First Observation of the Σ_c^{*+} Baryon and a New Measurement of the Σ_c^{*+} Mass

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Using data recorded with the CLEO II and CLEO II.V detector configurations at the Cornell Electron Storage Rings, we report the first observation and mass measurement of the Σ_c^{*+} charmed baryon, and an updated measurement of the mass of the Σ_c^+ baryon. We find $M(\Sigma_c^{*+}) - M(\Lambda_c^+) = (231.0 \pm 1.1 \pm 2.0)$ MeV, and $M(\Sigma_c^+) - M(\Lambda_c^+) = (166.4 \pm 0.2 \pm 0.3)$ MeV, where the errors are statistical and systematic, respectively.

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Singly charmed baryons consist of a charmed quark in combination with two lighter quarks. Models of charmed baryon spectroscopy consider the two lighter quarks combined to make a diquark of specific spin and parity, which in turn combines with the charm quark to make the baryon. The Λ_c^+ consists of a charmed quark and two light (u or d) quarks, in an isospin zero configuration, whereas the $\Sigma_c^{(*)}$ states have the two light quarks in an isospin one configuration. In general, the spin and parity of the charmed baryon states have not been measured, and we rely upon the measurement of their masses and decay properties to make their identification. Thus is it important to observe all the predicted states, so that the full pattern can be revealed. The $J^P = \frac{1}{2}^+$ Σ_c^0 and Σ_c^{++} have been observed for many years. Their isospin partner, the Σ_c^+, is more difficult to detect as it decays to the Λ_c^+ with the emission of a neutral, as opposed to charged, pion. Neutral pion detection is typically prone to higher backgrounds and poorer momentum resolution than charged pion detection. The Σ_c^+ was reported in one event in 1980 [1], and then in a peak of 111 ± 16 events by the CLEO Collaboration in 1993 [2]. This analysis updates the earlier CLEO measurement with a much larger data sample. This permits a more accurate comparison of the isospin splitting of the Σ_c states.

The $J^P = \frac{3}{2}^+$ Σ_c^* states are more difficult to observe than the $J^P = \frac{1}{2}^+$ states because of the larger natural width, which leads to a poorer signal-to-noise ratio. The Σ_c^{*++} and Σ_c^{*0} have now been identified in $\Lambda_c^+\pi^\pm$ final states, and their masses and widths measured [3]. This analysis shows the first observation of their isospin partner, the Σ_c^{*+}, observed by its decay to $\Lambda_c^+\pi^0$. This observation completes the spectroscopy of the seven Λ_c and Σ_c baryons with $L = 0$ predicted by the quark model.

The data presented here were taken with the CLEO II and CLEO II.V detector configurations operating at the Cornell Electron Storage Ring (CESR). The data sample used in this analysis corresponds to an integrated luminosity of 13.7 fb^{-1} taken on the $\Upsilon(4S)$ resonance and in the continuum at energies just below the $\Upsilon(4S)$. Of this data, 4.7 fb^{-1} were taken with the CLEO II configuration [4]. We detected charged tracks with a cylindrical drift chamber system inside a 1.5 T solenoidal magnet, and we detected photons using an electromagnetic calorimeter consisting of 7800 cesium iodide crystals. The remainder of the data were taken with the CLEO II.V configuration [5], which has upgraded charged particle measurement capabilities, but the same cesium iodide array to observe photons.

In order to obtain large statistics we reconstructed the Λ_c^+ baryons using 15 different decay modes. (Charge conjugate modes are implicit throughout.) Measurements of the branching fractions into these modes have previously been presented by the CLEO Collaboration [6], and the general procedures for finding those decay modes can be found in those references. For this search and data set, the exact analysis used has been optimized for high efficiency and low background. Briefly, particle identification of p, K^-, and π candidates was performed using specific ionization measurements in the drift chamber, and, when present, time-of-flight measurements. Hyperons were found by detecting their decay points separated from the main event vertex.

We reduce the combinatorial background, which is highest for charmed baryon candidates with low momentum, by applying a cut on x_p, where $x_p = p/p_{\rm max}$, p is the momentum of the charmed baryon candidate, $p_{\rm max} = \sqrt{E_{\rm beam}^2 - M^2}$, $E_{\rm beam}$ is the beam energy, and M is the reconstructed mass of the candidate. Using a cut of $x_p > 0.5$ (charmed baryons produced from decays of B mesons near the $B\overline{B}$ threshold are kinematically limited to $x_p < 0.4$), we fit the invariant mass distributions for these modes to a sum of a Gaussian signal and a low-order polynomial background. Combinations within 1.6σ of the mass of the Λ_c^+ in each decay mode are taken as Λ_c^+ candidates, where the resolution of each decay mode is taken from a Monte Carlo simulation (for the CLEO II and CLEO II.V datasets separately). In this x_p region, we find a total yield of Λ_c^+ signal of ≈58 000 combinations, and a signal-to-background ratio ≈1:1.2.

Photons were detected by their energy deposition in the crystal calorimeter. Each photon candidate was required to be well isolated from charged particles, and to have an energy profile consistent with being due to a single photon. To ensure good signal-to-noise ratio, the transition π^0 candidates were made from the combination of two photons each from the central part of the detector ($\theta < 0.7$), which has the best energy resolution. The calculated invariant mass of the photon pair was required to be within 2.5 standard deviations of the known π^0 mass, and the momentum of the π^0 candidate was required to be greater than 150 MeV/c. This momentum cut was optimized to maximize the ratio of the signal to the square root of the background for a resonance in the expected Σ_c^{*+} mass range using a Monte Carlo simulation. The kinematics of the Σ_c^{*+} and Σ_c^+ are sufficiently similar that the optimization is approximately valid for the latter case as well. The π^0 candidates were then kinematically fit to the π^0 mass, a procedure that improves the mass resolution of the Σ_c^{*+} by around 20%.

The Λ_c^+ candidates were combined with each π^0 candidate in the event and the mass difference $M(\Lambda_c^+\pi^0) - M(\Lambda_c^+)$ was calculated. Our requirement on the fractional momentum, $x_p > 0.6$, is placed on the $\Lambda_c^+\pi^0$ combination, not on the Λ_c^+ itself. Given the energetics of the decays to $\Lambda_c^+\pi^0$, such a criterion corresponds roughly to $x_p > 0.5$ for the Λ_c^+ daughters. The mass difference spectrum, shown in Fig. 1, shows two clear peaks. The first, near 167 MeV, is due to Σ_c^+ decays. The second, near 230 MeV, we identify as the Σ_c^{*+}. If we fit this distribution to the sum of a third-order Chebychev polynomial distribution and two Gaussian signals, we obtain a yield of 661^{+63}_{-60} events and a width of $\sigma = (2.84^{+0.31}_{-0.28})$ MeV for the Σ_c^+, and a yield of (327^{+78}_{-73}) events and $\sigma = (5.6 \pm 1.4)$ MeV for the second peak. The widths of these Gaussian signals are greater than the detector resolution, calculated from a GEANT-based [7] Monte Carlo simulation program, of 1.90 and 3.55 MeV, respectively, in the relevant mass regions, indicating the likelihood that the particles have nonnegligible intrinsic widths. If we fit the distribution instead to a sum of two *p*-wave Breit-Wigner functions convoluted with fixed-width Gaussian resolution functions, we obtain values of the intrinsic width Γ of $(3.1^{+0.9}_{-0.8})$ MeV and (7^{+6}_{-5}) MeV, respectively, for which the errors are statistical only. The pole masses obtained from this fit are $M(\Sigma_c^+) - M(\Lambda_c^+) = (166.44 \pm 0.24)$ MeV and $M(\Sigma_c^{*+}) - M(\Lambda_c^+) = (231.0 \pm 1.1)$ MeV, where again the quoted errors are from the statistical errors in the fit. It is this second fit which has a χ^2 of 73.3 for 93 degrees of freedom, that is shown in Fig. 1. If the Σ_c^{*+} signal were not included in the fit, it would have a χ^2 of 123 for 96 degrees of freedom. To obtain an estimate of the relative cross sections for Λ_c^+, Σ_c^+, and Σ_c^{*+} baryons, we find the yield each of the three states with an x_p cut on each candidate of 0.6. After correcting for the efficiency of the transition π^0, we find the ratio $N(\Sigma_c^+)$:$N(\Lambda_c^+) = 0.116^{+0.016}_{-0.014} \pm 0.022$ and $N(\Sigma_c^{*+})$:$N(\Lambda_c^+) = 0.043^{+0.016}_{-0.012} \pm 0.007$, where the errors are statistical and systematic, respectively. The systematic uncertainty includes the uncertainty in the π^0 reconstruction efficiency and differences in the yield obtained with different signal shapes. We note that we are not calculating the production ratios of these states, as we are unable to measure their full momentum spectra.

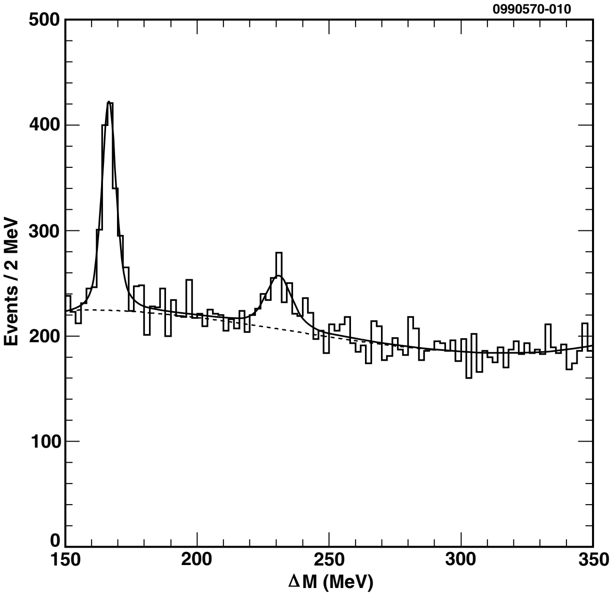

FIG. 1. Mass difference spectrum, $M(\Lambda_c^+\pi^0) - M(\Lambda_c^+)$. The solid line fit is to a third-order polynomial background shape and two *p*-wave Breit-Wigner functions smeared by Gaussian resolution functions for the two signal shapes. The dashed line shows the background function.

We have considered many different possible sources of systematic uncertainty in the measurements of the masses and widths of these resonances. We have checked the consistency of the results obtained with each of the two detector configurations separately, different criteria on the π^0 momenta, and different Λ_c^+ decay modes. We find the dominating systematic uncertainties in the mass measurement of the Σ_c^+ to be due to signal shape (0.2 MeV) and the uncertainty in the π^0 momentum measurement (0.2 MeV). These combine to give a total systematic uncertainty in the measurement of the mass difference $M(\Sigma_c^+) - M(\Lambda_c^+)$ of 0.3 MeV. The maximum variation of the extracted mass difference obtained using different orders of polynomial, or a threshold function, for the background function, and fitting with a maximum likelihood (binned or unbinned), or χ^2 fit, is an order of magnitude less than the total uncertainty.

In the case of the Σ_c^{*+}, the mass measurement is sensitive to both the shape of the signal and also to the shape of the background function used, and we estimate a total systematic uncertainty of 2 MeV in the measurement of the pole mass. Although the intrinsic width measurement of the Σ_c^+ is statistically nearly four standard deviations from 0, there should also be added a systematic uncertainty which we estimate to be 0.8 MeV, due mostly to uncertainties in the energy resolution of the transition pion. The combination of statistical and systematic uncertainties leads us to set an upper limit of 4.6 MeV (at the 90% confidence level) on $\Gamma(\Sigma_c^+)$. The width of the Σ_c^{*+} is particularly sensitive to the parametrization of the background shape, and we estimate a systematic uncertainty of 5 MeV in the measurement of $\Gamma(\Sigma_c^{*+})$ mostly from this source. This, combined with the statistical error, leads to a 90% confidence level limit of $\Gamma < 17$ MeV.

Our result for the mass of the Σ_c^+ is lower than the previous CLEO measurement [2], which was based upon a small subset of these data. Our result is also lower than the measured masses of the Σ_c^{++} and Σ_c^0, for which more experimental data are available [8]. This is in agreement with the theoretical expectation [9] that, by analogy with the noncharmed Σ and Σ^* isotriplets, the mass of the Σ_c^+ should be less than the average of its isospin partners. The mass of the Σ_c^{*+} is also lower than the average of its isospin partners, but the experimental errors are too large for this splitting to be significant.

In conclusion, we have made a new measurement of the mass of the Σ_c^+ and find $M(\Sigma_c^+) - M(\Lambda_c^+) = (166.4 \pm 0.2 \pm 0.3)$ MeV. We report the first observation of the Σ_c^{*+} and find $M(\Sigma_c^{*+}) - M(\Lambda_c^+) = (231.0 \pm 1.1 \pm 2.0)$ MeV. These measurements are consistent with expectations based upon the previously observed isospin partners of these two particles.

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