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Λ_c^+ Production and Semileptonic Decay in 29-GeV e^+e^- Annihilation

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We present results on Λ_c^+ production in 29-GeV e^+e^- annihilation. The Λ_c^+ are observed via their semileptonic decays to Λe^+X and $\Lambda\mu^+X$. With radiative corrections, we find $\sigma(e^+e^-\to\Lambda_c^+X)\times B(\Lambda_c^+\to e\Lambda X)=1.5\pm0.6\pm0.5$ pb or $0.0038\pm0.0015\pm0.0012$ $\Lambda_c^+\to\Lambda e^+X$ decay per hadronic event, and $\sigma(e^+e^-\to\Lambda_c^+X)B(\Lambda_c^+\to\mu\Lambda X)=1.4\pm1.4\pm0.4$ pb or $0.0035\pm0.0035\pm0.0011\Lambda_c^+\to\Lambda\mu^+X$ decay per hadronic event. These results can be used to place constraints on the predictions of various production models.

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As the lightest charmed baryon, the Λ_c^+ is of great interest. However, fairly little is known about it. In particular, its semileptonic decays, which are the most accessible theoretically,[1] are almost unstudied experimentally. Also, although Λ_c^+ production rates are a strong test of e^+e^- fragmentation models, no previous results on Λ_c^+ production have been reported at the energies of the SLAC and DESY storage rings PEP and PETRA. We describe here the observation of a Λ_c^+ signal in e^+e^- annihilation at 29 GeV. The Λ_c^+ is observed via its decays to a final state containing a Λ plus a lepton.[2]

This analysis is based on an integrated luminosity of 207 pb^{-1} of data, collected over a period of three years with the original Mark II/PEP 5 detector at PEP. The detector has been described elsewhere.[3] Charged particles are tracked in a 16-layer cylindrical drift chamber and a 7-layer precision drift chamber in a 2.3-kG magnetic field. Charged-particle momenta p (GeV/c) are measured with a resolution of $\delta p/p=[(0.010p)^2+(0.025)^2]^{1/2}$. Electrons are identified by their energy deposition pattern in a lead–liquid-argon calorimeter, which covers 64% of the 4π solid angle. Muons are identified over 45% of the 4π solid angle, by their penetration of a 4-layer steel absorber stack.

Hadronic events are selected with a standard set of cuts. Briefly, we require at least five reconstructed charged tracks which form a vertex less than 4 cm radially and less than 7 cm axially from the expected e^+e^- annihilation point. The sum of the momenta of all charged tracks is required to be at least 3.0 GeV and the total visible charged plus neutral energy is required to be at least 7.5 GeV.[4] The tracks used in this analysis are required to have a momentum perpendicular to the beam axis, p_{xy}, greater than 100 MeV/c, and have $|\cos(\theta)|<0.8$, where θ is the angle between the particle track and the beam axis.

Λ candidates are selected by finding vertices for all oppositely charged track pairs in the plane perpendicular to the beam (the x-y plane). The higher-momentum particle in each pair is assumed to be the proton. This assignment is always correct for Λ with momenta over 250 MeV/c. Pairs which meet the following criteria are considered to be Λ candidates: (1) The distance from the reconstructed decay vertex to the center of the interaction region in the x-y plane must be greater than 10 mm. (2) The pion must have a distance of closest approach to the interaction region of greater than 1 mm in the x-y plane. (3) The proton must have a distance of closest approach to the interaction region of greater than 0.6 mm in the x-y plane. (4) At their x-y vertex, the two tracks must have a z difference of less than 4 cm. (5) The Λ candidate must have a momentum of at least 1.5 GeV/c. Λ candidates with lower momenta are unlikely to come from Λ_c^+ decays.

The proton and pion momenta are adjusted to compensate for dE/dx loss in the beam pipe and the two tracks are constrained in a three-dimensional vertex fit. For Λ candidates with momenta p_Λ less than 2 GeV/c, the calculated mass is required to be within 5 MeV/c^2 of the actual Λ mass. For candidates with momenta more than 2 GeV/c, the calculated mass is required to be within 4 MeV/c^2+$0.0005p_\Lambda$ (MeV/c) of the actual Λ mass.

These Λ candidates are paired with all lepton candidates. The lepton identification criteria and background are described in Ref. 4. Briefly, electrons are identified by the pattern of their energy deposition in the liquid-argon calorimeter. The detection efficiency for electrons in the fiducial volume varies with momentum, but is roughly 90%. Muons are identified by their penetration into a steel absorber stack. For muons in the fiducial volume, the efficiency is roughly 85%, increasing with momentum. Electrons are required to have $p > 1.5$ GeV/c, while muons must have $p > 2$ GeV/c. The leptons are required to be in the same hemisphere as the Λ, where boundaries of the hemisphere are determined by a plane perpendicular to the thrust axis.

For a Λl^+ pair comings from a Λ_c^+ decay, a positively charged lepton will be paired with a Λ, while a negatively charged lepton will accompany a $\bar{\Lambda}$. In both cases, the Λl^+ pair invariant mass will be less than the Λ_c^+ mass. The invariant-mass spectra of the combinations are shown in Fig. 1, separately for right- and wrong- sign combinations. Below the Λ_c^+ mass of 2.28 GeV/c^2, there are 19 right-sign (13 electron, 6 muon) and 6 wrong-sign (3 electron, 3 muon) combinations, while above the Λ_c^+ mass, there are 2 right-sign (both electrons) and 3 wrong-sign combinations (all electrons).

The background was studied with a Monte Carlo simulation, and compared with the wrong-sign candidates.[5] In decreasing order of importance, the major background sources are K_S and random track combinations misidentified as Λ (roughly 70% of the background), fake leptons, as discussed in Ref. 4 (roughly 25% of the background), and random lepton-Λ combinations (roughly 5%). All of these sources populate the right- and wrong-sign plots equally. There are two small additional sources which can produce only wrong-sign pairs. The first is semileptonic B decays, where a B meson or baryon decays to a lepton plus a Λ_c^+, and the Λ_c^+ subsequently decays to a Λ. The estimated background from this source is negligible, as can be seen by examining the excess of wrong events above the Λ_c^+ mass, where most decays of this type will appear. Secondly, if an antiproton is produced in association with a Λ, and the antiproton annihilates in the liquid-argon calorimeter to mimic an electron, this can produce a wrong-sign pair. The possible background from this source is included as a systematic error.

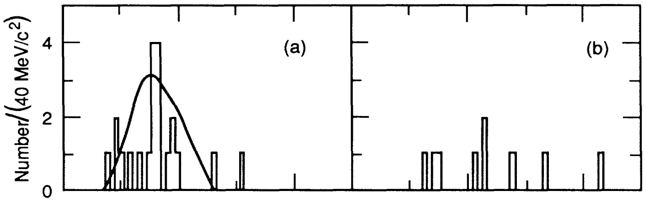

FIG. 1. Invariant-mass spectra for (a) Λl^+ and (b) Λl^-. The solid line in (a) is the Lund-model prediction for $\Lambda_c^+ \rightarrow \Lambda l^+ \nu$, with arbitrary normalization.

The wrong-sign combinations should therefore be a good measure of the background. After background subtraction, the signal is 10 ± 4 electron and 3 ± 3 muon events.

Measuring the production cross section times branching ratio requires a knowledge of the detection efficiency, which, along with the shapes of many interesting distributions, depends heavily on which specific decay modes are dominant. To determine which modes are most likely to be important, we are forced to rely on theoretical arguments, and allow for uncertainties as a systematic error. Some possible modes are $\Lambda l^+ \nu$, $\Sigma^0 l^+ \nu$, $\Sigma^{*0} l^+ \nu$, $\Lambda \pi^0 l^+ \nu$, $\Sigma^0 \pi^0 l^+ \nu$, and $\Lambda(\pi\pi)^0 l^+ \nu$. Other modes are Cabbibo suppressed, or have little phase space.

Theory predicts that most of the above modes are suppressed. Since the Λ_c^+ is an isosinglet, the final-state hadrons should have isospin 0, suppressing the isospin-1 modes $\Sigma^0 l^+ \nu$, $\Sigma^{*0} l^+ \nu$, and $\Lambda \pi^0 l^+ \nu$. Another restriction comes from the dynamics of the decay. When the $c \rightarrow s l^+ \nu$ decay occurs, the strange quark gets a perpendicular momentum kick from the W, while the u and d quarks are spectators. If additional quark-antiquark pairs are created, they should appear between the s quark and the u and d quarks. The baryon producing the ud diquark will be separated from the strange quark, reducing the probability of a final-state Λ in modes involving extra pions. We can also compare the Λ_c^+ with the charmed meson sector, where semileptonic D-meson decays generally lead to a charged lepton, a neutrino, and a single hadron.[6]

Two final arguments come from the data. We searched for the final state $\Lambda \pi^+ \pi^- l^+ X$, and found no candidates. Since the acceptance for this mode is quite good, compared with the acceptance for $\Lambda l^+ X$, we conclude that this mode should be negligible. Finally, the Monte Carlo prediction for the Λl^+ mass spectrum from

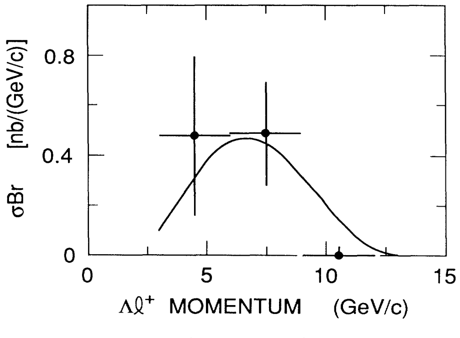

FIG. 2. The background-subtracted momentum spectra for the Λl^+. The solid line is the Lund-model prediction for $\Lambda_c^+ \rightarrow \Lambda l^+ \nu$, normalized to agree with the data in the 3–12-GeV/c region.

$\Lambda_c^+ \rightarrow \Lambda l^+ \nu$, shown in Fig. 1, agrees with the data. So, we will therefore assume that $\Lambda_c^+ \rightarrow \Lambda l^+ \nu$ dominates and include the possibility of other Λ-containing decays as a systematic error in the efficiency.

Another important consideration in calculating the efficiency is the momentum spectrum. Figure 2 compares the observed momentum spectrum of the Λl^+ combination with the Lund-model prediction. Because of the limited momentum range and statistics, it is not possible to extract the original Λ_c^+ momentum spectrum.

The overall efficiency is found with a Monte Carlo simulation. It is 3.3% for the electron channel and 1.4% for the muon channel. From this, it is possible to calculate the Λ_c^+ production cross-section rate times $B(\Lambda_c^+ \rightarrow \Lambda l^+ X)$. The major systematic errors come from the uncertainties in the Λ_c^+ momentum spectrum and decay modes (25%). If other decay modes are present, they will manifest themselves as a decrease in the average Λl invariance mass and momentum. The reasonable agreement shown in Fig. 2, together with the ARGUS[7] and CLEO[8] observations that the Λ_c^+ fragmentation function is similar to the D fragmentation function, limits the error due to uncertainty in the momentum spectrum. The uncertainty due to decay modes is estimated from a comparison of the invariant-mass and momentum spectra for the modes $\Lambda l^+ \nu$ and $\Lambda \pi^0 l^+ \nu$.[5] Other sources of systematic uncertainty are in the tracking efficiency (3% per track, or 9%), detector variations over time (10%), luminosity (2%), Monte Carlo simulation (10%), and Monte Carlo statistics (8%). The electron measurement has an additional 14% systematic uncertainty due to the possibility of antiproton-electron misidentification.

After corrections for acceptance and initial-state radiation, we find

$$\sigma(e^+e^- \rightarrow \Lambda_c X) B(\Lambda_c^+ \rightarrow \Lambda e^+ X) = 1.5 \pm 0.6 \pm 0.5 \text{ pb}$$

or $0.0038 \pm 0.0015 \pm 0.0012$ $\Lambda_c^+ \rightarrow \Lambda e^+ X$ decay per hadronic event, and

$$\sigma(e^+e^- \rightarrow \Lambda_c X) B(\Lambda_c^+ \rightarrow \Lambda \mu^+ X) = 1.4 \pm 1.4 \pm 0.4 \text{ pb}$$

or $0.0035 \pm 0.0035 \pm 0.0011$ $\Lambda_c^+ \rightarrow \Lambda \mu^+ X$ decay per hadronic event.

To put this in perspective, we need to consider the Λ_c^+ branching ratios. Mark II at the SLAC storage ring SPEAR measured[9] $B(\Lambda_c^+ \rightarrow e^+ X) = (4.5 \pm 1.7)\%$ and $B(\Lambda_c^+ \rightarrow \Lambda e^+ X) = (1.1 \pm 0.8)\%$. A Fermilab neutrino beam experiment also measured[10] $B(\Lambda_c^+ \rightarrow \Lambda e^+ X) < 2.2\%$ at a 90% confidence level.

Using this upper limit, we get a lower limit on the production rate of $0.17 \pm 0.07 \pm 0.05$ Λ_c^+ per hadronic event, neglecting uncertainty from the branching-ratio limit. This limit can be compared with the predictions of various models.

The Lund model[11] predicts 0.06 Λ_c^+ per hadronic event. The UCLA model[12] bases hadron production rates on their mass, and since the Λ_c^+ mass is high, the predicted rate is much lower, 0.018 Λ_c^+ per hadronic event, somewhat lower than the data indicate. The Webber model[13] predicts 0.026 Λ_c^+ per hadronic event, also somewhat lower than the data indicate.

We have also searched for hadronic decays of the Λ_c^+. The final states $pK^-\pi^+$, $\Lambda\pi^+$, $\Lambda 3\pi$, pK_S, and $pK_S\pi^+\pi^-$ were studied. No evidence for any of these states was found. The most interesting upper limit was for the decay to $\Lambda 3\pi$. The cuts used in the search where chosen to match the semileptonic analysis cuts as closely as possible. The Λ_c^+ were required to have a momentum of at least 5.5 GeV/c, chosen to match the 4-GeV/c Λl^+ momentum requirement as closely as possible. The same Λ selection criteria were used. Each of the three pions were required to have a momentum of at least 400 MeV/c. The resulting mass spectrum is shown in Fig. 3. To find an upper limit on the rate, the invariant-mass spectrum was fitted by a Gaussian, with fixed width determined by Monte Carlo simulation, plus a linear background. The position of the Gaussian was allowed to vary within the systematic mass uncertainty; the position that give the worst upper limit was used. This led to a 90%-confidence-level upper limit of

$$\frac{B(\Lambda_c \rightarrow \Lambda 3\pi)}{B(\Lambda_c^+ \rightarrow \Lambda e^+ X)} < 1.7 .$$

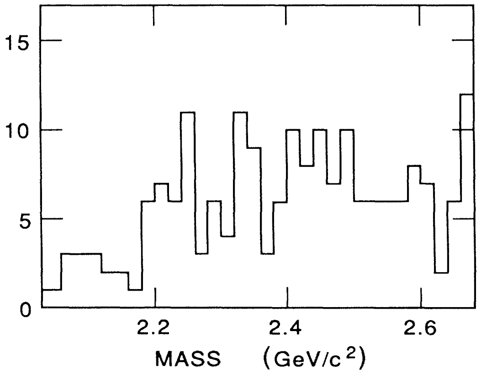

FIG. 3. The invariant-mass spectra for $\Lambda\pi^+\pi^-\pi^+$. No Λ_c^+ signal is visible.

We have also searched for the Σ_c, via the decay chain $\Sigma_c \rightarrow \Lambda_c^+ \pi$, by studying the mass difference $\Delta m = m(\Sigma_c) - m(\Lambda_c)$ for Σ_c candidates. Because of the missing ν momentum, the Δm resolution is poor, about 60 MeV/c^2. There are one Σ_c^{++} and two Σ_c^0 candidates, which are completely compatible with background. With these candidates, and assuming that all Σ_c decay to $\Lambda_c^+ \pi$, we find $\sigma(\Sigma_c^{++})/\sigma(\Lambda_c^+) < 0.48$ and $\sigma(\Sigma_c^0)/\sigma(\Lambda_c^+) < 0.67$, both at a 90% confidence level.

To conclude, we have observed semileptonic Λ_c^+ decays in 29-GeV e^+e^- annihilation. The Λ_c^+ are identified by their decays to a final state containing a Λ plus a lepton with an invariant mass below the Λ_c^+ mass. Using previous measurements of the Λ_c^+ semileptonic branching ratios, we find that the UCLA and Webber models predict too little Λ_c^+ production, while the Lund model gives reasonable agreement with the data.

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