Atomic Mass Dependence of $D^{\pm}$ and $D^0,\overline{D}^0$ Production in 250 GeV $\pi^{\pm}$-Nucleon Interactions

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We measure the relative cross sections for D mesons produced in interactions of π^- and π^+ beams with targets of Be, Cu, Al, and W. The measurement is based on 1400 fully reconstructed decays of the types $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, and charge conjugates. We find that the cross section for the production of both neutral and charged D's by either π^- or π^+ is well fitted by the form A^α where A is the atomic mass and $\alpha = 1.00 \pm 0.05 \pm 0.02$, where the errors are statistical and systematic, respectively. There is no significant dependence of α on the transverse or longitudinal momentum of the D meson or on the charge of either the incident pion or the produced D meson.

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Measurement of the nuclear target dependence of the hadroproduction of charm mesons allows one to probe the distance scale important in the production and hadronization of charmed quarks. Also, since in the standard model the dominant subprocess contributing to charm quark production is gluon-gluon fusion, this measurement provides a means for studying the distribution of gluons in nuclear matter. If the distance scale is small compared to the size of a nucleon, and if the gluon distribution is the same in different nuclei, then the cross section per nucleon should not depend on the target type. If the dependence of the cross section per nucleus on atomic mass, A, is parametrized by the form A^α, then the behavior described above is characterized by $\alpha = 1$. In contrast, for the total inelastic cross section in pion-nucleon collisions, $\alpha = 0.75$ [1], which can be compared to the value of 2/3 expected from scattering by a totally absorbing sphere. The target dependence of the charm cross section is also important in comparing results from experiments with different target materials and in choosing the target material for future heavy quark experiments.

The measurements presented here are from Fermilab experiment E769. This experiment utilized a charged, secondary beam of momentum 250 GeV. Data were taken with both negative and positive charged beams. These beams consisted of a mixture of pions, kaons, and protons. The beam content was measured with a differential Cherenkov counter (DISC) [2]. The negative beam consisted of 93% π^-, 5% K^-, and 1.5% $\overline{p}$, and the positive polarity beam consisted of 61% π^+, 4.4% K^+, and 34% p. During normal data taking, the DISC detected kaons, with an efficiency of about 40% and negligible contamination from pions. After removing DISC-tagged kaons, the negative beam sample used in this analysis consisted of 95% π^- with a contamination of 3% K^- and 2% $\overline{p}$. The pions were tagged in the positive data with a transition radiation detector (TRD) [3] with a typical efficiency of 87%. After tagging, the positive beam sample consisted of 98% π^+ and contamination of 2% p. The beam particle measurement was also aided by 8 multiwire proportional chambers (MWPC's) and 2 silicon microstrip detectors (SMD's).

The A dependence measurement was made by simultaneously exposing foils of Be, Al, Cu, and W with total nuclear interaction length of 2%. The high-Z materials were located mostly upstream, to minimize multiple scattering effects. The Be, Al, and Cu foils were each 250 μm thick, and the W foils were each 100 μm thick. The foils were separated by 1.6 mm gaps along the beam direction. The coincident exposure of all targets allowed cancellation of systematic errors associated with beam conditions, experimental dead time, and relative luminosity. Since the total nuclear interaction length through all the target foils was only 2%, nearly all the beam struck each target foil.

The open-geometry spectrometer used in E769 was substantially the same as previously used in Fermilab photoproduction experiment E691 [4]. For E769, the downstream spectrometer included an 11-plane SMD vertex detector, 2 analyzing magnets, 35 drift chambers, 2 MWPC's, 2 segmented, threshold Cherenkov counters, electromagnetic and hadronic calorimeters, a muon detector, and a high-rate, microprocessor-based data acquisition system. More detailed descriptions of the apparatus are found in the references cited in [5]. Using a trigger based on transverse energy measured in the calorimeters, we recorded about 150×10^6 events from π^- interactions and 87×10^6 from π^+ interactions.

In an off-line analysis we reconstructed the complete data sample and then selected a subset of events passing a secondary vertex filter, as described in [5]. Using this event subset, we illustrate the foil structure of the target by the distribution of reconstructed primary vertices along the beam direction, shown in Fig. 1(a). The four most upstream Be foils were not used in the A dependence analysis. This avoided misidentification of the foil target from degradation of the primary vertex resolution due to multiple Coulomb scattering in the high-Z foils. The primary vertex resolution is further improved in subsequent analysis after selecting events where the decay tracks from the reconstructed D are removed from consideration as coming from the primary vertex.

The charm mesons are detected by fully reconstructing the decays $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, and charge conjugates. (In this Letter, reference to a decay implicitly includes the charge conjugate.) To select events with these decays, we applied further analysis cuts to the events that passed the secondary vertex filter. The significance of the vertex separation along the beam direction was required to be $>12\sigma$ (8σ) for charged (neutral) decays. The direction of the D was calculated from the summed three-momenta of the decay products. The summed P_T^2 of the decay tracks, with P_T measured relative to the direction of the parent, was required to be >0.5 GeV^2 (0.7 GeV^2) for charged (neutral) decays. The distance between the primary vertex and the line of flight of the parent D was required to be < 80 μm for both charged and neutral decays. For the charged D's, the decay vertex was required to be isolated from tracks from other vertices: No tracks other than those of the decay particles were allowed to pass within 60 μm of the reconstructed decay vertex. We further required that the reconstructed tracks from the candidate D pass closer to

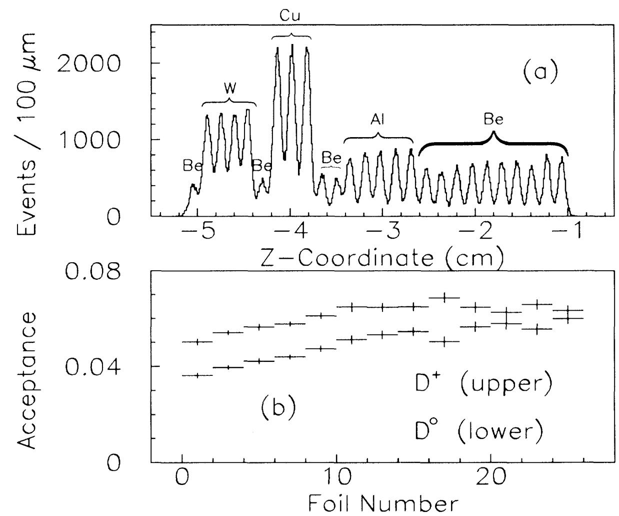

FIG. 1. (a) The coordinate along the beam direction of reconstructed primary vertices in the 26 foil targets. (b) Acceptance for $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$. For simplicity, the acceptance shown is the average for consecutive pairs of foils. In the analysis for α, the acceptance is evaluated for the sum of all the foils used for each material. The acceptances shown are for incident π^-. For incident π^+, the shapes of the acceptances are the same, but the efficiencies are about half those for π^-, due to the higher instantaneous beam flux for π^+ compared to π^-.

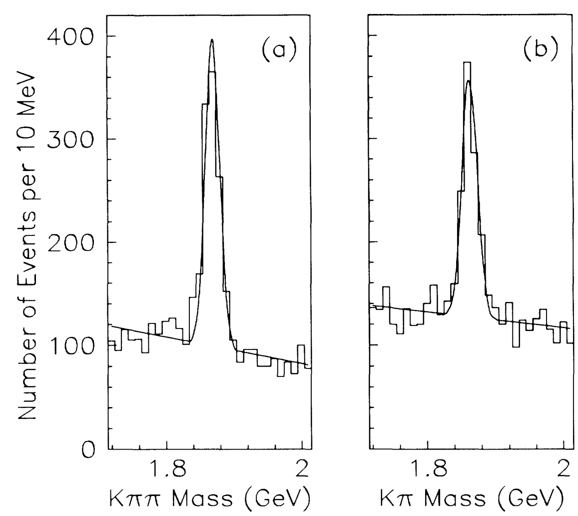

FIG. 2. Invariant mass distribution for (a) $D^+ \to K^-\pi^+\pi^+$ and (b) $D^0 \to K^-\pi^+$. The curves show the results of least-squares fits by Gaussian signals plus linear backgrounds.

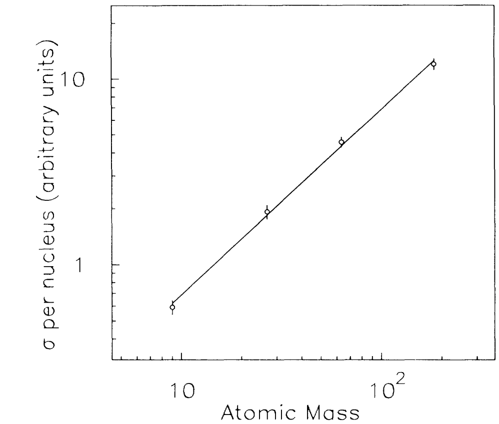

FIG. 3. Relative cross section for D^+ and D^0 production vs atomic mass. The line is a fit by the form A^α with $\alpha = 1.00 \pm 0.05$.

the decay vertex than to the interaction point. We calculated, for each decay track, the ratio of its distance from the secondary vertex to its distance from the primary vertex. The product of these terms over the decay tracks was required to be < 0.006 (0.1) for charged (neutral) decays. Using the Cherenkov counters, we excluded identified pions as candidate kaons from charm decay. The resulting invariant mass plots for the two decay channels are shown in Fig. 2. The number of reconstructed decays is 776 ± 35 D^+ and 650 ± 36 D^0 as determined from fits to the invariant mass distributions. Of the reconstructed D mesons, 20% were produced with the π^+ beam, the remainder with the π^- beam. There are two reasons for this composition. First, the integrated beam flux was less for π^+ than for π^-, as previously discussed. Second, the instantaneous beam flux was higher for π^+ than for π^-, resulting in detector efficiencies lower for π^+ than π^-.

The number of events in each target type was converted to a relative cross section using the number of nuclei and spectrometer acceptance for each target type. The acceptance was calculated from a complete Monte Carlo simulation which included the effects of the resolution, geometry and efficiency of all detectors, interactions in the apparatus, and all analysis cuts. The acceptances

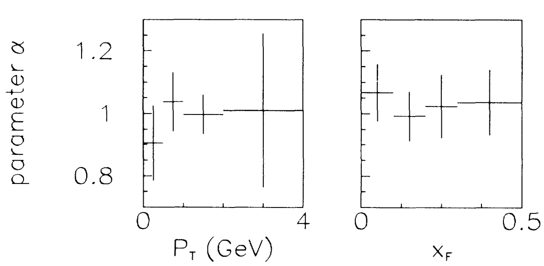

FIG. 4. Dependence of the parameter α on P_T and x_F for D^+ and D^0.

TABLE I. Comparison of the values of α measured in this experiment with others [6, 7] using π^- beams.

Expt.	P(beam) (GeV)	Detected charm	α	x_F range
E769	250	D^0, D^+	1.00 ± 0.05	> 0.0
WA82	340	D^0, D^+	0.92 ± 0.06	> 0.0
WA78	320	Inclusive μ^-, μ^+	0.81 ± 0.05	> 0.2

for charged and neutral D's, in the range $0.0 < x_F < 0.8$, as a function of foil position, are shown in Fig. 1(b). We studied the size of systematic errors due to uncertainties in the target composition, misidentification of the target material due to primary vertex resolution, attenuation of the beam flux from interactions in the foils, trigger efficiency, detector efficiencies, and signal estimation from fitting the mass plots. We estimate the overall systematic error due to these effects to be ± 0.02, which is negligible in comparison with the statistical errors in the data. In the discussion below, we quote only the statistical error in α.

The relative cross section for D^+ and D^0 for incident π^- and π^+, combined, versus A, is shown in Fig. 3. The four data points are well fitted by a function of the form A^α, giving $\chi^2/N_{\rm DF}$ of 0.7 with $\alpha = 1.00 \pm 0.05$.

The dependences of α on the transverse momentum (P_T) of the D and the longitudinal momentum fraction (Feynman x or x_F) are shown in Fig. 4 for the same data set as in Fig. 3. The values of α for D^0 and D^+, separately, are 1.05 ± 0.07 and 0.95 ± 0.06, respectively. The values of α for π^- and π^+, separately, are 1.00 ± 0.05 and 1.03 ± 0.15, respectively. Thus, there is no significant dependence of α on the transverse or longitudinal momentum of the D meson, the type of D meson (neutral or charged), or the beam polarity.

A comparison of our results with other measurements of α [6, 7] for charm production by pions is shown in Table I. The measurement of α from WA78, based on the inclusive muon spectrum, suggested that the A dependence for charm production was similar to that for the total inelastic cross section. However, our result, together with the measurement from WA82, suggests that α is close to 1. This reinforces the picture that charm production and fragmentation are short-range processes and that the gluon distributions in various nuclei, in the x range probed by charm production, are similar.

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