Prompt Muon Production at Small X_F and P_T in 350-GeV p-Fe Collisions

J. L. Ritchie, A. Bodek, R. N. Coleman, W. Marsh, and S. Olsen
University of Rochester, Rochester, New York 14627

and

B. C. Barish, R. L. Messner, M. H. Shaevitz, and E. J. Siskind
California Institute of Technology, Pasadena, California 91125

and

H. E. Fisk and Y. Fukushima
Fermilab, Batavia, Illinois 60510

and

G. Donaldson, F. S. Merritt,[(a)] and S. G. Wojcicki
Stanford University, Stanford, California 94309
(Received 24 October 1979)

Total prompt muon production rate for muons with $P_{lab} > 8$ GeV has been measured in 350-GeV p-Fe collisions. A prompt rate of $(3.29 \pm 0.45) \times 10^{-4}$ per collision is determined, yielding $\mu/\pi = (0.93 \pm 0.13) \times 10^{-4}$. The μ/π ratio does not show the rise at small X_F and small P_T seen in intersecting-storage-ring electron/π measurements. A charm production cross section of 22 ± 9 μb/nucleon is extracted from the contributions of prompt single muons to the total prompt rate.

Experimental measurements of *prompt-electron* production at ISR[1] ($\sqrt{s} = 53$ GeV) and also BNL[2] ($\sqrt{s} = 4.5$–7) energies have indicated a large increase in the prompt electron/pion ratios for low transverse momentum (P_T) in the central region (Feynman $X_F \simeq 0$). We report on the first measurement of *prompt muon* production in this region.

The apparatus (Fig. 1) is a modified version of a detector used in an earlier prompt-muon experiment[3] which established that prompt *single* muons account for about half of all prompt muons in the region $P_T \cong 1$ GeV/c, and indicated a charm production cross section in the range 13–60 μb/nucleon. The apparatus was modified to extend the study to low X_F and low P_T. We present results from data obtained during a one-week run.

The experiment was performed in the Fermilab N5 beamline with about 1×10^4 350-GeV protons per pulse. The incident protons interacted in a target-calorimeter which consists of 49 (76×76 cm^2) steel plates (a total of 2.44 m of steel) which are independently mounted on rails so that the interplate spacing can be varied. The calorimeter was followed by a muon range detector consisting of 88 3.05-m$\times$3.05-m$\times$5.08-cm steel plates interspersed with 42 3.05-m$\times$3.05-m$\times$3.2-cm liquid scintillation counters with wave-shifter light collectors,[4] and 22 3.2$\times$3.2-m^2 spark chambers with magnetostrictive readout.[5] The amount of light for each muon in the scintillation counters (fifteen photoelectrons) was sufficient to allow discrimination between one and two muons by use of counter pulse heights alone. Additional components of the detector (e.g., muon spectrometer, etc.) are not described here since they were not used in this analysis.

The trigger required a proton interaction in the calorimeter in coincidence with a muon that penetrated at least 5.75 m of steel. Because of the

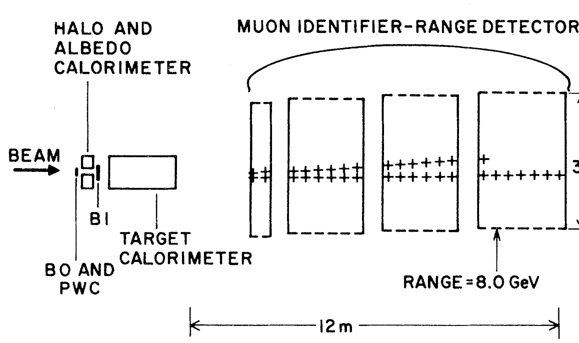

FIG. 1. Plan view of the apparatus. The beam is incident from the left. A dimuon event is shown to illustrate the spark-chamber locations. In addition to the 22 3$\times$3-m^2 spark chambers, the 360-ton range detector (Ref. 5) contains 42 3$\times$3-m^2 scintillation counters.

large size of the range detector, this trigger effectively selected all muons of momentum $P_\mu > 8$ GeV, corresponding to almost the entire forward hemisphere in the center-of-mass system (Fig. 2).

Most muons satisfying this trigger were due to the decay of pions and kaons. This nonprompt background was measured by uniformly expanding the first 38 plates (1.68 m of steel) of the calorimeter, thereby proportionally increasing the mean path length and decay probability of hadrons in this region. Data were taken at three different densities: fully compacted, expanded by a factor of 1.75, and expanded by a factor of 2.5. The mean density of the compacted calorimeter is about $\frac{3}{4}$ that of steel since there are gaps between plates where scintillation counters are mounted. Because of the large size of the muon detector the trigger acceptance is independent of density. The use of two independent muon triggers insured a constant trigger efficiency.

The muon event rate (i.e., events with at least one muon with $P_\mu > 8$ GeV) per interacting proton exhibits a linear dependence on inverse density, ρ (Fig. 3). The intercept at $1/\rho = 0$ of $(3.95 \pm 0.40) \times 10^{-4}$ is the prompt rate. (The effect of nonlinearity due to hyperon decays is less than 1% of the prompt rate.) However, to get the total rate, events with two muons both satisfying the requirement $P_\mu > 8$ GeV must be counted twice. This rate, determined with use of the scintillation counters in the range detector after correlations for accidentals,[6] is $(0.94 \pm 0.01) \times 10^{-4}$, giving a total prompt muon rate of $(4.89 \pm 0.40) \times 10^{-4}$ per interacting proton. This rate has been corrected for a density-independent background [$(8 \pm 4)\%$] from decays occurring downstream of the expanded region. This contribution was determined by a measurement in which only the downstream portion of the calorimeter was expanded.

The above quoted rate is for a thick target and includes contributions from secondary and tertiary hadron and photon interactions. To extract the contribution of the first collision we have performed a shower-development calculation based on radial scaling parametrization of particle production data from hydrogen[7] modified for nuclear effects.[8] The contribution from secondary and tertiary interactions was calculated[9] to be $(1.60 \pm 0.2) \times 10^{-4}$, and subtracted from the total prompt muon rate. The remaining rate of $(3.29 \pm 0.45) \times 10^{-4}$ is the prompt-muon rate for primary collisions. We can express this rate as a $(\mu^+ + \mu^-)/(\pi^+ + \pi^-)$ ratio by dividing by the number of π's (with $P_\pi > 8$ GeV) produced by each primary proton collision. The number of π's of 3.55, extracted from the measured nonprompt muon rate and the shower development calculation,[10] yields $\mu/\pi = (0.93 \pm 0.13) \times 10^{-4}$. The errors here are sta-

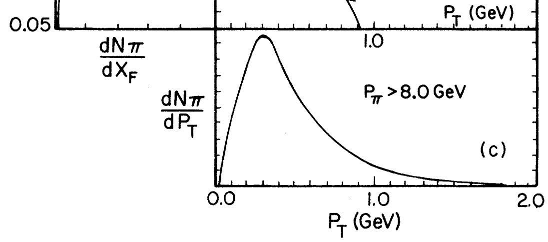

FIG. 2. A calculated spectrum of pions produced in 350-GeV p-Fe interactions with $P_\pi > 8$ GeV, vs X_F and P_T. The acceptance of the experiment covers almost the entire forward hemisphere in the center of mass, except for a small region around the point $X_F = 0$, $P_T = 0$. The region covered by the ISR 30° direct electron experiment is shown for comparison.

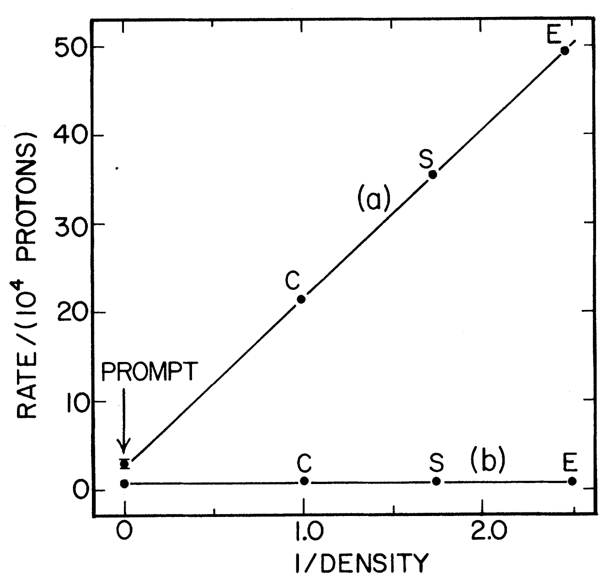

FIG. 3. The event rate vs inverse density. The extrapolated rate is the prompt signal. Curve a, events with at least one muon with $P_\mu > 8$ GeV; curve b, events with two muons each with $P_\mu > 8$ GeV.

tistical. However, fairly conservative assumptions[11] yield an upper limit of 1.38×10^{-4} and a lower limit of 0.78×10^{-4}. The measurement is consistent with the trend of other μ/π data[12] at higher values of X_F as shown[13] in Fig. 4(b). In a similar X_F and P_T region, ISR 30° data [Fig. 4(a)] indicate that the average[14] e/π is (between 3.2 and $4.8)\times10^{-4}$. The trend of the ISR 90° data[15] is in agreement with our measurement.

We now discuss possible sources of the factor of 4.3 difference between our μ/π results and the 30° ISR e/π measurements. If all the difference were attributed to nuclear effects (p-Fe vs pp), then the A dependence of prompt muons at small X_F and small P_T would have to be $A^{0.43}$ (i.e., much less than the inelastic cross section which rises as $A^{0.70}$). Such as unusual A dependence is unlikely. For example, the A dependence of π production (for π's with $P_\pi > 8$ GeV) is $A^{0.79}$ yielding only a 30% difference between p-Fe [3.55 π's (Ref. 8)] and pp [2.45 π's (Ref. 7)] interactions.

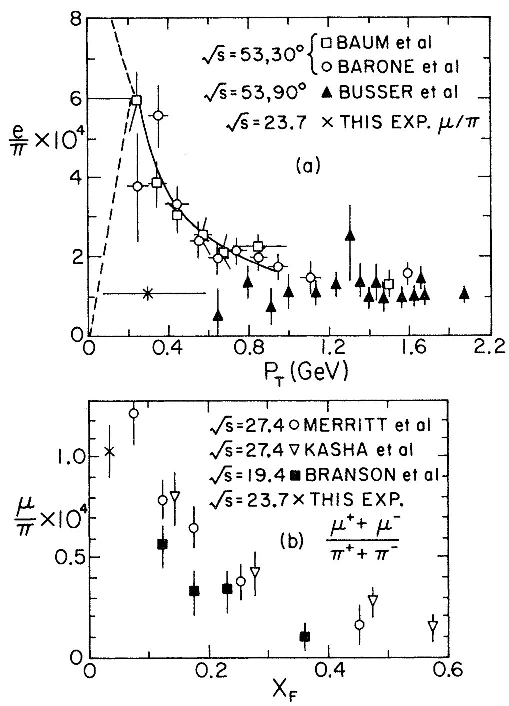

FIG. 4. The μ/π ratio measured in this experiment (p-Fe at 350 GeV) compared with (a) ISR p-p direct electron data at small X_F vs P_T (Refs. 1 and 23), and (b) prompt-muon data at small P_T vs X_F (Ref. 12). The data of Kasha *et al.* (Ref. 12) (p-Cu) is at 400 GeV and of Branson *et al.* (Ref. 12) (p-Fe) is at 200 GeV. The experiment of K. W. B. Merritt *et al.* (Ref. 12) (p-Fe, 400 GeV) was performed with an earlier version of our apparatus.

Also, at higher X_F ($X_F \geq 0.1$) the A dependence for $\mu^+\mu^-$ pairs has been measured[16] to be $\sim A^{0.70}$ for low $M_{\mu\mu}$ and $A^{1.0}$ for high $M_{\mu\mu}$.

Another possibility is that the difference is due to the larger ISR center-of-mass energy. This explanation initially appeared unlikely since a low-energy[2] experiment also indicated a large e/π ratio. However, the experimental situation at low energies is somewhat unclear since more recent low-energy experiments[17] indicate a *small* e/π ratio. We conclude that s-dependent effects cannot be ruled out.

Finally, it is possible that the source of low-P_T electrons does not yield a corresponding rate of low-P_T muons. This would be the case if the low-P_T electrons were from low-mass pairs (because of the muon-electron mass difference) rather than from, for example, charm decays. Baum *et al.*,[18] on the basis of their $e\mu$ measurements, have concluded that charm production[19] is not the source of the large direct-electron rate. Since they veto on very low-mass e pairs, they conclude that the source of direct electrons at low P_T is e^+e^- pairs with $m_{ee} > 0.1$ GeV. Recently, it has been suggested[20] that backgrounds from copious low-P_T η production at ISR energies ($\eta \to ee\gamma$, $B = 0.5\%$ vs $\eta \to \mu\mu\gamma$, $B = 1.5\times10^{-4}$) could be larger than originally estimated by the ISR experimenters. A source such as this could account for the difference between our μ/π and the 30° ISR e/π results. If future measurements indicate that low-P_T η production at ISR energies is not copious, then the difference between the two results may imply a new unknown source of prompt electrons at ISR energies (assuming there is no breakdown of μ-e universality).

The data can also be used to estimate the hadronic charm production cross section. A preliminary separation of one-muon and two-muon events (with use of only the scintillation counters) yields a prompt *single*-muon rate[21] of $(1.15\pm0.5)\times10^{-4}$ per interaction. Using an acceptance[22] of $39\pm1\%$, we estimate[23] a σ_{charm} of 22 ± 9 μb/nucleon assuming linear A dependence [$\sigma_{inel}(p\text{-Fe}) = 13$ mb/nucleon] and a semileptonic branching ratio of 8%. We will report on our charm-production studies in a future publication following a complete analysis of the single muon and two muon distributions.

We thank the staff of Fermilab and the Neutrino Department for their support. One of us (A. B.) would like to thank the A. P. Sloan Foundation for its support. This work was supported in part by grants from the U. S. Department of Energy and the National Science Foundation.

[(a)]Present address: University of Chicago, Chicago, Ill. 60637.

[1]M. Barone *et al.*, Nucl. Phys. B132, 29 (1978); L. Baum *et al.*, Phys. Lett. 60B, 485 (1976).

[2]E. W. Beier *et al.*, Phys. Rev. Lett. 37, 1117 (1976).

[3]K. W. Brown *et al.*, Phys. Rev. Lett. 43, 410 (1979).

[4]B. C. Barish *et al.*, IEEE Trans. Nucl. Sci. 25, 532 (1978).

[5]The range detector consists of half of the neutrino target described by D. Theriot, Fermilab Report No. Fermilab-CONF-79/79-EXP (unpublished).

[6]The accidental 2μ rate originates from uncorrelated decays of two pions. It is determined from the square of the single-muon rate at each density and subtracted.

[7]F. E. Taylor *et al.*, Phys. Rev. D 14, 1217 (1976).

[8]We used an approximate representation of the data summarized by T. Ferbel, in *Proceedings of the Nineteenth International Conference on High Energy Physics, Tokyo, Japan, August 1978*, edited by S. Homma, M. Kawaguchi, and H. Miyazawa (Physical Society of Japan, Tokyo, 1979), p. 465:

$$(dN/dX_F)_A/(dN/dX_F)_H = A^{B(X_F)-0.70},$$

where A is the atomic weight, N is the number per interaction, and $B(X_F) = 0.45 + 0.40(1-X_F)^{2.5}$ for $X_F > 0$; the P_T distributions were modified by a factor $A^{0.23P_T}$.

[9]We have used a parametrization $\mu/\pi = A(s)B(X_F) \times 10^{-4}$, with $A(s) = (-1.91 + 0.88 \ln\sqrt{s})$ for $\sqrt{s} > 15.44$, $A(s) = 0.5$ for $\sqrt{s} < 15.44$, and $B(X_F) = (1-2X_F)$ for $X_F > 0.4$, $B(X_F) = (1-X_F)/3$ for $0.4 < X_F < 1.0$. This form was used with the hadron spectra from secondary and tertiary interactions and yielded a contribution of 1.22×10^{-4} prompt muons per interaction. An additional contribution of 0.38×10^{-4} from photon conversions was calculated using π^0 spectra.

[10]The shower calculation correctly predicted the observed nonprompt muon rate of 18×10^{-4} per interaction in the compacted configuration. A contribution of 7.2×10^{-4} per interaction comes from the decay of 3.55 pions and 0.39 kaons (with $P_\pi > 8$ GeV) produced in the primary collision. An additional 10.5×10^{-4} originates from the 2.7 pions and 0.3 kaons produced in secondary and tertiary collisions.

[11]The upper limit is obtained by dividing the prompt-μ rate from all generations (primaries, secondaries, and tertiaries) by the 3.55 primary π's only. The lower limit is obtained by assuming that the $\sqrt{s}$ dependence of μ/π is flat (i.e., same for primaries and secondaries). The prompt-μ rate from all generations is then divided by the 6.25 π's from all generations.

[12]J. G. Branson *et al.*, Phys. Rev. Lett. 38, 457 (1977) (200 GeV); this reference also presents the 400-GeV μ^+/π^+ and μ^-/π^- data of H. Kasha *et al.*, Phys. Rev. Lett. 36, 1007 (1976), as $(\mu^+ + \mu^-)/(\pi^+ + \pi^-)$ by using π^+/π^- data. The 400-GeV data of K. W. B. Merritt *et al.*, to be published, were presented by M. Shaevitz in *New Results in High Energy Physics—1978*, edited by R. S. Panvini and S. E. Csorna, AIP Conference Proceedings No. 45 (American Institute of Physics, New York, 1978), p. 138.

[13]The value of $\mu/\pi = 0.93 \times 10^{-4}$ is an average over all X_F and P_T (Fig. 2). Using the parametrization of Ref. 9 we have applied a 10% correction yielding $\mu/\pi = (1.03 \pm 0.14) \times 10^{-4}$ at $X_F = 0.03$. This value is plotted in Fig. 4.

[14]An average value of 4.0×10^{-4} was obtained by taking a fit to the ISR data [Fig. 4(a)]: $e/\pi = 1.42 \times 10^{-4}$ for $P_T > 1.06$ GeV, $e/\pi = (1.5/P_T) \times 10^{-4}$ for $0.25 \leq P_T \leq 1.06$, and $e/\pi = 6.0 \times 10^{-4}$ for $P_T \leq 0.25$ GeV, and folding it against the P_T spectrum of pions with $P_\pi > 8$ GeV. The range of $(3.2-4.8) \times 10^{-4}$ is obtained by use of extreme assumptions about the behavior of e/π for $P_T < 0.2$ [i.e., the three curves shown in Fig. 4(a)].

[15]F. W. Busser *et al.*, Nucl. Phys. B113, 189 (1976).

[16]J. G. Branson *et al.*, Phys. Rev. Lett. 38, 1334 (1977).

[17]J. Ballam *et al.*, Phys. Rev. Lett. 41, 1207 (1978); Y. Makdisi *et al.*, Phys. Rev. Lett. 41, 367 (1978).

[18]L. Baum *et al.*, Phys. Lett. 77B, 337 (1978), and 68B, 279 (1977).

[19]Large charm baryon cross sections have been reported by ISR experiments [see A. Kernan, in Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies, Batavia, Illinois, 23–29 August 1979 (to be published)] but these measurements are at large X_F as compared with the small X_F of Ref. 17.

[20]W. M. Geist, CERN Report No. CERN/EP 79-78, 1979 (unpublished).

[21]The observed prompt 1μ rate is $(2.31 \pm 0.4) \times 10^{-4}$, and the 2μ rate ($P_{\mu 1} > 8$ GeV, $P_{\mu 2} > 5$ GeV) is $(1.64 \pm 0.01) \times 10^{-4}$. A preliminary estimate of $(1.16 \pm 0.3) \times 10^{-4}$ for misidentified 2μ's (i.e , 2μ's with $P_{\mu 2} < 5$ GeV) yields a prompt 1μ rate of $(1.15 \pm 0.5) \times 10^{-4}$.

[22]We have calculated our charm acceptance by assuming that D's are produced according to the distribution

$$E\, d^3\sigma/dp^3 = C(1-X_F)^\beta \exp^{(-\alpha P_T)}.$$

Because of our large forward acceptance we are not very sensitive to changes in α and β. For α in the range 2.0–3.5 $(\mathrm{GeV}/c)^{-1}$ and $\beta > 3$ (the region allowed by Ref. 3), we find a charm acceptance of $(39 \pm 1)\%$.

[23]The cross section has been reduced by 10% to account for charm production by secondaries.