by neutrinos with three muons in the final state. Both events contain an energetic μ^- and two additional muons with low kinetic energy in the hadronic rest frame. Two mechanisms which may contribute to this signal are (1) low-mass muon pairs from virtual photons and/or decay of vector mesons, and (2) associated production of new hadrons which decay leptonically.

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Search for Muons Produced in Conjunction with the J/ψ Particle*

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In a large-acceptance spectrometer at Fermilab, we have searched for multimuon events produced in collisions of 225-GeV/c protons and $\pi^\pm$ mesons with nuclei. In particular, additional muons accompanying the $J/\psi \to \mu\mu$ decay could signal charmed-particle production. For all data combined, the 90%-confidence limit on charmed-particle production in association with the J/ψ is $\sigma_{JC\bar{C}}/\sigma_J < 0.01$; the limit on production of J/ψ pairs is $\sigma_{JJ}/\sigma_J < 0.021$. Limits are also given for each beam particle separately.

The small width of the J/ψ particle is attractively accounted for[1] if this particle is a bound state of a charmed quark and its antiquark. The Okubo-Zweig-Iizuka (OZI) rule[2] would then predict that the J/ψ may be produced strongly in conjunction with pairs of charmed particles ($C\bar{C}$). On the other hand, should the J/ψ itself carry a new quantum number,[3] then it should be produced in pairs ($J\bar{J}$). Both schemes can be tested by searching for multimuon events resulting from the following processes:

$$\begin{array}{l} \left.\begin{matrix}\pi^{\pm}\\ p\end{matrix}\right\} + \text{nucleus} \to J/\psi + (C + \bar{C}) + \text{anything}, \qquad (1) \\ \qquad\qquad\qquad\qquad\qquad \hookrightarrow \mu^{\pm} + \nu + X \\ \qquad\qquad\qquad\qquad \hookrightarrow \mu^{+} + \mu^{-} \end{array}$$

and

$$\begin{array}{l} \left.\begin{matrix}\pi^{\pm}\\ p\end{matrix}\right\} + \text{nucleus} \to J/\psi + J/\psi + \text{anything}. \qquad (2) \\ \qquad\qquad\qquad\qquad\qquad \hookrightarrow \mu^{+} + \mu^{-} \\ \qquad\qquad\qquad\qquad \hookrightarrow \mu^{+} + \mu^{-} \end{array}$$

We have performed an experiment at Fermilab in which J/ψ's were produced by beams of 225-GeV/c π^+, π^-, and protons incident on carbon and tin targets. They were then detected in the Chicago cyclotron magnet spectrometer via their $\mu^+\mu^-$ decays. The details of the apparatus and the method of data analysis have been reported elsewhere.[4] Briefly, the beam (4 cm×4 cm in size) struck a short nuclear target placed 1.4 m upstream of a 2.2-m-thick iron hadron absorber, which was itself 5 m upstream of the center of the magnet. Additional muon identification was provided by a 53-element scintillator hodoscope placed 16 m downstream of the magnet and behind a second iron absorber, 2.5 m thick. Particles emerging from the first absorber were momentum-analyzed using multiwire proportional chambers upstream and spark chambers downstream of the magnet, all placed between the two absorbers. In the experiment a data sample of 10^6 dimuons ($\mu^+\mu^-$), containing 2100 J/ψ events, was collected. The event distribution of this J/ψ data, uncorrected for efficiency, is shown in Fig. 1(a), as a function of the Feynman x variable (x_F). [Also shown in Fig. 1(a), for discussion below, is the detection efficiency for any additional muons accompanying a dimuon.]

In the entire dimuon sample there are 2541 multimuon candidates, i.e., events which have at least three tracks, each pointing to different counters in the muon-identifying hodoscope. To determine the number of multimuons from Reactions (1) and (2) we must first find how much of the sample arises from background processes. The first source we consider is the misidentification of hadron tracks in the chambers as muons. The rate of hadrons actually penetrating both absorbers is negligible. However, if a hadron penetrates the first absorber and its track points at an accidentally hit hodoscope counter, a multimuon event can be simulated. From measured rates in the hodoscope we conclude that fewer than 4% of the candidates arise from this source.

A second source of background is an accidental coincidence between a dimuon event and one of the halo of muons that accompany the hadron beam as it enters the lab. Because the beam line is very long the muon flux into the lab is several percent of the hadron flux in the beam. Muons outside the beam were rejected by veto counters. Beam muons were suppressed by requiring that the pulse heights in two beam-defining counters each be consistent with only one beam particle arriving within a ± 60-nsec interval. We further eliminated halo events by requiring in the analysis that (1) no muon have a momentum greater than 100 GeV/c, (2) all muons reconstruct to vertices within 12.5 cm transverse to the beam, and (3) all muons reconstruct to the same vertex as determined by a χ^2 test. Requirement (1) eliminates 687 candidates, with negligible loss of dimuon events. The data indicate that requirements (2) and (3) eliminate 5% of dimuon events while removing an additional 344 multimuon candidates. In summary, the muon halo cuts reduce the sample from 2541 to 1510 candidates. It is important to note that their effect on the multimuon signal is determined from the observed properties of the dimuon and multimuon data, not from computer simulations.

For the remaining multimuon events, Fig. 1(b) shows the distribution in mass, M_{+-}, of all $\mu^+\mu^-$ pairs. (Each three-muon event appears twice.) There are only two events with $M_{+-} > 2.3$ GeV/c^2, both proton-induced J/ψ events with one additional muon. To ascertain the rate of real multimuon events, we must now subtract the background from decays of secondary π's and K's. Most of this occurs in the 1.6-m effective decay path between the target and one absorption length into

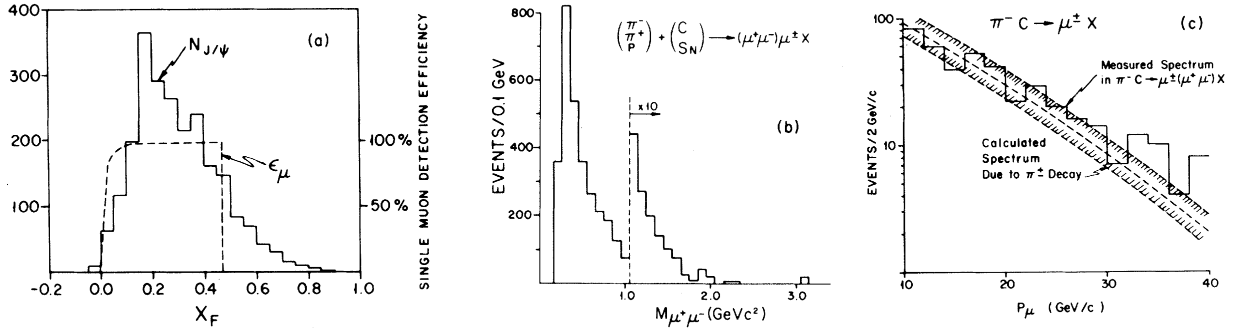

FIG. 1. (a) The solid line shows the distribution in x_F of J/ψ events. The efficiency ϵ_μ for detecting a *single* muon is shown by the dashed line; the transverse-momentum distribution of single muons used in obtaining ϵ_μ was $d\sigma/dp_T^2 \sim \exp(-5p_T)$. (b) Spectrum of M_{+-} for multimuon events. Each $\mu^+\mu^-\mu^\pm$ event appears twice. $p_{\text{beam}} = 225$ GeV/c. (c) Comparison of the observed third-muon momentum spectrum with hadron decay prediction, for π^--induced events. Each observed $\mu^+\mu^-\mu^\pm$ event appears twice. Similar agreement was found for π^+- and proton-induced events.

the first absorber. Because of the high energies involved, we cannot infer from the event reconstruction whether or not a decay took place. Evidence for a real multimuon signal must therefore consist of an excess over the number of events expected from hadron decay.

To measure this decay background we have used two classes of events. First, we attribute all multimuon events in which $M_{+-} < 2.3$ GeV/c^2 to decays of π and K mesons, because the OZI mechanism does not enhance the production of charmed particles in association with dimuons of this mass region. Second, we ascribe all "like-sign" dimuon events, $\mu^+\mu^+$ and $\mu^-\mu^-$, to decays of two hadrons. To check these two assumptions we have used measured π and K production spectra[5] to calculate the decay contamination. We find, for example, that for each interacting proton there are 8.7×10^{-4} μ^+ and 5.5×10^{-4} μ^- with energies greater than the 7 GeV required to penetrate the iron. The detection efficiency for single μ's is shown as the dashed curve in Fig. 1(a). (The cutoff at $x_F = 0.43$, or $p_{\rm lab} = 100$ GeV, is discussed above.) Tertiary hadron production in the first absorber followed by decay increases these yields by approximately 15%. In Table I, the number of three-muon events expected from decays is compared with the observed yields, for $M_{+-} < 2.3$ GeV/c^2. Reasonable agreement is seen. As a consistency check, we also give in the table the calculated and observed values of the three-muon charge ratio, $R = N(\mu^+\mu^-\mu^+)/N(\mu^+\mu^-\mu^-)$; again, there is reasonable agreement. The errors on all observed numbers are statistical. The errors on predicted quantities are due mainly to uncertainties in the acceptance for the lowest-energy muons, caused by straggling. As seen in Fig. 1(c), the shape of the single-μ momentum spectrum calculated for decay muons also agrees well with that of the observed "third" muons (i.e., the muon in addition to the $\mu^+\mu^-$ pair).

As a final check on the estimate of decay contamination, we have calculated the yield of like-sign dimuons, taking into account the known two-pion correlations.[5] The calculated result, $N(\mu^+\mu^+ + \mu^-\mu^-)/N(\mu^+\mu^-) = 0.035 \pm 0.007$, is reasonably close to the observed value of 0.05. Similarly, we compare the calculated charge ratio, $N(\mu^+\mu^+)/N(\mu^-\mu^-) = 2.5 \pm 0.2$, to the observed value, 2.1 ± 0.05. From the general consistency between data and the above calculations of hadron decay yields and charge ratios, we conclude that all multimuon events with $M_{+-} < 2.3$ GeV arise from decay contamination.

We now use the observed multimuon data to calculate the decay background accompanying $J/\psi \rightarrow \mu^+\mu^-$, assuming that the production of a J/ψ does not significantly alter the π and K production spectra. As seen in Table I, the observed and calculated yields are consistent. We thus conclude that there is no evidence for prompt production of extra muons in conjunction with the J/ψ particle. Subtracting the predicted decay contamination, we obtain 90%-confidence-level upper limits of 4.0, 1.1, and 1.5 events for production of a prompt third muon by protons, π^+, and π^-, respectively.

To set upper limits for production cross sections, we used a Monte Carlo technique to calculate the probability of detecting a third muon, given the detection of the $J/\psi \rightarrow \mu^+\mu^-$ decay. For Reaction (1) we assumed that the C (or $\bar{C}$) and J/ψ were produced correlated in their rapidities, the rapidity difference given[2] by the distribution

TABLE I. Properties of observed multimuon events, and comparison with the assumption that they arise from hadron decays. For $M_{+-} < 2.3$ GeV/c^2, the predicted quantities are results of a Monte Carlo calculation. For M_{+-} in the J/ψ region, the expected decay contamination was calculated from the observed multimuon sample as described in the text.

Range of M_{+-} (GeV/c^2)	Beam	Observed data Events $\mu^+\mu^-$	3μ	4μ	R	Predictions from π and K decay Events 3μ	R
0.21–2.3	p	740 000	803	5	1.59 ± 0.12	1053 ± 263	1.60 ± 0.15
	π^+	162 000	419	1	1.63 ± 0.16	300 ± 75	1.75 ± 0.15
	π^-	146 000	278	2	0.91 ± 0.11	320 ± 80	0.80 ± 0.10
2.7–3.5	p	1195	0	0	···	1.3	···
(J/ψ)	π^+	471	0	0	···	1.2	···
	π^-	434	0	0	···	0.8	···

$\exp(-2|Y_C - Y_J|)$. The C ($\bar{C}$), with mass of 1.87 GeV/c^2, then decayed via $C \rightarrow \mu + \nu + X$, where X was either a K meson ($M_X = 0.5$ GeV/c^2) or a collection of hadrons with $M_X = 1.0$ GeV/c^2. Three-body phase space was used to distribute the momenta of the decay products. The efficiency for detecting the muon from charmed-particle decay, on the condition that the $J/\psi \rightarrow \mu^+\mu^-$ is detected, was 0.52 (0.43) for hadron mass M_X of 0.5 GeV/c^2 (1.0 GeV/c^2). Using the lower detection efficiency, and a branching ratio of 0.1 for $C \rightarrow \mu + \nu + X$, we obtain the following upper limits, with 90% confidence:

$\sigma_{JC\bar{C}}/\sigma_J$	Type of production
<0.040	p-induced
<0.028	π^+-induced
<0.041	π^--induced
<0.010	Combined

For Reaction (2) we assumed that each J/ψ of the pair was produced with the distribution in x_F and p_T as measured in inclusive J/ψ production.[4] For proton- and pion-induced events, respectively, the probability of detecting at least one muon from the second $J/\psi \rightarrow \mu\mu$ decay is 0.67 and 0.63. Including the 7% branching ratio for $J/\psi \rightarrow \mu\mu$ we find the 90%-confidence limits:

σ_{JJ}/σ_J	Type of production
<0.072	p-induced
<0.052	π^+-induced
<0.079	π^--induced
<0.021	Combined

The large acceptance of the spectrometer makes our result insensitive to the assumption made about the production of the second J/ψ. Even reasonably strong correlations between the two J/ψ's do not change our conclusion by more than 20%.

Although the spectrometer has a large acceptance for four-muon states (> 25% of the $J/\psi \rightarrow \mu\mu$ acceptance under reasonable assumptions), only eight events were seen. All of these have a four-muon invariant mass of less than 1.9 GeV/c^2 and can be accounted for by conventional processes. We calculate the upper limit for the four-muon cross section above 1.9 GeV/c^2 to be less than 3×10^{-4} of the J/ψ cross section (at 90% confidence level).

A comparable experiment, using a broad-band neutron beam at Fermilab ($\langle E_n \rangle \approx 300$ GeV), has been reported by Binkley *et al.*[6] Finding no multimuon events above background, they have used models of production similar to those described above to set the 90%-confidence-level limits of $\sigma_{JC\bar{C}}/\sigma_J < 0.03$ and $\sigma_{JJ}/\sigma_J < 0.12$, consistent with our results for pions and protons. It thus appears, if we combine these results, that the OZI rule is responsible for less than 1% of J/ψ production in hadron-hadron collisions at Fermilab energy.

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