J/ψ Longitudinal Polarization from πN Interactions

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The spin alignment of 2.2×10^6 J/ψ particles produced in 252-GeV πN interactions has been measured via their decay to $\mu^+\mu^-$ in an experiment at Fermilab. Whereas J/ψ's are produced unpolarized over most of the kinematic range, they are found to become longitudinally polarized as $x_F \to 1$.

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The angular distribution of the muons from the decay $J/\psi \to \mu^+\mu^-$ provides a measure of the J/ψ spin alignment which in turn reflects the production mechanism. Previous experiments[1-3] have generally determined that J/ψ's are produced unpolarized in πN interactions over a wide kinematic range of longitudinal and transverse momenta (p_L and p_T, respectively). However, the interesting high-x_F region was not explored, where $x_F = p_L/p_{L,\max}$ is the Feynman x evaluated in the πN center-of-mass frame. We report here on an experiment performed at Fermilab which collected data sufficient to study J/ψ events produced near $x_F=1$ for the first time.

The experiment has been described in detail elsewhere.[4] Pions of 252-GeV energy interacted in a 20-cm-long W target which was located 1 m upstream of a 7.3-m-long magnet filled with Be, C, and BeO. Hadrons and electrons were absorbed in the magnet, allowing muons to pass through a spectrometer located farther downstream. The spectrometer consisted of a second magnet with multiwire chambers, drift chambers, and scintillator hodoscopes on either side. An on-line mass processor triggered the detector on muon pairs with mass $\gtrsim 2$ GeV/c^2.

For the off-line analysis we required that events have two and only two reconstructed tracks, which resulted in a data set containing 1.6×10^6 J/ψ events with an incident π^- beam and 0.6×10^6 J/ψ events with an incident π^+ beam. To reduce the background of proton-induced interactions, only J/ψ events with $x_F>0.75$ were used in the analysis of the π^+-beam sample. With this cut we estimate that 93% of the total J/ψ sample was pion induced, 5% was kaon induced, and 2% was proton induced. It was also required that negative (positive) muons from the π^- (π^+) data sample have angles relative to the beam of >5 mrad and momenta <200 GeV/c in order to eliminate beam muons.

Even with our large data sample the measurement of the J/ψ decay angular distribution involved averaging over sizable regions of x_F and p_T. A proper acceptance correction required detailed knowledge of the dependence of the J/ψ production cross section on these variables. In the first stage of the analysis the number of

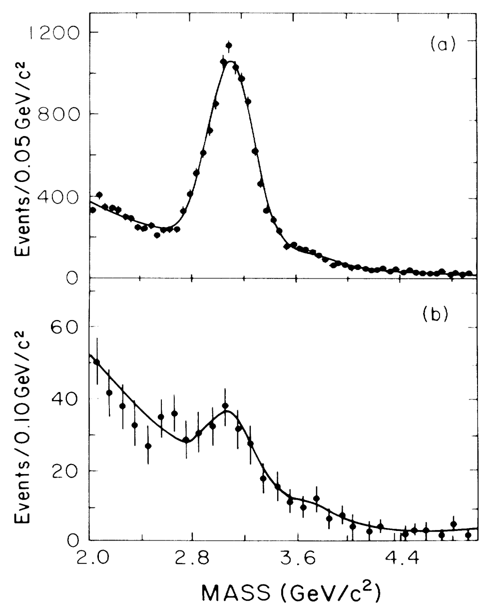

FIG. 1. (a) The raw $\mu^+\mu^-$ mass distribution in the kinematic range $0.80<x_F<0.85$ and $0.5<p_T<1.0$ GeV/c. The solid line is the result of a seven-parameter fit described in the text. (b) The raw mass distribution in the kinematic range $0.95<x_F<1.0$, $-0.2\pi<\phi<0.2\pi$, and $-0.2<\cos\theta<0.2$, where the decay angles θ and ϕ are defined in the text.

J/ψ's in each region (bin) of x_F and p_T was found by a fit to the raw $\mu^+\mu^-$ mass distribution. The production cross section was then ascertained by a fit to the numbers of J/ψ's found in the various bins. This procedure is described in more detail in the next two paragraphs.

The data were divided into fifteen regions of x_F and six regions of p_T in the kinematic range $x_F > 0.25$ and $p_T < 5.0$ GeV/c. For each bin of x_F and p_T the raw $\mu^+\mu^-$ mass distribution was fitted by a seven-parameter form involving Gaussian distributions for the J/ψ and ψ' and a quadratic polynomial plus an exponential of a first-order polynomial for the continuum muon-pair background. For the Gaussian distributions we used the actual J/ψ and ψ' masses and a constant mass resolution of $\sigma = 180$ MeV/c^2, which was determined from a Monte Carlo simulation of the experiment. A 2.5% systematic error was added in quadrature to the error in the number of J/ψ's from the fit since the Monte Carlo simulation observed slight deviations of the J/ψ raw mass distribution from a purely Gaussian form. As an example of the fitting procedure, Fig. 1(a) shows the raw mass distribution and resulting fit for the kinematic region $0.80 < x_F < 0.85$ and $0.5 < p_T < 1.0$ GeV/c.

The fitted numbers of J/ψ's in the ninety bins of x_F and p_T were then corrected for acceptance, and the resulting J/ψ production cross section was fitted by the empirical form

$$d^2\sigma/dx_F\,dp_T^2 \propto (1-x_F)^A/(1+p_T^B/S)^T,$$

where $S = C + D(1-x_F)^2$ and $T = E + F(1-x_F)^2$. This form allows the p_T distribution to change with x_F and the cross section to approach zero as $x_F \to 1$. The fit has $\chi^2 = 72.4$ for 83 degrees of freedom, and the result of the fit is given in Table I. Also shown in Table I are the results of fits for the kinematic regions $0.25 < x_F < 0.50$, $0.50 < x_F < 0.75$, and $0.75 < x_F < 1.0$, which show that the x_F distribution tends to flatten as $x_F \to 1$. The x_F distribution is shown in Fig. 2(a), together with another measurement[3] with similar incident pion momentum. An A^1 cross-section dependence has been assumed,[5] where A is the atomic mass of the target nucleus. As seen in Fig. 2(b) the $\langle p_T \rangle$ decreases as $x_F \to 1$. For $x_F > 0.25$ we measure a cross section times branching ratio for $J/\psi \to \mu^+\mu^-$ of $B\sigma(x_F > 0.25) = 3.8$ nb/nucleon, where there is a 20% systematic error due to uncertainty in our beam normalization.

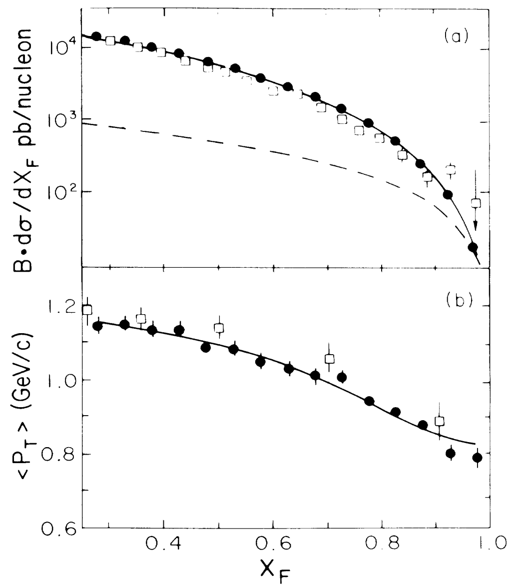

FIG. 2. (a) The x_F distribution for J/ψ production at 252 GeV/c (dots, this experiment) and 280 GeV/c (squares, Ref. 3). The solid line is the result of the fit described in the text. The dashed curve is the prediction of a $q\bar{q}$ annihilation model, also described in the text. (b) The $\langle p_T \rangle$ as a function of x_F.

As x_F is defined to be the J/ψ longitudinal momentum in the center-of-mass frame divided by the maximum possible momentum, we take into account the mass and p_T of the J/ψ when calculating x_F. Near $x_F = 1$ we estimate our resolution to be $\sigma(x_F) = 4\%$, which is due to a 3% spread in the beam momentum plus contributions from Fermi motion and measurement error. These effects are included in our Monte Carlo simulation of the experiment. In addition, we estimate that there is a 1% uncertainty in the beam momentum, which corresponds to a 1% uncertainty in x_F at $x_F = 1$.

To determine the J/ψ decay angular distribution we divided the data into fifteen regions of x_F, five regions of $\cos\theta$, and five regions of ϕ in the kinematic range $x_F > 0.25$, $-1 < \cos\theta < 1$, and $-\pi < \phi < \pi$. The angles θ and ϕ are measured in the muon-pair center-of-mass frame, and represent the polar and azimuthal angles of the μ^+ with respect to the t-channel (Gottfried-Jackson) axes. For each bin of x_F, $\cos\theta$, and ϕ the raw $\mu^+\mu^-$

TABLE I. The result of fits of the J/ψ production cross section by the empirical form described in the text.

x_F range	A	B	C	D	E	F
$0.25 < x_F < 1.0$	1.88 ± 0.02	1.54 ± 0.02	5.1 ± 0.2	66 ± 6	10.0 ± 0.1	54 ± 6
$0.25 < x_F < 0.50$	2.13 ± 0.19	1.61 ± 0.03	3.4 ± 0.4	40 ± 2	7.0 ± 0.6	30 ± 1
$0.50 < x_F < 0.75$	1.88 ± 0.04	1.53 ± 0.03	4.8 ± 0.2	55 ± 1	8.8 ± 0.1	50 ± 1
$0.75 < x_F < 1.0$	1.70 ± 0.05	1.45 ± 0.03	5.5 ± 0.1	162 ± 3	12.5 ± 0.2	149 ± 9

mass distribution was again fitted by a seven-parameter form, and as an example Fig. 1(b) shows the raw mass distribution and resulting fit of the kinematic region $0.95 < x_F < 1.0$, $-0.2 < \cos\theta < 0.2$, and $-0.2\pi < \phi < 0.2\pi$. Although the resonance-to-continuum ratio decreases as $x_F \to 1$, this ratio is still about 1.0 and 1.5 for the regions $0.95 < x_F < 1.0$ and $0.90 < x_F < 0.95$, respectively. There are over 1200 J/ψ events found in the region $0.95 < x_F < 1.0$.

The numbers of J/ψ's in the 375 bins of x_F, $\cos\theta$, and ϕ were then corrected for acceptance and for each of the fifteen regions of x_F the J/ψ angular distribution was fitted by the general form[6]

$$d^2\sigma/d\cos\theta\, d\phi \propto 1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \tfrac{1}{2}\nu\sin^2\theta\cos 2\phi.$$

The fit has $\chi^2 = 355.4$ for 315 degrees of freedom, and the values of λ, μ, and ν are given in Figs. 3(a)–3(c) for the fifteen bins of x_F. As expected for unpolarized production, λ, μ, and ν are consistent with zero over a wide range of x_F. However, λ approaches -1 at high x_F, which corresponds to longitudinally polarized J/ψ production.[7] Figs. 4(a)–4(e) show the $\cos\theta$ distributions for the five regions of ϕ in the highest x_F bin, $0.95 < x_F < 1.0$, while Fig. 4(f) is the $\cos\theta$ distribution summed over all ϕ. The histograms are the result of the fit.

Our result is consistent with earlier results which had much smaller data samples. The previous best measurement[2] of the J/ψ angular distribution at high x_F determined that $\lambda = 0.06 \pm 0.25$ for the interval $0.8 < x_F < 1.0$.[8] This agrees with the value of $\lambda = -0.02 \pm 0.06$ which we find on averaging over the same interval. The J/ψ angular distributions and production cross sections from the π^- and π^+ data samples have furthermore been determined separately and are found to be the same within errors for $x_F > 0.75$. No strong p_T dependence of the angular distribution has been observed.

We have performed a number of checks on the analysis procedure to ensure that our result of $\lambda = -0.80 \pm 0.17$ for J/ψ production in the interval $0.95 < x_F < 1.0$ is stable. For example, if the raw mass data are summed over the variable ϕ before fitting so that the J/ψ stands out clearly from background in all bins, we obtain $\lambda = -0.65 \pm 0.24$. If only an exponential of a first-order polynomial is used for the continuum background, then $\lambda = -0.74 \pm 0.17$. We also find that $\lambda = -0.74 \pm 0.19$ if the $\langle p_T \rangle$ used in the Monte Carlo decreases from 0.82 to 0.74 GeV/c. This is an important test since the $\cos\theta$ acceptance is most sensitive to the assumed p_T distribution.

We have further tested our mass-fit procedure by studying ψ' production. Problems with this procedure would show up most vividly in the ψ' sample since the signal-to-background ratio is much smaller for the ψ'

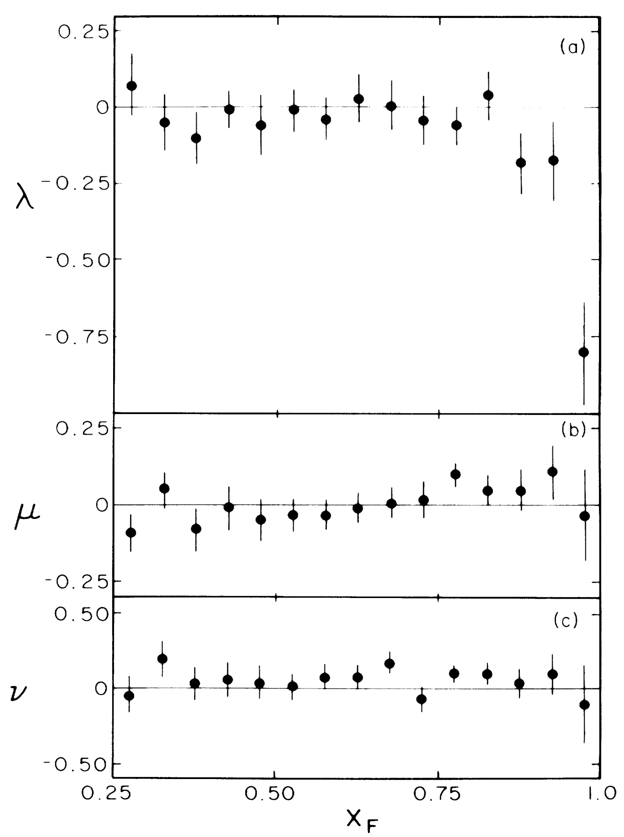

FIG. 3. The x_F dependence of the parameters fitted to the J/ψ decay angular distribution described in the text: (a) λ, (b) μ, (c) ν.

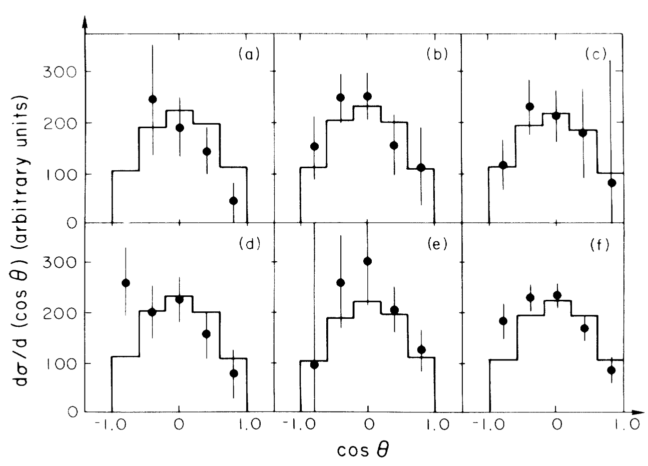

FIG. 4. The J/ψ decay angular distribution vs $\cos\theta$ for the five regions of ϕ, and summed over all ϕ in the highest x_F bin, $0.95 < x_F < 1.0$. The histograms are the result of the fit described in the text. (a) $-\pi < \phi < -0.6\pi$, (b) $-0.6\pi < \phi < -0.2\pi$, (c) $-0.2\pi < \phi < 0.2\pi$, (d) $0.2\pi < \phi < 0.6\pi$, (e) $0.6\pi < \phi < \pi$, (f) $-\pi < \phi < \pi$.

than for the J/ψ. However, the $\langle p_T \rangle$ and x_F distributions of the ψ' and the observed $\psi'/(J/\psi)$ cross-section ratio all vary smoothly with x_F up to the highest interval, $0.95 < x_F < 1.0$. Additional analyses of ψ' production and of the angular distribution of the continuum background will be presented elsewhere.

A possible explanation for the change in spin alignment of the J/ψ at high x_F involves higher-twist effects.[9] Gluon-gluon annihilation mechanisms and charmonium decays dominate J/ψ production at low and moderate x_F.[1,3] However, if quark-antiquark annihilation mechanisms ($q\bar{q} \rightarrow c\bar{c}$) dominate near $x_F = 1$, then gluon-exchange interactions between the annihilating quarks and the spectator quarks (higher-twist interactions) would cause the J/ψ to become longitudinally polarized as $x_F \rightarrow 1$.

The number of J/ψ events produced by quark-antiquark annihilation can be estimated by replacing the one-photon $q\bar{q}$ annihilation cross section in the Drell-Yan model with the Breit-Wigner resonant production formula.[10] The calculation for J/ψ production by $q\bar{q}$ annihilation is shown as the dashed curve on Fig. 2(a). For $x_F > 0.95$ the $q\bar{q}$ annihilation model accounts for the J/ψ signal to within a factor of 2.

Our evidence for longitudinal polarization of J/ψ's at high x_F is then consistent with the higher-twist effect observed in Drell-Yan continuum production.[2,10,11] Other evidence for this effect has been found in deep-inelastic scattering,[12] high-p_T jet production,[13] and prompt ρ^0 production.[14] The present result confirms the importance of such effects in particle interactions occurring near the limits of phase space.

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[8]Reference 2 actually uses the variable x_1, the fraction of the pion momentum carried by the antiquark, instead of x_F. However, for J/ψ production at high x_F the two variables are almost the same.

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