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D. Buchholz
Department of Physics, California Institute of Technology
Pasadena, California 91125

and

H. J. Frisch and M. J. Shochet
The Enrico Fermi Institute, University of Chicago
Chicago, Illinois 60637

and

Rolland P. Johnson
Fermi National Accelerator Laboratory
Batavia, Illinois 60510

and

R. L. Sumner
Department of Physics, Joseph Henry Laboratories
Princeton University, Princeton, New Jersey 08540

and

O. Fackler and S. L. Segler
Department of Physics, Rockefeller University
New York, New York 10021

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D. Buchholz+
Department of Physics, California Institute of Technology
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H. J. Frisch and M. J. Shochet
The Enrico Fermi Institute, University of Chicago
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Fermi National Accelerator Laboratory, Batavia, Illinois 60510

R. L. Sumner
Department of Physics, Joseph Henry Laboratories
Princeton University, Princeton, New Jersey 08540

O. Fackler and S. L. Segler
Department of Physics, Rockefeller University, New York, New York 10021

Abstract

Direct muon production in the forward direction in 300 GeV proton-uranium collisions has been measured at Fermilab. The measurements were made for muons with $P_\perp$ less than 400 MeV/c and with momenta 90 GeV/c and 150 GeV/c. The values for the μ/π ratios are $\mu^-/\pi^- = 1.83 \pm .43 \times 10^{-4}$, and $\mu^+/\pi^+ = 6.4 \pm 1.3 \times 10^{-5}$ at 90 GeV/c; and $\mu^-/\pi^- = 4.2 \pm 2.3 \times 10^{-5}$ at 150 GeV/c. The ratio μ^+/μ^- at 90 GeV/c is $1.05 \pm .1$. The signal is too large to be accounted for by known processes.

The direct production of leptons in hadron collisions has been observed previously[1-5] at large $P_\perp$(> 1 GeV/c) and $x \approx 0$.[6] These observations over the BNL to ISR energy range show the inclusive single lepton yield to be at the level of about 10^{-4} of the pion yield and essentially independent of s and $P_\perp$, as well as A, the target atomic number.[2] Measurements of direct lepton production in the forward direction at BNL energies[7] show a strong dependence on the outgoing muon momentum, with the direct production falling rapidly with increasing momentum.

Measurements of the forward muon production, as opposed to production at high $P_\perp$, are particularly interesting because contributions to the direct muon signal from dileptonic decays of massive vector mesons should be suppressed. Also, since the π yield increases at low $P_\perp$, a constant value of μ/π would imply a large total cross section for the production of direct muons. The experiment described here extends the measurements of μ/π to intermediate x ($x \approx .3$) and small $P_\perp$(< .4 GeV/c) to investigate this question and thus the source of the observed direct leptons.

A schematic diagram of the beam and experiment is shown in Fig. 1. The first stage of the Meson Lab M1 beam line at Fermilab was used to transport a 300 GeV/c secondary proton beam to a variable density target of twenty-three 2.54 cm thick uranium plates. Immediately following the target, 3 m of steel was used to absorb hadrons produced in the target. An ion chamber upstream of the target monitored the incident proton flux which was typically 1×10^8 protons per pulse.

Directly upstream of the target, the beam passed through a 60-m long helium-filled threshold Cherenkov counter set to count muons and pions, but not protons. An RCA 31000M photomultiplier was used to achieve single photoelectron resolution. Use of this counter essentially eliminated muons in the incoming beam as a background. This counter was empirically found to be 95% efficient for muons.

The downstream stage of the M1 beam line was used as a spectrometer to momentum analyze and transport produced muons to a muon detector located 90 m downstream of the target. Six small scintillation counters (B1-B6) with air light-guides defined the trajectories of the muons in the spectrometer. The muon detector consisted of 5 m of steel and two large scintillation counters, μ1 and μ2. More than 99% of all particles which emerged from the target and first steel absorber and counted in B1 through B6 also counted in μ1 and μ2.

The quadrupoles Q5-Q8 focused the beam at B4, which defined a ±7% momentum bite. The spectrometer acceptance was 1.1 μsr at a mean production angle of 0° with a full width (half maximum) of 1.3 mr in the horizontal and .8 mr in the vertical. The $P_{\perp}$ acceptance is shown in Fig. 2 at x = 0.3.

Most of the data were taken with a trigger consisting of the coincidence

$$B \equiv B3 \cdot B4 \cdot B5 \cdot B6$$

For each event, the pulse heights of the Cherenkov counter and scintillators B1 and B2 were recorded on magnetic tape via a 2.5 km link to a PDP9 Computer located in the Proton Lab. Scalers and the ion chamber were recorded for each accelerator pulse.

The direct muon to pion ratio was determined by varying the effective density of the U target. Data were taken in alternating runs with the target closed (density $\rho = 0.88\ \rho_U$, where ρ_U is the density of uranium) and target open ($\rho = 0.25\ \rho_U$). The slope of the muon yield vs ρ_U/ρ arises from muons created by the decay of pions and kaons. The average distance these secondary particles travel before interacting is inversely proportional to the density of the target. Extrapolating to infinite density thus eliminates muons created in pion and kaon decays, with the intercept being the direct muon signal. If the shapes of the spectra of pions and kaons produced in the target are known, the slope of the muon yield vs density curve can be used to determine the pion flux. Thus, the ratio of intercept to slope determines the muon to pion ratio.

The negative particle flux was measured by lowering the target and steel out of the beam and allowing the beam to strike a 15 cm thick uranium target. The incident beam intensity was lowered to a countable rate by adjusting the upstream collimators. The measured π^- flux from the 15 cm U target was fit well[8] in the interval x = .3 to x = .7, by the function $(1-x)^4$. The calculated direct-muon-to-pion ratio is not very sensitive to the spectrum: the ratio calculated using a somewhat steeper spectrum measured at 0.8 mr from an aluminum target by Aubert *et al.*[9] differs from that calculated using the measured spectrum from uranium by less than 20%. The positive pion flux was not measured as it was not possible to discriminate positive pions from the more abundant secondary protons. Consequently, the π^+/π^- ratios of Aubert *et al.* and the π^- spectrum measured in this experiment were used to generate a π^+ spectrum.

The contribution from kaon decay was calculated by parameterizing the K^-/π^- and K^+/π^+ ratios measured by Aubert *et al.* as a function of x. We calculate the contribution from K^- to be 16% of that of π^- at x = .3, from K^+ to be 25% of π^+ at x = .3, and from K^- to be 2.3% of π^- at x = .5. The μ/π ratio has been corrected for these contributions (see Table II).

The spectrum used in the slope calculation was determined with the thin target. In the case of the thick target, secondary interactions affect the calculated slope and may affect the intercept. The slope is increased by muons from pions and kaons in the later generations of the hadron shower. This contribution has been calculated by numerical integration of measured pion yields[10]; the thick target slope is 5% greater than the thin target slope at $x = 0.3$. The production of direct muons in the secondary showers changes the intercept. If the direct muon/pion ratio is the same for pion induced reactions as for proton induced reactions, the slope to intercept ratio is unaffected by secondary interactions. The data have not been corrected for these contributions.

The data reduction consisted of determining the ratio $B\cdot\overline{C}$/ion-chamber from the events recorded on magnetic tape, where $B\cdot\overline{C}$ represents the Cherenkov counter in anti-coincidence with the trigger B. For most of the data, B1 and B2 were included in B by examining the pulse height. The Cherenkov counter pulse height threshold was set at 2 or more photoelectrons to eliminate a small but troublesome efficiency for protons. This requirement reduced the muon efficiency to 81%; the number of incoming beam muons was correspondingly corrected. The data were corrected for accidental counts in the Cherenkov counter. These corrections were less than 5%. The data have been corrected for the small difference in detection efficiency (5%) between open and closed target positions.

Backgrounds associated with the beam halo were investigated by intentionally mis-steering the beam. Possible background associated with muons in the incoming beam was investigated by lowering the incident beam intensity and by varying the pressure in the Cherenkov counter confirming that incoming protons produced outgoing muons. This test also excluded off-axis beam muons as a background. There are two possible backgrounds which could not be investigated in the short time available: i) the leakage from the back of the target of high energy protons which then give rise to muons in the steel absorber just downstream; and ii) protons which interact in material upstream of the target, giving rise to muons. Because the target was ~5 absorption lengths thick, i) is expected to be very small. Background ii) occurs only for material after the Cherenkov counter and in front of the target, as muons from interactions upstream of the Cherenkov counter are vetoed. The number of muons produced by material downstream of the Cherenkov counter was estimated by scaling the decay muons detected from the closed target (average absorption length 13.5 cm) by the fraction of protons which interact times the decay length. The total contributions to the signal are listed in Table I. The data have been corrected for these contributions.

The corrected μ/ion-chamber data are shown in Fig. 3. The final μ/π ratios are given in Table II. Note that the number of μ^+ is equal to the number of μ^- per incident proton at x = .3, within statistics. This is expected, for example, if the direct muons are produced only in pairs.

There are two known sources of muons produced in the target itself: i) Bethe-Heitler pair production of muons from γ-rays coming mostly from π^0's, and ii) the production of vector mesons ρ, ω, ϕ, and ψ which can subsequently decay to muon pairs. The contribution to the μ/π ratio from the Bethe-Heitler process can be calculated if the production cross sections for neutral and charged pions are known as a function of x. The calculation has been performed for a number of parameterizations of the pion cross sections, and at x = 0.3, $\mu^-/\pi^-|_{BH} = 1.0 \pm 0.4 \times 10^{-5}$ and $\mu^+/\pi^+|_{BH} = 0.6 \pm 0.3 \times 10^{-5}$. At x = 0.5, $\mu^-/\pi^-|_{BH}$ drops to $\sim 0.35 \times 10^{-5}$. Measurements[11] of electron and pion yields at x = 0.25 in the forward direction are consistent with these calculations.

The production of the lighter vector mesons ρ, ω, and ϕ will also contribute to the "direct" muon signal. The cross section for inclusive ρ

production in p-p collisions has been measured at 12 and 24 GeV by Blobel *et al.*,[12] and at 205 GeV/c by Singer *et al.*[13] At each of these energies, the overall ρ^0 cross sections are about 1/12 to 1/15 of the π^- cross sections. However, because the acceptance of the present experiment is limited to muons with $P_\perp \leq 400$ MeV/c, the ρ contribution is suppressed. Assuming that the ρ^0/π^- ratio is independent of x, the calculated contribution to the μ^-/π^- ratio from ρ decay is $< 1.0 \times 10^{-5}$. There is indirect evidence from Blobel *et al.*, at 24 GeV that the ω inclusive production is equal to that of ρ production. Thus the sum of the ρ and ω contributions is less than 2×10^{-5}. Blobel *et al.* have set a limit on inclusive ϕ production of $\phi/\rho < .01$ at 22 GeV; the ϕ decays are therefore ignored. Also, because the ψ and ψ' are heavy, their contribution to the signal at small $P_\perp$ is negligible.

In conclusion, a non-zero direct muon signal in 300 GeV/c p-U collisions has been measured at values of $P_\perp \leq 400$ MeV/c. The ratio of μ^+/μ^- is unity. The size of the signal is too large to be accounted for by the Bethe-Heitler process and vector meson decay. The signal at very small $P_\perp$ is comparable to that measured at larger values of $P_\perp$. The equality of μ^+ and μ^- production at such small values of $P_\perp$ favors the hypothesis that direct muons are produced in low-mass pairs.

References

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+ Present address: Northwestern University, Evanston, Illinois 60201.

1. G. B. Bondarenko *et al.*, Proc. XVI Intl. Conf. on High Energy Physics, Batavia, Illinois (1972), Vol. 2, p. 329.
2. J. P. Boymond *et al.*, Phys. Rev. Lett. 33, 112 (1974).
3. J. A. Appel *et al.*, Phys. Rev. Lett. 33, 722 (1974).
4. F. W. Busser *et al.*, Phys. Lett. 53B, 212 (1974).
5. D. Bintinger *et al.*, Phys. Rev. Lett. 35, 72 (1975).
6. The Feynman scaling variable, x_F, is defined as $x_F = P_\parallel/P_{\parallel max}$ evaluated in the c.m. The variable x defined as P_μ/P_{beam} measured in the lab differs from x_F insignificantly at these momenta.
7. P. J. Wanderer *et al.*, Phys. Rev. Lett. 23, 729 (1969); C. M. Ankenbrandt *et al.*, Phys. Rev. D 3, 2582 (1971); L. B. Leipuner *et al.*, Phys. Rev. Lett. 34, 103 (1975).
8. The function $\frac{d\sigma^2}{dx d\Omega}\Big|_{\pi^-}$ was parameterized by $(1-x)^4$. The π^+ spectrum $\frac{d^2\sigma}{dx d\Omega}\Big|_{\pi^+}$ was less steep and was parameterized by $x(1-x)^4$.
9. B. Aubert *et al.*, preprint FERMILAB-Conf-75/31-EXP 7300.001 (submitted to the Intl. Colloquium of the CNRS on "Neutrino Physics at High Energy," Ecole Polytechnique, Poincare Amphitheatre, Paris, France (March 18-20, 1975). The spectrum from a uranium target measured in the present experiment is steeper by approximately a factor of (1-x) than that from aluminum of Aubert *et al.* This is consistent with the A dependence measured by Eichten *et al.*, Nuclear Phys. B44, 333 (1972).

10. W. Morris *et al.*, Phys. Lett. 56B, 395 (1975).

11. T. Yamanouchi, private communication.

12. V. Blobel *et al.*, Phys. Lett. 48B, 73 (1974).

13. P. Singer *et al.*, preprint ANL-HEP-PR-75-48 (submitted to Physics Letters B).

Table I - Calculated background contribution to the μ/π ratios from material in the beam.

	fraction interacting × decay path (ft)	
	target open	target closed
upstream	.222	.334
U target	1.57	.450
total	1.79	0.784
$\frac{\text{upstream}}{\text{total}}$	0.124	0.426

Table II - The corrected intercept to slope ratios and the calculated μ/π ratios at x = .3 and .5 for negative muons and x = .3 for positive muons.

sign	P_μ (GeV/c)	intercept (arbitrary units)	intercept/slope*	$\mu/(\pi+K) \times 10^4$	$\mu/\pi \times 10^4$
+	90	4.95 ± 0.51	4.0 ± 0.6	0.48 ± 0.07	0.64 ± 0.13
-	90	4.72 ± 0.18	15.4 ± 3.6	).54 ± 0.36	1.83 ± 0.43
-	150	0.87 ± 0.12	11.2 ± 6.2	0.40 ± 0.22	0.42 ± 0.23

* per unit change in ρ_U/ρ

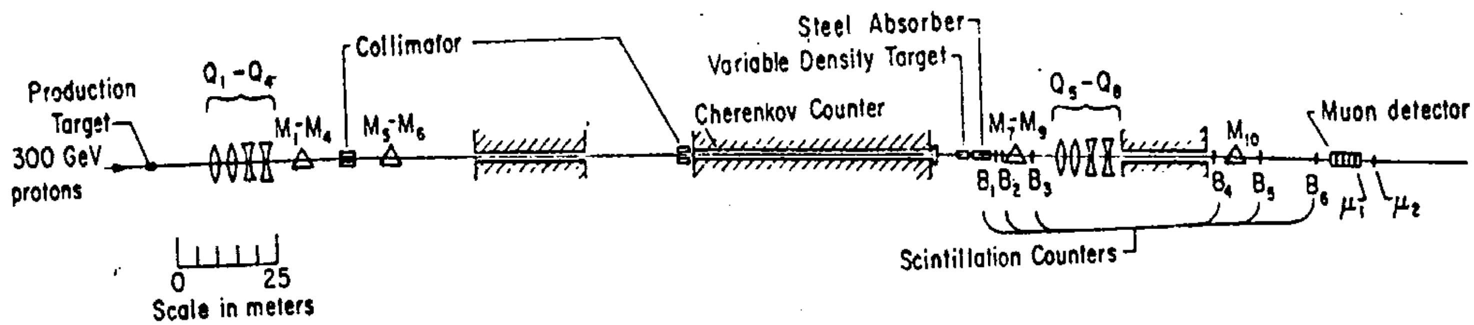

Fig. 1 - The beam and experimental apparatus. The first stage of the beam-line transported 300 GeV protons to the variable density target. The beam-line downstream of the target was used to select and identify muons.

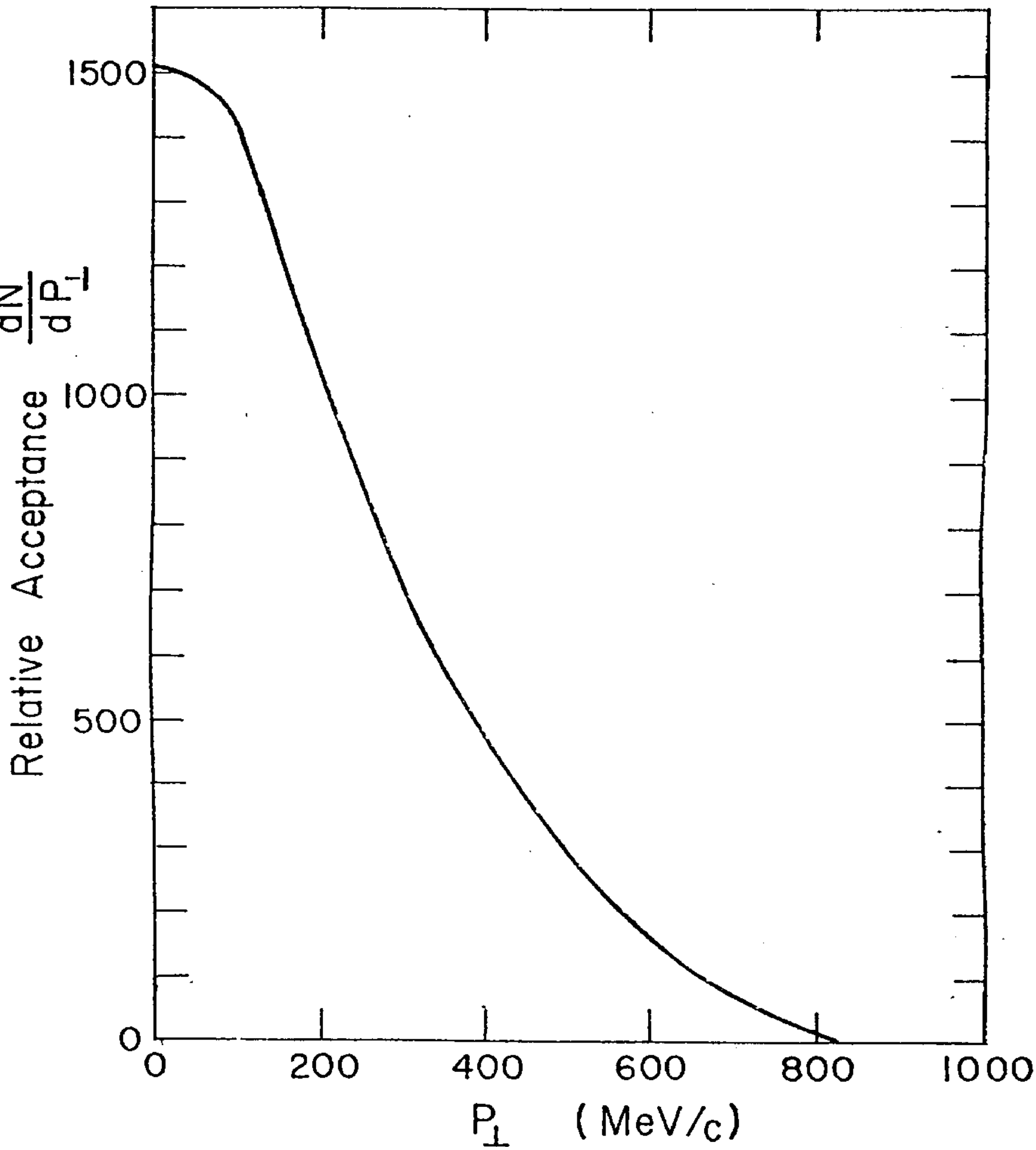

Fig. 2 - The $P_\perp$ acceptance of the apparatus as determined by a Monte Carlo calculation.

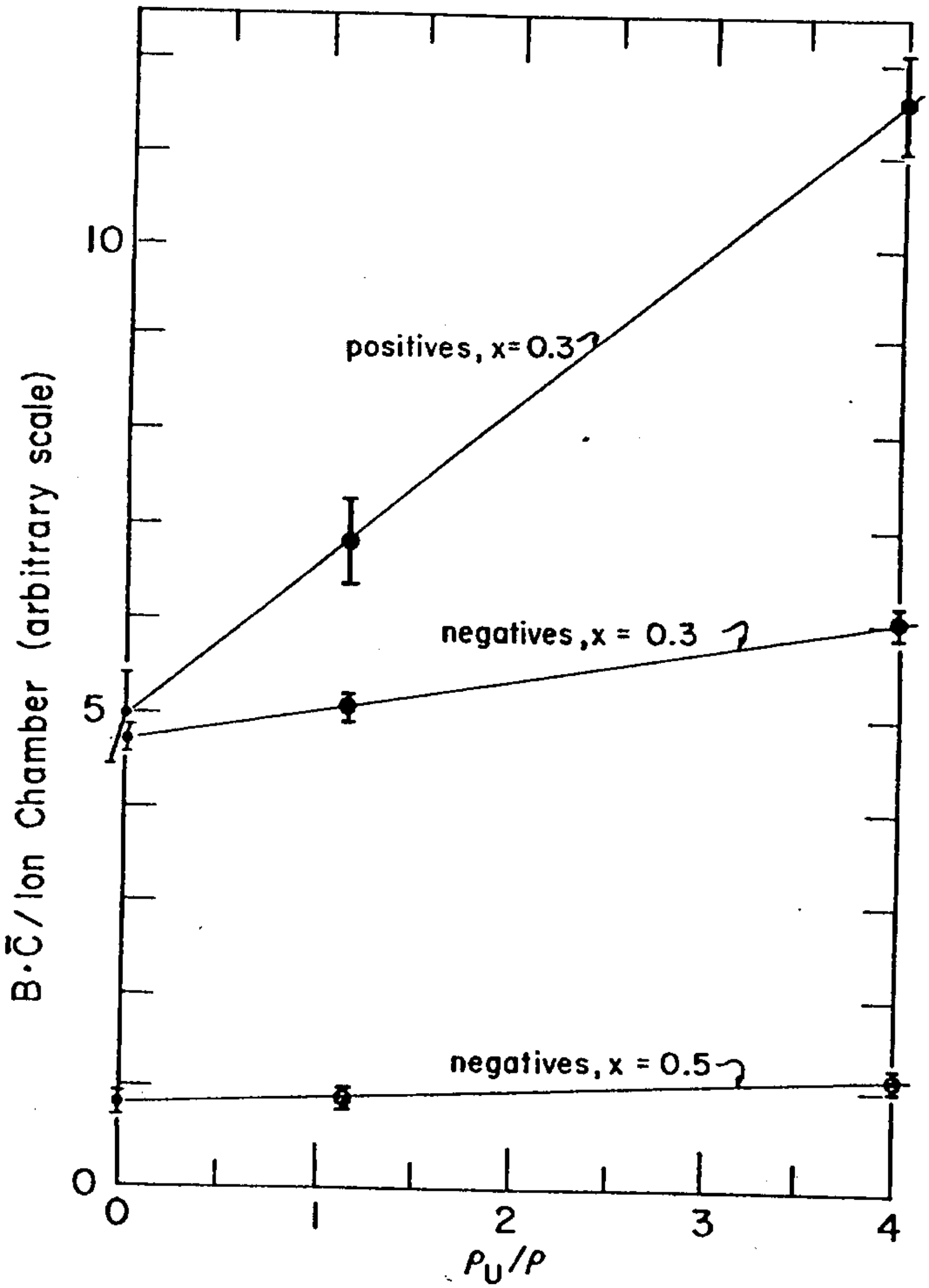

Fig. 3 - The corrected muon flux/ion-chamber vs inverse target density. The intercept corresponds to the direct muon signal per incident proton (arbitrary units).