New Results on Charm Photoproduction at Fermilab

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Abstract. FOCUS is a high statistics photoproduction experiment at Fermilab. From among the many results that are being obtained, in the context of the CP violation issue, we measured the values of the $D^o\overline{D^o}$ lifetime mixing parameter $y_{CP}(=\Delta\Gamma/2\Gamma)$ and compared the double Cabibbo suppressed amplitude R_{WS} to the measurement of CLEO-II. We compared also the CP violation asymmetry parameter for several decays to other experiments. New lifetime measurements are presented for both mesons and baryons, together with a new *very preliminary* measurement of the Ω_c^o mass.

INTRODUCTION

FOCUS is a high statistics photoproduction experiment at Fermilab. It collected over 7 billion triggers enriched in charm events and fully reconstructed close to 1.5 million charm decays; it offers therefore a very high sensitivity to investigate rare phenomena in the charm sector and eventually probe New Physics.

Three are the topics addressed in the present paper:

a- the Standard Model predictions for D^o-$\overline{D^o}$ mixing and CP violation in charm decays are generally expected to be orders of magnitude below the sensitivities of current experiments[1].

Mixing occurs since the two weak eigenstates D^o and $\overline{D^o}$ are not mass eigenstates

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(or CP eigenstates in the limit of CP conservation). The mixing effects are typically parametrized by the two variables: $x = \frac{\Delta M}{\Gamma}$ and $y = \frac{\Delta\Gamma}{2\Gamma}$, referring respectively to the mass difference ΔM of the two mass eigenstates and to their width difference $\Delta\Gamma$, both scaled by the average decay width. The mixing effects are investigated experimentally by either studying D^o wrong sign decays or comparing the lifetimes of opposite CP final states.

CP violation asymmetries can be also investigated by looking for particle antiparticle asymmetries in several decay channels such as $D^+ \to K^-K^+\pi^+$, $D^0 \to K^-K^+$, $D^0 \to \pi^-\pi^+$. In single Cabibbo suppressed D decays, the penguin terms in the effective Hamiltonian may provide the different phases of the two weak amplitudes. The direct CP violating asymmetries for these decays are expected to be at most 10^{-3}[2].

b- the lifetimes of all charmed mesons would be the same in absence of W-exchange or W-annihilaition diagrams as well as final state interactions. The contribution of the fully leptonic decays to the total decay width is completely negligible, while the semileptonic widths of D^o and D^+ are equal within errors[3]. Thus, the fact that the two lifetimes are different[3], implies that the two hadronic widths are different. The W-exchange diagram, contributes to the D^o decay while the W-annihilation diagram contributes to the D_s^+ decay and the two contributions might not be identical.

c- the lifetimes of the charmed baryons are known at best with a 5% uncertainty and new measurements are needed. Here, final state interactions and spin effects contribute to specific jerarchies in their lifetimes. In addition, evidence for the double charmed baryon Ω_c^o is still somewaht weak and FOCUS is able now to provide at least a very preliminary value of its mass.

The analysis presented here is mostly based on the full data sample collected by the experiment during the Fermilab 1996-1997 fixed-target run with photons having an average energy of 180 GeV in a segmented BeO target, usingd an upgraded version of the E687 spectrometer[4]. The vertex detector is formed by 16 layers of silicon microstrips [four (x,y) interleaved with the target segments and 12 (x,y,u) downstream] which provide an excellent proper time resolution $\sigma_\tau \approx 30$ fs. The charged particle momenta are measured from their deflections by two analysis magnets of opposite polarity and the hits left into five stations of multiwire proportional chambers. Particle identification is provided by three multicell threshold Cerenkov counters, two electromagnetic calorimeters, one hadron calorimeter and two arrays of muon counters.

MIXING PARAMETERS

The mixing amplitude (squared) is easily written as:

$$| < \overline{D^o} | D^o(t) > |^2 \approx e^{-\Gamma_1 t}[1 + e^{\Delta\Gamma t} - 2e^{\frac{\Delta\Gamma t}{2}} cos(\Delta M t)] \quad (1)$$

being Γ the total decay width.

Defining $x = \frac{\Delta M}{\Gamma}$ and $y = \frac{\Delta\Gamma}{2\Gamma}$, in the case of $|x|, |y|$ small, one can write the mixing amplitude as:

$$A_{mix} \approx \frac{y + ix}{2} \, \Gamma t \; e^{-\frac{\Gamma t}{2}} \quad (2)$$

Integrating $|A_{mix}|^2$ over time, the rate for the mixing process is described by:

$$R_{mix} = \frac{\Gamma_{mix}}{\Gamma_{unmix}} = \frac{x^2+y^2}{2} \tag{3}$$

Upper limits on R_{mix} (e.g.: 95% confidence level) draw circles in the x,y plane. To measure R_{mix} from ΔM one needs accuracies in the mass difference out of reach (less than 100 μeV or so); to measure R_{mix} from $\Delta\Gamma$, one needs very good lifetime measurements.

Measurements of R_{mix} are performed by using semileptonic decays and looking at the *wrong sign* (hereafter WS) leptons. The particle-antiparticle ambiguity is solved by selecting the decays $D^{*\pm} \rightarrow D^o\pi^{\pm}$, able to discriminate what D^o has been produced. Contrary to neutral kaons, hadronic charm decays are complicated since doubly Cabibbo suppressed (hereafter DCS) channels come into play, adding a new term to the box diagram, as well as a new strong phase ϕ (relative to the Cabibbo favoured decay). The decay amplitude R_{WS} is then written as:

$$R_{WS}(t) = [R_{DCS} + y'\Gamma t\sqrt{R_{DCS}} + \frac{x'^2+y'^2}{2}\frac{\Gamma^2 t^2}{2}]e^{\Gamma t} \tag{4}$$

where $x' = xcos\delta + ysin\delta$ and $y' = ycos\delta - xsin\delta$. When the mixing effects are very small, the branching ratio R_{WS} of the *wrong sign* decay is close to that of the DCS channel.

LIFETIME MIXING

The y mixing parameter can be evaluated by directly measuring the lifetimes of pure CP states. Assuming CP conservation, the y parameter equals y_{CP}, the width asymmetry $\Delta\Gamma$ between the $CP = +1$ and $CP = -1$ states. The discovery of two CP eigenstates, say D^o_1 and D^o_2 similar to the K^o_1 and K^o_2 states, would be important "per se", independent of CP violation.

FOCUS has measured y_{CP} using the channel $D^o \rightarrow K^-K^+$ as $CP = +1$ state and the CP mixed state $D^o \rightarrow K^-\pi^+$. Assuming that $K^-\pi^+$ is an equal mixture of $CP = \pm 1$

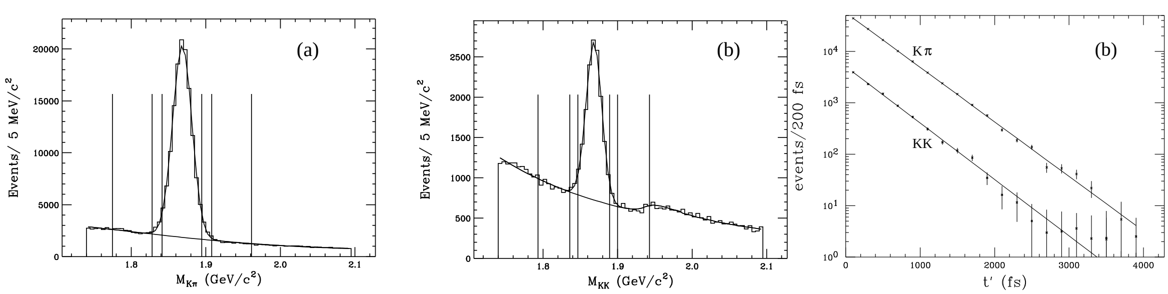

FIGURE 1. Mass and time distributions: a)- mass for 119738 $D^0 \rightarrow K^-\pi^+$ events; b)- mass for 10331 $D^0 \rightarrow K^-K^+$ events (b) Vertical lines show the selected signal and sideband regions for lifetime and y_{CP} fit; c)- reduced proper time distributions for $D^o \rightarrow K^-K^+$ and $D^o \rightarrow K^-\pi^+$ events. The distributions are background subtracted and include very small Monte Carlo corrections.

states, y_{CP} can be written in terms of the two lifetimes:

$$y_{CP} = \frac{\Gamma_{CP-even} - \Gamma_{CP-odd}}{\Gamma_{CP-even} + \Gamma_{CP-odd}} = \frac{\tau(D^o \rightarrow K\pi)}{\tau(D^o \rightarrow KK)} - 1 \tag{5}$$

To get a value of $\tau(D^o \rightarrow KK)$ with an error of $\approx 1\%$ one needs a sample of at least $10,000$ events in the Cabibbo suppressed channel $D^o \rightarrow K^+K^-$. Fig. 1 shows the selected 119738 events for the decay $D^0 \rightarrow K^-\pi^+$ (fig. 1a) and the 10331 events for the decay $D^o \rightarrow K^-\pi^+$ (fig. 1b); fig. 1c shows instead, the 2 reduced proper time distributions, together with the binned-likelihood simultaneous fit using y_{CP} and $\tau(K^-\pi^+)$ as free parameters. The fit is performed over 20 bins, 200fs wide, and spans over more than $6\tau(K^-\pi^+)$. The values obtained are[5]: $y_{CP} = (3.42 \pm 1.39 \pm 0.74)$ and $\tau(K^-\pi^+) = (409.2 \pm 1.3)$ fs. We quote only the 0.3% statistical error as we must wait for values from other channels such as $D^o \rightarrow K^-\pi^-2\pi^+$ to estimate any systematic error.

The value of y_{CP} is bearly compatible with zero and definitely needs confirmation. The experiments at the B factories are clear candidates to provide a check of the result.

WRONG SIGN AND DOUBLY CABIBBO SUPPRESSED DECAY

Starting with a sample of over 200,000 D^* events, FOCUS tackled the measurement of the WS branching ratio i.e.: $D^o \rightarrow K^+\pi^-$ or $\overline{D^o} \rightarrow K^-\pi^+$ decays relative to the *right sign* (RS) decays. The sign of the D^* identifies unambiguously the C state of the neutral meson. Obviously, the D^* requirement reduces significantly the available statistics. The event selection depends upon the capacity of separating pions from kaons. Four different backgrounds are relevant: a- $D^o \rightarrow \pi^+\pi^-$; b- $D^o \rightarrow K^+K^-$; c- partially reconstructed D's and finally *doubly misidentified* $D^o \rightarrow K\pi$ decays. In particular, when the mass of the pion and the kaon are interchanged -leaving unchanged their charge- the final state produces a broad peak in the $\Delta M = M(D^*) - M(D^o)$ distribution at the charm mass difference. To deal with the different types of background we divided the $\Delta M vs M(K\pi)$ scatter plot into 80 ΔM bins, each 1 MeV wide, and fitted for each bin the RS and WR $K\pi$ mass distributions with the above backgrounds generated by Montecarlo[6].

The result of the overall fit is shown in fig. 2a. From the fit we get 149 ± 31 WS events compared to $36,760 \pm 195$ RS events. This provides a Branching Ratio:

$$R_{WS} = \frac{\Gamma(D^o \rightarrow K^+\pi^-)}{\Gamma(D^o \rightarrow K^-\pi^+)} = (0.405 \pm 0.085 \pm 0.025)\%. \tag{6}$$

The time evolution for the $D^o \rightarrow K^+\pi^-$ decay is given by equation (4). If mixing is negligible, the branching ratio R_{WS} provides a measurement of the DCS branching ratio, which is expected to be of order $tan^4\theta_c \approx 0.25\%$. If mixing is significant, R_{WS} depends upon the lifetime acceptance of our analysis. To investigate this point, in an adequate Monte Carlo sample of $D^0 \rightarrow K^-\pi^+$ decays, generated with a nominal lifetime, we re-weighted the accepted events by the ratio of the survival probability provided by its lifetime given by eq. (4) and the probability provided by the nominal lifetime. We then

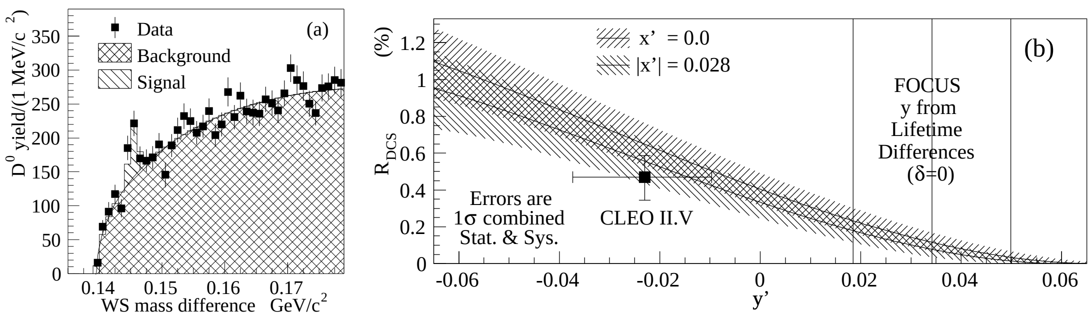

FIGURE 2. a) The $D^0 \rightarrow K^+\pi^-$ mass difference distribution with the signal and background contributions shown. b) R_{DCS} plotted as a function of y'. Contours are given for two values of x' covering the 95% CL of the CLEO result.

obtained R_{DCS} as a function of x' and y', which depend on our measurement for R_{WS} and on the average values $< t >$ and $< t^2 >$ obtained from our Monte Carlo. We determined two bands in the R_{DCS}-y' plane shown in fig. 2b. They correspond to the two values of x' which cover the CLEO 95% CL of $|x'| < 0.28$. For comparison, the CLEO ranges for R_{DCS} and y' are also shown. The two experiments are compatible, although FOCUS may be suggestive of a possible y_{CP} mixing different from zero.

CP VIOLATION

To tackle the CP violation issue, FOCUS selected the single Cabibbo suppressed decay modes: $D^+ \rightarrow K^-K^+\pi^+$, $D^o \rightarrow K^-K^+$, $D^o \rightarrow \pi^-\pi^+$ and their C conjugate states. The D^o flavour is tagged by the $D^{*\pm}$ decays. These decays are normalized to their allowed modes to correct for the difference in the D - $\overline{D}$ photoproduction rates.

For instance, for the single Cabibbo suppressed decay mode $D^0 \rightarrow K^-K^+$ and the normalizing mode $D^0 \rightarrow K^-\pi^+$ the normalization is written as:

$$\eta(D) = \frac{N(D^o \rightarrow K^-K^+)}{N(D^o \rightarrow K^-\pi^+)} \tag{7}$$

Here, $N(D^o \rightarrow K^-K^+)$ is the efficiency corrected number of candidate decays. The use of the η ratio has the additional benefit that most of the corrections due to efficiencies cancel out, therefore reducing the systematic uncertainties [2].

The CP asymmetries are then written as:

$$A_{CP} = \frac{\eta(D) - \eta(\overline{D})}{\eta(D) + \eta(\overline{D})} \tag{8}$$

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[2] It is assumed that there is no measurable CP violation in the Cabibbo favoured decays.

TABLE 1. Measured CP asymmetries(10^{-2}) (see Ref.[8] and ref. therein).

Experiment	$D^+ \to K^-K^+\pi^+$	$D^o \to K^-K^+$	$D^o \to \pi^-\pi^+$
E687	-3.1 ± 6.8	$+2.4 \pm 8.4$	
CLEO II		$+8.0 \pm 6.1$	
E791	-1.4 ± 2.9	$-1.0 \pm 4.9 \pm 1.2$	$-4.9 \pm 7.8 \pm 3.0$
CLEO II[7]		$+0.05 \pm 2.18 \pm 0.84$	$+1.95 \pm 3.22 \pm 0.84$
FOCUS[8]	$+0.6 \pm 1.1 \pm 0.5$	$-0.1 \pm 2.2 \pm 1.5$	$+4.8 \pm 3.9 \pm 2.5$

In Table 1 the FOCUS results are compared to those from other experiments. The values are all consistent with zero. They altogether represent a substantial improvement over previous published limits.

LIFETIMES

E687[9] measured the lifetime of all charmed mesons and baryons and FOCUS plans to remeasure them with smaller errors. The present situation of the uncertainties in charmed lifetimes -as given by the 2000 edition of the Particle Data Book[3] is summarized in Table 2.

TABLE 2. Uncertainties in lifetime measurements.

Particle	$\sigma(\tau)/\tau$ $(stat)$ %	$\sigma(\tau)/\tau$ $(syst)$ %	Particle	$\sigma(\tau)/\tau$ $(stat)$ %	$\sigma(\tau)/\tau$ $(syst)$ %
D^+	1.4	1.0	Λ_c^+	5.9	3.7
D^o	1.0	1.0	Ξ_c^+	≈ 20	≈ 5
D_s^+	3.6	1.5	Ξ_c^o	≈ 25	≈ 5
			Ω_c^o	≈ 30	≈ 14

It will be hard to dominate the systematic errors in FOCUS to significantly improve the measurement of τ_{D^+} given by E687 with a 1.% systematic error. The analysis described in the lifetime mixing section provides a new measurement of τ_{D^o} with a statistics over hundred thousand events and a 0.3% statistical error.

Here we present still preliminary measurements of all the remaining lifetimes but $\tau_{\Omega_c^o}$.

The D_s^+ lifetime has been measured on 50% of the $D_s^+ \to \pi^+\phi$ FOCUS sample and provides a value: $\tau(D_s^+) = 506 \pm 8$ fs. This improves the present uncertainty by about a factor 3.

If the new world average for $\tau(D_s^+) = 499.9 \pm 6.1$ fs and the value of $\tau(D^o)$ given before are used, we calculate a ratio $\frac{\tau(D_s^+)}{\tau(D^o)} = 1.235 \pm 0.016$ which is a value almost 15σ away from unity, thus indicating that the W-exchange diagram and the W-annihilation diagram play different roles in the weak charm decays.

The lifetime values for charmed baryons whose uncertainties are reported in Table 2 can be considered not much more than estimates. Infact, only $\tau(\Lambda_c^+)$ has a statistical error of about 6%.

FOCUS has a preliminary remeasurement of $\tau(\Lambda_c^+)$ on 80% of the total sample: $\tau(\Lambda_c^+) = 204.5 \pm 3.4$ fs. This improves the uncertainty by more than a factor 3 and

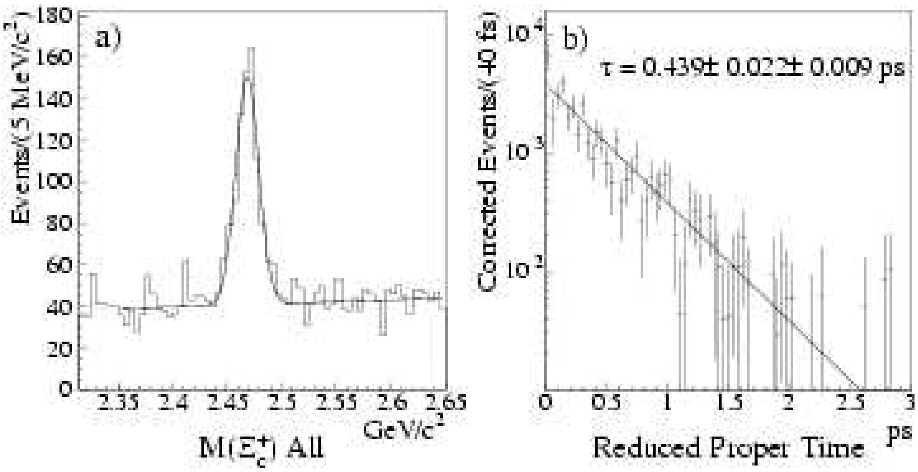

FIGURE 3. a- Cumulative mass distribution for the decays of the Ξ_c^+ baryon; b- reduced proper time distribution for the same decays.

sets as preliminary new world average a value $\tau(\Lambda_c^+) = (201.9 \pm 3.1)$ fs.

The lifetimes of the other charmed baryons will be dealt with in the next Section.

STRANGE-CHARMED BARYONS

In the charmed baryon sector, information on the strange-charmed particles is still rather scanty. FOCUS has remeasured the lifetimes of the Ξ baryons[3] and has in progress the remeasurement of the mass of the Ω_c^o particle.

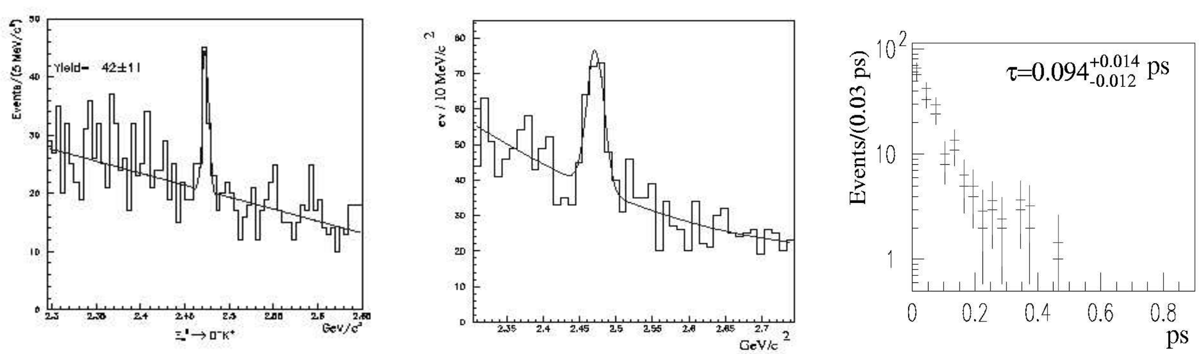

FIGURE 4. a- Mass distribution for the decay $\Xi_c^o \to \Omega^- K^+$; b- mass distribution for the decay $\Xi_c^o \to \Xi^- \pi^+$; c- reduced proper time distribution for the two samples.

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[3] Preliminary data were presented at previous Conferences[10]a.

Collecting 300 events of the decay $\Xi_c^+ \rightarrow \Xi^- 2\pi^-$, 130 events of the decay $\Xi_c^+ \rightarrow \Sigma^+ K^- \pi^+$; 58 events of the decay $\Xi_c^+ \rightarrow \Lambda^o K^- 2\pi^+$ and 45 events of the Cabibbo suppressed decay $\Xi_c^+ \rightarrow pK^-\pi^+$ (for a total of 533 events shown in fig. 3a, we measured a lifetime[11] $\tau(\Xi_c^+) = (439 \pm 22 \pm 9)$ fs (see fig. 3b). This value improves the world sample[3] by more than a factor 2 and reduces the error by almost a factor 4.

The Ξ_c^o baryon has been observed in two channels: $\Xi_c^o \rightarrow \Omega^- K^+$ (42 events) and $\Xi_c^o \rightarrow \Xi^- \pi^+$ (117 events). The preliminary signals are shown in fig.s 4a,b respectively. The lifetime measurement on the total sample -reduced proper time distribution shown in fig. 4c- gives a still preliminary value for the lifetime: $\tau(\Xi_c^o) = 94^{+14}_{-12}$ fs, where the error is statistical only. Although the statistics improves by a factor 3 compared to the Particle Data Group, the error is still large and better measurements are to be expected.

Finally the Ω_c^o baryon issue is still open. The mass is still uncertain and the lifetime measured with very limited statistics[4].

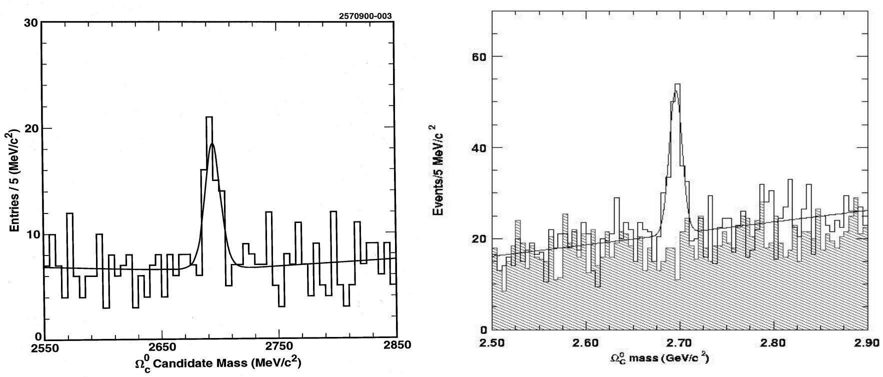

FIGURE 5. a- Cumulative mass distribution for the 5 Ω_c^o decay channels observed by CLEO; b- cumulative mass distribution for the 4 Ω_c^o decay channels observed by FOCUS.

Cleo[12] analyzed six different decay channels of the Ω_c^o, i.e.: $\Omega_c^o \rightarrow \Omega^-\pi^+$, $\Omega_c^o \rightarrow \Omega^-\pi^+\pi^o$, $\Omega_c^o \rightarrow \Omega^-\pi^-2\pi^+$, $\Omega_c^o \rightarrow \Xi^- K^- 2\pi^+$, $\Omega_c^o \rightarrow \Xi^o K^-\pi^+$, getting a total of 40.4 ± 9.0 events but did not find evidence for the decay $\Omega_c^o \rightarrow \Sigma^+ 2K^-\pi^+$. The cumulative mass distribution is shown in fig. 5a.

FOCUS performed a very preliminarly analysis and selected the four charged decay channels (we did not tackle yet final states containg neutral pions), i.e.: $\Omega_c^o \rightarrow \Omega^-\pi^+$, $\Omega_c^o \rightarrow \Omega^-\pi^-2\pi^+$, $\Omega_c^o \rightarrow \Xi^- K^- 2\pi^+$, $\Omega_c^o \rightarrow \Sigma^+ 2K^-\pi^+$, collecting over 100 events shown in fig. 5b. The very preliminary values for the mass and width found, as well as the yeld for each decay are collected and compared to previous experiments in Table 3

4 It is indeed peculiar that WA89 never published a value for the mass of their 86 Ω_c^o events.

TABLE 3. Mass width and observed yield of the Ω_c^o (**very preliminary**)

FOCUS: Decay mode	Mass (Mev/c^2)	Width (Mev/c^2)	Yield
$\Omega_c^o \to \Omega^- \pi^+$	2696.0 ± 4.5	11.4 ± 4.1	22.5 ± 8.7
$\Omega_c^o \to \Omega^- 2\pi^- \pi^+$	2695.5 ± 2.0	7.8 ± 2.1	21.0 ± 7.2
$\Omega_c^o \to \Xi^- K^- 2\pi^+$	2605.5 ± 2.2	5.2 ± 1.9	42.3 ± 11.3
$\Omega_c^o \to \Sigma^+ 2K^- \pi^+$	2696.5 ± 2.5	6.4 ± 2.1	28.5 ± 9.5
cumulative histogram	2695.5 ± 2.2	7.8 ± 2.1	115.5 ± 17.6
Experiment			
E687 $\Omega_c^o \to \Omega^- \pi^+$	$2705.9 \pm 3.3 \pm 2.0$	=	10
E687 $\Omega_c^o \to \Sigma^+ 2K^- \pi^+$	$2699.9 \pm 1.5 \pm 2.5$	=	42
CLEO 5 decay modes	$2694.6 \pm 2.6 \pm 1.9$	=	40
FOCUS 4 decay modes	2695.9 ± 1.3	=	115

CONCLUSIONS AND ACKNOWLEDGMENTS

FOCUS obtained remarkable results on charm physiscs. In competition with Cleo and the B factory experiments BaBar and Belle, it will continue to provide valuable contributions to the understanding of both charmed mesons and baryons.

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