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Diffractively Produced Charm Final States in 800 GeV/c pp Collisions

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We report the first observation of diffractively produced open charm in 800 GeV/c pp collisions of the type $pp \to pD^{*}X$. We measure cross sections of $\sigma_{\rm diff}(D^{*+}) = (0.185 \pm 0.044 \pm 0.054)\mu b$ and $\sigma_{\rm diff}(D^{*-}) = (0.174 \pm 0.034 \pm 0.029)\mu b$. Our measurements are based on 4.3×10^9 events recorded by FNAL E690 in the fixed target run of 1991. We compare our results with previous fixed target charm experiments and with diffractive hard scattering results from HERA and the Tevatron.

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Diffractive charm hadroproduction received much attention over two decades ago when it was thought to account for the large Λ_c cross sections at forward x_F reported at the CERN ISR [1]. Subsequent agreement between data from higher statistics experiments and improved NLO calculations of perturbative QCD predictions for charm production, however, indicated that diffraction did not play a significant role in hadronic charm production [2]. In 1991, FNAL E653 reported no evidence for diffractively produced charm in 800 GeV/c proton-Si interactions and set an upper limit of $\sigma_{\rm diff}(c\overline{c}) < 26$ μb/Si nucleus [3].

More recently, there has been renewed interest in diffractive heavy flavor production as a means to investigate properties of the pomeron based on the model of Ingelman and Schlein [4]. Recent results from HERA and the Tevatron suggest that the factorization proposed by this model breaks down, and that the pomeron does not possess the simple and universal nature expected. In this paper, we report the first observation of diffractively produced open charm in hadron-hadron collisions. We present a cross section measurement for diffractive charm production in 800 GeV pp collisions and compare our results with the diffractive hard scattering data from experiments at HERA and the Tevatron.

Our measurements are based on data acquired by FNAL E690 during the fixed target run of 1991. E690 was designed to measure beam diffraction reactions of the type $pp \to p_{\rm fast}X$. The experiment used an 800 GeV/c proton beam and a liquid hydrogen target. The apparatus (Fig. 1) consisted of a multiparticle spectrometer and a beam spectrometer. The beam spectrometer measured the trajectory of incoming beam particles and the momentum of scattered beam particles with momentum ≥ 540 GeV/c. The multiparticle spectrometer had an angular coverage of ±580 mrad in the horizontal (bend) direction, and ±410 mrad in the vertical direction. Particle identification was provided by 102 time-of-flight scintillation counters and a 96 cell Cerenkov counter (π threshold = 2.57 GeV/c). The E690 apparatus is described in greater detail elsewhere [6].

Events selected for the cross section measurement are single diffractive dissociation reactions:

$$pp \longrightarrow p(D^{*+} \to (D^0 \to K^-\pi^+)\pi^+)X \qquad (1)$$

$$pp \longrightarrow p(D^{*-} \to (\overline{D}^0 \to K^+\pi^-)\pi^-)X \qquad (2)$$

Candidates for reaction (2) are selected from the 4.3×10^9 events collected by E690, and 3.2×10^9 of these (the subset for which useful time-of-flight information exists) are used for selecting candidates for reaction (1). The following cuts are used: A primary interaction vertex is required within a 13.84 cm long fiducial region of the LH_2 target. The vertex is required to have at least three charged tracks (not counting the scattered beam proton) assigned to it, and the tracks are required to have the correct charges to form a $K^{\mp}\pi^{\pm}\pi^{\pm}$ invariant mass combination. The calculated value of the invariant mass is required to be $|M(K\pi\pi) - 2.010 \text{ GeV/c}^2| < 0.2 \text{ GeV/c}^2$. The two tracks from the D^0 decay are required to be identified by the Čerenkov counter as a K and a π. The Q of the D^* decay (where $Q = M(K\pi\pi) - M(K\pi) - M(\pi)$) is required to be $|Q - 5.83| < 0.5 \text{ MeV/c}^2$. To facilitate comparisons with other analyses, we impose the coherence condition requiring the fractional momentum of the

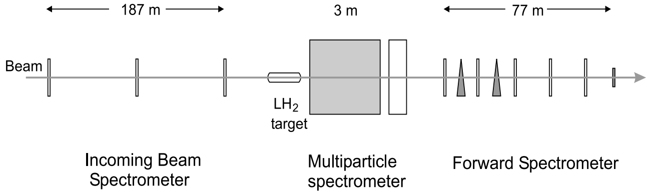

FIG. 1. E690 Spectrometer.

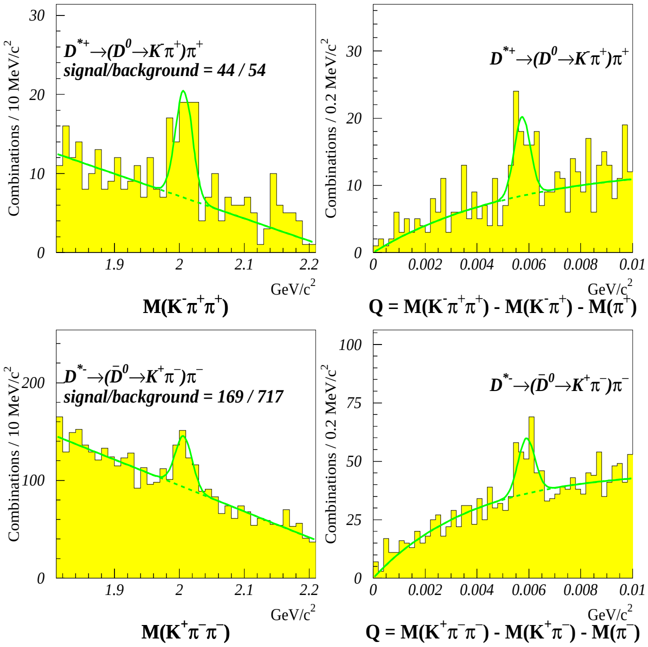

FIG. 2. Histograms in the left column show $K\pi\pi$ invariant mass distributions for events of reactions (1) and (2). Q distributions for these events are shown on the right.

scattered beam proton in the c.m. frame of the initial state protons to be $x_F > 0.85$ [7]. Time-of-flight identification is required on the slow π^+ from D^{*+} decay. This requirement is not imposed on the D^{*-} since background for the slow π^- consists mostly of other π^-'s.

Events meeting these requirements are histogrammed in 10 MeV/c^2 bins of the invariant $K\pi\pi$ mass. Fitting the resulting distributions (Fig. 2, left column) to a Gaussian plus a linear background yields 44 ± 11 events for reaction (1) and 169 ± 32 events for reaction (2). The $M(K\pi\pi)$ invariant masses obtained from these fits are $M(K^-\pi^+\pi^+) = 2.007 \pm .004$ GeV/c^2 and $M(K^+\pi^-\pi^-) = 2.007 \pm .003$ GeV/c^2 for events of reactions (1) and (2) with Gaussian widths of $\sigma = .013 \pm .003$ GeV/c^2 for both cases.

Q distributions for these events are shown on the right of Fig. 2 with the Q cut replaced with a cut on the D^* mass, $|M(K\pi\pi) - 2.010\ \mathrm{GeV/c^2}| < 0.03$ GeV/c^2 and $|M(K\pi\pi) - 2.010\ \mathrm{GeV/c^2}| < 0.01$ GeV/c^2 for events for reactions (1) and (2), respectively. Fitting these Q distributions to a Gaussian plus an exponential ($A(1-e^{-BQ})$) yields $Q = 5.74 \pm 0.1$ MeV/c^2 and $Q = 5.91 \pm 0.08$ MeV/c^2 for the two reactions with Gaussian widths of $\sigma = .3 \pm .06$ MeV/c^2 in both cases.

The p_T^2 distributions of the scattered beam proton p_{fast} for events in the signal region ($|M(K\pi\pi) - 2.010\ \mathrm{GeV/c^2}| < 0.05$) are shown in Fig. 3. These distributions exhibit pronounced forward peaking with slope parameters of $b \sim 8 - 11$ (GeV/c)$^{-2}$ characteristic of hadronic diffraction. They clearly show that the events in this sample are the result of diffractive production. As shown in Fig. 4 for the D^{*+}, the D^* signal is not strongly correlated to the x_F of the scattered proton.

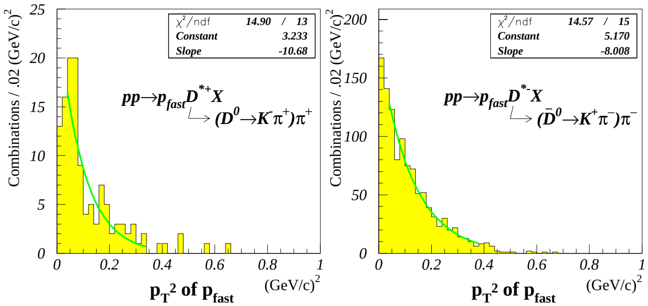

FIG. 3. p_T^2 distributions of the scattered beam proton for events with $|M(K\pi\pi) - 2.010\ \mathrm{GeV/c^2}| < 0.05$

The diffractive D^* production cross section is calculated with the formula:

$$\sigma_{\mathrm{diff}}(D^{*\pm}) = \left(\frac{A}{N_A \rho l}\right) \frac{N_{\mathrm{diff}}^{obs}(D^{*\pm})}{\epsilon_A B_1 B_2 N_{\mathrm{beam}}} \tag{3}$$

with the constants $A = 1.00794$ gm/mole, $N_A = 6.0221367 \times 10^{23}$/mole, $\rho = 0.07492$ gm/cm^3 [8,9], and $l = 13.84$ cm. $N_{\mathrm{diff}}^{obs}(D^{*\pm})$ is the number of observed D^*'s, ϵ_A the D^* acceptance, and N_{beam} the number of beam particles. B_1 and B_2 are the $D^* \to D^0\pi$ and $D^0 \to K\pi$ branching ratios [10].

N_{beam} is determined indirectly from the number of reconstructed Ξ^-'s. Counting Ξ^-'s instead of directly counting beam particles avoids problems associated with trigger inefficiencies and with undercounting beam particles in events with multiple beam protons. Ξ^-'s are identified by their cascade decay to $\Lambda^0\pi^-$. They are required to be associated with a primary vertex in the LH_2 target and to have a proper lifetime greater than 10% of the mean Ξ^- lifetime of 1.639×10^{-10} sec [10]. A total of 446,232 Ξ^-'s are selected by these requirements, corresponding to 1.25×10^{11} incident beam protons.

Acceptance for events of reactions (1) and (2) are calculated using Monte Carlo events generated with POMPYT [11]. In our simulation, the pomeron flux factor is taken to be $f_{I\!P/p}(x_{I\!P}, t) = \frac{1}{2}\frac{1}{\sigma(I\!Pp)}\frac{1}{x_{I\!P}}(6.38e^{8t} + 0.424e^{3t})$ [12] in agreement with our observed p_T^2 distributions in Fig. 3. We use a pomeron made up only of quarks, antiquarks, and gluons, with a structure function $f_{q,g/I\!P}(z) = (1 - R_g)f_{q/I\!P}(z) + R_g f_{g/I\!P}(z)$. We use a gluon fraction of $R_g = 0.54$ determined by CDF from their diffractive W, dijet, and b-quark data [13] and a flat parton density of $f_{q,g/I\!P}(z) = 1/z$ favored by the HERA results [14].

Event generation is followed by a full detector simulation using code specifically written for experiment E690. The output of the detector simulation, which is written in a format identical to that of a real data tape, is subjected to the same track finding, vertex reconstruction, and analysis stages as the real data. ϵ_A, the D^* acceptance, is given by the ratio of reconstructed to generated

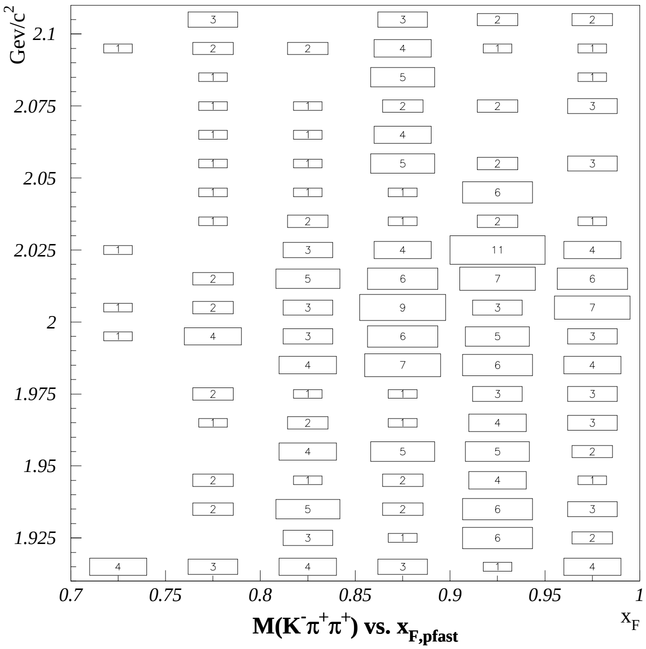

FIG. 4. $K^-\pi^+\pi^+$ invariant mass versus x_F of the scattered beam proton.

D^*'s.

The resulting diffractive $D^{*\pm}$ cross sections are:

$$\sigma_{\text{diff}}(D^{*+}) = [0.185 \pm 0.044(\text{stat}) \pm 0.054(\text{syst})]\mu\text{b} \quad (4)$$
$$\sigma_{\text{diff}}(D^{*-}) = [0.174 \pm 0.034(\text{stat}) \pm 0.029(\text{syst})]\mu\text{b} \quad (5)$$

where the systematic errors include contributions from uncertainties in the LH_2 target density ($\sim 2\%$), the target length ($\sim$ 0.5%), the total number of beam particles ($\sim$ 5%), and the model dependence of the D^* acceptance correction. This model dependence is estimated [15] by calculating the D^* acceptance using a wide range of POMPYT input parameters. In addition to the pomeron structure function described above, we use soft ($f_{q,g/I\!P}(z) = 6(1-z)^5/z$), flat ($f_{q,g/I\!P}(z) = 1/z$), and hard ($f_{q,g/I\!P}(z) = 6(1-z)$) parton density functions in a pomeron consisting only of quarks (R_g=0) or gluons (R_g=1).

To reduce the model dependence of our results and to facilitate comparisons with future measurements, we also compute the D^* production cross section in a narrow region of D^* x_F and p_T in which our spectrometer acceptance is good and reasonably uniform. We restrict the range of these variables to $-0.3 \le x_F < -0.1$ and $(0 \le p_T < 1.5)$GeV/c. Within these limited ranges, the D^* acceptances, ϵ_A, calculated using the different pomeron structure functions in POMPYT differ by $\lesssim$ 10%. We calculate the D^* cross sections within these limited ranges using the acceptance determined from POMPYT with the exponentially damped pomeron flux and flat pomeron structure consisting of quarks and gluons ($R_g = 0.54$) described above. For a recoil beam proton with $x_F > 0.85$, we find:

$$\sigma_{\text{diff}}(D^{*+}) = [0.066 \pm 0.018(\text{stat}) \pm .006(\text{syst})]\mu\text{b} \quad (6)$$
$$\sigma_{\text{diff}}(D^{*-}) = [0.066 \pm 0.015(\text{stat}) \pm .007(\text{syst})]\mu\text{b} \quad (7)$$

where the systematic errors are determined in the same way as in results (4) and (5) but with the uncertainty in the model dependent acceptance determined only within this limited region.

Using the diffractive $D^{*\pm}$ to total diffractive $c\overline{c}$ production rates determined from POMPYT with R_g = 0.54 and the flat pomeron structure function described above, we find total diffractive charm cross sections of $\sigma_{\text{diff}}(c\overline{c}) = [0.69 \pm 0.17(\text{stat}) \pm 0.28(\text{syst})]\mu$b and $\sigma_{\text{diff}}(c\overline{c}) = [0.61 \pm 0.12(\text{stat}) \pm 0.11(\text{syst})]\mu$b, respectively, from results (4) and (5) above. The upper limit of $\sigma_{\text{diff}}(c\overline{c}) < 26$ μb/Si nucleus reported by E653 [3] is equivalent to $\sigma_{\text{diff}}(c\overline{c}) < 2.8$ μb and $\sigma_{\text{diff}}(c\overline{c}) < 0.93$ μb in pp at $\sqrt{s} = 40$ GeV if the cross section is assumed to scale with atomic weight as $A^{2/3}$ and A, respectively. Our measurements are below these upper limits and hence consistent with their results.

Fig. 5 compares the E690 results with those from CDF and ZEUS. This plot shows the discrepancy between the measured and predicted diffractive results as a function of the gluon fraction in the pomeron. The CDF and ZEUS curves are taken from Ref. [13]. The shaded band labeled E690(a) represents the E690 results including statistical errors determined from events of both reactions (1) and (2) with $D = \sigma_{\text{diff}}^{meas}(c\overline{c})/\sigma_{\text{diff}}^{pred}(c\overline{c})$. $\sigma_{\text{diff}}(c\overline{c})$ is defined as the production cross section for all charm accompanied by a final state proton with momentum fraction $x_F > 0.85$. For $\sigma_{\text{diff}}^{meas}(c\overline{c})$ we use the estimates based on our measurements for $\sigma_{\text{diff}}(D^*)$. $\sigma_{\text{diff}}^{pred}(c\overline{c})$ is the sum of the POMPYT diffractive charm cross section and the PYTHIA [16] non-diffractive charm background for $x_F > 0.85$. At $R_g = 0.54$, we find $D = 0.339 \pm 0.075$ and $D = 0.295 \pm 0.061$ for the two respective reactions

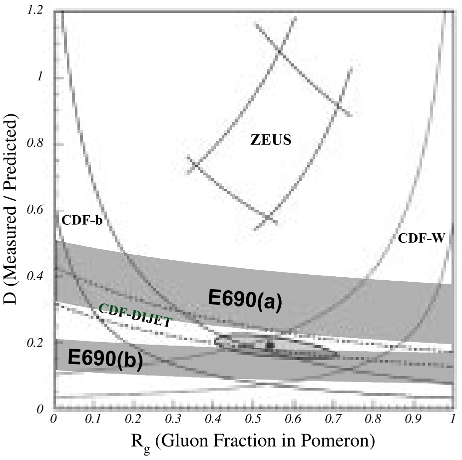

FIG. 5. Discrepancy factor $D = \sigma_{\text{diff}}^{meas}(c\overline{c})/\sigma_{\text{diff}}^{pred}(c\overline{c})$, band labeled E690(a), and $D = R_{c\overline{c}}^{meas}/R_{c\overline{c}}^{pred}$, band labeled E690(b), plotted as a function of the gluon fraction in the pomeron. Also shown are the ZEUS and CDF curves from Ref. [13].

which are roughly a factor of 2 lower than those of ZEUS and the same factor higher than those of CDF.

The shaded band in Fig. 5 labeled E690(b) represents the E690 results with the discrepancy factor defined as $D = R_{c\bar{c}}^{meas}/R_{c\bar{c}}^{pred}$, the ratio of the measured to predicted diffractive fraction in charm production [17]. $R_{c\bar{c}} = \sigma_{\rm diff}(c\bar{c})/\sigma_{\rm tot}(c\bar{c})$ is the diffractive to total charm production ratio. For $R_{c\bar{c}}^{meas}$, $\sigma_{\rm tot}(c\bar{c}) = (41.5 \pm 7.6)\mu$b is determined by multiplying the $D\overline{D}$ results from E653 and E743 by 1.5 to account for Λ_c and D_s production [18]. For $R_{c\bar{c}}^{pred}$, $\sigma_{\rm tot}(c\bar{c})$ is the sum of the PYTHIA total charm cross section and the POMPYT diffractive charm cross section. This band overlaps those of CDF but are roughly a factor of 6 lower than those of ZEUS.

The disagreement between the CDF and ZEUS results is interpreted as signalling the breakdown of factorization in Ingelman and Schlein's model of diffraction. The E690 results in Fig. 5 provide further evidence to support this view. However, these results do not support the flux renormalization scheme proposed in Ref. [19] which predicts D at our c.m. energy of $\sqrt{s} = 40$ GeV to be about a factor of 7 larger than the CDF value.

In conclusion, we report the first observation of diffractively produced open charm in pp collisions at $\sqrt{s} = 40$ GeV. We measure diffractive $D^{*\pm}$ cross sections of $\sigma_{\rm diff}(D^{*+}) = (0.185 \pm 0.044 \pm 0.054)\mu b$ and $\sigma_{\rm diff}(D^{*-}) = (0.174 \pm 0.034 \pm 0.029)\mu b$ for events of the type $pp \longrightarrow p(D^* \rightarrow (D^0 \rightarrow K\pi)\pi)X$ with a scattered beam proton having $x_F > 0.85$. Our measurements are consistent with the cross section upper limits set by FNAL E653 but incompatible with predictions of the pomeron based model of Ingelman and Schlein as calculated by POMPYT.

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[1] A. Kernan and G. VanDalen, Phys. Rep. **106**, 297 (1984); S. P. K. Tavernier, Rep. Prog. Phys. **50**, 1439 (1987); S. J. Brodsky, P. Hoyer, C. Peterson, and N. Sakai Phys. Lett. **93**, 451 (1980); S. J. Brodsky, C. Peterson, and N. Sakai, Phys. Rev. **23**, 2745 (1981).

[2] J. A. Appel, Annu. Rev. Nucl. Part. Sci. **42**, 367 (1992).

[3] K. Kodama *et al.*, Phys. Lett. B **316**, 188 (1993).

[4] G. Ingelman and P.E. Schlein, Phys. Lett. B **152**, 256 (1985).

[5] The measured quantity is actually the difference in longitudinal momentum between the scattered beam particle and an unscattered beam particle (taken to have a momemtun of 800 GeV/c).

[6] E.P. Hartouni *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **317**, 161 (1992); D.C. Christian *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **345**, 62 (1994); M.H.L.S. Wang, Ph.D. thesis, University of Massachusetts, Amherst, 2000.

[7] K. Goulianos, Phys. Rep. **101**,169 (1983).

[8] R. B. Stewart and H. M. Roder, in *Technology and Uses of Liquid Hydrogen*, edited by R. B. Scott, W. H. Denton, and C. M. Nichols (Macmillan, New York, 1964).

[9] The temperature of the LH$_2$ target averaged 16.6 K throughout the run, corresponding to $\rho = 0.07492$ g/cm^3.

[10] Particle Data Group: C. Caso *et al.*, Eur. Phys. J. C **3**, 1 (1998).

[11] P. Bruni and G. Ingelman, Proc. of the International Europhysics Conference on High Energy Physics, edited by J. Carr and M. Perrotet, Marseille, France, July 1993.

[12] M. Bozzo *et al.*, Phys. Lett. B **136**,217 (1984).

[13] T. Affolder *et al.*, Phys. Rev. Lett. **84**, 232 (2000).

[14] M. Derrick *et al.*, Z. Phys. C **68**, 569 (1995); Phys. Lett. B **356**, 129 (1995).

[15] This is taken to be half the spread between the maximum and minimum acceptance values calculated using the varying production model assumptions.

[16] T. Sjöstrand, Comput. Phys. Commun. **82**, 74 (1994).

[17] PYTHIA total charm cross sections are 2-3 times lower than experimental results. POMPYT which is based on PYTHIA can be assumed to predict diffractive cross sections differing from true values by the same factor. Comparing diffractive to total charm production rates instead of absolute cross sections eliminates the effect of the smaller predicted diffractive cross sections.

[18] K. Kodama *et al.*, Phys. Lett. B **263**, 573 (1991); R. Ammar *et al.*, Phys. Rev. Lett. **61**, 2185 (1988); S. Frixione, M. Mangano, P. Nason, and G. Ridolfi, hep-ph/9702287 v2, 1997.

[19] K. Goulianos, Phys. Lett. B **358**,379 (1995).