FERMILAB–Pub–04/082–E

Confirmation of the Double Charm Baryon $\Xi_{cc}^{+}(3520)$ via its Decay to $pD^{+}K^{-}$

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The SELEX collaboration observes a signal for the double charm baryon Ξ_{cc}^{+} in the charged decay mode $\Xi_{cc}^{+} \to pD^{+}K^{-}$ to complement the previously reported decay $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-}\pi^{+}$ in data from SELEX, the charm hadroproduction experiment (E781) at Fermilab [1]. In this new decay mode we observe an excess of 5.4 events over an expected background of 1.6 ± 0.35 events. The Poisson probability that a background fluctuation can produce the apparent signal is less than 1.5×10^{-5}. The observed mass of this state is 3518 ± 3 MeV/c^2, consistent with the published result. Averaging the two results gives a mass of 3518.7 ± 1.7 MeV/c^2. The observation of this new weak decay mode confirms the previous SELEX suggestion that this state is a double charm baryon. The relative branching ratio $\Gamma(\Xi_{cc}^{+} \to pD^{+}K^{-})/\Gamma(\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-}\pi^{+}) = 0.078 \pm 0.045$.

PACS numbers: 14.20.Lq, 14.40.Lb, 13.30.Eg

In 2002 the SELEX collaboration reported the first observation of a candidate for a double charm baryon, decaying as $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-}\pi^{+}$ [1]. The state had a mass of 3519 ± 2 MeV/c^2, and its observed width was consistent with experimental resolution, less than 5 MeV/c^2. The final state contained a charmed baryon and negative strangeness (Λ_c^+ and K^-), consistent with the Cabibbo-allowed decay of a Ξ_{cc}^+ configuration. 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. The report in Ref. [1] emphasized that this new state was produced by the baryon beams (Σ^-, proton) in SELEX, but not by the π^- beam. It also noted that the apparent lifetime of the state was significantly shorter than that of the Λ_c^+, which was not expected in model calculations [2].

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 $\Xi_{cc}^+ \to pD^+K^-$. Confirmation of the Ξ_{cc}^+ state would be a mass peak within 2 σ (± 4 MeV/c^2) of the $\Xi_{cc}^+ \to \Lambda_c^+ K^-\pi^+$ peak at 3519 MeV/c^2 reported in Ref. [1] in a channel combining a proton with a D^+K^- pair but not a D^-K^+ pair. Here we report the first observation of $\Xi_{cc}^+ \to pD^+K^-$.

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 [3, 4]. 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 [5], and a high-resolution tracking system that has momentum resolution of $\sigma_P/P < 1\%$ for a 150 GeV/c proton.

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 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 ($P \gtrsim 22\,\mathrm{GeV}/c$) 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 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.

In this study we began with the SELEX $D^\pm$ sample that has been used in lifetime and hadroproduction studies [6]. The sample-defining cuts are described in that reference. No new cuts on the D mesons were introduced in this analysis. The D meson momentum vector had to point back to the primary vertex with $\chi^2 < 12$. (The double charm lifetime is known to be much shorter than the D meson lifetime, so the D meson pointback is not affected by having come from a secondary decay.) The D meson decay point must have a separation significance of at least 10 σ from the primary vertex. Everywhere in these analyses the vertex error used is the quadrature sum of the errors on the primary and secondary vertices. The K was positively identified by the RICH detector. The pions were required to be RICH-identified if they went into its acceptance. The $D^+ \to K^-\pi^+\pi^+$ and $D^- \to K^+\pi^-\pi^-$ mass distributions are shown in Fig. 1. There are 1450 $D^+ \to K^-\pi^+\pi^+$ decays and 2450 $D^- \to K^+\pi^-\pi^-$ decays in these samples. The $D^+ \to K^-\pi^+\pi^+$ events contribute to the signal channel. The $D^- \to K^+\pi^-\pi^-$ events cannot come from the decay of a double charm baryon and will be used as a topological background control sample.

The track-based search code is the same code package that was used on the Λ_c^+ sample in the original investigation [1]. The premise is that a ccd state will make a secondary decay vertex between the primary production vertex in one of the thin foil targets and the observed D meson decay vertex, which must lie outside material. We looked for intermediate vertices using all zero-charge pairs of tracks from the set of reconstructed tracks not assigned to the D meson candidate. The D meson momentum vector is also used

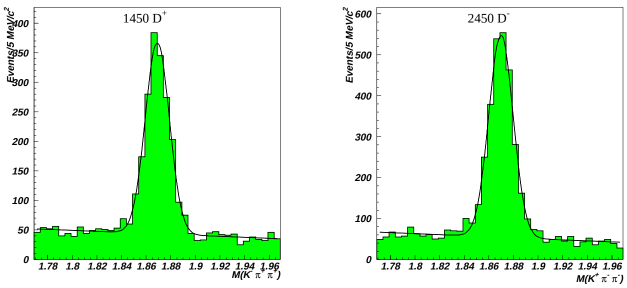

FIG. 1: $D^+ \to K^-\pi^+\pi^+$ (left) and $D^- \to K^+\pi^-\pi^-$ (right) mass distributions with cuts used in this analysis

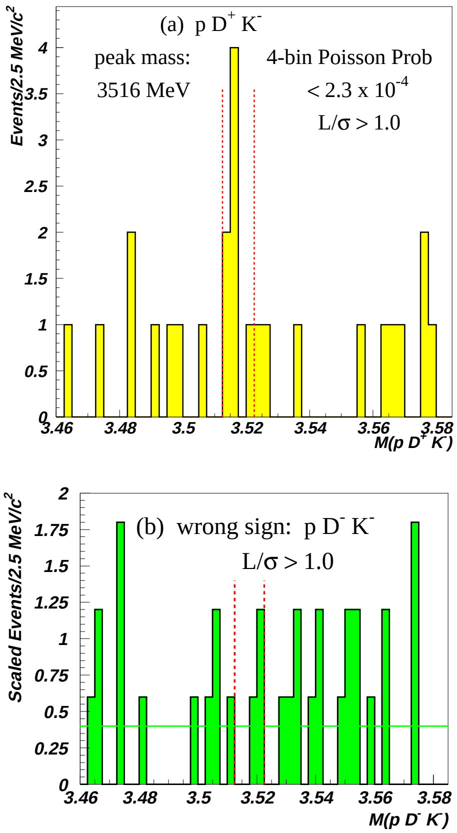

FIG. 2: (a) $\Xi_{cc}^+ \to pD^+K^-$ mass distribution for right-sign mass combinations. Vertical dashed lines indicate the region of smallest fluctuation probability as described in the text. (b) Wrong-sign events with a D^-K^+, scaled by 0.6 as described in the text. Line shows maximum likelihood fit to occupancy.

to attempt a 3-prong vertex fit. The additional positive track in this final state must be RICH-identified as a proton if it traverses the RICH. The negative track in the new vertex is assigned the kaon mass. We made background studies by (i) assigning the negative track a pion mass; (ii) looking for proton plus positive track combinations with a D meson; and (iii) looking at proton D^-K^- combinations (wrong-sign charm). We require a good 3-prong vertex fit with a separation significance of at least 1.0 σ from the primary vertex, the same requirement used in Ref. [1]. The primary position was recalculated from the beam track and secondary tracks assigned to neither the D nor the pK^- vertex. Results presented in this paper come from this analysis. We also observe the $\Xi_{cc}^+ \to pD^+K^-$ signal using a completely different analysis scheme that combines a D^+ with any zero-charge pair that has a vertex significance of at least 0.5. No new events are found with this method.

The right-sign mass combinations in Fig. 2(a) show an excess of 5.4 events over a background of 1.6 events in the mass interval 3517.7 ± 5 MeV/c^2. The wrong-sign mass combinations ($\overline{c}$ quark in the decay) for the pD^-K^+ final state are also plotted in Fig. 2 (b), scaled by 0.6 for the D^+/D^- ratio. The wrong-sign background shows no evidence for a significant narrow structure. The average wrong-sign occupancy is 0.4 events/bin, exactly the background seen in the right-sign channel. This confirms the combinatoric character of the background population in the right-sign signal. We have investigated all possible permutations of particle assignments. The only significant structure observed is in the channel $\Xi_{cc}^+ \to pD^+K^-$, where double charm baryon decay can occur.

The number of events in Fig. 2 is too small to apply Gaussian statistics. In order to assign a significance level to this peak, we have performed a Poisson sampling study, using the sideband region of the distribution to determine the mean occupation per bin of the combinatoric background. For this purpose we excluded the ± 10 MeV/c^2 region of the plot centered on the peak, i.e., another 2 bins on each side of the dashed lines in Fig. 2 in the usual spirit of keeping the sideband region isolated from possible signal contamination. There are 16 events in 42 bins in this sideband region, a mean occupancy of 0.4 events per bin. We produced sets of 10^6 40-bin histograms in which each bin had this mean occupancy but had a Poisson-distributed number of events. As expected, the average occupancy of each histogram was 16 with an rms spread of 4.5. We sorted the 10^6 distributions in each set to look for fluctuation patterns with occupancies equal to or greater than the distribution in Fig. 2. Because the data search required one bin with a large single-bin spike, the fluctuation study began with a search for a single bin having 4 or more events. We then asked that an adjacent bin (left or right) have 2 or more counts and that the 4-bin region keyed on the 4-event spike contain 7 or more counts. We searched for all possible permutations of the signal pattern. The average number of fluctuations that correspond to our signal pattern at the mass predicted from the $\Xi_{cc}^+ \to \Lambda_c^+ K^-\pi^+$ signal is 230 per million tries, or a fully-permuted Poisson fluctuation probability of 2.3×10^{-4}. Because we are looking for a specific decay at a pre-determined mass value, we take this low fluctuation probability as solid evidence that the peak is a real double charm candidate.

The combinatoric background in Fig. 2 is dominated by events in which a real D^- points toward the accidental overlap of a real proton and a negative track from the primary interaction, as shown by the wrong-sign events. Because primary tracks are characterized by lower P_T than charm tracks, we look at the prospects of cutting on the P_T values of the $\Xi_{cc}^+ \to pD^+K^-$ state and the $D^+ \to K^-\pi^+\pi^+$ state in order to suppress the accidental background. This is a blind optimization. We base the cuts strictly on comparing Monte Carlo signal retention to sideband background rejection.

Monte Carlo simulation of $\Xi_{cc}^+ \to pD^+K^-$ production with a Gaussian P_T spectrum and mean $P_T \sim 1$ GeV/c shows that most of the $\Xi_{cc}^+ \to pD^+K^-$ events have $P_T > 0.5$ GeV/c. In fact, all of the events in Fig. 2 pass such a cut. The simulation shows that when the $\Xi_{cc}^+ \to pD^+K^-$ state passes this cut, the D meson also has $P_T > 0.5$ GeV/c most of the time. When we apply this cut to data, one event is lost from the signal region and 4 events are removed from the sidebands, consistent with Monte Carlo expectations. The Poisson fluctuation likelihood drops to 1.5×10^{-5} ($4.3\,\sigma$). This confirms that the alleged signal behaves like double charm.

One expects a mass resolution of 4 MeV/c^2 for the decay $\Xi_{cc}^+ \to pD^+K^-$. Our simulation correctly reproduces the observed widths of all our reported single charm mesons and baryons. In order to estimate the mass of the $\Xi_{cc}^+ \to pD^+K^-$ state in light of the sparse statistics in Fig. 2, we fixed the width of the Gaussian to 4 MeV/c^2 and fitted the data distribution around the signal peak. The fit mass is 3518 ± 3 MeV/c^2. This agrees beautifully with the measurement of 3519 ± 2 MeV/c^2 from the original double charm baryon report. We present these data as confirmation of the double charm state at 3519 MeV/c^2 in a new decay mode $\Xi_{cc}^+ \to pD^+K^-$. The weighted average mass is 3518.7 ± 1.7 MeV/c^2. The mass distributions for the two channels are shown in Fig. 3.

We have used the simulation to study the relative acceptance for the two decay channels $\Xi_{cc}^+ \to pD^+K^-$ and $\Xi_{cc}^+ \to \Lambda_c^+ K^-\pi^+$ in order to quote a relative branching ratio. The overall acceptance, including the single charm selection and the proton identification requirements in the $\Xi_{cc}^+ \to pD^+K^-$ mode, is very similar. The relative phase space favors the $\Xi_{cc}^+ \to \Lambda_c^+ K^-\pi^+$ mode by a factor of 4.6. SELEX measures the relative branching ratio $\Gamma(\Xi_{cc}^+ \to pD^+K^-)/\Gamma(\Xi_{cc}^+ \to \Lambda_c^+ K^-\pi^+) = 0.078 \pm 0.045$. The systematic error due to acceptances is well understood from single charm studies and is negligible compared to the statistical error.

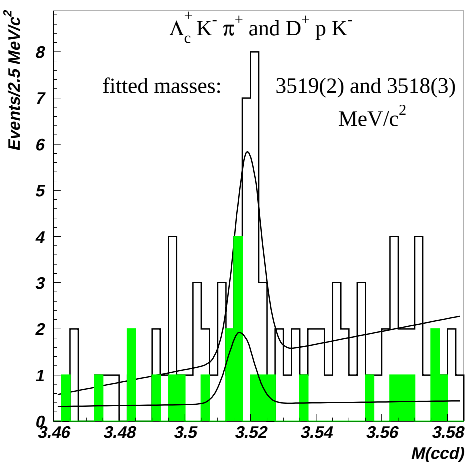

FIG. 3: Gaussian fits for $\Xi_{cc}^+ \to \Lambda_c^+ K^-\pi^+$ (unshaded) and $\Xi_{cc}^+ \to pD^+K^-$ (shaded) on same plot

In Ref. [1] we reported that all observed ccd events were produced by the baryon beams. None came from pions. In this sample, 2 events out of the 26 in Fig. 2 (one off-peak, one in-peak) are pion-induced. This is lower than but not inconsistent with the pion luminosity fraction of 10%. In another comparison, we had found that the $\Xi_{cc}^+ \to \Lambda_c^+ K^-\pi^+$ decays had an exceptionally short reduced proper time distribution, indicating a ccd decay lifetime 5-10 times shorter than the Λ_c^+ lifetime. That feature is confirmed by the $\Xi_{cc}^+ \to pD^+K^-$ channel. As we noted in Ref. [1], our lifetime resolution is excellent but we cannot exclude zero lifetime for these events (strong decay). The width of this peak is completely consistent with simulation of a zero-width state, unlikely for a strong decay of a massive state. Also, we do not see an increase in the signal when we reduce the vertex significance cut L/σ below 1. If this were a strong decay, one would expect as many events with L/σ of -1 as +1, so the signal should grow significantly. It does not.

In Ref. [1] we noted that the $\Xi_{cc}^+ \to \Lambda_c^+ K^-\pi^+$ yield and acceptance implied that a large fraction of the Λ_c^+ decays seen in SELEX came from double charm decays. That was a surprise. For the $\Xi_{cc}^+ \to pD^+K^-$ case that is not true. Only a few percent of the SELEX D^+ events are associated with double charm.

SELEX reports an independent confirmation of the double charm baryon Ξ_{cc}^+, previously seen in the $\Xi_{cc}^+ \to \Lambda_c^+ K^-\pi^+$ decay mode, via the observation of its decay $\Xi_{cc}^+ \to pD^+K^-$. Using only very loose cuts gives the statistically significant signal shown in Fig. 2. Cutting gently on the D-meson $P_T > 0.5$ GeV/c as suggested by Monte Carlo simulation increases the signal significance, as expected for a real double charm state.

The authors are indebted to the staff of Fermi National Accelerator Laboratory and for invaluable technical support from the staffs of collaborating institutions. This project was supported in part by Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie, Consejo Nacional de Ciencia y Tecnología (CONACyT), Conselho Nacional de Desenvolvimento Científico e Tecnológico, Fondo de Apoyo a la Investigación (UASLP), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), the Israel Science Foundation founded by the Israel Academy of Sciences and Humanities, Istituto Nazionale di Fisica Nucleare (INFN), the International Science Foundation (ISF), the National Science Foundation (Phy #9602178), NATO (grant CR6.941058-1360/94), the Russian Academy of Science, the Russian Ministry of Science and Technology, the Turkish Scientific and Technological Research Board (TÜBİTAK), and the U.S. Department of Energy (DOE grant DE-FG02-91ER40664 and DOE contract number DE-AC02-76CHO3000).

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