

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 show no polarization at small x_F and 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 are compared with an NRQCD calculation that predicts a transverse polarization in bottomonium production arising from quark-antiquark fusion and gluon-gluon fusion diagrams.

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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 Non-Relativistic 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. The quark-antiquark fusion and gluon-gluon fusion diagrams which are ex-

pected 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,

$$p + Cu \rightarrow \mu^+\mu^- + X.$$

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 Reference [6].

Here we present polarizations derived from the angular distribution of 2 million dimuons in the range $8.1 < m_{\mu^+\mu^-} < 15.0$ GeV. The data, after analysis cuts, cover the kinematic range $0.0 < x_F < 0.6$ (x_F is the fractional longitudinal momentum of the dimuon in

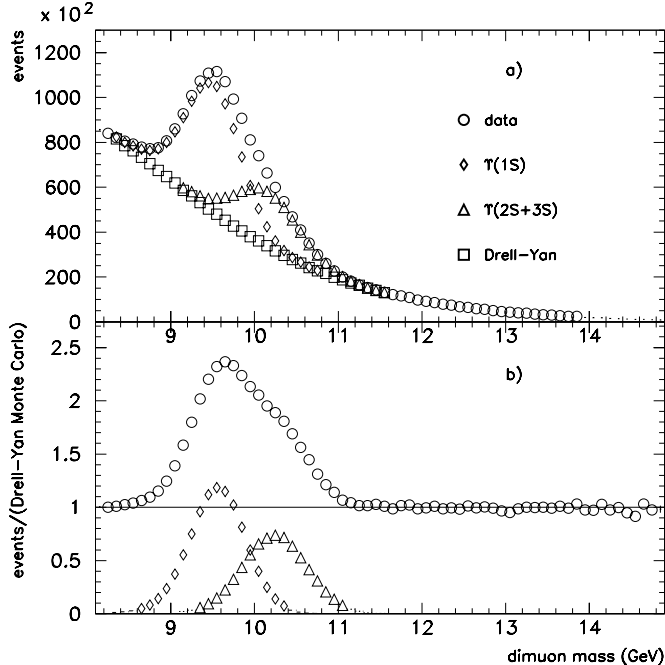


FIG. 1. a) Mass spectrum of dimuons produced by 800 GeV protons incident on a copper dump. The fit described in the text for the Drell-Yan dimuon continuum, the $\Upsilon(1S)$, and the sum of the $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances is also shown. b) The ratio of the data to the Monte Carlo-generated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

the nucleon-nucleon center-of-mass frame), and $p_T < 4.0$ GeV/c (p_T is the transverse momentum of the dimuon).

For this measurement the currents of the two spectrometer magnets were set to 4200 A and 4265 A, 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 GeV to 15.0 GeV dimuon mass. 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 4m-thick copper target.

The Drell-Yan dimuon continuum is described well with a PQCD calculation [12] incorporating a recent MRST determination of the proton structure functions [13]. 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

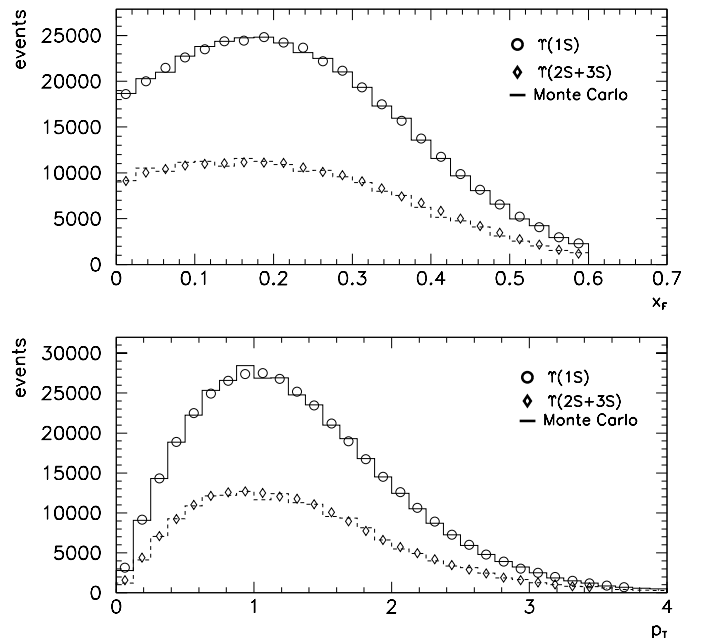


FIG. 2. The observed x_F and p_T distributions of the $\Upsilon(1S)$. The data distributions are formed by subtracting the Monte Carlo-generated Drell-Yan dimuons, and the generated $\Upsilon(2S+3S)$ dimuon decays, from the observed dimuon data. The Monte Carlo-generated $\Upsilon(1S)$ decay spectra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

$x_1 - x_2 = x_F$; 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 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. Due to the 330 MeV rms mass resolution of this measurement, we cannot resolve the 2S and 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 data 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 the results in this paper are insensitive to this assumption within statistics.

We generated twice as many accepted Monte Carlo events as were observed in the data. The Drell-Yan dimuon continuum was generated using PQCD with MRST parton distributions [13], a shape versus p_T that

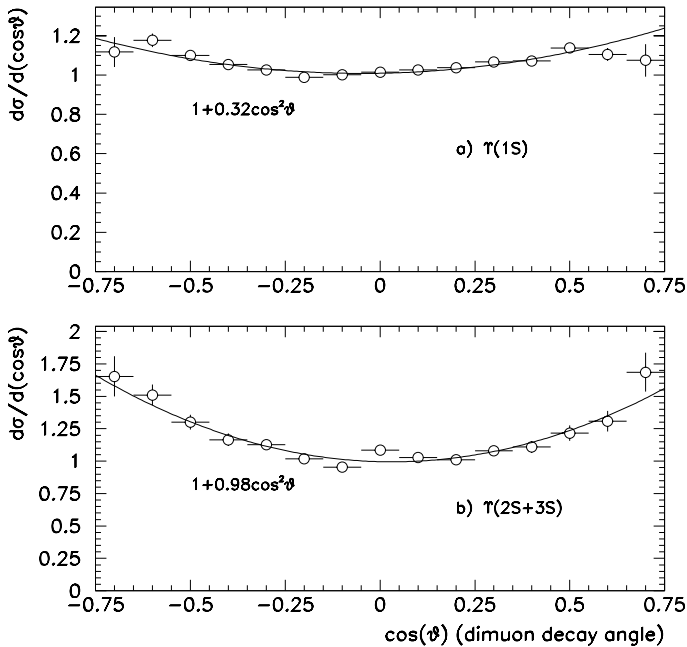


FIG. 3. a) Decay angular distribution of $\Upsilon(1S)$ dimuon decays, formed by subtracting the fit contributions of the Drell-Yan, $\Upsilon(2S)$, and $\Upsilon(3S)$ decays from the data (in the bin $8.8 < m_{\mu^+\mu^-} < 10.0$ GeV and $p_T > 1.8$ GeV/c). A fit to the form $1 + \alpha \cos^2(\theta)$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

fit the data, and a transverse polarization of 100%. The Drell-Yan continuum events were then weighted with quadratic polynomial functions of x_1 and x_2 to match the data exactly. The weighting polynomials (which varied in value from 0.85 to 1.15) correct for small inaccuracies in the modelling 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 modelled 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 with p_T and x_F shapes and a relative 1S/2S/3S weight 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 resolution mentioned above).

The final fit independently varied the shapes of the pro-

duction distributions and the polarizations of the Drell-Yan, $\Upsilon(1S)$ and $\Upsilon(2S+3S)$ 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.

In figure 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 either the analysed $\Upsilon(1S)$ or $\Upsilon(2S+3S)$ data is 0.23 and the average p_T 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 figure 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, figure 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 4 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 figure 4a. The results versus x_F (4 bins, boundaries at 0.0, 0.12, 0.23, 0.35 and 0.6) are shown in figure 4b. The points are plotted at the cross-section-weighted average value of the abscissa. A systematic error in α of ± 0.06 should be added to the values of the onium polarizations in figure 4. This was estimated by varying the form of the fitting function for the Drell-Yan continuum dimuons and by varying the width of the mass bins used to fit the onium resonances and the Drell-Yan continuum.

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 $0.06 < x_2 < 0.4$, a region where no significant nuclear shadowing is observed [17]. A fit to the Drell-Yan sideband data (for all x_F and p_T) yields $\alpha = 1.008 \pm 0.016$ with an estimated systematic error of ± 0.020 .

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

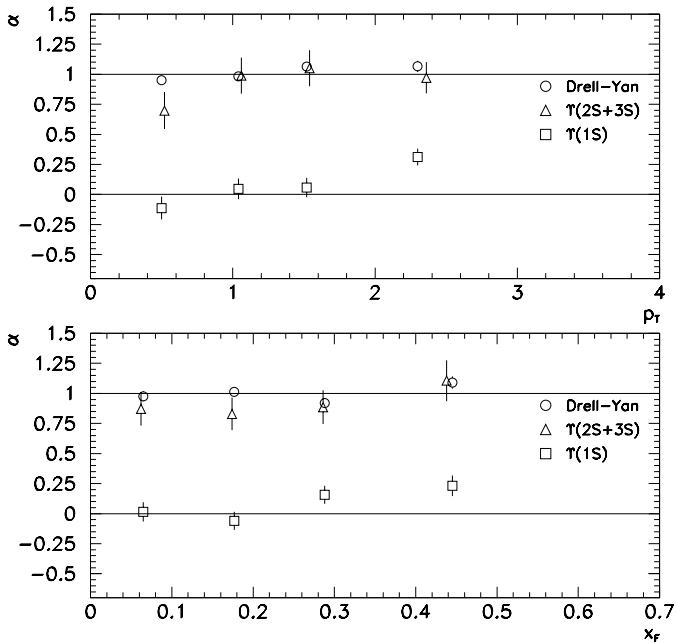


FIG. 4. a) α versus p_T for the Drell-Yan sidebands ($8.1 < m_{\mu^+\mu^-} < 8.45$ GeV and $11.1 < m_{\mu^+\mu^-} < 15.0$ GeV), $\Upsilon(1S)$ ($8.8 < m_{\mu^+\mu^-} < 10.0$ GeV), and $\Upsilon(2S+3S)$ ($10.0 < m_{\mu^+\mu^-} < 11.1$ GeV). b) α versus x_F for the same mass regions. The errors shown are 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.

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 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 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 upson 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 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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