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NAL PROPOSAL NO. 453

A PROPOSAL TO CONTINUE
MEASUREMENTS OF DIRECT MUON PRODUCTION IN THE FORWARD DIRECTION

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Abstract

We recently have measured the direct muon production in the forward direction at small $p_\perp$ and find a large direct muon to pion ratio. At x = 0.3 the ratio is $\mu^-/\pi^- = 1.83 \pm 0.43 \times 10^{-4}$ for negatives and $\mu^+/\pi^+ = 6.4 \pm 1.3 \times 10^{-5}$ for positives. The direct production of μ^+ and μ^- are equal although the π^+/π^- ratio is large. We propose to continue these measurements and extend them to higher x. These new measurements would also include the A dependence of the μ/π ratio. Based on our experience with this apparatus, we believe it is possible to extend these measurements of single lepton production to production by incident pions and kaons.

I. INTRODUCTION

The origin of direct lepton production[1-5] is as yet not understood. The phenomenon was first discovered at large values of $p_\perp$ ($p_\perp > 1.5$ GeV/c), a kinematic region which itself is not well understood. Questions of the s, x, and $p_\perp$ dependence of the direct muon to pion ratio are still with us almost two years after the publication of the first Fermilab results.[2,3] We recently have completed the first measurements of the direct muon production at very low $p_\perp$, i.e. $p_\perp \leqslant 0.4$ GeV/c. These measurements were made in Experiment E-335 at Fermilab in the M1 beam of the Meson Area. The results, as well as the original E-335 proposal, are attached to this proposal.

A brief summary of the results and their significance is presented here:

1) In 300 GeV proton-Uranium collisions the ratio of direct muons to pions is larger at $p_\perp \leqslant 0.4$ GeV and $x = 0.3$ than for $p_\perp > 1.5$ GeV at $x = 0$.

2) The ratio μ^-/π^- is smaller at $x = 0.5$ than at $x = 0.3$; i.e., the direct muon production is steeper in x than the pion production.

3) Equal numbers of direct μ^+ and μ^- are created, although far more π^+ are created than π^-. This is consistent, for example, with the direct muons (or their parents) being created in pairs.

These results rule out heavy vector mesons as the source of direct leptons. They are consistent, however, with the many-body semi-leptonic decay of a heavy particle, or with either lighter vector parents or continuum creation of the muons.

Although the above results are significant, the measurements are not complete. We would like to finish the job. A brief summary of the problems encountered and overcome is necessary:

1. The operation of the first stage of the M1 beam line at 300 GeV required running magnets at 5250 amps. One entire week of running time was wasted as the power supplies were not phased correctly in spite of the valiant attempts of the Meson Lab technical staff.

2. There were severe halo problems associated with operating the M1 beam line as a quasi-diffracted beam (the M1 line had never been run in this mode before). Because halo creates muons, detecting single muons may become easier than one might wish. Skill in tuning the beam and measuring the backgrounds took time to develop.

3. The Cherenkov counter singles rates were high due partly to beam halo passing through the quartz window in front of the phototube. This could be cured by a more sophisticated optical system in the Cherenkov counter.

4. Access. Because the detector was inside the meson area tunnels, the detector could not be accessed except on down days or by shutting off the Meson Area program. Because a major part of the experiment is the study of systematics and backgrounds, easy access to the target area is essential. Access turned out to be one of the major problems in running Experiment 335.

The data presented in the attached paper represents 18 hours of running, the time remaining after solving background and equipment problems.

II. EXPERIMENTAL APPARATUS

To continue and extend these measurements in the M1 beam line in the present location would require improvements in the beam and apparatus. The beam halo and magnet regulation problems would be greatly diminished by running the beam at 200 GeV/c instead of at 300 GeV/c. The 200 GeV/c beam would improve the beam/halo ratio by almost an order of magnitude. Magnet regulation is less of a problem at 200 GeV/c as the magnets would operate at 2/3 of their peak current. The Cherenkov counter optics would be rebuilt with a more sophisticated design. To continue the experiment with the variable density target in its present location would require 200 GeV/c protons on the Meson Area target. Operation at 300 GeV/c is possible, but at 400 GeV/c is not.

However, we propose substantially improving the experiment by relocating the target and the forward spectrometer downstream of the present location into the M1 or M2 beam lines in the Meson Area Detector Building. A countable beam of less than approximately 5×10^6 particles/pulse could then be used. By shortening the spectrometer, an increase in solid angle would compensate for the loss of a factor of 10 in rate, while still maintaining the acceptance in the region $p_\perp < 400$ MeV/c. Again a threshold Cherenkov counter is necessary to tag incoming muons.

A schematic of the spectrometer is shown in Fig. 1. The target and absorber would be followed by three small (less than 5" × 2") MWPC's with 1.5 mm wire spacing. Small counter hodoscopes with horizontal slats provide additional constraints. Two standard 10-foot long EPB dipoles conservatively operated at 11 kg give a total bend of 10 mr at 200 GeV/c. Three more MWPC's follow the magnets. Muon identification would be performed with four 12" × 12" × 36" steel blocks and plastic scintillators. This setup has 20 times the solid angle and 5 times the momentum bite of the original E-335 spectrometer and has comparable resolution. Parameters of the spectrometer are listed in Table I. If the slightly larger aperature 6-3-120 EPB magnet were available, the solid angle would be double that listed in Table I.

This arrangement eliminates the access and halo problems which were major impediments in carrying out E-335.

The variable density target technique depends on assumptions on the shape of the x distribution in the hadron shower, and on the absorption length in the target. The technique can be refined by measuring the hadron flux from thick targets of different lengths in order to actually measure the hadron shower at different depths in the absorber. This would be done by removing the steel absorber downstream of the target and measuring the hadron spectra from the target with different numbers of Uranium plates removed from the downstream end. These measurements allow a quantitative calculation of backgrounds due to the cascading of hadrons in the thick target, hadron leakage from the downstream end of the target, and Bethe-Heitler pair production from π° production and decay. With this refinement, the variable density target is a viable technique for measuring single direct muon production in the forward direction.

III. TIME SCALE

To move and rebuild the spectrometer requires the construction of:

1) The Cherenkov counter.
2) Eight planes of small MWPC's or drift chambers.
3) Readout, computer, and associated Camac interface.

Based on previous experience with building large Cherenkov counters, the Cherenkov counter can be constructed in six months. That amount of time is adequate also to build the small MWPC's and Camac readout based on the standard EFI design which was worked well on several experiments. The necessary fast logic and Camac interface would also be required. We would hope this time to have the computer located in the same experimental area as the apparatus.

IV. RUNNING TIME

The running time is estimated as follows:

1)	Tuning the spectrometer, background studies	200 hrs.
2)	Data taking with incident protons	100 hrs.
3)	A dependences	100 hrs.
4)	Incident pions and kaons--limited x range	200 hrs.

The data in the attached paper were taken in the last 18 hours of the experiment. The positive x = 0.3 data represent less than two hours of running time.

IV. MANPOWER

At present we have the same commitments to big existing or approved epxeriments[6] as we did when we ran E-335. By spring several of these commitments will be over. We thus count at least one full time experimenter, six half-time experimenters, and possibly two students. We also have available to us technical support from our respective institutions. Based on our previous experience, this manpower is well matched to the experiment.

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6. A. Pope, *On the Collar of a Dog*.

TABLE I

Spectrometer Specifications

Momentum bite:	50%
Dispersion:	20%/inch
Bend angle:	10 mr @ 200 GeV
Acceptance:	20 μster
MWPC wire spacing:	1.5 mm
$p_\perp$ resolution:	$\lesssim$ 400 MeV/c

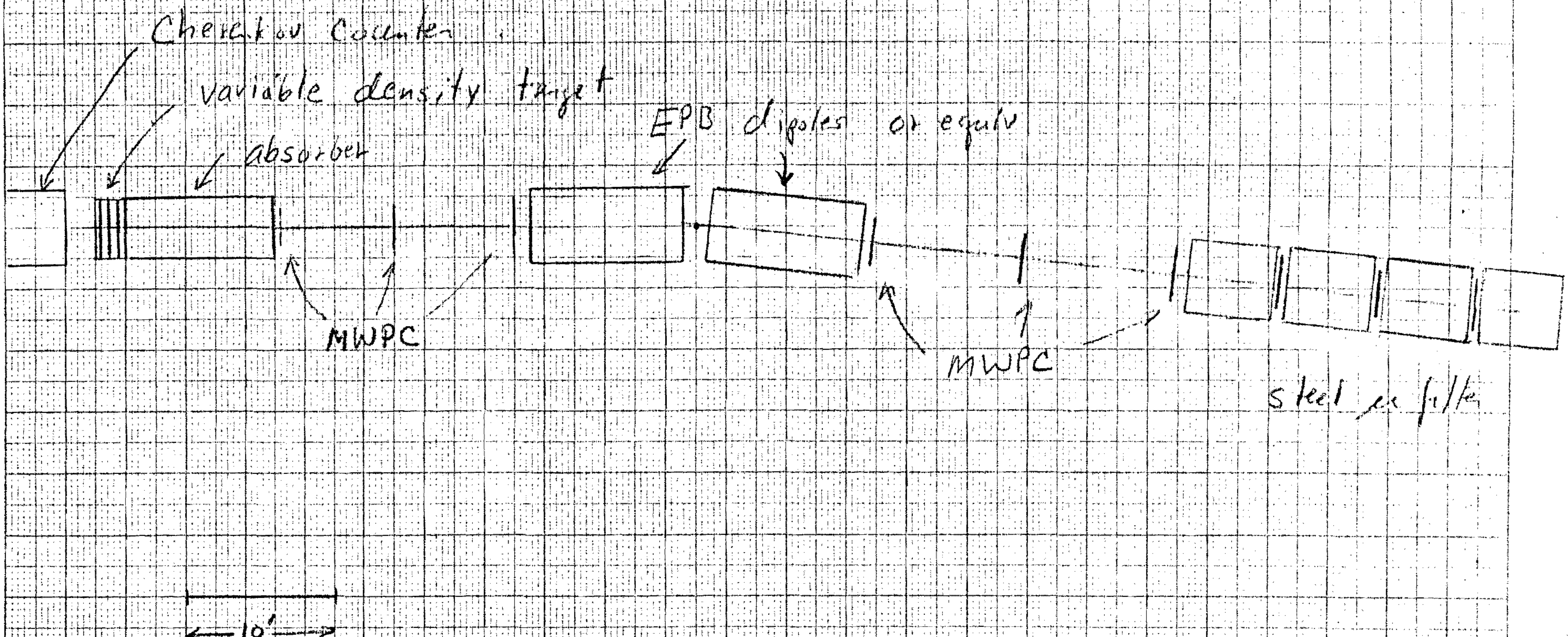
Cherenkov Counter
variable density target
absorber
EPB dipoles or equiv
MWPC
MWPC
steel μ filter
10'

FIGURE 1

A Measurement of Direct Muon Production in the Forward Direction*

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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 of momenta 90 GeV/c and 150 GeV/c with $P_\perp$ less than 400 MeV/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. This signal is too large to be accounted for by decays of known vector mesons.

The direct production of leptons in hadron collisions has been observed previously[1-5] at large $P_\perp$ (> 1 GeV/c) and $x \simeq 0$.[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. 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.

As present, there is no theoretical explanation which adequately describes all of the above measurements. Contributions from decays of vector mesons ρ, ω, ϕ, ψ are too small.[8] Attempts to predict theoretically a continuum of massive virtual photons by parton-antiparton annihilation[9] have been unsuccessful.

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 ($x \simeq .3$) and small $P_\perp$ ($\lesssim .4$ 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 proton beam to a variable density target of twenty-four 2.54 cm thick Uranium plates, each 15 cm × 15 cm. 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/pulse.

Directly upstream of the target, the beam passed through a 60-m long He-filled threshold Cherenkov counter, set to count muons and pions, but not protons. An RCA 31000M photomultiplier was used to permit single photoelectron resolution. Use of this counter essentially eliminated muons from upstream sources 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 with air light-guides (B1-B6) 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. This detector provided an additional rejection against hadrons of 10^{-3}, although any particles which emerged from the 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.

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 by 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 $1/\rho$ 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 shape of the spectra of pions and kaons produced in the target is known, the slope of the muon yield vs density curve can be used to determine the pion flux. Thus, the ratio of slope to intercept determines the muon to pion ratio directly.

One assumption crucial to this argument is that the pions and kaons which decay into muons and the direct muons are produced by the incident protons and are not produced later in the hadron shower. At values of x where the pion production is falling rapidly with x, this assumption is reasonable. At values of x where the pion production is not steep, however, one would need to understand the full hadron shower inside the thick target. This would preclude extrapolating this technique to zero x.

The negative particle flux was measured independently 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[10] in the interval x = .3 to x = .7, by the function $(1-x)^4$. This is somewhat steeper than spectra measured at 0.8 mr from an Al target with 300 GeV protons by Aubert *et al.*[11] 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^- spectra measured in this experiment were used to generate a π^+ spectrum. The change in the calculated direct muon to pion ratio is less than 20% depending on which spectrum is used. This systematic error is not included in the final error.

The contribution from kaon decay was calculated by parameterizing the K^-/π^- and K^+/π^+ ratios as 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.

The data reduction consisted of determining the ratio $B\cdot\overline{C}$/ion-chamber from the events recorded on magnetic tape. 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 reduced the muon efficiency to 81%. The data were corrected for accidental counts in the Cherenkov counter. These corrections were less than 5%. Finally, the data have been corrected for the small difference in detection efficiency (5%) between open and closed target positions and for the effects of upstream sources. (See Table I)

The corrected μ/ion-chamber data are shown in Fig. 3. 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.

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, with the Cherenkov counter set above proton threshold, counting incoming protons associated with outgoing muons. 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 $\sim$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 material downstream of the Cherenkov counter is listed in Table I. The number of muons produced by this material was estimated by scaling the decay muons detected from the target by the ratio of the number of protons interacting in the material to those interacting in the target. The total contribution to the signal is listed in Table I.

There are two other 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 very simply 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 $\sim 0.35 \times 10^{-5}$.

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 $p_\perp \lesssim 400$ 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 $P_\perp \lesssim 400$ MeV/c. 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 $p_\perp$. This would seem to rule out a vector parent for these leptons which is heavy (>>1 GeV), as one would expect a very small contribution at such low values of $p_\perp$.

References

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10. The function $\frac{d\sigma^2}{dxd\Omega}\Big|_{\pi^-}$ was parameterized by $(1-x)^4$. The π^+ spectrum $\frac{d^2\sigma}{dxd\Omega}\Big|_{\pi^+}$ was less steep and was parameterized by $x(1-x)^4$.

11. B. Aubert *et al.*, preprint FERMILAB-Conf-75/31-EXP 7300.001 (submitted to the International Colloquium of the CNRS on "Neutrino Physics at High Energy," Ecole Polytechnique, Poincare Amphitheatre, Paris, France (March 18-20, 1975). The spectrum measured in the present experiment is steeper by approximately a factor of (1-x) than that of Aubert *et al.*

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Figure Captions

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).

Table Captions

Table I - Material in the beam downstream of the Cherenkov counter and its calculated background contribution to the μ/π ratios.

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.

TABLE I

Material	Thickness	λ_{ABS} (cm)	fraction interacting	mean decay length (ft) open	mean decay length (ft) closed	fraction × decay length (ft) open	fraction × decay length (ft) closed
Helium C (1.6 PSIA)	50'	335,500. (1ATM)	0.49×10^{-3}	46	50.3	22.5×10^{-3}	24.7×10^{-3}
MYLAR Mirror	.030"	56 cm	1.36	21	25.3	28.6	34.4
Helium (1.6 PSIA)	4'	335,500. (1ATM)	0.02	19	23.3	0.4	0.5
Al Window	.008"	37 cm	0.55	17.0	21.3	9.35	11.7
Ion Chamber	.004"	20 cm	0.51	15.1	19.4	7.7	9.9
Scintillator	.125"	69 cm	4.60	14.6	18.9	67.2	86.9
Air (1ATM) Open (16.8')	199"	67,500 cm	7.49	8.7	-	65.2	-
Air (1ATM) Closed (20.9')	251"	"	9.44	-	10.9	-	102.9
Ti	.005"	20 cm	0.61	3.75	8.0	2.3	4.9
Scintillator	.250"	69 cm	9.20	2.04	6.36	18.8	58.5
				Upstream Total		0.222	.334
U Target	∞	12.0	100%	1.568	0.450	1.57	0.450
				Total		1.79	0.784
				Upstream Source/Target Fraction		0.124	0.426

TABLE II

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	1.54 ± 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 $1/\rho$

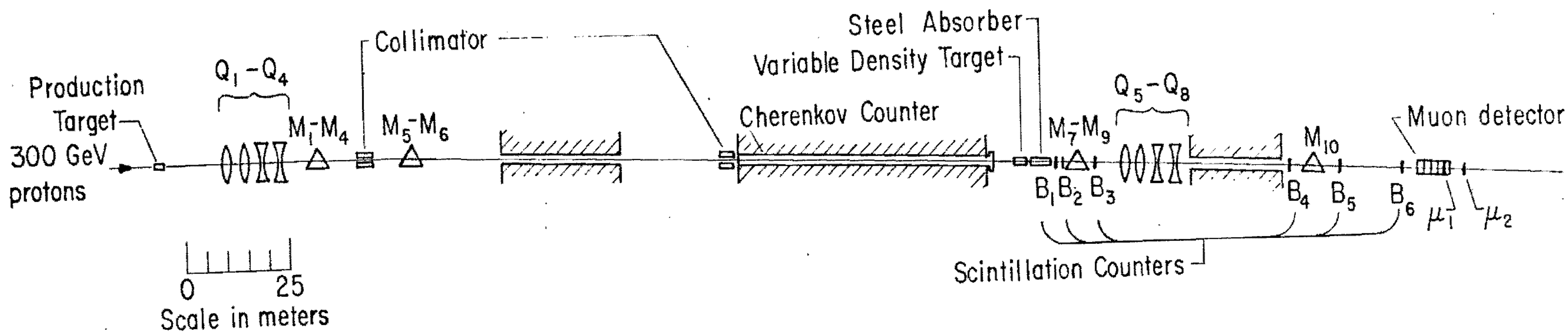
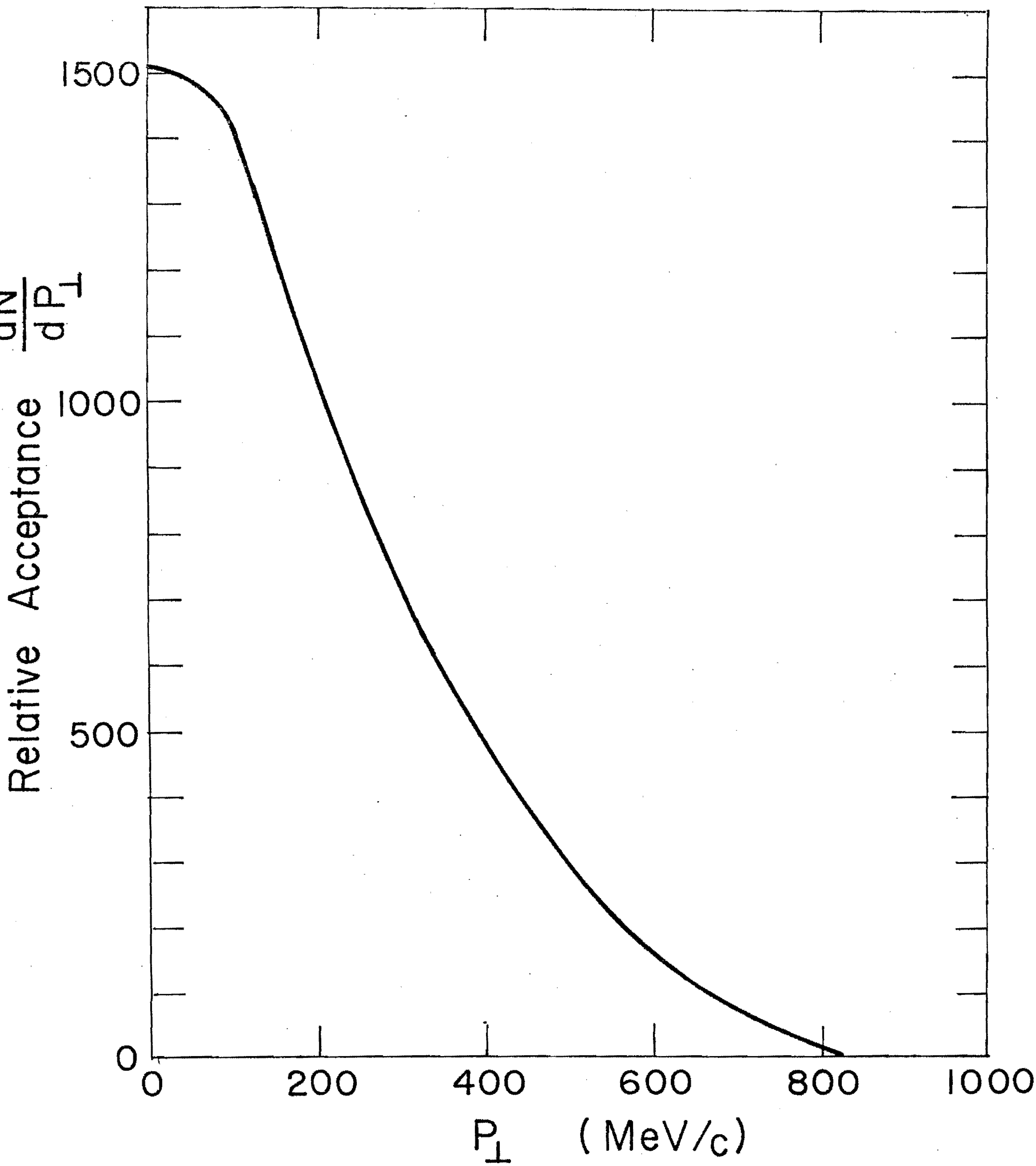

Production
Target
300 GeV
protons
$Q_1 - Q_4$
M_1-M_4
M_5-M_6
Collimator
Cherenkov Counter
Steel Absorber
Variable Density Target
M_7-M_9
$Q_5 - Q_8$
M_{10}
Muon detector
B_1 B_2 B_3
B_4 B_5 B_6
μ_1 μ_2
Scintillation Counters
0 25
Scale in meters

Figure 1



1500
1000
500
0
Relative Acceptance $\frac{dN}{dP_\perp}$
0
200
400
600
800
1000
$P_\perp$ (MeV/c)

Figure 2

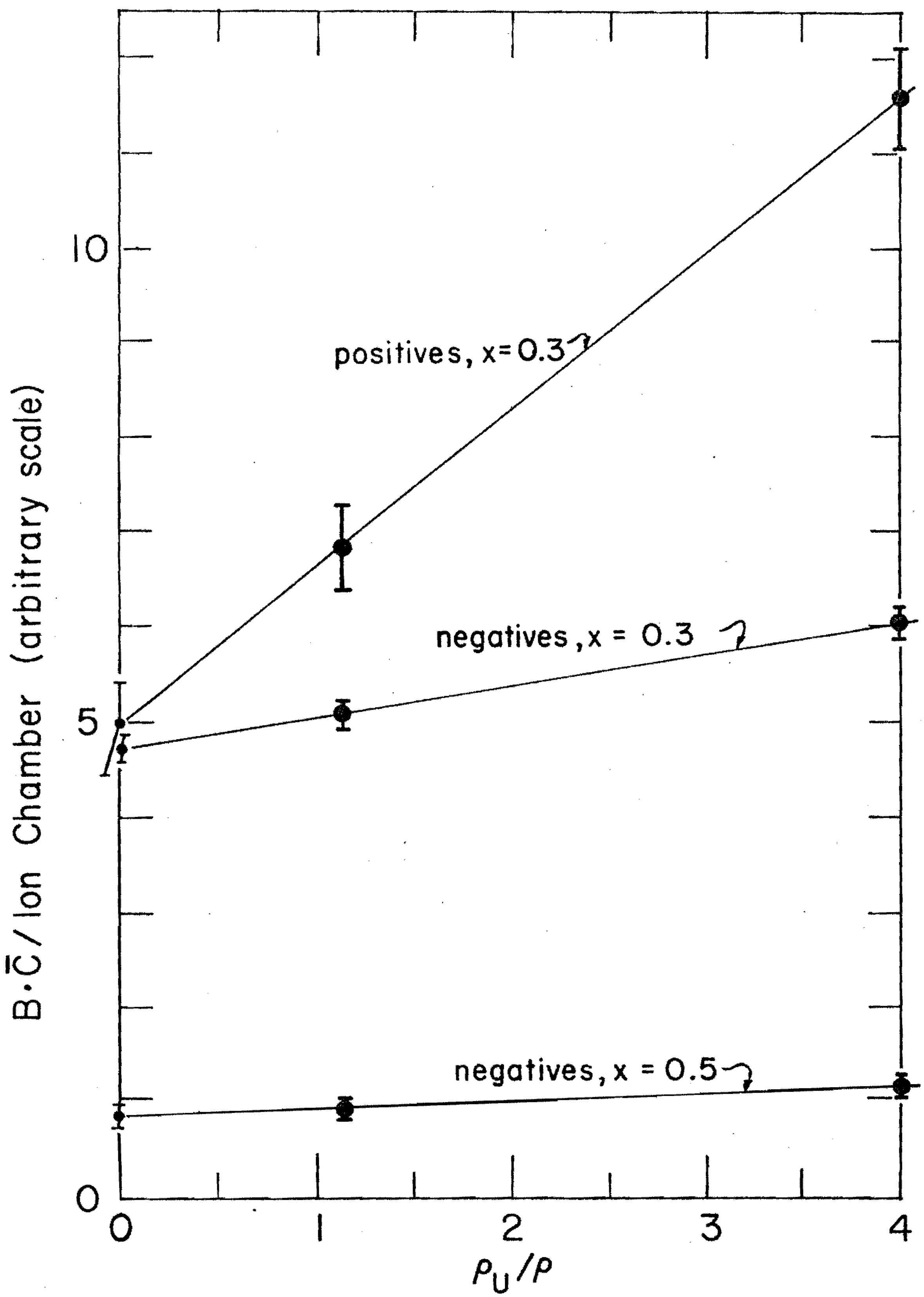

B·C̄/Ion Chamber (arbitrary scale)
10
5
0
positives, x=0.3
negatives, x = 0.3
negatives, x = 0.5
0
1
2
3
4
ρU/ρ

Figure 3

Incoming Particle Associated with an Outgoing Muon

Sign	P_{μ}(GeV/c)	Target Position	Protons	Muons	Accidentals	Corrected muons μ_c	Corrected protons p_c	μ_c/p_c	Accidentals/p_c	μ_c/tot
-	90	open	1542	237	48	292	1488	.196	.032	.164
-	90	closed	1312	167	63	205	1273	.161	.049	.139
+	90	open	757	223	39	274	706	.389	.055	.280
+	90	closed	495	206	33	253	448	.566	.074	.361
-	150	open	132	5	4	6	126	.049	.032	.046
-	150	closed	110	10	6	12	98	.126	.061	.111

A SEARCH FOR DIRECT MUON PRODUCTION IN THE FORWARD DIRECTION

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ABSTRACT

We propose to search for direct muon production in the forward direction from 300 GeV protons incident on a heavy nuclear target. By using the first stage of the M1 beam as a source of a diffracted proton beam and the second and third stages of M1 as a spectrometer, one can make a measurement of the direct muon to pion ratio at values of x between 0.3 and 0.75. If this ratio is on the order of 10^{-4}, the event rates are on the order of 800 direct muons/hr. at an x of .5. The modifications to the M1 beam are minor.

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I. Physics Motivation

Three of the most interesting recent results in high energy physics have involved lepton-hadron processes: 1) the scaling[1,2] of the structure functions in deep inelastic lepton-hadron scattering, 2) the production of hadrons in e^+e^- collisions at CEA[3] and SPEAR[4], and 3) the observation of direct muon pairs at BNL[5] and directly produced single muons and electrons at NAL[6,7,8], the ISR[9], and Serphukov[10]. It is likely that, at very high energies, it will be in such experiments as these, rather than in standard strong interaction experiments, that one will learn about the fundamental structure of hadrons.

The SPEAR results, the BNL dilepton production, and the newly observed single lepton production all are surprising in that the coupling between hadrons and leptons is much stronger than conventional wisdom[11] would predict. There is also another experiment, the small angle muon pair electroproduction experiment at Cornell[12], which sees an order of magnitude more muon pairs than one would expect. Moreover, Adair has reported[13] that at $\sqrt{s} = 7.6$ GeV, the direct muon to pion ratio was on the order of 10^{-4} in the forward direction, a value much greater than expected from electromagnetic decays of strongly produced particles. All of these enhancements are especially interesting in the light of the current excitement about theories which unify the strong, weak, and electromagnetic interactions, including some which involve a direct relationship between leptons and hadrons.[14]

The large dilepton production cross-sections found at BNL are related to the surprising SPEAR results on the constant cross-section for the production of hadrons.[15] It is not yet clear, however, whether or not the copious production of single leptons is related to either of these processes, or whether it has a more conventional, strong interaction source, such as the dileptonic decays of known vector mesons.

The present high energy data on single lepton production at large values of $P_\perp$ show that the ratio of cross-sections for the production of direct muons and of pions ($\mu D/\pi$) is a constant approximately equal to 10^{-4} over a wide range in $P_\perp$ and $\sqrt{s}$. Specifically, at $\sqrt{s}$ = 23.7 GeV the cross-section is constant from $P_\perp$ = 1.5 GeV to a $P_\perp$ of 5.35 GeV.[6] A measurement[16] at $\sqrt{s}$ = 19.4 also finds the ratio $\mu D/\pi$ is 10^{-4}. Measurements at the ISR[9] (on electron production) at a $\sqrt{s}$ of 53 GeV, at Serphukov[10] at a $\sqrt{s}$ of 12 GeV, and at Fermilab[8] for 11 GeV < $\sqrt{s}$ < 24 GeV also find approximately the same ratio for $\mu D/\pi$. One can thus conclude that in the kinematic region around 90° in the c.m. and at fairly large values of $P_\perp$ there is no systematic energy or $P_\perp$ dependence in the ratio $\mu D/\pi$.

It is possible that these leptons come from the dileptonic decays of vector mesons, such as the ρ, ω. and ϕ. If we assume that each of these is produced with equal cross-section, the production of each of the vector mesons would have to be 1.8, 3.0 and 4.6 times the pion production for $P_\perp$ = 1.5, 3.0, and 4.5 GeV, respectively. While these numbers seem large, and a mechanism that makes the vector meson production grow in such a way that μ_D/π stays constant would seem unusual, vector mesons cannot be ruled out as a source for the high $P_\perp$ leptons.

If the ratio $\mu D/\pi$ were also equal to 10^{-4} at low $P_\perp$ for a wide range of x, the vector mesons would have to be produced at least as copiously as pions in strong interactions. Leipuner et al. have reported[13] that in a Brookhaven experiment[17, 18] at $\sqrt{s}$ = 7.6 GeV the direct muon to pion ratio was on the order of 10^{-4}. These data rule out the known vector mesons as the source of the single leptons: the ρ meson production has been measured at $\sqrt{s}$ = 7.0 GeV by Blobel et al.,[19] who find that the ρ production cross-section is approximately 1/15 of the pion cross-section.

The measurements proposed here would extend the measurements of Adair to higher energies and a wider range in x. The constancy of the ratio μ_D/π at high $P_\perp$ over a wide range in $P_\perp$ and $\sqrt{s}$, where the cross section changes by more than a factor of 10^5, raises the possibility that, barring phase space effects, the ratio is a constant independent of x and $P_\perp$. It is possible that the change in μ_D/π with x, as seen by Leipuner et al. at Brookhaven National Laboratory, is in fact a threshhold effect, i.e., a heavy particle is the source of these muons. This seems to be corroborated by the measurements at the ZGS by Lamb et al.[20], who have showed that direct muons are not seen at $P_\perp = 1.4$ GeV at a level of approximately $3\text{-}4 \times 10^{-5}$. The fact that the c.m. energy available at NAL is probably many times the masses of the source of these muons allows this measurement over a wide range of x without the complicating effects of being near the edge of phase space.

We should note that the proposed search would be sensitive to muons from other exotic sources, such as charmed particles or heavy leptons. For example, if charmed particles are as copiously produced as kaons and decay weakly into leptons with a branching ratio of 10%, one would expect a strong muon signal at a level of approximately 10^{-3} to 10^{-4} of the pion flux. This is certainly a possible candidate for the source of the muons.

Experimental Technique

The diffracted proton beam impinges on a heavy variable density target approximately 6 absorption lengths thick. Immediately downstream of this a fixed 10' steel absorber filters out the hadronic cascade. The target consists of plates with variable spacing between them such that the average density is variable by a factor of four. (See Fig. 1). The muon flux will be measured at three different densities, and the production extrapolated to infinite density, i. e., zero effective decay length. Figure 2 shows such an extrapolation. The intercept of the line at zero effective decay length gives the component of muons which are direct - that is, do not come from the decay of long-lived particles such as the π and the K.

The slope of the extrapolation versus density measures the pion flux, thus measuring the direct muon to pion ratio. To do this, one need only know the shape of the pion production spectrum, and not the absolute normalization. If one parameterizes the pion spectrum in the forward direction versus x by the experimentally determined function[21]

$$\frac{d\sigma}{dx} \propto x(1-x)^4$$

one can calculate for a given slope the pion production. Conversely, for illustrative purposes, Fig. 2 shows the extrapolation plot as calculated for $x = .5$ assuming a value of μ_D/π of 10^{-4}, and a pion spectrum $\frac{d\sigma}{dx} \propto x(1-x)^4$.

The error bars shown represent a shift of data taking per point assuming the event rates are 1/3 of those calculated.

The value of x for a measurement is determined by the ratio of the momenta set in the downstream stages of the beam relative to that of the first stage. Thus changing the x value measured is very easy.

Experimental Apparatus

The beam layout is shown in Fig. 3. We propose to use the first stage of the M1 beam line to transport a 300 GeV/c diffracted proton beam to the target located just upstream of B_{7-9}. The incident beam intensity will be monitored upstream of the target. The beam line downstream of the variable density target is used as a spectrometer to select, momentum analyze, and transport any resulting muons to a muon detector similar to that presently in use in the M1 beam line.

The quadrupoles Q_{7-9} focus the beam horizontally at the 900 ft. level where a scintillation counter S_2 defines a ± 7% momentum bite. The spectrometer's acceptance is 0.36 μster at a mean production angle of 1.6 mr. The quadrupoles Q_{10-13} focus the beam upstream of the muon detector. The other scintillation counters are used to define the beam.

The muon detector would be located in one of two possible positions: either at the upstream end of the meson detector building, or at the 1000 ft. region of the M1 beam line. (The latter location for the muon detector would result in a factor of 5 increase in the yields discussed on p. 6 of this proposal.)

The only equipment needed that is not already in use in the M1 beam line is the variable density target, the scintillators S_1-S_6, miscellaneous other scintillators for antis, and the modification of the 200' vacuum pipe into a Čerenkov counter. Also, if necessary, a simple new muon detector of steel and scintillator would be constructed.

We should note that the M1 beam line may not be unique in being suitable for this experiment. We are looking into other beam lines which have the capability of being run as two separate focusing dispersive stages, with a vacuum pipe upstream of the suitable target location.

Event Rates

We assume a diffracted proton beam of 5×10^8 protons/pulse incident on our target, and make the assumption[22] that the production increases by a factor of 6.8 at 225 GeV/c in going from the measurements at 3.6 mr to a 1.6 mr production angle. The spectrometer acceptance, $\Delta\Omega \frac{\Delta p}{p}$, is 5.8×10^{-8} steradians. We can thus calculate the event rates shown in Table 1. The rates are shown for π^-; the π^+ rate is about a factor of 3 higher. The event rates in direct muons/hr are shown in Fig. 4.

TABLE 1

Spectrometer Momentum	X	π^-/pulse	μ_D^-/pulse *
90	0.3	2.7×10^4	2.7
150	0.5	1.3×10^4	1.3
175	0.58	8000	0.8
200	0.67	4000	0.4
225	0.75	2000	0.2

*assuming $\mu_D/\pi = 10^{-4}$

If the muon detector were to be located in the 1000' region rather than in the meson detector building, the rates would be a factor of five higher than shown in Table 1 or Fig. 4.

We should emphasize that a search for a rare process like direct lepton production is not by nature a high statistics experiment.

The smallest event rate listed in Table I, while appearing very small, is a factor of 100 larger than the smallest direct lepton rate successfully measured in the high $P_\perp$ experiments.[16]

The A Dependence of Direct Muon Production

If the direct production rates are sufficiently large, we propose to study the μ_D/π ratio as a function of the atomic number (A) of the target. The production depends on the atomic number of the target nucleus in a fashion determined by the nature of the production process itself. Measurements at high $P_\perp$ have shown[6] that the muon production has the same A dependence as the pion production. However, the pion production at high transverse momentum is not yet understood. The A dependence of the pion production itself is not the $A^{2/3}$ one might expect, but rises with $P_\perp$ to an $A^{1.1}$ dependence[23].

Backgrounds

We consider as background any muons that are detected in the counter telescopes and in the muon detector and which are not directly produced. There are three sources of background of which we have thought:

1) Muons from the decay in flight of π's and K's produced in the cascade inside the target and absorber.

2) Muons from hadrons which emerge from the downstream end of the absorber

3) Muon contamination in the beam.

The component of muons from process 1 can be measured by changing the effective density of the target and, as described above, is essential in the measurement of μ_D/π .

The background from process 2 should be very small, but if any exists, it is directly measurable. It is hard to estimate how many fast pions will emerge from a block 18 absorption lengths long on which protons have impinged, but it should be very small. However, of those pions which do emerge, less than 3% decay. Thus by measuring the π flux downstream of the absorber at a given x one can measure the muon contribution from pion punchthrough. This can be done by using the threshhold counter downstream to separate protons from pions, and the muon detector to identify hadrons as distinct from muons.

The third source of background, muon contamination of the incoming beam, is the most dangerous. Muons in the beam would behave just like directly produced muons in that they are independent of the decay distance. One can make only a crude estimate of this background - to really know how serious it is, one has to try.

We would take the following steps to suppress this background: 1) One would expect the muon background to be spatially broader than the diffracted proton beam. One can measure this with counters downstream of the absorber. 2) One can define the incoming proton beam with anti counters on the upstream side of the berm at the 450' region and veto events in which protons interact in the transport system close to the absorber. 3) We would add a mirror, phototube, and gas system to the 200' vacuum pipe upstream of the absorber to turn it into a threshhold counter capable of separating protons from muons. This should allow a rejection factor against muons of at least 100, and would allow the measurement of the muon contamination.

A crude estimate of the background, probably good to an order magnitude, assumes that these muons came from proton interactions in the beam transport upstream of the target. If one assumes that 10% of the beam is lost, and that on the average a pion produced travels 50 ft. before it interacts with something, and with the rejection of the Cerenkov counter, the background will occur at a level of $< 10^{-6}$. However, there is a large solid angle factor suppressing this number, depending on where the pions are made.

Comparison of this Proposal with NAL Experiment 48

The pending FNAL experiment 48 of Adair and co-workers to measure the intensity and polarization of directly produced muons does not have much overlap with this proposal. We are proposing a quick systematic search in the forward direction at a series of well determined values of x, at a fixed small $P_\perp$. This would be an immediate follow-up to the high $P_\perp$ single lepton discoveries. In contrast E48 is larger, more sensitive, but will measure the intensity at large $P_\perp$ averaged over a range of values in $P_\perp$ and x.

The major differences between of the two experiments are listed below:

1. Sensitivity. Our present proposal is far less sensitive than E48 should be in terms of the cross section one could measure if there were no background. The apparatus we propose has a solid angle of 3.6×10^{-7} steradians. The 6' x 6' counters in the E48 proposal subtend a solid angle at 700' of approximately 8×10^{-5} steradians. Because we are using a secondary beam, we are limited to approximately 5×10^{8} protons/pulse, while E48 can use the extracted proton beam, i.e., on the order of 5×10^{12}/pulse. Thus while E48 is capable of reaching cross sections in the 10^{-38} range, our proposal would reach only to the 10^{-32} range.

However we should point out that if $\mu_D/\pi = 10^{-4}$ at x = .5, the cross section we wish to measure is on the order of 10^{-30}. At the estimated rate of 800 direct muons per hour we would then have a good measurement of μ_D/π in a shift of running at one x value. It does not require extraordinary sensitivity to measure the direct muon production if in fact the μ_D/π ratio is on the order of 10^{-4}. This is the reason that E48 emphasizes the region where $P_{\perp}$ is large, because it is there that the background due to pion decay is small. In fact, if $\mu_D/\pi = 10^{-4}$ at x = .5, the direct muon signal would be approximately 10 times the background due to pion decay. It is the possibility of such a large signal that motivates a quick search.

2. Kinematic Region of Search. We propose to measure the ratio of the direct muon flux to the pion flux at very small values of $P_{\perp}$, i. e., $P_{\perp} <$ 300 MeV. We would perform this measurement at discrete values of x between x = .3 and x = .75 with a precision in x of ± 5%. These measurements would determine whether the results at high $P_{\perp}$ hold true in the region where the more conventional strong interactions are known to dominate, i. e., at low $P_{\perp}$. We emphasize that both the x and the $P_{\perp}$ of the muon would be measured accurately in the magnetic spectrometer downstream of the target.

In contrast, the E48 proposal does not determine either the momentum or the $P_{\perp}$ of the muon very well. For instance at an x of .5, the uncertainty in $P_{\perp}$ will be on the order of 2 GeV, and the uncertainty in x will be on the order of 50%. This lack of resolution will result in averaging the μ_D/π ratio over the kinematic variables.

The E48 apparatus is not sensitive in the forward direction. Because they emphasize the detection of muons with $P_{\perp}$ greater than 2 GeV, their apparatus is situated to the side of the undeflected beam line. In contrast, the present proposal accepts muons only in the forward direction, and with $P_{\perp}$'s of less than 300 MeV.

Changes necessary to the M1 beam line

The changes needed to use the M1 beam line result from using the first stage to transport a diffracted proton beam and the second stage as a muon spectrometer. Q_{1-2} require an excitation current of 110 amps rather than the nominal good field limit of 100 amps. To be really conservative the two Acme power supplies powering these quads can be ramped.

It would be necessary to power B_{5-6} and B_{7-9} separately - they are now run in series. This can be done by severing one bus from the 5 power supplies now in the M2 service building and changing a second supply over to the current regulator mode. The B_{5-6} magnets would require 5,300 amps which the Transrex supplies presently powering the magnets would supply. To provide this current the calibration of the transductor must be changed, which we are told is a fairly minor job. These magnets will have been ramped by the time this experiment would begin, so that the power dissipation would be under control.

Some shielding would need to be added outside of the service door to the M1 tunnel downstream of the variable density target. Installing the variable density target would require removing some vacuum pipe and the C 7 collimator upstream of B_{7-9} in order to increase the length of the air gap in that region. We would like to attach a Čerenkov counter head to the vacuum pipe in the beam upstream of the variable density target.

The installation of the variable length target, the scintillation counter and the above changes could be accomplished over several of the Thursday shutdowns and should not necessitate any interruption in the utilization of the M1 beam line.

Running Time

We request a short test run in the M1 beam line. We would need an integrated proton intensity of about 10^{17} protons over one week's time in order to tune the beam and the electronics, check backgrounds, and make a measurement of the direct muon production at one x value. Most of the electronics setup and testing can be done in a non-interfering parasitic mode.

If direct muons are produced at 10^{-4} of the pion flux, we can make a detailed measurement at one value of x in a day's running. For instance, at x = .5, the projected rate is for 800 direct muons per hour, leading to approximately 16,000 direct muons/day.

Given the presence of direct muon production at a reasonable level, we would like at a later time an integrated proton flux of 2×10^{17} to measure the μ^+ and μ^- production spectrum with $P_\perp \leq$ 400 MeV/c over a wide range in x. Under normal running conditions, this flux could be obtained in a week.

References

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22. This factor of 6.8 is equal to $e^{-4.5\Delta P_\perp}$ where $\Delta P_\perp$ is the change in the transverse momentum due to changing the production angle from 3.6 to 1.6 mr. The slope of 4.5 at $x \geq .5$ was determined from the p - p data of the Bonn-Hamburg-Munich collaboration. The ratio of the fluxes obtained from preliminary measurements in the M1 and M2 beam lines differs by a factor of 2 from the $e^{-4.5\Delta P_\perp}$ prediction. These rates would predict a much flatter slope, i.e., $e^{-2P_\perp}$, and would consequently lower our rates by approximately a factor of 3.

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Figure Captions

Figure 1. The variable density target configuration.

Figure 2. A typical extrapolation plot as calculated for x=0.5 and $\mu_D/\pi = 10^{-4}$.

Figure 3. The M1 beam line and apparatus layout.

Figure 4. The rate for detecting direct muons for 3×10^{12} 300 GeV protons/pulse on the meson lab target.

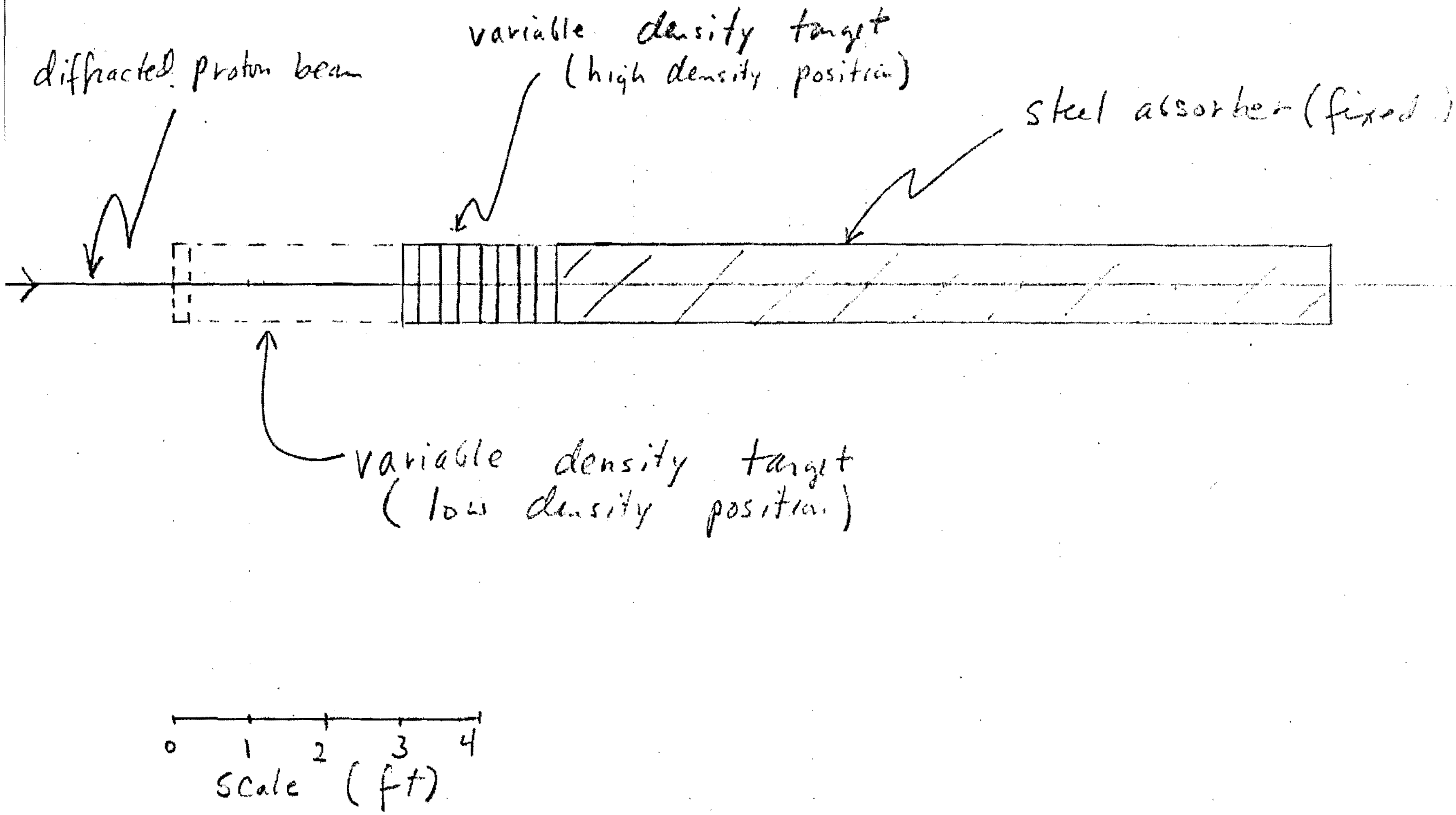

diffracted proton beam
variable density target
(high density position)
steel absorber (fixed)
variable density target
(low density position)
0 1 2 3 4
scale (ft)

Figure 1

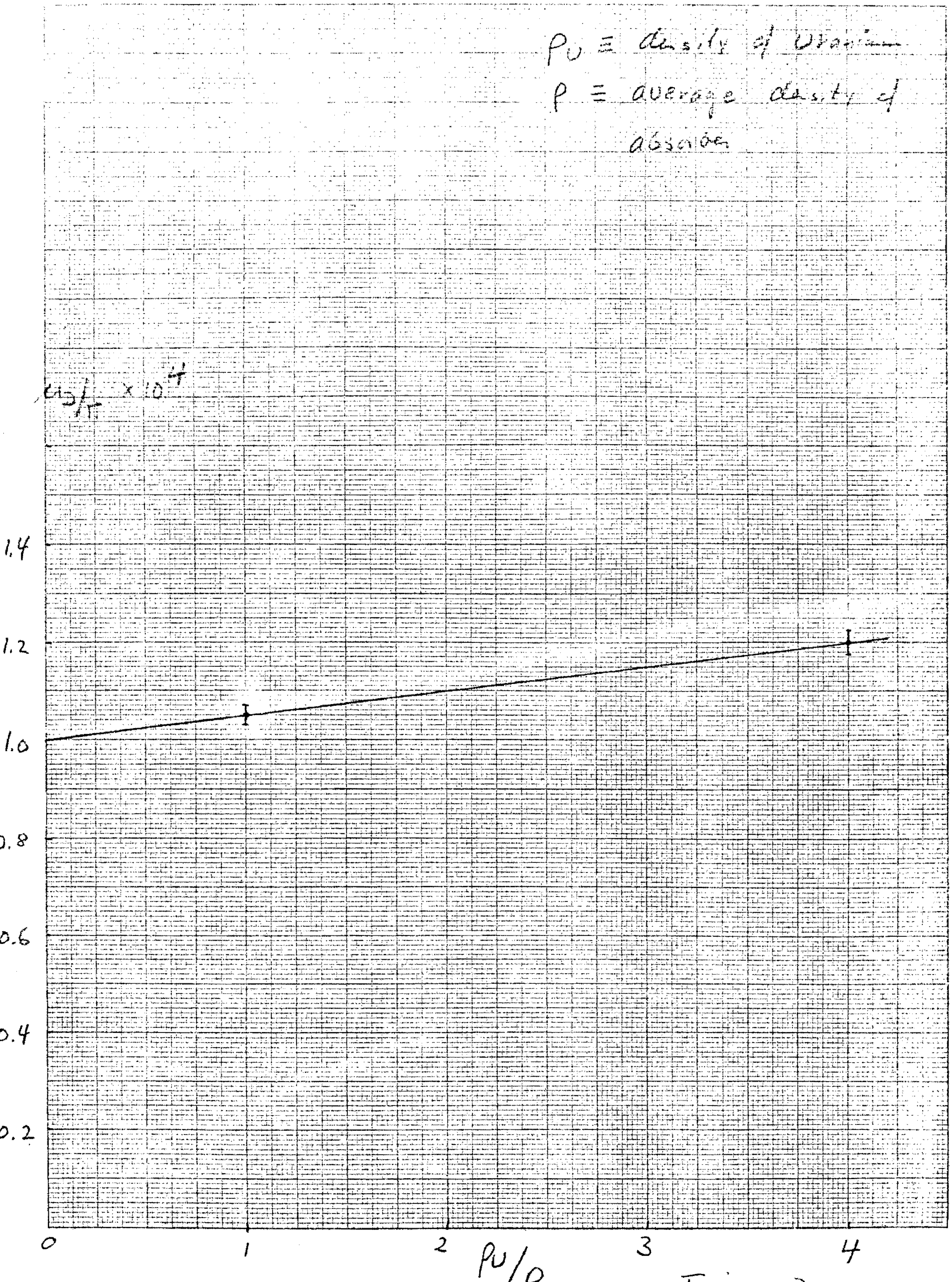
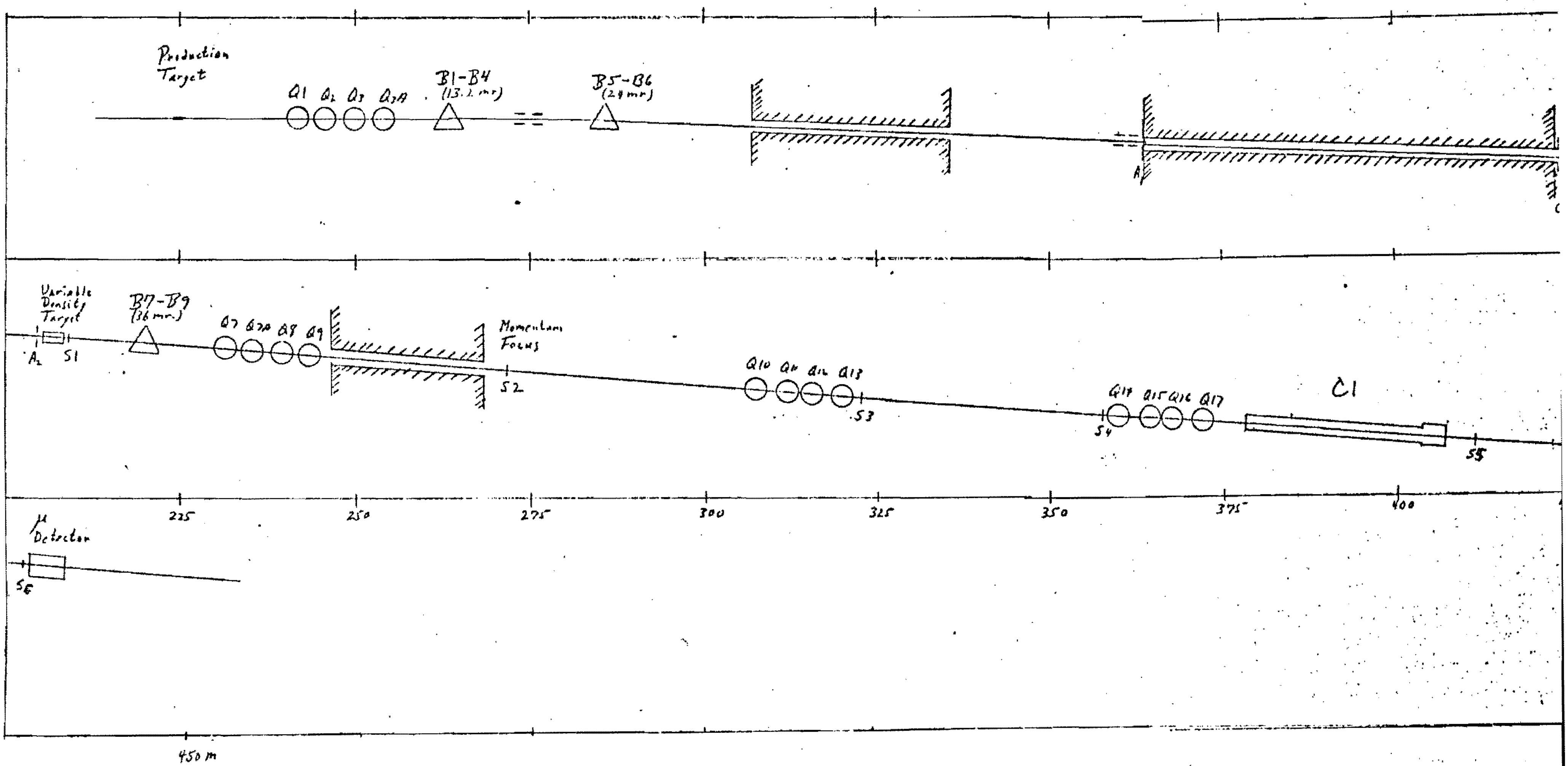

ρU ≡ density of Uranium
ρ ≡ average density of absorber
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
1
2
3
4
ρU/ρ

Figure 2



Production Target
Q1 Q2 Q3 Q3A
B1-B4 (13.2 mr)
B5-B6 (24 mr)
A
Variable Density Target
A2 S1
B7-B9 (36 mr)
Q7 Q7A Q8 Q9
Momentum Focus
S2
Q10 Q11 Q12 Q13
S3
Q14 Q15 Q16 Q17
S4
C1
S5
225
250
275
300
325
350
375
400
μ Detector
S6
450 m

Fig 3

DIRECT μ's / HOUR