Production of the J/ψ and $\psi'(3.7)$ by 225-GeV/c $\pi^{\pm}$ and Proton Beams on C and Sn Targets*

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We present results of a large-acceptance experiment in which muon pairs were observed in the mass range 0.6 to 6.0 GeV/c^2. Emphasis is given to features of the production of J/ψ and $\psi'(3.7)$ particles. We find $[B\sigma]_{\psi'(3.7)}/[B\sigma]_{J/\psi}$ to be 0.007 ± 0.004 for p-C and 0.018 ± 0.007 for π^+-C interactions. Comparison with results from e^+e^- storage rings indicates that both the J/ψ and the $\psi'(3.7)$ are produced strongly rather than electromagnetically in our experiment.

We have performed an experiment at Fermilab in which we observe muon pairs produced by hadron beams striking nuclear targets. This work extends our previous studies[1,2] in several ways: (1) The present exposure is 15 times the previous, some 2100 J/ψ particles having been observed; (2) the beam energy was raised to 225 GeV to map the threshold rise of J/ψ production; (3) a π^- beam was used as well as π^+ and p, allowing a search for the Drell-Yan or other electromagnetic process by comparison of π^+-induced with π^--induced production; (4) carbon and tin targets were used to investigate the A dependence of dimuon production.

The experiment utilized the University of Chicago cyclotron magnet spectrometer facility described elsewhere.[1] A third threshold Cherenkov counter was added to the beam line for greater reliability in particle identification. The proportional chambers upstream of the hadron absorber[2] were not used in this analysis; the muon pairs were observed only after elimination of the hadrons. For part of the experiment low-mass pairs were suppressed in the trigger by requiring a minimum separation of the muons in a scintillator hodoscope placed directly after the hadron absorber. A suppression factor of 2.2 in the trigger rate was achieved without any loss in efficiency for pairs with mass above 1.5 GeV/c^2.

For each observed pair the mass, Feynman x ($x_F = 2p_L^*/\sqrt{s}$), transverse momentum, and helicity angle of the μ^- in the pair rest frame are determined. A fitting procedure is used in which an assumed event vertex at the center of the target provides a constraint on the observed muon tracks, which have suffered multiple scattering in the hadron absorber. An extensive Monte Carlo simulation of the experiment is used to determine the detection efficiency as a function of the four kinematic variables, as well as their experimental resolution. For masses above 1 GeV/c^2, there is negligible contamination from events originating in the absorber; in the ρ-ω mass region (0.65–0.95 GeV/c^2), however, a 5–10% contamination is present. Pairs with masses less than 0.65 GeV/c^2 will be discussed in a future publication.

We present below the cross sections for directly produced $\mu^+\mu^-$ pairs. To account for pairs due to the decay of two oppositely charged pions or kaons, we first subtract the like-sign-pair cross sections ($\mu^+\mu^+$ and $\mu^-\mu^-$) from the raw $\mu^+\mu^-$ cross sections, assuming that the like-sign pairs are entirely due to meson decays.[3] Figure 1 shows the cross section for $\mu^+\mu^-$ produced in p-C interactions corrected for meson decays, as well as the observed like-sign-pair signal. The datum point at 4.7 GeV/c^2 represents five events between masses 4.2 and 5.9 GeV/c^2. Among the pion-induced events there are seven with masses above 4.2 GeV/c^2 including one at 9.5 GeV/c^2.

To display the general features of the data we group it into several mass intervals and parametrize the invariant cross section, $E\,d^3\sigma/dp^3$, by the form $A\exp(-Bp_T)(2-x_F)^C$. The results of this procedure are given in Table I, where the normalization factor A is per nucleus, integrated over the mass interval. The broad features of the x_F and p_T dependence of the data are similar to those reported in our previous work[2] as well as by others.[4,5] Discussion of the dependence on target nucleus and comparison of the nonresonant continuum production by various beams will be found in the following Letter.[6] The remainder of this Letter emphasizes features of J/ψ produc-

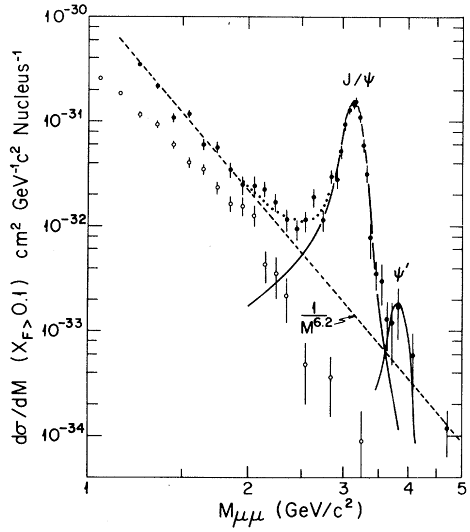

FIG. 1. Distribution of $d\sigma/dM$ for $x_F > 0.1$ for proton-carbon interactions. The solid points are $\mu^+\mu^-$ data corrected for π and K decay and the open points are $\mu^+\mu^+$ and $\mu^-\mu^-$ data combined. The solid curves are Monte Carlo estimates of the line shapes of the J/ψ and $\psi'(3.7)$. The dashed curve is an estimate of the muon-pair continuum in the mass region 2–2.7 GeV/c^2, extrapolated to higher masses. A small shoulder near 3.7 GeV/c^2 is the $\psi'(3.7)$ signal.

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Figure 2(a) illustrates the x_F dependence of J/ψ production for the π^+-, π^--, and p-C interactions, where we include all events with masses between 2.7 and 3.5 GeV/c^2 in the J/ψ signal. The pion-induced distributions are flatter than the proton-induced ones by a factor of approximately $(1-x_F)^{-2}$. Fits by the form $(1-x_F^2)^C$ yield poorer χ^2 values in all mass intervals. From fits to $d\sigma/dx_F$ the inclusive cross section per nucleus times the branching fraction for $x_F > 0$ is determined to be 141 ± 10 nb for π^--C interactions, 122 ± 14 nb for π^+-C, and 82 ± 4 nb for p-C. Systematic uncertainty is estimated to be 10%.

Figure 2(b) shows the transverse-momentum dependence of the J/ψ to be $\approx \exp(-2p_T)$ for all three beams. The data have been corrected for the systematic effect of multiple Coulomb scattering on the reconstructed value of p_T. Below p_T of 0.4 GeV/c the correction is substantial and somewhat unreliable; therefore this region has been excluded from the fits. While a fit by the form $\exp(-Bp_T^2)$ is marginally preferable for the p_T range of our J/ψ data, it is inferior to the given fits in the lower-mass regions.

In Fig. 2(c) we present helicity-angle distributions for J/ψ and ρ-ω events. The J/ψ data are from all beams and both targets combined, while the ρ-ω data are from pion interactions with carbon only. We look for evidence of polarization by fitting with the form $1 + P\cos^2\theta$. For the ρ-ω data it is necessary to restrict x_F to be greater than 0.3 to obtain a broad region of useful detection efficiency, as indicated by the dashed curve in Fig. 2(c). The fitted values of the polarization parameter, P, are 0.02 ± 0.07 for the ρ-ω data, and

TABLE I. Results of fits of the invariant cross section, $E\,d^3\sigma/dp^3$, by the form $A\exp(-Bp_T)(1-x_F)^C$ in seven mass intervals for each of the various beam and target combinations. The normalization is per nucleus, integrated over the mass interval.

TARGET	MASS INTERVAL (GeV/c^2)	π^+ BEAM A nb/GeV^2/c^3	π^+ BEAM B (GeV/c)$^{-1}$	π^+ BEAM C	π^- BEAM A nb/GeV^2/c^3	π^- BEAM B (GeV/c)$^{-1}$	π^- BEAM C	PROTON BEAM A nb/GeV^2/c^3	PROTON BEAM B (GeV/c)$^{-1}$	PROTON BEAM C
C	0.65 - 0.95	8.81 ± .36 x 10^3	3.87 ± .06	1.35 ± .08	7.45 ± .33 x 10^3	3.81 ± .05	.92 ± .07	1.14 ± .04 x 10^4	3.64 ± .06	3.14 ± .08
	0.95 - 1.1	1.26 ± .09 x 10^3	3.57 ± .07	1.67 ± .17	1.09 ± .09 x 10^3	3.51 ± .09	1.60 ± .16	1.55 ± .09 x 10^3	3.39 ± .06	3.82 ± .14
	1.1 - 1.5	690 ± 100	3.39 ± .09	2.30 ± .33	469 ± 67	3.14 ± .09	1.81 ± .33	820 ± 84	3.19 ± .09	4.26 ± .29
	1.5 - 1.9	130 ± 28	3.19 ± .21	2.17 ± .41	87 ± 18	2.88 ± .21	2.04 ± .33	109 ± 15	2.65 ± .11	4.09 ± .33
	1.9 - 2.3	8.1 ± 7.2	2.17 ± .93	.80 ± .44	13.1 ± 6.0	2.38 ± .42	1.28 ± .59	29.3 ± 6.8	2.71 ± .20	3.25 ± .47
	2.3 - 2.7	4.3 ± 2.6	2.10 ± .50	.75 ± .67	8.1 ± 4.4	2.15 ± .35	1.06 ± .75	10.4 ± 3.3	2.02 ± .23	3.89 ± .61
	2.7 - 3.5	84.8 ± 15.0	2.06 ± .10	1.33 ± .21	102 ± 19	1.98 ± .13	1.93 ± .20	89.8 ± 9.5	2.05 ± .09	3.44 ± .14
Sn	0.65 - 0.95	4.95 ± .38 x 10^4	3.44 ± .08	2.23 ± .18				6.58 ± .51 x 10^4	3.28 ± .07	4.47 ± .20
	0.95 - 1.1	7.51 ± .79 x 10^3	3.19 ± .11	2.16 ± .24				9.57 ± .89 x 10^3	3.11 ± .07	4.76 ± .21
	1.1 - 1.5	5.70 ± 1.04 x 10^3	3.36 ± .14	2.71 ± .48				6.58 ± .68 x 10^3	3.11 ± .09	5.39 ± .31
	1.5 - 1.9	475 ± 100	2.61 ± .27	2.05 ± .92				1.19 ± .24 x 10^3	3.20 ± .18	4.28 ± .53
	1.9 - 2.3	59 ± 51	1.36 ± .48	2.30 ± 1.30				219 ± 83	2.42 ± .29	3.59 ± .80
	2.3 - 2.7	160 ± 166	1.78 ± .76	4.24 ± 1.88				47 ± 29	2.22 ± .35	2.53 ± 1.21
	2.7 - 3.5	513 ± 118	1.78 ± .15	1.50 ± .28				776 ± 161	2.02 ± .14	4.01 ± .37

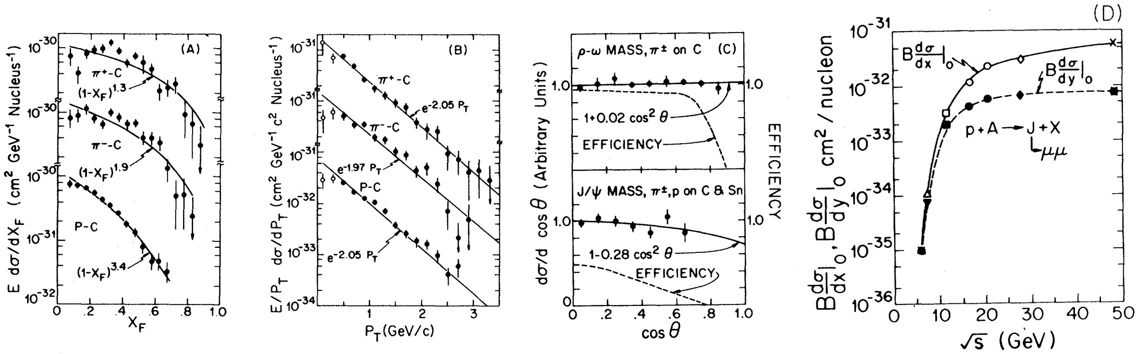

FIG. 2. (a) Distribution of $E\,d\sigma/dx_F$ for the mass interval 2.7–3.5 GeV/c^2, for production of muon pairs in π^+,π^-, and proton interactions with carbon. The solid lines are fits (see text). (b) Distribution of $(E/p_T)d\sigma/dp_T$ for the same data as in (a). We require $x_F > 0.1$. The data plotted with open circles were not used in the fits (see text). (c) Distributions of $d\sigma/d\cos\theta$, where θ is the helicity angle of the μ^- in the pair rest frame, for events with masses in the range 0.65–0.95 and 2.7–3.5 GeV/c^2. The solid lines are fits (see text), while the dashed lines are the detection efficiencies. (d) Energy dependence of J/ψ production at 90° in the c.m. frame, plotted for two forms of the cross section. The curves are only to guide the eye. △,▼, Ref. 7; □,■, Ref. 8; ○,●, this experiment; ◇,◆, Ref. 5; ×,✱, Ref. 9.

-0.28 ± 0.22 for the J/ψ data. As the error on the J/ψ result is large it is useful to note that the confidence level for the hypothesis $P=0$ is 35%, while for $P=1$ it is 0.01% and for $P=-1$ it is 0.6%.

The energy dependence of J/ψ production is shown in Fig. 2(d), where we have extrapolated our data to $x_F=0$ (and rapidity $y=0$) to compare with other results. Linear dependence on atomic weight is used.[4,6] The increase in cross section above threshold is remarkably slow, with the invariant cross section, $d\sigma/dy$, reaching a plateau above $\sqrt{s}=20$ GeV.

Finally, we consider the evidence for production of the $\psi'(3.7)$ particle. Figure 1 shows $d\sigma/dM$ for $x_F > 0.1$ in the vicinity of the J/ψ mass for the proton beam. The solid curve is a Monte Carlo estimate of the line shape of the J/ψ. After subtracting the tail of the J/ψ in the mass region 2–2.7 GeV/c^2 we obtain the dashed curve with $1/M^{6.2}$ behavior as the estimate of the μ-pair continuum in the region 2–4 GeV/c^2. This estimate extrapolates well towards our one high-mass datum point at 4.7 GeV/c^2. A significant signal remains above both this continuum[10] and the high-mass tail of the J/ψ near the mass 3.7 GeV/c^2. Subtracting both effects we obtain the ratios of branching fraction times cross section for production with $x_F > 0.1$:

$$\frac{[B\sigma]_{\psi'(3.7)}}{[B\sigma]_{J/\psi}} = 0.007 \pm 0.004\ (p\text{-C})$$

$$= 0.018 \pm 0.007\ (\pi^+\text{-C}).$$

Because of the higher level of the μ-pair continuum in π^--C interactions it is difficult to evaluate this ratio which appears, if anything, larger. Our result for proton beams is somewhat smaller than a previous result[5] at 400-GeV beam energy and $x_F=0$, which may, however, be due to different energy dependences of the cross sections of the J/ψ and $\psi'(3.7)$.

Although the $\psi'(3.7)$ appears to be much less copiously produced than the J/ψ we may still conclude that it is produced by a strong interaction rather than an intermediate virtual photon by the following argument. As an extreme we suppose that all of the continuum production of muon pairs shown in Fig. 1 is due to an electromagnetic interaction, such as the Drell-Yan[11] process. Then we may compare our ratios of resonance to continuum production (integrated over a suitable interval) to those obtained from J/ψ and $\psi'(3.7)$ production at SPEAR.[12,13] For the J/ψ our resonance/continuum signal is 80 times stronger than that at SPEAR, while for the $\psi'(3.7)$ it is 15 times stronger. This analysis, while includes the effects of branching-fraction and cross-section mass dependence, thus indicates that both the J/ψ and $\psi'(3.7)$ are hadronically produced in our experiment.

This observation, as well as the flatter x_F distributions for pion-induced J/ψ events compared to proton-induced events, is in agreement with gluon fusion models[14,15] in which the J/ψ and $\psi'(3.7)$ come principally from decays of even-charge-conjugation charmonium states,[16] rather than from direct production. The absence of charmed-particle production in association with the J/ψ events[4,17] also supports the gluon fusion picture.

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Hadronic Production of Massive Muon Pairs: Dependence on Incident-Particle Type and on Target Nucleus*

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Data from a study of muon pairs produced in hadron-nucleus collisions are compared with the Drell-Yan model. Comparison of dimuon production by π^+ and π^- mesons on an isoscalar target shows evidence for a charge asymmetry characteristic of an isospin-nonconserving electromagentic process. The average transverse momentum of the pairs increases smoothly with pair mass. Data taken on carbon and tin targets are used to extract the dependence on target atomic weight.

As part of our study at Fermilab of muon pairs produced in hadron-nucleus collisions, we present results for nonresonant and resonant dimuons which illustrate the dependence of the production on incident-particle type and on target nucleus. We compare several features of this data with predictions of the Drell-Yan model.[1] In the preceding Letter[2] we discuss other aspects of this data sample, obtained with 225-GeV/c beams of π^+, π^-, and protons incident on carbon and tin targets.

Many authors[1,3-5] predict the formation of nonresonant muon pairs by the electromagnetic annihilation of fractionally charged quarks and antiquarks in the target and projectile. Recent experiments with proton beams[6,7] at 300 and 400 GeV have measured cross sections $(d^2\sigma/dMdy)_{y=0}$ which are in reasonable agreement with some of the