Observation of a Narrow Charm-Strange Meson $D_{sJ}^+(2632) \rightarrow D_s^+ \eta$ and $D^0 K^+$

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We report the first observation of a charm-strange meson $D_{sJ}^+(2632)$ at a mass of 2632.5 ± 1.7 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 $D^0 K^+$. In the $D_s^+ \eta$ decay mode we observe a peak with 101 events over a combinatoric background of 54.9 events at a mass of 2635.4 ± 3.3 MeV/c^2. There is a corresponding peak of 21 events over a background of 6.9 at 2631.5 ± 2.0 MeV/c^2 in the decay mode $D^0 K^+$. The decay width of this state is <17 MeV/c^2 at 90% confidence level. The relative branching ratio $\Gamma(D^0 K^+)/\Gamma(D_s^+ \eta)$ is 0.14 ± 0.06. The mechanism that 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 [4–9]. A prediction relevant to 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 Cherenkov (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 three lead glass photon detectors, one following each spectrometer magnet. The photon angular coverage in the center of mass typically exceeds 2π. For this analysis, the photon energy threshold was 2 GeV. Previous SELEX D_s studies showed that most of the signal came from the Σ^- beam [14]. We restrict ourselves in this analysis to the 10×10^9 Σ^--induced interactions.

In this study we began with the SELEX $D_s^{\pm} \to K^+K^-\pi^{\pm}$ sample used in lifetime and hadro-production studies [14,15]. Charged conjugate final states are included here and throughout this Letter. The sample-defining cuts are defined in the references. The 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 eight from the primary. Tracks that traversed the RICH ($p \gtrsim 22$ GeV/c) were identified as kaons if this hypothesis was most likely. 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.

Because of high-multiplicity, photon detection in an open charm-trigger is challenging. SELEX has three lead glass calorimeters covering much of the forward solid angle. The energy scale for the detector was set first by using electron beam scans. Then π^0 decays were reconstructed from exclusive trigger data, which selected low-multiplicity radiative final states: $\eta \to \gamma\gamma$ and $\pi^+\pi^-\pi^0$, $\omega \to \pi^+\pi^-\pi^0$ as well as η' and $f(1285)$ mesons [16]. The final energy scale corrections were developed using π^0 decays from the high-multiplicity charm-trigger data. Further checks in the charm data set were made using 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 $E_{\gamma\gamma} > 15$ GeV. The $\gamma\gamma$ mass distribution from 10^6 charm-trigger events (0.1% of the data) is shown in Fig. 1 where 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 consistent with the PDG value [17]. The mass uncertainty for this and all subsequent states is only statistical.

The observed resolution is 28 ± 4 MeV/c^2, consistent with the SELEX simulation result, 30 MeV/c^2. The simulation includes all the material in the spectrometer and also reproduces the observed π^0 width as a function of energy [16]. The η signal fraction is 5% within a ±60 MeV/c^2 mass window when we eliminate events with more than five η candidates in this mass window.

We searched for high-mass charm-strange decays that followed the pattern D_s plus pseudoscalar meson. We had good acceptance and efficiency for the $D_s\ \eta$ channel. The event selection used included the η selection above, and the D_s selection described above, which yields a S/N of 4/1. The $D_s$momenta are typically 150 GeV/c in the SELEX data set; the $E_\eta > 15$ GeV energy cut is very loose. We rejected events in which there were more than five η candidates in the signal region. This cut removed 18 D_s candidates (3.3%) while reducing the η candidate list by 20%. The η signal region is shown in Fig. 1. The final sample consisted of 615 η candidates from 526 D_s candidates.

The results of our search are shown in the $M(KK\pi^{\pm}\eta)$-$M(KK\pi^{\pm})$ mass-difference distribution in Fig. 2(a). In this plot we fixed the η mass at the particle

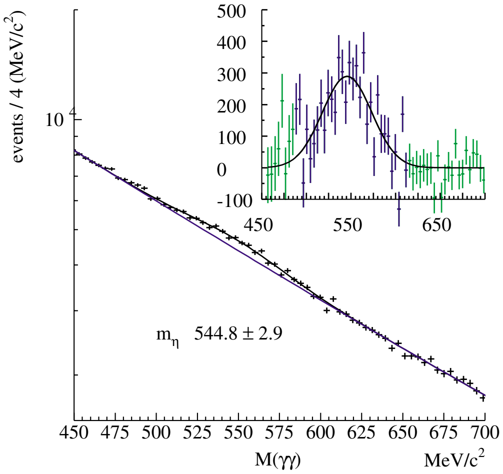

FIG. 1 (color online). $M(\gamma\gamma)$ distribution for photon pairs in the η mass region from 0.1% of the data sample. Results for the fit shown are in Table I. The inset shows the background subtracted η signal. The dark points indicate the η signal region.

data group (PDG) value [17] by defining an η four vector with the measured η momentum and the PDG η mass. A clear peak is seen at a mass difference of 666.9 ± 3.3 MeV/c^2.

To estimate the combinatoric background, we matched each D_s candidate with η candidates from 25 other sample events to form a event-mixed sample representing the combinatoric background of true single charm production and real η candidates. The event-mixed mass distribution was then scaled down by 1/25 to predict the combinatoric background in the signal channel. As can be seen in Fig. 2, the event-mixed background models the background shape very well, but produces no signal peak.

To estimate the signal yield we subtracted the combinatoric background (light shaded area) from the signal data. The resulting difference histogram is plotted in the inset in Fig. 2 in the mass-difference range appropriate to our search (D_{sJ}^+ masses up to 2900 MeV/c^2). Outside the peak region the data scatter about 0. The width in the D^0K^+ mode, to be discussed below, is consistent with a 4.9 MeV/c^2 Gaussian. We are insensitive to the natural width in the $D_s^+\eta$ mode. Therefore we fit the difference histogram with only a Gaussian with no residual background terms. The Gaussian width is fixed at the simulation value of 10.9 MeV/c^2. The fit yield is 43.4 ± 9.1 events at a mass of 2635.4 ± 3.3 MeV/c^2. The reduced χ^2 is 1.10 with a confidence level of 31%.

To assess the Poisson fluctuation probability to observe this excess we note that the resolution is about one bin; we take a 6-bin cluster as a signal region and perform a counting experiment. There are 101 events over a background of 54.9 ± 1.5 events, giving an excess of 46.1 events in six adjacent bins. The Poisson fluctuation probability for this excess is 3×10^{-7} including the uncertainty in the background. A conservative estimate of the fluctuation probability anywhere in the search region (up to 2900 MeV/c^2) is 6×10^{-6}.

The signal does not change with variations of ±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, were observed. The η population in this sample, corrected for η's from the signal channel, has a signal fraction of 0.12 ± 0.05, 1.4σ higher than the global average of 0.05. It is not possible to separate statistical fluctuation from a possible η enrichment of the overall $D_s$sample.

A GEANT simulation was also used to determine the overall acceptance for these signals. If we detected the D_s from a $D_{sJ}^+(2632) \rightarrow D_s^+\eta$ decay, then $35 \pm 2\%$ of the time we also detected the $\eta \rightarrow \gamma\gamma$. This acceptance was obtained by embedding $D_{sJ}^+(2632) \rightarrow D_s^+\eta$ decay events in existing events from the real data. About 55% of the D_s decays in SELEX come through this high-mass state. For comparison, about 25% of the D_s come from $D_s(2112)$ decays and a small fraction from either $D_{sJ}^+(2317)$ or $D_{sJ}^+(2460)$ decays, which are marginally visible in SELEX data.

The decay $D_{sJ}^+(2632) \rightarrow D^0K^+$ is kinematically allowed. After finding the $D_{sj}^+(2632) \rightarrow D_s^+\eta$ signal, we searched for this second decay mode as confirmation. The D^0 sample is the Σ^--induced $D^0 \rightarrow K^-\pi^+$ subset of the sample used in our measurement of the D^0 lifetime

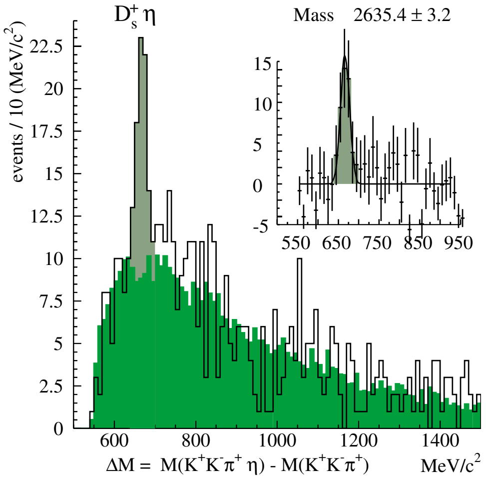

FIG. 2 (color online). $M(KK\pi^{\pm}\eta)$-$M(KK\pi^{\pm})$ mass-difference distribution. Charged conjugates are included. The darker shaded region is the event excess used in the estimation of signal significance. The lighter shaded region is the event-mixed combinatoric background described in the text. The inset shows the difference of the two with a Gaussian fit to the signal. Results for the fit shown are in Table I.

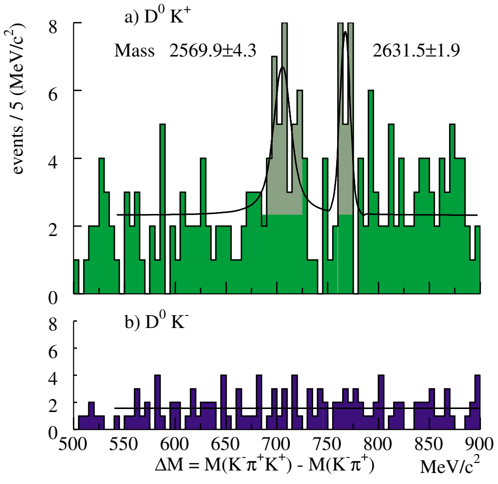

FIG. 3 (color online). (a) $D_s(2632) \rightarrow D^0K^+$ mass-difference distribution. Charged conjugates are included. The shaded regions are the event excesses used in the estimation of signal significances. Results for the fit shown are in Table I. (b) Wrong-sign background D^0K^- events, as described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

[18] with tight D^0 cuts ($L/\sigma > 6$, pointback $\chi^2 < 5$, 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), where we see both the known $D_{sJ}^+(2573)$ state clearly and another peak above the $D_{sJ}^+(2573)$. We fit each peak with a Breit-Wigner convolved with a fixed width Gaussian plus 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, $\Delta M = 705.4 \pm 4.3$ MeV/c^2 and $\Gamma = 14^{+9}_{-6}$ MeV/c^2, respectively, agree well with the PDG values [17] of $\Delta M = 707.9 \pm 1.5$ MeV/c^2 and $\Gamma = 15^{+5}_{-4}$ MeV/c^2. The fitted mass difference of the second Breit-Wigner is 767.0 ± 2.0 MeV/c^2, leading to a mass for the new peak of 2631.5 ± 2.0 MeV/c^2. The fitted yield is 13.2 ± 4.9 events. The signal spread is consistent with the Gaussian resolution, even when plotted in 2.5 MeV/c^2 bins, limiting the possible natural width. For the Breit-Wigner fit we find a limit for the width of <17 MeV/c^2 at 90% confidence level. This signal has a significance ($[S - B]/\sqrt{B}$) of 5.3σ in a ±15 MeV/c^2 interval. The mass difference between this signal and the one seen in the $D_s^+\eta$mode is 3.9 ± 3.8 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^+ 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.

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. We estimate the relative acceptance ratio from simulation as 91 ± 3%. The relative branching ratio is $\Gamma(D^0K^+)/\Gamma(D_s^+\eta) = 0.14 \pm 0.06$. Relative phase space favors the D^0K^+ mode by a factor of 1.53, making this low branching ratio even more surprising.

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 43.4 ± 9.1 events with a Poisson fluctuation probability $<6 \times 10^{-6}$ at a mass difference of 666.9 ± 3.3 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 5.3σ at the same mass. The combined measurement of the mass of this state is 2632.5 ± 1.7 MeV/c^2. The SELEX mass scale systematic error is under study, but all charm meson masses measured in SELEX agree with PDG values within 1 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 that 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 ~7 despite having half the phase space.

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TABLE I. Fit results for Figs. 1–3and $D_s^{*+}(2112) \to D_s^+\gamma$.

Figure	State	Fitted yield	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	13.3σ	28 ± 4		1.17
2	$D_s^+(2632) \to D_s^+\eta$	43.4 ± 9.1	666.9 ± 3.3	2635.4 ± 3.3	6.2σ	10.9		1.10
3	$D_s^+(2573) \to D^0K^+$	25 ± 9	705.4 ± 4.3	2569.9 ± 4.3	5.4σ	4.9	14^{+9}_{-6}	0.77
3	$D_s^+(2632) \to D^0K^+$	13.2 ± 4.9	767.0 ± 2.0	2631.5 ± 2.0	5.3σ	4.9	<17(90%CL)	
	$D_s^{*+}(2112) \to D_s^+\gamma$	60.1 ± 14.9	143.7 ± 1.5	2112.0 ± 1.5	4.8σ	5.9		0.94

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Note added.—At the summer conferences, the B-factory experiments [19,20] and the FOCUS photoproduction experiment [21] all reported negative results in their search for $D_{sJ}(2632)$ production. The SELEX data have an unusually low ratio of $R_s \equiv D_s^{*+}(2112)/D_s^+$ production (Table I) compared to e^+e^- machines. The SELEX R_s ratio can be brought into agreement with the published CLEO result [2] if we *exclude* the D_s events that come through $D_{sJ}(2632)$ decays (55% of the SELEX D_s yield). This fact, together with the strong production asymmetry in the SELEX data, can be interpreted as two-component production of charm-strange states from the Σ^- beam. One component involves normal fragmentation like in photoproduction; the other involves a different mechanism connected with the beam hadron. To understand this production conundrum and 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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