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New Particle Observations in SELEX

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Particle observations in data from SELEX, the charm hadro–production experiment (E781) at Fermilab are reviewed. These include observations of the doubly charmed baryon $\Xi_{cc}^{+}(3520)$ and the charmed strange meson $D_{sJ}^{+}(2632)$.

1 The SELEX Experiment

The SELEX experiment used the Fermilab charged hyperon beam at 600 GeV to produce charm particles in a set of thin foil targets of Cu or diamond. The negative beam composition was about 50% Σ^- and 50% π^-. The positive beam was 90% protons. A beam Transition Radiation Detector identified each beam particle as meson or baryon with zero overlap. The three-stage magnetic spectrometer is shown elsewhere [1]. The most important features are the high-precision, highly redundant, vertex detector that provides an average proper time resolution of 20 fs for the charm decays, a 10-m long Ring-Imaging Cerenkov (RICH) detector that separates π from K up to 165 GeV/c [2], and a high-resolution tracking system that has momentum resolution of $\sigma_P/P < 1\%$ for a 150 GeV/c proton. Photons are also detected in 3 lead glass photon detectors, one following each spectrometer magnet. The photon angular coverage in the center of mass typically exceeds 2π. The uncertainty in the photon energy scale is less than 2%. Details of photon detection and energy calibration can be found in Ref. [3].

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 ($P \leq 15$ 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 any of the fast tracks in the event 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 sample was 67% Σ^--induced, 14% π^--induced and 18% from protons.

The offline analysis selected single charm events with a topological identification procedure. Only charged tracks with reconstructed momenta were used. Tracks which traversed the RICH ($P \geq 22$ 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 offline using all found tracks. For those events having one or more tracks which were inconsistent with having come from a single primary vertex, secondary vertices were formed geometrically and then tested against a set of charge, RICH-identification and mass conditions to identify candidates for the different single charm states. Candidate events were written to a charm data summary file. Subsequent analysis began by selecting particular single-charm species from that set of events.

2 Double Charm Baryon $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ and pD^+K^-

The broken symmetry of SU(4) demands the doubly charmed baryons which contain two valence charmed quarks. The properties of doubly charmed baryons provide a new window into the structure of baryonic matter. There have been many predictions of the masses and other properties of these states [4, 5, 6]. I review the first observation of the double charm baryon $\Xi_{cc}^+(3520) \to \Lambda_c^+ K^- \pi^+$ [7] and the confirmation via its decay to pD^+K^- [8].

The $\Xi_{cc}^+(3520)$ analysis began with a sample of Λ_c^+ single-charm baryons decaying to $pK^-\pi^+$. Candidates were selected with a topological identification of 3-prong positively-charged secondary vertices, requiring a momentum measurement for each track. RICH identification of the proton and kaon was required. The other positive track was identified by the RICH as a pion when possible, otherwise it was assumed to be a pion. A Cabibbo-allowed decay of a doubly charmed baryon must have a net positive charge and contain a charmed quark, a strange quark and a baryon. We chose to search for decay modes like $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ with an intermediate $K^-\pi^+$ secondary vertex between the primary vertex and the Λ_c^+ vertex.

Events were analyzed for evidence of a secondary vertex composed of an opposite-signed pair between the primary and the Λ_c^+ decay point. We used all tracks not assigned to the Λ_c^+ candidate in the search. A new primary vertex was formed from the beam track and tracks assigned to neither the Λ_c^+ nor the $K^-\pi^+$ vertices. The new secondary vertex had to have an acceptable fit χ^2 and a separation of at least 1σ from the new primary. The $\Lambda_c^+ K^- \pi^+$ transverse momentum with respect to the incident beam direction is required to be in the range $0.2 < p_t[\text{GeV}/c] < 2.0$. Most tracks from the $K^-\pi^+$ vertex have insufficient momentum to reach the RICH. For the signal channel negative tracks are assigned the kaon mass and positive tracks the pion mass. As a background check we also kept wrong-sign combinations in which the mass assignments are reversed. A candidate event from the $\Lambda_c^+ K^- \pi^+$ sample is shown in Fig. 1 (Left).

In Fig. 1(a), we plot the invariant mass of the $\Lambda_c^+ K^- \pi^+$ system, fixing the Λ_c^+ mass at 2284.9 MeV/c^2 [9]. The data, plotted in 5 MeV/c^2 bins, show a large, narrow excess at 3520 MeV/c^2. This excess is stable for different bin widths and bin centers. Fig. 1(b) shows the wrong-sign invariant mass distribution of the $\Lambda_c^+ K^+ \pi^-$ system with the same binning as in (a). There is no significant excess. In Fig. 1(c) the shaded region from (a) is re-plotted in 2.5 MeV/c^2 bins

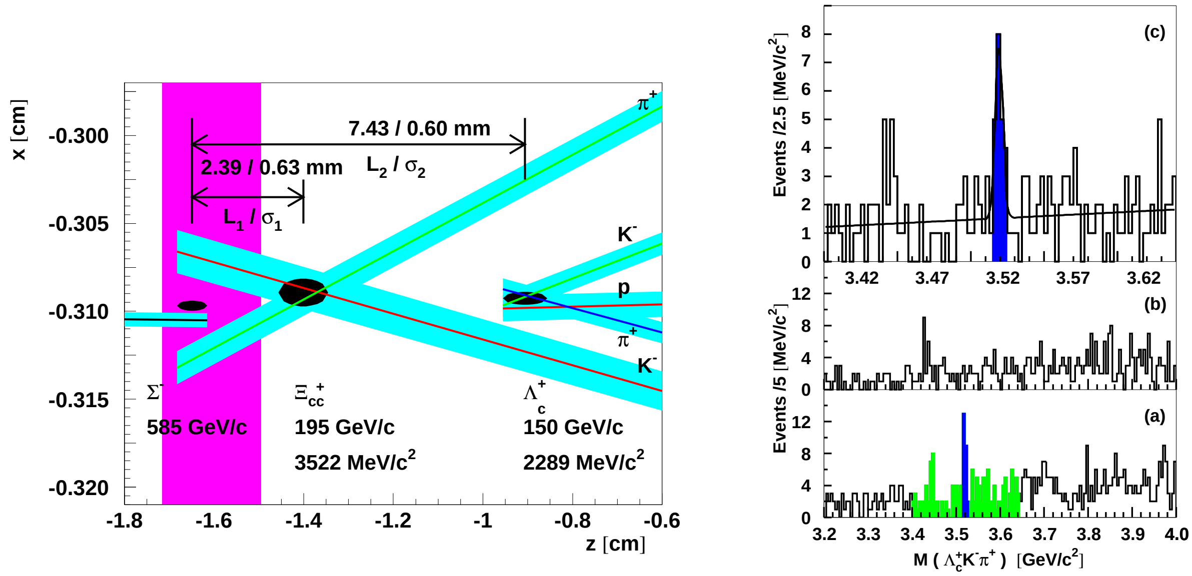

Figure 1: (Left) A candidate event with production target, 1σ track error corridors and vertex error ellipses. Three additional found tracks which form the primary vertex with the beam track are not shown. (Right) (a) The $\Lambda_c^+ K^- \pi^+$ mass distribution in 5 MeV/c^2 bins. The shaded region 3.400-3.640 GeV/c^2 contains the signal peak and is shown in more detail in (c). (b) The wrong-sign combination $\Lambda_c^+ K^+ \pi^-$ mass distribution in 5 MeV/c^2 bins. (c) The signal (shaded) region (22 events) and sideband mass regions with 162 total events in 2.5 MeV/c^2 bins. The fit is a Gaussian plus linear background.

and fit with a maximum likelihood technique to a Gaussian plus linear background. The fit has $\chi^2/\text{dof} = 0.45$, indicating that the background is linear in this region.

To determine the combinatoric background under the signal peak we exploit the linearity of the background justified by the fit. We define symmetric regions of the mass plot in Fig. 1(c): (i) the signal region ($3520 \pm 5\text{MeV}/c^2$) with 101 events; and (ii) 115 MeV/c^2 sideband regions above and below the signal region, containing $162 - 22 = 140$ events. We estimate the number of expected background events in the signal region from the sidebands as $240 \times 5/(115) = 6.1 \pm 0.5$ events. This determination has a (Gaussian) statistical uncertainty, solely from counting statistics. The Poisson probability of observing at least this excess, including the Gaussian uncertainty in the background, is 1.0×10^{-6}.

This state has a fit mass of 2635.4 ± 3 MeV/c^2. Our expected mass resolution, from a simulation of the decay $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ is 5 MeV $/c^2$. We observe a Gaussian width of 3 ± 1 MeV/c^2, consistent with our simulation. The width we observe is consistent with statistical fluctuations in this small sample. The wrong-sign mass combination is plotted in Fig. 1(b). Those events show comparable fluctuations to the sidebands of the signal channel and give no evidence for a significant narrow structure.

A weakly-decaying Ξ_{cc}^+ state has two c quark decay amplitudes plus a W-exchange amplitude for $c + d \to s + u$. This suggests that its lifetime will be of the order of the Ξ_c^0 or shorter, rather than like the long-lived Ξ_c^+. The upper limit for the Ξ_{cc}^+ lifetime at 90% confidence is 33 fs. This short lifetime is difficult to understand theoretically. It is not an analysis bias. Simulation shows that SELEX is fully efficient for Ξ_{cc}^+ lifetime of 750 fs or larger.

It is interesting to compare production of the Ξ_{cc}^+ state by different beam hadrons. Results for the signal region and sidebands shows that the doubly charmed baryon candidates are produced solely by the baryon beams. The proton/Σ^- ratio for Ξ_{cc}^+ production and for all interactions is the same. One can also ask if there a dependence on the target nucleus. Events produced by different target materials shows that the diamond/copper ratio of the signal events is similar to the sideband events, which in turn behave like single-charm production.

The yield of this state is larger than most production models predict [10]. The acceptance for the 15.9 events we observe in this final state, given that we observe a Λ_c^+, is 11%. Using a factor 1.5 from isospin to account for the $\Xi_{cc}^+ \to \Lambda_c^+ \overline{K}^0 \pi^0$ mode and Bjorken's estimate [11] of 1.6 to include other decay modes with Λ_c^+ in the final state, we find that ~20% of the Λ_c^+ in this sample are produced by Ξ_{cc}^+ decay.

In order to confirm the interpretation of this state as a double charm baryon, it is essential to observe the same state in some other way. Other experiments with large charm baryon samples, e.g., the FOCUS and E791 fixed target charm experiments at Fermilab or the B-factories, have not confirmed the double charm signal. This is not inconsistent with the SELEX results due to the fact that this new state was produced by the baryon beams (Σ^-, proton) in SELEX, but not by the photon or π^- beams.

Another way to confirm the Ξ_{cc}^+ is to observe it in a different decay mode that also involves a final state with baryon number and charm (not anti-charm). One such mode involving only stable charged particles is the channel $\Xi_{cc}^+ \to pD^+K^-$. Using SELEX $D^\pm$ sample, SELEX confirmed the $\Xi_{cc}^+ \to pD^+K^-$ signal using a completely different analysis scheme that combines a proton with a D^+K^- pair but not a D^-K^+ pair. SELEX reported an excess of 5.4 events over a background of 1.6 events at 3518 ± 3 MeV/c^2 and measured the relative branching ratio $\Gamma(\Xi_{cc}^+ \to pD^+K^-)/\Gamma(\Xi_{cc}^+ \to \Lambda_c^+K^-\pi) = 0.078 \pm 0.045$.

3 Charm–Strange Meson $D_{sJ}^+(2632) \to D_s^+\eta$ and D^0K^+

In 2003 the BaBar collaboration reported the first observation of a massive, narrow charm-strange meson $D_{sJ}^+(2317)$ below the DK threshold [12]. Confirmation quickly followed from CLEO [13] and BELLE [14]. 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 [15, 16, 17, 18, 19, 20]. I reviewe the first observation of a narrow charmed–strange meson $D_{sJ}^+(2632) \to D_s^+\eta$ and D^0K^+ [21].

The $D_{sJ}^+(2632)$ analysis began with a sample $D_s^\pm \to K^+K^-\pi^\pm$. 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 8 from the primary. Tracks which traversed the RICH were identified as kaons if this hypothesis was most likely. The pion was required to be RICH-identified if it went into the RICH acceptance. There are 544 ± 29 Σ^- induced signal events with these cuts. The $\eta \to \gamma\gamma$ candidates had $\gamma\gamma$ masses from 400 to 800 MeV/c^2. We searched for other D_s plus pseudoscalar meson decay channels in this mass range. We had good acceptance and efficiency for the $D_s\eta$ channel.

Event selection for the η required $E_\gamma > 2$ GeV and $E_{\gamma\gamma} > 15$ GeV. The D_s selection, described above, 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 5 η candidates in the signal region. This cut removed 18 D_s candidates (3.3%) while reducing the η candidate list by 20%. The final sample consisted of 615 η candidates from 526 D_s candidates.

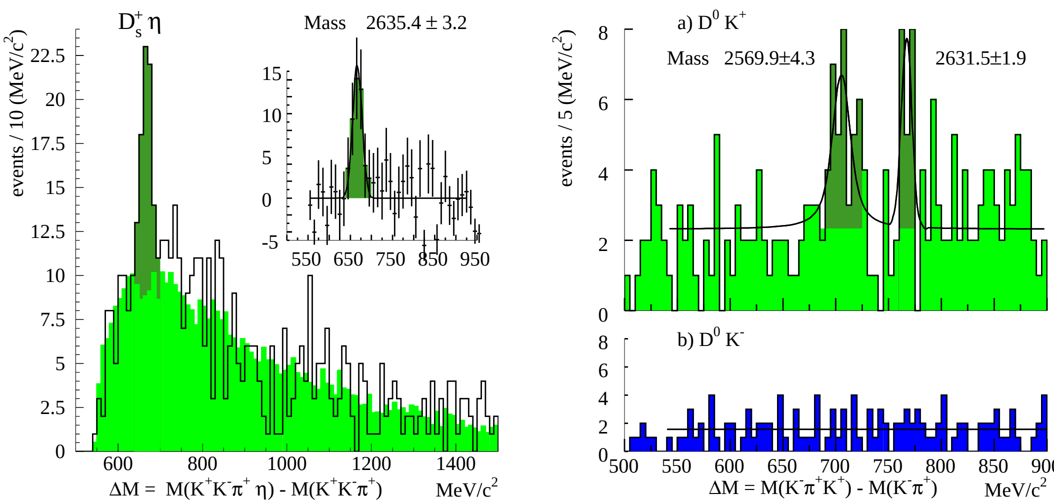

Figure 2: (Left) M($KK\pi^\pm\eta$) - M($KK\pi^\pm$) mass difference distribution. The darker shaded region is the event excess used in the estimation of signal significance. The lighter shaded region is the event-mixed combinatoric background described in the text. The inset shows the difference of the two with a Gaussian fit to the signal. (Right) $D_{sJ}^+(2632) \to D^0K^+$ mass difference distribution. The shaded regions are the event excesses used in the estimation of signal significances. Wrong sign background D^0K^- events are shown in the bottom.

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 PDG value [9] by defining an η 4-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. 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%. There are 101 events over a background of 54.9 ± 1.5 events giving an excess of 46.1 events in 6 adjacent bins. 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 show only smooth combinatoric backgrounds.

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 $35 \pm 2\%$ of the time we also detected the $\eta \to \gamma\gamma$. 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. D_s yield from $D_s(2112)$ decays is very different from e^+e^- production, where this ratio is typically 60–80 % depending on D_s momentum cuts [13].

The decay $D_{sJ}^+(2632) \to D^0K^+$ is kinematically allowed. After finding the $D_s^+\eta$ signal we searched for this second decay mode as confirmation. The D^0 sample is the Σ^- induced $D^0 \to K^-\pi^+$ 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. 2(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 [9] 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. For the Breit-Wigner fit we find a limit for the width of < 17 MeV/c^2 at 90% confidence level. The mass difference between this signal and the one seen in the $D_{sJ}^+\eta$ 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^+. The wrong-sign combinations are shown in Fig. 2(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 $D_{sJ}^+\eta$ mode. The relative branching ratio is $\Gamma(D^0K^+)/\Gamma(D_{sJ}^+\eta) = 0.14 \pm 0.06$. Relative phase space favors the D^0K^+ mode by a factor of 1.53, making this low branching ratio even more surprising.

4 Summary

SELEX has observed a narrow state at 3520 MeV/c^2 decaying into $\Lambda_c^+K^-\pi^+$ and pD^+K^-, consistent with the weak decay of the doubly charmed baryon Ξ_{cc}^+. The apparent lifetime of the state was significantly shorter than that of the Λ_c^+, which was not expected in model calculations [22]. SELEX also observed a clear peak of 43.4 ± 9.1 events of $D_s\eta$ at a mass difference of 666.9 ± 3.3 MeV/c^2 above the ground state D_s. 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 2632.5 ± 1.7 MeV/c^2. The mechanism which keeps this state narrow is unclear. The branching ratios for this state are also unusual. The $D_{sJ}^{+}\eta$ decay rate dominates the D^0K^+ rate by a factor of ~ 7 despite having half the phase space.

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