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# Measurement of Double Charmonium Production in $e^+e^-$ Annihilations at $\sqrt{s} = 10.6$ GeV

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We study $e^+e^- \to J/\psi\, c\bar{c}$ by measuring the invariant mass distribution recoiling against fully reconstructed $J/\psi$ decays, using $124.4\,\mathrm{fb}^{-1}$ of data collected with a center-of-mass energy of 10.6 GeV with the *BABAR* detector. We observe signals for $\eta_c(1S)$, $\chi_{c0}$, and $\eta_c(2S)$ in the recoil mass distribution, thus confirming previous measurements. We measure $\sigma(e^+e^- \to J/\psi + c\bar{c})\,\mathcal{B}(c\bar{c} \to > 2\,\mathrm{charged})$ to be $17.6 \pm 2.8(\mathrm{stat})^{+1.5}_{-2.1}(\mathrm{syst})$ fb, $10.3 \pm 2.5(\mathrm{stat})^{+1.4}_{-1.8}(\mathrm{syst})$ fb, and $16.4 \pm 3.7(\mathrm{stat})^{+2.4}_{-3.0}(\mathrm{syst})$ fb with $c\bar{c} = \eta_c(1S)$, $\chi_{c0}$, and $\eta_c(2S)$, respectively.

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Prompt $J/\psi$ and $\psi(2S)$ production in $e^+e^-$ annihilations around $\sqrt{s} = 10.6$ GeV has been observed by both the *BABAR* [1] and Belle [2] experiments. These interactions provide an opportunity to study both perturbative and non-perturbative effects in QCD and to search for new charmonium states [3, 4].

Belle [5] reported the observation of $\eta_c(1S)$, $\chi_{c0}$, and $\eta_c(2S)$ in the mass distribution of the system recoiling against a reconstructed $J/\psi$ in $e^+e^-$ annihilations. The production cross sections measured by Belle are about one order of magnitude higher than those predicted by non-relativistic QCD (NRQCD) calculations [4, 6] for $e^+e^- \to \gamma^* \to J/\psi\, c\bar{c}$ reactions, where $c\bar{c}$ is a charmonium state with even C-parity. There have been attempts [7–11] to reconcile the large discrepancy between the observed cross section and predictions, and the validity of NRQCD approximations has been questioned [8]. It has also been suggested that at least part of the double charmonium production might be due to two virtual-photon interactions [9], *i.e.*, $e^+e^- \to \gamma^*\gamma^* \to J/\psi\, c\bar{c}$, where odd C-parity states could be produced.

In this paper we present a measurement of the cross sections for $e^+e^- \to J/\psi\, \eta_c(1S)$, $e^+e^- \to J/\psi\, \chi_{c0}$, and $e^+e^- \to J/\psi\, \eta_c(2S)$, and set limits on the yields for other known charmonium states produced in association with a $J/\psi$. We calculate the mass ($M_{\mathrm{rec}}$) of the system recoiling against a fully reconstructed $J/\psi$ via:

$$M^2_{\mathrm{rec}} = (\sqrt{s} - E^*_{J/\psi})^2 - p^{*2}_{J/\psi}\ , \qquad (1)$$

where $\sqrt{s}$ is the $e^+e^-$ annihilation energy in the center-of-mass (CM) system, and $E^*_{J/\psi}$ and $p^*_{J/\psi}$ are the energy and momentum of the $J/\psi$ candidate in the CM system.

In this paper, we analyze $112.4\,\mathrm{fb}^{-1}$ of data collected at the peak of the $\Upsilon(4S)$ resonance and $12.0\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 10.54$ GeV, just below the $\Upsilon(4S)$, with the *BABAR* detector [12] operating at the asymmetric energy PEP-II $e^+e^-$ storage ring. The *BABAR* detector includes a five-layer, double-sided silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) in a 1.5-T solenoidal magnetic field, which detects charged particles and measures their momenta and specific ionizations ($\mathrm{d}E/\mathrm{d}x$). Photons and electrons are detected with a CsI(Tl)-crystal electromagnetic calorimeter (EMC). An internally reflecting ring-imaging Cherenkov (DIRC) is used for particle identification. Penetrating muons are identified by an array of resistive-plate chambers (RPC) embedded in the steel of the flux return (IFR).

We select events with at least five well reconstructed charged tracks in the DCH, within the fiducial volume $0.41 < \theta < 2.54$, where $\theta$ is the polar angle. Electron candidates have a $\mathrm{d}E/\mathrm{d}x$, a Cherenkov cone angle, an EMC shower energy divided by momentum, and a number of EMC crystals that are consistent with an electron hypothesis. A muon candidate is selected on the basis of energy deposited in the EMC, the number and distribution of hits in the IFR, and the match between the IFR hits and the extrapolation of the DCH track into the IFR. A more detailed explanation of particle identification is given elsewhere [1].

A pair of oppositely charged lepton candidates originating from a common vertex is selected as a $J/\psi$ candidate if its mass ($m(\ell^+\ell^-)$) falls within [-50,30] MeV/$c^2$ (for $e^+e^-$) or [-30,30] MeV/$c^2$ (for $\mu^+\mu^-$), of the nominal $J/\psi$ mass of 3.097 MeV/$c^2$ [13]. In the calculation of $m(e^+e^-)$, electron candidates are combined with nearby photon candidates in order to recover some of the energy lost through bremsstrahlung radiation. These mass intervals are referred to as the $J/\psi$ mass windows. In order to improve the $p^*_{J/\psi}$ resolution, we perform a kinematic fit where the $J/\psi$ candidate is constrained to have the nominal $J/\psi$ mass.

There are two main background sources in this analysis: events with genuine $J/\psi$ mesons and combinatorial background. The region $60\,\mathrm{MeV}/c^2 < |M(\ell^+\ell^-) - M(J/\psi)| < 200\,\mathrm{MeV}/c^2$, defined as the $J/\psi$ mass sidebands, where $M(J/\psi)$ is the nominal $J/\psi$ mass, is used to estimate the combinatorial background due to random tracks. This background is largely rejected by particle identification, and by a requirement on the lepton helicity angle in the $J/\psi$ decay, $|\cos\theta_l| < 0.9$, as shown in Fig. 1(a) and 1(c).

The largest backgrounds are due to real $J/\psi$ mesons from QED processes such as $J/\psi$ or $\psi(2S)$ mesons produced via initial state radiation (ISR). $J/\psi$ mesons from $B$ meson decay have $p^* < 2\,\mathrm{GeV}/c$ and do not constitute a background for recoil masses below $6.6\,\mathrm{GeV}/c^2$. Most QED backgrounds have low multiplicity, and may

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have electrons or photons escaping detection along the beam line. These backgrounds are suppressed by the requirement of at least five charged tracks and the following requirement: for each event we calculate the energy deposited in the EMC plus the energy that can be attributed to an undetected electron or photon,

$$E_{\rm QED} = E_{\rm EMC} + p_{\rm miss}\,, \tag{2}$$

where $E_{\rm EMC}$ is the total energy deposited in the EMC, and $p_{\rm miss}$ is the missing momentum in the lab frame in the event. We require $E_{\rm QED} - E_{\rm beams} < -1.0\,{\rm GeV}$ as shown in Fig. 1(b) and 1(d), where $E_{\rm beams}$ is the sum of the $e^+e^-$ beam energies calculated in the lab frame. We reject the $J/\psi$ background from $\psi(2S)$ events by vetoing events if the invariant mass of the $J/\psi$ candidates combined with any pair of oppositely charged tracks with pion mass hypothesis is within $15\,{\rm MeV}/c^2$ of the $\psi(2S)$ mass.

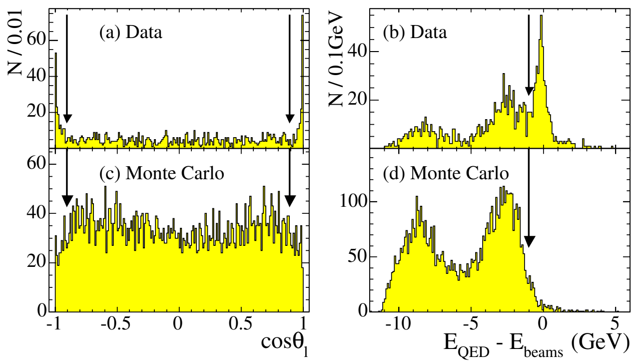


FIG. 1: Distributions of (a) $\cos\theta_l$ and (b) $E_{\rm QED} - E_{\rm beams}$ in the data, (c) $\cos\theta_l$ and (d) $E_{\rm QED} - E_{\rm beams}$ in the signal Monte Carlo. The arrows point to where the selection criteria are applied.

The recoil mass distribution for events in the $J/\psi$ mass window is shown as points with error bars in Fig. 2. The ISR $\psi(2S)$ background is estimated using a Monte Carlo sample of ISR $\psi(2S)$ events. The $\psi(2S)$ feeddown background from continuum production is estimated using continuum $\psi(2S)$ events selected in the data.

The spectrum in Fig. 2 is fit to the sum of signal functions representing the $\eta_c(1S)$, $\chi_{c0}$, and $\eta_c(2S)$ lineshapes, plus a second-order polynomial background function. The signal line shapes are obtained by convoluting the Breit-Wigner line shape of each resonance with a fixed-width Gaussian representing the recoil mass resolution function. The widths of the Gaussians are determined from a Monte Carlo simulation of the momentum of the reconstructed $J/\psi$; the $J/\psi$ momentum resolution is different for the $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$ samples, but independent of the recoiling system. This shape in turn is convolved with a long radiative tail that is calculated to $\mathcal{O}(\alpha^2)$ [14] for ISR photons that carry off an energy greater than 10 MeV. The free parameters in the data fit are the coefficients for the background parameterization, the event yields for each resonance, the masses of the resonances, and the $\eta_c(2S)$ total width. The total widths for the $\eta_c(1S)$ and the $\chi_{c0}$ are fixed to their world average values [13] of $17.3\,{\rm MeV}/c^2$ and $10.1\,{\rm MeV}/c^2$, respectively. The fit is performed simultaneously to the recoil mass spectra in the $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$ samples, and the total event yield for each resonance is given by the sum of the yields in each mode.

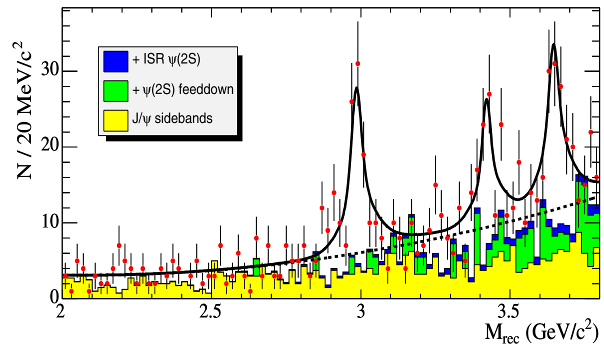


FIG. 2: The fit to the recoil mass distribution is represented by the solid curve. The dashed curve is a second-order polynomial representing the background. The points with error bars refer to the events in the $J/\psi$ mass window. The histograms represent different sources of backgrounds.

TABLE I: Result of the fits to the recoil-mass spectrum. The errors are statistical only. Where indicated, the value of the corresponding parameter is fixed to the current world average [13]. The primary fit is obtained including signals of $\eta_c(1S)$, $\chi_{c0}$, and $\eta_c(2S)$. The event yield for the other resonances is determined by including each resonance in the primary fit.

| Recoil System | Number of Events | Mass $({\rm MeV}/c^2)$ | Total Width $({\rm MeV}/c^2)$ |
|---|---|---|---|
| $\eta_c(1S)$ | $126 \pm 20$ | $2984.8 \pm 4.0$ | fixed |
| $\chi_{c0}$ | $81 \pm 20$ | $3420.5 \pm 4.8$ | fixed |
| $\eta_c(2S)$ | $121 \pm 27$ | $3645.0 \pm 5.5$ | $22 \pm 14$ |
| $J/\psi$ | $-26 \pm 13$ | fixed | fixed |
| $\chi_{c1}$ | $-5 \pm 16$ | fixed | fixed |
| $\chi_{c2}$ | $-12 \pm 16$ | fixed | fixed |
| $\psi(2S)$ | $30 \pm 27$ | fixed | fixed |

The fit result is given in Table I and is shown as the solid curve in Fig. 2. Other known charmonium states may also be produced in association with the $J/\psi$ via two virtual-photon interactions. We therefore attempt to include in our primary fit each one of the other known charmonium resonances in turn to determine their event yields, which are presented in Table I. We find no evidence for $J/\psi$, $\chi_{c1}$, $\chi_{c2}$, or $\psi(2S)$ in the mass spectrum of the system recoiling against a $J/\psi$.

The topological branching fraction is unknown for the $\eta_c(1S)$, $\chi_{c0}$, and $\eta_c(2S)$, so we report the product of the branching fraction for final states with more than two charged tracks ($\mathcal{B}_{>2}(c\bar{c} \to >2\,{\rm charged})$) times the dou-

TABLE II: Summary of systematic errors: variations of cross sections and masses due to the selection and fitting procedure (Fit), particle identification (PID) efficiency, and recoil-mass scale uncertainty. $\Delta M$ refers to the mass difference between the $\eta_c(2S)$ and $\eta_c(1S)$.

| | Variations(%) in Cross-section | | | Variations( MeV/$c^2$) in Mass | | | |
|---|---|---|---|---|---|---|---|
| Source | $\eta_c(1S)$ | $\chi_{c0}$ | $\eta_c(2S)$ | $\eta_c(1S)$ | $\chi_{c0}$ | $\eta_c(2S)$ | $\Delta M$ |
| Selection | $^{+3.5}_{-8.3}$ | $^{+0.3}_{-9.2}$ | $^{+12.6}_{-15.6}$ | $^{+3.0}_{-0.2}$ | $^{+1.2}_{-0.7}$ | $^{+1.0}_{-5.1}$ | $-7.2$ |
| Fit | $^{+6.7}_{-8.1}$ | $^{+13.5}_{-14.2}$ | $^{+6.8}_{-8.3}$ | $^{+0.1}_{-3.4}$ | $^{+9.9}_{-8.0}$ | $^{+3.3}_{-3.7}$ | $^{+7.1}_{-2.3}$ |
| PID | $\pm3.5$ | $\pm3.5$ | $\pm3.5$ | - | - | - | - |
| Mass Scale | - | - | - | $\pm1.5$ | $\pm1.5$ | $\pm1.5$ | 0 |
| Sum | $^{+8}_{-12}$ | $^{+14}_{-17}$ | $^{+15}_{-18}$ | $^{+4.5}_{-5.0}$ | $^{+11.5}_{-9.5}$ | $^{+4.9}_{-7.8}$ | $^{+7.1}_{-7.6}$ |

ble charmonium production cross section. In order to include the effect of ISR, the yields reported in Table I are calculated with a line shape based on a model of the $\sqrt{s}$ dependence of double charmonium production model. To allow a direct comparison of experimental results, we follow the same method used by Belle [5] to remove this model dependence by determining cross section values that correspond to the non-tail fraction of the fit shape ($f_{rad} = 0.61$) [14] where no ISR photon with an energy greater than 10 MeV is radiated. We use

$$\sigma(e^+e^- \to J/\psi\ c\bar{c})\,\mathcal{B}_{>2} = \frac{N_{c\bar{c}} f_{rad}}{\mathcal{B}(J/\psi \to \ell^+\ell^-)\,\mathcal{L}\,\varepsilon}\,, \qquad (3)$$

where $N_{c\bar{c}}$ is the event yield, $\mathcal{L}$ is the integrated luminosity, $\mathcal{B}(J/\psi \to \ell^+\ell^-)$ is the $J/\psi$ branching fraction, and $\varepsilon$ is the detection efficiency. The value of $\varepsilon$ is determined using a Monte Carlo simulation with the assumption that exclusive $J/\psi\eta_c(nS)$ production is $P$ wave and that exclusive $J/\psi\,\chi_{c0}$ production is $S$ wave, as expected for a single virtual-photon process. The efficiency is determined to be (28.8±0.7)% for the $\eta_c(1S)$, (31.5±0.7)% for the $\chi_{c0}$, and (28.9±0.8)% for the $\eta_c(2S)$.

The systematic error is estimated taking into account contributions from the event selection and the fitting procedure, the particle identification efficiency, and the recoil-mass scale uncertainty. The contributions from uncertainties in integrated luminosity and $J/\psi$ branching fraction are negligible. The contributions from individual sources (listed in Table II) are added in quadrature, except for the systematic errors due to the mass-scale uncertainty, which are added linearly, to determine the total systematic errors.

We obtain $\sigma(e^+e^- \to J/\psi\ c\bar{c})\,\mathcal{B}(c\bar{c} \to > 2\,\text{charged})$ to be $17.6 \pm 2.8^{+1.5}_{-2.1}$ fb for $J/\psi\ \eta_c(1S)$, $10.3 \pm 2.5^{+1.4}_{-1.8}$ fb for $J/\psi\ \chi_{c0}$, and $16.4\pm3.7^{+2.4}_{-3.0}$ fb for $J/\psi\ \eta_c(2S)$. Throughout this paper, the first error is statistical and the second systematic. Our values of the cross sections are consistent with Belle's measurements [5] for all three resonances. The cross sections measured by both experiments are much larger than those predicted by many NRQCD calculations.

TABLE III: Comparison of cross-sections ($\sigma \times \mathcal{B}_{>2}$ in fb) with Belle's results [5], and with theoretical expectations that do not include the $\mathcal{B}_{>2}$ factor.

| $J/\psi\ c\bar{c}$ | $\eta_c(1S)$ | $\chi_{c0}$ | $\eta_c(2S)$ |
|---|---|---|---|
| *BABAR* | $17.6 \pm 2.8^{+1.5}_{-2.1}$ | $10.3 \pm 2.5^{+1.4}_{-1.8}$ | $16.4 \pm 3.7^{+2.4}_{-3.0}$ |
| Belle [5] | $25.6 \pm 2.8 \pm 3.4$ | $6.4 \pm 1.7 \pm 1.0$ | $16.5 \pm 3.0 \pm 2.4$ |
| NRQCD [6] | $2.31 \pm 1.09$ | $2.28 \pm 1.03$ | $0.96 \pm 0.45$ |
| NRQCD [4] | 5.5 | 6.9 | 3.7 |

From the fit to the recoil mass spectrum we determine the $\eta_c(2S)$ mass to be $3645.0 \pm 5.5^{+4.9}_{-7.8}$ MeV/$c^2$, and the total width to be $22 \pm 14$ MeV/$c^2$. The systematic uncertainty reflects the systematic uncertainty of the $J/\psi$ momentum measurement. We use ISR $J/\psi$ and ISR $\psi(2S)$ data samples to determine the momentum scale and extrapolate to the $p^*_{J/\psi}$ corresponding to $J/\psi\ c\bar{c}$ processes. The mass difference ($\Delta M$) between the $\eta_c(2S)$ and $\eta_c(1S)$ does not significantly depend on the absolute momentum scale and common systematic errors mostly cancel. We measure $\Delta M = 660.2\pm6.8^{+7.1}_{-7.6}$ MeV/$c^2$, which is in good agreement with the mass difference previously reported by this experiment [15] and by other experiments [5, 16].

In summary, we have measured the cross section for double charmonium production $\sigma(e^+e^- \to J/\psi\ c\bar{c})\,\mathcal{B}(c\bar{c} \to > 2\,\text{charged})$ for $J/\psi\,\eta_c(1S)$, $J/\psi\,\chi_{c0}$, and $J/\psi\ \eta_c(2S)$. We confirm the unexpectedly large cross sections previously reported by the Belle experiment for these processes. No evidence is found for $e^+e^- \to J/\psi\ J/\psi$, $J/\psi\,\chi_{c1}$, $J/\psi\,\chi_{c2}$, or $J/\psi\ \psi(2S)$. We also measure the mass difference between the $\eta_c(2S)$ and the $\eta_c(1S)$ to be $660.2 \pm 6.8^{+7.1}_{-7.6}$ MeV/$c^2$.

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