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Inclusive charged-D^* production in 205-GeV/c π^- Be interactions

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The inclusive cross section for charged-D^* production by 205-GeV/c π^- mesons incident on a beryllium target was measured with a two-arm spectrometer triggered by prompt muons. Using the mass-difference technique often employed in D^* studies, a signal of 31 ± 11 charged D^*'s was isolated; it includes contributions from both the D^{*+} and D^{*-} charged modes in correlation with triggering muons of the proper charge. This corresponds to an inclusive charged-D^* production cross section of $220\pm77^{+77}_{-57}$ μb per Be nucleus or $24\pm9^{+9}_{-6}$ μb per nucleon when the cross section is scaled linearly with atomic mass number. The first error is statistical and the second is systematic.

Twelve years after the discovery of charm particles, charm hadroproduction remains the subject of lively experimental inquiry. The D^*, with its kinematically striking decay into $D\pi$, has been useful in establishing charm hadroproduction levels.[1–4] In this paper we report the observation of $D^{*\pm}$ production by energetic pions using a prompt-muon trigger.

This experiment (E515) was performed in the M1-West beam line at Fermilab with a 205-GeV/c π^- beam on a beryllium target. The experiment was designed to study the associated production of charm:

$$\pi^- + \mathrm{Be} \to C + \bar{C} + X\,,\quad C \to \mu^+ X',\ \bar{C} \to \text{hadrons}\quad \text{or}\quad C \to \text{hadrons},\ \bar{C} \to \mu^- X''$$

where the symbol $C+\bar{C}$ represents a pair of charmed hadrons. Such reactions were selected by triggering the apparatus on the prompt muon from the semileptonic decay of either of the charmed hadrons. For those triggered events with reconstructed muons, information from a magnetic spectrometer was used to calculate the invariant mass of various combinations of charged particles. The resulting invariant-mass spectra were then investigated for evidence of decay of the associated charm state into charged hadrons.

The spectrometer (Fig. 1) was comprised of two arms: a muon trigger arm which subtended +42 to +170 mrad vertically and ±150 mrad horizontally and a large, open-geometry forward arm which subtended -80 to $+42$ mrad vertically and ±200 mrad horizontally. The trigger arm consisted of tungsten absorber followed by steel absorber interspersed with scintillation hodoscopes and a set of eight proportional wire chambers (PWC's). The upstream face of the tungsten absorber was placed as close as possible to the target to minimize the free space available for the semimuonic decay of pions and kaons. The trigger required hits in each of five trigger-arm hodoscopes ($M00,M0,M1,M2,M3$) in coincidence with hits in two overlapping scintillation counters which masked the front face of the beryllium target. Muons needed a momentum of at least 4 GeV/c to penetrate the trigger-arm absorber, which included the return yoke of the spectrometer magnet. Since the muons passed through the magnetized yoke, their momenta and charges were determined. The forward arm was instrumented with PWC's, drift chambers, a 46-cell threshold Čerenkov counter filled with nitrogen at atmospheric pressure, a lead–liquid-argon electromagnetic calorimeter,[5] and two muon hodoscopes located downstream of a 2.9-m steel filter. The large-aperture dipole magnet provided a horizontal momentum impulse of 0.8 GeV/c to particles in the forward arm.

In the off-line analysis, trigger muons were identified by linking tracks in the trigger-arm PWC's downstream of the magnet with information from upstream hodo-

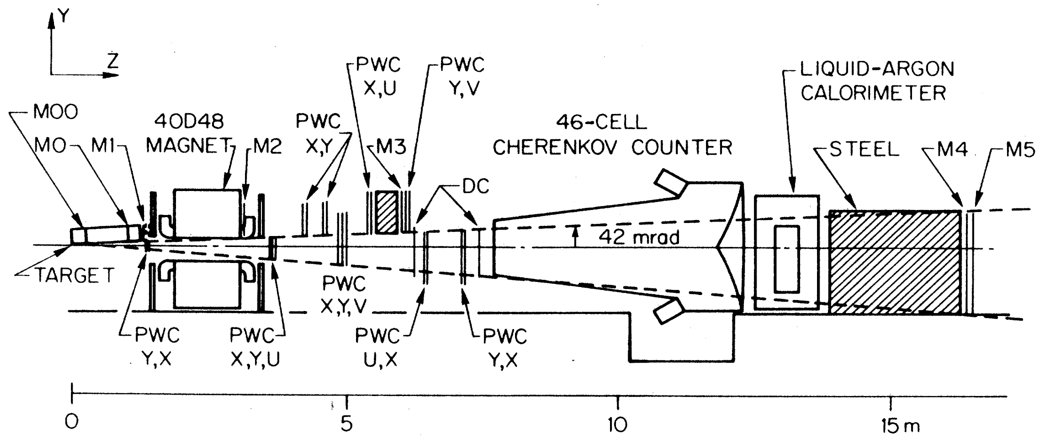

FIG. 1. Elevation view of spectrometer.

scopes and chambers. Muon momentum was determined to within 25% by an iterative procedure that took into account energy loss and multiple scattering in the absorber. Requiring a reconstructed trigger muon reduced the original sample of 1.9×10^6 recorded events to a final sample of 3.8×10^5 events.

For tracking in the forward arm, a set of Chebyshev polynomials was used to link information from wire chambers upstream and downstream of the magnet.[6] This technique improved the tracking efficiency over previous analyses of these data for particles with momenta below 7 GeV/c (Ref. 7). Good tracking efficiency at low momentum is important because the pion from the D^* decay carries only a small fraction, $\sim 8\%$, of the D^* momentum. A second set of Chebyshev polynomials was used to calculate the momentum and charge for each reconstructed particle trajectory.

Information from the Čerenkov counter was used to distinguish between pions and kaons in the momentum range 7–20 GeV/c. Particles for which Čerenkov information was either unavailable or inconclusive were assigned both kaon and pion identities.[8]

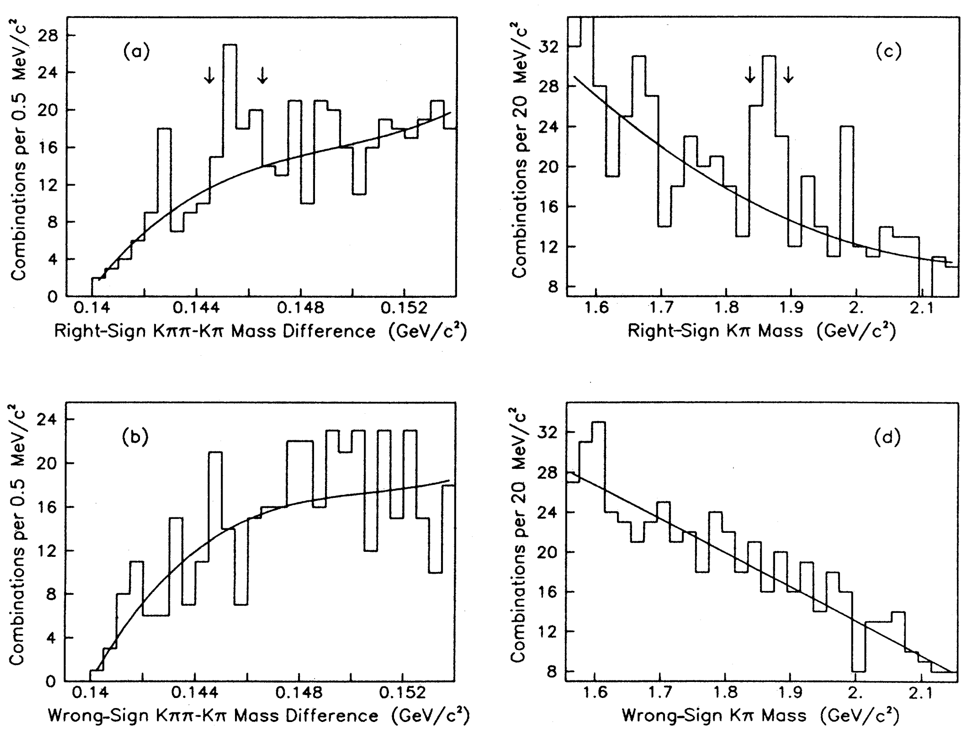

FIG. 2. (a) Right-sign $K^{\pm}\pi^{\mp}\pi^{\mp}-K^{\pm}\pi^{\mp}$ mass-difference distribution, (b) wrong-sign mass-difference distribution, (c) right-sign $K\pi$ mass distribution, (d) wrong-sign mass distribution. The arrows indicate both the cuts employed in the complementary plot and the region where the excess combinations appear.

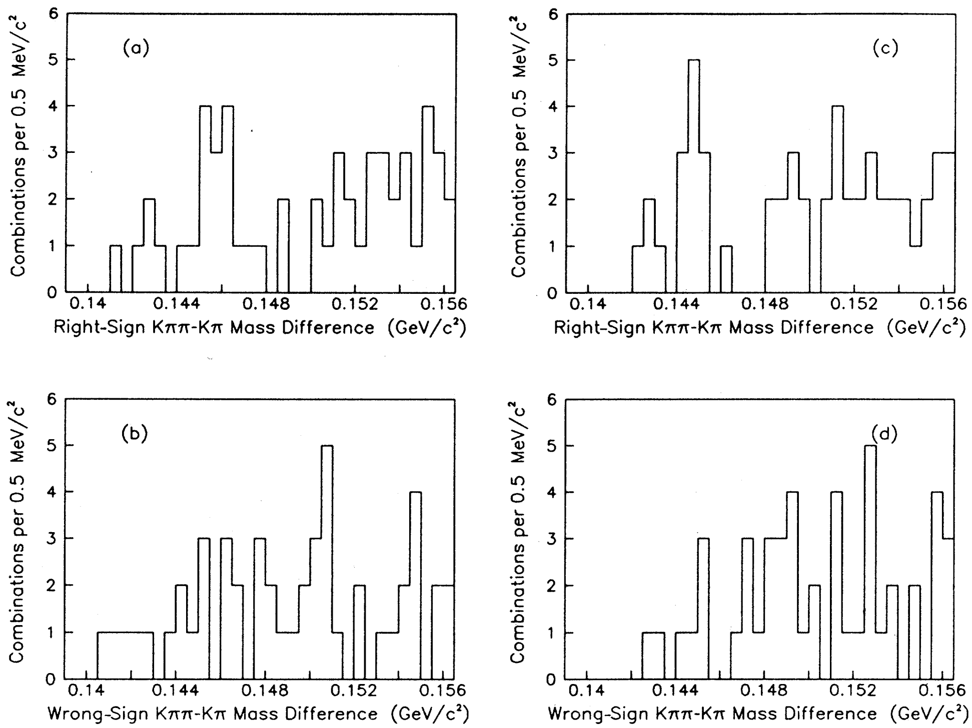

FIG. 3. (a) Right-sign $K^+\pi^-\pi^- - K^+\pi^-$ mass-difference distribution, (b) wrong-sign $K^+\pi^-\pi^- - K^+\pi^-$ mass-difference distribution, (c) right-sign $K^-\pi^+\pi^+ - K^-\pi^+$ mass-difference distribution, (d) wrong-sign $K^-\pi^+\pi^+ - K^-\pi^+$ mass-difference distribution.

The following reaction and its final-state charge conjugate are addressed in this paper:

$$\pi^- + \text{Be} \to D^{*+} + \bar{C} + X\,,\quad D^{*+} \to D^0 + \pi^+,\quad D^0 \to K^- + \pi^+,\quad \bar{C} \to \mu^- + \bar{\nu}_\mu + X'$$

where the muon is the triggering particle. In the absence of $D\bar{D}$ mixing,[9] the triggering muon and the kaon from the cascade decay of the associated charm state will be of like sign. Therefore, the $K^\pm\pi^\mp$ mass spectrum with a $\mu^\pm$ trigger contains all of the D meson signal while the $K^\mp\pi^\pm$ mass spectrum with a $\mu^\pm$ trigger contains only background. Consequently, none of the signal is lost and the background level is significantly reduced by considering only like-sign combinations. We call the first case *right sign* and the second case *wrong sign*. For the D^*, the background level can be reduced still further by employing the D^* isolation technique[10] based on the extremely small mass difference, 0.1455 GeV/c^2, between the charged D^* and the neutral D meson.[11]

The $K^\pm\pi^\mp$ mass and $K^\pm\pi^\mp\pi^\mp - K^\pm\pi^\mp$ mass-difference distributions are presented in Fig. 2 for both the right-sign and wrong-sign combinations. Entries in the $K^\pm\pi^\mp\pi^\mp - K^\pm\pi^\mp$ mass-difference distributions were required to have $K^\pm\pi^\mp$ masses between 1.835 and 1.895 GeV/c^2. Entries in the $K^\pm\pi^\mp$ mass distributions were required to have $K^\pm\pi^\mp\pi^\mp - K^\pm\pi^\mp$ mass differences between 0.144 and 0.146 GeV/c^2. These ranges are com-

TABLE I. Constants employed in cross-section calculation.

Quantity	Description	Value
L	Integrated luminosity	0.12 (pb/nucleus)$^{-1}$
f	Event-cut correction	0.90
$B(D^0\to\mu^+X)$		$0.075\pm0.011\pm0.004$[a]
$B(D^+\to\mu^+X)$		$0.170\pm0.019\pm0.007$[a]
$B(D^0\to K^-\pi^+)$		$0.042\pm0.004\pm0.004$[b]
$B(D^{*+}\to D^0\pi^+)$		$0.57\pm0.04\pm0.04$[c]
B_T	Average D-to-muon branching ratio	$0.112\pm0.010\pm0.004$
B_F	$B(D^{*+}\to D^0\pi^+)B(D^0\to K^-\pi^+)$	$0.024\pm0.003\pm0.003$

[a]Reference 18.
[b]Reference 19.
[c]Reference 20.

TABLE II. Inclusive charged-D^* production cross section for several values of n.

n	b $[(\mathrm{GeV}/c)]^{-2}$	A_T	A_F	Sensitivity $[(\mu\mathrm{b/nucleus})^{-1}]$	$\sigma_{\mathrm{nucleus}}$[a] ($\mu$b)	σ/nucleon[b] (μb)
1	1.1	0.0104	0.0450	0.136	$230\pm81^{+80}_{-59}$	$25\pm9^{+9}_{-7}$
3	1.1	0.0167	0.0292	0.142	$220\pm77^{+77}_{-57}$	$24\pm9^{+9}_{-6}$
4	1.1	0.0197	0.0219	0.125	$250\pm88^{+87}_{-64}$	$28\pm10^{+10}_{-7}$
5	1.1	0.0217	0.0148	0.093	$330\pm118^{+116}_{-86}$	$37\pm13^{+13}_{-10}$
6	1.1	0.0232	0.0136	0.092	$340\pm120^{+119}_{-88}$	$38\pm13^{+13}_{-10}$

[a]Inclusive charged-D^* production cross section in 205-GeV/c π^- Be interactions.
[b]In calculating σ/nucleon the cross-section dependence on mass number was assumed to be A^1. Diffractive production should favor $A^{2/3}$ while central production should favor A^1. Since the Lexan Bubble Chamber–European Hybrid Spectrometer (LEBC-EHS) and Amsterdam-Bristol-CERN-Cracow-Munich-Rutherford (ACCMOR) Collaborations reported that D^* production seems to be central (Refs. 1 and 16), A^1 was used.

mensurate with Monte Carlo estimates of the spectrometer resolution for mass (±30 MeV/c^2) and mass difference (±1 MeV/c^2) in these regions. Both the right-sign mass and mass-difference distributions exhibit excess combinations above the polynomial-fitted background. The signal as determined from these two distributions is 31 ± 11 combinations. The corresponding regions in the wrong-sign distributions yield essentially no excess combinations (2 ± 10).

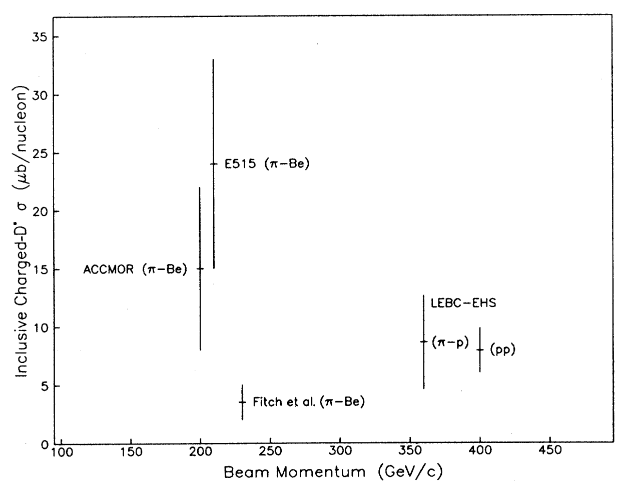

FIG. 4. Comparison of inclusive charged-D^* production cross sections by π^- and proton beams. The LEBC-EHS results from 360-GeV/c $\pi^- p$ interactions (Ref. 1) were multiplied by 2 to cover all x_F. The LEBC-EHS results from 400-GeV/c pp interactions (Ref. 2) already included this factor. The result of Fitch *et al.* (Ref. 3), an average of data taken at 200 and 250 GeV/c, was scaled to take into account updated hadronic branching ratios. The ACCMOR entry in the plot was derived from cross-section ratios (Ref. 4) and reflects an updated $D^0 \rightarrow K^-\pi^+$ branching ratio. All of these results were also rescaled to the recently reported $D^{*\pm} \rightarrow D^0\pi^\pm$ branching ratio (Ref. 20). The error bars reflect statistical uncertainties only.

Figure 3 indicates that both D^{*+}'s and D^{*-}'s contribute to the signal. These mass-difference distributions were made with a more restrictive cut on the $K\pi$ mass (1.855 to 1.875 GeV/c^2) and with the requirement that the cosine of the angle between the direction of the K in the D^0 rest frame and the D^0 in the laboratory frame be greater than -0.85. A substantial portion of the background ($\sim35\%$) and only a small fraction of the signal ($\sim5\%$) are eliminated by imposing this angle cut.[12]

The production cross section for charged D^*'s is obtained from the results of the fits in Fig. 2, using the following assumptions (see Table I).

(1) All triggering muons from charm sources come from D's, either directly or from D^*'s decaying into D's. The contributions from Λ_c's and D_s's are ignored.

(2) The production cross section ratio of D^0's to D^+'s is 1.6 (Ref. 13). (This ratio is used to determine the weighted average of the D^0 and D^+ semileptonic branching ratios into muons.)

(3) D mesons decay semileptonically into K and K^* at an equal rate.[14]

(4) Each D of a $D\bar{D}$ pair is produced according to the following production distribution:

$$\frac{d^2N}{dx_F dp_T^2} \propto (1-|x_F|)^n e^{-bp_T^2} .$$

The inclusive charged-D^* production cross section for 205-GeV/c π^- mesons on a beryllium nucleus is then obtained from the number of detected D^*'s ($N_d^{D^*}=31\pm11$) as

$$\sigma_{\mathrm{nucleus}}(D^*)=\frac{N_d^{D^*}}{LB_TB_FA_TA_Ff} ,$$

where L is the integrated luminosity, B_T is the branching ratio for the associated charm particle to decay into a muon, B_F is the product of the branching ratios for the charged D^* to decay into a neutral D and a charged π and for the neutral D to subsequently decay into a charged K and charged π, A_T is the trigger-arm acceptance for the muon from the decay of the associated D meson, and A_F is the forward-arm acceptance for the decay products of a D^*. A_T and A_F include the effects of geometric acceptance and detector efficiencies. The factor f accounts for several analysis cuts[15] not modeled in the Monte Carlo acceptance studies. The values of these parameters appear in the tables. The resulting D^* production cross section is listed in Table II for several production model assumptions. For $n=3$ and $b=1.1$ (Ref. 16) the production cross section is $220\pm77^{+77}_{-57}$ μb per Be nucleus or $24\pm9^{+9}_{-6}$ μb per nucleon if linear A dependence is assumed. The first error is statistical and the second is systematic.

Figure 4 shows a comparison of these results with several recent measurements of the hadronic production cross section for charged D^*'s. The cross-section values have been scaled to reflect current branching ratios and to cover all x_F.

The observation of 31 charged D^*'s implies that $(44\pm16)\%$ of the events with reconstructed trigger muons contained charm.[17] This result suggests that a prompt-muon trigger can be quite effective in selecting charm events.

In summary, we observed inclusive charged-D^* production in 205-GeV/c π^- Be interactions with a cross section of $(220\pm77^{+77}_{-57})$ μb per Be nucleus. When scaled linearly with atomic mass number this corresponds to $(24\pm9^{+9}_{-6})$ μb per nucleon.

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[1]M. Aguilar-Benitez *et al.*, Phys. Lett. **169B**, 106 (1986).
[2]M. Aguilar-Benitez *et al.*, Phys. Lett. B **189**, 476 (1987).
[3]V. L. Fitch *et al.*, Phys. Rev. D **33**, 1486 (1986).
[4]R. Bailey *et al.*, Z. Phys. C **30**, 51 (1986).
[5]W. Sakumoto *et al.*, Nucl. Instrum. Methods A **235**, 61 (1985).
[6]A variation on an idea presented in C. Lechanoine, M. Martin, and H. Wind, Nucl. Instrum. Methods **69**, 122 (1969).
[7]The use of Chebyshev polynomials in the vertical (nonbend view) tracking algorithm is a major difference between the analysis reported here and that described in G. Ginther *et al.*, Phys. Rev. D **35**, 1541 (1987). An improved interaction location determination is another notable difference. These refinements were implemented to improve event reconstruction and yielded a more significant D^* signal. The same data set was used in both analyses.
[8]Particles were treated as ambiguous if they missed the Čerenkov counter, were outside the 7–20 GeV/c momentum range, were spatially near another charged particle, or yielded amounts of light in the counter which were not clearly indicative of either a pion or kaon source. See Patrick J. Mooney, Ph.D. dissertation, University of Notre Dame, 1986, pp. 46 and 47.
[9]In J. C. Anjos *et al.*, Phys. Rev. Lett. **60**, 1239 (1988), a 90%-confidence-level upper limit on $D\bar{D}$ mixing of 0.37% was reported.
[10]V. L. Fitch *et al.*, Phys. Rev. Lett. **46**, 761 (1981).
[11]H. Albrecht *et al.*, Phys. Lett. **150B**, 235 (1985).
[12]Patrick J. Mooney, Ph.D. dissertation, University of Notre Dame, 1986, pp. 19 and 20.
[13]A weighted average of the results reported in Refs. 1, 2, and 4 yielded the 1.6 ± 0.2 ratio for D^0 to D^+ production used here.
[14]W. Bacino *et al.*, Phys. Rev. Lett. **43**, 1073 (1979).
[15]These cuts are ambiguous vertex (7%), showers in the trigger arm (1%), ambiguous triggering-muon charge (1%), and hardware or software errors (2%).
[16]This is consistent with the values reported in R. Bailey *et al.*, Z. Phys. C **30**, 51 (1986) of 2.9 ± 0.6 and $1.0^{+0.2}_{-0.1}$ for n and b, respectively.
[17]This can be calculated using the formula $N_\mu^{\text{charm}}=3.8N_d^{D^*}/(B_F A_F f)$, where $N_d^{D^*}$ is the number of D^*'s detected (31 ± 11) and N_μ^{charm} is the number of muons from charm decay which should have triggered the apparatus in order for us to reconstruct $N_d^{D^*}$ D^*'s in the forward arm. The factor of 3.8 appears because the inclusive D cross section is about 3.8 times the charged D^*'s (Ref. 2). Values for B_F and f can be found in Table I. Using the value of A_F associated with $n=3$ from Table II one obtains $N_\mu^{\text{charm}}=1.88\times10^5$. The number of reconstructed trigger muons adjusted for the analysis cuts is $3.82\times10^5/f$ or 4.25×10^5. Dividing 1.88×10^5 by 4.25×10^5 yields $(44\pm16)\%$.
[18]R. M. Baltrusaitis *et al.*, Phys. Rev. Lett. **54**, 1976 (1985).
[19]J. Adler *et al.*, Phys. Rev. Lett. **60**, 89 (1988). A very similar result is reported in S. Abachi *et al.*, Phys. Lett. B **205**, 411 (1988).
[20]J. Adler *et al.*, Phys. Lett. B **208**, 152 (1988).