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

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Hadronic charm production was investigated with a two-arm magnetic spectrometer. The experiment was triggered on muons from the semileptonic decay of charm particles in one arm while reconstructing the mass of the associatively produced partners in the other arm. An excess of 153±46 combinations above background for the neutral $D \rightarrow K\pi$ mode was observed. This corresponds to a model-dependent $D\bar{D}$ production cross section of $41 \pm 12^{+15}_{-11}$ μb per nucleon, where the first uncertainty is statistical and the second is systematic.

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In the past few years considerable effort has gone into the study of hadronic production of charm [1]. Detailed information has been difficult to obtain from these studies because the multiplicity of secondaries produced in hadronic events results in large combinatorial backgrounds.

Because of their short lifetimes and relatively large semileptonic branching ratios, charm particles are a significant source of prompt leptons. Fermilab experiment E515 was a study of 205-GeV/c π^--beryllium interactions selected with a prompt-muon trigger. A two-arm spectrometer was built for this study (see Fig. 1). The "trigger arm" contained a dense absorber positioned close to the target to absorb pions and kaons before they could decay into muons. The angular acceptance of this arm was ±150 mrad horizontally and +42 to +170 mrad vertically. Accepted muons in the trigger arm had momenta greater than 4 GeV/c. The "forward arm" was an open geometry magnetic spectrometer with charged- and neutral-particle identification capabilities. The acceptance of this arm was ±200 mrad horizontally and −80 to +42 mrad vertically. The strategy of this experiment was to trigger the apparatus upon the detection of prompt muons from charm decays in the trigger arm and to observe the decay products of the associatively produced charm system in the forward arm.

In the off-line analysis, trigger muons were identified by reconstructing tracks in the trigger arm wire chambers downstream of the magnet. Muon momenta were determined within 25% by a least-squares fit which included corrections for energy loss and multiple scatter-

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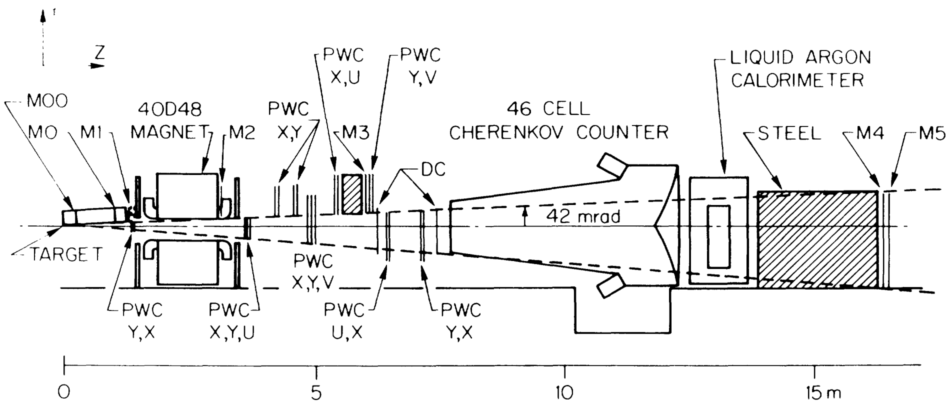

FIG. 1. Elevation view of the E515 spectrometer, showing both the trigger and forward arms. The trigger arm included those elements above a plane inclined +42 mrad from the horizontal. $M0$, $M00$, $M1$, $M2$, and $M3$ were scintillation counters employed in the prompt-muon trigger.

ing in the absorber. For tracking in the forward arm, a set of Tchebycheff polynomials was used to link information from wire chambers upstream and downstream of the magnet [2,3].

Of the 1.9×10^6 events recorded with the prompt-muon trigger, 3.8×10^5 had a reconstructed trigger muon. This sample was used for the subsequent charm-particle analysis described here.

Pion and kaon separation in the forward arm was provided by a 46-cell threshold Čerenkov counter filled with nitrogen at atmospheric pressure. The Čerenkov analysis program assigned a value of Q_K (for kaon quality) to each tracked particle based upon the amount of light detected in the counter associated with that particle. The value of Q_K ranged from 0 to 1, with higher Q_K values indicative of kaons (or protons) and lower Q_K values indicative of pions (or muons and electrons) [4]. Particles were identified as kaons when they satisfied the following conditions: (1) they were within the geometric acceptance of the Čerenkov counter; (2) they were isolated from other particles in the counter; and (3) their momenta were in the interval 7–25 GeV/c and their Q_K were greater than 0.8. All other particles were labeled pions.

Using an event-mixing simulation, it was determined that kaons with momenta in the interval 7–25 GeV/c and which satisfied conditions (1) and (2) had a 65% probability of being correctly identified [5]. Pions in the same momentum range and also satisfying conditions (1) and (2) had a 99% probability of being correctly identified.

Pair production of charm particles and their subsequent Cabibbo-favored decays lead to significant charge correlations among final-state particles. In the absence of $D\bar{D}$ mixing [6], the charge of the triggering muon from the semileptonic decay of one of the charm particles is the same as that of the charged kaon from the decay of the associatively produced charm meson provided that the decay products of the charm meson contain only one valence quark of nonzero strangeness. Such charge correlations allow us to separate the invariant-mass spectra into "right-sign" and "wrong-sign" plots. The right-sign plots should contain the charm signals whereas the wrong-sign plots should contain predominantly background.

Right-sign combinations for the channel $K^{\pm}\pi^{\mp}$ are shown in Fig. 2(a). An enhancement at the neutral-D mass can be seen. The wrong-sign combinations are shown in Fig. 2(b) and no enhancement is observed. To determine the size of the signal, the distribution in Fig. 2(a) was fit to a fourth-order polynomial excluding the contributions between 1.795 and 1.935 GeV/c^2. The same polynomial shape is shown in Fig. 2(b) on the wrong-sign distribution with the normalization determined by the number of entries. Figures 2(c) and 2(d) show the difference between the fit and the data for both sign modes. In the right-sign case, Fig. 2(a), the number of combinations above background between 1.835 and 1.895 GeV/c^2 is 153 ± 46 [7]. We interpret this excess as evidence of neutral-D production. In the wrong-sign case, Fig. 2(b), the number of excess $K\pi$ combinations between 1.835 and 1.895 GeV/c^2 is -21 ± 45.

The $D\bar{D}$ production cross section can be obtained from the neutral-D data described above using the following assumptions.

(1) All trigger muons from charm sources come from D mesons. This assumption neglects contributions from other states such as Λ_c and D_s.

(2) The ratio of inclusively produced neutral D's to charged D's is 1.6 [8–11]. We extract from this assumption the weighted average of the neutral and charged D semileptonic branching ratios.

(3) D mesons decay semileptonically via K and K^* at an equal rate [12].

(4) Each D of a $D\bar{D}$ pair is produced according to an uncorrelated production distribution.

(5) Dependence on mass number is linear [13].

Under these assumptions the average branching ratio for D mesons into muons is

TABLE I. Constants employed in cross-section calculation.

L	Integrated luminosity	1.10 $(\text{pb/nucleon})^{-1}$
f	Event cut correction	0.90
$B(D^0 \to \mu^+ X)$		$0.075 \pm 0.011 \pm 0.004$[a]
$B(D^+ \to \mu^+ X)$		$0.170 \pm 0.019 \pm 0.007$[a]
$B(D^0 \to K^- \pi^+)$		$0.042 \pm 0.004 \pm 0.004$[b]
$B_{D \to \mu}$	Average D-to-muon branching ratio	$0.112 \pm 0.010 \pm 0.004$
$N(D^0/\bar{D}^0)/N(D^{\pm})$	Ratio of neutral to charged D production	1.6 ± 0.2

[a]Reference [16].
[b]Reference [17].

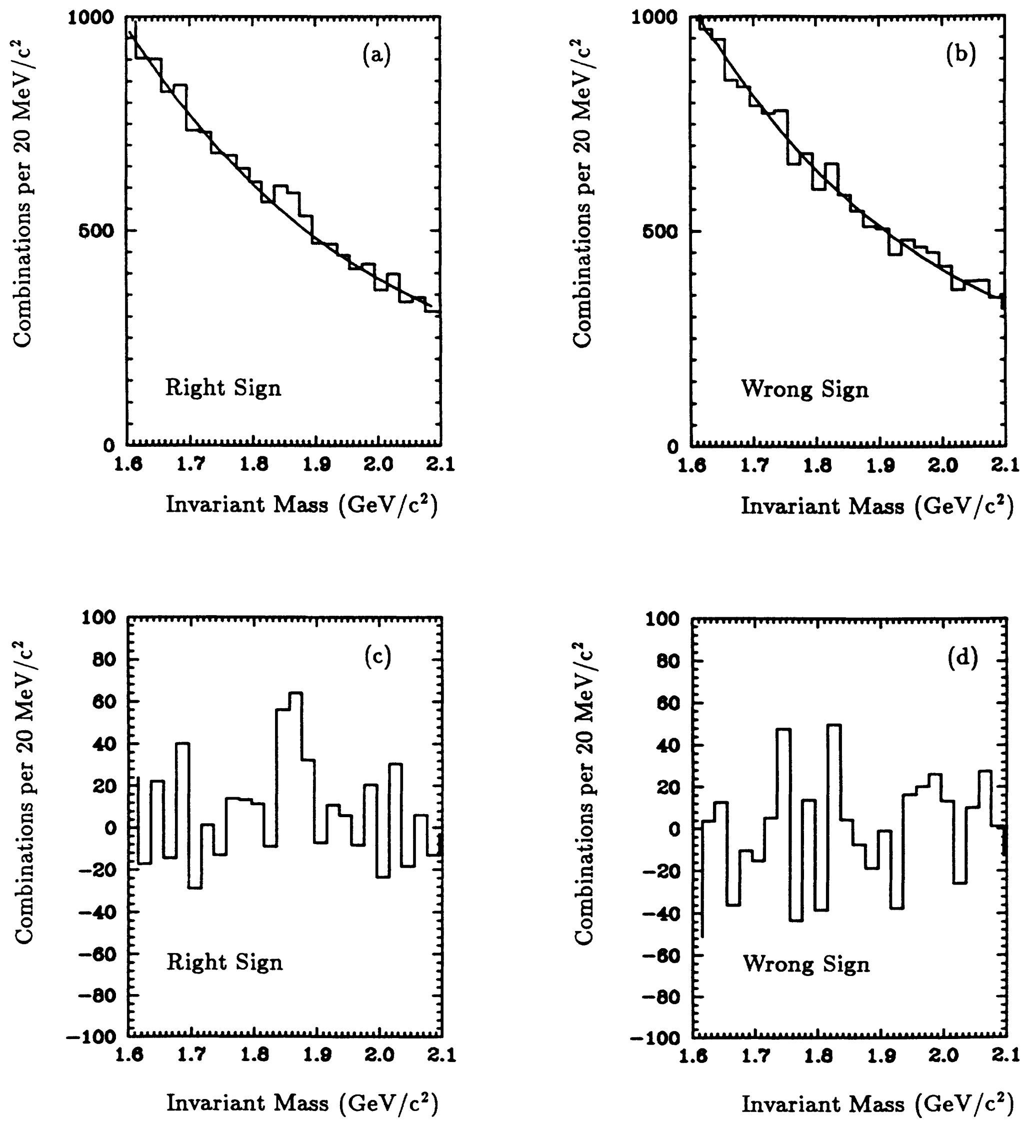

FIG. 2. (a) Right-sign $K\pi$ mass combinations. The curve is a fourth-order polynomial fit to the histogram excluding the signal region. (b) Wrong-sign $K\pi$ mass combinations. The curve is the same fourth-order polynomial used in the right-sign fit, normalized to the number of entries in this wrong-sign plot. (c) Difference between the histogram and the polynomial fit for right-sign combinations. (d) Difference between the histogram and the polynomial for wrong-sign combinations.

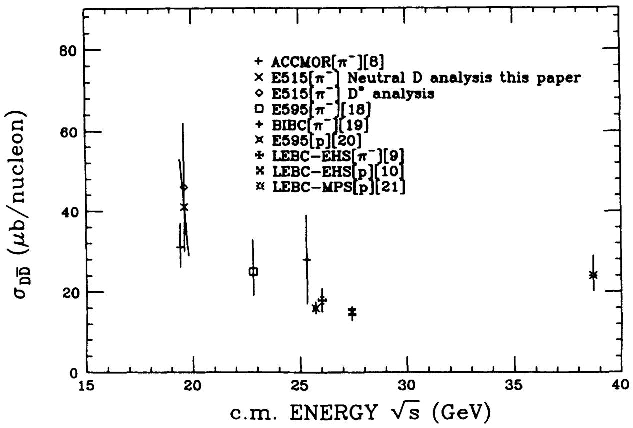

FIG. 3. Comparison of the $D\bar{D}$ production cross section as measured by this experiment with other measurements as a function of the center of mass (c.m.) energy [8–10, 18–21]. The error bars represent only statistical uncertainties.

$$B_{D\to\mu}=\frac{N(D^0/\bar{D}^0)}{N(D^0/\bar{D}^0)+N(D^{\pm})}B(D^0\to\mu+X)+\frac{N(D^{\pm})}{N(D^0/\bar{D}^0)+N(D^{\pm})}B(D^+\to\mu+X)\ ,$$

$$B_{D\to\mu}=0.62\times0.075+0.38\times0.170=0.112\ .$$

The inclusive production cross section per nucleon for neutral D mesons in coincidence with triggering muons from associated partners (assumed to be D mesons) can be expressed as

$$\sigma_{(D^0\bar{D})}+\sigma_{(\bar{D}^0D)}=\frac{N_{D^0\mu^-}+N_{\bar{D}^0\mu^+}}{LB_FA_FA_\mu B_{D\to\mu}f}\ . \tag{1}$$

The branching fraction $B_{D\to\mu}$ is the average charm semileptonic branching ratio described above. The numerator in Eq. (1) is the observed signal above background in the right-sign $K\pi$ invariant-mass spectrum, L is the intergrated luminosity, A_μ is the acceptance in the trigger arm for a muon from the decay of a triggering D meson, A_F is the acceptance in the forward arm for the decay products of a neutral D meson, B_F is the branching ratio of a neutral D into $K\pi$, and f accounts for several cuts not modeled in acceptance studies (principally ambiguities in locating the primary interactions). Constants used in the cross-section calculations are listed in Table I. The values for the spectrometer acceptance A_F and A_μ were determined from a Monte Carlo simulation in which the following uncorrelated production model was employed:

$$\frac{d^2\sigma}{dx_Fdp_T^2}=(1-|x_F|)^ne^{-bp_T^2}\ ,$$

where b was fixed at 1.1 $(\text{GeV}/c)^{-2}$.

Interpreting the observed excess of 153±46 combinations in the right-sign mass spectrum [Fig. 2(a)] as evidence for neutral-D-meson production and using the assumptions previously outlined, the inclusive neutral-D production cross section is calculated. Table II contains values of $\sigma_{(D^0\bar{D})}+\sigma_{(\bar{D}^0D)}$ obtained for different values of n. The inclusive $D\bar{D}$ cross section may be inferred from the model described above and is given by

$$\sigma_{D\bar{D}}=\frac{N(D^0/\bar{D}^0)+N(D^{\pm})}{N(D^0/\bar{D}^0)}\ \frac{\sigma_{(D^0\bar{D})}+\sigma_{(\bar{D}^0D)}}{2}\ .$$

These values are also presented in Table II. For the case $n=3$, we obtain a value of $\sigma_{D\bar{D}}=41\pm12^{+15}_{-11}$ μb per nucleon. This result is compared with other measurements at various energies in Fig. 3. Also included in the figure is a value of $\sigma_{D\bar{D}}$ obtained from a D^* signal observed in this experiment [14]. Whenever possible, the cross sections have been scaled to employ a consistent set of branching ratios and to cover all x_F.

The observation of 153±46 neutral D mesons implies that 45±13% of the events with reconstructed trigger muons contained charm. This is consistent with a similar results, 44±16%, obtained from a D^* analysis of the same data [15].

In summary, Fermilab experiment E515 recorded prompt-muon triggered events with a two-arm spectrometer to study charm particles. We have observed evidence of neutral-D-meson production in π^- beryllium interactions at 205 GeV/c. Based on the observed neutral-D signal of 153±46 events and assuming a $(1-|x_F|)^3$ production model, the inclusive $D\bar{D}$ production cross section is $41\pm12^{+15}_{-11}$ μb per nucleon.

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TABLE II. $D\bar{D}$ production cross section determined from the right-sign $K\pi$ mass spectrum of Fig. 2(a).

n	b	A_μ	A_F	$\sigma_{(D^0\bar{D})}+\sigma_{(\bar{D}^0D)}$ (μb/nucleon)	$\sigma_{D\bar{D}}$ (μ b/nucleon)
1	1.1	0.0104	0.0314	$101\pm30^{+36}_{-26}$	$82\pm25^{+29}_{-21}$
3	1.1	0.0167	0.0386	$51\pm15^{+18}_{-13}$	$41\pm12^{+15}_{-11}$
6	1.1	0.0232	0.0456	$31\pm9^{+11}_{-8}$	$25\pm8^{+9}_{-7}$

[1] See, for example, J. Spalding, in *The Storrs Meeting,* Proceedings of the Annual Meeting of the Division of Particles and Fields of the APS, Storrs, Connecticut, 1988, edited by K. Haller, D. G. Caldi, M. M. Islam, R. L. Mallet, P. D. Mannheim, and M. S. Swanson (World Scientific, Singapore, 1989), pp. 401–407; M. V. Purhoit, *ibid.* pp. 616–625.

[2] A variation of an idea presented by C. Lechanoine, M. Martin, and H. Wind, Nucl. Instrum. Methods **69**, 122 (1969).

[3] The use of Tchebycheff polynomials in the vertical (nonbend view) tracking algorithm is a major difference between the analysis reported here and that described by 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 as well as tracking efficiency for low-momentum particles. The same data set was employed in both analyses.

[4] Richard R. Pemper, Ph.D. thesis, University of Notre Dame, 1983.

[5] A track from a previous event was inserted into a given event and a light distribution was generated for the track assuming a particular particle type. The kaon identification algorithm was then used to determine the particle's identity.

[6] Results from the ARGUS Collaboration [H. Albrecht *et al.,* Phys. Lett. B **199**, 447 (1987)] and the Tagged Photon Laboratory (TPL) spectrometer at Fermilab [J. C. Anjos *et al.,* Phys. Rev. Lett. **60**, 1239 (1988)] indicate no evidence for $D^0\bar{D}^0$ mixing. An upper limit of 1.4% (90% C. L.) is quoted by ARGUS, and TPL reports less than 0.0037 at the 90% confidence level for the ratio of wrong-sign decays from mixing to right-sign decays.

[7] The uncertainty in the number of excess combinations was obtained by adding the statistical uncertainty determined from the total number of combinations between 1.835 and 1.895 GeV/c^2 in quadrature with the uncertainty in the number of background combinations determined from the covariance matrix of the polynomial fit.

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[11] A weighted average of the results reported in Refs. [8–10].

[12] W. Bacino *et al.,* Phys. Rev. Lett. **43**, 1073 (1979).

[13] M. MacDermott and S. Reucroft, Phys. Lett. B **184**, 108 (1987), have compared the data from two different experiments using different target materials (hydrogen and beryllium) and have obtained an estimate of the mass number dependence of charm hadroproduction. They parametrize this dependence as A^α where $\alpha \approx 0.9$ for $x_F \geq 0.0$.

[14] The inclusive $D\bar{D}$ production cross section is obtained from the inclusive charged D^* cross section $\sigma(D^{*\pm})$ reported by P. Mooney *et al.* [Phys. Rev. D **39**, 2494 (1989)] as

$$\sigma_{D\bar{D}} = \frac{N(D^0/\bar{D}^0)+N(D^\pm)}{N(D^{*\pm})}\,\frac{\sigma(D^{*\pm})}{2} \,.$$

Assuming $[N(D^0/\bar{D}^0)+N(D^\pm)]/N(D^*\pm)=3.8$ [10], the equation above yields a value of $\sigma_{D\bar{D}}=46\pm16^{+16}_{-12}$ μb per nucleon for $n=3$.

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