Measurement of Natural Widths of Σ_c^0 and Σ_c^{++} Baryons

The FOCUS Collaboration

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Abstract

In this paper we present a measurement of the natural widths of Σ_c^0 and Σ_c^{++}. Using data from the FOCUS experiment, we find $\Gamma(\Sigma_c^0) = 1.55^{+0.41}_{-0.37} \pm 0.38$ MeV/c^2 and $\Gamma(\Sigma_c^{++}) = 2.05^{+0.41}_{-0.38} \pm 0.38$ MeV/c^2. The first errors are statistical, the second systematic. These results are obtained with a sample of 913 $\Sigma_c^0 \to \Lambda_c^+\pi^-$ decays and 1110 $\Sigma_c^{++} \to \Lambda_c^+\pi^+$ decays. These results are compared with recent theoretical predictions.

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The natural widths of the excited charmed baryons have become experimentally accessible [1–3] only in the last several years. The widths of most of the known excited charmed baryons are poorly determined with either no existing measurement or with an upper limit;[1] most of the lower mass excited states appear to have widths comparable to or less than the resolution of current experiments. Combined with relatively low statistics, this has made such measurements challenging. Direct measurements of the Σ_c widths are important since most of the current theoretical models predict the widths of charmed baryons by extrapolating from the hyperon widths. Accurate measurements of the Σ_c widths will enable more accurate predictions of the widths of these and other excited charm states and test the physics underlying these models.

In this paper, we use data from the FOCUS experiment to obtain measure-

[1] During final preparation of this manuscript, we became aware of a measurement of Σ_c^0 and Σ_c^{++} intrinsic widths by the CLEO collaboration [4].

ments of $\Gamma(\Sigma_c^0)$ and $\Gamma(\Sigma_c^{++})$. The Σ_c^0 and Σ_c^{++} mass differences with respect to the Λ_c^+ were presented in an earlier paper [5]. FOCUS is an upgraded version of FNAL-E687 [6] which collected data using the Wideband photon beamline during the 1996–1997 Fermilab fixed-target run. The FOCUS experiment utilizes a forward multiparticle spectrometer to study charmed particles produced by the interaction of high energy photons ($\langle E\rangle \approx 180$ GeV) with a segmented BeO target.

Charged particles are tracked within the spectrometer by two silicon microvertex detector systems. One system is interleaved with the target segments; the other is downstream of the target region. These detectors provide excellent separation of the production and decay vertices. Further downstream, charged particles are tracked and momentum analyzed by a system of five multiwire proportional chambers and two dipole magnets with opposite polarity. Three multicell threshold Čerenkov detectors are used to discriminate among electrons, pions, kaons, and protons [7].

The Σ_c candidates are reconstructed via the decay chain $\Sigma_c \to \Lambda_c^+\pi^\pm$, with Λ_c^+ candidates found in four decay modes,[2] $\Lambda_c^+ \to pK^-\pi^+$, pK_S^0, $\Lambda^0\pi^+$, and $\Lambda^0\pi^+\pi^-\pi^+$. The reconstruction of K_S^0's and Λ^0's is described elsewhere [8]. Due to topological differences and varying levels of background, the values of the analysis cuts for each of the four Λ_c^+ decay modes vary. A decay, or secondary, vertex is formed from selected reconstructed tracks; the momentum vector of this charm candidate is then used as a seed to intersect other reconstructed tracks in the event to find the production, or primary, vertex [6]. We impose a minimum detachment cut which requires that the measured separation of these two vertices divided by the error on that measurement be greater than our cut (typically 3–5). We also ensure that both vertices are well formed by requiring a confidence level greater than 1% on the fit to each vertex. To remove longer lived charm backgrounds we also require the reconstructed proper lifetime to be less than some amount, typically 4–5 times the mean Λ_c^+ lifetime. Finally, momentum and particle identification cuts are applied to each decay mode. Invariant mass plots for each of the decay modes are shown in Fig. 1.

The Σ_c candidates are reconstructed by combining the Λ_c^+ candidates within approximately $2\,\sigma$ of the mean Λ_c^+ mass with a charged pion.[3] The vertex formed by the Λ_c^+ candidate, the pion candidate, and at least one other track must have a confidence level greater than 1%. Čerenkov identification on the soft pion requires that the pion hypothesis is not heavily disfavored with respect to any other identification hypothesis.

To remove systematic effects due to the reconstruction of the Λ_c^+ mass, we

[2] Throughout, charge conjugate states are implied.
[3] Referred to as a "soft pion" since it is usually a low momentum particle.

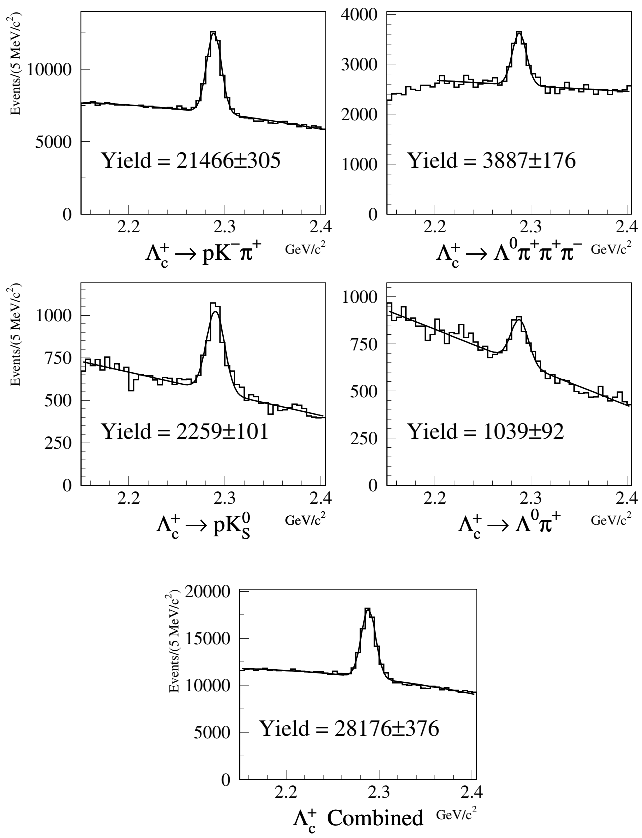

Fig. 1. Invariant mass distributions for Λ_c^+ candidates. Shown are the four Λ_c^+ decay modes used in the analysis and, on the bottom, the combined invariant mass plot for all four decay modes.

compute and plot the invariant mass differences ($\Delta M = M(\Lambda_c^+\pi^\pm) - M(\Lambda_c^+)$). Because most of the uncertainty in the mass difference arises due to multiple scattering of the soft pion, we improve the measurement of the soft pion momentum as follows. The primary vertex is refit without the soft pion and the soft pion is constrained to originate from this new primary vertex. If the confidence level of this constraint is less than 1%, the candidate is discarded. The measured Λ_c^+ momentum and mass are combined with the constrained pion momentum and known mass to form $M(\Lambda_c^+\pi^\pm)$. The computed Λ_c^+ mass is subtracted to obtain the invariant mass difference, ΔM. The reconstructed mass difference distributions are shown in Fig. 2.

To measure $\Gamma(\Sigma_c)$, we fit the Σ_c signal distributions with a relativistic constant width Breit–Wigner function convoluted with a parameterization of the experimental resolution derived from Monte Carlo. The experimental resolution is determined by generating Monte Carlo events with $\Gamma(\Sigma_c) = 0$ and fitting the resulting Σ_c distributions to a sum of two Gaussians, $G(x; \mathrm{Yield}, \sigma, \bar{x})$, with the same central value $\bar{x}$:

$$G\left(\Delta M; (1-f)Y, \sigma_1, M_{\mathrm{fit}}\right) + G\left(\Delta M; fY, \sigma_2, M_{\mathrm{fit}}\right)\ . \tag{1}$$

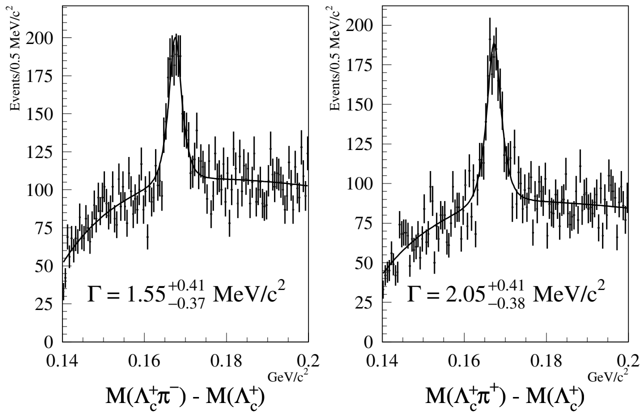

Fig. 2. Invariant mass differences for Σ_c^0 (left) and Σ_c^{++} (right) candidates. The fit functions, over their range of 140–200 MeV/c^2, are shown as are the widths and statistical errors.

Table 1
Σ_c resolution parameters calculated in Monte Carlo.

State	σ_1 (MeV/c^2)	σ_2 (MeV/c^2)	f Yield$_2$/(Yield$_1$ + Yield$_2$)
Σ_c^0	0.84 ± 0.03	1.93 ± 0.05	0.53 ± 0.03
Σ_c^{++}	0.83 ± 0.03	1.92 ± 0.05	0.56 ± 0.03

We use a background function described by

$$N(1 + \alpha(\Delta M - m_\pi)\Delta M^\beta) \tag{2}$$

where m_π is the $\pi^\pm$ mass. N, α, and β are allowed to vary. Three parameters of interest are extracted from the fit: σ_1, σ_2, and $f = Y_2/Y$ which describe, respectively, the resolution of the narrow and wide portions of the resolution function and the ratio of the second yield to the total. The extracted parameters are shown in Table 1. $M_{\rm fit}$ is the $\Sigma_c - \Lambda_c^+$ mass difference.

We determine the shape parameters (α and β) of the background function (Eq. (2)) by fitting the sum of the $M(\Lambda_c^+\pi^+)$ and the $M(\Lambda_c^+\pi^-)$ data distributions to Eq. (2) and a convoluted Breit–Wigner signal shape. The values of α and β are fixed to these values when fitting the individual distributions.

While the fits for Σ_c^0 and Σ_c^{++} distributions to a Breit–Wigner convoluted with the resolution function use a total of nine parameters, only four of these are free parameters (yield, $M(\Sigma_c - \Lambda_c^+)$, $\Gamma(\Sigma_c)$, and N, the background normalization). The parameters α, β, σ_1, σ_2, and f are previously determined and are fixed. Performing the fit as described above we obtain values of $\Gamma(\Sigma_c^0) = 1.55^{+0.41}_{-0.37}$ MeV/c^2 and $\Gamma(\Sigma_c^{++}) = 2.05^{+0.41}_{-0.38}$ MeV/c^2 with yields of 913 ± 77 and 1110 ± 83 respectively. The extracted mass differences are consistent with our previous measurement [5].

Table 2
Comparison of D^{*+} line shape parameters for data and Monte Carlo. Statistical errors only.

State	σ_1 (MeV/c^2)	σ_2 (MeV/c^2)	f
D^{*+} Data	0.66 ± 0.00	3.5 ± 0.2	0.05 ± 0.02
D^{*+} MC	0.61 ± 0.00	2.8 ± 0.5	0.05 ± 0.02

The largest systematic uncertainties in this measurement arise from our imperfect knowledge of the experimental mass resolution. To better understand our experimental resolution in a kinematically similar situation, we have used the decay $D^{*+} \to D^0\pi^+$ as a benchmark. The D^{*+} is much closer to decay threshold and should expose any problems with our simulation of the experimental resolution. We compare the resolution of classes of events seen in the data with that seen in the simulation. The Monte Carlo uses an input D^{*+} natural width of 96 keV/c^2, the value from a recent CLEO [9,10] report. For both Monte Carlo and data we fit the distributions to the sum of Eq. (1) and Eq. (2). No value of $\Gamma(D^{*+})$ is determined by or included in the fit. (Since $\Gamma(D^{*+}) \ll \sigma(\Delta M(D^{*+}))$, the precise value of $\Gamma(D^{*+})$ influences the fit results only slightly. The Breit–Wigner modifications to the line shape are negligible and are safely ignored.) By studying any discrepancies in the D^{*+} case, we understand our experimental resolution better for the Σ_c.

We find that for the D^{*+}, our overall experimental resolution matches that predicted by the Monte Carlo quite well and find no definitive evidence for any discrepancy except for σ_1 which is about 10% less in Monte Carlo. The values of the fits to the D^{*+} line shape for data and Monte Carlo are shown in Table 2. To be conservative, we test the effects of varying the experimental resolution by the maximum allowed by our D^{*+} studies. In our description of the predicted resolution we independently vary the three parameters σ_1, σ_2, and f by $\pm 10\%$, $\pm 20\%$, and $\pm 15\%$ respectively. These changes induce variations of approximately ∓ 0.20, ∓ 0.25, and ∓ 0.20 MeV/c^2 in $\Gamma(\Sigma_c)$, respectively.

In addition, we have studied the resolution function for the D^{*+} as a function of target configurations, the production target segment, decay modes, and the detachment cut. The resolution is clearly dependent on the production target segment and the several target configurations used in FOCUS. The dependence of the resolution on these two variables is well predicted by the Monte Carlo simulation and the distribution of Σ_c events as a function of these variables is also well matched by the Monte Carlo. The resolution function also depends somewhat on the kinematic variables, most strongly on the momentum of the excited state. As an example, in Table 3, we show the variation of σ_1 for the D^{*+} in four bins of momentum. The data and Monte Carlo disagree by less than 10% as shown in Table 2, but the disagreement is constant vs. D^{*+}

Table 3
Comparison of D^{*+} core resolution, σ_1 (MeV/c^2), vs. momentum.

$p(D^{*+})$ GeV/c	< 60	60–80	80–100	> 100
D^{*+} Data	0.61 ± 0.01	0.63 ± 0.01	0.65 ± 0.01	0.70 ± 0.01
D^{*+} MC	0.57 ± 0.00	0.59 ± 0.00	0.62 ± 0.00	0.66 ± 0.00

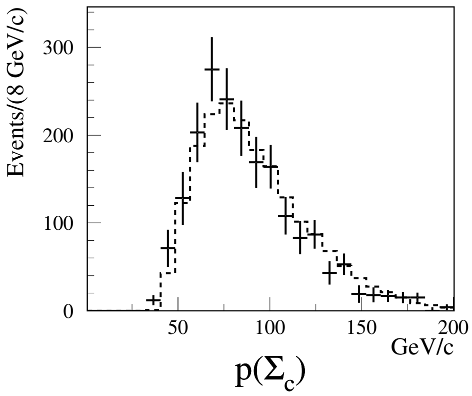

Fig. 3. Momentum spectrum of Σ_c^0 and Σ_c^{++} (summed) for data (points) and Monte Carlo (dashed curve). Both Monte Carlo and data are sideband subtracted.

momentum. In Fig. 3, we show that the Σ_c momentum distribution is well modeled by the Monte Carlo. Other variations in resolution are found as a function of soft pion momentum and charm and soft pion directions, with a weaker dependence on these kinematic variables.

We also perform two additional tests of our fitting and reconstruction method. In the first, we produce a large number of distributions which are statistically similar to the data. These distributions are then fit with the same methods used for the real data. The extracted fit parameters are compared with the known input parameters. From this source we estimate a maximum bias in the fitting technique of 0.05 MeV/c^2 and confirm the validity of our statistical errors.

In the second test, we generate Monte Carlo events with a natural width which is comparable to what is measured and measure the width of these events using the same methods. From this study we find no evidence for a systematic error.

Adding all the systematic errors in quadrature, we find a total systematic error of ± 0.38 MeV/c^2 for each $\Gamma(\Sigma_c)$ measurement. This gives final values of $\Gamma(\Sigma_c^0) = 1.55^{+0.41}_{-0.37} \pm 0.38$ MeV/c^2 and $\Gamma(\Sigma_c^{++}) = 2.05^{+0.41}_{-0.38} \pm 0.38$ MeV/c^2.

There are several recent theoretical predictions for the widths of the Σ_c states [11–16]; all predict $\Gamma(\Sigma_c)$ in the range 1–3 MeV/c^2. Several different theoretical models are used, including the Relativistic Three Quark Model (RTQM), Heavy Hadron Chiral Perturbation Theory (HHCPT), and the Light Front

Table 4
Predicted Σ_c widths from various theoretical models. All units are MeV/c^2.

Author	$\Gamma(\Sigma_c^0)$	$\Gamma(\Sigma_c^{++})$	Method
Ivanov, et al. [11,12]	2.65 ± 0.19	2.85 ± 0.19	RTQM
Tawfig, et al. [13]	1.57	1.64	LFQM
Huang, et al. [14]	2.4	2.5	HHCPT
Pirjol, et al. [15]	1.0–3.0	1.1–3.1	HHCPT
Rosner [16]	1.32 ± 0.04	1.32 ± 0.04	Ratios

Quark Model (LFQM).

These models predict partial widths, but since $\Sigma_c \to \Lambda_c^+\pi$ is the only allowed strong or electromagnetic decay mode for the states under study, we safely take the partial width as the total width for each state. The resulting predictions from the models are shown in Table 4. Our measurements are not of sufficient precision to strongly favor any one of these models over another.

In conclusion, we present measurements of the natural widths of the Σ_c^0 and Σ_c^{++} excited charmed baryons using data from the FOCUS experiment. We find $\Gamma(\Sigma_c^0) = 1.55^{+0.41}_{-0.37} \pm 0.38$ MeV/c^2 and $\Gamma(\Sigma_c^{++}) = 2.05^{+0.41}_{-0.38} \pm 0.38$ MeV/c^2 which are consistent with most current theoretical predictions.

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