Charm Photoproduction

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(Received 14 September 1988)

We present results on the photoproduction of 10000 charmed particles from the 10^8 recorded triggers of Fermilab experiment E691. The total cross section for the photoproduction of D^0 and D^+ particles (and antiparticles) for $x_F > 0.2$ is measured to be $3.88 \pm 0.06 \pm 0.40$ μb/Be nucleus at $\langle E_\gamma \rangle = 145$ GeV. We have also measured the relative production of different charmed particles, their p_T^2 and x_F distributions, and the energy dependence of the total charm cross section. The mean p_T^2 is 1.16 ± 0.04 GeV$^2/c^2$ and the ratio of charm cross sections at 200 and 100 GeV is 1.96 ± 0.24. Results of fits to the x_F distribution are also reported.

PACS numbers: 13.60.Le, 13.60.Rj

The photoproduction of charm is simply described in leading-order QCD by the photon-gluon fusion model.[1] This model has several attractive features. There is only one structure function involved, viz., the gluon structure function which enters to first order as does the QCD coupling constant α_S. In the photoproduction there are no leading-particle effects as there are not extra quarks within the photon. Finally, the next-to-leading-order corrections are expected to be smaller than for hadronproduction. In addition to the simple description afforded by this model, it is also true that at Fermilab energies, photons produce a factor of 5–10 more charm (as a fraction of the hadronic cross section) than do hadrons. In this paper we present results on the production and fragmentation of charm.

Our charm-production experiment, E691, collected data using the Tagged Photon Spectrometer at Fermilab. The photons ranged in energy from 80 to 230 GeV ($\langle E_\gamma \rangle = 145$ GeV), and were incident on a beryllium target followed by a high-resolution silicon-microstrip vertex detector and a spectrometer.[2] A review of previous fixed-target charm-photoproduction experiments can be found in Ref. 3.

A study of production mechanisms requires measurement of the energy of each photon. Our photon beam was created by the bremsstrahlung of electrons whose energies were measured both before and after radiating, thereby providing a measurement of the energy of the beam photons ($\sigma_E/E \approx 0.8$). The electron tagging failed for approximately 23% of our charm events due to the combined effect of acceptance, counter inefficiencies, and the difficulty of reconstructing multiple showers. These events have been entirely removed from those analyses that depend on the energy measurement.

A total of 10^8 triggers were recorded of which 11% required just the presence of hadronic interactions. The remaining 89% were triggers with a high global transverse calorimetric energy, E_T. Using the interaction trigger events, we measured the efficiency of the E_T trigger, for both charm as well as noncharm events, to be $(79 \pm 2)\%$ and $(31 \pm 1)\%$, respectively.

In this study, we pay particular attention to the high-statistics modes $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^+\pi^+\pi^-$, and $D^+ \to K^-\pi^+\pi^+$. We also report some results on the modes $D_s^+ \to \phi\pi^+$, $D_s^+ \to \bar{K}^{*0}K^+$, and $\Lambda_c^+ \to pK^-\pi^+$. (Charge-conjugate states are included throughout this paper unless otherwise stated.)

The number of events in each mode was determined from the mass distribution by a fit to a Gaussian signal shape plus a linear background in the immediate neighborhood of the mass peak. For the total charm cross-section ($\sigma_{c\bar{c}}$) measurement we used only events with a

TABLE I. Cross sections and antiparticle/particle ratios (R) for the high-statistics modes. The cross sections are the sum of the particle and antiparticle cross sections.

Particle	Mode	Raw signal	R	Branching ratio used[a] (%)	σ on Be ($x_F > 0.2$) (μb)
D^0	$K^-\pi^+$	4252 ± 92	1.08 ± 0.03	$4.2 \pm 0.4 \pm 0.4$	$2.42 \pm 0.05 \pm 0.39$
D^{*+}	$D^0\pi^+$	988 ± 34	1.15 ± 0.07	55.5 ± 4.5	$1.37 \pm 0.05 \pm 0.25$
	$D^0 \rightarrow K^-\pi^+$			$4.2 \pm 0.4 \pm 0.4$	
D^{*+}	$D^0\pi^+$	1267 ± 47	1.23 ± 0.07	55.5 ± 4.5	$1.60 \pm 0.06 \pm 0.31$
	$D^0 \rightarrow K^-\pi^+\pi^+\pi^-$			$9.1 \pm 0.8 \pm 0.8$	
D^+	$K^-\pi^+\pi^+$	4864 ± 109	1.04 ± 0.3	$9.1 \pm 1.3 \pm 0.4$	$1.34 \pm 0.03 \pm 0.23$

[a]Reference 7.

charm particle above $x_F = 0.2$. A Monte Carlo simulation based on photon-gluon fusion and the Lund model[4] for hadronization followed by a detailed simulation of the detector was used to correct for the acceptance. We then corrected for the efficiency of the E_T trigger, the fraction of events when the tagging failed, and the experimental dead time. The charm cross sections were obtained by multiplying the ratio of the number of charm events to the number of hadronic events by the total hadronic cross section[5,6] of 861 ± 40 μb per Be nucleus.

Systematic errors in the acceptance (obtained from the Monte Carlo simulation) were estimated by varying the cuts used in isolating charm events. Typical cuts were a 5σ minimum on the separation of charm and primary vertices, a minimum joint Čerenkov probability for particle identification of 20%, and the requirement that the charmed particle pass within 80 μm of the primary vertex. The Monte Carlo simulation of the detector was tuned to both charm and noncharm data. Particular attention was paid to the per-plane tracking efficiencies (within 1% of the data), Čerenkov identification, and calorimeter simulations which used shower shapes from data. The agreement between the D^{*+} cross section measured in two different modes (see Table I) is further evidence that the Monte Carlo program provided a good simulation of the detector.

Cross sections for producing charmed particles are listed in Tables I and II. The sum of the D^0, $\bar{D}^0$, D^+, and D^- cross sections in the range $x_F > 0.2$ was measured to be $3.88 \pm 0.06 \pm 0.40$ μb. Note that the D^0 cross section is averaged over the two decay modes listed.

TABLE II. Cross section times branching ratios (σB) and antiparticle/particle ratios (R) for the D_s^+ and Λ_c^+. The σB are the sum of the particle and antiparticle σB's.

Particle	Mode	Raw signal	R	σB on Be ($x_F > 0.2$) (nb)
D_s^+	$\phi\pi^+ + \bar{K}^{*0}K^+$	203 ± 17	0.92 ± 0.14	$25.0 \pm 2.2 \pm 1.9$
Λ_c^+	$pK^-\pi^+$	101 ± 13	0.79 ± 0.17	$40.4 \pm 5.4 \pm 5.1$

Our Monte Carlo simulation, which agrees well with the data in the measured x_F region, predicts that 45% of the cross section lies below $x_F = 0.2$ giving $7.06 \pm 0.11 \pm 0.72$ μb per Be nucleus for all x_F. After adding the estimated 21% of the cross section that goes towards producing other charmed particles (according to our Monte Carlo simulation) and then dividing by 2 we determined $\sigma_{c\bar{c}}$, the cross section for producing a charm event (2 charm particles per event) to be $4.49 \pm 0.07 \pm 0.46$ μb per Be nucleus. Since the total hadronic cross section has an A dependence[6] of the form A^α where $\alpha = 0.920 \pm 0.002$ and the incoherent cross section for J/ψ production has a similar form[8] with $\alpha = 0.94 \pm 0.02 \pm 0.03$, we assumed that $\alpha = 0.93$ for our case. This leads to a total charm-production cross section per nucleon of 0.58 ± 0.01 ± 0.06 μb at $E_\gamma = 145$ GeV. (If $\alpha = 1$ were chosen instead, we would obtain $\sigma_{c\bar{c}} = 0.50 \pm 0.01 \pm 0.05$.) These numbers are in good agreement with the measurements of the European Muon Collaboration (EMC)[9] and Berkeley-Fermilab-

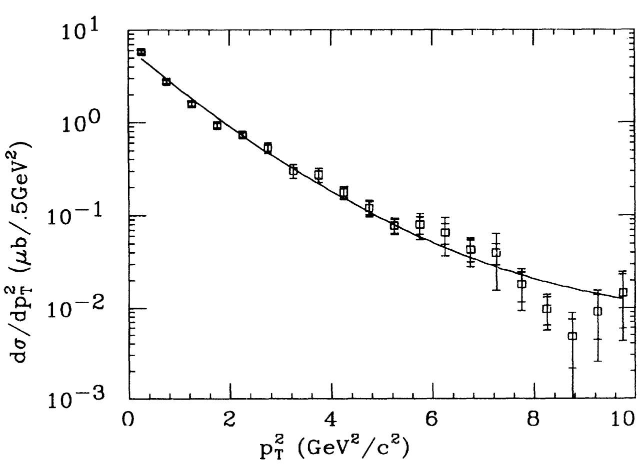

FIG. 1. The p_T^2 dependence of the cross section on Be for all D mesons. The inner error is statistical, and the outer error also includes in quadrature all systematic errors except those which affect only the overall scale. The fitted curve is described in the text.

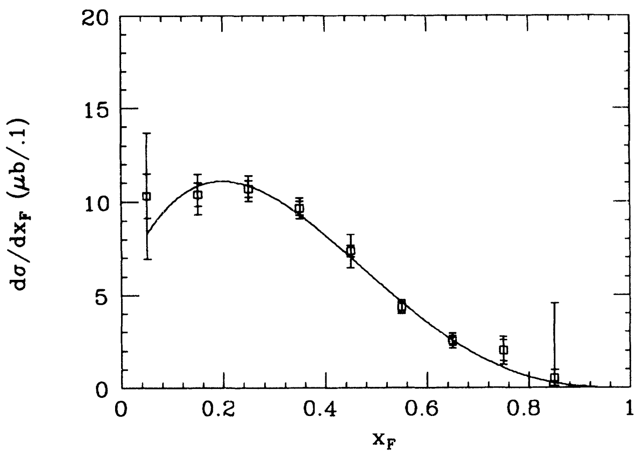

FIG. 2. The x_F dependence of the cross section on Be for all D mesons. The inner error is statistical, and the outer error also includes in quadrature all systematic errors except those which affect only the overall scale. The fitted curve is described in the text.

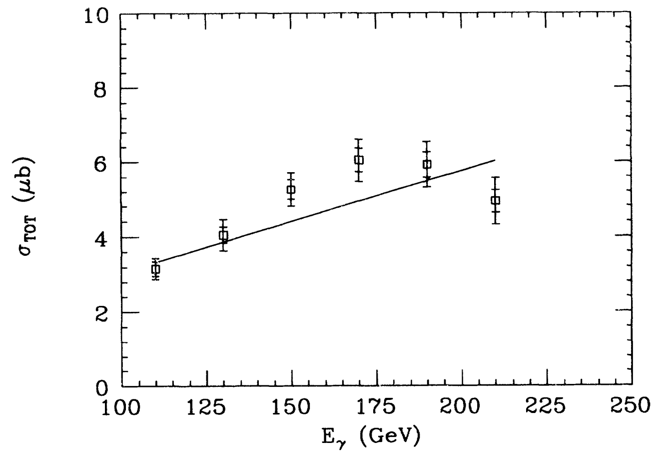

FIG. 3. The E_γ dependence of the cross section on Be for production of charm events ($\sigma_{c\bar{c}}$). The inner error is statistical, and the outer error also includes in quadrature all systematic errors except those which affect only the overall scale. Also shown is a simple linear fit to the data points.

Princeton (BFT) experiments[10] which, when interpolated to our mean energy, yield $\sigma_{c\bar{c}}=0.59\pm0.08$ and 0.67 ± 0.11 μb, respectively. It should be noted the latter are muoproduction experiments and the quoted cross sections involve extrapolation in both Q^2 and A.

Tables I and II also list the ratio of antiparticles to particles, R, in the measured x_F region, $x_F>0$. This ratio for all D mesons (including D^* mesons) is 1.075 ± 0.021. This implies that the amount of associated production (i.e., the fraction of $\bar{D}$'s produced in association with Λ_c^+) at our energies is $(7.5\pm2.1)\%$ (i.e., less than 12% at the 95% C.L.). Further, we found no significant dependence of R on x_F or beam energy.

The fraction of D^0 from D^{*+} is measured to be $0.32\pm0.01\pm0.03$, in good agreement with a simple model in which D^* and D mesons are produced in proportion to the number of spin states available (3:1) which predicts 0.29 ± 0.02 for the ratio. Averaging $\sigma(D^0)$ from both the observed D^0 decay modes, the ratio $\sigma(D^+)/\sigma(D^0)$ is measured to be $0.53\pm0.02\pm0.11$, also in agreement with the above model which predicts 0.41 ± 0.03. For the above calculations we used a world average of the measurements[7] of the branching ratio of the D^{*+} into the D^0, which we computed to be $(55.5+4.5)\%$.

The p_T^2 and x_F distributions and the energy dependence of $\sigma_{c\bar{c}}$ for all D mesons combined were corrected for acceptance and Fermi motion effects. The results are shown in Figs. 1, 2, and 3. The acceptance correction has a slight dependence ($\sim2\%$) on the parameters of the Lund fragmentation function[4] which were varied within their known statistical errors and the Fermi-motion corrections were small. The effects of changing our most important cuts have also been included as systematic errors. Since the energy dependence of the total cross section is obtained by comparing charm events with all hadronic events, uncertainties in the energy dependence of the total hadronic cross section[5,6] are also included as systematic errors.

The mean values of p_T^2 measured for the copious

TABLE III. Results of fits to the p_T^2, x_F, and energy dependence for various modes. The errors on the parameters in the last three columns include systematic errors.

Particle	Mode	$\langle p_T^2\rangle$	α in Eq. (2)	n in Eq. (2)	$\frac{\sigma(200\text{ GeV})}{\sigma(100\text{ GeV})}$
D^0	$K^-\pi^+$	1.13 ± 0.07	27 ± 2	3.35 ± 0.11	2.04 ± 0.40
D^{*+}	$D^0\pi^+$ $D^0\to K^-\pi^+$	1.27 ± 0.13	33 ± 40	3.34 ± 0.39	1.45 ± 0.39
D^{*+}	$D^0\pi^+$ $D^0\to K^-\pi^+\pi^+\pi^-$	1.27 ± 0.16	8 ± 1	2.66 ± 0.48	2.37 ± 0.65
D^+	$K^-\pi^+\pi^+$	1.21 ± 0.06	9 ± 7	2.63 ± 0.35	1.89 ± 0.39
D^0,D^+ mesons		1.16 ± 0.04	14 ± 10	2.95 ± 0.22	1.96 ± 0.24

modes are reported in Table III and are found to be in good agreement with the average for all D mesons (1.16 ± 0.04 GeV$^2/c^2$). The $\langle p_T^2 \rangle$ for the D_s^+ and the Λ_c^+ were measured to be 1.30 ± 0.26 and 0.86 ± 0.21 GeV$^2/c^2$, respectively. The differential cross section $d\sigma/dp_T^2$ is displayed in Fig. 1 and is fitted well by the form

$$d\sigma/dp_T^2 \propto \exp(-bp_T^2 - cp_T^4) , \qquad (1)$$

with $b = 1.07 \pm 0.05$ and $c = -0.04 \pm 0.01$. The x_F distributions were fitted to the form

$$d\sigma/dx_F = A(1 + \alpha x_F)(1 - x_F)^n \qquad (2)$$

and are in good agreement with those generated by the Monte Carlo simulation. The fitted values for the parameters α and n are reported in Table III and the fit for all D mesons is displayed in Fig. 2. The values of n for the D_s^+ and Λ_c^+ are 3.8 ± 1.2 and 4.1 ± 0.5, respectively.

The rise of the charm cross section is quantified as the ratio σ(200 GeV)/σ(100 GeV) (see Table III) and was fitted by a straight line as shown in Fig. 3. The observed rise σ(200 GeV)/σ(100 GeV) $= 1.96 \pm 0.24$ is consistent with the values 1.65 ± 0.50 and 1.44 ± 0.61 measured by the EMC and BFP experiments, respectively.[9,10] The ratio σ(200 GeV)/σ(100 GeV) is 1.3 ± 0.9 for the D_s^+ and also 1.3 ± 0.9 for the Λ_c^+.

In conclusion, we have measured the cross section for photoproduction of D^0 and D^+ particles (and antiparticles) at $\langle E_\gamma \rangle = 145$ GeV to be $3.88 \pm 0.06 \pm 0.40$ μb, from which we deduce the per-nucleon charm-production cross section to be $0.58 \pm 0.01 \pm 0.06$ μb. The mean p_T^2 of D mesons is measured to be 1.16 ± 0.04 GeV^2 and the parameter n in the x_F dependence of the cross section [see expression (2)] is measured to be 2.95 ± 0.22. We have also measured the charm cross section as a function of E_γ and find a rising dependence quantified as σ(200 GeV)/σ(100 GeV) $= 1.96 \pm 0.24$. All the measured quantities are in agreement with our QCD-based Monte Carlo simulation which uses the Lund model for hadronization. Finally, the ratio of $\bar{D}/D = 1.075 \pm 0.021$ for $x_F > 0$, indicating that associated production is small at these energies, in contrast to the up to 70% effect seen at lower energies.[11,12] Our results can be interpreted in the photon-gluon fusion model. We report on those investigations and on the studies of events with two reconstructed charm particles in a forthcoming paper.

We gratefully acknowledge the assistance of the staff of Fermilab and of all the participating institutions. This research was supported by the U.S. Department of Energy, by the Natural Science and Engineering Research Council of Canada through the Institute of Particle Physics, by the National Research Council of Canada, and by the Brazilian Conselho Nacional de Desenvolvimento Científico e Tecnológico. The Fermi National Accelerator Laboratory is operated by the Universities Research Association, Inc. under contract with the U.S. Department of Energy.

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