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Measurements of the Σ_c^0 and Σ_c^{++} Mass Splittings

The FOCUS Collaboration

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Abstract

Using a high statistics sample of photoproduced charmed particles from the FOCUS experiment at Fermilab (FNAL-E831), we measure the mass splittings of the charmed baryons Σ_c^0 and Σ_c^{++}. We find $M(\Sigma_c^0 - \Lambda_c^+) = 167.38 \pm 0.21 \pm 0.13$ MeV/c^2 and $M(\Sigma_c^{++} - \Lambda_c^+) = 167.35 \pm 0.19 \pm 0.12$ MeV/c^2 with samples of 362 ± 36 and 461 ± 39 events, respectively. We measure the isospin mass splitting $M(\Sigma_c^{++} - \Sigma_c^0)$ to be $-0.03 \pm 0.28 \pm 0.11$ MeV/c^2. The first errors are statistical and the second are systematic.

Many experiments [1–8] have measured the mass differences of the Σ_c^0 and Σ_c^{++} baryons with respect to the Λ_c^+. Only FNAL-E791 [1] and CLEO II [2] have measured the mass differences with respect to the Λ_c^+ to a total (statistical and systematic) precision of less than 0.5 MeV/c^2. Some of these previous measurements have suggested that the Σ_c multiplet is unique in that the masses of the isospin states *increase* with the quark substitution $d \to u$. Such a result is not at odds with theoretical calculations since there are several canceling terms necessary to calculate the hyperfine mass splittings. In addition to the constituent quark mass differences, effects from the potential model used as well as the Coulomb interaction and hyperfine interactions must also be considered [9].

In this paper, we present a measurement using data from the FOCUS experiment which improves upon the earlier measurements and confirms that the Σ_c isospin mass splitting is much smaller than for other baryon isospin multiplets. FOCUS collected data using the Wideband photon beamline during the 1996–1997 Fermilab fixed-target run and is an upgraded version of FNAL-E687 [10]. The FOCUS experiment utilizes a forward multiparticle spectrometer to study the interactions 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

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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 between electrons, pions, kaons, and protons.

To reconstruct the decays $\Sigma_c \to \Lambda_c^+ \pi^\pm$, we first obtain a sample of Λ_c^+ baryons [17] using the decay mode $\Lambda_c^+ \to pK^-\pi^+$. During its run, FOCUS collected in excess of 25 000 fully reconstructed decays in the channel $\Lambda_c^+ \to pK^-\pi^+$ from 6×10^9 hadronic triggers. Potential Λ_c^+ candidates are distinguished from background hadronic interactions primarily by requiring that the production and decay vertices are distinct. We apply a minimum detachment requirement of 6, which requires that the measured separation of the two vertices divided by the error on that measurement is greater than 6. We also ensure that both vertices are well formed by requiring a confidence level greater than 1% on the fit to each vertex.

The $\Lambda_c^+ \to pK^-\pi^+$ decay channel is separated from other three body decays that reconstruct with masses in the Λ_c^+ mass window by applying Čerenkov based particle identification to the daughter particles. The Čerenkov particle identification cuts used in FOCUS are based on likelihood ratios between the various stable particle identification hypotheses. The product of all firing probabilities for all cells within the Čerenkov cones in each detector produces a χ^2-like variable $W_i = -2\ln(\text{likelihood})$ where i ranges over the electron, pion, kaon, and proton hypotheses.

Tight cuts are placed on the proton candidate particle requiring that the proton hypothesis is favored over both the pion and kaon hypotheses. We require that $W_\pi - W_p > 4$ and $W_K - W_p > 1$. For the kaon candidate, the kaon hypothesis is required to be favored over the pion hypothesis by requiring $W_\pi - W_K > 3$. For the pion candidate, we require that no hypothesis is favored over the pion hypothesis with a ΔW exceeding 6.

The Λ_c^+ candidates are required to have a momentum greater than 40 GeV/c and a proper decay time less than 10 times the mean lifetime of the Λ_c^+. This final requirement is effective in removing background contamination from the longer lived charm mesons. The invariant mass distribution for Λ_c^+ candidates which satisfy all the selection criteria is shown in Figure 1.

Σ_c candidates are reconstructed by combining the Λ_c^+ candidates within 2.1σ of the mean Λ_c^+ mass with a charged pion. [18] As before, a vertex with confidence level greater than 1% is required between the Λ_c^+ candidate and the pion. For the soft pion candidate, we require that no hypothesis is favored over the

[17] Throughout this paper, charge conjugate states are implicitly included unless stated otherwise.
[18] Referred to as a "soft pion" since it is usually low momentum.

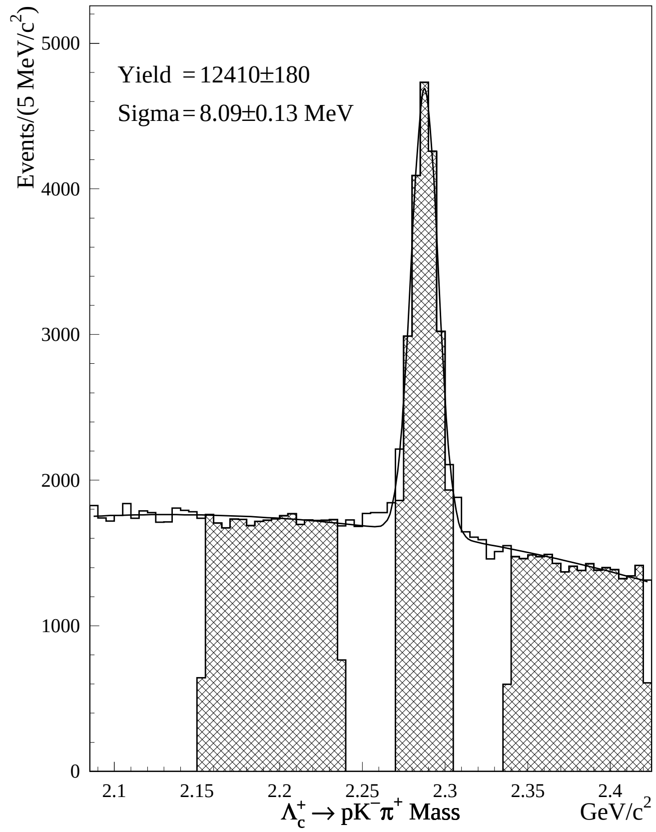

Fig. 1. $\Lambda_c^+ \to pK^-\pi^+$ candidates used in the reconstruction of Σ_c^0 and Σ_c^{++} candidates. The central hatched region illustrates the cut around the nominal Λ_c^+ mass. The outer hatched sidebands are used in background studies. The mass cut and bin boundaries do not coincide.

pion hypothesis with a ΔW exceeding 4. We obtain a sample of 362 ± 36 $\Sigma_c^0 \to \Lambda_c^+\pi^-$ and 461 ± 39 $\Sigma_c^{++} \to \Lambda_c^+\pi^+$ decays.

To remove any systematic effects due to the reconstruction of the Λ_c^+, we compute and plot the invariant mass difference. The computed Λ_c^+ momentum and mass are combined with the pion momentum and known mass to form $M(\Sigma_c)$. The computed Λ_c^+ mass is subtracted to obtain ΔM.

The resulting distributions are then fit with the background function

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

where N, α, and β are allowed to vary. A Gaussian fitting function is used to represent the Σ_c signals. A small component (described below) attributed to $\Lambda_{c1}^{*+}(2625) \to \Lambda_c^+\pi^+\pi^-$ decays is also included. The invariant mass distributions, fits, and fit values are shown in Figure 2. Backgrounds in both invariant mass plots vary smoothly across the region of the mass peak and in a similar

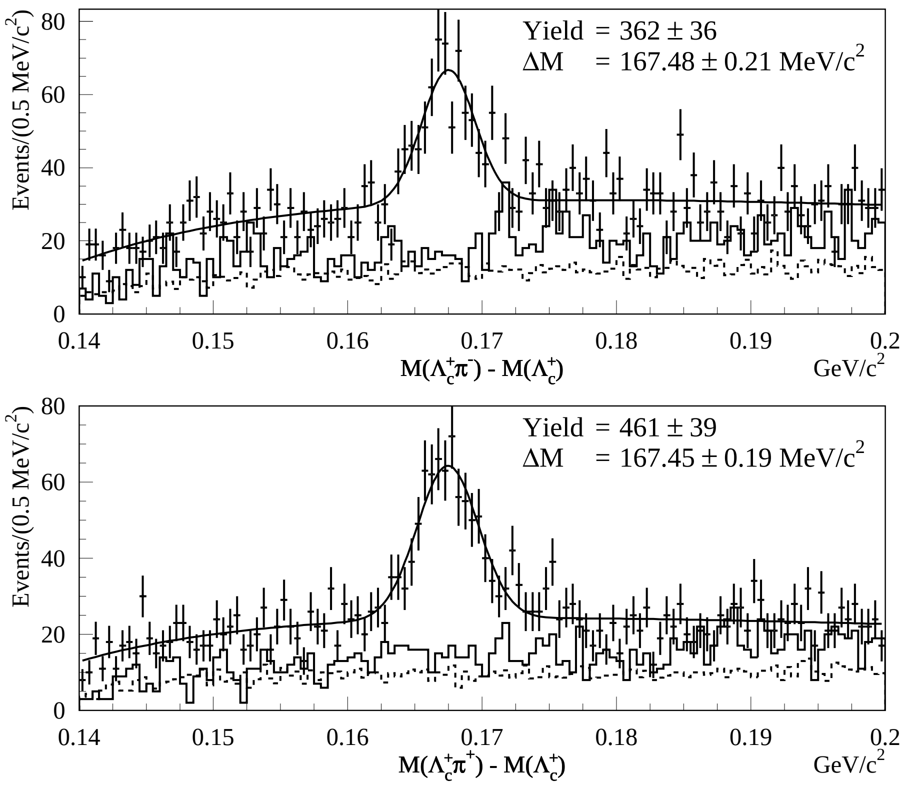

Fig. 2. Mass difference distributions for $M(\Sigma_c^0 - \Lambda_c^+)$ and $M(\Sigma_c^{++} - \Lambda_c^+)$. The dotted histograms are from the sidebands in Figure 1. The lower solid histograms are those formed by combining Λ_c^+ candidates with pions from the previous event containing a Λ_c^+ candidate. These mass difference values have not been corrected with the mass calibration adjustment described in the text.

fashion to the data outside the peak. Thus, the use of a smoothly varying function such as Equation (1) is justified.

Several sources of systematic error were investigated, including knowledge of our momentum scale, reconstruction and fitting biases, and biases in the analysis cuts. Systematic errors on the three measured quantities are calculated separately since systematic effects on the value of $M(\Sigma_c^{++} - \Sigma_c^0)$ are expected to be smaller than those on the measurements of the $\Sigma_c - \Lambda_c^+$ mass differences.

From studies of the reconstructed D masses and the decay $D^{*+} \to D^0\pi^+$ we estimate that the measured $\Sigma_c - \Lambda_c^+$ mass differences are 0.10 ± 0.05 MeV$/c^2$ above the true values. The final values quoted are adjusted for this shift and a systematic uncertainty of 0.05 MeV$/c^2$ is incorporated into the systematic error. Our measurement of the $\Sigma_c^{++} - \Sigma_c^0$ mass difference is unchanged by this shift. We attribute this effect to a slight momentum miscalibration.

We find a maximum systematic shift of ± 0.04 MeV$/c^2$ on the measurements of $M(\Sigma_c^0 - \Lambda_c^+)$ and $M(\Sigma_c^{++} - \Lambda_c^+)$ when we reconstruct Monte Carlo events and compare the measured values to the input values. No uncertainty on $M(\Sigma_c^{++}-\Sigma_c^0)$ is found from this source. These shifts are included as systematic errors.

We also vary the fitting and reconstruction methods and assess the effect on the final measurement. We change the background description to two components of the functional form of Equation (1). The shapes of the two components are derived from using Λ_c^+ candidates from the mass sidebands (shown in Figure 1) and from combinations of Λ_c^+ candidates from one event with pions from a different event. Both distributions are shown in Figure 2. The shapes of these distributions are fixed and the normalizations are allowed to vary. The effect of using an alternate background function given by

$$A + B\sqrt{\Delta M^2 - m_\pi^2} + C \cdot \Delta M \tag{2}$$

where A, B, and C are allowed to vary, has also been studied.

By default, we include the contribution from the decay $\Lambda_{c1}^{*+}(2625) \to \Lambda_c^+\pi^+\pi^-$. The magnitude of this contribution is obtained from a Monte Carlo simulation normalized to the number of reconstructed $\Lambda_{c1}^{*+}(2625) \to \Lambda_c^+\pi^+\pi^-$ decays. This contribution accounts for approximately 500 events in each of the $\Lambda_c^+\pi^\pm$ backgrounds. The effect of excluding this feed-down contribution was also studied and found to be minimal.

Finally, we measure the Σ_c mass differences using direction vectors obtained from the "downstream" silicon detector rather than those obtained by combining information from both silicon detectors. The systematic errors obtained in these variations range from 0.02–0.06 MeV/c^2, depending on the measurement.

The final systematic checks are performed using a "split sample" technique to estimate systematic errors. In this technique, we divide the data into two roughly equal portions based on kinematic variables or running conditions and perform the measurement on each statistically independent subsample. We choose variables where we might expect, either through reconstruction methods or changes in running conditions, to introduce a bias in the measured quantity. By using a method similar to the S-factor method of the Particle Data Group [11, pg. 10], an attempt is made to consider only systematic effects which arise from true differences in the measured values, rather than from the expected statistical fluctuations. We split the data based on particle/antiparticle, [19] detachment cut, Λ_c^+ momentum, soft pion momentum, and into two

[19] This check is especially important since any difference in the reconstruction of positively and negatively charged soft pions could introduce a systematic error into the measurement of $M(\Sigma_c^{++} - \Sigma_c^0)$.

Table 1
Systematic errors for Σ_c^{++} and Σ_c^0 mass differences.

	Error (MeV/c^2)		
Source	$\Sigma_c^{++} - \Lambda_c^+$	$\Sigma_c^0 - \Lambda_c^+$	$\Sigma_c^{++} - \Sigma_c^0$
p scale	0.05	0.05	0.00
Bias from MC	0.04	0.04	0.00
Fitting	0.02	0.06	0.04
Split samples	0.10	0.10	0.10
Total	0.12	0.13	0.11

Table 2
Comparison of measurements of Σ_c^{++} and Σ_c^0 mass differences.

	Mass difference (MeV/c^2)		
Experiment	$\Sigma_c^{++} - \Lambda_c^+$	$\Sigma_c^0 - \Lambda_c^+$	$\Sigma_c^{++} - \Sigma_c^0$
CLEO II [2]	$168.20 \pm 0.30 \pm 0.20$	$167.10 \pm 0.30 \pm 0.20$	$+1.10 \pm 0.40 \pm 0.10$
E791 [1]	$167.76 \pm 0.29 \pm 0.15$	$167.38 \pm 0.29 \pm 0.15$	$+0.38 \pm 0.40 \pm 0.15$
World avg. [11]	167.87 ± 0.20	167.31 ± 0.21	$+0.66 \pm 0.28$
This work	$167.35 \pm 0.19 \pm 0.12$	$167.38 \pm 0.21 \pm 0.13$	$-0.03 \pm 0.28 \pm 0.11$

running periods, one before and one after the installation of the interleaved silicon system. We estimate the combined split sample systematic error to be 0.10 MeV/c^2 for the $M(\Sigma_c - \Lambda_c^+)$ measurements as well as for the $M(\Sigma_c^{++} - \Sigma_c^0)$ measurement.

As an additional check on our ability to reconstruct excited charm states in an unbiased manner, many of the same systematic effects were studied for the decay $D^{*+} \to D^0\pi^+$ using a significant portion of the FOCUS data sample. This mode is not statistically limited and allows for the detection of very small systematic effects. No such effects of consequence were discovered.

The systematic errors on these measurements are summarized and totaled in Table 1. The totals are determined by adding the various errors in quadrature.

Considering both the statistical and systematic errors and applying the shift due to the momentum miscalibration, we find final values of $M(\Sigma_c^0 - \Lambda_c^+) = 167.38 \pm 0.21 \pm 0.13$ MeV/c^2, $M(\Sigma_c^{++} - \Lambda_c^+) = 167.35 \pm 0.19 \pm 0.12$ MeV/c^2, and $M(\Sigma_c^{++} - \Sigma_c^0) = -0.03 \pm 0.28 \pm 0.11$ MeV/c^2, where the first errors are statistical and the second are systematic. Our values are compared with the two previous measurements of comparable precision in Table 2.

Our measurement does not support the conclusion that the Σ_c^{++} is more mas-

Table 3
Theoretical predictions of $M(\Sigma_c^{++} - \Sigma_c^0)$.

Author	$M(\Sigma_c^{++} - \Sigma_c^0)$ (MeV/c^2)
Capstick [12]	1.4
Chan [13]	0.3
Hwang [14]	3.0
Isgur [15]	-2.0
Richard [16]	-2 or 3
Sinha [17]	1.5 ± 0.2
Varga [18]	-6 to 18

sive than the Σ_c^0; rather our measurement of the mass difference between the Σ_c^{++} and Σ_c^0 is consistent with zero. However, for all other well measured baryons the corresponding difference is positive. The Σ_c multiplet does appear to be unique in this regard.

A number of theoretical calculations of $M(\Sigma_c^{++} - \Sigma_c^0)$ are presented in Table 3; many are excluded by the present measurement. (The calculations presented in Varga, et al. are recent recalculations of a number of earlier predictions.)

In conclusion, we report new measurements of the quantities $M(\Sigma_c^0 - \Lambda_c^+)$, $M(\Sigma_c^{++} - \Lambda_c^+)$, and $M(\Sigma_c^{++} - \Sigma_c^0)$ which represent significant improvements on the world's best measurements. We find no evidence for an isospin mass splitting between the Σ_c^0 and Σ_c^{++} baryons.

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