The $D_s^+\eta$ decay rate dominates the D^0K^+rate by a factor of ∼ 6 despite having half the phase space. The $D_{sJ}^+(2632)$ lies approximately twice as far above the ground state D_s as the recently-discovered $D_{sJ}^+(2317)$ state. It is only 77 MeV/c^2 above the center of mass of the doublet of D_s states at 2536 and 2573 MeV/c^2 . If this state belongs to the usual heavy-light spectroscopy, there should be a partner within 40 MeV/c^2 that decays to the excited charm meson and the pseudoscalar. To place this new state in the spectroscopy of the charm-strange meson system will require careful study from a number of experiments in the future.

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