

**$J/\psi$  Polarization in 800-GeV  $p$ -Cu Interactions**

T. H. Chang,<sup>7,\*</sup> M. E. Beddo,<sup>7</sup> C. N. Brown,<sup>3</sup> T. A. Carey,<sup>6</sup> W. E. Cooper,<sup>3</sup> C. A. Gagliardi,<sup>9</sup> G. T. Garvey,<sup>6</sup>  
 D. F. Geesaman,<sup>2</sup> E. A. Hawker,<sup>9,6,†</sup> X. C. He,<sup>4</sup> L. D. Isenhower,<sup>1</sup> D. M. Kaplan,<sup>5</sup> S. B. Kaufman,<sup>2</sup> D. D. Koetke,<sup>10</sup>  
 P. L. McGaughey,<sup>6</sup> W. M. Lee,<sup>4,‡</sup> M. J. Leitch,<sup>6</sup> J. M. Moss,<sup>6</sup> B. A. Mueller,<sup>2</sup> V. Papavassiliou,<sup>7</sup> J. C. Peng,<sup>6,\*</sup>  
 P. E. Reimer,<sup>6,2</sup> M. E. Sadler,<sup>1</sup> W. E. Sondheim,<sup>6</sup> P. W. Stankus,<sup>8</sup> R. S. Towell,<sup>1,6</sup> R. E. Tribble,<sup>9</sup> M. A. Vasiliev,<sup>9,§</sup>  
 J. C. Webb,<sup>7,||</sup> J. L. Willis,<sup>1</sup> and G. R. Young<sup>8</sup>

(FNAL E866/NuSea Collaboration)

<sup>1</sup>Abilene Christian University, Abilene, Texas 79699, USA

<sup>2</sup>Argonne National Laboratory, Argonne, Illinois 60439, USA

<sup>3</sup>Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

<sup>4</sup>Georgia State University, Atlanta, Georgia 30303, USA

<sup>5</sup>Illinois Institute of Technology, Chicago, Illinois 60616, USA

<sup>6</sup>Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

<sup>7</sup>New Mexico State University, Las Cruces, New Mexico 88003, USA

<sup>8</sup>Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA

<sup>9</sup>Texas A&M University, College Station, Texas 77843, USA

<sup>10</sup>Valparaiso University, Valparaiso, Indiana 46383, USA

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We present measurements of the polarization of the  $J/\psi$  produced in 800-GeV proton interactions with a copper target. Polarization of the  $J/\psi$  is sensitive to the  $c\bar{c}$  production and hadronization processes. A longitudinal polarization is observed at large  $x_F$ , while at small  $x_F$  the state is produced essentially unpolarized or slightly transversely polarized. No significant variation of the polarization is observed versus  $p_T$ .

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A detailed understanding of the production mechanism of charmonium is important for ongoing research at the BNL Relativistic Heavy Ion Collider, where this process can play an important role in the search for quark-gluon plasma formation [1], as well as for the investigation of the gluon contribution to the proton spin structure [2,3]. In the nonrelativistic QCD formalism (NRQCD), charmonium polarization can probe [4] details of the production process [5] that are perturbatively calculable.

NRQCD is an effective field theory that approximates the full QCD Lagrangian for large quark masses. Uncalculable matrix elements for the production of various Fock-space components of the quarkonium wave function are ranked, using simple scaling rules, according to their order in  $v$ , the relative quark-antiquark velocity in the quarkonium rest frame; for charmonium, this has a value of  $\sim 0.5$ . The leading matrix elements can then be extracted from fits to experimental data and used in calculating other processes.

A determination [6] of the various matrix elements from available high-energy data defines to a large extent the expected production properties of charmonium, one of which is the polarization. For a spin-1 particle, given the fraction  $\xi$  of particles produced in the  $j_z = 0$  ("longitudinal") state, we can define the polarization  $\lambda = (1 - 3\xi)/(1 + \xi)$ ;  $\lambda$  is positive (negative) for transverse (longitudinal) polarization. While several of the

intermediate  $c\bar{c}$  states are color-octet states and must be followed by multiple gluon emission before a physical charmonium state is produced, heavy-quark symmetry implies that gluon radiation leaves the quark spins unchanged, providing definite predictions for the spin state of the final charmonium [5].

The polarization of the  $J/\psi$  has been measured with relatively high statistical precision only in fixed-target experiments, in pion [7] and proton [8,9] interactions with solid nuclear targets. No significant polarization has been seen in either, with the exception of an intriguing large longitudinal polarization at the highest  $x_F$  value of the pion-induced data. Measurements in collider experiments, at energies and transverse momenta where theoretical calculations should be more robust and which are free of potential complications from nuclear effects, suffer from low statistics [10]. Finally, in a recent study of fixed-target bottomonium production [11], the  $Y(1S)$  was found to be largely unpolarized, while the  $Y(2S, 3S)$  states had strong transverse polarization.

In this experiment, we accumulated [12] a much larger sample — approximately  $9 \times 10^6$  — of reconstructed  $J/\psi$  than any previous study, in interactions of an 800-GeV/ $c$  proton beam with a copper target.  $J/\psi$  decays were measured using the Fermilab Meson-East dimuon spectrometer [13], which consisted of three dipole magnets, SM0, SM12, and SM3, and three stations of drift chambers and

trigger scintillator hodoscopes. Data were collected during a month-long dedicated run in which the copper beam dump inside SM12 was used in place of a target; the first dipole was switched off during this run. A copper absorber filtered out all hadrons and electrons produced in the interactions, allowing only muons to enter the spectrometer. Additional hadron rejection was obtained using a muon identifier, consisting of proportional tubes and scintillator hodoscopes behind a thick absorber at the downstream end of the apparatus. Events were recorded when the trigger condition of two oppositely charged muons was satisfied.

Events were reconstructed offline from the recorded hits in the drift chambers. Tracks were traced back through the magnetic fields to the dump and/or target, where a vertex was formed, consistent with the beam position. Energy losses and multiple Coulomb scattering in the absorber and the dump were taken into account in the traceback. The momentum of the muons was determined by their bending in SM3, and this was used to calculate their trajectories in SM12.

The invariant mass of the muon pair was calculated from the muon momenta and opening angle at the vertex. Since the energy loss and multiple scattering are known only on average and not on an event-by-event basis, the mass resolution, typically  $\approx 500$  MeV (FWHM), was not sufficient to separate the  $J/\psi$  and  $\psi'$  peaks in this run using this extended target. While the two charmonium states cannot be separated, it is estimated that the  $\psi'$  contributes only about 1% to the total event count, based on the relative production cross sections and branching ratios into muons. Therefore, the  $\psi'$  is not considered in the following discussion.

The mass distributions were plotted in bins in the Feynman- $x$  variable  $x_F$ , transverse momentum  $p_T$ , and the dimuon polar angle  $\vartheta$  in the dimuon rest frame. We use the Collins-Soper frame [14]. This is identical to the Gottfried-Jackson frame [15], used in several earlier experiments, for  $p_T = 0$ , and to a very good approximation equivalent even at the highest  $p_T$  values in this experiment.

The invariant mass distribution in each  $(x_F, p_T)$  bin was fitted to a Gaussian peak plus an exponential or polynomial background. All of the parameters, including the mass, were determined by the fit. The number of events under the peak gave the combined  $J/\psi$  and  $\psi'$  triple-differential, unnormalized cross section in  $x_F$ ,  $p_T$ , and  $\vartheta$ . Distributions as a function of  $\vartheta$  were then formed in each  $x_F$  and  $p_T$  bin.

The spectrometer and trigger acceptance was calculated with the help of a Monte Carlo simulation of the  $J/\psi$  production process, which included all the measured magnetic fields and detector efficiencies and geometry. The known properties of  $J/\psi$  production from previous experiments were used. However, because of the binning in  $x_F$  and  $p_T$ , exact knowledge of the form of the cross

section as a function of these two variables was not crucial. Events were generated with a flat  $\cos\vartheta$  distribution, corresponding to unpolarized production. Simulated data were passed through the same analysis chain as the real data. The Monte Carlo reproduced quite accurately the main features of the data, including the mass and vertex resolutions.

The azimuthal-angle ( $\phi$ ) dependence of the production cross section was assumed to be flat in the Monte Carlo, since the two interacting hadrons were unpolarized. The corresponding measured acceptance-corrected distribution was essentially flat, consistent with a 2% uncertainty in the direction of the incoming beam. The decay distribution was also assumed to be flat in  $\phi$ , consistent with previous results [7]. No attempt was made to extract the  $\phi$  dependence of the decay in this analysis.

The  $\vartheta$  distributions of the data in all bins were divided by the corresponding ones of the simulation, resulting in acceptance-corrected  $\vartheta$  distributions. These were then used to calculate the polarization in  $x_F$  and  $p_T$  bins, according to the formula  $d\sigma/d\cos\vartheta = A(1 + \lambda\cos^2\vartheta)$ , where the normalization constants  $A$  were left free. Results were obtained separately for two experimental runs with the current in the SM12 magnet set to 2040 and 2800 A, respectively, resulting in substantially different acceptances.

Figure 1 shows the polarization parameter  $\lambda$  as a function of  $x_F$  in four  $p_T$  bins; it can be seen that results from the two magnet settings are in reasonable agreement, giving some confidence that the acceptance is understood and providing an estimate for the magnitude of the relevant systematic uncertainties. The  $x_F$  dependence of  $\lambda$  appears to be independent of  $p_T$ .

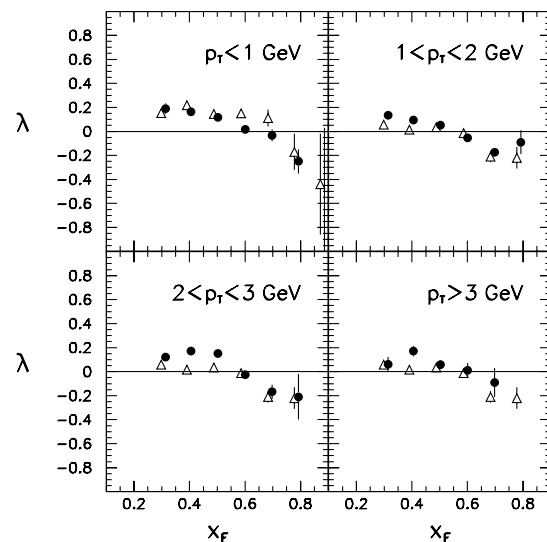


FIG. 1.  $J/\psi$  polarization parameter  $\lambda$  versus  $x_F$  in  $p_T$  bins. Solid dots are the results obtained with the 2800 A magnet setting, open triangles with the 2040 A setting. Only statistical errors are shown.

Systematic errors from various sources were considered. Inexact knowledge of the  $p_T$  dependence of the production cross section, coupled with a strong  $p_T$  dependence of the acceptance versus decay angle  $\vartheta$ , led to an uncertainty of  $\pm 0.06$  in  $\lambda$ , independent of  $x_F$ . Additional contributions included mass-peak fitting errors (0.04–0.08, depending on the  $x_F$  bin) and uncertainties in the exact position (0.02) and angle (0.02–0.04) of the incoming beam and in the fields in the analyzing magnets (0.01). Uncertainties from various sources are largely uncorrelated; they were added in quadrature for the overall systematic error.

Figure 2 presents the polarization parameter  $\lambda$  as a function of  $p_T$  for two  $x_F$  ranges, where the two data sets have been statistically combined. The two intervals in  $x_F$  approximately correspond to regions where the gluon-gluon and quark-antiquark processes are dominant. No significant  $p_T$  dependence is seen in either region after the systematic errors are taken into account. At large  $p_T$ , charmonium production is understood [16] to be dominated by gluon bremsstrahlung with subsequent fragmentation into a  $c\bar{c}$  pair. In this case, the charmonium state is expected [5,17] to retain to a large degree the transverse polarization of the high- $p_T$ , on-shell gluon. However, the  $p_T$  range of the experiment, extending to 4 GeV, may not be sufficient to see clearly such an effect. It must be noted that this effect is also not observed at the high  $p_T$  values available at collider energies [10], where, if anything, polarization appears to be longitudinal. In the following, we assume there is no significant  $p_T$  dependence and the results are presented integrated over all  $p_T$ .

Figure 3 shows the polarization  $\lambda$  as a function of  $x_F$  for the combined data set. The one-sigma systematic uncertainty is shown as a dark band. Also shown are the results previously obtained by the Chicago-Iowa-Princeton (CIP) Collaboration [7], which used a 252-GeV pion beam and a tungsten target. Our results suggest that the  $J/\psi$  is produced slightly transversely polarized at small-to-

intermediate  $x_F$ . Within the systematic uncertainties, the results are consistent with the CIP experiment [7], which saw no polarization in this range, albeit with much larger statistical uncertainties. It should be noted that in this range the  $q\bar{q}$  annihilation process is expected to play a more important role with a pion beam than with a proton beam, where  $gg$  fusion dominates. For  $x_F > 0.6$ , the polarization turns to longitudinal, outside the margins of the systematic error. This is similar to a pattern seen in the CIP experiment, although the behavior appears smoother as a function of  $x_F$  and begins at smaller  $x_F$  than the sudden turnover near  $x_F \approx 0.85$  in the latter. However, the results are not incompatible. It is also interesting to note that the clear change in polarization in this experiment roughly coincides with the transition from gluon-fusion dominance to quark-annihilation dominance.

Integrated over the entire  $x_F$  range, the measured polarization is  $\lambda = 0.069 \pm 0.004 \pm 0.08$  (statistical and systematic errors). This small value, consistent with no polarization if systematic errors are taken into account, is in agreement with previous proton-beam experiments [8,9], which had insufficient statistics to study the  $x_F$  dependence.

As a cross-check of the analysis, the polarization of the Drell-Yan continuum was also studied using the same technique. This can be done only for dimuon invariant masses greater than 4 GeV, since the  $J/\psi$  peak dominates the spectrum at lower masses. An additional complication arises from random coincidences of uncorrelated pairs of muons, which in the case of the  $J/\psi$  were removed by the fitting procedure. These were estimated and subtracted from the Drell-Yan sample by studying the distributions of same-charge muon pairs. A fit to the formula  $1 + \lambda \cos^2 \vartheta$  for dimuon masses from 4 to 7 GeV gave  $\lambda = 0.98 \pm 0.04$ , in good agreement with the 100% transverse polarization expected and previously observed [11] in the Drell-Yan process. While the kinematic range is not the

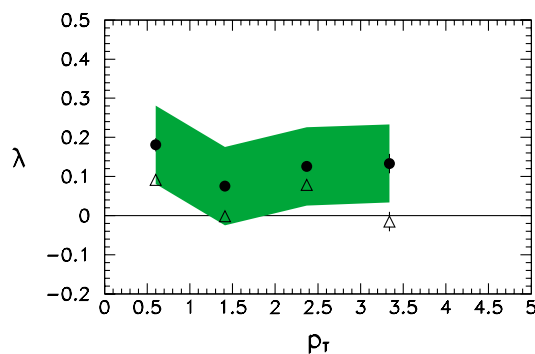


FIG. 2 (color online).  $J/\psi$  polarization parameter  $\lambda$  versus  $p_T$  for two  $x_F$  ranges:  $x_F < 0.45$  (solid circles) and  $x_F > 0.45$  (open triangles). Statistical errors are smaller than the data points. Systematic errors for the small  $x_F$  data are shown as a dark band; those for large  $x_F$  (not shown) are slightly smaller.

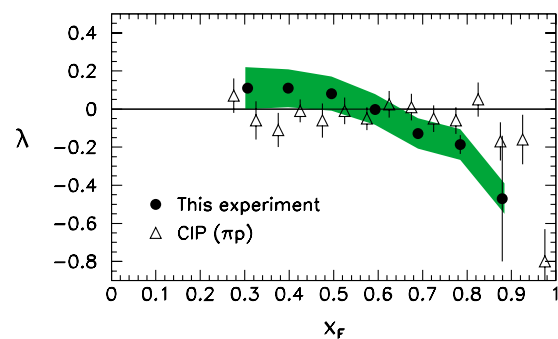


FIG. 3 (color online).  $J/\psi$  polarization parameter  $\lambda$  versus  $x_F$  from this experiment (solid circles). Statistical errors are shown as error bars, systematic as a dark band. Data values are tabulated in [12]. The CIP [7] results are also shown (open triangles).

same as for the  $J/\psi$  measurement, this agreement with expectations increases confidence in the soundness of the  $J/\psi$  analysis. The level of statistics was not adequate to investigate any  $x_F$  dependence of the Drell-Yan polarization.

The results are not in agreement with published predictions for  $J/\psi$  polarization based on NRQCD, which are in the range  $0.31 < \lambda < 0.63$  [18], or with similar predictions [19] based on an early model that considers only color-singlet intermediate states. The small positive values at  $x_F \lesssim 0.5$  are very similar to the results obtained for  $Y(1S)$  by this experiment in a similar  $p_T$  range, and in sharp contrast to the essentially 100% transverse polarization of the (unresolved)  $Y(2S)$  and  $Y(3S)$  states [11].

To understand the behavior of the polarization, all sources of  $J/\psi$  production must be considered. While  $b$ -quark production is not a major source at these energies, almost half of the produced  $J/\psi$  are the decay products of higher-mass charmonium resonances, mainly the  $3P_J$  states  $\chi_{cJ}$ . Feed-down from  $\chi_{c2}$ , produced exclusively in the  $J_z = 2$  state from gluon-gluon fusion, results in 100% transverse  $J/\psi$ , increasing the observed values of  $\lambda$ . The turnover at high  $x_F$  may reflect the transition, at  $x_F \simeq 0.6$ , to the quark-annihilation graph [20], which produces a mix of  $\chi_{c2}$  spin states. As for the overall level, it cannot be explained without a substantial contribution from  $\chi_{c1}$ , which in general produces longitudinal  $J/\psi$ . Beneke and Rothstein [18] originally estimated the  $\chi_{c1}$  contribution to be about 10 times smaller than that from  $\chi_{c2}$ , but it was later found experimentally [21] to be of comparable size. NRQCD calculations which retain higher orders in  $v$  can also accommodate substantial  $\chi_{c1}$  contributions [22]. It would probably require a contribution near the experimental and theoretical upper limits in order to obtain  $\lambda$  values as small as experimentally measured, within the context of NRQCD.

In addition, it must be noted that no existing calculation takes into account nuclear effects, which strongly affect the production cross section [23]. The formation length of the  $J/\psi$  at these energies is generally longer than the nuclear size [24], and it is conceivable that color-singlet and color-octet components of the wave function are absorbed differently while propagating through the nuclear medium, resulting in a different mix of Fock states compared to the free-nucleon production, thus altering the polarization. Furthermore, the polarization of the  $\chi_c$  states themselves is predicted to have a nuclear dependence [25] which would feed down to the  $J/\psi$  polarization. Finally, at the highest values of  $x_F$ , higher-twist effects may become important [19].

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\*Present address: University of Illinois, Urbana, IL 61801, USA.

†Present address: University of Cincinnati, Cincinnati, OH 45221, USA.

‡Present address: Florida State University, Tallahassee, FL 32306, USA.

§On leave from Kurchatov Institute, Moscow, Russia.

¶Present address: Indiana University, Bloomington, IN 61801, USA.

- [1] T. Matsui and H. Satz, Phys. Lett. B **178**, 416 (1986).
- [2] R.W. Robinett, Phys. Rev. D **43**, 113 (1991).
- [3] O. Teryaev and A. Tkabladze, Phys. Rev. D **56**, 7331 (1997).
- [4] G.T. Bodwin, E. Braaten, and G.P. Lepage, Phys. Rev. D **51**, 1125 (1995).
- [5] P.L. Cho and M.B. Wise, Phys. Lett. B **346**, 129 (1995).
- [6] B.A. Kniehl and G. Kramer, Eur. Phys. J. C **6**, 493 (1999).
- [7] C. Biino *et al.*, Phys. Rev. Lett. **58**, 2523 (1987).
- [8] E771 Collaboration, T. Alexopoulos *et al.*, Phys. Rev. D **55**, 3927 (1997).
- [9] E672/E706 Collaboration, A. Gribushin *et al.*, Phys. Rev. D **62**, 012001 (2000).
- [10] CDF Collaboration, T. Affolder *et al.*, Phys. Rev. Lett. **85**, 2886 (2000).
- [11] E866 Collaboration, C.N. Brown *et al.*, Phys. Rev. Lett. **86**, 2529 (2001).
- [12] T.-H. Chang, Ph.D. thesis, New Mexico State University, 1999; hep-ex/0012034.
- [13] E605 Collaboration, G. Moreno *et al.*, Phys. Rev. D **43**, 2815 (1991).
- [14] J.C. Collins and D.E. Soper, Phys. Rev. D **16**, 2219 (1977).
- [15] K. Gottfried and J.D. Jackson, Nuovo Cimento **33**, 309 (1964).
- [16] E. Braaten and T.C. Yuan, Phys. Rev. Lett. **71**, 1673 (1993).
- [17] E. Braaten, B.A. Kniehl, and J. Lee, Phys. Rev. D **62**, 094005 (2000).
- [18] M. Beneke and I.Z. Rothstein, Phys. Rev. D **54**, 2005 (1996).
- [19] M. Vanttinen, P. Hoyer, S.J. Brodsky, and W.-K. Tang, Phys. Rev. D **51**, 3332 (1995).
- [20] E789 Collaboration, M.S. Kowitt *et al.*, Phys. Rev. Lett. **72**, 1318 (1994).
- [21] E771 Collaboration, T. Alexopoulos *et al.*, Phys. Rev. D **62**, 032006 (2000).
- [22] M. Beneke, hep-ph/9703429.
- [23] E866 Collaboration, M.J. Leitch *et al.*, Phys. Rev. Lett. **84**, 3256 (2000).
- [24] G.R. Farrar, L.L. Frankfurt, M.I. Strikman, and H. Liu, Phys. Rev. Lett. **64**, 2996 (1990).
- [25] L. Gerland, L. Frankfurt, M. Strikman, H. Stocker, and W. Greiner, Phys. Rev. Lett. **81**, 762 (1998).