FORWARD PRODUCTION OF CHARM STATES AND PROMPT SINGLE MUONS IN 278 GeV π^-–Fe INTERACTIONS ☆

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The forward production of charm states in 278 GeV π^-–Fe interactions has been studied via the production of prompt single muons with momentum $\gtrsim 20$ GeV/c. The production of prompt $1\mu^-$ is significantly larger than the production of prompt $1\mu^+$ events. For $x_D \gtrsim 0.2$ the data indicate that on the average D mesons are produced with a $(1-x)^2$ distribution. The experimental distributions are compared with various charm production models. A fit to a model incorporating both central and forward production yields a production cross section of $17.5^{+5.4}_{-3.9}$ μb/nucleon ($x > 0$), assuming a linear A dependence and an 8% average semileptonic branching ratio.

In a previous letter [1] we have reported on a study of the forward production of charm states in 350 GeV proton–Fe interactions from measurements of the production of prompt single muons. In this communication we report on a similar study for 278 GeV/c π^-–Fe interactions. A comparison of proton and pion charm production is of interest because in QCD models [2] q–$\bar{\text{q}}$ annihilation processes are expected to contribute in addition to the dominant gluon–gluon process. The flatter quark, antiquark and gluon x distributions in the pion lead to a prediction of flatter x distributions for the produced charm state. In addition the possibility of recombination of charm quarks with the valence quarks of the π^- ($\bar{\text{u}}$d) yielding final states

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with D^0's ($c\bar{u}$) and D^-'s ($\bar{c}d$) (as opposed to $\bar{D}^0$'s ($\bar{c}u$) and D^+'s ($c\bar{d}$)) may be investigated by using the difference in the D^0 and D^- semileptonic branching ratios.

The apparatus and the analysis are described in detail for both the proton and pion data in ref. [3]. Briefly, data were taken with both 350 GeV protons and 278 GeV π^-'s incident on an iron "beam dump" instrumented with scintillation counters. Single muons and dimuons were detected and tracked in a large acceptance iron-scintillator muon identifier which was followed by an iron toroid muon spectrometer. The density extrapolation technique was used to separate prompt muons from non-prompt muons originating from the decays of long-lived particles such as π's. K's and hyperons. The mean interaction point was kept fixed for the three target densities used. The most compact density of the target calorimeter was about 3/4 that of steel. The density of the first 10 interaction lengths was varied in the ratio 1:2/3:1/2. Data were taken with beam intensities varying from 10^4 to 10^5 interactions per second and with two different triggers Both triggers required a single incoming hadron to interact in the first 40 cm of the calorimeter and be in coincidence with a muon in the muon identifier. In addition, the first trigger required a muon with a momentum $P > 8$ GeV/c, and the second one required a muon to penetrate the entire toroid spectrometer system. This corresponded to a requirement of $P \gtrsim 20$ GeV/c. In this communication we report on the analysis of the $P_\mu \gtrsim 20$ GeV/c data taken with incident pions.

The 278 GeV π^- beam was produced by targeting 350 GeV protons on a 1 interaction length aluminum target located in the neutrino area at Fermilab. Negatively charged secondaries were transported by the N5 beam line [4] to the detector located in Laboratory E. The hadron composition of the beam was [‡1] predominantly π^-'s with about a 0.3% K^- contamination. Unlike the case of the 350 GeV diffracted proton beam, the negative beam had a small (~1%) muon component. The effects of the muon component and the muon halo had to be removed from the data.

The muons from the decays of π's and K's in the beam led to four sources of background which only affected events with final state negative muons. These were: (A) accidental coincidences between a hadron interaction and a beam or halo muon, (B) decays just upstream of the calorimeter of the type $\pi^- \to \mu^-\bar{\nu}\gamma$ (BR $= 1.2 \times 10^{-4}$), $K^- \to \mu^-\bar{\nu}\pi^0$ (BR = 3.2%) and $K^- \to \gamma\mu^-\bar{\nu}$ (BR = 0.5%) where the photon shower in the calorimeter simulated an interaction, (C) muon interactions of the type $\mu^- + \mathrm{Fe} \to \mu^- + \mathrm{Fe} + \gamma$, $\mu^- + \mathrm{Fe} \to \mu^- + \mathrm{Fe} + e^+ + e^-$ and $\mu^- + e^- \to \mu^- + e^-$, and (D) muon interactions of the type $\mu^- + \mathrm{Fe} \to \mu^-$ + hadrons.

The contribution of accidental coincidences between a hadron and a beam muon (source A) was greatly reduced in hardware using two large halo counters. The remaining accidental events were removed using the following cuts: (1) the muon and hadron were required to be in the same RF bucket (i.e. be in time within ±5 ns), (2) the total energy in the calorimeter plus the energy of the muon was required to be less than 1.2 times the beam energy, (3) it was required that there be only one incident particle with momentum within ±2.5% of the nominal beam momentum (using the upstream beam tagging spectrometer) and (4) the muon track was required to point at the location of the interaction. As a check, data were taken at a factor of 10 lower intensity. After imposition of the off-line cuts described above the event rate per interaction for the low-intensity and high-intensity data were the same, within errors.

Muon events from sources (B) and (C) were recognized by the fact that electromagnetic showers have a much shorter longitudinal length than those of hadronic interactions. Typically, outgoing muons in such events had very high momentum (peaking around 240 GeV/c) with a tail extending to lower momenta. Therefore, only events with $P_\mu < 150$ GeV/c were used in the analysis. At these momenta the shower length distributions were used to determine the small fraction of muon background events in each momentum bin and for each density setting. The total background to the single μ^- rate from sources (B), (C) and (D) ranged from 6% for the most compacted density, to 3% for the lowest-density data. The largest contribution came from electromagnetic processes (source C). Rare decays (source B) contributed a negligible 0.3%, and the small background from inelastic scattering (source D) was computed [3] to be about 0.6%. The event rates (with these backgrounds removed for $P_\mu < 150$ GeV/c) are shown in fig. 1 for single muon and dimuon event categories as a function of inverse density. The difference between the slopes of the $1\mu^+$ and $1\mu^-$ data is a result

[‡1] The particle composition of the secondary beam as a function of Feynman x was obtained from ref. [5].

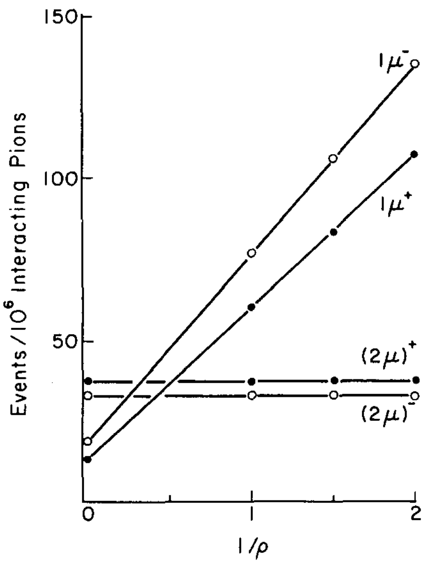

Fig. 1. Density extrapolations for single muon ($1\mu^+$ and $1\mu^-$) and dimuon [$(2\mu)^+$ and $(2\mu)^-$] events (for $P_\mu < 150$). The contribution of beam muon interactions has been removed from the rates μ^- at each density. The + or − refer to the sign of the muon satisfying the trigger conditions. The rates are based on a total sample of 178 992, 140 159, and 198 020 events for $1/\rho = 1$, $1/\rho = 1.5$ and $1/\rho = 2$ respectively. The error bars are smaller than the points on the drawing.

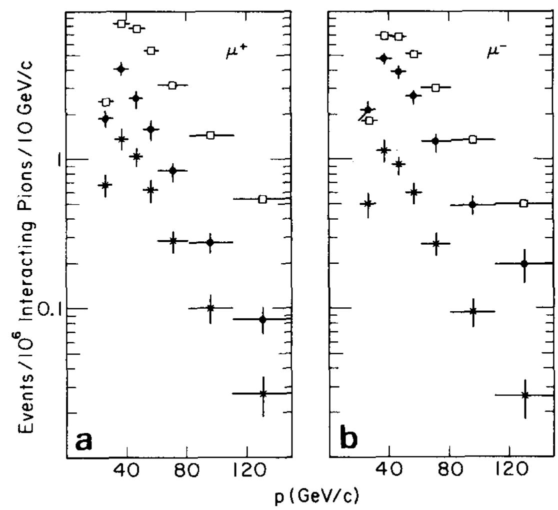

Fig. 2. Rates for observed dimuons (open squares), raw prompt single muons (dark circles) and the calculated background (crosses) from highly asymmetric dimuons versus momentum for events with triggering (a) μ^+'s and (b) μ^-'s.

of the fact that for incident negative beam the production of π^-'s is larger than π^+'s in the forward direction.

The largest remaining background in the single muon data came from highly asymmetric dimuon events because muons of momenta less than 5 GeV/c were not identified. Fig. 2 shows the raw rates for prompt dimuon and single muon events as a function of momentum. Also shown is the contribution of the misidentified dimuon background calculated as described in ref. [3]. After all background subtractions total prompt $1\mu^+$ and $1\mu^-$ rates are $(7.78 \pm 0.74) \times 10^{-6}$ and $(13.85 \pm 0.87) \times 10^{-6}$ per interacting pion, respectively. The prompt $1\mu^-/1\mu^+$ ratio is 1.78 ± 0.20. Fig. 3 shows the ratio of prompt $1\mu^-/1\mu^+$ events for momenta greater than $P_\mu^{\min}$. The trigger efficiency for μ^+ and μ^- events is nearly the same (dashed line in fig. 3). The large asymmetry between the forward production of prompt $1\mu^+$ and $1\mu^-$ events in π^- interactions is very different from the near equality of the corresponding rates observed in proton interactions [1] (where the ratio $1\mu^-/1\mu^+$ is 1.08 ± 0.19).

The dominant source of the observed prompt single muons is the production and subsequent semileptonic decay of charm states. The prompt single muon distributions were compared to the predictions of a model

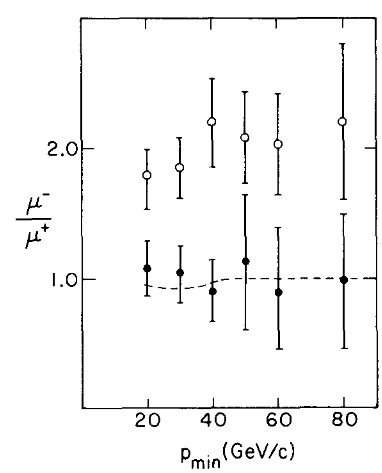

Fig. 3. The ratio of prompt single $1\mu^-/1\mu^+$ events for muon momenta greater than $P_\mu^{\min}$, as a function of $P_\mu^{\min}$ for pions (open circles) and protons (solid circles), respectively. Data are shown for both 278 GeV incident π^- and for 350 GeV protons. The dashed line shows the ratio expected for equal μ^+ and μ^- production taking detector acceptance into account.

in which the only source of prompt single muons are D mesons produced according to an invariant cross section of the form

$$E\, d^3\sigma_D/dP^3 \propto (1-|x|)^\alpha f(P_t), \qquad (1)$$

where x and P_t are the Feynman x and transverse momentum of a D meson, respectively. We have assumed that the semileptonic decay modes of the D are $D \to K\mu\nu$ (60%) and $D \to K^*\mu\nu$ (40%). Single muons from the semileptonic decays of D's generated according to the model were propagated through the apparatus using a Monte Carlo program which included the effects of multiple scattering, dE/dx and resolution. The resulting Monte Carlo "data" tapes were analyzed in the same way as the regular data. The model predictions included D production by secondary interactions in the calorimeter (which amounted to ~15% of the primary contribution). In the calculation of the contribution of secondary interactions we have used the energy dependence of charm production from the QCD calculation of Carlson and Suaya [2]. The results that we quote for cross sections and distributions are for the *primary collisions* only.

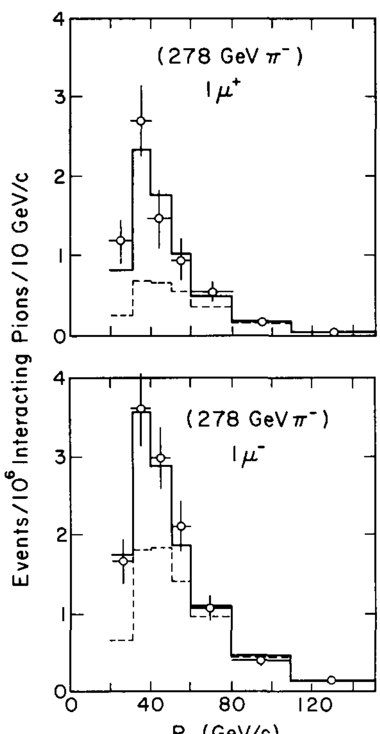

Fig. 4. Prompt single muon distributions for 278 GeV incident π^- on iron versus P_μ. The solid line shows the sum of forward and central charm production contributions. The dashed line shows the forward component only.

Because of multiple Coulomb scattering in the calorimeter the data do not constrain the P_t fits very well. A fit using $f(P_t) = \exp(-aP_t^2)$ yields $a = 0.70 \pm 0.15$. A fit using $f(P_t) = \exp(-bm_T)$ where $m_t^2 = P_t^2 + m_D^2$ yields $b = 3.5 \pm 0.5$, and a fit using $f(P_t) = \exp(-cP_t)$ yields $c = 2.0 \pm 0.2$. These numbers are similar to what we obtain with incident protons [1] [‡2]. The CERN NA16 experiment [6] using the high-resolution bubble chamber LEBC obtains $a = 1.1 \pm 0.3$ in 360 GeV π^-–p interactions.

The x distribution of D meson production can be inferred from the data by comparing the model prediction to the momentum distributions of single muon events (see fig. 4). The best fit to the $1\mu^+$ data is obtained with $(1-|x|)^{2.1\pm0.5}$ (for $x \geqslant 0.2$). *Extrapolation of this form* to $x = 0$ yields a total cross section σ_D $(x \geqslant 0) = 8.8 \pm 0.8$ (± 1.6) μb/nucleon. The best fit to the $1\mu^-$ data is obtained with a $(1-|x|)^{1.6\pm0.3}$ distribution which yields a cross section $\sigma_{\bar{D}}$ $(x \geqslant 0) = 13.2 \pm 0.8$ (± 1.5) μb/nucleon. The first error is statistical and the second error is the error from the uncertainty in the exponent of $(1-|x|)^\alpha$. The cross sections are determined using an average semileptonic branching ratio of 8% and a linear atomic weight (A) dependence of the cross section [‡3]. These cross sections would be a factor of 3.8 larger if an $A^{2/3}$ dependence of the cross section were assumed. Since the extraction of the total cross section requires an extrapolation from $x \gtrsim 0.2$ to $x = 0$, the extracted values depend on the assumed form of the x distributions.

Several possible hypotheses can be suggested to explain the observed difference in the μ^+ and μ^- rates. Some of the possibilities are:

(a) Different x distributions for D and $\bar{D}$ production.

(b) Production of an additional channel, e.g. $\Lambda_c\bar{D}$ production.

(c) Additional production mechanism, e.g. D, $\bar{D}$ pro-

‡2 The fits to our 350 GeV proton data yield $a = 0.75 \pm 0.2$, $b = 3.5 \pm 0.7$ and $c = 2.0 \pm 0.4$.

‡3 We have normalized to the inelastic cross sections of 12.6 μb/nucleon and 9.9 μb/nucleon [7] for p–Fe and π–Fe interactions, respectively.

duction via quark recombination mechanism.

We next discuss each one of these alternatives in more detail.

The fits to the x distributions extracted from the μ^+ and μ^- are consistent with the same x dependence, as discussed above On the other hand, the data also do not exclude a flatter μ^- (i.e. $\bar{\mathrm{D}}$) distribution which would give a higher μ^- yield because of the better acceptance of our detector at high x. However, the large observed difference between the prompt $1\mu^+$ and $1\mu^-$ rates would require a difference in the x distribution which is larger than indicated by the above fits.

We now turn to the hypothesis of additional production mechanisms. More specifically, we assume a central $\mathrm{D}\bar{\mathrm{D}}$ production mechanism that yields identical distributions for the D and $\bar{\mathrm{D}}$ mesons and an additional production mechanism that enhances forward μ^-. As mentioned above associated $\Lambda_c\bar{\mathrm{D}}$ production would be one possibility, the rate of μ^+ from Λ_c being suppressed both by the lower Λ_c semileptonic branching ratio [8,9] and the relatively backward production of Λ_c.

We have fit the *difference* between the prompt $1\mu^-$ and prompt $1\mu^+$ rates as a function of momentum. We find that a forward component in which $\bar{\mathrm{D}}$'s are produced as $E\,\mathrm{d}^3\sigma_{\bar{\mathrm{D}}}/\mathrm{d}P^3 \propto (1-x)^{0.8\pm0.6}$ yields a muon distribution that fits the $1\mu^- - 1\mu^+$ distribution. These data also yield $B'\sigma_{\bar{\mathrm{D}}}^{\mathrm{assoc.}} = 0.3 \pm 0.05\ (\pm 0.10)\ \mu\mathrm{b}/$nucleon where B' is the average semileptonic branching ratio of the D^- and $\bar{\mathrm{D}}^0$ mesons produced in this forward process Thus, for B' in the range of 5% to 10%, the $1\mu^- - 1\mu^+$ data indicate $\sigma_{\bar{\mathrm{D}}}^{\mathrm{assoc.}}$ between 3 and 6 μb/nucleon. The above cross sections were extracted assuming atomic weight dependence of the cross section of $A^{1.0}$.

Another mechanism which can give a charge asymmetric forward μ component is the quark recombination process. If there is a significant recombination of the charmed quarks with the valence quarks of the incident pion then final states with D^-'s would dominate over $\bar{\mathrm{D}}^0$'s and final states with D^0's would dominate over D^+'s at large values of x. In this case the difference in branching ratios [9] between the charged and neutral D's would yield a μ^-/μ^+ asymmetry. Recent data from CERN experiment NA16 [6] and CERN experiment NA11 [10] indicate that the forward production of D^-'s and D^0's is larger than that of D^+'s and $\bar{\mathrm{D}}^0$'s and thus is consistent with this hypothesis.

To quantify this hypothesis we have fitted the μ^+ and μ^- distributions to a sum of a central (non-recombination) contribution $\propto (1-|x|)^{\alpha_c}$ and a forward (recombination) contribution $\propto (1-|x|)^{\alpha_f}$. Other parameters in the fit were the total cross section times branching ratio $B_{\mathrm{ave}}\sigma_{\mathrm{charm}}$, the fraction of the total which belongs to the forward contribution F_f, and the ratio of semileptonic branching ratios to μ^- versus μ^+ for charm states produced in the forward component, $R(\mathrm{D}^-/\mathrm{D}^0)$ (see below). We find $\alpha_c = 6.6^{+4.5}_{-2.3}$, $\alpha_f = 0.5 \pm 0.5$ and $R(\mathrm{D}^-/\mathrm{D}^0) = 2.5^{+1.0}_{-0.5}$. For these values of α_c and α_f the acceptance of this experiment is 4% for the central and 22% for the forward components ($x \geqslant 0$). We also find $\sigma_{\mathrm{charm}} = 17.5^{+5.4}_{-3.9}\ \mu$b/nucleon and $F_f = 25\%^{+15\%}_{-10\%}$. The total cross section was extracted for $x > 0$ assuming $B_{\mathrm{ave}} = \frac{1}{2}\,[B(\mathrm{D}\to\mu^+) + B(\bar{\mathrm{D}}\to\mu^-)]\ \mu^- = 0.08$ for both central and forward production, and a linear $A^{1.0}$ dependence of the cross section. The forward cross section ‡4 $F_f\,\sigma_{\mathrm{charm}}$ of 4.2 μb/nucleon would be increased by a factor of 3.8 if an $A^{2/3}$ dependence is assumed for forward production. The errors in the cross section include statistical and systematic errors. The errors from the assumption on the branching ratios, A dependence, or the model assumption are not included. The cross sections extracted using a non-invariant form of the cross section are given in footnote 5. The above pion cross sections can be compared to the cross section $\sigma_{\mathrm{proton}}^{\mathrm{total}} = 10.7 \pm 1.1\ (\pm 1.8)\ \mu$b/nucleon ($x > 0$) extracted from our 350 GeV p–Fe data [1,3].

The possibility of two components in D meson production with incident pions has been suggested by the CERN NA16 experiment [6] (LEBC). They obtain ‡5 best fits to the *non-invariant* D meson distributions of $(1-\mathbf{x})^{6\pm3}$ for the central component and $(1-x)^{1\pm1}$ for the forward component in 360 GeV/c π^-–p interactions. Their data indicate a *total* charm production

‡4 Fits to the forward and central components separately yield $B_f(1-B_f)\,\sigma_f = 0.32^{+0.17}_{-0.14}\ \mu$b/nucleon and $B_c(1-B_c)\,\sigma_c = 0.96^{+0.41}_{-0.32}\ \mu$b/nucleon where B_f and σ_f and B_c and σ_c are the semileptonic branching ratios and production cross sections for the forward and central components, respectively.

‡5 If we use the non-invariant form in our fits (i.e. $\mathrm{d}\sigma/\mathrm{d}x \propto (1-x)^n$), $n_c = 5.9^{+3.2}_{-1.6}$, $n_f = 0.9^{+0.9}_{-0.6}$, $F_f = 0.24 \pm 0.16$, $R = 2.7^{+1.6}_{-0.8}$ and $\sigma_{\mathrm{charm}} = 20.2^{+4.4}_{-3.7}\ \mu$b/nucleon ($x > 0$) for 278 GeV incident pions. Fits to our 350 GeV proton data using the non-invariant form yield $n = 6 \pm 0.8$ and $\sigma_{\mathrm{charm}} = 8.2 \pm 0.8 \pm 1.4\ \mu$b/nucleon ($x > 0$).

cross section $\sigma_{D\bar{D}} = 20^{+8}_{-4}\ \mu b$, and a forward component of about 30%. Note that in QCD models [2] [‡6] only about 22% increase in the cross section is expected between 278 GeV (our data) and 360 GeV (LEBC data) interactions. The similarity of the LEBC results on hydrogen with our data on iron is consistent with an $A^{1.0}$ dependence.

The value $R(D^-/D^0) = 2.5^{+1.0}_{-0.5}$ is the ratio of the D^- to D^0 branching fractions only if no D^*'s are produced. The effect of D^*'s is to reduce the measured value of this number, leading to an underestimate of the actual ratio of the D^- to D^0 branching fractions. Therefore we can set a lower limit

$$B(D^- \to \mu X)/B(D^0 \to \mu X) > 1.8\ (90\%\ \mathrm{CL}).$$

In summary, the fits to our data on the production of prompt single muons in 278 GeV π^-–Fe interactions yield a total charm production cross section of $17.5^{+5.4}_{-3.9}\ \mu b$/nucleon assuming a two-component production mechanism. The large asymmetry between μ^+ and μ^- production suggests that a fraction (~25%) of the cross section consists of D^0 and D^- mesons produced with fairly flat distribution. The cross sections were extracted assuming a linear A dependence and an 8% average semileptonic branching ratio for charm states.

[‡6] A rough fit to the QCD model of Carlson and Suaya [2] for π–N collisions is $\sigma \propto \exp[-33.5/\sqrt{s}\ (\mathrm{GeV})]$.

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