Fermi National Accelerator Laboratory

FERMILAB-Conf-88/200-E
[E-691]

Charm Physics*

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December 1988

*Presented by the author at the BNL Workshop on Glueballs, Hybrids, and Exotic Hadrons, Brookhaven National Laboratory, Upton, New York, August 29-September 11, 1988.

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Operated by Universities Research Association Inc. under contract with the United States Department of Energy

CHARM PHYSICS

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Abstract

The status of charm physics with emphasis on recent high statistics results from fixed target experiments is presented. The topics covered include charm production, $D^0\overline{D}^0$ mixing, charm baryons and excited states such as the D^{**}. Also reviewed are charm decays: hadronic, leptonic as well as semileptonic. Finally, we take a brief look at charm lifetimes before concluding with a look to the future.

CHARM PRODUCTION

The production of charm is a field that is finally maturing, albeit more slowly than one would wish. We now have more data indicating that the production cross-section does not increase as rapidly as A^1, that there may be no leading particle effect and the new QCD calculations may not need large K-factors to explain the data. We present a short summary of the present state of knowledge in this field. For details and references, the reader is referred to a recent review.[1]

The cross-section for the photoproduction of $c\bar{c}$ pairs has now been measured well by E-691 to be 580±10±60 nb/nucleon at $< E_\gamma >$=145 GeV. This is in agreement with the earlier muon experiments EMC and BFP. Cross-section measurements for the hadroproduction of $c\bar{c}$ pairs are dominated by the efforts of the LEBC (-EHS or -MPS) group and now average ~20μb at 400 GeV and ~30μb at 800 GeV. The A-dependence of charm production can now confidently be said to be slower-than-A. If parameterized as A^α, recent experiments[1] find that α=.77±.03.

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Recently, R. K. Ellis et al.[2] calculated the next-to-leading order expressions for heavy flavour production in QCD. They find that the total cross-section is about a factor of 3 larger for charm production than in the leading order case. The total cross-section measurements are in agreement with these new QCD predictions with a charm quark mass close to 1.5 GeV/c^2. High-statistics measurements are still needed for comparisons with the differential cross-sections.

The mean p_T^2 for charmed particles has been measured by many hadroproduction experiments and they all agree that it is around 1.2 GeV^2/c^2. Again, E-691 provides an accurate photoproduction value: 1.16±.04 GeV^2/c^2. The x_F distribution from E-691 peaks at ~0.2, as expected for photoproduction. When parameterized as $(1\text{-}x_F)^n$, the x_F distributions from experiments at or below 400 GeV in beam energy favour n≈3, while the 800 GeV experiments observe more central production (n≈10). There seems to be no further evidence for a leading particle effect in hadroproduction of charm. Meagre data from NA32 so far do not indicate an enhancement of D_s production by kaons, however higher statistics are needed.

Finally, the distributions of variables associated with observed charm pairs mostly agree with the QCD fusion model. However, there may be a disagreement among experiments in the variable ϕ, the angle between the two charm particles in the transverse plane. LEBC-EHS and WA75 find that the ϕ distribution peaks at 180° as expected, however the preliminary distribution using 30 events from E653 is intriguingly flat.

$D^0\overline{D}^0$ MIXING

The rate for $D^0\overline{D}^0$ mixing, r, can be defined by

$$r = \frac{\Gamma(D^0 \to \overline{D}^0 \to X')}{\Gamma(D^0 \to X)} \approx \frac{(\Delta m/\Gamma)^2}{2} \qquad (\frac{\Delta m}{\Gamma} \ll 1, \frac{\Delta\Gamma}{\Delta m} \ll 1)$$

Using the box diagram, the standard model predicts $\Delta m/\Gamma = 10^{-6}$—$10^{-4}$. However, Wolfenstein[3] has pointed out that larger mixing may result if contributions from intermediate hadronic states add coherently and this gives a probable value of $\Delta m/\Gamma \sim .02$ and a limit of $\Delta m/\Gamma < 0.1$. This further translates into $r \sim 2\text{x}10^{-4}$, definitely $r < 5\text{x}10^{-3}$.

Experimentally, there are three methods employed to search for mixing. The obvious technique, of looking for D^0D^0 pairs (or $\overline{D}^0\overline{D}^0$ pairs) is used only by the Mark III experiment. Mark III observe[4] 3 events possibly due to mixing out of a total of 224 and on a background of 0.4±0.2 events. This may be interpreted as mixing at the 1.2% level, although doubly Cabibbo-suppressed decays (DCSD) are expected to contribute ~1.1 events.

The other technique, used by ARGUS and E-691, is to look for wrong sign D^0 decays when the D^0 is a D^{*+} product and the slow pion tags the D^0. ARGUS[5] find r < 1.4%. E-691 has the unique advantage that the mixing lifetime dependence would be visible if mixed events occured. The lifetime dependence of DCSD background is simply $e^{-t/\tau}$, while that of mixed events is $\sim t^2 e^{-t/\tau}$. Using this powerful tool for further background reduction, E-691[6] find that r < 0.4% using 1554±54 events in the $K\pi$ decay mode of the D^0. This is in direct contradiction to the Mark III result. Finally, E615 and BCDMS look for same-sign dimuons; however this technique is model-dependent. In any case, with recent values for the production cross-sections and branching ratios, the limits from E615[7] and BCDMS[8] are 2% and 1.2% respectively. These limits leave the E-691 limit of 0.4% as the best limit for $D^0\overline{D}^0$ mixing.

CHARM BARYONS and EXCITED CHARM MESONS

The charm baryons most likely to be found at this time are the weakly decaying Λ_c^+ (cud) and the Σ_c^0, Σ_c^+, Σ_c^{++} triplet which decays to the Λ_c^+. The other weakly decaying baryons, the Ξ_c^0, Ξ_c^+ and Ω_c^0 are also being searched for. The cleanest Λ_c^+ signal comes from the NA32[9] experiment which sees ~136 events in the $pK\pi$ mode and determines the mass of the Λ_c^+ to be 2285.1±0.3 MeV/c^2. E-691[10] also see ~120 events on a larger background in this mode at a mass of 2286.2±1.8 MeV/c^2.

It is easy to combine the observed Λ_c^+ particles with pions in the event and look for Σ_c^0 and Σ_c^{++} particles. This has been attempted by ARGUS,[11] E-691[12] and also E-400.[13] Their results are summarized in table 1. ARGUS and E-691 agree on the $\Sigma_c^0 - \Lambda_c^+$ mass splitting. Further, the ARGUS value for $M_{\Sigma_c^{++}}-M_{\Sigma_c^0}$ agrees with the Quigg, Rosner and Kwong model.[14] E-400, however, is at variance with both agreements and therefore further data is awaited. Finally, it should be noted that WA62[15] may have observed the Ξ_c^+ decay into $\Lambda K^-\pi^+\pi^+$ at a mass of 2460±15 MeV/c^2.

Experiment	$M_{\Sigma_c^0}-M_{\Lambda_c^+}$ (MeV/c^2)	$M_{\Sigma_c^{++}}-M_{\Lambda_c^+}$ (MeV/c^2)	$M_{\Sigma_c^{++}}-M_{\Sigma_c^0}$ (MeV/c^2)
ARGUS	167.0±0.5 σ=2.0 70±19 evts	168.2±0.5 σ=2.0 92±19 evts	1.2±0.7±0.3
E-400	178.2±.4±2. σ=1.4±.3 84±22 evts	167.4±.5±2.1 σ=1.2±.3 46±13 evts	1-0.8±3.0
E-691	168.4±1.0±0.3 σ=2.4±0.3 14±4 evts	5±3 evts	

Table 1. Σ_c observations.

The orbital angular momentum of the L=1 excited D mesons combines with S=0,1 to give rise to four different states. The masses of these states increase with increasing J, and the widths get correspondingly narrower in most models. The 0^+ and 2^+ states can decay to $D\pi$, while the 1^+ and 2^+ states can decay into $D^*\pi$. ARGUS[16] (and CLEO) observed a $D^{*+}\pi^-$ state with mass M=2426±6 MeV/c^2 and width Γ=75±20 MeV/c^2. This could be an overlap of 1^+ and 2^+ states. The $D\pi$ states are better separated and the 2^+ state is expected to be narrower. E-691[17] has reported a state which could fit this description: a $D^+\pi^-$ resonance at 2458.2±3.4 MeV/c^2 and Γ=22.9±7.9 MeV/c^2, a $5\frac{1}{2}\sigma$ signal. E-691 also confirms the presence of the D^{**0} seen by ARGUS and CLEO.

CHARM DECAYS

Charm decays can be broadly classified as leptonic, semi-leptonic and hadronic. Only the D^+ and D_s^+ can decay into leptons alone ($e^+\nu_e$, $\mu^+\nu_\mu$ or $\tau^+\nu_\tau$). The largest leptonic branching ratio is for the D_s^+ to decay into the $\tau^+\nu_\tau$ (~1.5% see, for example, ref. 18). Similarly, the branching ratio for the decay $D^+ \rightarrow \mu^+\nu_\mu$ is ~.014%. While this is the same order of magnitude as the Mark III[19] limit of 7.2x10^{-4}, it is clear that a much higher statistics is needed to get to the prediction.

A study of semileptonic decays on the other hand, offers much more prospect of reward. This is because semileptonic branching ratios are large (~10%), but these decays do not suffer from the problems afflicting hadronic decays, viz., the complications due to exchange, annihilation and colour suppression diagrams and due to final-state interactions. In the naive spectator

model, there are five open channels for decay (3 colours of the lightest $q\bar{q}'$ pair, $e\nu$ and $\mu\nu$). This leads to a BR = 20%. Non-leptonic channels are enhanced due to hard gluon contributions, leading to B(D→lνX)≈15%, a value that is indeed observed.

The differential distribution for the decay $D^0 \to K^- e^+ \nu_e$ is governed by

$$\Gamma \sim G^2 |V_{cs}|^2 |f_+(t)|^2 \qquad times \quad kinematic \quad factors$$

where $t \equiv m^2_{e\nu} = (p_D - p_K)^2$ and

$$f_+(t) = f_+(0) \frac{M^2_{D_s^*}}{M^2_{D_s^*} - t}$$

is a form-factor related to the mass of the D_s^*. E-691 has observed this decay for D^0s from D^{*+} decays using two techniques. The first technique uses the known D^0 direction, constrains its mass and forms a mass peak for the D^{*+}. In the second technique, one looks for an enhancement in a $m_{K\pi e}$ vs. m_{Ke} mass plot when comparing the right sign to the wrong sign. Results for the branching ratio from the two methods agree well and the second method is, in fact, insensitive to radiative corrections. The final result is[20]

$$\frac{\Gamma(D^0 \to K^- e^+ \nu_e)}{\Gamma(D^0 \to K^- \pi^+)} = 0.91 \pm .07 \pm .11$$

This is in good agreement with the Mark III[21] value of 0.93±.20±.16 for the above ratio. The first method also yields the t distribution. E-691 finds $M_{D_s^*} = 2.1^{+.3}_{-.2}$GeV/c^2, in good agreement with the direct Mark III[22] result of $M_{D_s^*} \sim 2.11$GeV/c^2. Finally, using $|V_{cs}|$=0.975, E-691[20] find that $|f_+(0)| =$ .73±.05±.07.

Unlike the decays of pseudoscalar charm mesons, vector meson decays involve three form-factors and are therefore more complicated. However, they form the only independent test of the models for form factor evaluation. E-691 has attempted to extract a signal for the decays $D^+ \to \overline{K}^{*0} e^+ \nu_e$. Since there is no small-Q-value trick to be used as in the D^0 case, the technique used is to make very tight cuts on the K, π and e identification, on a good Kπe vertex and on the primary-secondary vertex separation. The background is available directly from the data: by simply looking at the wrong sign Kπe combinations.

Among other checks, the effective "lifetime" of the Kπe can be compared to Monte Carlo predictions and the agreement is excellent.

Figure 1 shows the right and wrong sign Kπe mass distributions from E-691.[23] The evidence for a signal is clear. The signal is almost entirely due to $D^+ \to \overline{K}^{*0} e^+ \nu_e$, the non-resonant contribution being virtually negligible. The ratio of branching ratios $B(D^+ \to \overline{K}^{*0} e^+ \nu_e)/B(D^+ \to K^- \pi^+ \pi^+) = 0.49 \pm 0.04 \pm 0.05$. Combining this with the $B(D^0 \to K^- e^+ \nu_e)$, one finds that the ratio of transition rates

$$\Gamma(D^+ \to \overline{K}^{*0} e^+ \nu_e)/\Gamma(D^0 \to K^- e^+ \nu_e) = 0.45 \pm 0.09 \pm 0.07$$

which is about half the theoretically expected value. A study of the distribution of the angle θ between the K^* decay pion and the D^+ direction in the K^* frame indicates a large longitudinal polarization of the $\overline{K}^{*0}$:

$$\Gamma_L/\Gamma_T = 2.4^{+1.7}_{-0.9} \pm 0.2$$

This is evident from the $\cos(\theta)$ distribution displayed in figure 2.

Finally, we turn to non-leptonic decays. As these dominate the total width (or lifetime) of charmed particles it seems appropriate to recall that precision measurements of the charm meson lifetimes have been made by the E-691 group[24]. E-691 have also reported the Λ_c^+ lifetime[10] to be $0.22 \pm .03 \pm .02$ ps, in good agreement with the new NA32 result[25] $0.20 \pm .02$ ps. Theoretically, one expects the ratio of lifetimes for the other weakly decaying charm baryons to be[26]

$$\tau(\Omega_c^0) : \tau(\Xi_c^0) : \tau(\Lambda_c^+) : \tau(\Xi_c^+) = 0.6 \quad : \quad 0.6 \quad : \quad 1 \quad : \quad 1.6$$

Experimentally, only the Ξ_c^+ and the Ω_c^+ have been observed[27] and therefore precise lifetimes await a high-statistics experiment.

Much more progress has been made however, on the general issue of non-leptonic decays. The lifetime differences and ratios of branching ratios of various modes are used along with (mostly) tree-level diagrams to explain features of non-leptonic decays. Most importantly, workers in the field have tried to pin down the relative importance of W-annihilation, W-exchange, interference, colour suppression, final-state interactions and resonant structure. Interference in the two D^+ decay diagrams explains the long D^+ lifetime and the hierarchy of D meson lifetimes while explaining the equality of their semileptonic

decay widths. It remains to be seen if the hierarchy of charm baryon lifetimes demands such an explanation. Evidence for W-annihilation, W-exchange and colour suppression seems to be mostly absent. However, final-state interactions and two-body diagrams both seem to play a large role.

In conclusion, it is clear that the field of charm physics is maturing. This means that many basic questions have been answered (lifetimes, production) while raising new questions in turn (explanation of lifetime hierarchies, mixing limits etc.). Experimental measurements on charm baryons, $D^0\overline{D}^0$ mixing, leptonic and semileptonic decays, rare non-leptonic decays and charm pair production are awaited. Fermilab experiment E-791 aims to collect and analyze 20 times the E-691 charm sample in late 1989[28] and should answer most of these questions.

ACKNOWLEDGEMENT

I would like to thank Prof. R. J. Morrison for valuable discussions on semileptonic decays.

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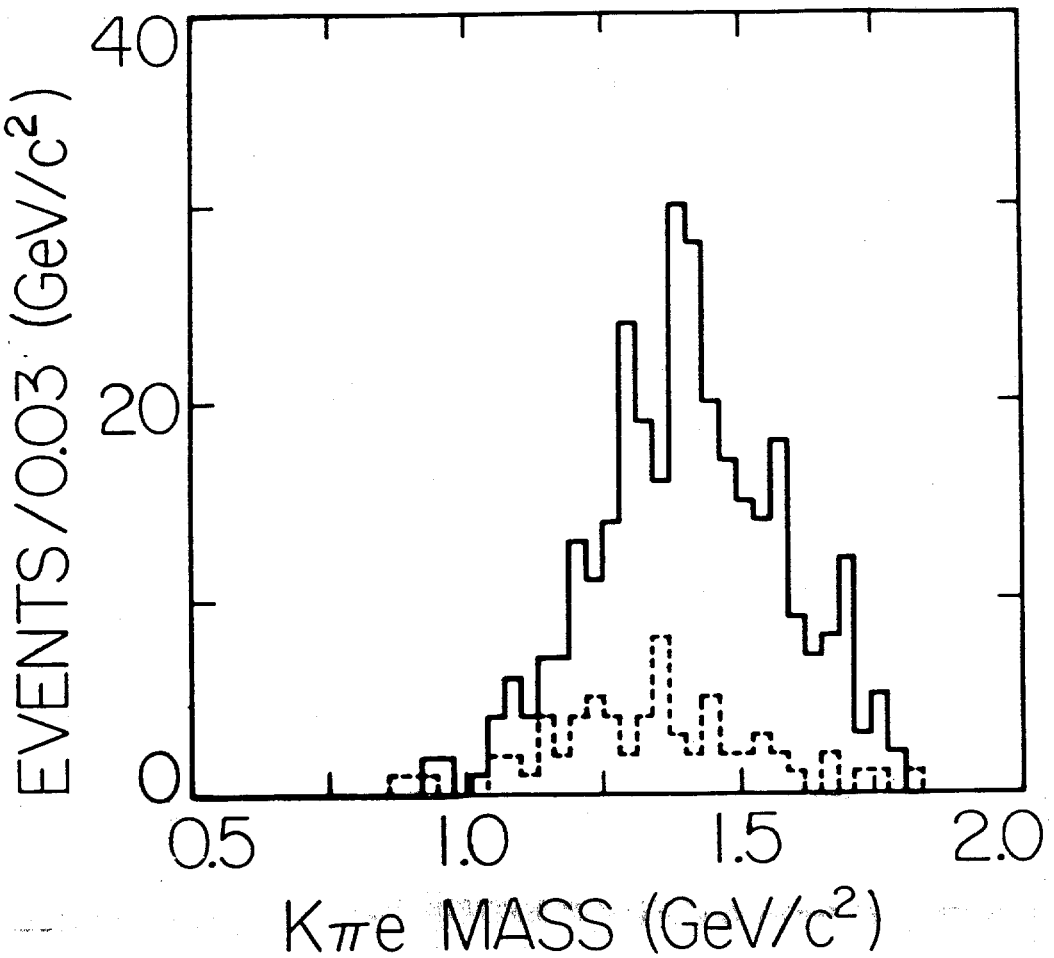

Figure 1. Right and wrong sign $K\pi e$ mass distributions from E-691. The much larger right-sign distribution is evidence for the $D^+ \rightarrow \overline{K}^{*0} e^+ \nu_e$ decay.

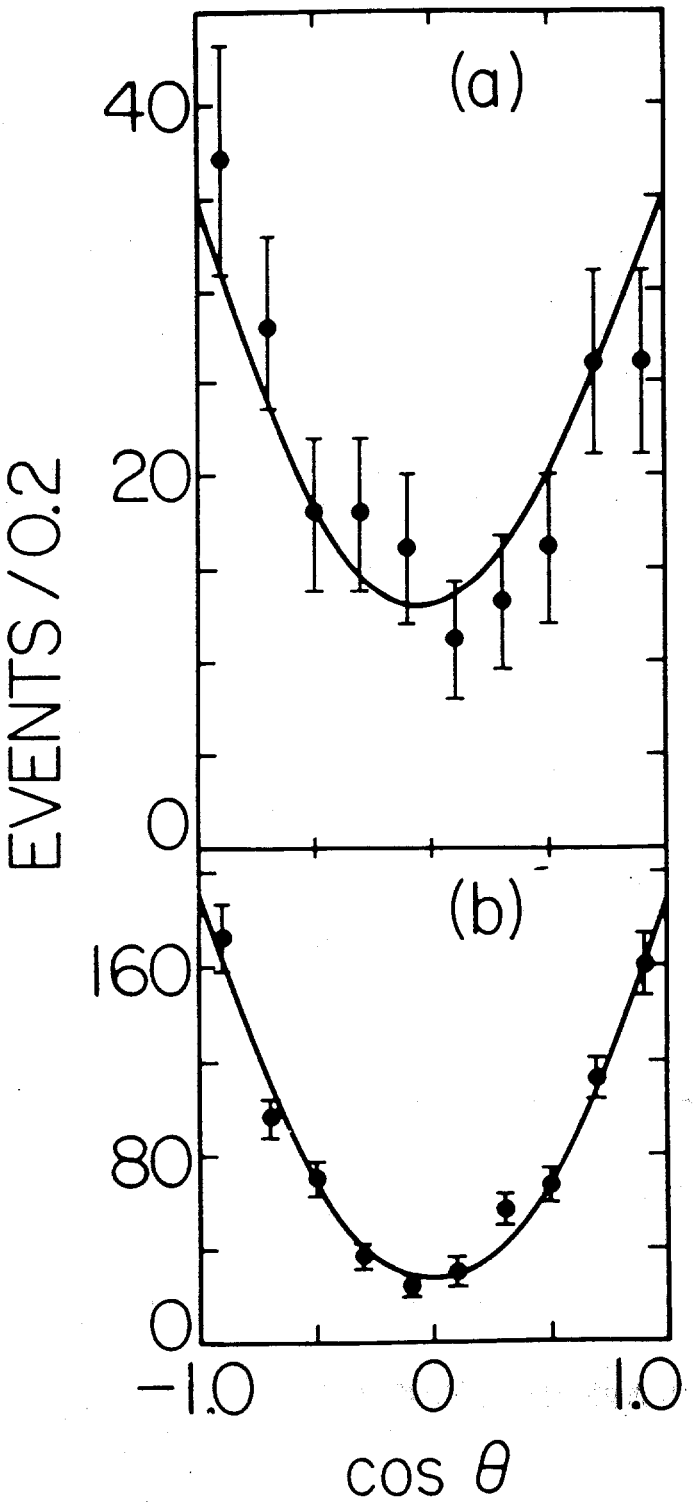

Figure 2. The distribution of the angle θ between the K^* decay pion and the D^+ direction in the K^* frame from E-691 shows large longitudinal polarization of the K^*.