Fermi National Accelerator Laboratory

FERMILAB-Conf-95/376-E
E687

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December 1995

Submitted to the Proceedings of the *Production and Decay of Hyperons, Charm and Beauty Hadrons*, Strasbourg, France, September 5-8, 1995

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

Fermilab E687 Results and Future High Statistics Charm Experiment FOCUS/E831

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Results from the Fermilab charm photoproduction experiment E687 are reviewed. The physics goals and the improvements being made for the next experiment (FOCUS/E831) are described. We expect to accumulate a million fully reconstructed charm decays which represent an order of magnitude improvement over E687.

1. BRIEF HISTORY OF E687

Fermilab E687 is a fixed target photoproduction experiment located at the wideband photon beam at Fermilab. The main aim of the experiment is the study of the production and decays of charm hadrons.

The first physics run of the experiment was in 1987, when about 10^4 charm decays were fully reconstructed. The second run of the experiment lasted for about 12 months between 1990 and 1992, when about 500 million events were recorded on tape. This second run ended in January 1992 and the data processing was completed 7 months later in August 1992. In this run alone we accumulated about 10^5 fully reconstructed charm decays which has so far lead to 24 published physics papers in Physics Letters, Physical Review Letters and Physical Review D. The first paper was published in February 1993.

Some of the results, including recent ones are reviewed in the first part of this paper. Although there will be more physics papers from E687, we are also preparing for a future run using an upgraded spectrometer. The new experiment is E831, named FOCUS ("Photoproduction of Charm in an Upgraded Spectrometer"), and is the subject of the second part of this paper. The physics goals of the future experiment and the changes required to accumulate a million fully reconstructed charm decays are discussed.

*For the E687 Collaboration [1].
Talk given at the conference on Production and Decay of Hyperons, Charm and Beauty Hadrons, Strasbourg, France, Sept. 5-8 1995.

2. HIGHLIGHTS OF E687 RESULTS

Results from data collected in the second E687 run will be reviewed in this section. More recent results will be highlighted.

2.1. Lifetimes

E687 has the World's best measurements of the charm particle lifetimes [2,3]. Figure 1 shows the E687 lifetime measurements of all the weakly decaying singly charm hadrons together with the 1992 PDG world averages. The errors on the E687 measurements are comparable to or smaller than those of the 1992 PDG averages. The 1994 PDG averages [4] are now dominated by the E687 measurements.

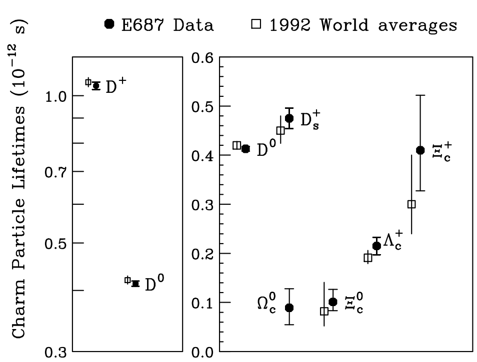

Figure 1. Charm particle lifetimes.

Although the current data supports the following lifetime hierarchy:

$$\tau(D^+) > \tau(D_s^+) > \tau(D^0)$$

$$\tau(D^0) \sim \tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) \sim \tau(\Omega_c^0)$$

it is still only at the 2.5-3 sigma level, and we cannot yet distinguish between the predictions of many of the different models [5,6]. This hierarchy does show that W-exchange is important for baryons ($\tau(\Lambda_c^+), \tau(\Xi_c^0) < \tau(D^0)$), and that both destructive ($\tau(D^+) > \tau(D^0)$) and constructive ($\tau(\Xi_c^0), \tau(\Omega_c^0), < \tau(\Lambda_c^+)$) interference occurs. In some cases (*e.g.* the Ω_c^0 lifetime) the data does provide enough information to help define the validity and exact implementation of particular models [6,7].

2.2. Charm Baryon Decays

In additional to the lifetime measurements E687 has many other results on charm baryon decays. In particular we have used a novel method of reconstructing $\Sigma^+ \to p\pi^0, n\pi^+$ and $\Sigma^- \to n\pi^-$ to find the first conclusive evidence for the Ω_c^0 [8] and to make the first measurement of its lifetime [3]. We measure the mass of the Ω_c^0 to be 2699.9±1.5±2.5 MeV/c^2 and the lifetime to be 86^{+27}_{-20}±28 fs. There is now additional evidence for the Ω_c^0 and another measurement of its lifetime [9]. We have also used this technique to give the first observation of the decay $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+$ [10], finding a branching ratio $\Gamma(\Lambda_c^+ \to \Sigma^-\pi^+\pi^+)/\Gamma(\Lambda_c^+ \to \Sigma^+\pi^+\pi^-) = 0.53 \pm 0.15 \pm 0.07$.

We have made the best measurement of a Cabibbo-suppressed decay of a charm baryon: $\Lambda_c^+ \to pK^-K^+$ [11], and have confirmed both the $\Lambda_c^{*+}(2625)$ [12] and the $\Lambda_c^{*+}(2593)$ [13]. Figure 2 shows the E687 data for these two excited Λ_c^+ states. The $\Lambda_c^{*+}(2625)$ was first observed by ARGUS [14] who measured a mass of 2626.6±0.5±1.5 MeV/c^2. The $\Lambda_c^{*+}(2593)$ was first seen by CLEO [15] and they measured a mass difference $M(\Lambda_c^{*+}(2593)) - M(\Lambda_c^+)$ of 307.5±0.4±1.0 MeV/c^2. We measure the mass difference $M(\Lambda_c^{*+}(2625)) - M(\Lambda_c^+)$ to be 340.4±0.6±0.3 MeV/c^2, and $M(\Lambda_c^{*+}(2593)) - M(\Lambda_c^+)$ to be 309.2±0.7±0.3 MeV/c^2. Our results for the resonant decays $\Lambda_c^{*+} \to \Sigma^{0,++}\pi^\pm$ agree with those of CLEO and support the interpretation of the $\Lambda_c^{*+}(2593)$ as the $J^P = \frac{1}{2}^-$ state and the $\Lambda_c^{*+}(2625)$ as the $J^P = \frac{3}{2}^-$ state of the orbitally excited Λ_c^{*+} doublet. We have also measured the relative photoproduction cross sections given in Table 1. We estimate that the fraction of inclusively produced Λ_c^+ coming from higher mass states is >25% at 90% confidence level [13].

Table 1
Relative Photoproduction Cross Sections

	$\sigma_{\Sigma_c}/\sigma_{\Lambda_c}$ or $BR \cdot \sigma_{\Lambda_c^*}/\sigma_{\Lambda_c}$ (%)
Σ_c^0	$7.77 \pm 2.07 \pm 0.31$
Σ_c^{++}	$6.70 \pm 1.92 \pm 0.27$
$\Lambda_c^{*+}(2593)$	$3.34 \pm 1.23 \pm 0.27$
$\Lambda_c^{*+}(2625)$	$7.01 \pm 1.93 \pm 0.56$

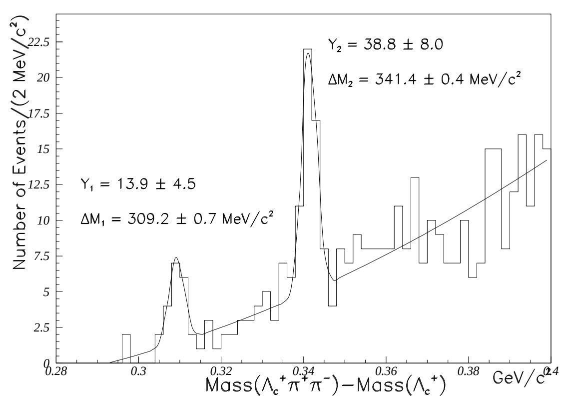

Figure 2. Mass difference plot showing evidence for both the $\Lambda_c^{*+}(2625)$ and $\Lambda_c^{*+}(2593)$.

2.3. Charm Semileptonic Decays

E687 has produced many competitive results on charm semileptonic decays. We have measured the $D^+ \to K^{*0}\mu^+\nu_\mu$ branching ratios and form factors [16], as well as the branching ratio and form factors for the decay $D_s^+ \to \phi\mu^+\nu_\mu$ [17,18].

We now have final results on the decay $D^0 \to K^-\mu^+\nu_\mu$ using both the D^{*+} tagged D^0 mesons as well as inclusive D^0 mesons to increase statis-

Table 2
Results on $D^0 \to K^-\mu^+\nu_\mu$

$\frac{BR(D^0\to K^-\mu^+\nu_\mu)}{BR(D^0\to K^-\pi^+)}$	Pole Mass
0.852±0.034±0.028	$1.87^{+0.11+0.07}_{-0.08-0.06}$ (GeV/c^2)
$f_+(0)$	$f_-(0)/f_+(0)$
0.71±0.03±0.03	$-1.3^{+3.6}_{-3.4}\pm0.6$

tics [19]. Table 2 shows the results for the branching ratio, pole mass, form factor and a first measurement of the $f_-(0)/f_+(0)$ form factor ratio. The results represent a significant improvement over past semimuonic measurements [20], and our errors are comparable to the best measurement of the semielectronic mode [21]. From our results we calculate $BR(D^0 \to K^{*-}\mu^+\nu\mu)/BR(D^0 \to K^-\mu^+\nu_\mu) = 0.62 \pm 0.07 \pm 0.09$ which is closer to 0.5 (as seen by other recent experiments) than 1.0 (as predicted by some theories [22]). We find that the pole mass is less than the D_s^{*+} mass and that $BR(D^0 \to K^-\mu^+\nu_\mu) < BR(D^0 \to K^-e^+\nu_e)$ [19].

We have preliminary results on $D^0 \to K^-e^+\nu_e$ and $D^0 \to \pi^-e^+\nu_e$ [23], and we also have forthcoming results on $D^0 \to \pi^-\mu^+\nu_\mu$ and $D^+ \to K_s^0\mu^+\nu_\mu$.

2.4. Charm Meson Hadronic Decays

We have performed detailed amplitude analyses of three $D \to K\pi\pi$ Dalitz plots [24] and $D^+, D_s^+ \to K^-K^+\pi^+$ [25]. We also have preliminary results on $D^+, D_s^+ \to \pi^+\pi^-\pi^+$ [26]. The results of these analyses provide information on the role of different decay mechanisms. Also knowledge of the quantum mechanical decay amplitude allows interference effects to be properly accounted for in calculations of the branching ratios.

In addition to these 3-body hadronic decays, we have also made considerable improvements in the measurements of multi-body modes, the 4-body decays of the D^0 to 4π, $2K2\pi$ and $3K\pi$ [27]. We expect results in the future on 5-body decays [26]. Although theoretical predictions are limited mainly to 2-body decay modes, it is worthwhile to complete the experimental picture of charm decays especially as it represents unchartered territory and the knowledge gained may be useful in multi-body B decay modes.

Due to the relatively long lifetime of the K_s^0, ~90% these mesons are not reconstructed in the silicon vertex detector and thus have relatively poor track resolution. However a significant fraction of charm decays involve one or more K_s^0 mesons. We have made new measurements of decays involving K_s^0 mesons, including a first measurement of $D^+ \to \overline{K^0}K^{*+}$ [28,29].

2.5. Charm Production and Spectroscopy

Charm production and spectroscopy are good areas to test QCD since there exists some detailed calculations based on QCD. As well as our new results on excited Λ_c^+ baryons, we have published results on orbitally excited charm mesons [30].

We have a large (~325) D$\overline{\text{D}}$ sample which we have used to test QCD production mechanisms [31,32]. We find that next-to-leading order (NLO) QCD calculations when supplemented with a fragmentation model and an intrinsic k_t kick can yield results that give a satisfactory description of our data. An intrinsic k_t^2 kick of ≈ 0.5 GeV^2 is required to match our D$\overline{\text{D}}$ acoplanarity data while a larger value $\approx 1-2$ GeV^2 is needed to give a good description of our inclusive p_t^2 distributions.

Our preliminary results on production asymmetries indicates a small enhancement of $\overline{D}$ over D production in our kinematic region [32,33]. No asymmetry is expected in leading order perturbative QCD.

2.6. CP Violation and Rare Decays

Within the Standard Model, CP violation, D^0-$\overline{D^0}$ mixing and rare charm decays (*e.g.* due to Penguin contributions or even long distance effects) are expected to be unobservable. This provides a background free environment to search for physics beyond the Standard Model since some models can predict experimentally observable effects [34]. We have searched for direct CP violation in D^0 and D^+ decays and have reported the best limits so far [35]. In order to measure D^0-$\overline{D^0}$ mixing we have to contend with background from doubly Cabibbo suppressed decays (DCSD). Recent results have show that

$D^0 \rightarrow K^+\pi^-$ may be large compared to a signal expected from D^0-$\overline{D^0}$ mixing [36]. We have made a measurement of $D^+ \rightarrow K^+\pi^-\pi^+$ where one can assess the DCSD contribution without complications from D^0-$\overline{D^0}$ mixing. We find a $D^+ \rightarrow K^+\pi^-\pi^+$ DCSD signal of 20.9±6.6 events and measure $\Gamma(D^+ \rightarrow K^+\pi^-\pi^+)/\Gamma(D^+ \rightarrow K^-\pi^+\pi^+) = 0.0072 \pm 0.0023 \pm 0.0017$ [37]. We have also searched for DCSD $D^+ \rightarrow K^+K^-K^+$ and $D^+ \rightarrow K^+\phi$ and have set 90% confidence level upper limits on the following branching ratios: $BR(\phi K^+)/BR(\phi\pi^+) < 0.021$; $BR(K^+K^-K^+)/BR(\phi\pi^+) < 0.025$ [38].

3. GOALS OF FUTURE EXPERIMENT FOCUS

The next run of E687 is E831, named FOCUS [39]. The goal is to accumulate a million fully reconstructed charm decays [40]. We have some tremendous experience gained in E687 and think we can achieve our goals in a photoproduction experiment by running at five times the luminosity of E687 and by improving the combined efficiency of the data acquisition system (DAQ) and the detector by a factor of two. We like to stress that our goal is not only to get ten times more data than in E687 but also to significantly improve the quality of the data through improvements in almost all the detector systems.

We discuss in this paper the goals of FOCUS and the changes in the E687 spectrometer that have to be made.

4. PHYSICS GOALS FOR FOCUS

4.1. High Precision Studies of the D Semileptonic Decays

We antipiciate a 30 fold increase in the number of semimuonic charm decays in FOCUS over E687. The extra factor of three comes from several factors. Only the inner muon system was working in E687 and only for half the time during the 1990 run. In 1991 the detectors in the highest acceptance region were removed to allow the photon beam to reach another experiment downstream of E687. FOCUS will have both a new inner and outer muon system, this will improve efficiency as well as reduce muon misidentification by a factor of 5. A new electromagnetic calorimeter will also improve the efficiency for electrons. We expect to be able to measure $|V_{cd}|/|V_{cs}|$ to a statistical precision of about 1.5% . (Uncertainties in the value of f_+^π/f_+^K are not included in this error). We should have precision measurements of all the form factors as well as measurements of the q^2 dependence.

4.2. Leptonic Decays

With the help of a new target region silicon detector we will try to measure the f_{D_s} decay constant through $D_s^+ \rightarrow \mu^+\nu_\mu$, and f_D through $D^+ \rightarrow \mu^+\nu_\mu$. We will also try to observe $D_s^+ \rightarrow \tau^+\nu_\tau$.

4.3. Absolute Branching Fractions

Since theorists calculate absolute decay rates, it is worthwhile to improve our knowledge of the abolute charm branching fractions. Using D^{*+} and D^{*0} tagging we should be able to make measurements of the absolute branching fractions of $D^0 \rightarrow K^-\pi^+$ to better than 3%, and $D^+ \rightarrow K^-\pi^+\pi^+$ to better than 4%.

4.4. Hadronic Decays of the $\mathbf{D^0}$ and $\mathbf{D^+}$

Using much improved signal-to-noise and higher statistics we will be able to perform very accurate Dalitz plot analyses of many decay modes. With our new hadronic calorimeter we will try to reconstruct charm decays using K_L^0 mesons.

4.5. Charm Production

We should be able to make detailed comparisons with the results of different models and an antipicated large sample of double charm events ($> 10^4$) will be particularly useful.

4.6. $\mathbf{D_s^+}$ and $\mathbf{\Lambda_c^+}$ Decays

We should have about 20,000 $D_s^+ \rightarrow K^+K^-\pi^+$ and 20,000 $\Lambda_c^+ \rightarrow pK^-\pi^+$ decays. We will look for new decay modes and study the excited states. We are hoping to be able to make a measurement of the absolute branching ratio of the Λ_c^+ [33].

4.7. $\mathbf{D^{**}}$ States

We plan to look carefully at excited D meson states, particularly with very clean double D samples.

4.8. Charm Baryon Spectroscopy and Lifetimes

With the new electromagnetic calorimeter we should have the new ability to use Ξ^0 as a daughter decay particle as well as Λ^0, $\Sigma^{\pm}$, Ξ^- and Ω^-. We will also search for doubly charm baryons which may be observable in FOCUS.

4.9. $\mathrm{D^0} - \overline{\mathrm{D^0}}$ Mixing and DCSD

Although current SM predictions for $\mathrm{D^0} - \overline{\mathrm{D^0}}$ mixing are smaller than our antipicated sensitivity, various new phenomena could produce visible mixing effects ($r_D > 10^{-3}$) [34]. With the increased statistics we expect to conclusively identify several DCSD channels.

4.10. Rare and Forbidden D Decays and CP Violation

With improved statistics and sensitivities, we will of course continue to search for new physics in rare and forbidden D decays, (*e.g.* $D^0 \to \mu^+\mu^-, e^+e^-$, $D^0 \to \rho\gamma, K^*\gamma$ and $D^0 \to \mu^+e^-$), and in CP violation.

5. THE FOCUS SPECTROMETER AND BEAMLINE

The changes to the E687 beamline and spectrometer required to accumulate ten times more data are summarized in Table 3. Figure 3 shows the FOCUS beamline. To increase the beam intensity, both positrons and electrons will be used in FOCUS to generate the photon beam and the energy of the electron/positron beam will be lowered to about 250 GeV from 350 GeV. In addition, we have reduced the amount of material in the beam and we plan to run about 1.5 times longer at a higher primary proton intensity.

FOCUS will use an improved DAQ to handle the higher rates. To improve the livetime we are using a new faster hadronic calorimeter. By moving the hadronic energy trigger from the second to the first level trigger and reducing the readout time of each detector system, we can increase the livetime by a factor of 1.5.

Changes to the spectrometer are of two types: changes to handle the higher beam intensity and changes to improve efficiency. The changes needed to handle higher rates are to deaden the wire chambers in the e^+e^- beam conversion pair region and get back the acceptance in this region by using new straw chambers.

There will be five new detector systems in FOCUS. The spectrometer is shown in Figure 4. There is a new target region silicon strip detector, a new inner and a new outer muon system, a new electromagnetic and a new hadronic calorimeter. In addition 2 of the 5 multiwire proportional chambers are being rebuilt, the silicon vertex detector is being improved, a new tile tie-breaker system has been installed in the outer electromagnetic calorimeter, and the beam shower counters are being rebuilt. All these changes will increase the efficiency as well as the quality of the data. Just the inclusion of the new target region silicon detector has been estimated to increase the charm efficiency by a factor of about 1.4 or more. The mass resolution and signal-to-noise are also improved.

By segmenting the target, and maybe using a denser (BeO) target we will be able to reconstruct more charm hadrons that decay outside the target. The signal-to-noise is much better for these decays and the background for these decays are easier to model. Thus the systematic error due to background should be reduced in FOCUS.

Table 3
Changes for FOCUS from E687.

UPGRADES TO THE BEAMLINE	GAIN
Use positron beam	$\times 1.50$
Lower secondary energy	$\times 2.65$
$\to$effect on charm cross section	$\times 0.75$
Reduce material in beamline	$\times 1.10$
More proton intensity/run longer	$\times 1.50$
Total increase in flux	$\times 5$
DAQ, TRIGGER, DETECTORS	
DAQ, HC and trigger upgrade	$\times 1.5$
Upgrades to spectrometer	$\times 1.4$
Total increase in livetime/efficiency	$\times 2$
TOTAL INCREASE IN CHARM	$\times 10$

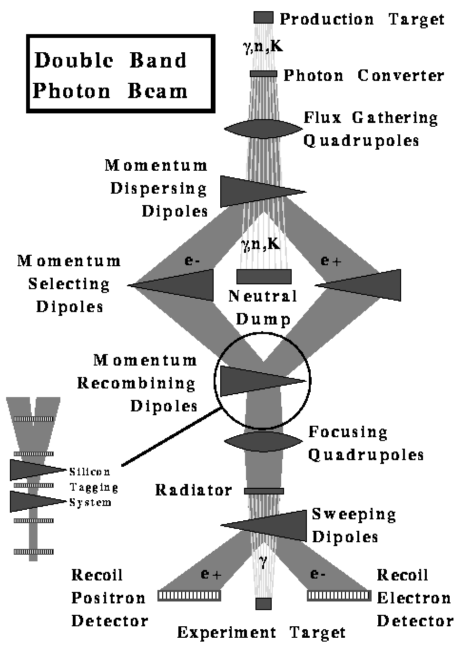

Figure 3. Pictorial representation of the FOCUS beamline.

6. SUMMARY

Fermilab E687 was a very successful experiment and is still producing interesting physics results. The next experiment, FOCUS, expected to start in July 1996 should accumulate a million fully reconstructed charm events and be equally successful.

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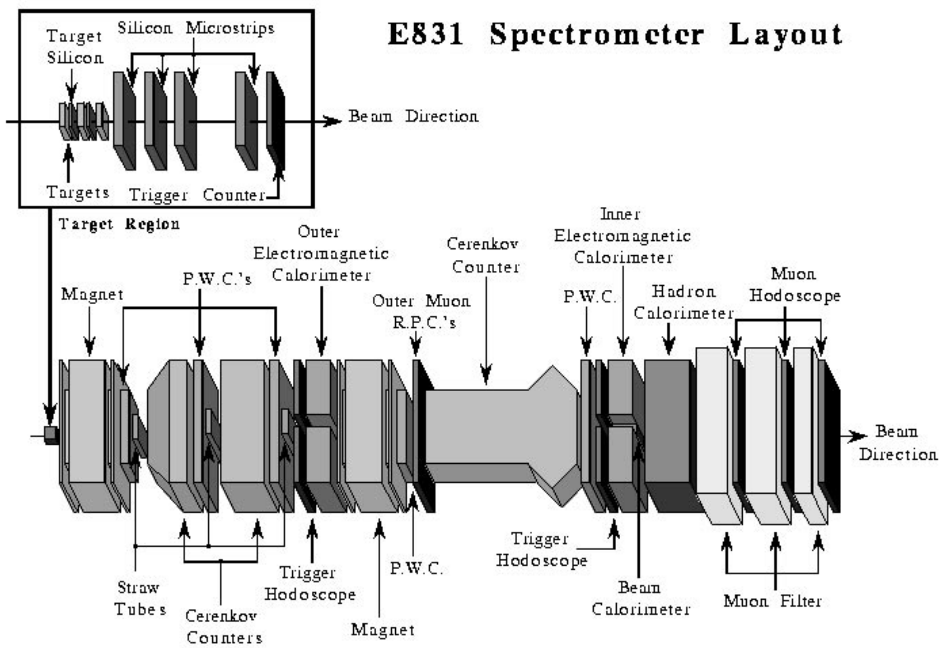

Figure 4. Pictorial representation of the FOCUS spectrometer.

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