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Production of Muon Pairs by 150-GeV/c π^+ and Protons*

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We have measured the cross section for $\mu^+\mu^-$ production in the reactions $(\pi^+, p) + \text{Be} \rightarrow \mu^+ + \mu^- + X$, at an incident momentum of 150 GeV/c. This Letter covers the pairs with masses above 2 GeV/c², in which region the signal is dominated by production of the $J(3.1)$. No events with μ -pair mass > 4.1 GeV/c² were seen, although the experiment is sensitive up to ≥ 12 GeV/c².

We report the first results of a comprehensive study of μ -pair production now under way at Fermilab to measure the reactions $(\pi, p, K) + A \rightarrow \mu + \mu + X$ (the experiment is also sensitive to events with more than two muons). In a recently completed run with a 150-GeV/c positive beam, we have accumulated 4×10^5 triggers from the processes $\pi^+ + \text{Be} \rightarrow \mu + \mu + X$ and $p + \text{Be} \rightarrow \mu + \mu + X$, and have analyzed those with μ pairs of masses > 2 GeV.

The detector is shown in Fig. 1. The 2-cm $\times$ 2-cm-wide beam, composed mainly of protons and pions in the ratio $\approx 3.3/1$, was incident on a 5-cm-diam, 10-cm-thick Be target, with a typical total flux of $\approx 5 \times 10^5$ particles/burst. Two He-filled Cherenkov counters set just below the proton threshold separated π^+ from protons (kaon and muon components were only $\approx 1\%$). A 2.2-m-thick iron block placed 1.3 m downstream from the target absorbed hadrons before decay, allowing only muons to emerge into a large cylindrical magnet (the former University of Chicago cyclotron), 2.1 m in radius and 1.27 m in gap height. Downstream from the magnet, the muons had to

penetrate an additional 2.5 m of iron, after which they were detected by a large scintillation-counter hodoscope (shown as P in Fig. 1.) The events induced by π^+ and protons were accumulated simultaneously; hence their comparison is particularly insensitive to systematic effects. The trigger requirements were as follows: (1) One and only one beam particle and no "halo" particles within a time interval of ≈ 100 nsec. (2) ≥ 2 particles

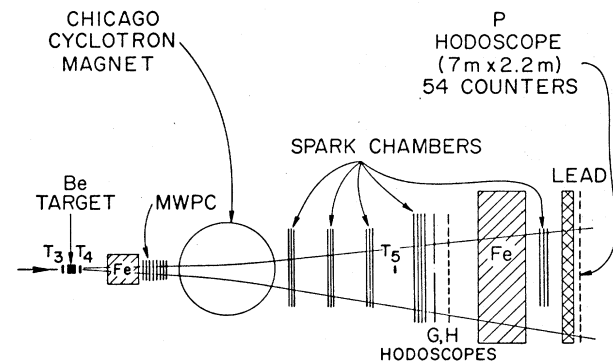


FIG. 1. The spectrometer.

leaving the target, as determined by the pulse height in counter T_4 situated just downstream of the target. (3) ≥ 1 particle in the hodoscope G . (4) ≥ 2 muons in the hodoscope P . To reject single μ 's accompanied by low-energy electromagnetic showers, hodoscope P was mounted flush against the downstream side of a 20-cm-thick Pb wall. Additional rejection was accomplished by requiring the muon pulses to be in nonadjacent counters. (5) No count in T_5 , a 7.5-cm² counter downstream of the magnet to veto beam muons. Approximately 70% of the triggers were unaccompanied muon pairs. The rest, mainly single μ 's with wide-angle showers, posed no problem for the analysis. The trigger rate was $\approx 8/(10^6 \text{ beam particles})$.

The particle trajectories were measured upstream of the magnet by eight planes of multi-wire proportional counters (MWPC's), 1 m $\times$ 1 m in size and 1.5-mm wire spacing, and downstream of the magnet by twenty planes of wire spark chambers of sizes 2 m $\times$ 4 m and 2 m $\times$ 6 m. This large number of detectors gives more than adequate redundancy to eliminate spurious sparks and avoid biases from chamber inefficiencies. Event reconstruction was straightforward since the MWPC's and spark chambers had in general well over 90% efficiency, and the probability that a μ pair was accompanied by an extra track in the spectrometer was less than 5%. A small contamination ($< 2\%$) from beam muons was eliminated, with no loss of good events, by rejecting any event in which the laboratory momentum of either muon exceeded 130 GeV/c.

To separate μ pairs produced in the target from those produced in the steel absorber we required that two distinct calculations of the μ -pair effective mass agree within 0.6 GeV/c². In the first calculation only the slopes of the muon trajectories were used; their intercepts, and hence the position of the decay vertex, were disregarded. In the second, a best fit was made to the true trajectories using the slopes, the intercepts, and also the assumption that the vertex was at the center of the target. Monte Carlo studies showed that this procedure had a negligible effect on pairs from the target, but removed events originating elsewhere.

The mass spectra for p -induced and π -induced pairs are shown in Fig. 2, uncorrected for the efficiency of the spectrometer. The distribution of vertex positions of these events shows no indication of any source other than the target. Background from hadron decays is also negligible

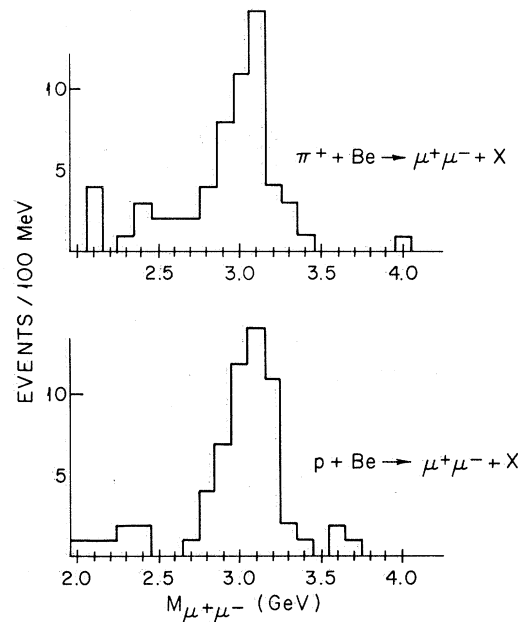


FIG. 2. Mass spectra, uncorrected for spectrometer acceptance.

since only a single like-charged event ($\mu^+\mu^+$ or $\mu^-\mu^-$) was observed in the entire exposure, specifically a p -induced $\mu^+\mu^+$ event with $M_{\mu\mu} = 2.3$ GeV/c². If we define J events to be all those in the interval $2.6 < M_{\mu\mu} < 3.5$ GeV/c², there are 47 events induced by π^+ , and 52 by protons. (The effective beam composition was 3.3 protons for every π^+ .) No events were seen above 4.1 GeV/c², although we have an efficiency of $> 10\%$ for masses well above 10 GeV/c². The line shape of the prominent J peak, primarily determined by multiple scattering in the first Fe absorber, is nearly Gaussian, with $\sigma \approx 130 \text{ MeV}/c^2$. The fraction of J events falling below 2.6 GeV/c² or above 3.5 GeV/c² is less than 2%, as determined by a Monte Carlo study which included the correlation between lateral and angular scattering in the shield, fluctuations in ionization energy loss, and fluctuations in energy loss through radiative processes. Hence the seven p -induced events and eleven π^+ -induced events are from some other source.

The J events are plotted in Fig. 3(a) as a function of $x_F \approx 2p_{\parallel}^{c.m.}/\sqrt{s}$, after having been corrected for acceptance and reconstruction efficiency. The proton-induced spectrum is reasonably well fitted by $\exp(-5x_F)$; a broader spectrum is seen for the π^+ -induced J events. Figure 3(b) shows the dependence on $p_{\perp}^2$. The π^+ - and p -induced events

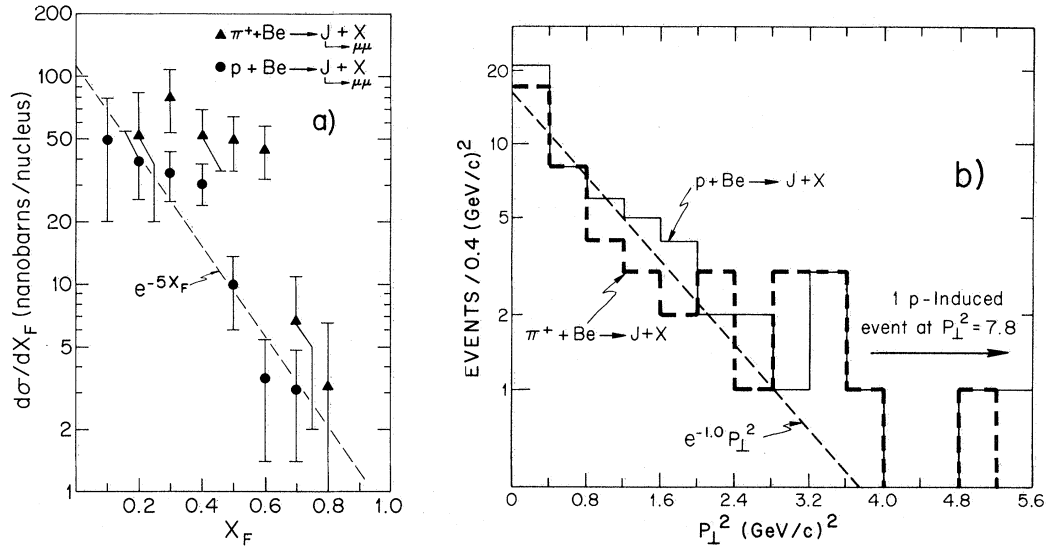


FIG. 3. (a) Cross sections for J production by π^+ and protons. (b) Relative distributions in $p_{\perp}^2$ for J production, uncorrected for acceptance. [The acceptance is uniform in $p_{\perp}^2$ to within $\pm 10\%$ out to $p_{\perp}^2$ of 3 $(\text{GeV}/c)^2$.]

exhibit similar broad spectra, as is seen by comparing with the curve $\exp(-1.0 p_{\perp}^2)$.

The calculation of the spectrometer acceptance is straightforward because it extends smoothly over a wide range: $0.05 < x_F < 1$; $0.5 < M_{\mu\mu} < 12 \text{ GeV}/c^2$; $0 < p_{\perp} \leq 4 \text{ GeV}/c$. The only model-dependent aspect is the need to assume a particular distribution for the decay angle of the μ pair in its rest frame. (We have a large acceptance, $0 < |\cos\theta_{\mu\mu}^{c.m.}| < 0.8$, but our sample is too small to measure the distribution.) The results below are based on a uniform distribution—a 30% decrease in the total acceptance occurs if $1 + \cos^2\theta_{\mu\mu}^{c.m.}$ is assumed, although there is no change in the shape of the acceptance as a function of x_F or $p_{\perp}$.

In comparing the production of μ pairs by π^+ and protons we obtain the following cross-section

ratios: (a) J production ($2.6 < M_{\mu\mu} < 3.5 \text{ GeV}/c^2$),

$$\frac{\sigma(p + \text{Be} \rightarrow J + X)}{\sigma(\pi^+ + \text{Be} \rightarrow J + X)} = \begin{cases} 0.59 \pm 0.15, & x_F > 0.05, \\ 0.16 \pm 0.05, & x_F > 0.45. \end{cases}$$

(b) Continuum μ pairs ($2.0 < M_{\mu\mu} < 2.6 \text{ GeV}/c^2$),

$$\frac{\sigma(p + \text{Be} \rightarrow \mu^+ + \mu^- + X)}{\sigma(\pi^+ + \text{Be} \rightarrow \mu^+ + \mu^- + X)} = 0.21 \pm 0.11, \quad x_F > 0.05.$$

The absolute cross sections and 90% confidence limits for the production of μ pairs in various charge states and mass regions are presented in Table I. (The errors include both statistical and systematic effects.) To convert from cross section per nucleus to cross section per nucleon we have assumed a linear A dependence.¹ The cross sections for J production ($2.6 < M_{\mu\mu} < 3.5 \text{ GeV}/c^2$) include a subtraction of continuum μ pairs (6%

TABLE I. Absolute cross sections for μ -pair production at 150 GeV/c incident momentum. Upper limits are for 90% confidence. Statistical and systematic errors are included.

Charge state	Mass range (GeV/c^2)	Range of x_F	$\sigma(p + \text{Be} \rightarrow \mu + \mu + X)$ (nb/nucleus)	$\sigma(p + \text{Be} \rightarrow \mu + \mu + X)$ (nb/nucleon)	$\sigma(\pi^+ + \text{Be} \rightarrow \mu + \mu + X)$ (nb/nucleus)	$\sigma(\pi^+ + \text{Be} \rightarrow \mu + \mu + X)$ (nb/nucleon)
+-	2.0-2.6	0.05-1.0	2.4 ± 0.9	0.27 ± 0.10	11 ± 4	1.3 ± 0.5
+- (J)	2.6-3.5	0.05-1.0	17 ± 4	1.9 ± 0.4	29 ± 6	3.2 ± 0.7
+-	3.5-4.1	0.20-1.0	1.0 ± 0.6	0.11 ± 0.07	< 4.0	< 0.44
++	2.0-4.1	0.20-1.0	< 1.3	< 0.15	< 2.4	< 0.27
--	2.0-4.1	0.20-1.0	< 0.75	< 0.08	< 2.4	< 0.27
++, +-, --	4.1-10	0.4-0.6	< 0.84	< 0.09	< 2.8	< 0.31

TABLE II. Production of J particles at various energies. To compare p -Be and p - p interactions, a linear A dependence has been used. Errors are not given, but are small compared to variations in cross sections between experiments.

Reference	Interaction	$\sqrt{s}$ (GeV)	$\frac{d\sigma}{dx_F} _{x_F=0}$ (cm ² /nucleon)	$\frac{d\sigma}{dy} _{y=0}$ (cm ² /nucleon)
5	p -Be	6.1	1×10^{-35}	1×10^{-35}
5	p -Be	7.3	1×10^{-34}	8×10^{-35}
This expt.	p -Be	16.8	1.2×10^{-32}	4.5×10^{-33}
6	p - p	48(av)	6×10^{-32}	7.5×10^{-33}

for π^+ , 3% for protons). If we designate as $\psi(3.7) \rightarrow \mu + \mu$ the three p -induced events in the mass range 3.5–4.1 GeV/ c^2 , we can place a limit on $\psi(3.7)$ production, obtaining a $\psi(3.7)$ cross section $\approx 40\%$ of that of J production. The cascade $\psi(3.7) \rightarrow J \rightarrow \mu + \mu$ would then account for $\approx 20\%$ of our $J \rightarrow \mu + \mu$ signal.

In a recent experiment at ≈ 250 GeV/ c incident momentum,² the cross section $\sigma(n + \text{Be} \rightarrow (J \rightarrow \mu + \mu) + X) = 3.6$ nb/nucleon has been measured with a factor-2 uncertainty, for $|x_L| > 0.24$. Our comparable result,³ $\sigma(p + \text{Be} \rightarrow (J \rightarrow \mu + \mu) + X) = 5.4 \pm 0.8$ nb/nucleon, is in reasonable agreement.⁴

In Table II we compare our results to experiments at widely differing energies,⁷ listing the quantities $(d\sigma/dx_F)_{x_F=0}$ and $(d\sigma/dy)_{y=0}$ (the total cross sections, unfortunately, have not been measured at all these energies). To scale between differing nuclei (Be versus protons) we have used a linear A dependence. The dramatic increase from $\sqrt{s} = 7.3$ to $\sqrt{s} = 16.8$ GeV does not continue out to $\sqrt{s} = 48$ GeV.

To conclude, we summarize the essential features of J production that we have measured: The π -induced and p -induced J cross sections are comparable at low x_F , but the π^+ events dominate for $x_F \gtrsim 0.45$; the $p_\perp$ spectra are broader, if anything, than $\exp(-1.0p_\perp^2)$, with no significant difference between π^+ - and p -induced spectra.

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whose spectrometer we have used in a slightly modified form for this work. We are indebted to R. Armstrong, T. Nunamaker, K. Wright, H. Edwards, and their shop staffs at Chicago and Princeton.

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¹The parton model predicts such an A dependence —S. Brodsky, private communication. Also, see P. M. Fishbane and J. S. Trefil, to be published.

²B. Knapp *et al.*, Phys. Rev. Lett. **34**, 1044 (1975), and in Proceedings of the International Symposium on Lepton-Photon Interactions at High Energy, Stanford, California, August 1975 (to be published).

³Knapp *et al.* assume the A dependence of J production to be the same as that of the total n -Be cross section. To compare with them we have scaled our data by $A^{2/3}$ and restricted our sample to their x_F region.

⁴G. J. Blunar *et al.*, Phys. Rev. Lett. **35**, 346 (1975), have also measured J production for π^- and p interactions in an iron absorber, over a more limited x_F region.

⁵J. J. Aubert *et al.*, Phys. Rev. Lett. **33**, 1404 (1974); S. C. C. Ting, in Proceedings of the International Conference on High Energy Physics, Palermo, Italy, June 1975 (unpublished); U. Becker, private communication.

⁶F. W. Busser *et al.*, Phys. Lett. **56B**, 482 (1975).

⁷The work of Ref. 4 is not compared because of the large extrapolation required to $x_F = 0$, and because it used a much heavier target nucleus.