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DIRECT PRODUCTION OF MUONS IN THE FORWARD DIRECTION BY 300-GeV PROTONS ON URANIUM[†]

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The experiment¹ described here was a modest effort designed to answer a simple question: Is the μ/π ratio, which has been measured just about everywhere² to be $\sim 10^{-4}$, compatible with the idea that the muons are decay products of massive mesons? The method and direction used to answer this question is straight-forward.

The pion inclusive cross-section increases with decreasing $p_{\perp}$. For a dileptonic decay ($\pi \rightarrow \mu\mu$ or $\pi \rightarrow \mu\nu$) of an object of mass M , the $p_{\perp}$ distribution peaks at $p_{\perp} \approx M/2$. The ratio of such muons to the pion flux must diminish at $p_{\perp}$ much less than $M/2$.

As will be shown, the μ/π ratio does not diminish for $p_{\perp} \gtrsim 400$ MeV/c. Known processes such as vector meson decay and Bethe-Heitler conversions of photons from π^0 and μ^0 are estimated to be about 20% of the measured signal. The excess signal can be taken as a hint of something exciting or mildly interesting or as an indication that something mundane has been left out, depending on the sobriety of the reader.

That the experiment was modest is a euphemism; most of the equipment was usurped. Of course, any experiment which uses a finite amount of time at a $\sim \$40M$ /year accelerator cannot be called cheap.

The M1 beam line at the Fermilab Meson Area was violated to allow a measurement of the direct μ/π ratios at $x = .3$ and $.5$ and very small $p_{\perp}$ of the muons. The first part of the beam line was used to transport a quasi-diffractive proton beam ($\sim 10^8$ /ppp) to a variable density target. The second stage of the beam formed a $\sim 1\mu sr$ spectrometer to select muons produced in the variable target.

The spectrometer had a $p_{\perp}$ acceptance shown in Figure 1. The momentum bite was $\frac{\Delta p}{p} \sim \pm 7\%$. The Feynman variable x for the data here is $\frac{p_{\mu}}{p_p} = \frac{p_{\mu}}{300}$. Six scintillation counters $B_1 - B_6$ defined the muon trajectory and counters μ_1 and μ_2 after $15'$ of Fe identified the muon. Upstream of the variable density target, an ion chamber monitored the proton flux and a segmented wire ion chamber monitored the beam profile and steering. The target consisted of 23 U plates, each 1" thick, which moved as an accordion to allow the effective target density to be varied from 0.88 to 0.25 times the density of Uranium. Ten feet of steel downstream of the target (6 absorption lengths of U) absorbed the debris from the hadronic cascade.

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Figure 1

Figure 2

Upstream of the Uranium target a 200' vacuum pipe was modified to be a 0.1 atmosphere He-filled threshold Cherenkov counter to identify muons and pions in the proton beam incident on the variable target. Figure 2 shows a schematic of the apparatus.

The event trigger was $B \equiv B_3 B_4 B_5 B_6$. The pulse heights of the two counters downstream of and nearest to the U target, B_1 and B_2 , as well as the Cherenkov counter were recorded on magnetic tape. The data analysis consisted of determining the number of downstream muons not associated with an incoming π or μ in the Cherenkov counter (C), per incident proton for each effective density of the Uranium target. A small, but troublesome, efficiency for protons at the one photoelectron level required raising the Cherenkov counter threshold in the off-line analysis which in turn reduced the efficiency from 95% to 81%. The photoelectron distribution was used to determine the 19% inefficiency correction; since the fraction of triggers caused by beam muons was in the worst case ~ 0.25 and usually ~ 0.10 , the Cherenkov counter was entirely adequate to determine the rates of proton-induced muons from the U target to a few percent.

These rates were normalized to an ion chamber upstream of the U target. Figure 3 shows the data for three different settings of the downstream spectrometer, $P_\mu = \pm 90$, and $+150$ GeV/c. These correspond to Feynman x values of $x = .3$ and $.5$ for either positive or negative muons as indicated.

The open circles correspond to the data after corrections for Cherenkov inefficiency and for Cherenkov accidentals ($< 5\%$). The closed circles with error bars are the same data after corrections for acceptance (5% at the target open position) and for material in the beam between the Cherenkov counter and the Uranium target. The acceptance correction was determined using a Monte Carlo calculation which included the multiple scattering of the muons in the U and Fe. This correction was checked by using a 6" U target in place of the variable density target and absorber to determine the hadron flux for different target positions.

The correction for the material between the Cherenkov counter and the U was made by determining the product of the absorption length of the various items in the beam, times the decay path from the item to the U. This product, for all such items can be compared to the excess of events seen above the ∞ density intercept on Figure 3. For events in this figure, where the excess over the intercept at any target density comes from π and K decay, the fraction of protons interacting in the 6 absorption lengths of U is $\sim 100\%$. The average π and K decay path is the effective absorption length of the target. The size of the upstream material correction also depends on whether the target is open or closed because the effective decay paths for the upstream items change. The size of the corrections can be seen from the figure. As a check on the sensitivity of the final μ/π ratios on this correction, one can calculate the change in the answer for different assumed values of the absorption length of the U target. A 20% change in the absorption length changes the μ/π ratio by less than 5% in all cases. Since the masses, positions and absorption lengths of all items are known to better than 10%, this systematic error is negligible in comparison to the statistical errors.

The infinite density intercepts of the lines on Figure 3 correspond to the prompt muon production. At infinite density the π and K 's have no time to decay and the source of the muons must be some other mechanism. The slopes of the lines are then due to increasing contributions from π and K decay as the target density is decreased. In fact, given the π and K inclusive spectra as a function of x , it is possible to determine the pion and kaon flux per incident proton from the slopes on Figure 3. The intercept/slope ratio is then proportional to the $\mu/(\pi+K)$ ratio. The proportionality constant is determined by integrating the appropriate inclusive spectra. To determine the inclusive spectrum, the 6" U target was used with the variable target and absorber lowered out of the beam. In the interval $.3 < x < .7$ the negative spectrum fit $\frac{d\sigma}{dx} \approx (1-x)^4$. Since the positive spectrum is dominated by protons, the direct measurement would have involved a large correction. So the $\frac{\pi^+}{\pi^-}$ ratios of Aubert et al.,³ were used to determine a π^+ spectrum from the measured negative spectrum. The π^+ spectrum used was $\frac{d\sigma}{dx} \approx x(1-x)^4$. For K^+ and K^- , the spectra used for the calculation were steeper by a factor of x and less steep by a factor of x than the respective pion spectra of the same sign. The spectra and relative K/π ratios were taken from the data of Aubert et al.

Table I shows the final results for the 3 direct μ/π ratios. The calculated proportionality constants are implicit in the figure. In general, a change in the assumed π spectra of a factor of x changes the μ/π ratio by about 20%.

Contributions to the direct lepton signal from vector meson decay as well as Bethe-Heitler conversions from photon decay of π^0 have been calculated. At small $p_\perp$, massive $V^0 \rightarrow \mu\mu$ decays do not contribute significantly to the direct μ rate. For the acceptance of the apparatus and inclusive ρ^0 , ω^0 , and ϕ^0 data measured at 24 and 205 GeV^b, the Monte Carlo calculations indicate that

$$\left(\frac{\mu^-}{\mu^+} \right)_\rho \approx \left(\frac{\mu^-}{\mu^+} \right)_\omega \approx 1.0 \times 10^{-5},$$

and the ϕ^0 contribution is negligible.

For various parameterizations of the π^0 spectra, the $\frac{\mu^-}{\pi^-}$ ratio from the Bethe-Heitler process is about 1.0×10^{-5} . More significant is the fact that there are some relevant data on this subject. Calibrations of Pb-glass Cherenkov counters at Fermilab with similar s and x show that the $\frac{e^-}{\pi^-}$ rate is about 0.3 for 100% of the photons converting. Scaling by the square of the ratio of lepton masses implies a $\frac{\mu^-}{\pi^-}$ ratio due to the Bethe-Heitler process of 0.75×10^{-5} , in good agreement with the Monte Carlo calculation.

The measurement of the $\frac{\mu^-}{\pi^-}$ ratio at $x = .3$ for $p \gtrsim 300$ MeV/c is

Figure 3

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

sign	P_μ (GeV/c)	intercept (arbitrary units)	slope due to $\pi + K$	slope due to π only (slope _{π})	$\frac{\text{intercept}}{\text{slope}_\pi}$	$\nu/\pi \times 10^4$
+	90	4.95 ± 0.51	1.66 ± 0.22	$1.28 \pm .22$	3.88 ± 0.79	0.47 ± 0.10
-	90	4.72 ± 0.18	0.333 ± 0.077	0.303 ± 0.071	15.6 ± 3.7	1.56 ± 0.40
-	150	0.87 ± 0.12	0.085 ± 0.045	0.085 ± 0.046	10.2 ± 5.6	0.38 ± 0.21

about 5 times larger than conventional mechanisms would indicate. The first possibility is that the measurement is wrong. The only other experiment with similar x , s , and p does, indeed, disagree somewhat with our findings. The results of Leipuner et al.⁵ are shown in Figure 4 along with the results of this experiment. As can be seen, our μ^- data are larger by a factor of 5, and μ^+ by a factor of 2.5 than those of Leipuner et al. There are some differences in the two experiments which, in principle, could account for the discrepancies.

Table II - Differences.

	Leipuner et al.	This Experiment
A dependence	Cu target	U target
E_{inc}	400 GeV	300 GeV
x acceptance	minimum range requirement	$\frac{\Delta p}{p} \sim \pm 7\%$
$p_{\perp}$ acceptance	broad, due to more multiple scattering	Figure 1

To the extent that our Bethe-Heitler and vector meson calculations can be applied to the experiment of Leipuner et al., one might judge that their results near $x = .3$ are explainable. Ours seem not to be.

It is amusing to note that the fraction of the "explained" contribution relative to the total μ/π ratio estimated by Leipuner et al. (~20%) is the same as for the experiment reported here. Since the data of the two experiments differ by a factor of 5, this implies that the calculations are different by a factor of 5.

What is needed is an experiment which would simultaneously measure the direct μ/π ratios and the contributions due to pairs from vector meson decays and Bethe-Heitler conversions.

REFERENCES

- ¹D. Buchholz et al., preprint FERMILAB-Pub-75/88-EXP (Dec. '75) and to be published in Phys. Rev. Lett.
- ²J. P. Boymond et al., Phys. Rev. Lett. 33, 112 (1974).
F. W. Busser et al., Phys. Lett. 53B, 212 (1974).
J. A. Appel et al., Phys. Rev. Lett. 33, 722 (1974). etc.
- ³B. Aubert et al., preprint FERMILAB-Conf-75/31-EXP 7300.001.
- ⁴V. Blobel et al., Phys. Lett. 48B, 73 (1974).
P. Singer et al., preprint ANL-HEP-PR-75-48.
- ⁵L. B. Leipuner et al., Phys. Rev. Lett. 35, 1613 (1975).