Forward Cross-sections for Production of D^+, D^0, D_s, D^{*+}, and Λ_c in 250 GeV $\pi^\pm$, $K^\pm$, and $p-$Nucleon Interactions

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Abstract

We measure forward ($x_F > 0$) cross-sections for production of D^+, D^0, D_s, D^{*+}, and Λ_c in collisions of $\pi^\pm$, $K^\pm$, and p on a nuclear target. Production induced by different beam particles is found to be the same within statistics. Strange and baryonic final states are seen to make an appreciable contribution to the total charm cross-section, which our measurements indicate is larger than but not inconsistent with next-to-leading order (NLO) QCD predictions. The energy dependence mapped out by these measurements, together with previous ones, is also consistent with current theory. Measurements of leading-particle asymmetries for K and p-induced charm production are also presented.

13.85.Ni, 12.38.Qk, 25.40.Ve, 25.80.-e

The absolute cross-section for charm production in high-energy hadronic interactions, despite more than twenty years of experimental activity, remains an issue of considerable interest. Early cross-section measurements are characterized by orders-of-magnitude discrepancies. Results from modern experiments (i.e. capable of full mass reconstruction and/or decay vertex detection) are relatively few in number and, although agreement among them has improved, still suffer from low statistics and large systematic errors [1]. The $c\bar{c}$ cross-sections for collisions of light hadrons (π, K, p) on nuclei are an independent test of assumptions underlying perturbative QCD predictions for heavy-quark production, which for even the heavier b system are not well-established [2]. In addition, it has been proposed that enhanced production of charm above this baseline might be used as an indicator and probe of quark-gluon plasma formation in heavy-ion collisions [3].

In this Letter we report Fermilab E769 measurements of forward cross-sections for the hadronic production of D^+, D^0, D_s, D^{*+}, and Λ_c. E769 data, obtained with mixed beams of hadrons, provides unique information on the beam dependence of charm production. In addition to significant high-statistics contributions to current knowledge on π^- and p-induced production, we present the first precise K^- beam measurements as well as the only measurements for π^+ and K^+. For K and p beams, these results also include measurements of leading-particle asymmetries, with the effect of a leading strange quark addressed for the first time. (A leading charm particle is defined, for $x_F > 0$, as one which shares at least one light quark or antiquark flavor with the beam particle.) Results on the beam dependence of D meson differential cross-sections are presented in a concurrently-submitted Letter [4].

Using collisions of mixed hadron beams on a multifoil target (Be, Cu, Al, W), E769 collected $\sim$400 million physics events at the TPL Spectrometer during the 1987-88 fixed target run. Transverse-energy triggers were used to enhance the charm content of the recorded data set. Detailed descriptions of our apparatus, triggers, event reconstruction, and secondary vertex filter are found in [5] and references quoted therein.

E769 conducted runs with 250 GeV mixed secondary beams of both signs; some 15% of the negative beam data was taken at 210 GeV. The negative beam consisted of 93% π^-, 5% K^-, and 1.5% $\overline{p}$, the positive of 61% π^+, 4.4% K^+, and 34% p. Event-by-event beam particle identification was accomplished through the use of a differential Čerenkov counter (DISC) [6] and a transition radiation detector (TRD) [7], the latter for the positive beam only. The DISC, which identified beam particles with an efficiency of about 40%, was set to tag kaons (either kaons or protons) in the negative (positive) running. A trigger on DISC output was used to enhance the fraction of K and p beam events in the data sample. If for a particular event in the positive running the DISC did not positively identify the beam particle, the TRD was used to distinguish pions from protons or kaons with a typical efficiency of 87%. Data samples used in this analysis were required to satisfy beam particle identification criteria corresponding to at least a 90% probability of correct tagging, resulting in the low beam contaminations listed in Table I.

For the present analysis, the following decays are fully reconstructed:

$$D^+ \rightarrow K^-\pi^+\pi^+, \tag{1}$$

$$D^0 \rightarrow K^-\pi^+, \tag{2}$$

$$D_s^+ \rightarrow \begin{cases} \phi\pi^+,\ \phi \rightarrow K^+K^- \\ \overline{K}^*(892)^0 K^+,\ \overline{K}^{*0} \rightarrow K^-\pi^+, \end{cases} \tag{3}$$

$$D^{*+} \rightarrow D^0\pi^+,\ D^0 \rightarrow K^-\pi^+, \tag{4}$$

$$\Lambda_c^+ \rightarrow pK^-\pi^+. \tag{5}$$

Throughout this paper charge conjugate decays are also implied.

With the exception that D^*'s are reconstructed using only the $K\pi$ decay mode of the D^0, analyses for all D mesons are substantially unchanged from those described in [4,5,8]. Analysis cuts for the $\Lambda_c \rightarrow pK\pi$ decay mode are similar to those used for the D^+, with additional cuts being placed on the Λ_c lifetime ($< 5\tau_{\Lambda_c}$) and Čerenkov identification probabilities of the decay pion and proton. Invariant mass plots for the D^+, D^0, D_s, and Λ_c are shown in Fig. 1; signals for all beams are combined.

Binned maximum-likelihood fits to Gaussian signals of fixed widths (centers fixed at

PDG masses [9]) with linear or quadratic backgrounds were performed on the mass plots for each beam in order to obtain signal estimates. The final event totals are 994 ± 47 D^+, 847 ± 55 D^0, 100 ± 15 D_s, 209 ± 19 D^*, and 35 ± 9 Λ_c. An approximate breakdown of these signals by beam particle follows: 49% π^-, 17% π^+, 5% K^-, 13% K^+, and 16% p.

Acceptances were calculated using a complete Monte Carlo simulation of the experiment, as described in [5]. The simulation models the effects of the resolution, geometry, and efficiency of the spectrometer components, efficiencies associated with the transverse-energy triggers and data acquisition system, and all analysis cuts. Monte Carlo events were weighted to give them our measured (or plausible, in the case of Λ_c) x_F and p_T distributions [4] and PDG lifetimes [9]. Excluding efficiencies due to beam-particle identification and data acquisition, acceptances for the D mesons ranged from 2 to 6% and were a factor of ten lower for the Λ_c.

Systematic errors on the cross-sections include those due to uncertainties in differential distributions (0-2%), lifetimes (1-6%), drift chamber efficiencies (0-2%), Čerenkov identification efficiency (4-8%), and trigger efficiencies (0-1%). Other systematics include uncertainties in the signal estimates associated with the fitting procedure (1-9%), data acquisition livetime (2%), and fractional $\pi/K/p$ composition of the positive beam (5-9%).

Cross-section results are given in Table II. PDG branching fractions [9] are used to obtain cross-sections; errors on these (4-14%) are not included in the tabulated systematic errors. Linear dependence of the cross-section per nucleus on target atomic mass is assumed, consistent with recent findings [8,10–12]. No significant beam dependence in the cross-section totals is found, suggesting that at least comparable fractions of pion, kaon, and proton momenta are carried by gluons. By combining π^- and π^+ beam results and summing over weakly-decaying species, we obtain our most precise partial measure of the charm plus anticharm particle cross-section ($x_F > 0$): $15.8 \pm 1.3 \pm 0.9 \mu$b/nucleon. Forward production of Λ_c, the lightest of the charm baryons, is evidently not suppressed with respect to D^+ at this energy. In fact, there is some indication that the former is favored in collisions of protons on nuclei. This and the significant D_s cross-section make it probable that undetected (including charm strange) baryonic species contribute appreciably to the total charm cross-section. Our D_s and Λ_c cross-sections are consistent with those measured by ACCMOR with a 230 GeV π^- beam: $1.4 \pm 0.2 \pm 0.2\,\mu$b/nucleon and $4.1 \pm 0.5 \pm 0.7\,\mu$b/nucleon, respectively [13,14].

In Figs. 2 and 3, we compare E769 results for π^- and p-induced production of charm mesons (D^+, D^-, D^0, and $\overline{D}^0$) to results of previous experiments [13,15–17] as a function of beam energy. These latter cross-section values have been adjusted where necessary to correspond to current PDG branching fractions and their systematic errors changed accordingly. Also plotted are NLO QCD predictions for the total charm plus anticharm particle forward cross-section; these are obtained by multiplying the $c\bar{c}$ cross-section, generated using the program of Mangano *et al.* [18], by a factor of 2 and requiring the c quark to have $x_F > 0$. HMRSB (SMRS2) parton distribution functions are assumed for target nucleons and beam protons (pions) [19], and theoretical parameters have been set to the default values used in [20]. An underestimate of the theoretical uncertainty has been obtained by varying the renormalization scale; other contributions, most notably those due to uncertainties in the charm quark mass and factorization scale, are expected to be at least as large [20].

If fragmentation is assumed to be constant as a function of energy, the energy dependence of D meson cross-sections can be directly compared to the theory for quarks; the agreement over the energy range shown appears reasonable. Allowing for unseen charm species, it is evident that the NLO QCD central prediction for the total charm cross-section is low by about a factor of three. Given the huge latitude in normalization allowed by the current state of theory, however, this discrepancy is not particularly telling. It is interesting, nevertheless, to note that the $b\bar{b}$ cross-section predicted by QCD is also low compared with measurements [2].

One aspect of hadroproduction which cannot be treated perturbatively is the leading-particle effect. The leading-particle asymmetry A is defined as

$$A \equiv \frac{\sigma(\text{leading}) - \sigma(\text{nonleading})}{\sigma(\text{leading}) + \sigma(\text{nonleading})} \tag{6}$$

where $\sigma(x)$ is the number of x events divided by the acceptance, as a function of x_F, integrated over $x_F > 0$. Measured values of A for production of various charm particles for K and p beams are shown in Table III. The asymmetry induced by a leading s quark is found to be consistent with that of the lighter quarks, while enhancement of leading production of Λ_c appears to be quite pronounced. These A values should be compared with our previously-published π beam results, $A_{D+} = 0.18 \pm 0.06$ and $A_{D^*} = 0.09 \pm 0.06$ [5,8,21].

In summary, we have measured forward production cross-sections for a number of charm particles, which taken together constitute the bulk of the total charm cross-section. These results, obtained for five beam-particle types, provide new information on the gluon structure of these initial-state hadrons. Our results, together with previous data, are consistent with the energy dependence predicted by perturbative QCD. Our measured cross-sections are higher than but consistent with theory.

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FIGURES

FIG. 1. Invariant mass distributions for (a) $D^+ \to K^-\pi^+\pi^+$, (b) $D^0 \to K^-\pi^+$, (c) $D^+, D_s^+ \to K^-K^+\pi^+$ (combined $\phi\pi$ and K^*K modes), and (d) $\Lambda_c^+ \to pK^-\pi^+$. Charge conjugates are also implied.

FIG. 2. $\sigma(\pi^-N \to DX,\ x_F > 0)$, $D = D^+, D^-, D^0$, and $\overline{D}^0$. Measured values for E769 and previous experiments [13,15,17] compared to NLO QCD prediction [18] for total forward $c\bar{c}$ production. The band bordered by the dotted lines is an underestimate of the theoretical uncertainty in the central value represented by the solid line. Error bars include branching fraction uncertainty.

FIG. 3. $\sigma(pN \to DX,\ x_F > 0)$, $D = D^+, D^-, D^0$, and $\overline{D}^0$. See explanation in Fig. 2 caption. Here, cross-sections shown for NA27 [15], E743 [16], and E653 [17] are 50% of values published for all x_F.

TABLES

TABLE I. Beam contaminations.

Beam	π	K	$p, \overline{p}$
π^-	–	3.8%	1.5%
K^-	1.0%	–	0.0%
π^+	–	0.0%	0.6%
K^+	0.1%	–	0.0%
p	0.3%	4.8%	–

TABLE II. Charm meson and baryon hadroproduction forward cross-sections. Cross-sections shown are the sum of particle and antiparticle contributions. The beam energy is 250 (210) GeV for cross-sections without (with) parentheses. Errors quoted are statistical and systematic, in that order, and do not include branching fraction uncertainties. Inequalities are given for 90% confidence level lower and upper limits.

	σ (μb/nucleon), $x_F > 0$				
Beam	D^+	D^0	D_s	D^{*+}	Λ_c
π^-	$3.6 \pm 0.2 \pm 0.2$	$8.2 \pm 0.7 \pm 0.5$	$2.1 \pm 0.4 \pm 0.2$	$2.7 \pm 0.3 \pm 0.2$	$> 1.7, < 5.2$
	$(1.7 \pm 0.3 \pm 0.1)$	$(6.3 \pm 0.9 \pm 0.3)$			
π^+	$2.6 \pm 0.3 \pm 0.2$	$5.7 \pm 0.8 \pm 0.4$	$2.0 \pm 0.6 \pm 0.2$	$3.1 \pm 0.5 \pm 0.3$	$> 1.7, < 10.6$
$\pi^\pm$	$3.2 \pm 0.2 \pm 0.2$	$7.2 \pm 0.5 \pm 0.4$	$2.0 \pm 0.4 \pm 0.2$	$2.8 \pm 0.3 \pm 0.2$	$3.3 \pm 1.1 \pm 0.5$
K^-	$3.3 \pm 0.7 \pm 0.2$	$7.6 \pm 2.0 \pm 0.4$	$> 0.9, < 4.2$	$> 0.4, < 2.3$	$> 1.1, < 9.9$
	$(3.3 \pm 1.0 \pm 0.2)$				
K^+	$2.9 \pm 0.4 \pm 0.1$	$7.0 \pm 1.2 \pm 0.4$	$3.3 \pm 1.0 \pm 0.5$	$1.9 \pm 0.6 \pm 0.1$	$> 0.4, < 4.5$
$K^\pm$	$3.0 \pm 0.3 \pm 0.2$	$7.2 \pm 1.0 \pm 0.4$	$3.0 \pm 0.8 \pm 0.3$	$1.7 \pm 0.5 \pm 0.1$	$> 0.4, < 4.4$
p	$3.2 \pm 0.4 \pm 0.3$	$5.6 \pm 1.3 \pm 0.5$	$> 0.5, < 2.5$	$1.8 \pm 0.6 \pm 0.1$	$> 5.0, < 21.2$

TABLE III. Leading-particle asymmetries (A, defined in text). Inequalities are given for 90% confidence level lower limits.

Beam	Particle	A
K	D_s	0.25 ± 0.11
	Λ_c	> 0.6
p	D^+	0.18 ± 0.05
	D^0	0.06 ± 0.06 [a]
	D^{*+}	0.36 ± 0.13
	Λ_c	> 0.6 [b]

[a]While the flavor of the light quark involved in production depends on whether the D^0 is directly produced or results from a D^* decay, for p beam its leading/nonleading character does not.

[b]Production of the Λ_c^+ for p beam is *doubly* leading, diquarks possibly playing a role.