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# Measurement of $J/\psi$ production in continuum $e^+e^-$ annihilations near $\sqrt{s} = 10.6\,\mathrm{GeV}$

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The production of $J/\psi$ mesons in continuum $e^+e^-$ annihilations has been studied with the *BABAR* detector at energies near the $\Upsilon(4S)$ resonance, approximately 10.6 GeV. The mesons are distinguished from $J/\psi$ production in $B$ decays through their center-of-mass momentum and energy. We measure the cross section $e^+e^- \to J/\psi X$ to be $2.52 \pm 0.21 \pm 0.21$ pb; for momentum above $2\,\mathrm{GeV}/c$, it is $1.87 \pm 0.10 \pm 0.15$ pb. We set a 90% confidence level upper limit on the branching fraction for direct $\Upsilon(4S) \to J/\psi X$ decays at $4.3 \times 10^{-4}$.

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The development of non-relativistic QCD (NRQCD) represents a significant advance in the theory of the production of heavy quarkonium ($q\overline{q}$) states [1]. In particular, it provides an explanation [2] for the cross section for $\psi(2S)$ production observed by CDF [3], which is a factor of 30 larger than expected from previous models. The enhancement is attributed to the production of a $c\overline{c}$ pair in a color octet state, which then evolves into the charmonium ($c\overline{c}$) meson along with other light hadrons. A similar contribution is expected in NRQCD for $J/\psi$ production in $e^+e^-$ annihilation [4, 5], but is absent in the color singlet model [6].

Significant continuum $J/\psi$ production—as distinct from production in $B$ decay at the $\Upsilon(4S)$ resonance—has not been observed previously in $e^+e^-$ annihilation below the $Z$ resonance. It therefore represents a good test of NRQCD. In particular, matrix elements extracted from different $J/\psi$ production processes should be consistent [7]. In addition, momentum, polarization and particularly the angular distributions of the $J/\psi$ distinguish between theoretical approaches [8]. Despite NRQCD's successes, it is not clear that it correctly explains [9] the CDF measurements of $J/\psi$ polarization [10], or measurements of $J/\psi$ photoproduction at HERA [11, 12].

The study reported here uses $20.7\,\mathrm{fb}^{-1}$ of data collected at the $\Upsilon(4S)$ resonance (10.58 GeV) and $2.59\,\mathrm{fb}^{-1}$ collected at 10.54 GeV, below the threshold for $B\overline{B}$ creation. The luminosity-weighted center-of-mass (CM) energy is 10.57 GeV.

The data were collected with the *BABAR* detector [13] located at the PEP-II collider at the Stanford Linear Accelerator Center. PEP-II collides 9 GeV electrons with 3.1 GeV positrons to create a center of mass moving along the $z$ axis with a Lorentz boost of $\beta\gamma = 0.56$.

The momentum and trajectory of charged particles are reconstructed with two detector systems located in a 1.5-T solenoidal magnetic field: a five-layer, double-sided silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH). The fiducial volume covers the polar angular region $0.41 < \theta < 2.54$, 86% of the solid angle in the CM frame. The transverse momentum $p_t$ resolution is 0.47% at $1\,\mathrm{GeV}/c$.

The energies of electrons and photons are measured in a finely-segmented CsI(Tl) electromagnetic calorimeter (EMC) in the fiducial volume $0.41 < \theta < 2.41$, 84% of the solid angle in the CM frame. The resolution at 1 GeV is 3.0%. The EMC is also sensitive to the energy deposited by interacting hadrons. Muons are detected in the IFR—the flux return of the solenoid, which is instrumented with resistive plate chambers. The DIRC, a unique Cherenkov radiation detection device, distinguishes charged particles of different masses.

$J/\psi$ mesons are reconstructed via their decay to an electron or muon pair in events that satisfy criteria described later. The leptons must be high-quality tracks with $0.41 < \theta < 2.41$: they must have $p_t > 0.1\,\mathrm{GeV}/c$ and momentum below $10\,\mathrm{GeV}/c$, have at least 12 hits in the DCH, and approach within 10 cm of the beam spot in $z$ and within 1.5 cm of the beam line. The beam spot rms size is approximately 0.9 cm in $z$, 120 $\mu$m horizontally and 5.6 $\mu$m vertically.

One electron candidate must have an energy deposit in the EMC of at least 75% of its momentum. The other must have between 89% and 120%, and must also have an energy deposition in the DCH and a signal in the DIRC consistent with expectations for an electron. Both must satisfy criteria on the shape of the EMC deposit. If possible, photons radiated by electrons traversing material prior to the DCH are combined with the track.

Muon candidates must deposit less than 0.5 GeV in the EMC (2.3 times the minimum-ionizing peak), penetrate at least two interaction lengths $\lambda$ of material, and have a pattern of hits consistent with the trajectory of a muon. We require that the material traversed by one candidate be within 1 $\lambda$ of that expected for a muon; for the other candidate, this is relaxed to 2 $\lambda$.

The mass of the $J/\psi$ candidate is calculated after constraining the two lepton candidates to a common origin.

To reject interactions with residual gas in the beam pipe or with the beam pipe wall, we construct an event vertex using all tracks in the fiducial volume and require it to be located within 6 cm of the beam spot in $z$ and within 0.5 cm of the beam line. To suppress a substantial background from radiative Bhabha ($e^+e^-\gamma$) events in which the photon converts to an $e^+e^-$ pair, five tracks are required in events with a $J/\psi \to e^+e^-$ candidate.

At this point, the data includes $J/\psi$ mesons both from our signal—continuum-produced $J/\psi$ mesons and $J/\psi$ mesons from the decay of continuum-produced $\psi(2S)$ and $\chi_{cJ}$ mesons—and from other known sources. We apply additional selection criteria to suppress these other sources based on their kinematic properties.

The most copious background, $B \to J/\psi X$, is eliminated by requiring the $J/\psi$ momentum in the CM frame ($p^*$) to be greater than $2\,\mathrm{GeV}/c$, above the kinematic limit for $B$ decays. This requirement is dropped for data recorded below the $\Upsilon(4S)$ resonance.

Other background sources include initial-state radiation (ISR) production of $J/\psi$ mesons, $e^+e^- \to \gamma J/\psi$, or of the $\psi(2S)$, with $\psi(2S) \to J/\psi X$. ISR production of lower-mass $\Upsilon$ resonances is negligible. Two photon production of the $\chi_{c2}$ can produce $J/\psi$ mesons via $\chi_{c2} \to \gamma J/\psi$. Because the out-going electron and positron are rarely reconstructed, this process, like the ISR $J/\psi$ production, contains only two tracks. We therefore require three high-quality tracks with $0.41 < \theta < 2.54$.

The remaining background is primarily ISR $\psi(2S)$ decays to $J/\psi\ \pi^+\pi^-$, plus some ISR $J/\psi$ events in which the ISR photon converts. To suppress these, we require the visible energy $E$ to be greater than 5 GeV, and the ratio of the second to the zeroth Fox-Wolfram moment [14], $R_2$, to be less than 0.5. Both are calculated from tracks and neutral clusters in the fiducial volume. Figure 1, which displays the visible energy and $R_2$ distributions for our signal and for simulated ISR background, motivates these criteria.

The ISR distributions in Fig. 1 are obtained from a full detector simulation. ISR kinematics ensures $E < 5\,\mathrm{GeV}$ when the photon momentum is along the beam line. However, if the photon interacts in material outside of the fiducial volume, sufficient energy can be observed to satisfy the criteria. The rate of such interactions is not accurately simulated and so is obtained by a comparison to data for $E < 5\,\mathrm{GeV}$. Approximately 3.5% of the $J/\psi$ mesons above 5 GeV are due to interacting photons; an additional $\sim 1.6\%$ are ISR events with the photon in the fiducial volume. Systematic errors on the remaining backgrounds are estimated from a comparison between simulation and data for $E < 5\,\mathrm{GeV}/c$ and for events in which the ISR photon is reconstructed.

$J/\psi$ production as a function of $E$ is obtained in data by fitting the dilepton mass distribution in 1-GeV wide energy intervals after applying all other selection criteria. The fit uses a polynomial function for the background distribution. The $J/\psi$ mass function is obtained from a complete simulation of $B \to J/\psi X$ events, convoluted with a Gaussian distribution to match the resolution of $12\,\mathrm{MeV}/c^2$ observed in data in a sample of approximately 14,000 $B \to J/\psi X$ events. The signal distribution in $E$ is obtained by subtracting the ISR backgrounds from the data distribution.

A similar process is used for $R_2$. Figures 1(c) and (d) show there is little signal above $R_2$ of 0.5. In this respect, these events are more similar to $B\overline{B}$ events, in which the energy is distributed spherically, than $c\overline{c}$ events, which tend to be jet-like.

The mass distributions of the selected $J/\psi$ candidates show clear signals for both $e^+e^-$ and $\mu^+\mu^-$ final states, both on and below resonance (Fig. 2).

To determine the production cross section, we perform mass fits in 15 $p^*$ - $\cos\theta^*$ bins, where $\theta^*$ is the polar angle of the candidate in the CM frame. This allows

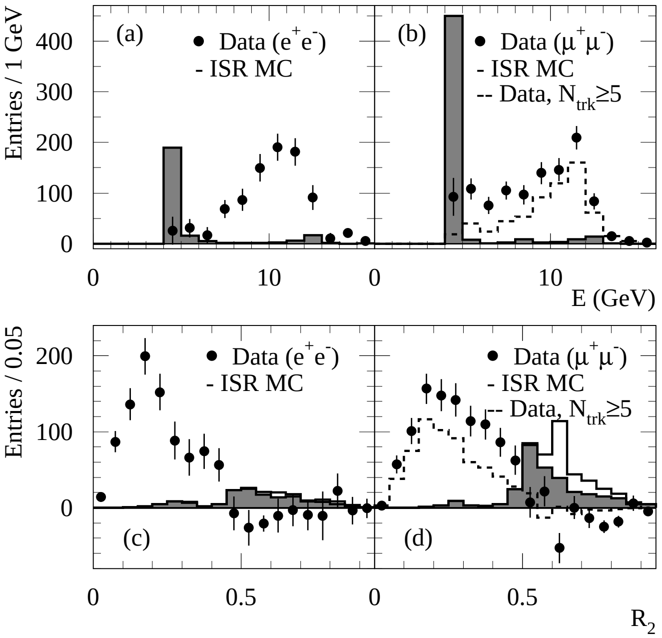

FIG. 1: Fitted number of $J/\psi$ signal events observed as a function of visible energy $E$ in the (a) $e^+e^-$ and (b) $\mu^+\mu^-$ final states; $R_2$ distribution for (c) $e^+e^-$ and (d) $\mu^+\mu^-$ final states. The histogram is the predicted ISR background that has been subtracted from data; the filled histogram is the ISR $\psi(2S)$ component only. A requirement of $\geq 5$ tracks is applied to the $e^+e^-$ sample only; applying it to the $\mu^+\mu^-$ sample produces the dashed histogram. Event preselection requires events to satisfy $E > 4\,\mathrm{GeV}$ and $R_2 < 0.95$.

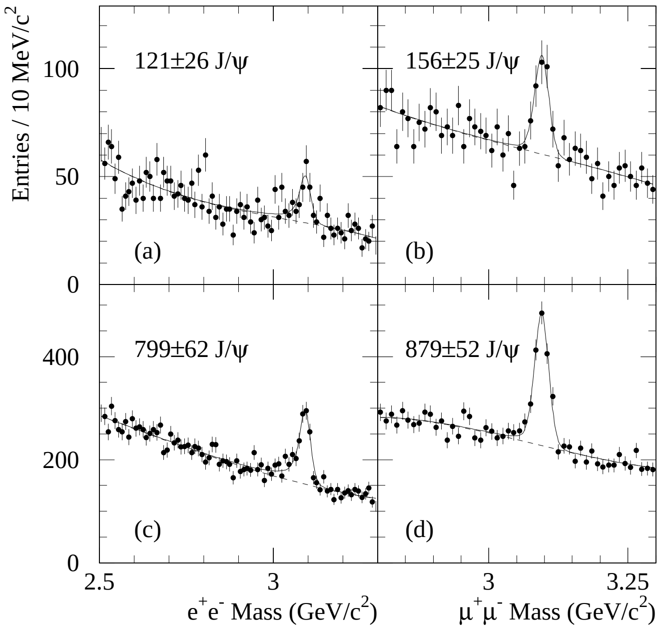

FIG. 2: Mass distribution of $J/\psi$ candidates reconstructed in data recorded below the $\Upsilon(4S)$ resonance in the (a) $e^+e^-$ and (b) $\mu^+\mu^-$ final states. Mass distributions for $p^* > 2\,\mathrm{GeV}/c$ in data at the $\Upsilon(4S)$ resonance in (c) $e^+e^-$ and (d) $\mu^+\mu^-$ final states. The number of $J/\psi$ mesons extracted by a fit to the distribution is shown on each graph.

us to correct for the variation of efficiency with $p^*$ and $\cos\theta^*$. The cross section is given by:

$$\sigma_{e^+e^-\to J/\psi X} = \sum_{i,j} \frac{(N_{ij}-B_{ij})}{\epsilon^R_{ij}\cdot\epsilon^E\cdot\mathcal{B}_{J/\psi\to\ell^+\ell^-}\cdot\mathcal{L}_i}, \tag{1}$$

where the sum is over three $p^*$ ($i$) and five $\cos\theta^*$ ($j$) bins. $N_{ij}$ is the number of $J/\psi$ mesons in the bin, where electrons and muons are analyzed separately, but off and on-resonance data are combined. The sum of the yields from the 15 fits agrees to within 1% with the yields in Fig. 2. $B_{ij}$ is the ISR background, $\mathcal{B}_{J/\psi\to\ell^+\ell^-}$ is the $J/\psi\to e^+e^-$ or $\mu^+\mu^-$ branching fraction [15], and $\mathcal{L}_i$ is the integrated luminosity—sum of on plus off-resonance for $p^* > 2\,\mathrm{GeV}/c$, off-resonance only for $p^* < 2\,\mathrm{GeV}/c$.

The reconstruction efficiency $\epsilon^R_{ij}$ (acceptance, track quality and lepton identification) is calculated in each bin with simulated unpolarized $J/\psi$ mesons uniformly distributed in $p^*$ and $\cos\theta^*$. The efficiency decreases with increasing $p^*$ and $\cos\theta^*$ due to acceptance. The average $\epsilon^R_{ij}$ is 0.63 for $J/\psi\to e^+e^-$ and 0.48 for $J/\psi\to\mu^+\mu^-$, where the difference is due to lepton identification.

Particle identification efficiency is verified in data by comparing the number of $J/\psi$ mesons in $B$ decays in which one or both leptons satisfy the requirements. The efficiency of the track-quality selection is studied by comparing tracks found in the SVT and DCH.

The components of $\epsilon^E$, the event selection efficiency, are determined as follows. We estimate the efficiency of the requirements on three or more high-quality tracks, event primary vertex and total energy to be the average of simulated $c\overline{c}$ and $B\overline{B}$ events, and the uncertainty to be one-half the difference. We use $B\overline{B}$ events for $R_2$.

The efficiency of the five track requirement applied to $e^+e^-$ candidates is obtained by comparing the net $J/\psi$ yield in events passing and failing this requirement. The values obtained in $e^+e^-$ or $\mu^+\mu^-$ final states with on or off-resonance data are consistent, with an average of 0.67. Overall, $\epsilon^E = 0.59$ for $e^+e^-$ and 0.89 for $\mu^+\mu^-$.

The calculations of the $J/\psi X$ cross section from the $e^+e^-$ and $\mu^+\mu^-$ final states are consistent: the ratio $\sigma(\mu^+\mu^-)/\sigma(e^+e^-)$ is $1.24\pm0.22$. The two values are combined, distinguishing systematic errors common to both from those unique to one, to obtain

$$\sigma_{e^+e^-\to J/\psi X} = 2.52\pm0.21\pm0.21\ \text{pb}, \tag{2}$$

where the first error is statistical and the second systematic. With existing values for matrix elements, color singlet cross section estimates range from 0.45 to 0.81 pb [4–6], while NRQCD cross sections, including a color octet component, range from 1.1 to 1.6 pb [4, 5].

The dominant component of the 8.3% systematic error is a 7.2% uncertainty on $\epsilon^E$ common to both the $e^+e^-$ and $\mu^+\mu^-$ cases and a 4.9% uncertainty due to the five track requirement. Other contributions include 2.4% due to track quality cuts; 1.5% from the luminosity; 1.8% (electrons) or 1.4% (muons) from particle identification; and 1.2% from the ISR background.

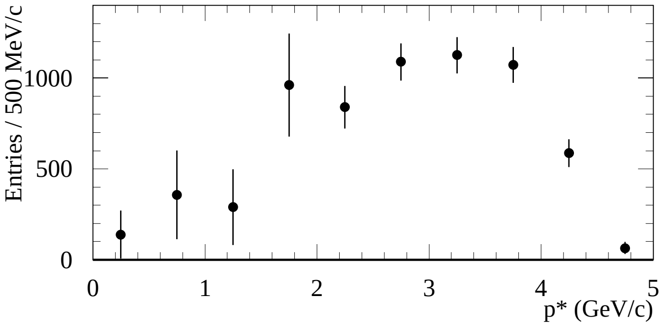

FIG. 3: Center of mass momentum distribution of $J/\psi$ mesons produced in continuum $e^+e^-$ annihilation. Data points below $2\,\mathrm{GeV}/c$ are from off-resonance data only.

The statistical error is dominated by the uncertainty on the contribution below $p^*$ of $2\,\mathrm{GeV}/c$. Restricting the measurement to $p^* > 2\,\mathrm{GeV}/c$ gives $\sigma_{e^+e^-\to J/\psi X} = 1.87\pm0.10\pm0.15\,\mathrm{pb}$.

In determining the cross sections, we assume that there are no $J/\psi$ mesons from direct $\Upsilon(4S)$ decays. We quantify this statement using the $p^* > 2\,\mathrm{GeV}/c$ component. We scale the off-resonance event yield to the on-resonance luminosity and subtract it from the on-resonance yield. The excess, attributable to $\Upsilon(4S)$ decays, is consistent with zero: $-120\pm179$ $e^+e^-$ events and $176\pm138$ $\mu^+\mu^-$, in a sample of $(22.7\pm0.4)\times10^6$ $\Upsilon(4S)$ decays. Using the average reconstruction efficiency for $p^* > 2\,\mathrm{GeV}/c$ (0.62 for $e^+e^-$ and 0.45 for $\mu^+\mu^-$), we obtain $\mathcal{B}_{\Upsilon(4S)\to J/\psi X} = (1.5\pm2.2\pm0.1)\times10^{-4}$. We calculate a 90% confidence level upper limit by adding to the central value 1.28 times the statistical and systematic errors added in quadrature:

$$\mathcal{B}_{\Upsilon(4S)\to J/\psi X} < 4.3\times10^{-4}\ (90\%\ \text{CL}), \tag{3}$$

for $J/\psi$ with $p^* > 2\,\mathrm{GeV}/c$. This result disagrees with a previous publication [16], but is consistent with NRQCD predictions, which are in the range $(1.0\text{–}2.5)\times10^{-4}$ [5, 17]. Note that if the true branching fraction were $10^{-4}$, we would have overestimated the continuum production cross section (Eq. 2) by 0.10 pb.

Production and decay properties of the $J/\psi$ have also been studied. The $p^*$ distribution is obtained by dividing the sample into $500\,\mathrm{MeV}/c$ wide intervals, fitting the resulting mass distribution, subtracting predicted ISR backgrounds, correcting for the reconstruction efficiency, and normalizing for different luminosities (Fig. 3).

The distribution of the signal in $\cos\theta^*$ has been extracted and fit with $1 + A\cdot\cos^2\theta^*$. Both NRQCD and color singlet calculations predict a flat distribution ($A\approx0$) at low $p^*$. At high momentum, NRQCD predicts $0.6 < A < 1.0$ while the color singlet model predicts $A\approx-0.8$ [8]. We measure the distribution sep-

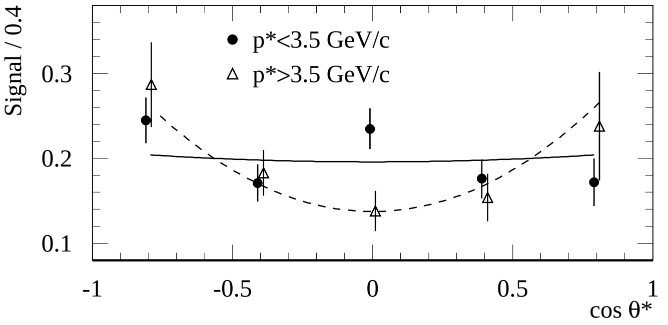

FIG. 4: Production angle distribution for $J/\psi$ mesons produced in continuum $e^+e^-$ annihilation. Solid curve is the fit to $p^* < 3.5\,\mathrm{GeV}/c$; dashed curve is for $p^* > 3.5\,\mathrm{GeV}/c$.

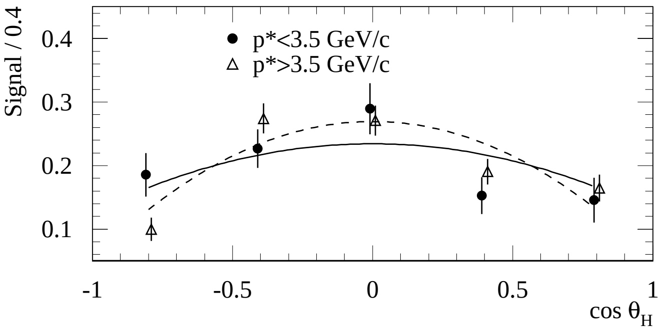

FIG. 5: Helicity distribution for $J/\psi$ mesons produced in continuum $e^+e^-$ annihilation. Solid curve is the fit to $p^* < 3.5\,\mathrm{GeV}/c$; dashed curve is for $p^* > 3.5\,\mathrm{GeV}/c$.

arately for low and high momentum mesons, selecting $p^* = 3.5\,\mathrm{GeV}/c$ as the boundary. We proceed as for the $p^*$ distribution, with mass fits performed in $\cos\theta^*$ intervals of width 0.4. The distributions are then normalized to unit area (Fig. 4). We find $A = 0.05 \pm 0.22$ for $p^* < 3.5\,\mathrm{GeV}/c$ and $A = 1.5 \pm 0.6$ for $p^* > 3.5\,\mathrm{GeV}/c$, clearly favoring NRQCD.

Finally, we obtain the helicity angle $\theta_H$ distribution for the two $p^*$ ranges by fitting mass distributions in intervals of width 0.4 in $\cos\theta_H$ (Fig. 5). The helicity is the angle, measured in the rest frame of the $J/\psi$, between the positively charged lepton daughter and the direction of the $J/\psi$ measured in the CM frame. Fitting the function $3\left(1+\alpha\cdot\cos^2\theta_H\right)/2\,(\alpha+3)$, we obtain a $J/\psi$ polarization $\alpha = -0.46 \pm 0.21$ for $p^* < 3.5\,\mathrm{GeV}/c$ and $\alpha = -0.80 \pm 0.09$ for $p^* > 3.5\,\mathrm{GeV}/c$. $\alpha = 0$ indicates an unpolarized distribution, $\alpha = 1$ transversely polarized, and $\alpha = -1$ longitudinally polarized.

In summary, we measure the cross section $\sigma_{e^+e^-\to J/\psi X} = 2.52 \pm 0.21 \pm 0.21\,\mathrm{pb}$. Restricting to $p^* > 2\,\mathrm{GeV}/c$, we find $1.87 \pm 0.10 \pm 0.15\,\mathrm{pb}$. The total cross section and the angular distribution favor the NRQCD calculation over the color singlet model. We set a 90% CL upper limit on the branching fraction $\Upsilon(4S) \to J/\psi X$ of $4.3 \times 10^{-4}$.

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