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Measurements of the Σ_c^0-Λ_c^+ and Σ_c^{++}-Λ_c^+ Mass Differences

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Measurements of Σ_c^0-Λ_c^+ and Σ_c^{++}-Λ_c^+ mass differences have been made in a beam of incident neutrons. Our Σ_c^{++}-Λ_c^+ mass-difference measurement is 167.4 ± 2.1 MeV/c^2, in good agreement with previous results. We measure the Σ_c^0-Λ_c^+ mass difference to be 178.2 ± 2.0 MeV/c^2. We use these measurements to determine the Σ_c^{++}-Σ_c^0 mass splitting to be -10.8 ± 2.9 MeV/c^2.

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The establishment of the charmed baryons has been prolonged in contrast to that of the charmed mesons because of the short lifetime of the Λ_c, the comparatively low rates for baryon/antibaryon production in e^+e^- annihilation and neutrino interactions, and the large background in hadron-hadron experiments. An accurate determination of the Σ_c^{++}-Σ_c^0 mass difference is extremely valuable. Several models[1-11] exist where mass differences within the Σ_c family arise from such effects as constituent quark masses, the color hyperfine interaction, and the QCD Coulomb quark force. The mass-difference predictions from these models vary from $+6.5$ MeV/c^2 to -18 MeV/c^2.

In this Letter we report on measurements of the mass differences $\Sigma_c^{++} - \Sigma_c^0$, $\Sigma_c^0 - \Lambda_c^+$, and $\Sigma_c^{++} - \Lambda_c^+$. The latter two transitions arise from strong decays of the Σ_c: $\Sigma_c^0 \to \Lambda_c^+ + \pi^-$ and $\Sigma_c^{++} \to \Lambda_c^+ + \pi^+$ with $\Lambda_c^+ \to pK^-\pi^+$. Throughout this paper we use the convention that reference to a particle state implies the charge-conjugate state as well. Because of the small mass difference between the Σ_c and the Λ_c, the mass resolution on the splitting is excellent, approximately 2 MeV/c^2, and should provide a powerful tool for future experiments. We also note that measurements of mass differences, as opposed to actual-state masses, are in general very insensitive to systematic errors in the mass scale.

Evidence for the production of the charmed baryon Σ_c^{++} has been reported by many experiments,[12-16] but the Σ_c^+ has only been observed in a single experiment[17] and the Σ_c^0 has only been reported in two instances.[16,18] A beam of incident neutrons (quark content *udd*) may be expected to have more abundant Σ_c^0 (quark content *cdd*) production than an e^+e^- experiment because of the presence of valence quarks in the beam and target.

The experiment was performed in the Proton East beam line at Fermi National Accelerator Laboratory. A neutron beam was formed by the collimation of the neutrons produced at 0° by a beam of 800-GeV/c momentum protons incident on a beryllium target. The neutron energy spectrum ranged from 0 to 800 GeV/c^2 and was triangular in shape with a peak at approximately 640 GeV/c^2. The contribution to the neutral beam from photons and K_L^0's above 200 GeV/c^2 was negligible.

The detector shown in Fig. 1 consists of an active target and vertex detector, a magnetic spectrometer, a gas Cherenkov system, and electromagnetic and hadronic calorimetry. The target was composed of three segments consisting of 300 μm thickness of W, 2000 μm of Si, and 4000 μm of Be. The Si segment consisted of active wafers instrumented for charge readout. A fourth target segment of 600 μm of Si followed the target stack for use in the interaction trigger. The target segments were separated longitudinally by 2.5 cm. Thus the primary interaction took place at a well-defined point in z while long-lived charm decays occurred primarily in the space between target segments. Immediately following the target region was a vertex detector consisting of nine planes of multiwire proportional chambers (MWPC's) with 250-μm wire spacing in three views. The main magnetic spectrometer consisted of two analyzing magnets, M1 and M2, and five stations of MWPC's, P0 through P4. The angular acceptance for tracks through M1 was 100×200 mrad^2, decreasing to 40×50 mrad^2 for two-magnet tracks. The spectrometer has a measured resolution of $\sigma_p/p=0.0002p$ for tracks traversing both magnets, and $\sigma_p/p=0.0014p$ (p in GeV/c) for tracks traversing only the first magnet.

Charged-particle identification was accomplished with use of three 34-cell Cherenkov counters, operating with pion thresholds of 2.8, 10.8, and 5.7 GeV/c. Protons could be uniquely identified from 10 to 80 GeV/c, while kaons could be distinguished from pions from 2.8 to 40 GeV/c. Neutral kaons and lambdas were reconstructed if they decayed at least 15 cm downstream of the target and upstream of the center of $M2$.

The total event energy was obtained by the summation of the output of the three calorimeters LG, HC, and BD. The front calorimeter was a 22-radiation-length array of 120 lead glass blocks to measure electromagnetic energy. Immediately following were six absorption lengths of steel and scintillator to measure hadronic energy. Both detectors contained a beam hole of approximately 3.8 cm radius. A third calorimeter built of six absorption lengths of tungsten and scintillator was used to measure energy passing through the beam hole. The summed response of the first two calorimeters comprised our minimum-energy trigger. The neutron flux of approximately 1.5×10^7 per 20-s pulse was low enough to reduce the energy contamination from multiple neutrons to a negligible level.

The data for this analysis consisted of approximately 45×10^6 events. The event trigger required that all of the following conditions be satisfied: (a) a coincidence between target-region scintillation counter T1 and two coincidences in the downstream scintillator hodoscope HxV; (b) a minimum trigger energy of 265 GeV; (c) a minimum multiplicity of four charged tracks in the downstream spectrometer; (d) a deposited charge in the most downstream active silicon target equivalent to two or more charged tracks; (e) at least one charged kaon with momentum over 21 GeV/c or one proton over 40 GeV/c traversing the entire detector.

All triggers satisfying requirements (a) through (e) were processed through an analysis which found all charged tracks and a common vertex, then performed a Cherenkov counter analysis and searched for all K_S and Λ candidates. For the final state reported, all events containing a $pK^-\pi^+$ with an invariant mass between 2130

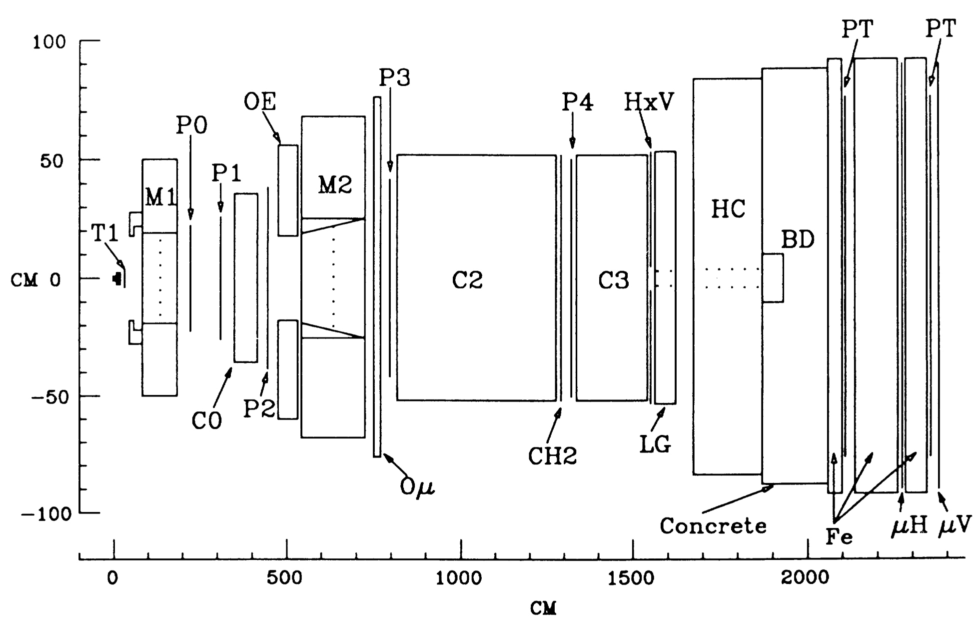

FIG. 1. E400 spectrometer.

and 2430 MeV/c^2 and total multiplicity less than twelve were further processed. The multiplicity cut was required to reduce the combinatoric background to an acceptable level. The effect of this cut on the relative Σ_c^0 and Σ_c^{++} yields is presently under study, but it has no effect on the mass difference. All tracks were traced through the vertex detector. An acceptable fit to all chamber hits, including drift-time information, was required for a successful link with tracks in the vertex detector. Approximately 10% of the main spectrometer tracks were unlinked and did not reconstruct as part of a K_S and Λ decay.

Particle identification was performed with the Cherenkov system. Protons were required to be uniquely identified as such, while kaons were allowed to be either uniquely identified as kaons or ambiguous with the proton hypothesis. All tracks not explicitly identified as kaons or protons were considered as pion candidates.

Tracks of appropriate charge to form a $pK^-\pi^+$ combination were selected to construct the Λ_c^+ candidates. Only linked tracks with an acceptable χ^2 from the fit to spectrometer hits were used. In addition, the fit to determine the primary vertex of the event was required to have a good χ^2. A kinematic cut was placed on the candidate requiring the proton momentum to be greater than the kaon momentum. Monte Carlo studies indicate that this cut is satisfied approximately 83% of the time for events within our acceptance.

We made use of the finite lifetime of the Λ_c using an analysis closely following that of Coteus *et al.*[19] For each $pK^-\pi^+$ combination, the primary vertex was formed from all remaining tracks. The verticizing algorithm rejected tracks whose impact parameter at the vertex of all other tracks exceeded twice their resolution, which was about 60 μm (σ) for linked full spectometer tracks. The measured resolution in z for minimum bias events with three or more charged tracks was approximately 1.0 mm (σ). To minimize the effects of other long-lived decays in the event, the primary vertex was constrained in z to the center of the nearest target module. The $pK^-\pi^+$ of the Λ_c were fitted simultaneously to a vertex constrained to a line from the primary vertex, along the Λ_c momentum vector. The free parameters were the $pK^-\pi^+$ track parameters and the z of the decay point. To isolate events with relatively long lifetimes, the quantity $z_\gamma = [z(\text{decay vertex}) - z(\text{primary vertex})]/\gamma$ was formed, where $\gamma = E_{\Lambda_c}/M_{\Lambda_c}$. Except for the error in the primary vertex, z_γ should be momentum independent, since the decay vertex error scales with the Λ_c momentum.

Σ_c candidates were formed by adding a pion to the Λ_c candidates just described. In order to increase the efficiency, the additional pion was not required to be linked. The three plots of Fig. 2 show the mass difference $M_{\Sigma_c^0} - M_{\Lambda_c^+}$ in the Λ_c-mass region ($2.275 < M_{\Lambda_c} < 2.315$ GeV/c^2) for different minimum

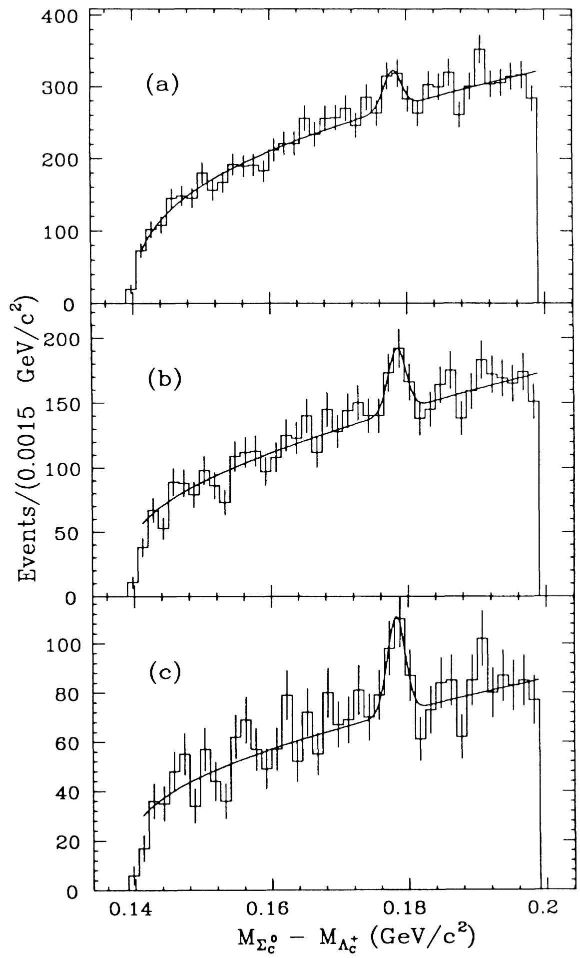

FIG. 2. $M_{\Sigma_c^0} - M_{\Lambda_c^+}$ for several Λ_c minimum lifetime cuts: (a) no z_γ cut; (b) $z_\gamma > 0.0$ cm; (c) $z_\gamma > 0.005$ cm (0.17 ps).

proper decay lengths. The corresponding plots for the $M_{\Sigma_c^{++}} - M_{\Lambda_c^+}$ mass difference are shown in Fig. 3. The behavior of the Λ_c under these cuts implies an upper limit of 0.28 ps for its lifetime. This limit is consistent with other accepted measurements of the Λ_c lifetime.[20] Also shown in the figure are fits to the data. The fitting function consists of a Gaussian signal plus a polynomial background. For the Σ_c^0 in Fig. 2(c), a least-squares fit yields 85 ± 18 Σ_c^0 events and thus a significance of 4.8 standard deviations. The measured mass difference is $M_{\Sigma_c^0} - M_{\Lambda_c^+} = 178.2 \pm 0.4 \pm 2.0$ MeV/c^2, where the first error is the statistical rms error, and in addition we estimate a possible systematic error of up to 2 MeV/c^2. The width of the signal is 1.3 ± 0.3 MeV/c^2, consistent with our expected resolution. For the Σ_c^{++} in Fig. 3(c), a similar fit yields 46 ± 14 events and thus a significance of 3.3 standard deviations. The mass difference is $M_{\Sigma_c^{++}} - M_{\Lambda_c^+} = 167.4 \pm 0.5 \pm 2.0$ MeV/c^2 and the width of the peak is 1.1 ± 0.3 MeV/c^2. In both figures the

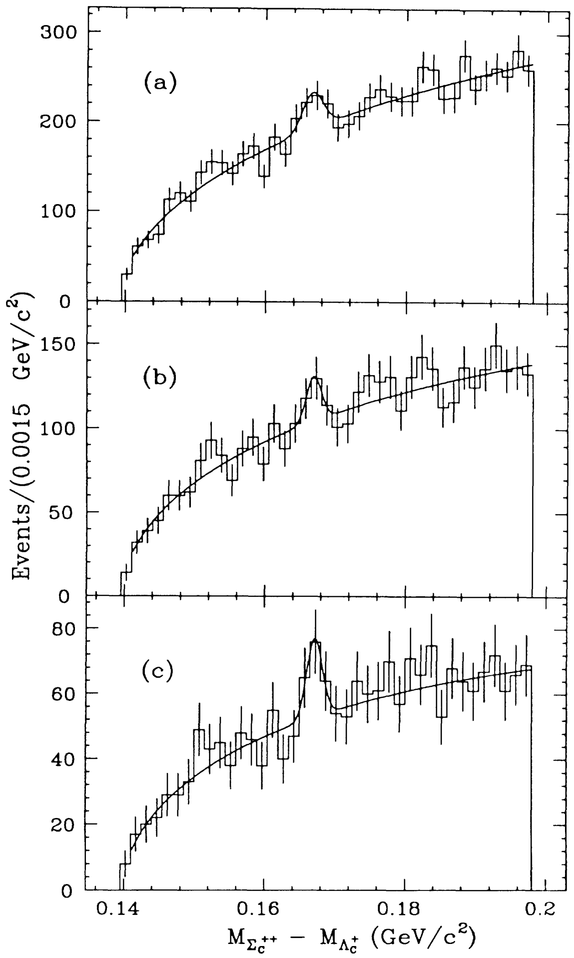

FIG. 3. $M_{\Sigma_c^{++}} - M_{\Lambda_c^+}$ for several Λ_c minimum lifetime cuts: (a) no z_γ cut; (b) $z_\gamma > 0.0$ cm; (c) $z_\gamma > 0.005$ cm (0.17 ps).

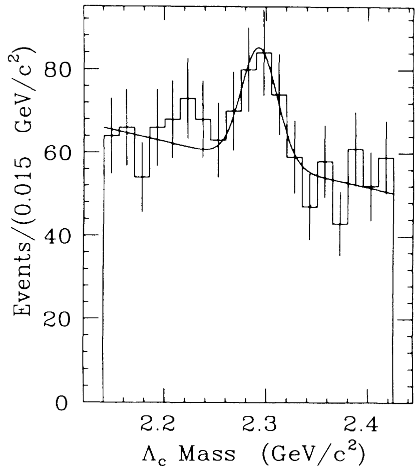

FIG. 4. Λ_c mass from Σ_c^0 with $177 < M_{\Sigma_c^0} - M_{\Lambda_c^+} < 180$ MeV/c^2 and $z_\gamma > 0.005$ cm (0.17 ps).

centers and widths of the peaks agree within errors for all three lifetime cuts.

Figure 4 shows the Λ_c mass from Σ_c^0 mass candidates after requiring $177 < M_{\Sigma_c^0} - M_{\Lambda_c^+} < 180$ and $z_\gamma > 0.005$ cm (0.17 ps). An enhancement at the Λ_c mass appears, as expected. A similar least-squares fit yields 78 ± 24 events, in good agreement with the event field of Fig. 2(c). The center of the Gaussian corresponds to a Λ_c mass of $2.293 \pm 0.006 \pm 0.030$ GeV/c^2, where the first error is statistical and the second error reflects our uncertainty in the overall mass scale. The width of the Gaussian is 17 ± 6 MeV/c^2 (σ), again consistent with our detector resolution for a narrow state.

We have observed the production of the charmed baryons Σ_c^{++} and Σ_c^0 in the final states $\Lambda_c\, \pi^{\pm}$. The mass, width, and lifetime of the Λ_c are in good agreement with previous observations and with our Monte Carlo simulations. Our measurement of the Σ_c^{++}-Λ_c^+ mass difference of 167.4 ± 2.1 MeV/c^2 is in good agreement with previous measurements.[12-16] We measure the Σ_c^0-Λ_c^+ mass difference to be 178.2 ± 2.0 MeV/c^2. Our measurements can be used to calculate the theoretically interesting mass splitting $\Sigma_c^{++} - \Sigma_c^0$, which we find to be -10.8 ± 2.9 MeV/c^2. This mass splitting disagrees with many but not all of the above-cited theoretical calculations

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