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Measurement of the masses and widths of the Σ_c^{++} and Σ_c^0 charmed baryons

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Using data recorded by the CLEO II and CLEO II.V detector configurations at CESR, we report new measurements of the masses of the Σ_c^{++} and Σ_c^0 charmed baryons, and the first measurements of their intrinsic widths. We find $M(\Sigma_c^{++})-M(\Lambda_c^+)=167.4\pm0.1\pm0.2$ MeV, $\Gamma(\Sigma_c^{++})=2.3\pm0.2\pm0.3$ MeV, and $M(\Sigma_c^0)-M(\Lambda_c^+)=167.2\pm0.1\pm0.2$ MeV, $\Gamma(\Sigma_c^0)=2.5\pm0.2\pm0.3$ MeV, where the uncertainties are statistical and systematic, respectively.

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In recent years there have been great advances in charmed baryon spectroscopy. However, the spin and parity of none of the states has been directly measured, and we rely upon the pattern of masses of the detected particles, together with their decay properties, to identify the different states. The existence of the $J^P=\frac{1}{2}^+ \Sigma_c$ states, which can be considered as a spin-1 light diquark in combination with a charmed quark, is now well established. In 1996, CLEO published [1] measurements of the masses and widths of the analogous $J^P=\frac{3}{2}^+$ states, the Σ_c^{*++} and Σ_c^{*0}. In the heavy quark symmetry [2] picture of heavy hadrons, the decays of the Σ_c^* and Σ_c states are closely analogous, and differ in rate only by calculable phase space and numerical factors. Previous studies [3,4] of the Σ_c baryons have not had sufficient detector resolution to measure their intrinsic widths. In this Rapid Communication, using a large sample of Λ_c^+ candidates found using the CLEO detector, we are now able to measure the shape of the Σ_c^{++} and Σ_c^0 baryons using the mass differences $M(\Lambda_c^+\pi^\pm)-M(\Lambda_c^+)$, and extract values of $\Gamma(\Sigma_c^0)$ and $\Gamma(\Sigma_c^{++})$.

The data presented here were taken by the CLEO II and CLEO II.V detectors operating at the Cornell Electron Storage Ring. The 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 detector, which is described in detail elsewhere [5]. We detect charged tracks with a cylindrical drift chamber system inside a solenoidal magnet, and we detect photons using an electromagnetic calorimeter consisting of 7800 cesium iodide crystals. The remainder of the data were taken with the CLEO II.V detector [6] which is an incremental upgrade of CLEO II, and incorporates a high resolution silicon vertex detector inside the CLEO II drift chamber system.

In order to obtain large statistics, we reconstructed Λ_c^+ baryons using 15 different decay modes.[1] Measurements of the relative branching fractions into these modes have previously been presented by the CLEO Collaboration [7], and the general procedures for finding those decay modes can be found in these 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 and $K_S^0\rightarrow\pi^+\pi^-$ decays were found by detecting their decay points separated from the main event vertex. Photons were detected using the CsI electromagnetic calorimeter.

We reduce the combinatorial background, which is highest for Λ_c^+ candidates with low momentum, by applying a cut on x_p, where $x_p=p/p_{max}$, p is the momentum of the charmed baryon, $p_{max}=\sqrt{E_{beam}^2-M^2}$, M is the mass of the Λ_c^+ candidate, and E_{beam} is the beam energy. Using a cut of $x_p>0.5$ (charmed baryons produced from decays of B mesons are kinematically limited to $x_p<0.4$), we fit each of the invariant mass distributions for these modes to a sum of a Gaussian signal and a low-order polynomial background. Combinations within 1.6 standard deviations of the observed Λ_c^+ mass peak are taken as Λ_c^+ candidates, where the resolution of each decay mode is taken from a Monte Carlo simulation (for the two data sets separately), and the Λ_c^+ candidates were kinematically constrained to the Λ_c^+ peak mass. In this x_p region, we find a total Λ_c^+ yield of 58 300 $\pm$380, and a signal to background ratio of approximately

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[1] Charge conjugate modes are implicit throughout.

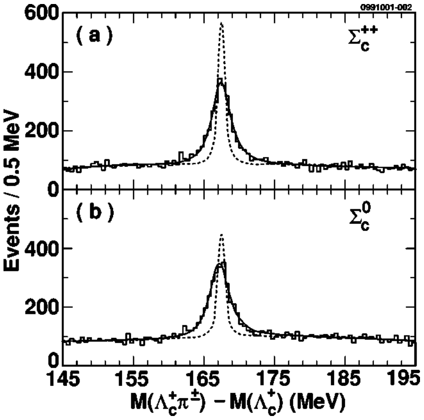

FIG. 1. Mass-difference spectra for (a) $\Lambda_c^+\pi^+$, and (b) $\Lambda_c^+\pi^-$. The lines shown are the results of fits allowing for a Σ_c intrinsic width (solid) and with no Σ_c intrinsic width (dashed).

1:1.2. This sample of Λ_c^+ decays is the same as used in our analysis of the Σ_c^+ and Σ_c^{*+} [8]. The x_p cut described above was used only to obtain these measures of the Λ_c^+ sample, and was released before continuing with the analysis as we prefer to apply an x_p cut only on the $\Lambda_c^+\pi^\pm$ combinations.

The Λ_c^+ candidates were then combined with each remaining charged π track in the event and the mass difference $\Delta M = M(\Lambda_c^+\pi^\pm) - M(\Lambda_c^+)$ was calculated. To optimize the resolution in this quantity, we calculated an event-by-event vertex point with those well measured tracks in the event which were consistent with coming from the beam spot, and then refit the Λ_c^+ and $\pi^\pm$ trajectories to come from this point. The main effect of this procedure was to improve the polar angle resolution of the $\pi^\pm$, and thus improve the mass-difference resolution. Those combinations that were inconsistent with coming from this point were rejected. We placed an $x_p > 0.5$ cut on the $\Lambda_c^+\pi^\pm$ combination.

Both of the mass-difference spectra (Fig. 1) show a clear peak of about 2000 events around 167 MeV due to $\Sigma_c \to \Lambda_c^+\pi^\pm$ decays. These distributions were each then fit to the sum of a polynomial background with a threshold suppression and a p-wave Breit-Wigner function convoluted with a double-Gaussian detector resolution function. We use a formalism of the Breit-Wigner signal function with a mass-dependent width, $\Gamma(M) \propto \Gamma_0(P/P_0)^3$, where P is the π momentum in the Σ_c rest frame, and P_0 is the π momentum calculated at the pole mass; we have tried relativistic and non-relativistic formalisms of the function and found negligible differences in our results.

The parameters of the two Gaussians in the resolution function were $\sigma_1 = 0.461$ MeV, $\sigma_2 = 1.35$ MeV, and $area_2/area_1 = 0.31$. These parameters were found from a Monte Carlo simulation using a GEANT-based program for the detector response. The generated Monte Carlo data used the CLEO II and CLEO II.V configurations in the same proportions as the real data, and assumed a zero-width Σ_c. The two Gaussians do not represent the ΔM resolution of each of the two different configurations, neither of which has a resolution which is well described by a single Gaussian function. The solid lines in Fig. 1 show the best fits to the data distributions; the extracted values using these fits are $M(\Sigma_c^{++}) - M(\Lambda_c^+) = 167.4 \pm 0.1$ MeV, $\Gamma(\Sigma_c^{++}) = 2.3 \pm 0.2$ MeV, and $M(\Sigma_c^0) - M(\Lambda_c^+) = 167.2 \pm 0.1$ MeV, $\Gamma(\Sigma_c^0) = 2.5 \pm 0.2$ MeV. The dashed lines show the best fits achievable using only the resolution function to describe the shape of the signal peaks, and no intrinsic width. The χ^2 of these latter fits are clearly unacceptable.

We have investigated many potential sources of systematic uncertainty in our measurement of the widths of these particles. We have analyzed our two data sets independently, using two different double-Gaussian resolution functions, and find statistically consistent results. The Monte Carlo studies indicate that the largest part of the detector resolution is from the determination of the trajectory of the $\pi^\pm$ trajectory rather than the measurement of the Λ_c^+ daughters; thus, as expected, the analysis produces consistent results for different Λ_c^+ decay modes. We assign a 15% uncertainty in the width of the resolution function, which translates into a 0.15 MeV uncertainty in the measurement of $\Gamma(\Sigma_c)$. This is a conservative estimate of the width uncertainty and is based upon the width measurements of the $\Lambda_{c1}(2625)$ which has similar kinematics to the Σ_c. In order to obtain a width of zero in the data, we would have to use a resolution function three times wider than that derived from Monte Carlo studies. We have also fit the mass-difference distributions to resolution functions varying from a single Gaussian to the sum of five Gaussians. The extracted Σ_c widths from the data vary by 0.15 MeV when changing from single- to double-Gaussian resolution functions, but are stable with the addition of further functions. We therefore assign 0.15 MeV as our uncertainty due to our imperfect knowledge of the shape of this resolution function.

The polynomial background shape we use is a good fit to the data, but we realize that this background may include non-phase space contributions arising from feed-down from other decays of excited charmed baryons, some of which are as yet undiscovered. For example, some of the Σ_c yield is due to $\Lambda_{c1}^+(2593) \to \Sigma_c\pi$ decays, and these may have a distorted ΔM shape due to the limited phase space available. However, if we place a veto on decays we observe to be from this source, our result changes by less than 0.15 MeV. We have also investigated a veto of those $\Lambda_c^+\pi^\pm$ combinations that are consistent with being due to $\Lambda_{c1}(2630)$ decays, with a similar null result. We have performed a large number of fits to the data with different background parametrizations, as well as different requirements on, for instance, the x_p of the combinations and the momentum of the $\pi^\pm$, and note only small variations in the extracted width of the Σ_c. From all these studies, we estimate the systematic uncertainty to be ± 0.2 MeV from uncertainties of the effect of feed-down from other particles, and a total systematic uncertainty of ± 0.3 MeV from all sources.

The measurements of the mass difference, $M(\Sigma_c) - M(\Lambda_c^+)$, are stable to changes in the background shape and the signal resolution function. A change from using a Gaussian signal function (as previous analyses have done), to a Breit-Wigner function, produces a shift of only 0.02 MeV in the extracted pole mass. Overall, including all systematic uncertainties in the fitting procedure, feed-down effects from the $\Lambda_{c1}(2593)$ and momentum measurements, we estimate a total systematic uncertainty of ± 0.2 MeV on the measured mass differences. Much of this systematic uncertainty cancels in the comparison of the two mass differences, giving an isospin mass splitting of $M(\Sigma_c^{++}) - M(\Sigma_c^0) = 0.2 \pm 0.1 \pm 0.1$ MeV. This result is consistent both with the recent measurement by FOCUS [3], as well as earlier results [4] that all indicate a small isospin splitting between these states. Theoretical models predict values of this mass splitting that vary from -3 to $+3$ MeV [9].

Using scaling laws and measures of the non-charmed Σ widths, Rosner [10] has predicted a value for the widths of the Σ_c^{++} and Σ_c^0 of 1.3 MeV, and Huang *et al.* [11] have predicted widths of around 2.4 MeV. Tawfiq and collaborators [12] use strange-baryon data and a light-front quark model to predict Σ_c widths of 1.6 MeV, whereas Ivanov *et al.* [13], use a relativistic three-quark model to predict Σ_c widths of around 2.7 MeV. Pirjol and Yan [14] have directly scaled from the measured Σ_c^* widths as input, and derived Σ_c widths of 2.0 MeV. Our results are consistent with these predictions, all of which use the Heavy Quark Symmetry model of baryon structure and decays.

In conclusion, we present new measurements of the masses of the Σ_c^{++} and Σ_c^0 charmed baryons relative to the Λ_c^+ mass. We measure $M(\Sigma_c^{++}) - M(\Lambda_c^+) = 167.4 \pm 0.1 \pm 0.2$ MeV and $M(\Sigma_c^0) - M(\Lambda_c^+) = 167.2 \pm 0.1 \pm 0.2$ MeV. These measurements of the masses of the Σ_c^{++} and Σ_c^0 are the most statistically precise available and are consistent with the world average values. They supercede the previous CLEO II numbers [15] which used a subset of the present data set. We make the first measurements of the intrinsic widths of these particles, and find $\Gamma(\Sigma_c^{++}) = 2.3 \pm 0.2 \pm 0.3$ MeV and $\Gamma(\Sigma_c^0) = 2.5 \pm 0.2 \pm 0.3$ MeV. These widths are consistent with theoretical expectations.

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