

First Observation of the Doubly Charmed Baryon Ξ_{cc}^+

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We observe a signal for the doubly charmed baryon Ξ_{cc}^+ in the charged decay mode $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$ in data from SELEX, the charm hadroproduction experiment at Fermilab. We observe an excess of 15.9 events over an expected background of 6.1 ± 0.5 events, a statistical significance of 6.3σ . The observed mass of this state is 3519 ± 1 MeV/ c^2 . The Gaussian mass width of this state is 3 MeV/ c^2 , consistent with resolution; its lifetime is less than 33 fs at 90% confidence.

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The addition of the charmed quark to the (uds) triplet extends the flavor symmetry of the baryon octet and decuplet from SU(3) to SU(4). Even though the large m_c breaks the symmetry, SU(4) still provides a good classification scheme for baryons composed of uds and c [1]. There is strong experimental evidence for all the predicted

baryon states which contain zero or one valence charmed quark [1]. In this Letter, we present the first experimental evidence for one of the six predicted baryon states which contain two valence charmed quarks—the doubly charmed baryons. There have been many predictions of the masses and other properties of these states [2–5]. The properties of

doubly charmed baryons provide a new window into the structure of baryonic matter.

The SELEX experiment uses the Fermilab 600 GeV/ c charged hyperon beam to produce charm particles in a set of thin foil targets of Cu or diamond. The three-stage magnetic spectrometer is shown elsewhere [6,7]. The most important features are (a) the high-precision, highly redundant, silicon vertex detector that provides an average proper time resolution of 20 fs for single-charm particle decays, (b) a 10-m-long ring-imaging Cherenkov (RICH) detector that separates π from K up to 165 GeV/ c [8], and (c) a high-resolution tracking system that has momentum resolution of $\sigma_p/P < 1\%$ for a 200 GeV/ c reconstructed Λ_c^+ .

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 a positive particle hodoscope after the second analyzing magnet. Event selection in the online filter required full track reconstruction for measured fast tracks ($p \geq 15$ 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 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. 67% of events were induced by Σ^- , 13% by π^- , and 18% by protons.

This analysis began with a sample of Λ_c^+ single-charm baryons decaying to $pK^-\pi^+$. Candidates were selected with a topological identification of three-prong positively-charged secondary vertices, requiring a momentum measurement for each track. RICH identification of the proton and kaon was required. Charged tracks with reconstructed momenta 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. The other positive track was identified by the RICH as a pion when possible; otherwise, it was assumed to be a pion. The primary vertex was refit using all other found tracks. Details of the selection procedure can be found in [9,10]. This Λ_c^+ sample (1630 events) contains the same $\Lambda_c^+ \rightarrow pK^-\pi^+$ events we used to measure the Λ_c^+ lifetime [9].

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 such as $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^-\pi^+$ with an intermediate $K^-\pi^+$ secondary vertex between the primary vertex and the Λ_c^+ vertex. In this analysis, we have incorporated the charm selection techniques developed for single-charm baryon states, as above.

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 $0.2 < p_{\perp} [\text{GeV}/c] < 2.0$. These cuts were developed and fixed in previous searches for short-lived single-charm baryon states. We have applied them here without change.

Most tracks from the $K^-\pi^+$ vertex have insufficient momentum to reach the RICH. Masses were assigned according to topology. 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. Further details of the Λ_c^+ reanalysis may be found in Ref. [6].

In Fig. 2(a) we plot the invariant mass of the $\Lambda_c^+ K^-\pi^+$ system, fixing the Λ_c^+ mass at 2284.9 MeV/ c^2 [1]. 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. Figure 2(b) shows the wrong-sign invariant mass distribution of the $\Lambda_c^+ K^+\pi^-$ system with the same binning as in 2(a). There is no significant excess.

In Fig. 2(c) the shaded region from 2(a) is replotted in 2.5 MeV/ c^2 bins and fit with a maximum likelihood technique to a Gaussian plus linear background. The fit has $\chi^2/\text{d.o.f.} = 0.45$, indicating that the background is linear in this region.

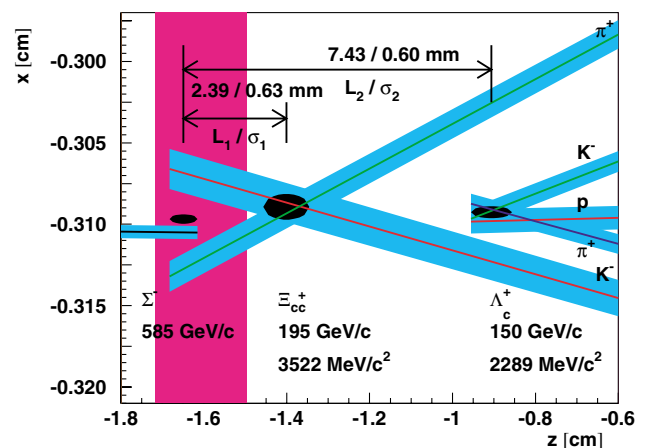


FIG. 1 (color online). A candidate event with production target, 1σ track error corridors, and vertex error ellipses. This is a plan view of three-dimensional tracks and vertices. Three additional found tracks which form the primary vertex with the beam track are not shown.

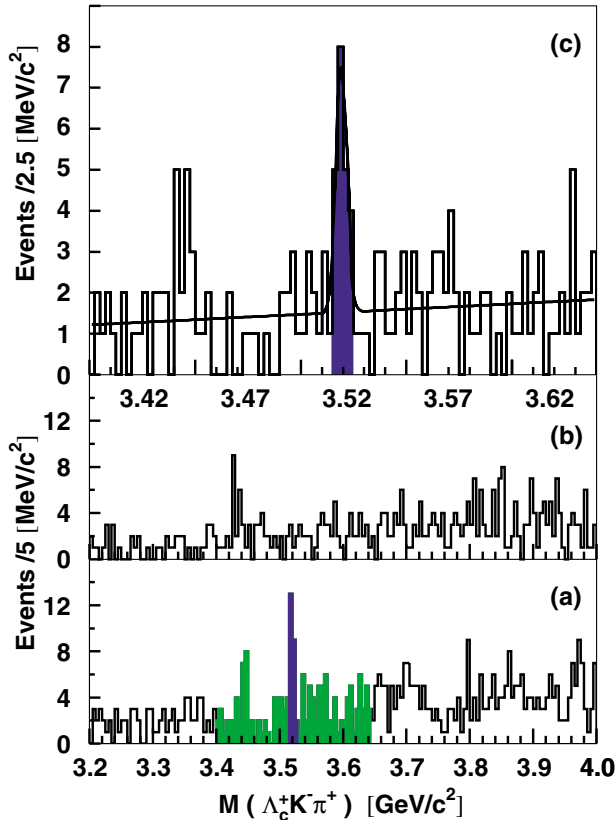


FIG. 2 (color online). (a) The $\Lambda_c^+ K^- \pi^+$ mass distribution in $5 \text{ MeV}/c^2$ bins. The shaded region $3.400\text{--}3.640 \text{ GeV}/c^2$ contains the signal peak and is shown in more detail in (c). (b) The wrong-sign combination $\Lambda_c^+ K^+ \pi^-$ mass distribution in $5 \text{ MeV}/c^2$ bins. (c) The signal (shaded) region (22 events) and sideband mass regions with 162 total events in $2.5 \text{ MeV}/c^2$ bins. The fit is a Gaussian plus linear background.

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. 2(c): (i) the signal region ($3520 \pm 5 \text{ MeV}/c^2$) with 22 events and (ii) $115 \text{ MeV}/c^2$ 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 $140 \times 5/(115) = 6.1 \pm 0.5$ events. This determination has a (Gaussian) statistical uncertainty, solely from counting statistics. The single-bin significance of this signal is the excess in the signal region divided by the total uncertainty in the background estimate: $15.9/\sqrt{(6.1 + 0.5^2)} = 6.3\sigma$ [11]. The Poisson probability of observing at least this excess, including the Gaussian uncertainty in the background, is 1.0×10^{-6} .

Our reconstruction mass window is $3.2\text{--}4.3 \text{ GeV}/c^2$ with 110 bins of width $10 \text{ MeV}/c^2$ in this interval. The overall probability of observing an excess at least as large as the one we see anywhere in the search interval is 1.1×10^{-4} .

This state has a fit mass of $3519 \pm 1 \text{ MeV}/c^2$. Our expected mass resolution, from a simulation of the decay $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$ is $\sim 5 \text{ MeV}/c^2$. We observe a Gaussian width of $3 \pm 1 \text{ MeV}/c^2$, consistent with our simulation. The confidence level for a fit with a Gaussian width fixed at our expected resolution is 20%. The width we observe is consistent with statistical fluctuations in this small sample.

The wrong-sign mass combination is plotted in Fig. 2(b). Those events show comparable fluctuations to the sidebands of the signal channel and give no evidence for a significant narrow structure. We have investigated all possible permutations of mass assignments for the non- Λ_c^+ tracks. The peak at $3520 \text{ MeV}/c^2$ disappears for any other mass choice, and no other significant structures are observed. Reconstructions with events from the Λ_c^+ mass sidebands produce relatively few entries and no significant structures in the doubly charmed baryon region.

The dependence of the signal significance, as defined above, on several of the selection cuts is shown in Fig. 3. The significance depends strongly only on the $K^- \pi^+$ vertex separation. The dependence is driven by a large increase in background at small separations and the absence of both signal and background events at large separations. The dependence on the width of the signal region is stable, only decreasing when made wider than the mass resolution. All other cuts have been checked; no significant dependence on any cut has been seen.

A weakly decaying Ξ_{cc}^+ state has two c quark decay amplitudes plus a W -exchange amplitude for $c + d \rightarrow s + u$. This suggests that its lifetime will be of the order of the Ξ_c^0 or shorter, rather than like the long-lived Ξ_{cc}^+ . For each

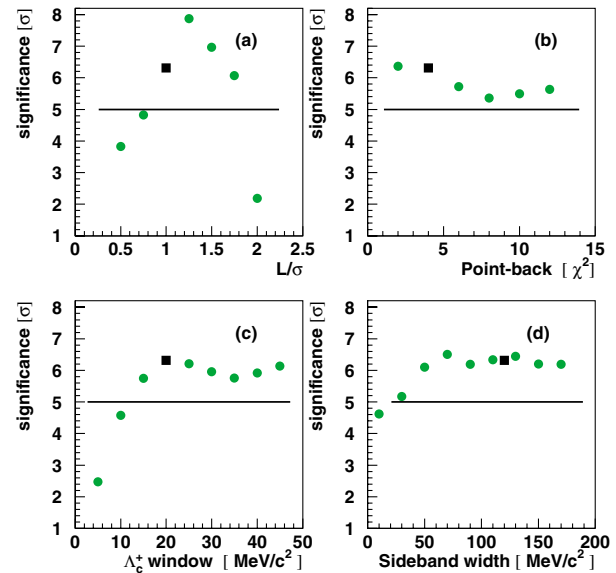


FIG. 3 (color online). The signal significance as a function of (a) the vertex significance of the $K^- \pi^+$ vertex, (b) the half-width of the signal region, (c) the mass window around the Λ_c^+ mass, (d) the half-width of the sideband region. The square points are the values used in this analysis.

TABLE I. The change in likelihood, $-\log(\mathcal{L}) + \log(\mathcal{L}_{\max})$ for different Ξ_{cc}^+ lifetimes. Increases of 0.5 and 2.0 in this statistic correspond to 1σ and 2σ , respectively.

τ (fs)	0	12.5	25	37.5	50
Signal region	0.2	0.0	0.58	1.54	2.70
Sideband region events	1.2	0.8	0.2	0.0	0.6

event we compute the reduced proper time $t = (m/p) \times (L - L_{\min})/c$. Here L is the flight path from the primary vertex to the Ξ_{cc}^+ decay point, and L_{\min} is the minimum flight path for a given event. In this analysis $L_{\min} = \sigma$, the error on the flight path. One can form the likelihood, $\mathcal{L}(\tau) = \prod_{i=1}^{N_{ev}} P(t_i, \tau)$ to observe a set $\{t_i\}$ of reduced proper time values, given the probability $P(t, \tau)$ for a given lifetime τ . $P(t, \tau)$ is the normalized probability of observing a given reduced proper time t for a true lifetime τ determined from the SELEX simulation.

Results for the change in likelihood from its maximum value are given in Table I for both the signal region and a sideband region, where combinatorial backgrounds dominate. In both cases the lifetime is much shorter than the single-charm Ξ_{cc}^0 lifetime of about 100 fs [1]. Given our single-event resolution of 20 fs [9], we cannot exclude a prompt decay for the signal events from the likelihood. However, the fact that the significance of the signal increases as the flight path L is increased [see Fig. 3(a)] suggests that the lifetime is not zero. From these data the upper limit for the Ξ_{cc}^+ lifetime at 90% confidence is 33 fs.

Production characteristics of the 22 signal plus background events are indistinguishable from the single-charm Λ_c^+ sample [10]. The mean p_t is 1 GeV/c and mean $x_F \sim 0.33$. It is interesting to compare production of the Ξ_{cc}^+ state by different beam hadrons. Results for the signal region and sidebands are listed in Table II. One sees that the doubly charmed baryon candidates are produced solely by the baryon beams. The top row gives the fraction of all interactions produced from each of the beams. The proton/ Σ^- ratio for Ξ_{cc}^+ production and for all interactions is the same. One can also ask if there is a dependence on the target nucleus. Table III shows that the diamond/copper ratio of the signal events is similar to the sideband events, which in turn behave like single-charm production. Production of Ξ_{cc}^+ candidates differs from Λ_c^+ production only in the absence of meson beam contributions.

The yield of this state is larger than most production models predict [12]. 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 $\Xi_{cc}^+ \rightarrow \Lambda_c^+ \bar{K}^0 \pi^0$ mode and Bjorken's estimate [13] of 1.6 to include other decay modes with Λ_c^+ in the final state, we find that $\sim 20\%$ of the Λ_c^+ in this sample are produced by Ξ_{cc}^+ decay.

TABLE II. Events produced by incident particle species.

	Σ^-	π^-	Proton	π^+
Interaction fraction	0.67	0.13	0.18	0.01
Signal region events	18	0	4	0
Sideband region events	110	7	21	2

Our production region has not been probed by other experiments. The large x_F , small p_t region is not amenable to perturbative QCD analysis. Two CERN experiments with π^- beams have reported anomalously large production of events with two charmed particles [14,15]. However, we do not know of any model calculation that would predict this large hadroproduction rate of doubly charmed events. The FOCUS charm photoproduction experiment at Fermilab has searched for doubly charmed baryons in their charm samples. They see very few candidate events and no signal peaks [16]. The BELLE B-factory experiment recently reported a very large production ratio for $(J/\psi c \bar{c})/(J/\psi)$ in continuum e^+e^- annihilation at 10.8 GeV [17]. The connection to the hadroproduction data is not clear.

In summary, we have observed a narrow state at 3520 MeV/ c^2 decaying into $\Lambda_c^+ K^- \pi^+$, consistent with the weak decay of the doubly charmed baryon Ξ_{cc}^+ . We report this state as the first observation of a doubly charmed baryon.

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TABLE III. Events produced by different target materials.

	Diamond	Copper
Fraction of Λ_c^+ signal events	0.68	0.32
Signal region events	18	4
Sideband region events	93	47

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