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First Observation of Doubly Charmed Baryons

The SELEX Collaboration

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1 Abstract

The SELEX experiment (E781) at Fermilab has observed two statistically compelling high mass states near 3.6 GeV/c^2, decaying to Λ_c^+K$^-\pi^+$ and Λ_c^+K$^-\pi^+\pi^+$. These final states are Cabibbo-allowed decay modes of doubly charmed baryons Ξ_{cc}^+ and Ξ_{cc}^{++}, respectively. The masses are in the range expected from theoretical considerations, but the spectroscopy is surprising. SELEX also has weaker preliminary evidence for a state near 3.8 GeV/c^2, a high mass state decaying to Λ_c^+K$^-\pi^+\pi^+$, possibly an excited Ξ_{cc}^{++} (ccu*). Data are presented and discussed.

2 Introduction

The quantum chromodynamics hadron spectrum includes doubly charmed baryons (DCBs): Ξ_{cc}^+ (ccd), $\Xi_{cc}^{++}(ccu)$, and Ω_{cc}^+ (ccs), as well as the triply charmed Ω_{ccc}^{++} (ccc). A 1996 DCB review [1] collected information on masses, lifetimes, internal structure, production cross sections, decay modes, branching ratios, yields, and experimental requirements for optimizing the signal and minimizing the backgrounds. DCB works published since then are given in Refs. [2, 3, 4, 5, 6, 7, 8, 9, 10]. The doubly and triply charmed baryons provide a new window for understanding the structure of all baryons. As pointed out by Bjorken [11], one should strive to study the triply charmed (ccc) baryon. Its excitation spectrum, including several narrow levels above the ground state, should be closer to the perturbative regime than is the case for the DCBs. The (ccq) studies are a valuable prelude to such (ccc) efforts.

Hadron structures with size scales much less than $1/\Lambda_{qcd}$ should be well described by perturbative QCD. The tightly bound color antitriplet (cc)$_{\bar{3}}$ diquark in (ccq) may satisfy this condition. But the DCB radius may be large, if it is dominated by the low mass q orbiting the tightly bound (cc) pair. The study of such configurations and their weak decays can help to set constraints on models of quark-quark forces [12, 13]. Stong [14] emphasized how the QQq excitation spectra can be used to phenomenologically determine the QQ potential, to complement the approach taken for $Q\bar{Q}$ quarkonium interactions.

Savage and Wise [15] discussed the (ccq) excitation spectrum for the q degree of freedom (with the (cc) in its ground state) via the analogy to the spectrum of $\bar{Q}q$ mesons, where the (cc) pair plays the role of the heavy $\bar{Q}$ antiquark. Fleck and Richard [12] calculated excitation spectra and other properties of (ccq) baryons for a variety of potential and bag models, which describe successfully known hadrons. In contrast to heavy mesons, the descriptions of light quark (qqq) and singly charmed (cqq) baryons are less successful. We need to better

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understand how the proton and other baryons are built from quarks. The investigation of the (ccq) system should help put constraints on baryon models, including light quark (qqq) and singly charmed (cqq) baryons, since the (ccq) has a quark structure intermediate between (qqq) proton and $\bar{Q}q$ meson structures.

In the double-charm system, there have been many predictions for the masses of the J=1/2 states and the J=3/2 hyperfine excitations [9]. Most results are consistent with expectations of a ground state mean mass around 3.6 GeV/c^2. The (cc) color antitriplet diquark has spin S=1. The spin of the third quark is either parallel (J=3/2) or anti-parallel (J=1/2) to the diquark. For (ccq), the J=1/2 states are expected to be lower than the J=3/2 states by around 80 MeV/c^2 [9, 10, 12, 16].

Bjorken [11] and also Fleck and Richard [12] suggest that internal W exchange diagrams in the Ξ^+_{cc} decay could reduce its lifetime to around $100 fs$, roughly half the lifetime of the Λ^+_c. Considering possible constructive interference between the W-exchange and two c-quark decay amplitudes, it is possible that this state should have an even shorter lifetime.

We describe qualitatively the perturbative production mechanism for DCBs. One must produce two c quarks (and associated antiquarks), and they must join to a tightly bound, small size anti-triplet pair. The pair then joins a light quark to produce the final (ccq). The two c-quarks may be produced (initial state) with a range of separations and relative momenta (up to say tens of GeV/c). In the final state, if they are tightly bound in a small size (cc) pair, they should have relative momentum lower than roughly 1 GeV/c. The overlap integral between initial and final states determines the probability for the (cc)-q fusion process. Such cross sections may be smaller by as much as 10^{-2}-10^{-3} compared to single-charm production. Aoki et al. [17] reported a low statistics measurement at $\sqrt{s}$ =26 GeV/c^2 for the ratio of double to single open charm pair production, of 10^{-2}. This $D\bar{D}D\bar{D}$ to $D\bar{D}$ cross section ratio was for all central and diffractive events. This high ratio is encouraging for (ccq) searches. Cross section guestimates are given in Ref. [1].

Brodsky and Vogt [18] suggested that there may be significant intrinsic charm (IC) $c\bar{c}$ components in hadron wave functions, and therefore also $cc\bar{c}\bar{c}$ components. The double intrinsic charm component can lead to (ccq) production, as the (cc) pairs pre-exist in the incident hadron. Intrinsic charm (ccq) production, with its expected high X$_f$ distribution, would therefore be especially attractive. When a double charm IC state is freed in a soft collision, the charm quarks should also have approximately the same velocity as the valence quark. Thus, coalescence into a (ccq) state is likely. Cross section guestimates are given in Ref. [1].

The semileptonic and nonleptonic branching ratios of (ccq) baryons were estimated by Bjorken [11] in 1986. He uses a statistical approach to assign probabilities to different decay modes. He first considers the most significant particles in a decay, those that carry baryon or strangeness number. Pions are then added according to a Poisson distribution. The Bjorken method and other approaches for charm baryon decay modes are described by Klein [19]. For the Ξ^{++}_{cc}, Bjorken [11] estimated the $\Lambda^+_c\pi^+K^-\pi^+$ final state to have 5% branching ratio; while for the Ξ^+_{cc}, he estimated the $\Lambda^+_c\pi^+K^-$ final state to have 3% branching ratio. One expects [1] that roughly 80% of the (ccq) decays are hadronic, with as many as one-third of these leading to final states with all charged hadrons.

3 Observation of DCBs at Fermilab SELEX

The SELEX experiment (E781) at Fermilab [20, 21, 22, 23] carries out DCB data analysis based on the sample of 1630 Λ^+_c and 10210 D-meson events from lifetime studies of these particles. SELEX used 600 GeV/c beams of π^-, Σ^-, and protons to produce charm particles in Carbon and Copper targets, detecting them with a magnetic spectrometer with high mass resolution ($\approx 5\ MeV/c^2$) and high proper lifetime resolution ($\approx$ 20 fs.), and Cerenkov particle identification of particles above 25 GeV/c.

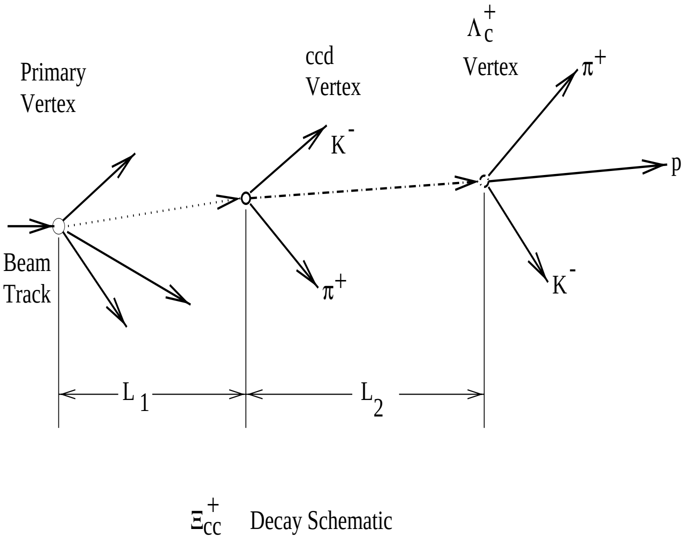

Figure 1: Schematic of $\Xi_{cc}^+ \to K^-\pi^+\Lambda_c^+$

SELEX has two statistically-compelling new high-mass states near 3.5 GeV/c^2 decaying to $\Lambda_c^+K^-\pi^+$ (3460 MeV/c^2) and $\Lambda_c^+K^-\pi^+\pi^+$ (3520 MeV/c^2) decay channels of DCBs Ξ_{cc}^+ (ccd) and Ξ_{cc}^{++} (ccu) [24, 25]. They appear to be members of the DCB family of new particles: (ccd) DCBs composed of two charm quarks and one down quark; and (ccu) DCBs composed of two charm quarks and one up quark. SELEX also has evidence [26] for a Ξ_{cc}^{++} (ccu) baryon near 3780 MeV/c^2, a high mass state decaying to $\Lambda_c^+K^-\pi^+\pi^+$, which may be a decay mode of an excited DCB Ξ_{cc}^{++} (ccu*). The 3520 MeV/c^2 state satisfies all expectations for being a Ξ_{cc}^+ state. Its mass is compatible with most model calculations for the DCB ground state. Its lifetime is shorter than 30 fs at 90% confidence. The 3460 MeV/c^2 state has the decay characteristics of a Ξ_{cc}^{++} state, and a comparable lifetime. However, it is difficult to understand the 60 MeV/c^2 mass difference between the Q=1 and Q=2 states if they are members of the ground state isodoublet. It is not yet confirmed that J = 1/2 for both states.

SELEX analysis and simulations continue for the charmed Lambda (Λ_c) decay-mode DCB data. SELEX also searches for the states observed to date in decay channels where the final state has a charmed D-meson rather than a Λ_c-baryon. Continuing SELEX data analysis aims to achieve a more complete understanding of the double charm sector, production with different beam particles, decay modes, cross sections and their A-dependence, X_F and p_t distributions.

3.1 Features of the Selex spectrometer

SELEX is a 3-stage magnetic spectrometer [20]. The negative 600 GeV/c Fermilab Hyperon Beam had about equal fluxes of π^- and Σ^-. The positive beam was 92% protons. For charm momenta in a range of 100-500 Gev/c, mass resolution is constant and primary (secondary) vertex resolution is typically 270 (560) μm. A RICH detector labelled all particles above 25 GeV/c, greatly reducing background in charm analyses. [21]. The details of single-charm analyses involving $\Lambda_c^+ \to pK^-\pi^+$ reconstructions can be found in [22, 23].

3.2 Double-charm Analysis for Λ_c Decay Modes

The double-charm search began with the sample of 1630 Λ_c^+ events (cud) used in the lifetime analysis. We ask for a weak-decay vertex lying between the primary vertex and the observed Λ_c^+ decay vertex. A Cabibbo-allowed ccd decay can give a final-state Λ_c^+, a K^-, and a π^+.

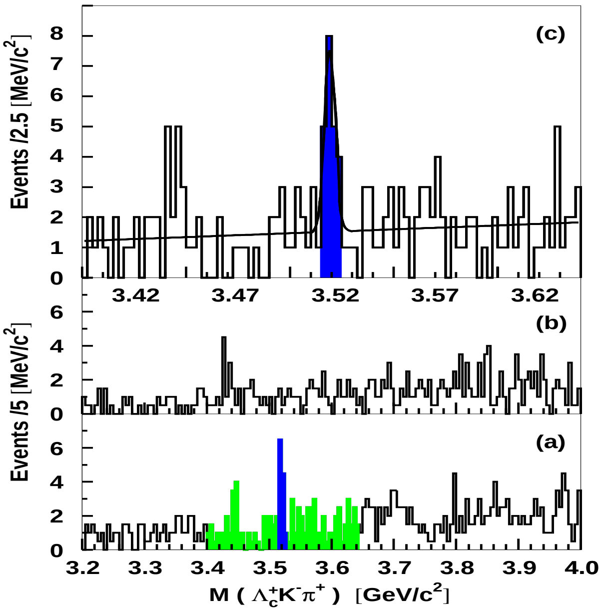

Figure 2: (a) The $\Lambda_c^+ K^- \pi^+$ mass distribution in 5 MeV/c^2 bins. The shaded region 3.400-3.640 GeV/c^2 contains the signal peak and is shown in more detail in (c). (b) The wrong-sign combination $\Lambda_c^+ K^+ \pi^-$ mass distribution in 5 MeV/c^2 bins. (c) The signal (shaded) region (22 events) and sideband mass regions (140 events) in 2.5 MeV/c^2 bins. The fit is a Gaussian plus linear background.

The c decays weakly, for example by $ccd \rightarrow csu + u\bar{u} + d\bar{d}$; corresponding for example to a $ccd \rightarrow \Lambda_c^+K^-\pi^+$ final state. The event topology contains two secondary vertices. In the first, a Λ_c^+ and a $K^-\pi^+$ meson pair are produced. This vertex may be distinguished from the primary vertex, if the (ccd) lifetime is sufficiently long. The Λ_c^+ now propagates some distance, and decays at the next vertex. The experiment must identify the two secondary vertices. The idea is shown schematically in Fig. 1.

We reconstruct total electric charge states Q=1 and Q=2 in separate reconstructions. The Q=1 sample consists of two oppositely-charged tracks along with a Λ_c^+. The Q=2 sample consists of a positively-charged triplet along with the Λ_c^+. Because the meson-pair tracks from the intermediate vertex may have energies below the RICH detection threshold (25 GeV/c for pions), or since they miss the RICH when they are emitted at wide angles, few achieve particle identification in the RICH. To be consistent with a $ccd \rightarrow \Lambda_c^+K^-\pi^+$ final state, the negative track should be a Kaon. We build "right-sign" and "wrong-sign" samples, based on calling the negative track a Kaon or a pion, respectively.

Event selection cuts used here were taken without change from previous single-charm studies. For short-lived states, $L_1/\sigma_1 \geq 1$ and the Λ_c^+ momentum vector must point back to the primary vertex within a χ^2 cut. We have varied the cuts and observe that no signal significance depends critically on any cut value. The signals seen here are stable.

3.2.1 Q = 1 reconstruction, 3520 MeV/c^2

Fig. 2. shows the K$^-\pi^+\Lambda_c^+$ mass distribution for single-charged baryons. Fig. 2(a) shows a Ξ_{cc}^+ candidate at 3520 MeV/c^2, consistent with most model calculations. The peak is 3 ± 1 MeV/c^2 wide, narrower than but consistent with simulation (5 ± .5 MeV/c^2). The final state

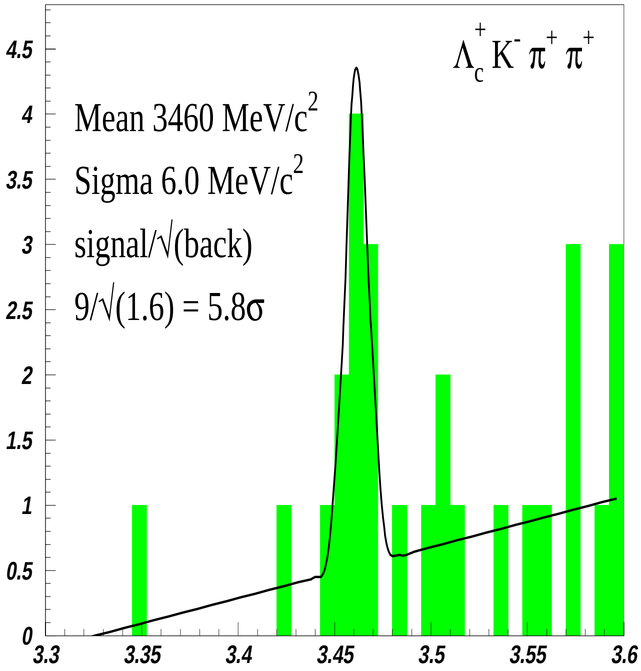

Figure 3: $\Xi_{cc}^{++} \to K^-\pi^+\pi^+\Lambda_c^+$ mass distribution in 7.5 MeV/c^2 bins.

meets the double-charm Cabibbo-favored criteria: final state single charm, final state baryon, final state K$^-$. The general agreement between right-sign (negative track is Kaon) and wrong-sign (negative track is pion) average levels and fluctuations in Fig. 2 confirms that most events are combinatoric background. The signal channel shows a 22-event excess over a background of 6.1 ± 0.51 events, for a single-bin significance of 6.3 σ. Treating this with gaussian statistics, the probability of such an excess is less than 10^{-8} for a single bin. We searched for a peak in the interval 3.2-4.3 GeV/c^2, or 110 bins. In each bin there is a Poisson-distributed number of events along with a Gaussian fluctuation on the background. Summing these effects gives the overall probability that our search would find such a fluctuation anywhere in the search interval of less than 10^{-4}.

We calculated the lifetime likelihood for signal and sideband regions in reduced proper time $t^* = M(L - L_{min})/pc$ for several different lifetime values. In this analysis $L_{\rm min} = \sigma_1$, the error on the vertex separation L_1 in the schematic from Fig. 1. From SELEX single-charm lifetime studies, we know the lifetime resolution is about 20 fs. Here, the sidebands show a lifetime of 30^{+18}_{-12} fs. The signal region result is shorter, with lifetime less than 30 fs at 90% confidence. These two results are, of course, statistically consistent with a common short lifetime for signal and sideband regions.

3.2.2 Q=2 Reconstruction, 3460 MeV/c^2

Fig. 3 shows a Ξ_{cc}^{++} candidate at 3460 MeV/c^2. The peak is narrow, 6 ± 1 MeV/c^2, matching our simulation width. The final state meets the double-charm Cabibbo-favored criteria: final state single charm, final state baryon, final state K$^-$. The Q=2 sample distribution is quite different from that for Q=1. The kinematic threshold for this channel opens near 3.0 GeV/c^2, yet we have only 2 events below the 3460 mass peak. The background under the peak is clearly Poisson-distributed. Making a likelihood fit to a linear background function, we find 9 events in the peak, compared to an expected background of 1.6 events. The Poisson probability that there is an excess of 7.4 events or more is 5 x 10^{-5}. This search looked for an isospin partner to the $\Xi_{cc}^{+}(3520)$ and was limited to the range 3.3-3.6 GeV/c^2, containing 13 bins of width

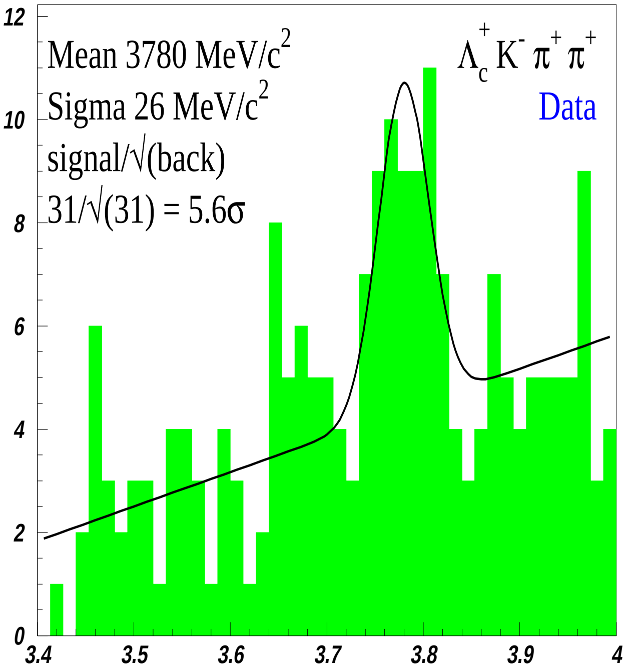

Figure 4: $\Xi_{cc}^{++} \to K^-\pi^+\pi^+\Lambda_c^+$ mass distribution in 7.5 MeV/c^2 bins. The linear background is determined from a liklihood fit in the mass range 3.41-3.99 GeV/c^2.

22.5 MeV/c^2. The probability for a statistical fluctuation up to a 7.4-event excess in any of these 13 bins is less than 7 x 10^{-4}.

There are too few events to attempt a lifetime analysis, either for signal or background. We have compared the rest-frame angular decay variables to a phase-space simulation. The comparison is good for the signal region. The background tends to be more peaked along the flight direction of the candidate, as one might expect for accidental reconstructions.

One can ask why there are so few Ξ_{cc}^{++} candidates compared to $\Xi_{cc}^{+}(3520)$ candidates. Simulation shows that the acceptance is substantially lower for the Q=2 system at masses below 3500 MeV/c^2 than for a corresponding Q=1 system. The SELEX spectrometer cuts off the slow pion acceptance from the higher-multiplicity state. This can be seen in the data by the presence of low-mass background in Fig. 2 and its absence in Fig. 3.

3.2.3 Q=2 Reconstruction, 3780 MeV/c^2

We also searched at higher mass for $\Lambda_c^+K^-\pi^+\pi^+$ decay of Ξ_{cc}^{++} (ccu) [24]. We have evidence [26] for a Ξ_{cc}^{++} ccu baryon near 3780 MeV/c^2, a state which may be an excited DCB Ξ_{cc}^{++} (ccu*). The data are shown in Fig. 4, with a linear fit to the background. Other fits are possible, with higher background levels, as in Fig. 5. The background curves are determined from the spectrum itself, from background simulation studies, and taking into account also the wrong-sign mass plot. The higher background in Fig. 5 is based on a simulation study, which shows that the excess near 3660 MeV may be due to combinatorial background of a real ccd with a π^+ from the primary vertex. This leads us to fit from 3650 MeV, to account for this effect. The number of signal events drops, the background increases, and the signal significance drops from 5.6σ to 4.0σ. The width of the peak is roughly three times wider than the low lying DCB peaks, which would be possible for a state which decays strongly. For this ccu* however, the data do not have a plausible explanation, in that roughly 50% of the signal events above background decay weakly (to $\Lambda_c^+K^-\pi^+\pi^+$) and 50% decay strongly (to $\pi^+\Xi_{cc}^{+}$). This is not possible for a single state. We can not now draw unambiguous conclusions. We

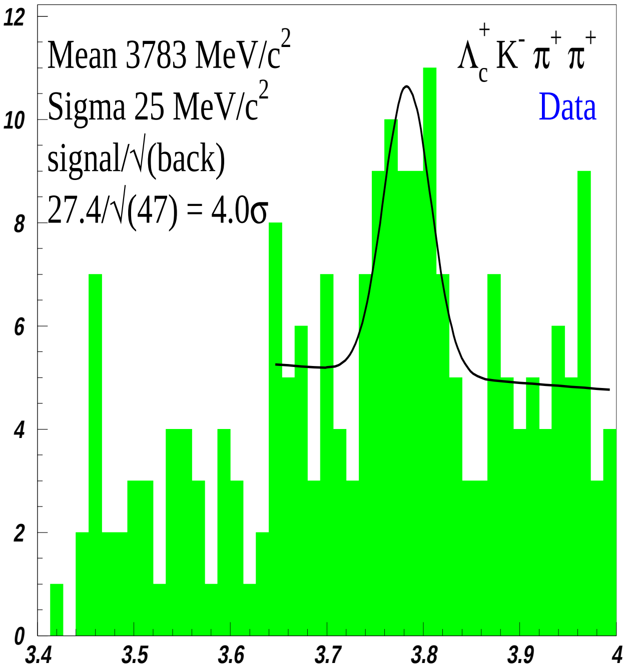

Figure 5: $\Xi_{cc}^{++} \to K^-\pi^+\pi^+\Lambda_c^+$ mass distribution in 7.5 MeV/c^2 bins. The linear background is determined from a liklihood fit in the mass range 3.65-3.99 GeV/c^2.

plan further study of these data and backgrounds.

3.3 Production

Production characteristics of the 22 signal plus background events at 3520 MeV/c^2 are indistinguishable from the single-charm Λ_c sample [23]. The mean p_t is 1 GeV/c and mean $x_F \sim 0.33$. This value of x_F is significantly higher than the value $x_F \approx 0.10$ that one expects [1] if the (ccd) is produced near threshold in a central collision.

We compared production of the Ξ_{cc}^+ and Ξ_{cc}^{++} states by different beam hadrons. The DCBs we see are produced solely by the baryon beams in SELEX data. There are no signal candidates from the pion beam. We also checked if there is a dependence on the target nucleus. We found [24] that the diamond/copper ratio of the signal events is similar to the sideband events, which in turn behave like single-charm production.

Count rate estimates for DCBs at were given previously [1] based on ccq cross section of at most 25 nb per nucleon (25 nb/N). This value is based on a reduction factor of 1000 per produced charm quark, considering that the open charm production cross section (25μb/N) is 1000 times lower than the total inelastic cross section 25 mb/N. But SELEX DCB cross sections are several orders of magnitude higher, as approximately 60 DCBs are observed in a sample of 1630 Λ_c. Simulation studies suggest that the double-charm states may account for as much as 40% of the Λ_c^+ sample seen in this experiment, a surprisingly high fraction. Work is in progress to calibrate the SELEX trigger efficiency factor, in order to fix the absolute value of the DCB cross sections. The high DCB cross section is reminiscent of the discovery of the Ξ_c^+ baryon in the WA62 experiment at CERN, using a 135 GeV/c hyperon beam [27]. That cross section was also anomalously large and still has no good theoretical explanation. The FOCUS photoproduction experiment at Fermilab has looked for these states using their Λ_c^+ events. They see very few candidate events and no signal peaks [28].

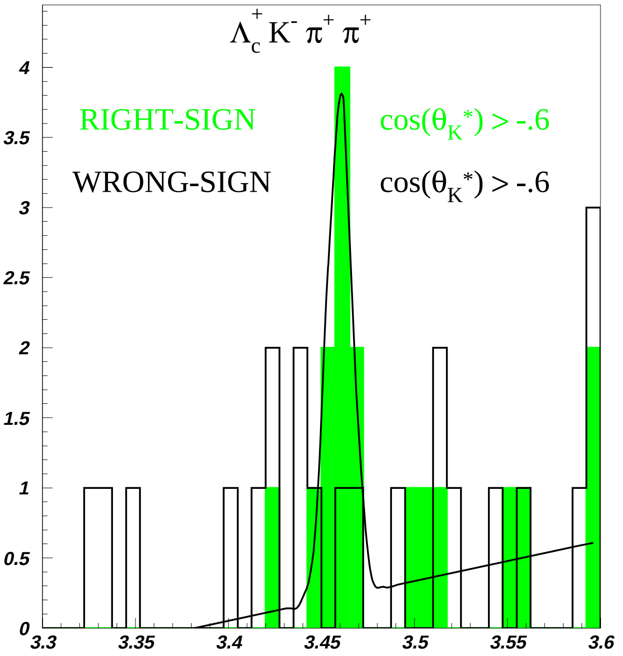

Figure 6: $\Xi_{cc}^{++} \rightarrow$ K$^-\pi^+\pi^+\Lambda_c^+$ mass distribution in 7.5 MeV/c^2 bins, with angle cut. Signal events are shaded. Wrong-sign background is shown as open histogram boxes.

3.4 Background Reduction Studies for Λ_c Decay Channels

The cleanest SELEX DCB data are for ccd and ccu lowest peaks, while for ccu* the backgrounds are significant. Consider the ccu at 3460 MeV. Events outside the signal region show a strong preference for the center-of-mass (CM) angle of the negative track to be near 180 degrees, where the angle is with respect to the Λ_c^+ direction. This suggests that these tracks represent accidental overlaps of a low energy primary track and a real secondary vertex. In the CM system, a low energy primary track is interpreted as a back-angle track from the secondary vertex.

Simulation indicates that a cut to remove such events should have little effect on the signal region for a phase-space distribution. That is indeed the case in the data. For the ccu at 3460 MeV, with a cut $cos(\theta_K^*) > -.6$, we obtain 1 background and 8 signal events. The spectrum is shown in Fig. 6. This angle cut gives result cleaner than without the angle cut, where we had previously 1.6 background and 7.4 signal events. Without this cut, the Poisson probability that there is an excess of 7.4 events in any of the 13 bins between 3.3-3.6 GeV/c^2 is less than 7 x 10^{-4}, and the signal significance is 5.8 σ. With this cut, the Poisson probability that there is an excess of 8 events in any of these 13 bins is reduced to 10^{-5}, and the signal significance is 7.9 σ. We will make similar studies for the ccu* data. The CM angle cut does affect the ccu* region strongly, but not in a way that is simple to understand. For ccu, ccu*, SELEX studies to what extent the decay angular distribution of the K$^-$ in the rest frame of the K$^-\pi^+\Lambda_c^+$ system is compatible with a phase-space simulation, both for signal and for background. With further simulations, SELEX will try to better understand such experimental distributions, and will explore other methods of reducing the backgrounds.

3.5 Search for double-charm baryons in D-meson decay modes

SELEX started complementary DCB data analysis of these same states based on our independent data for D-meson decays. Some possible decay modes of interest are: (D^+K^-p), $(D^0\bar{K}^0p)$

for (ccd); ($D^+\Lambda\pi^+$), ($D^0\Lambda\pi^+\pi^+$), ($D^+\bar{K}^0p$), ($D^{*+}\Lambda\pi^+$), ($D^+K^-p\pi^+$), for (ccu). This work is in progress.

4 Planning for the CERN COMPASS experiment

The SELEX efforts will help in the planning of a future state-of-the-art double charm measurement via the CERN COMPASS experiment, and elsewhere. The Sept. 2002 COMPASS-Future meeting at CERN included already a presentation of SELEX data, and initial COMPASS plans in response to consultations with SELEX on the SELEX DCB data [30]. Based on the SELEX results, one could expect from COMPASS [1, 30] up to 10,000 reconstructed DCBs for a 100 day run. The SELEX data have stimulated more detailed plans/prospects/efforts at COMPASS to study DCB and even triply charmed baryon spectroscopy.

5 Summary

We reviewed DCB theory. We presented SELEX data for two statistically-compelling new high-mass states that decay into a final state Λ_c^+, K^- and one or two π^+, as expected for double-charm baryon decays. The 3520 MeV/c^2 state satisfies all expectations for being a Ξ_{cc}^+ state. Its mass is compatible with most model calculations for the double-charm baryon ground state. Its lifetime is shorter than 30 fs at 90% confidence. The 3460 MeV/c^2 state has the decay characteristics of a Ξ_{cc}^{++} state. However, it is difficult to understand the 60 MeV/c^2 mass difference between the Q=1 and Q=2 states if they are members of the ground state isodoublet. We have not yet tried to confirm that J = 1/2 for both states. We also showed evidence [26] for a Ξ_{cc}^{++} (ccu) baryon near 3780 MeV/c^2, a high mass state decaying to $\Lambda_c^+K^-\pi^+\pi^+$, which may be a decay mode of an excited DCB Ξ_{cc}^{++} (ccu*). The SELEX data have been used already in the planning of the CERN COMPASS DCB experiment. Internet links to SELEX and COMPASS DCB presentations are given in Ref. [31].

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