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Observation of the Charmed Baryon Σ_c^+ and Measurement of the Isospin Mass Splittings of the Σ_c

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We observe the Σ_c^+ baryon decaying to $\Lambda_c^+\pi^0$ and measure the mass difference $M(\Sigma_c^+) - M(\Lambda_c^+)$ to be $168.5 \pm 0.4 \pm 0.2$ MeV/c^2. We also measure the mass differences $M(\Sigma_c^{++}) - M(\Lambda_c^+)$ and $M(\Sigma_c^0) - M(\Lambda_c^+)$ with improved precision and determine the isospin mass splittings $M(\Sigma_c^{++}) - M(\Sigma_c^0)$

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and $M(\Sigma_c^+) - M(\Sigma_c^0)$ to be $1.1 \pm 0.4 \pm 0.1$ MeV/c^2 and $1.4 \pm 0.5 \pm 0.3$ MeV/c^2, respectively. Our results indicate that the light quark mass difference does not dominate the isospin mass splitting in Σ_c.

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Several experiments [1–4] have reported the production of Σ_c^{++} and Σ_c^0. To date, only a single Σ_c^+ event consistent with the decay chain $\Sigma_c^+ \to \Lambda_c^+\pi^0$, $\Lambda_c^+ \to pK^-\pi^+$, has been reported [5] from the BEBC bubble chamber experiment in 1980.

In this paper, we report results on the observation of Σ_c^+ charmed baryon production in e^+e^- annihilation at $\sqrt{s} = 10.5$ GeV and measure the mass difference between the Σ_c^+ and the Λ_c^+ charmed baryon. We also measure the masses of the Σ_c^{++} and Σ_c^0 baryon relative to the mass of the Λ_c^+ baryon. From these mass difference measurements, we have obtained the isospin mass splittings $\Delta^{++} = M(\Sigma_c^{++}) - M(\Sigma_c^0)$ and $\Delta^+ = M(\Sigma_c^+) - M(\Sigma_c^0)$. Charge conjugate modes are implied throughout this paper, unless otherwise stated.

Different dynamical models of hadrons with a heavy quark can be tested from the measurement of the mass differences between hadrons that are members of the same isospin multiplet. Sources that play essential roles in determining the mass splittings between isospin multiplet states are the difference between the up quark and down quark masses and the electromagnetic interactions, which consists of electrostatic Coulomb interactions and spin-spin interactions between quarks [6]. It has been suggested [7] that the chromoelectric and chromomagnetic effects, such as the hyperfine mass splittings from the spin-spin interaction [8], may also be important.

The data sample used in this study was collected with the CLEO II detector [9] operating at the Cornell Electron Storage Ring (CESR). It consists of 1.48 fb^{-1} from the $\Upsilon(4S)$ resonance and from center-of-mass energies just below and above the $\Upsilon(4S)$ resonance. Inside the solenoidal superconducting coil, which produces a 1.5 T axial magnetic field, there are precision vertex detectors and a wire drift chamber system. Surrounding the drift chamber system is a time-of-flight (TOF) system, which in conjunction with the dE/dx measurements from the drift chamber, provides particle identification information. Outside the time-of-flight system, but still inside the solenoidal coil, is a high resolution CsI electromagnetic shower calorimeter. The whole detector covers more than 95% of 4π solid angle.

We search for the Σ_c^+ charmed baryons in the decay mode $\Lambda_c^+\pi^0$, which is expected to dominate Σ_c^+ decays. We first search for the Λ_c^+ charmed baryons in the decay modes $\Lambda_c^+ \to pK^-\pi^+$, $\Lambda_c^+ \to \Lambda\pi^+\pi^-\pi^+$, $\Lambda_c^+ \to p\overline{K}^0$, and $\Lambda_c^+ \to \Lambda\pi^+$, where $\Lambda \to p\pi^-$, $K_s^0 \to \pi^+\pi^-$. To reduce combinatorial background, only combinations with $x_p > 0.5$ are used, where $x_p = p/p_{\max}$, $p_{\max} = (E_{\text{beam}}^2 - m_{\Lambda_c^+}^2)^{1/2}$, and p is the momentum of the Λ_c^+. Λ_c^+ baryons produced in B meson decays are kinematically limited to $x_p < 0.5$. Thus, when we form $\Lambda_c^+\pi^0$ combinations to search for Σ_c^+ , we exclude contributions from Σ_c^+ baryons from B meson decays. To reduce the background due to fake Λ_c^+ candidates, particle identification is used for all four decay modes of the Λ_c^+. A combined weight for each hadronic particle type (π, K, p) is formed using information from both the dE/dx and (when available) TOF measurements, such that the sum of the three weights is normalized to 1.

For the modes involving a K^0 (or a Λ), a secondary vertex is first reconstructed from a pair of oppositely charged tracks which intersect at a radial distance of more than 1 mm from the primary vertex. The pair is identified as a K^0 (Λ) candidate if the invariant mass of the pair when interpreted as $\pi^+\pi^-$ $(p\pi^-)$ is within 3 standard deviations (3σ) of the measured K^0 (Λ) mass. The χ^2, which measures how well the net momentum of the reconstructed K^0 (Λ) is extrapolated back to the beam position, is required to be less than 3.0.

A photon candidate is constructed from a shower cluster distributed over many CsI crystals. The photon candidate is excluded if it matches the projection of charged tracks into the calorimeter or has less than 50 MeV of energy deposited in the CsI crystals. Only isolated showers, which have no large energy deposition in nearby crystals, are used. The π^0 is reconstructed from a pair of photon candidates, each of which has $|\cos\theta| < 0.71$, where θ is the angle of the photon direction with respect to the beam direction. This corresponds to the highest resolution region of our calorimeter. The neutral pions are

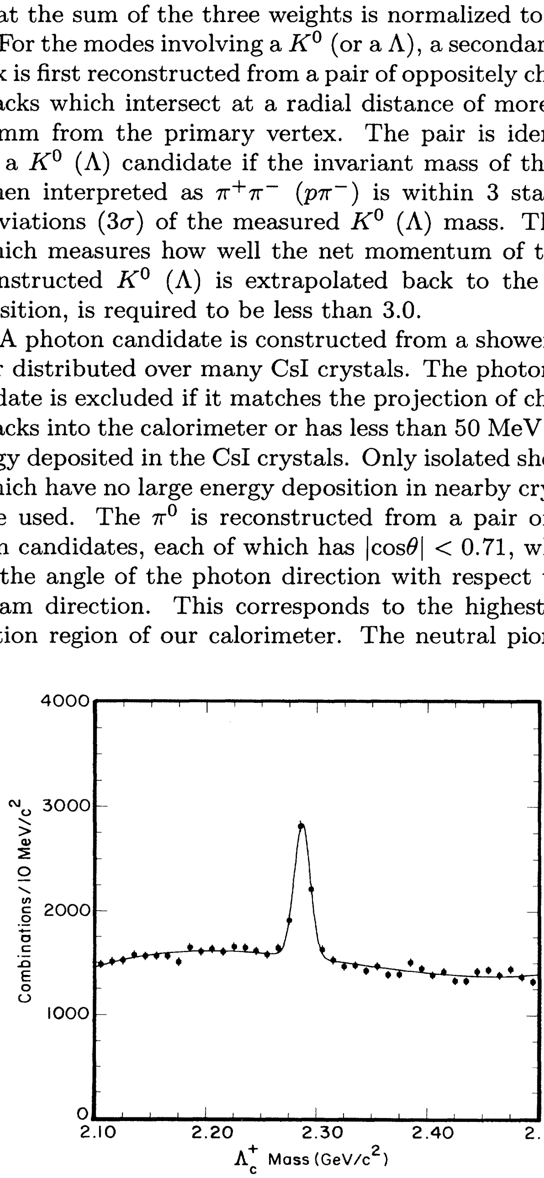

FIG. 1. Invariant mass distribution of Λ_c^+ $(x_p > 0.5)$.

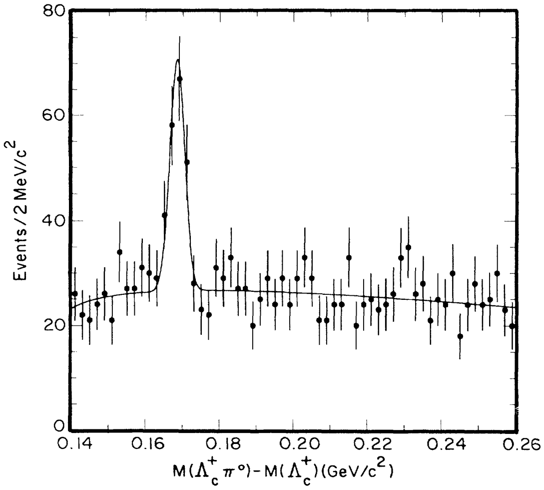

FIG. 2. Mass difference $M(\Lambda_c^+\pi^0) - M(\Lambda_c^+)$ distribution.

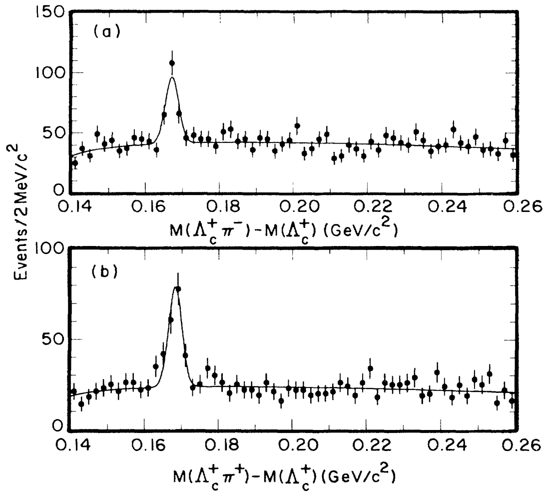

FIG. 3. Mass difference $M(\Lambda_c^+\pi^\pm) - M(\Lambda_c^+)$ distribution.

then selected by requiring that the $\gamma\gamma$ invariant mass be within 2.5σ of the known π^0 mass. A kinematic fit to the known π^0 mass is applied to the π^0 candidates.

The combined mass spectrum for all four decay modes of the Λ_c^+, for $x_p > 0.5$, is shown in Fig. 1. A fit to the data using a Gaussian signal function and a smooth polynomial function yields a signal area of 2402 ± 103 Λ_c^+ events [10]. All combinations within 3σ of the fitted Λ_c^+ mass are used as Λ_c^+ baryon candidates. Each Λ_c^+ candidate in an event is then combined with a neutral pion to form a Σ_c^+ candidate. It is also combined with an unused positively charged track interpreted as a π^+ to form a Σ_c^{++} candidate, and with an unused negatively charged track interpreted as a π^- to form a Σ_c^0 candidate.

The mass difference distribution $M(\Lambda_c^+\pi^0) - M(\Lambda_c^+)$ is shown in Fig. 2. In Figs. 3(a) and 3(b), the mass differences $M(\Lambda_c^+\pi^-) - M(\Lambda_c^+)$ and $M(\Lambda_c^+\pi^+) - M(\Lambda_c^+)$ are displayed. In each case the data is fit by a Gaussian function with width determined by a Monte Carlo study, plus a background function of the form $F(m) = A + B\sqrt{m^2 - m_\pi^2} + Cm$, where A, B, and C are constants, which is based on phase space considerations. The result of the fit for the mass difference plot (Fig. 2) yields 111 ± 16 events centered at $168.5 \pm 0.4 \pm 0.2$ MeV/c^2. The first error is statistical and the second is systematic. In Fig. 3, we find 126 ± 15 Σ_c^{++} events and 124 ± 17 Σ_c^0 events. Results of the fits are listed in Table I, together with measurements from other experiments.

Since we measure the mass differences between the Σ_c and Λ_c^+ baryons instead of measuring the Σ_c mass directly, most of the systematic errors from the reconstruction of Λ_c^+ charmed baryons are canceled. The systematic errors left are those introduced by the measurements of the soft pions in the final states, the momentum scale for charged pions and the energy scale for neutral pions, and the fitting procedure. Changes of the background shape used in the fitting only shift the mass differences by less than 0.1 MeV/c^2.

We calibrate out any residual time dependent shifts in the calorimeter response by requiring that the measured π^0 mass be constant from run to run. We then determine the sensitivity of the mass difference $M(\Sigma_c^+) - M(\Lambda_c^+)$ to the uncertainty of the shower energy calibration using both data and Monte Carlo simulation. We find that for every 1% change of the photon energy scale, the mass difference between Σ_c^+ and Λ_c^+ changes about 0.15 MeV/c^2. The energy scale is checked by comparing the mass difference $M(D^{*0}) - M(D^0)$, where $D^{*0} \to D^0\pi^0$, $D^0 \to K^-\pi^+$. To be conservative, we assign a systematic error due to energy scale of 0.2 MeV/c^2. Combining this with the other sources of systematic error gives the total systematic error listed in Table I.

TABLE I. Comparison between experiments.

	$\Delta m(\Sigma_c^{++} - \Lambda_c^+)$ (MeV/c^2)	$\Delta m(\Sigma_c^0 - \Lambda_c^+)$ (MeV/c^2)	$\Delta m(\Sigma_c^+ - \Lambda_c^+)$ (MeV/c^2)
ARGUS [1]	$168.8 \pm 0.6 \pm 1.6$	$167.6 \pm 0.3 \pm 1.6$	
BEBC [5]			168 ± 3
CLEO I.5 [2]	$167.8 \pm 0.4 \pm 0.3$	$167.9 \pm 0.5 \pm 0.3$	
CLEO II	$168.2 \pm 0.3 \pm 0.2$	$167.1 \pm 0.3 \pm 0.2$	$168.5 \pm 0.4 \pm 0.2$
E691 [4]		$168.4 \pm 1.0 \pm 0.3$	

TABLE II. Comparison with theoretical calculations.

	$\Delta m(\Sigma_c^{++} - \Sigma_c^0)$ (MeV/c^2)	$\Delta m(\Sigma_c^{+} - \Sigma_c^0)$ (MeV/c^2)
	Theoretical calculations	
Chan [15]	0.4	−0.7
Hwang [16]	3.0	−0.5
Wright [17]	−1.4	−2.0
Deshpande [18]	−3.3	−2.5
Sinha [19]	1.5	−0.3
Capstick [12]	1.4	−0.2
	Experimental measurements	
CLEO II	$1.1 \pm 0.4 \pm 0.1$	$1.4 \pm 0.5 \pm 0.3$
ARGUS [1]	$1.2 \pm 0.7 \pm 0.3$	
CLEO I.5 [2]	$-0.1 \pm 0.6 \pm 0.1$	

For charged soft pions in the final state, the systematic errors are dominated by the uncertainties in the magnetic field normalization and the energy-loss correction that is applied to the charged soft pions traversing the beam pipe and the inner drift chambers. We apply the same procedure as that used in the neutral pion to study the momentum scale. We use our measurement of the mass difference $M(D^{*+}) - M(D^0)$ to estimate the systematic error [11], where the momentum spectrum of the slow pions is similar and the mass difference technique is identical to our analysis of the Σ_c and Λ_c^+ mass difference. We conservatively assign a systematic error due to momentum scale of 0.2 MeV/c^2.

Many theoretical calculations [12–19] which take into account both the effect of the intrinsic mass difference between the up and down quarks in the so-called heavy-light baryon system and the effect of electromagnetic interactions which consists of electrostatic Coulomb interactions between the quarks and spin-spin interactions, predict Σ_c isospin mass splittings ranging from +18.0 MeV/c^2 to −6.5 MeV/c^2. Several calculations also include the contributions of QCD effects. Our measurements, together with measurements from other experiments, are listed in Table II; also listed are some selected theoretical predictions.

In summary, the Σ_c^+ baryon is observed in CLEO II. This is the first time that the particle has been observed with statistical significance. The mass differences $M(\Sigma_c^+) - M(\Sigma_c^0)$ and $M(\Sigma_c^{++}) - M(\Sigma_c^0)$ are determined to be $1.4 \pm 0.5 \pm 0.3$ MeV/c^2 and $1.1 \pm 0.4 \pm 0.1$ MeV/c^2, respectively. The latter is consistent, although more precise, with previous measurements [1,2,4]. It is the first time that the complete set of Σ_c isospin mass splittings have been measured in a single experiment and the systematic effects are thus reduced. The mass splittings reported in this paper indicate that the Σ_c is the first baryon isospin multiplet for which the intrinsic light quark mass difference is not the dominant source of isospin mass splitting.

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[11] The measured mass difference $M(D^{*+}) - M(D^0)$ in our data sample is 145.45 ± 0.01 MeV/c^2, in excellent agreement with the Particle Data Group value, which is 145.44 ± 0.06 MeV/c^2. We rely on Monte Carlo simulation to scale this error to our measurement of $M(\Sigma_c) - M(\Lambda_c^+)$.
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