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Confirmation of the doubly charmed baryon $\Xi_{cc}^{+}(3520)$ via its decay to $pD^{+}K^{-}$

SELEX Collaboration

A. Ocherashvili[l,1], M.A. Moinester[l], J. Russ[c], J. Engelfried[m], I. Torres[m], U. Akgun[p], G. Alkhazov[k], J. Amaro-Reyes[m], A.G. Atamantchouk[k,✠], A.S. Ayan[p], M.Y. Balatz[h,✠], N.F. Bondar[k], P.S. Cooper[e], L.J. Dauwe[q], G.V. Davidenko[h], U. Dersch[i,2], A.G. Dolgolenko[h], G.B. Dzyubenko[h], R. Edelstein[c], L. Emediato[s], A.M.F. Endler[d], I. Eschrich[i,3], C.O. Escobar[s,4], A.V. Evdokimov[h], I.S. Filimonov[j,✠], F.G. Garcia[s,e], M. Gaspero[r], I. Giller[l], V.L. Golovtsov[k], P. Gouffon[s], E. Gülmez[b], He Kangling[g], M. Iori[r], S.Y. Jun[c], M. Kaya[p,5], J. Kilmer[e], V.T. Kim[k], L.M. Kochenda[k], I. Konorov[i,6], A.P. Kozhevnikov[f], A.G. Krivshich[k], H. Krüger[i,7], M.A. Kubantsev[h], V.P. Kubarovsky[f], A.I. Kulyavtsev[c,e], N.P. Kuropatkin[k,e], V.F. Kurshetsov[f], A. Kushnirenko[c,f], S. Kwan[e], J. Lach[e], A. Lamberto[t], L.G. Landsberg[f,✠], I. Larin[h], E.M. Leikin[j], Li Yunshan[g], M. Luksys[n], T. Lungov[s], V.P. Maleev[k], D. Mao[c,8], Mao Chensheng[g], Mao Zhenlin[g], P. Mathew[c,9], M. Mattson[c], V. Matveev[h], E. McCliment[p], V.V. Molchanov[f], A. Morelos[m], K.D. Nelson[p,10], A.V. Nemitkin[j], P.V. Neoustroev[k], C. Newsom[p], A.P. Nilov[h], S.B. Nurushev[f], Y. Onel[p], E. Ozel[p], S. Ozkorucuklu[p,11], A. Penzo[t], S.V. Petrenko[f], P. Pogodin[p,12], M. Procario[c,13], V.A. Prutskoi[h], E. Ramberg[e], G.F. Rappazzo[t], B.V. Razmyslovich[k,14], V.I. Rud[j], P. Schiavon[t], J. Simon[i,15], A.I. Sitnikov[h], D. Skow[e], V.J. Smith[o], M. Srivastava[s], V. Steiner[l], V. Stepanov[k,14], L. Stutte[e], M. Svoiski[k,14], N.K. Terentyev[k,c], G.P. Thomas[a], L.N. Uvarov[k], A.N. Vasiliev[f], D.V. Vavilov[f], E. Vázquez-Jáuregui[m], V.S. Verebryusov[h], V.A. Victorov[f], V.E. Vishnyakov[h], A.A. Vorobyov[k], K. Vorwalter[i,16], J. You[c,e], Zhao Wenheng[g], Zheng Shuchen[g], R. Zukanovich-Funchal[s]

[a] *Ball State University, Muncie, IN 47306, USA*
[b] *Bogazici University, Bebek, 80815 Istanbul, Turkey*
[c] *Carnegie-Mellon University, Pittsburgh, PA 15213, USA*
[d] *Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*
[e] *Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*

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[f] *Institute for High Energy Physics, Protvino, Russia*
[g] *Institute of High Energy Physics, Beijing, PR China*
[h] *Institute of Theoretical and Experimental Physics, Moscow, Russia*
[i] *Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany*
[j] *Moscow State University, Moscow, Russia*
[k] *Petersburg Nuclear Physics Institute, St. Petersburg, Russia*
[l] *Tel Aviv University, 69978 Ramat Aviv, Israel*
[m] *Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico*
[n] *Universidade Federal da Paraíba, Paraíba, Brazil*
[o] *University of Bristol, Bristol BS8 1TL, United Kingdom*
[p] *University of Iowa, Iowa City, IA 52242, USA*
[q] *University of Michigan-Flint, Flint, MI 48502, USA*
[r] *University of Rome "La Sapienza" and INFN, Rome, Italy*
[s] *University of São Paulo, São Paulo, Brazil*
[t] *University of Trieste and INFN, Trieste, Italy*

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Abstract

We observe a signal for the doubly charmed baryon Ξ_{cc}^{+} in the decay mode $\Xi_{cc}^{+} \to pD^{+}K^{-}$ to complement the previous reported decay $\Xi_{cc}^{+} \to \Lambda_c^{+}K^{-}\pi^{+}$ in data from SELEX, the charm hadroproduction experiment at Fermilab. In this new decay mode we observe an excess of 5.62 events over a combinatoric background estimated by event mixing to be 1.38 ± 0.13 events. The mixed background has Gaussian statistics, giving a signal significance of 4.8σ. The Poisson probability that a background fluctuation can produce the apparent signal is less than 6.4×10^{-4}. The observed mass of this state is $3518 \pm 3\ \mathrm{MeV}/c^2$, consistent with the published result. Averaging the two results gives a mass of $3518.7 \pm 1.7\ \mathrm{MeV}/c^2$. 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 for these two modes is 0.36 ± 0.21.

E-mail address: jurgen@ifisica.uaslp.mx (J. Engelfried).

[1] Present address: Sheba Medical Center, Tel-Hashomer, Israel.

[2] Present address: Advanced Mask Technology Center, Dresden, Germany.

[3] Present address: University of California at Irvine, Irvine, CA 92697, USA.

[4] Present address: Instituto de Física da Universidade Estadual de Campinas, UNICAMP, SP, Brazil.

[5] Present address: Kafkas University, Kars, Turkey.

[6] Present address: Physik-Department, Technische Universität München, 85748 Garching, Germany.

[7] Present address: The Boston Consulting Group, München, Germany.

[8] Present address: Lucent Technologies, Naperville, IL, USA.

[9] Present address: Baxter Healthcare, Round Lake IL, USA.

[10] Present address: University of Alabama at Birmingham, Birmingham, AL 35294, USA.

[11] Present address: Süleyman Demirel Universitesi, Isparta, Turkey.

[12] Present address: Legal Department, Oracle Corporation, Redwood Shores, CA, USA.

[13] Present address: DOE, Germantown, MD, USA.

[14] Present address: Solidum, Ottawa, ON, Canada.

[15] Present address: Siemens Medizintechnik, Erlangen, Germany.

[16] Present address: Allianz Insurance Group IT, München, Germany.

✠ Deceased.

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1. Introduction

In 2002, the SELEX Collaboration reported the first observation of a candidate for a double charmed baryon, decaying as $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$[1]. The state had a mass of $3519 \pm 2\ \mathrm{MeV}/c^2$, and its observed width was consistent with experimental resolution, less than $5\ \mathrm{MeV}/c^2$. The final state contained a charmed hadron, a 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 E-791 fixed target charm experiments at Fermilab or the B-factories, have not confirmed the double charm signal. This is consistent 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 a model calculation based on heavy quark effective theory [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 $\Xi_{cc}^{+} \to p D^{+} K^{-}$. Observing a mass peak near the $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ peak at $3519\ \mathrm{MeV}/c^2$ reported in Ref. [1] in a channel combining a proton with a $D^{+}K^{-}$ pair but not a $D^{-}K^{+}$ pair would confirm the existence of the Ξ_{cc}^{+} state. Here we report the first observation of $\Xi_{cc}^{+} \to p D^{+} K^{-}$.

2. Experimental apparatus

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^{-}, 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 provided an average proper time resolution of 20 fs for the charm decays, a 10 m long Ring-Imaging Cerenkov (RICH) detector that separated π from K up to $165\ \mathrm{GeV}/c$ [5], and a high-resolution tracking system that had momentum resolution of $\sigma_p/p < 1\%$ for a $150\ \mathrm{GeV}/c$ 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 three-dimensional vertex fit was then performed. An event was written to tape if all the fast tracks in the event were *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 65% Σ^{-}-induced, with the balance split roughly equally between π^{-} and 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. An event was rejected if all tracks were consistent with one primary vertex. For those events which were inconsistent with 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.

3. Search strategy

In this study we began with the SELEX $D^{\pm}$ sample that has been used in lifetime and hadroproduction studies [7]. 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 vertex separation significance of at least 10σ from the primary. 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 yield asymmetry stems from the d-quark contribution of the Σ^- beam component that gives a sizable production asymmetry favoring leading D^- production over D^+ production, as we have reported for other charm systems [6].

The track-based search code is identical to that 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 charge zero pairs of tracks from the set of reconstructed tracks not assigned to the D-meson candidate. 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. (This track typically missed the RICH acceptance by being too soft or too wide-angle, as confirmed by simulation.) 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

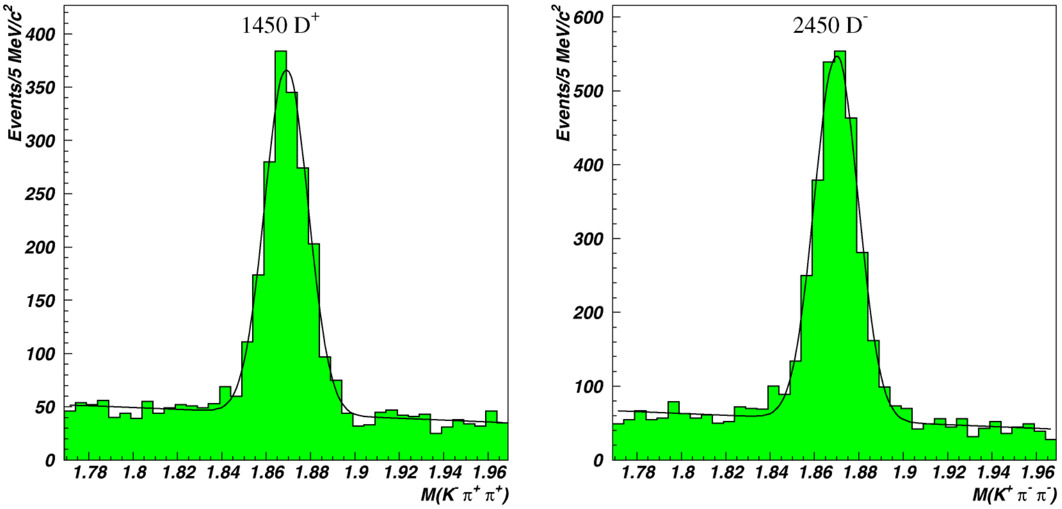

Fig. 1. $D^+ \to K^-\pi^+\pi^+$ (left) and $D^- \to K^+\pi^-\pi^-$ (right) mass distributions with cuts used in this analysis.

a separation significance of at least 1.0σ 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^- vertices. Results presented in this Letter come from this analysis.

4. Search results and significance

The signal search was based on a 10 MeV/c^2 window centered on the Ξ_{cc}^+ mass 3519 MeV/c^2 from Ref. [1]. The expected mass resolution for the decay $\Xi_{cc}^+ \to pD^+K^-$ is 4 MeV/c^2. Our simulation correctly reproduces the observed widths of all our reported single charm mesons and baryons. The 10 MeV/c^2 window should collect 80% of the events in a Ξ_{cc}^+ signal. The results are insensitive to changing bin boundaries by up to half a bin. The background, assumed to be flat, is evaluated outside a 20 MeV/c^2 window, to avoid putting the remaining 20% of any signal into the background.

The right-sign mass combinations in Fig. 2(a) show an excess of 5.4 events over a background of 1.6 events. The wrong-sign mass combinations ($\bar{c}$ quark in the decay) for the $pD^-\pi^+$ 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 near 3519 MeV/c^2. 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 $\Xi_{cc}^+ \to pD^+K^-$, the place where a double charm baryon decay can occur.

In order to assign a significance level to this peak, we have combined statistical methods used in the original double charm paper [1] and the event-mixing method used in Ref. [8]. We set out to test the hypothesis that the background events in Fig. 2 are random combinatoric tracks associated with real D^+ mesons. To mix events we took a D^+ meson in the peak region (Fig. 1) and combined it with proton and K^- tracks extracted from other events. Each D^+ was reused 25 times. To compare to the combinatoric background in Fig. 2, we scale the mixed-event background down for the multiple D^+ usage.

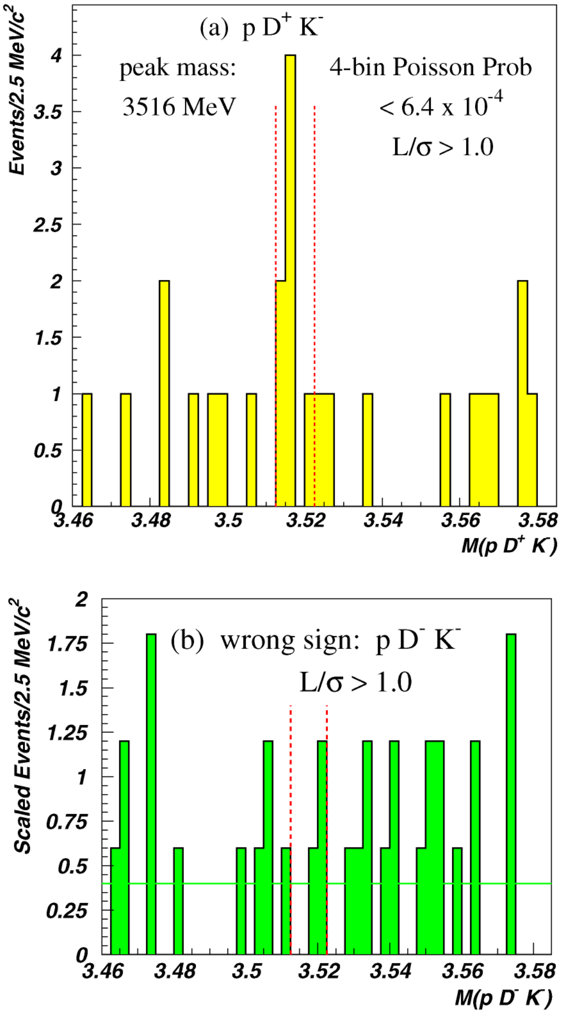

Fig. 2. (a) $\Xi_{cc}^+ \to pD^+K^-$ mass distribution for right-sign mass combinations. Vertical dashed lines indicate the region of smallest fluctuation probability as described in the text. (b) Wrong-sign events with a pD^-K^+, scaled by 0.6 as described in the text. The horizontal line shows a maximum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

The resulting background distribution predicts the observed distribution very well. The mean number of background events below, in, and above the 4-bin signal peak is 5.74 ± 0.26, 1.38 ± 0.13, and 10.60 ± 0.36. This agrees well with the 8, 1.6, and 10 events that we observe in the corresponding regions. A mass plot with the combinatoric background level is shown in Fig. 3. The background that we observe is completely consis-

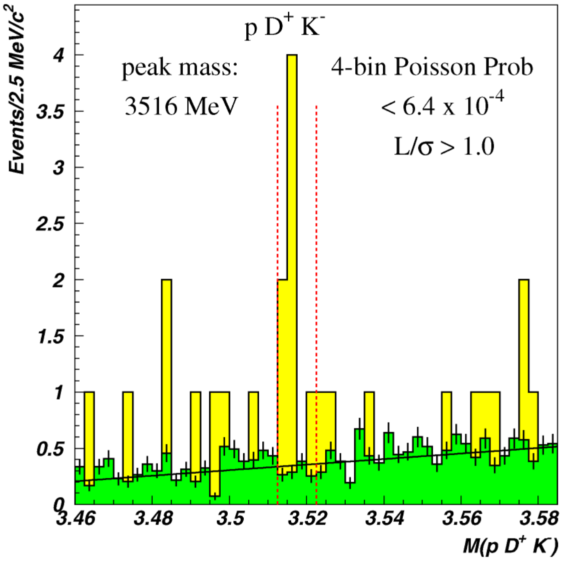

Fig. 3. $\Xi_{cc}^{+} \to pD^{+}K^{-}$ mass distribution from Fig. 2(a) with high-statistics measurement of random combinatoric background computed from event-mixing.

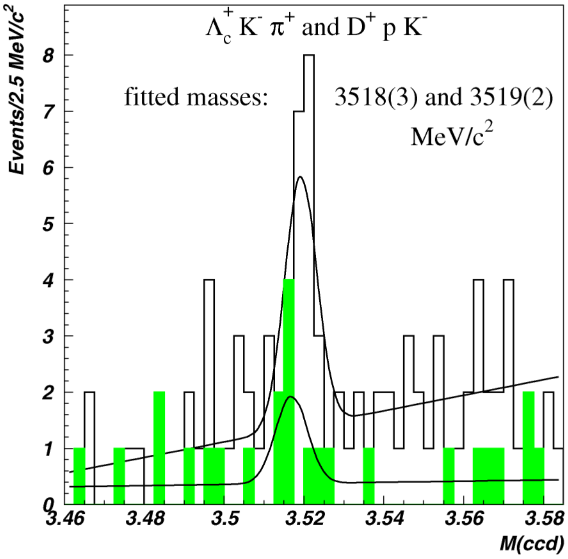

Fig. 4. Gaussian fits for $\Xi_{cc}^{+} \to \Lambda_c^{+}K^{-}\pi^{+}$ and $\Xi_{cc}^{+} \to pD^{+}K^{-}$ (shaded data) on same plot.

tent in shape and normalization with random combinatoric tracks associated with real D^{+} mesons.

We take the combinatoric background to give a proper measure of the expected background under the 7-event signal region. The single-bin significance of the signal, using the above background numbers, is: $S = (7 - 1.38)/\sqrt{1.38 + 0.13^2} = 4.8\sigma$. The Poisson probability of observing at least this much excess, including the Gaussian uncertainty in the background, is 6.4×10^{-4}. Both of these statistical significance calculations use methods identical to those in Ref. [1]. This indicates a robust signal atop a combinatoric background whose shape and normalization are very well understood. One can ignore the information from the combinatorial background study and estimate the signal significance from the non-signal regions of Fig. 2(a) alone. Using the same procedure as above, that significance estimate is 4.16σ with a Poisson excess probability of 0.0021.

5. Signal properties

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 $3518 \pm 3\ \text{MeV}/c^2$. This agrees beautifully with the measurement of $3519 \pm 2\ \text{MeV}/c^2$ from the original double charm baryon report. We present these data as confirmation of the double charm state at 3520 MeV/c^2 in a new decay mode $\Xi_{cc}^{+} \to pD^{+}K^{-}$. The weighted average mass is $3518.7 \pm 1.7\ \text{MeV}/c^2$. The mass distributions for the two channels are shown in Fig. 4.

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 ID requirements in the $\Xi_{cc}^{+} \to pD^{+}K^{-}$ mode, is very similar. SELEX measures the relative branching ratio $\Gamma(\Xi_{cc}^{+} \to pD^{+}K^{-})/\Gamma(\Xi_{cc}^{+} \to \Lambda_c^{+}K^{-}\pi^{+}) = 0.36 \pm 0.21$. The systematic error due to acceptances is well understood from single charm studies and is negligible compared to the statistical error.

In Ref. [1] we noted that all observed ccd events were produced by the baryon beams. None came from pions. In this sample, 1 event out of the 7 in the peak region seen in Fig. 2 is a pion beam event, and 1 of the 19 sideband events comes from the pion beam sample. This sample is consistent with the view that double charm baryons are produced dominantly by the baryon beams in SELEX. In another comparison, we had noted that the $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ decays had an exceptionally short reduced proper time distribution, indicating a Ξ_{cc}^+ decay lifetime 5–10 times shorter than the Λ_c^+ lifetime. That feature is confirmed by the $\Xi_{cc}^+ \to p D^+ K^-$ channel. As we noted in Ref. [1], our lifetime resolution is excellent but we cannot exclude 0 lifetime (strong decay) for these events. 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 $\Xi_{cc}^+ \to p D^+ K^-$ case that is not true. Only a few percent of the SELEX D^+ events are associated with double charm.

6. Summary

In summary, 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 into the $\Xi_{cc}^+ \to p D^+ K^-$ final state. Using only very loose cuts gives the statistically-significant signal shown in Fig. 2. A combinatoric background from event mixing describes the non-signal distribution well. The Gaussian significance using this background estimate is 4.8σ. This decay mode confirms that the Ξ_{cc}^+ lifetime is very short and that it is produced dominantly by baryon beams, as we reported in Ref. [1].

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