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Charmed Hadron Spectroscopy at FOCUS

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ABSTRACT

The FOCUS experiment at Fermilab is a high statistics charm photoproduction experiment, which acquired data in 1996 and 1997. This report presents a measurement of the $\Sigma_c^{++} - \Sigma_c^0$ isospin mass splitting and preliminary measurements of the natural widths of these states. It also presents preliminary measurements of the masses and widths of the Σ_c^+, Σ_c^{*++}, Σ_c^{*0}, D_2^{*0} and D_2^{*+}.

1 The FOCUS Detector

The FOCUS detector [2] was designed to make precision measurements of charmed hadrons produced by the interaction of a high energy photon with a beryllium oxide target. The detector was located in Fermilab the wideband photon beam and the data presented here were taken during the 1996-97 fixed target run.

The photon beam was created by the bremsstrahlung of electron and positron beams; typically the endpoint of the photon energy spectrum was about 300 GeV. This beam was incident on a segmented beryllium oxide target, and the resulting charmed hadrons were detected using the FOCUS detector, an upgraded version of the Fermilab E687 Spectrometer [3]. One of the upgrades was to replace the bulk target with a segmented target and to add silicon strip detectors interspersed among the target planes. Other upgraded systems include the EM calorimeter and the Čerenkov, muon and data acquisition systems. FOCUS has more than ten times the reconstructed charm yield of its predecessor.

The FOCUS charged particle tracking system consists of 4 planes of silicon strip detectors, which are interspersed among the target planes, a 12 plane silicon strip system, immediately downstream of the targets, and 5 stations of multiwire proportional chambers (MWPC), located further downstream. The momentum of a charged particle is determined by using the MWPC's to measure the bend of the trajectory in a pair of oppositely polarized dipole magnets. Three multicell threshold Čerenkov counters are used to discriminate among electrons, pions, kaons and protons.

Photons are detected using two EM calorimeter technologies. Photons in the central region are detected using the inner EM calorimeter, which is built from lead glass blocks. Photons at wider angles are detected using the outer EM calorimeter, a sampling calorimeter consisting of alternating layers of lead and plastic scintillator.

2 Candidate Driven Vertexing

All of the analyses discussed in this report use candidate driven vertexing, which will be described using the example of $\Lambda_c^+ \to pK^-\pi^+$.[1] The first step is to apply track quality and particle ID cuts to all measured tracks in an event. From the selected tracks all possible $pK^-\pi^+$ combinations are made. For each combination the three tracks are fitted to the hypothesis that they come from a common vertex and only candidates with a good confidence level are retained. Each surviving combination is used to seed a search for a primary vertex; one

[1] Any reference in this paper to a specific charge state also implies a reference to the charge conjugate state.

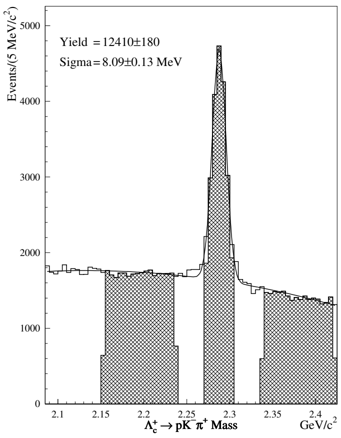

Figure 1: *Invariant mass of* $pK^-\pi^+$ *combinations which survive the candidate driven vertexing. The shaded regions indicate the* Λ_c^+ *signal region and two sideband regions; note that the boundaries of the regions do not coincide with bin boundaries.*

treats the $pK^-\pi^+$ system as just another track and searches for other tracks which intersect its trajectory. This process defines two vertices, the primary vertex at which the Λ_c^+ was produced, and a displaced secondary vertex at which it decayed. The minimal requirement is that the primary vertex be formed from the $pK^-\pi^+$ trajectory plus at least one other charged track, but some of the analyses presented here require at least two other charged tracks. It is also required that the decay length, L, be large compared to is error, σ_L. In typical FOCUS analyses the requirements on L/σ_L range from a loose cut of > 3 to a tight cut of > 10 or more. Two other isolation requirements are typically imposed: that none of the Λ_c^+ daughter tracks are consistent with passing through the primary vertex and that no other tracks in the event are consistent with passing through the $pK^-\pi^+$ decay vertex. If an event contains more than one $pK^-\pi^+$ combination which passes all of the above cuts, both are accepted and the primary vertex finding is done separately for each combination.

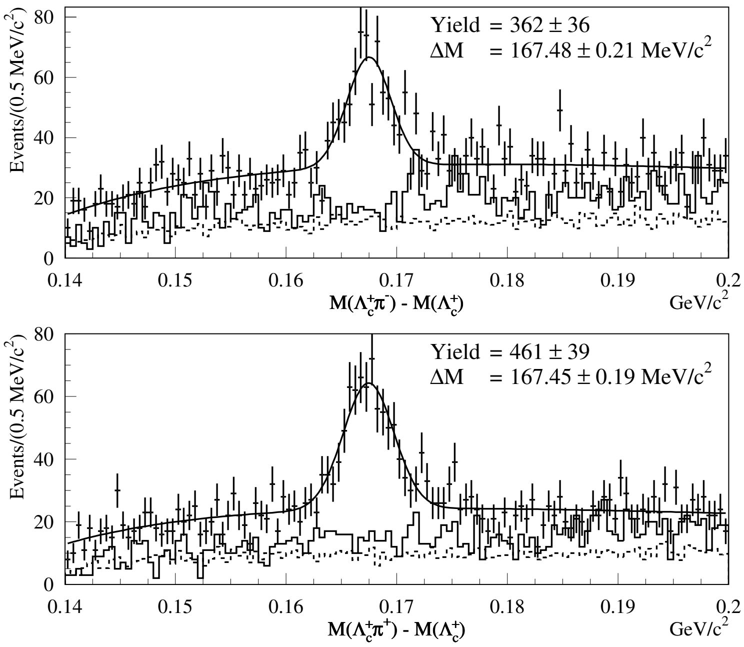

Figure 2: *$M((pK^-\pi^+)\pi^\pm) - M(pK^-\pi^+)$ for combinations passing the requirements discussed in the text. In each plot the data points show the experimental data and the solid curve shows the result of a fit described in the text. The histograms show that no signal is present in two background samples; the solid histogram shows the distribution obtained using $pK^-\pi^+$ combinations from the Λ_c^+ sideband and the dashed histogram shows the distribution obtained using a $pK^-\pi^+$ combination from one event and charged pions from the previous event.*

3 Σ_c Isospin Mass Splittings

This section discusses the measurement of the isospin mass splittings in the Σ_c system. The first two states considered are the Σ_c^{++} and the Σ_c^0, which were reconstructed using the decays, $\Sigma_c^{++} \to \Lambda_c^+\pi^+$ and $\Sigma_c^0 \to \Lambda_c^+\pi^-$, where $\Lambda_c^+ \to pK^-\pi^+$. The full details of this analysis have already been published [4]. The invariant mass distribution, for all $pK^-\pi^+$ combinations which passed the candidate driven selection are shown in fig.1. All combinations which fell within 2.1 σ of the nominal Λ_c^+ mass were retained as Λ_c^+ candidates; here σ is the measurement error on the $pK^-\pi^+$ invariant mass, determined separately for each combination. Each Λ_c^+ candidate was combined with each remaining charged pion candidate in the event and the mass difference, $M((pK^-\pi^+)\pi^\pm)-M(pK^-\pi^+)$ was computed. The mass difference distributions for the two charge states are shown in fig.2. In each histogram a prominent peak is present near a mass difference of 167 MeV/c^2; these correspond to the Σ_c^0 and. Σ_c^{++}. These distributions were fitted using a smooth function to parameterize the background and a gaussian to parameterize the signal; for this analysis the natural width of the states was ignored. The mass differences determined by the fits are summarized in tab.1. The systematic errors are dominated by the dependence of the result on variations to the analysis cuts; other contributions include the momentum scale of the FOCUS detector, fit variants and reconstruction biases. The precision of the measurement of $M(\Sigma_c^{++}) - M(\Sigma_c^0)$ is similar to that of the PDG average of published results [5]; there is a also new preliminary result by CLEO has slightly better precision [6].

The remaining chamed baryons studies presented here are still preliminary. Additional details about them are available in ref. [7].

The decay mode $\Sigma_c^+ \to \Lambda_c^+\pi^0$ was also investigated. This state has previously been seen by only one experiment [8] and the FOCUS observation represents the first independent confirmation. For this study Λ_c^+ candidates were selected in a fashion similar to that described above, but, in order to obtain a higher yield, the cuts were loosened slightly. Clusters of energy in the inner EM calorimeter were considered as photon candidates and pairs of photons were selected as π^0 candidates if the invariant mass of the pair was within 25 MeV/c^2 of the nominal π^0 mass. For each $(pK^-\pi^+)\pi^0$ combination in an event, the mass difference, $M((pK^-\pi^+)\pi^0) - M(pK^-\pi^+)$, was computed and the distribution of mass differences is shown in fig.3. The right hand plot was fitted with the same parameterization as the previous two distributions and the results of the fit are summarized in tab.1. The dominant systematic arises from uncertainty in the calibration of the geometry of the EM calorimeter.

The decay $\Sigma_c \to \Lambda_c\pi$ is a strong decay and is expected to have a natural width of a few MeV [9]. To measure the natural width of the Σ_c^{++} and the Σ_c^0, $\Lambda_c^+\pi^\pm$ candidates were selected in a fashion similar to that described above. A Monte Carlo (MC) simulation of the detector response showed that the detector resolutions are 2.32 ± 0.23 MeV/c^2 for the Σ_c^0 and 2.26 ± 0.24 MeV/c^2

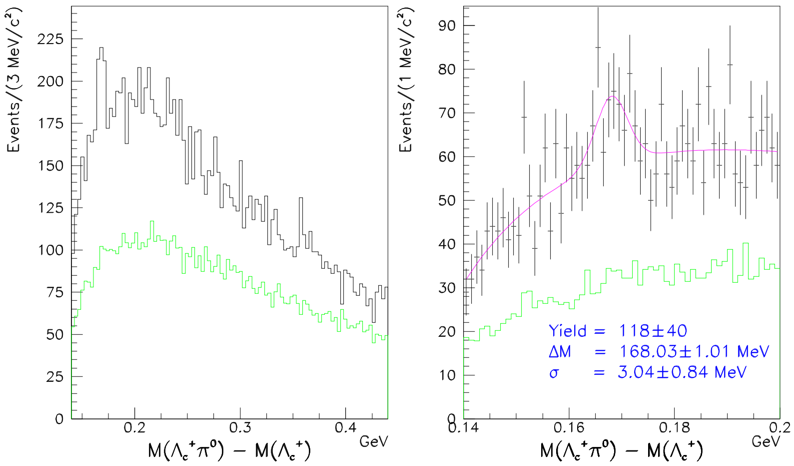

Figure 3: *Mass difference, $M((pK^-\pi^+)\pi^0) - M(pK^-\pi^+)$, for combinations which pass selection criteria described in the text. An enhancement near 168 MeV/c^2 is clearly visible in the left hand plot. The right hand plot shows the same data in a finer binning. In the right figure the data points represent the experimental data, the solid curve is the result of a fit described in the text and the histogram is the distribution obtained using $pK^-\pi^+$ combinations from the Λ_c^+ sidebands.*

for the Σ_c^{++}. The mass difference distributions, similar to those in fig.2, were fitted using a smooth function to describe the background and a Breit Wigner, convoluted with a gaussian detector resolution, to describe the signal. For the fit the resolution of the gaussian was fixed and the natural width of the Breit-Wigner was allowed to float. The widths obtained from the fit are summarized in tab.1. There are no published measurements for the widths of these states but CLEO Collaboration has presented preliminary results [6].

4 Observation of the Σ_c^*

FOCUS has preliminary observations of the decays $\Sigma_c^{*++/0} \to \Lambda_c^+\pi^\pm$. These states have previously been seen by only one experiment [6] [10] and the FOCUS observation represents the first independent confirmation. This analysis proceeded in a fashion similar to that of the $\Sigma_c^{++/0}$ analyses, with small changes to the details of the Λ_c^+ selection. Fig.4 shows the mass difference distributions for

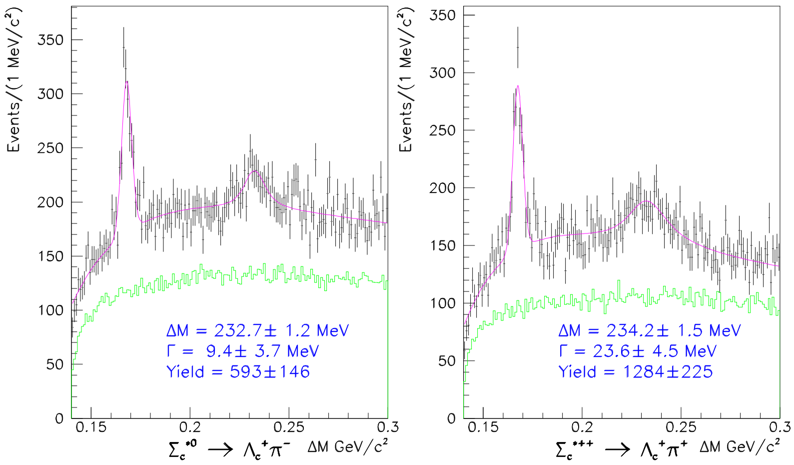

Figure 4: *Mass difference, $M((pK^-\pi^+)\pi^\pm) - M(pK^-\pi^+)$, for combinations which pass selection criteria described in the text. The data points are the experimental data, the solid curve is the result of a fit described in the text and the histogram is the estimate of the background from Λ_c^+ sidebands.*

these modes. The narrow structures near a mass difference of 168 MeV$/c^2$ are the $\Sigma_c^{++/0}$ states discussed previously and the broad structures near a mass difference of 233 MeV$/c^2$ are the Σ_c^{++} and Σ_c^0. A MC detector simulation showed that the mass resolution for both Σ_c^* states is 2.8 MeV$/c^2$. The distributions were fitted using a polynomial to parameterize the background, a gaussian to describe the Σ_c states and a Breit Wigner, convoluted with a gaussian resolution function, to parameterize the Σ_c^* states. The mass differences and widths determined by fit are summarized in tab.1.

5 Λ_c^* Reconstruction

FOCUS has also studied the P-wave charmed baryons $\Lambda_c(2593)$ and $\Lambda_c(2625)$. For space reasons this work cannot be included here but the interested reader is referred to the transparencies shown at the conference [11].

Table 1: *Summary of Σ_c Measurements. The measurements of the natural widths and all results pertaining to the Σ_c^+ or the Σ_c^* are preliminary.*

State	$M - M(\Lambda_c^+)$ (MeV/c^2)	Γ (MeV/c^2)	$M - M(\Sigma_c^0)$ (MeV/c^2)
Σ_c^{++}	$167.35 \pm 0.19 \pm 0.12$	$2.53 \pm 0.77^{+0.51}_{-0.56}$	$-0.03 \pm 0.28 \pm 0.11$
Σ_c^+	$168.0 \pm 1. \pm 0.3$	-	$0.6 \pm 1. \pm 0.3$
Σ_c^0	$167.38 \pm 0.21 \pm 0.13$	$2.58 \pm 0.79^{+0.51}_{-0.55}$	-
Σ_c^{*++}	234.2 ± 1.5	23.6 ± 4.5	$M(\Sigma_c^{*0}) - M(\Sigma_c^{*++})$
Σ_c^{*0}	232.7 ± 1.2	9.4 ± 3.7	$= -1.5 \pm 1.9$

6 D_2^* Analysis

Of the 12 predicted P-wave charmed mesons 6 have relatively small widths and have been observed previously. The remaining 6 states are predicted to be broad and, while there is some evidence for them, none are firmly established. FOCUS has observed the 5 of the 6 narrow P-wave charmed mesons: $D_2^{*0}(2460)$, $D_2^{*+}(2460)$, $D_1^0(2420)$, $D_{s1}^+(2536)$ and $D_{s2}^{*+}(2573)$. Preliminary results of the $D_2^*(2460)$ work are summarized here and the reader is referred to ref. [11] for preliminary results on the other modes.

The decay modes studied are, $D_2^{*0}(2460) \to D^+\pi^-$ followed by $D^+ \to K^-\pi^+\pi^+$, and $D_2^{*+}(2460) \to D^0\pi^+$ followed by $D^0 \to K^-\pi^+$ or $D^0 \to K^-\pi^+\pi^+\pi^-$. The D^0 and D^+ candidates were reconstructed using the candidate driven approach described in section 2; the combined yield of the two states was about 330,000 with $S/B \simeq 7$.

Each D^+ candidate was combined with each π^- candidate in the primary vertex and the mass difference, $\Delta_+ = M((K^-\pi^+\pi^+)\pi^-) - M(K^-\pi^+\pi^+)$, was computed. Fig.5a) shows the distribution of $\Delta_+ + M_{PDG}(D^+)$, which has two prominent features on top of a smoothly varying background. The peak near 2.46 GeV/c^2 corresponds to the D_2^{*0}. The structure near 2.3 GeV/c^2 corresponds to the decays $D_2^{*0} \to D^{*+}\pi^-$ and $D_1^0 \to D^{*+}\pi^-$, followed by $D^{*+} \to D^+\pi^0$ or $D^{*+} \to D^+\gamma$ in which neither the π^0 nor the γ are reconstructed. This structure will be referred to as the feed-down component and, for use in the fit, its expected shape was determined by a MC simulation. The distribution was fitted using an exponential to parameterize the background

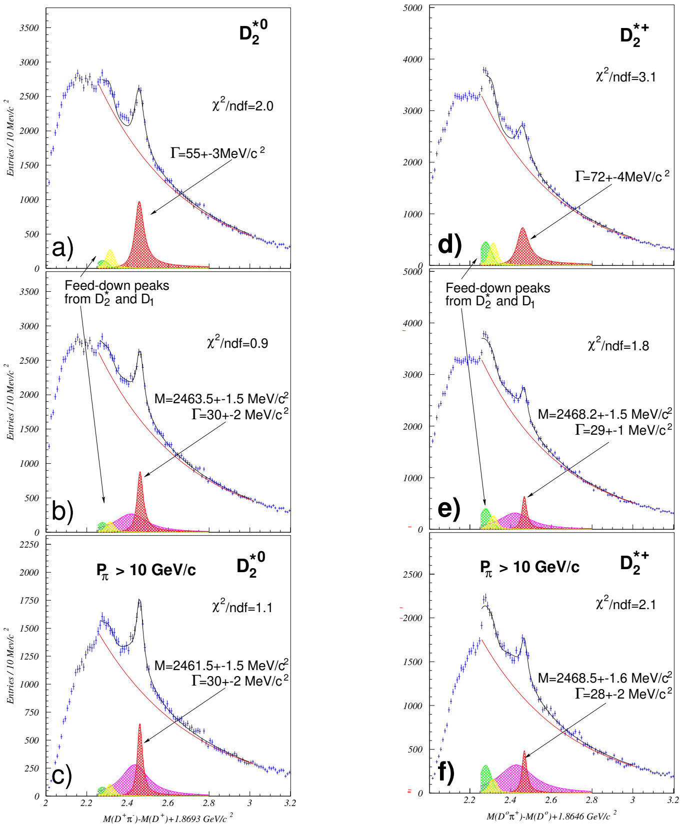

Figure 5: *Invariant mass distributions for* $D^+\pi^-$ *and* $D^0\pi^+$ *combinations, as described in the text.*

shape, a relativistic D-wave Breit-Wigner, convoluted with a gaussian resolution function, to parameterize the D_2^{*0} signal, and the feed-down shape with a free normalization. The σ of the gaussian was fixed at 7 MeV$/c^2$, as determined by a MC simulation. The slope of the exponential was fixed to that obtained from the mass difference distribution of wrong sign $(D^+\pi^+)$ combinations. The shapes inset at the bottom of the figure show the contributions of the signal and the feed-down to the overall fit. The fit is visibly bad and has a bad χ^2/dof of 2.0.

It is not too surprising that the fit is poor; this distribution should also

Table 2: *Summary of Preliminary D_2^* Results.*

State	Mass (MeV/c^2)		Width (MeV/c^2)	
	FOCUS	PDG [5]	FOCUS	PDG
D_2^{*+}	$2468.2 \pm 1.5 \pm 1.4$	$2459. \pm 4.$	$28.6 \pm 1.3 \pm 3.8$	$25. \pm 8.$
D_2^{*0}	$2463.5 \pm 1.5 \pm 1.5$	2458.9 ± 2.0	$30.5 \pm 1.9 \pm 3.8$	$23. \pm 5.$

contain contributions from the predicted broad P-wave states D_0^{*0} and D_1^0, a direct contribution from $D_0^{*0} \to D^+\pi^-$ and a feed-down contribution from $D_1^0 \to D^{*+}\pi^-$. Because the mass splitting between these two states is expected to be small compared to their width, their contribution can be parameterized by adding one new term to the fit, a relativistic S-wave Breit-Wigner with a free mass, width and normalization. Fig.5b) shows the same data as Fig.5a) but the superimposed fit includes the extra broad term. The inset at the bottom of this figure now includes the contribution of the broad shape. Visibly this fit is a far superior description of the data and it has good χ^2/dof of 0.9. The mass and width of the broad state are, roughly speaking, within the range predicted by theory. This is not, however, a definitive observation of such a state and the mass and width will not be quoted. The preliminary FOCUS numbers for the properties of the D_2^{*0} come from the fit to this distribution and they are summarized in tab.2; for comparison the corresponding PDG numbers are also included.

The systematic errors quoted in the table come from studies of cut variants. Fig.5c) shows the results of one such study. The π^- momentum spectrum for true D_2^{*0} decays is rather hard; therefore a requirement of $p_{\pi^-} > 10$ GeV/c improves the S/B. Fig.5c) shows the experimental data with the minimum momentum cut applied and the overlayed fit contains all of the terms included in the fit to Fig.5b). The fit has an acceptable χ^2/dof of 1.1 and the results of the fit are consistent with those of the previous fit.

Fig.5 parts d) through f) show a similar series of fits for the decay $D_2^{*+} \to D^0\pi^+$. Again it is necessary to include a term to allow for the predicted broad states. The preliminary FOCUS numbers for the properties of the D_2^{*+} come from the fit to fig.5e) and are summarized in tab.2.

7 Conclusions

The FOCUS data contains a wealth of information about charmed hadron spectroscopy. FOCUS has presented a measurement of the $\Sigma_c^{++} - \Sigma_c^0$ mass splitting which is competetive with the best published measurements. FOCUS confirms the existence of the Σ_c^+, the Σ_c^{*++} and the Σ_c^{*0} and preliminary numbers for their properties have been shown. And a non-zero natural width for the Σ_c is also confirmed at the 3 σ level. This report has also shown that there is promise for improvements to the world averages in the P-wave charmed meson sector.

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9 References

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