Observation of Polarization in Bottomonium Production at $\sqrt{s} = 38.8$ GeV

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We present a measurement of the polarization observed for bottomonium states produced in p-Cu collisions at $\sqrt{s} = 38.8$ GeV. The angular distribution of the decay dimuons of the $\Upsilon(1S)$ state shows no polarization at small values of the fractional longitudinal momentum x_F and transverse momentum p_T but significant positive transverse production polarization for either $p_T > 1.8$ GeV$/c$ or for $x_F > 0.35$. The $\Upsilon(2S + 3S)$ (unresolved) states show a large transverse production polarization at all values of x_F and p_T measured. These observations challenge NRQCD calculations of the polarization expected in the hadronic production of bottomonium states.

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It has been known for some time that the observed production rates of charmonium and bottomonium resonances in hadronic collisions are much larger than the predictions of lowest order perturbative quantum chromodynamics (PQCD) [1]. A calculational approach based upon nonrelativistic quantum chromodynamics (NRQCD) has emerged as a reliable framework for calculating onium production [2].

Data on the direct production of the charmonium mesons $\psi(1S)$ and $\psi(2S)$ at high energies, when compared with the predictions of NRQCD, indicate that color octet contributions dominate the cross section and that S state charmonia are produced through gluon fragmentation into a ${}^3S_1^{(8)}$ octet state [3]. Recent investigations have shown that the contribution of color octet states to onium production may also be very important at fixed target energies, but quantitatively the picture is far from complete [4]. In particular, NRQCD predictions disagree with measurements of the polarization of $\psi(1S)$ and $\psi(2S)$ mesons produced at collider [5] and fixed target energies [6].

In NRQCD, the predicted spin effects in onium production can provide further tests of and constraints on the various color octet contributions. Quark-antiquark fusion and gluon-gluon fusion diagrams, which are expected to dominate onium production at fixed target energies, yield significant transverse polarization [7] for the produced bottomonium mesons $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$. The polarization results in a $1 + \alpha\cos^2(\theta)$ decay angle distribution for the polar angle of the decay dimuons in the Collins-Soper frame [8]. Transversely, longitudinally, and unpolarized states decay with $\alpha = +1, -1$, and 0, respectively.

We have studied the production of dimuons in the collision of 800 GeV$/c$ protons with a copper beam dump,

$$p + \mathrm{Cu} \rightarrow \mu^+\mu^- + X\,.$$

The apparatus was originally constructed for Experiment 605 [9] and was located in the Meson East Laboratory at Fermilab. The data reported here were taken as part of a subsequent experiment, Experiment 866 [10]. Details of the apparatus used in E866 and a full description of a similar study of the polarization of dimuons from charmonium states can be found in Ref. [6].

Here we present polarizations derived from the angular distribution of 2×10^6 dimuons in the range $8.1 < m_{\mu^+\mu^-} < 15.0$ GeV. The data, after analysis and muon identification cuts, cover the kinematic range $0.0 < x_F < 0.6$ (x_F is the fractional longitudinal momentum of the dimuon in the nucleon-nucleon center-of-mass frame), and $p_T < 4.0$ GeV/c (p_T is the transverse momentum of the dimuon with respect to the beam axis).

For this measurement the currents of the two spectrometer magnets were set to their maximum excitation which produced a spectrometer acceptance that decreased rapidly for dimuon masses below 8 GeV. Figure 1 shows the observed dimuon mass spectrum from 8.1 to 15.0 GeV. The components of a fit described below are also indicated. The smooth continuum of dimuons under the bottomonium peaks arises from the production of dimuons via quark-antiquark annihilation, the Drell-Yan process [11]. The experimentally observed width of the intrinsically narrow onium states arises from muon multiple scattering and energy loss in the 4-m-thick copper target.

The Drell-Yan dimuon continuum is described well with a PQCD calculation [12] incorporating a recent determination of the proton structure functions by Martin *et al.* [13] referred to as MRST. The yield of Drell-Yan dimuons is modeled with a Monte Carlo simulation of the apparatus that generates events as a function of dimuon p_T and the apparent fractional momenta, x_1 and x_2, of the annihilating quark-antiquark pair (where $sx_1x_2 = m^2$ and $x_1 - x_2 = x_F$; m is the dimuon mass; s is the center-of-mass energy squared). A standard parametrization of the Drell-Yan production cross section versus p_T was fit to the data [14]. Drell-Yan virtual photons are produced

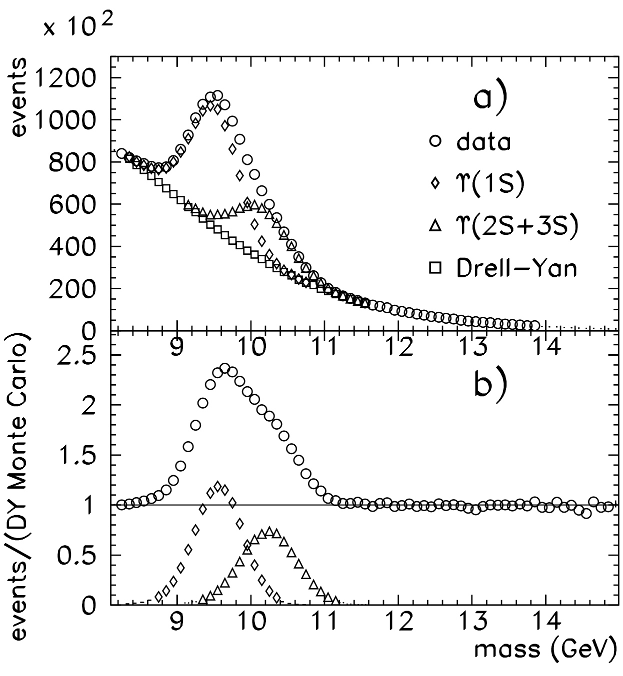

FIG. 1. (a) Mass spectrum of dimuons produced by 800 GeV protons incident on a copper dump. The fit described in the text for the Drell-Yan dimuon continuum, the $\Upsilon(1S)$, and the sum of the $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances is also shown. (b) The ratio of the data to the Monte Carlo generated Drell-Yan continuum events; the ratio of the $\Upsilon(1S)$ and the $\Upsilon(2S + 3S)$ generated events to the continuum fit is also shown.

transversely polarized and hence their dimuon decay is predicted to yield a $1 + \cos^2(\theta)$ angular distribution.

Since the mass of a bottomonium state is fixed, the production of a bottomonium state is a function of p_T and x_F only. The functional form of the production distributions can be found from the data directly. Because of the observed 330 MeV rms mass resolution of this measurement, we cannot resolve the $\Upsilon(2S)$ and $\Upsilon(3S)$ states. It has previously been observed that the p_T and x_F distributions of the $\Upsilon(2S)$ and $\Upsilon(3S)$ states are very similar [14]. Thus, in our fits (to the binned data and Monte Carlo events) to extract the decay angular distributions, we assume that the $2S$ and $3S$ states have the same p_T and x_F distributions. However, we note that within statistics the results in this paper are insensitive to this assumption.

We generated twice as many accepted Monte Carlo events as was observed in the data. The Drell-Yan dimuon continuum was generated using PQCD with MRST parton distributions [13], a shape versus p_T that fit the data, and a transverse polarization of 100%. The Drell-Yan Monte Carlo events were then weighted with a normalization constant and quadratic polynomial functions of x_1 and x_2 to match the shape of the data exactly versus x_1 and x_2 in the mass sidebands $8.1 < m_{\mu^+\mu^-} < 8.45$ GeV and $11.1 < m_{\mu^+\mu^-} < 15.0$ GeV. The weighting polynomials (which varied in value from 0.85 to 1.15) correct for small inaccuracies in the modeling of the apparatus and for variations of the p-Cu cross section from the PQCD prediction (there are known to be small nuclear effects in Drell-Yan dimuon yields [15]). The weighting is important since acceptance correlations between muon momenta and dimuon decay angle could lead to a false polarization signal if the observed yield is not modeled correctly versus x_F and p_T.

The Monte Carlo simulation of the bottomonium states generated unpolarized $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ events at their known masses with p_T and x_F shapes and relative $1S/2S/3S$ weights that matched the data. In the final fit to the data, the polarization parameter α of both the Drell-Yan continuum and the bottomonium resonances was allowed to vary. The polarizations of the $\Upsilon(2S)$ and $\Upsilon(3S)$ states were set equal in the fit after attempts to assign different polarizations to these two states led to large, negatively correlated statistical errors on α for the two states (consistent with the limited mass resolution mentioned above).

The final fit varied the polynomial weighting functions and polarization of the production distributions of the Drell-Yan, $\Upsilon(1S)$, and $\Upsilon(2S + 3S)$ Monte Carlo generated events to match the data. The shapes of the production distributions agree, within errors, with those obtained earlier [14]. Figure 1a shows the results of the fit versus dimuon mass for all the data. Figure 1b shows the ratio of the data and generated resonances to the generated Drell-Yan events. The separation of the $\Upsilon(1S)$ from the combined $\Upsilon(2S)$ and $\Upsilon(3S)$ states is sufficient to yield a stable fit.

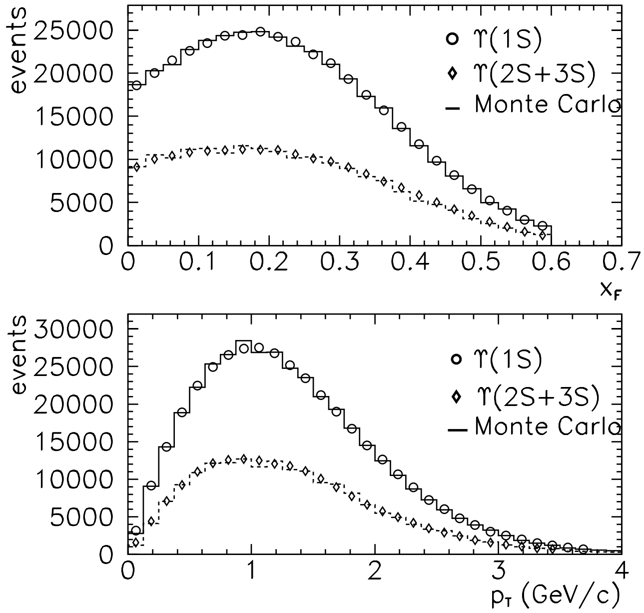

FIG. 2. The observed x_F and p_T distributions of the $\Upsilon(1S)$. The data distributions are formed by subtracting the Monte Carlo generated Drell-Yan dimuons, and the Monte Carlo generated $\Upsilon(2S + 3S)$ dimuon decays, from the observed dimuon data. The Monte Carlo generated $\Upsilon(1S)$ decay spectra are shown for comparison. A similar comparison is included for the sum of the $\Upsilon(2S)$ and $\Upsilon(3S)$ states.

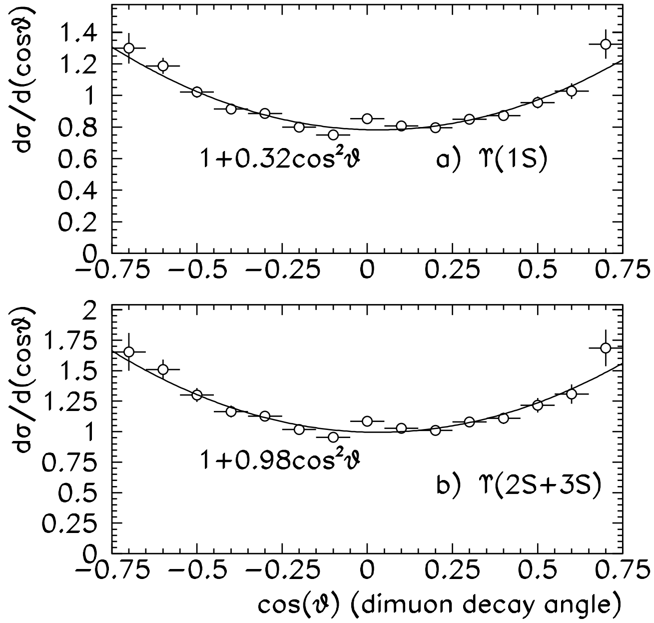

FIG. 3. (a) Decay angular distribution of $\Upsilon(1S)$ dimuon decays, formed by subtracting the fit contributions of the Drell-Yan, $\Upsilon(2S)$, and $\Upsilon(3S)$ decays from the data (in the bin $8.8 < m_{\mu^+\mu^-} < 10.0$ GeV and $p_T > 1.8$ GeV/c). A fit to the form $1 + \alpha\cos^2(\theta)$ is superimposed. (b) The corresponding decay distribution for $\Upsilon(2S + 3S)$ decays (for $10.0 < m_{\mu^+\mu^-} < 11.1$ GeV and $p_T > 1.8$ GeV/c).

In Fig. 2 we show the x_F and p_T distributions observed for the $\Upsilon(1S)$ ($8.8 < m_{\mu^+\mu^-} < 10.0$ GeV) data along with the fitted Monte Carlo distributions for the $\Upsilon(1S)$. The data spectra are obtained by subtracting the Monte Carlo fit distributions for the Drell-Yan, $\Upsilon(2S)$, and $\Upsilon(3S)$ dimuons from the data. The figure also includes similar curves for the sum of the $\Upsilon(2S)$ and $\Upsilon(3S)$ states. The acceptance varies more slowly than the observed event yield versus either x_F or p_T; the average x_F of both the $\Upsilon(1S)$ data and the $\Upsilon(2S + 3S)$ data is 0.23 and the average p_T of both is 1.3 GeV/c.

Figure 3 shows the angular distributions, in one of four p_T bins, for the $\Upsilon(1S)$ decays and for the sum of the $\Upsilon(2S)$ and $\Upsilon(3S)$ decays. Each point in Fig. 3a shows the data in a mass bin $8.8 < m_{\mu^+\mu^-} < 10.0$ GeV with the Monte Carlo generated contributions from Drell-Yan dimuons, $\Upsilon(2S)$ decays, and $\Upsilon(3S)$ decays subtracted away. Similarly, Fig. 3b shows the data in a mass bin from $10.0 < m_{\mu^+\mu^-} < 11.1$ GeV minus the Monte Carlo generated Drell-Yan and $\Upsilon(1S)$ events. The expected $1 + \alpha\cos^2(\theta)$ decay angle distribution fits well in both cases. The χ^2/DF of the fits are 0.7 and 1.2, respectively.

The values of α arising from the combined production distribution and decay angular distribution fit in the Drell-Yan sideband and two onium mass regions for four bins in p_T (bin boundaries at $p_T = 0.0$, 0.8, 1.3, 1.8, and 4.0 GeV/c) are shown in Fig. 4a. The results versus x_F (four bins, boundaries at 0.0, 0.12, 0.23, 0.35, and 0.6) are shown in Fig. 4b. The points are plotted at the cross-section-weighted average value of the abscissa. The only significant systematic error in these results arises from the fit. A systematic error in α of ± 0.06 (estimated by varying the form of the weighting functions and the boundaries of the mass regions used in the fit) should be added to the values of both the $\Upsilon(1S)$ and $\Upsilon(2S + 3S)$ polarizations in Fig. 4. Varying the mass of the peaks did not improve the fit or change the results significantly.

The observed polarization of the Drell-Yan continuum dimuons is consistent with 100% transverse polarization in all bins and with previous measurements [16]. The Drell-Yan sidebands have $0.2 < x_1 < 0.8$ and $0.06 < x_2 < 0.4$ (nuclear shadowing is observed only for $x_2 < 0.06$ [17]). A fit to the Drell-Yan sideband data (for all x_F and p_T) yields $\alpha = 1.008 \pm 0.016$ with a systematic error of ± 0.020 (estimated as described above).

The $\Upsilon(1S)$ data show almost no polarization at small x_F and p_T. The data show a finite transverse polarization at either large p_T or at large x_F (there are no significant x_F versus p_T production distribution correlations observed in the data).

This observation disagrees with an NRQCD calculation that predicts a polarization of 0.28 to 0.31 (averaged over x_F and p_T) at our energies [7]. If we fit the $1S$ state for a polarization independent of x_F and p_T, we get $\alpha = 0.07 \pm 0.04$.

The observation that the polarization of the cross-section-weighted average of the $2S + 3S$ states is much larger than that of the $1S$ state at all x_F and p_T contrasts

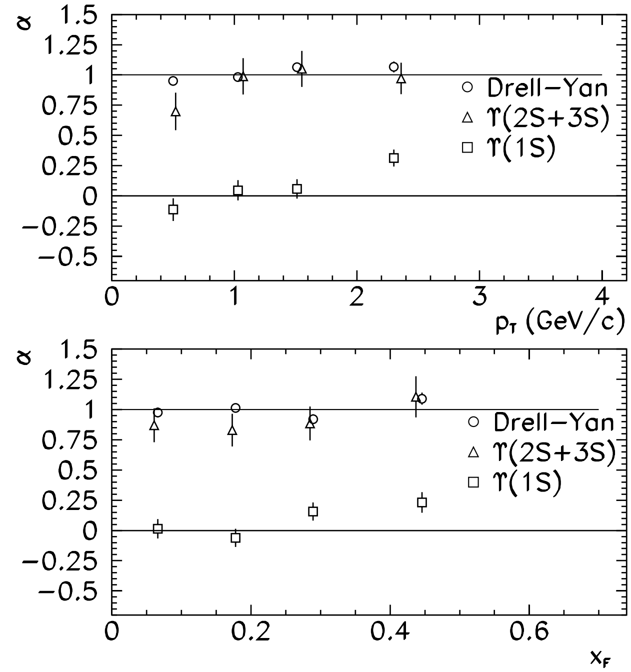

FIG. 4. (a) α versus p_T for the Drell-Yan sidebands ($8.1 < m_{\mu^+\mu^-} < 8.45$ GeV and $11.1 < m_{\mu^+\mu^-} < 15.0$ GeV), $\Upsilon(1S)$ ($8.8 < m_{\mu^+\mu^-} < 10.0$ GeV), and $\Upsilon(2S + 3S)$ ($10.0 < m_{\mu^+\mu^-} < 11.1$ GeV). (b) α versus x_F for the same mass regions. The errors shown are statistical; there is an additional systematic error not shown of 0.02 in α for Drell-Yan polarizations and 0.06 in α for onium polarizations.

sharply with what is seen in the charmonium system [5]. Although an NRQCD calculation [7] predicts that feed-down decays from higher S, P, and D upsilon states dilute the polarization of the $1S$ state, we can find no explicit calculation of the polarization expected for the $2S$ or $3S$ state.

In the kinematic range $0.0 < x_F < 0.6$ and $p_T < 4.0$ GeV/c, the fit to the data yields a ratio of $\Upsilon(2S + 3S)/\Upsilon(1S)$ events of 0.50 ± 0.01. A separate 3-peak fit (with the mass of the peaks fixed) yielded an overall ratio of $\Upsilon(3S)$ to $\Upsilon(2S)$ events of 0.46 ± 0.03 consistent with previous high resolution measurements [14]. Note that even if the $\Upsilon(3S)$ were 100% polarized, the $\Upsilon(2S)$ must be at least 35% polarized to yield the observed polarizations of the combined peaks. Likewise, if the $\Upsilon(2S)$ were 100% polarized, the $\Upsilon(3S)$ must have significant positive polarization in most bins.

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