Study of double charmonium production in $e^+e^-$ annihilation at
$\sqrt{s} \approx 10.6$ GeV

K. Abe,7 K. Abe,38 H. Aihara,40 Y. Asano,43 V. Aulchenko,1 T. Aushev,11 S. Bahinipati,4
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M. Yamauchi,7 S. L. Zang,9 C. C. Zhang,9 J. Zhang,7 Z. P. Zhang,33 and D. Žontar17,12
(The Belle Collaboration)

1Budker Institute of Nuclear Physics, Novosibirsk
Chiba University, Chiba
Chonnam National University, Kwangju
University of Cincinnati, Cincinnati, Ohio 45221
Gyeongsang National University, Chinju
University of Hawaii, Honolulu, Hawaii 96822
High Energy Accelerator Research Organization (KEK), Tsukuba
Hiroshima Institute of Technology, Hiroshima
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing
Institute of High Energy Physics, Vienna
Institute for Theoretical and Experimental Physics, Moscow
J. Stefan Institute, Ljubljana
Kanagawa University, Yokohama
Korea University, Seoul
Kyungpook National University, Taegu
Swiss Federal Institute of Technology of Lausanne, EPFL, Lausanne
University of Ljubljana, Ljubljana
University of Maribor, Maribor
University of Melbourne, Victoria
Nagoya University, Nagoya
Nara Women's University, Nara
National Kaohsiung Normal University, Kaohsiung
National United University, Miao Li
Department of Physics, National Taiwan University, Taipei
H. Niewodniczanski Institute of Nuclear Physics, Krakow
Nihon Dental College, Niigata
Niigata University, Niigata
Osaka City University, Osaka
Osaka University, Osaka
Panjab University, Chandigarh
Peking University, Beijing
Princeton University, Princeton, New Jersey 08545
University of Science and Technology of China, Hefei
Sungkyunkwan University, Suwon
University of Sydney, Sydney NSW
Tata Institute of Fundamental Research, Bombay
Toho University, Funabashi
We present a new analysis of double charmonium production in $e^+e^-$ annihilation. The observation of the processes $e^+e^- \rightarrow J/\psi \eta_c$, $J/\psi \chi_{c0}$, and $J/\psi \eta_c(2S)$ is confirmed using a dataset more than three times larger than that of Belle’s previous report, and no evidence for the process $e^+e^- \rightarrow J/\psi J/\psi$ is found. We perform an angular analysis for $J/\psi \eta_c$ production and set an upper limit on the production of $J/\psi J/\psi$. Processes of the type $e^+e^- \rightarrow \psi(2S)(c\bar{c})_{\text{res}}$ have been observed for the first time; their rates are found to be comparable to those of $e^+e^- \rightarrow J/\psi (c\bar{c})_{\text{res}}$ processes.

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The large rate for processes of the type $e^+e^- \rightarrow J/\psi \eta_c$ and $J/\psi (c\bar{c})_{\text{non-res}}$ reported by Belle remains unexplained. Following the publication of this result, the cross-section for $e^+e^- \rightarrow J/\psi \eta_c$ via $e^+e^-$ annihilation into a single virtual photon was calculated using non-relativistic QCD (NRQCD) to be $\sim 2 \text{ fb}$, which is at least an order of magnitude smaller than the measured value. Several hypotheses have been suggested in order to resolve this discrepancy. In particular, the authors of Ref. have proposed that processes proceeding via two virtual photons may be important. Other authors suggest that since the dominant mechanism for charmonium production in $e^+e^-$ annihilation is expected to be the color-singlet process $e^+e^- \rightarrow c\bar{c}gg$, the final states observed by Belle contain a charmonium state and a $M \sim 3 \text{ GeV}/c^2$ glueball. Such glueball states are predicted by lattice QCD and can have masses around $3 \text{ GeV}/c^2$. Possible glueball contributions to the $\chi_{c0}$ signal are also discussed in Ref.

The previous Belle analysis was performed with a data sample of $45 \text{ fb}^{-1}$. The process $e^+e^- \rightarrow J/\psi \eta_c$ was inferred from the $\eta_c$ peak in the mass spectrum of the system recoiling against the reconstructed $J/\psi$ in inclusive $e^+e^- \rightarrow J/\psi X$ events. In this paper we report an extended analysis of the $e^+e^- \rightarrow J/\psi (c\bar{c})_{\text{res}}$ process to check the above hypotheses and provide extra information that might be useful to resolve the puzzle. This study is performed using a data sample of $140 \text{ fb}^{-1}$ collected at the $\Upsilon(4S)$ resonance and $15 \text{ fb}^{-1}$ at an energy 60 MeV below the $\Upsilon(4S)$. The data were collected with the Belle detector at the
KEKB asymmetric energy $e^+e^-$ storage rings [7].

The analysis procedure is described in detail in Ref. [1]. For $J/\psi$ reconstruction we combine oppositely charged tracks that are both positively identified either as muons or electrons. For $J/\psi \rightarrow e^+e^-$, the invariant mass calculation includes the four-momentum of photons detected within 50 mrad of the $e^\pm$ directions, as a partial correction for final state radiation and bremsstrahlung energy loss. The $J/\psi \rightarrow \ell^+\ell^-$ signal region is defined by a mass window $|M_{\ell^+\ell^-} - M_{J/\psi}| < 30 \text{ MeV}/c^2 \approx 2.5 \sigma_M$. QED processes are significantly suppressed by the requirement that the total charged multiplicity ($N_{ch}$) in the event be $N_{ch} > 4$. The contribution from $J/\psi$ mesons in $B\bar{B}$ events is removed by requiring the center-of-mass (CM) momentum $p^*_{J/\psi}$ to be greater than 2.0 GeV/c. A mass-constrained fit is then performed to improve the $p^*_{J/\psi}$ resolution and the recoil mass $M_{\text{recoil}} = \sqrt{(E_{\text{CM}} - E^*_{J/\psi})^2 - p^*_{J/\psi}^2}$ is calculated, where $E^*_{J/\psi}$ is the $J/\psi$ CM energy after the mass constraint. $\psi(2S)$ is reconstructed via its decay to $J/\psi\pi^+\pi^-$ and the $\psi(2S)$ signal window is defined as $|M_{J/\psi\pi^+\pi^-} - M(\psi(2S))| < 10 \text{ MeV}/c^2 \approx 3 \sigma_M$.

The $M_{\text{recoil}}(J/\psi)$ spectrum for the data is presented in Fig. 1: clear peaks around the nominal $\eta_c$ and $\chi_{c0}$ masses are evident; another significant peak around $\sim 3.63 \text{ GeV}/c^2$ is identified as the $\eta_c(2S)$. The authors of Ref. [3] estimated that the two-photon-mediated process $e^+e^- \rightarrow J/\psi J/\psi$ has a significant cross-section and suggested that the observed $e^+e^- \rightarrow J/\psi \eta_c$ signal in [4] might also include double $J/\psi$ events, thereby producing an inflated cross-section measurement. Since $e^+e^-$ annihilation to $J/\psi J/\psi$ 

![FIG. 1: The mass of the system recoiling against the reconstructed $J/\psi$ in inclusive $e^+e^- \rightarrow J/\psi X$ events. The curves are described in the text.](image)
via a single virtual photon is forbidden by charge conjugation symmetry, it was ignored in our previous analysis. To allow for a possible contribution from the exchange of two virtual photons, we fit the spectrum in Fig. 4 including all of the known narrow charmonium states. In this fit, the mass positions for the $\eta_c$, $\chi_{c0}$ and $\eta_c(2S)$ are free parameters; those for the $J/\psi$, $\chi_{c1}$, $\chi_{c2}$ and $\psi(2S)$ are fixed at their nominal values. The expected line-shapes for these peaks are determined from a Monte Carlo (MC) simulation as described in our previous paper [1], the background is parameterized by a second order polynomial function, and only the region below the open charm threshold ($M_{\text{recoil}} < 3.7 \text{ GeV}/c^2$) is included in the fit. The fit results are listed in Table I. The yields for $\eta_c$, $\chi_{c0}$, and $\eta_c(2S)$ have statistical significances between 3.8 and 10.7. The significance of each signal is defined as $\sqrt{-2 \ln(L_0/L_{\text{max}})}$, where $L_0$ and $L_{\text{max}}$ denote the likelihoods with the corresponding signal yield fixed at zero and at the best-fit value, respectively. The fit returns negative yields for the $J/\psi$ and $\psi(2S)$; the $\chi_{c1}$ and $\chi_{c2}$ yields are found to be consistent with zero. A fit with all these contributions fixed at zero is shown as a solid line in Fig. 4; the difference in the $\eta_c$, $\chi_{c0}$ and $\eta_c(2S)$ yields compared to the default fit is small, and is included in the systematic errors. The dashed line in the figure corresponds to the case where the contributions of the $J/\psi$, $\chi_{c1}$, $\chi_{c2}$ and $\psi(2S)$ are set at their 90% confidence level upper limit values. The dotted line is the background function.

**TABLE I: Summary of the signal yields ($N$), charmonium masses ($M$), significances, and cross-sections ($\sigma_{\text{Born}} \times B_{>2}((c\bar{c})_{\text{res}})$) for $e^+e^- \rightarrow J/\psi (c\bar{c})_{\text{res}}$; $B_{>2}$ denotes the branching fraction for final states with more than two charged tracks.**

| (c\bar{c})_{\text{res}} | $N$    | $M$ [GeV/c^2] | Signif. | $\sigma_{\text{Born}} \times B_{>2}$ [fb] |
|-------------------------|-------|---------------|---------|------------------------------------------|
| $\eta_c$                | 235 ± 26 | 2.972 ± 0.007 | 10.7    | 25.6 ± 2.8 ± 3.4                         |
| $J/\psi$                | -14 ± 20 | fixed         | —       | < 9.1 at 90% CL                          |
| $\chi_{c0}$             | 89 ± 24  | 3.407 ± 0.011 | 3.8     | 6.4 ± 1.7 ± 1.0                          |
| $\chi_{c1} + \chi_{c2}$| 10 ± 27  | fixed         | —       | < 5.3 at 90% CL                          |
| $\eta_c(2S)$            | 164 ± 30 | 3.630 ± 0.008 | 6.0     | 16.5 ± 3.0 ± 2.4                         |
| $\psi(2S)$              | -26 ± 29 | fixed         | —       | < 13.3 at 90% CL                         |

Given the arguments in Ref. [3], it is important to check for any momentum scale bias that may shift the recoil mass values and confuse the interpretation of peaks in the $M_{\text{recoil}}$ spectrum. We use $e^+e^- \rightarrow \psi(2S)\gamma$, $\psi(2S) \rightarrow J/\psi \pi^+\pi^-$ events to calibrate and verify the recoil mass scale. Events with a reconstructed $\psi(2S)$ and with no other charged tracks form a pure $e^+e^- \rightarrow \psi(2S)\gamma$ sample with less
than 1% background as estimated using the $\psi(2S)$ sideband region. We use the $\psi(2S)$ momentum to calculate the square of the mass of the recoiling system; the resulting spectrum is shown in Fig. 2. The

scaled $\psi(2S)$ sideband is also shown. We perform a fit to the $M_{\text{recoil}}^2(\psi(2S))$ spectrum, using Monte Carlo simulation to determine the expected signal shape; second order QED corrections, which produce a higher $M_{\text{recoil}}^2$ tail, are taken into account. The peak position is left free in the fit and the non-$\psi(2S)$ background is ignored. The fit finds the shift in the data with respect to the MC function to be consistent with zero ($\Delta M_{\text{recoil}}^2 = 0.010 \pm 0.009 \text{ GeV}^2/c^4$). From this result we conclude that the $J/\psi$ recoil mass is shifted by not more than 3 MeV/c$^2$ in the region $M_{\text{recoil}}^2(J/\psi) \sim 3 \text{ GeV}/c^2$.

As an additional cross-check we fully reconstruct double charmonium events. The $\eta_c$ is reconstructed as $K_S^0 K^{\pm} \pi^\mp$ ($K_S^0 \rightarrow \pi^+ \pi^-)$ or $2(K^+ K^-)$ combinations within a window of $\pm 50 \text{ MeV}/c^2$ around the nominal $\eta_c$ mass. In events with $N_{\text{ch}} = 6$ we find 3 events with $J/\psi \eta_c$ combinations in a $\pm 100 \text{ MeV}$ window around the CM energy ($\approx 3 \sigma$). No events are seen in the $\eta_c$ sideband region ($100 < M(K_S K \pi^+2(KK)) - M_{\eta_c} < 350 \text{ MeV}$); a fit to the mass distribution gives an $\eta_c$ signal significance of $4.1 \sigma$. Based on the $\eta_c$ yield in the $M_{\text{recoil}}^2(J/\psi)$ distribution, we expect $2.6 \pm 0.8$ fully reconstructed events, consistent with the observed signal. Thus we conclude that the peak in $M_{\text{recoil}}^2(J/\psi)$ is dominated by $\eta_c$ production. We also search

FIG. 2: The square of the mass of the system recoiling against the reconstructed $\psi(2S) \rightarrow J/\psi \pi^+\pi^-$, in events with charged multiplicity equal to 4. Points with error bars show the data, the solid line shows the result of the fit described in the text. The hatched histogram (scarcely visible) shows the spectrum in the scaled $\psi(2S)$ sidebands.
for fully reconstructed double $J/\psi$ candidates in events with $N_{ch} = 4$. No $J/\psi J/\psi$ candidates are found in a window of $\pm 100$ MeV around the CM energy.

Based on the calibration of the $M_{\text{recoil}}(J/\psi)$ scale, the result of the fit to the $M_{\text{recoil}}(J/\psi)$ distribution and the full reconstruction cross-check, we confirm our published observation of the process $e^+e^- \rightarrow J/\psi \eta_c$ and rule out the suggestion of Ref. [3] that a significant fraction of the inferred $J/\psi \eta_c$ signal might be due to $J/\psi J/\psi$ events.

The reconstruction efficiencies for the $J/\psi \eta_c$, $J/\psi \chi_{c0}$, and $J/\psi \eta_c(2S)$ final states strongly depend on $\theta_{\text{prod}}$, the production angle of the $J/\psi$ in the CM frame with respect to the beam axis, and the helicity angle $\theta_{\text{hel}}$, defined as the angle between the decay $\ell^+$ direction and the boost direction of the CM frame in the $J/\psi$ rest frame. We therefore perform an angular analysis for these modes before computing cross-sections. We fit the $M_{\text{recoil}}(J/\psi)$ distributions in bins of $|\cos(\theta_{\text{prod}})|$ and $|\cos(\theta_{\text{hel}})|$, and correct the yield for the reconstruction efficiencies determined bin-by-bin from the MC. The results are plotted in Fig. 3, together with fits to functions $A(1 + \alpha \cos^2 \theta)$ (solid lines). We also perform simultaneous fits to the production and helicity angle distributions for each of the $(c\bar{c})_{\text{res}}$ states, assuming $J/\psi (c\bar{c})_{\text{res}}$ production via a single virtual photon and angular momentum conservation, thus setting $\alpha_{\text{prod}} \equiv \alpha_{\text{hel}}$. The values of the parameter $\alpha$ from the separate fits to $|\cos(\theta_{\text{hel}})|$ and $|\cos(\theta_{\text{prod}})|$, and from the simultaneous fits, are listed in Table II.

TABLE II: The $\alpha$ parameters obtained from fits to the production and helicity angle distributions for $e^+e^- \rightarrow J/\psi (c\bar{c})_{\text{res}}$.

| $(c\bar{c})_{\text{res}}$ | Separate fits | Simultaneous fits |
|--------------------------|---------------|-------------------|
|                          | $\alpha_{\text{prod}}$ | $\alpha_{\text{hel}}$ | $\alpha_{\text{hel}} \equiv \alpha_{\text{prod}}$ |
| $\eta_c$                 | $1.4^{+1.1}_{-0.8}$  | $0.5^{+0.7}_{-0.5}$ | $0.93^{+0.57}_{-0.47}$ |
| $\chi_{c0}$              | $-1.7^{+1.4}_{-0.5}$ | $-0.7^{+0.7}_{-0.5}$ | $-1.01^{+0.38}_{-0.33}$ |
| $\eta_c(2S)$             | $1.9^{+2.0}_{-1.2}$  | $0.3^{+1.0}_{-0.7}$ | $0.87^{+0.86}_{-0.63}$ |

The angular distributions for the $J/\psi \eta_c$ and $J/\psi \eta_c(2S)$ peaks are consistent with the expectations for production of these final states via a single virtual photon, $\alpha_{\text{prod}} = \alpha_{\text{hel}} = +1$ [2]. There is no evidence for the sharp rise in cross-section for large $|\cos(\theta_{\text{prod}})|$ expected for $J/\psi J/\psi$ production via two virtual photons [3]. The prediction for a spin-0 glueball contribution ($e^+e^- \rightarrow J/\psi G_0$) to the $J/\psi \eta_c$ peak, $\alpha_{\text{prod}} = \alpha_{\text{hel}} \simeq -0.87$ [4], is also disfavored.
FIG. 3: Distributions of cosines of the production (left) and $J/\psi$ helicity angles (right) for $e^+e^- \rightarrow J/\psi \eta_c$ (top row), $e^+e^- \rightarrow J/\psi \chi_{c0}$ (middle row) $e^+e^- \rightarrow J/\psi \eta(2S)$ (bottom row). The solid lines are results of the individual fits; the dotted lines are the simultaneous fit results.

The process $e^+e^- \rightarrow \gamma^* \rightarrow J/\psi \chi_{c0}$ can proceed via both S- and D-wave amplitudes, and predictions for the resulting angular distributions are therefore model dependent. Our results disfavor the NRQCD expectation $\alpha_{\text{prod}} = \alpha_{\text{hel}} \simeq 0.25$ [2, 5], and are more consistent with S-wave production, where $\alpha_{\text{prod}} = \alpha_{\text{hel}} = -1$.

To calculate the cross-sections for the processes $e^+e^- \rightarrow J/\psi \eta_c, J/\psi \chi_{c0}, J/\psi \eta(2S)$ we fix the production and helicity angle distributions in the MC to $1 + \cos^2 \theta$ for $J/\psi \eta_c (\eta_c(2S))$, and to $1 - \cos^2 \theta$ for $J/\psi \chi_{c0}$. The statistical errors in the $\alpha$ parameters for the angular distributions are translated into uncertainties in the efficiency determination and included in the systematic error. To set a conservative upper limit for $e^+e^- \rightarrow J/\psi J/\psi, J/\psi \chi_{c1(2)}, J/\psi \psi(2S)$, we use assumptions for the production and helicity angle distributions that correspond to the lowest detection efficiency. Note that for $J/\psi J/\psi$ and $J/\psi \psi(2S)$ the assumed angular distributions lead to lower efficiencies than those that follow from the predictions of Ref. [2].
To reduce the model dependence of our results due to the effect of initial state radiation (ISR), whose form-factor dependence on \( Q^2 \) of the virtual photon is unknown, we calculate cross-sections in the Born approximation. We first calculate the fraction of events in the signal \( M_{\text{recoil}}(J/\psi) \) distributions that are accompanied by an ISR photon of an energy smaller than a cutoff \( E_{\text{cutoff}} \) using MC. We then correct the cross-sections calculated for that cutoff value using a factor that yields the Born cross-section \[ \sigma_{\text{Born}} = 0.70 \cdot \sigma_{\text{full}}. \] The final result is then independent of the choice of the cutoff energy provided \( M_\ell \ll E_{\text{cutoff}} \ll E_{\text{CM}} \). As in Ref. [8], because of selection criteria we present our result in terms of the product of the cross-section and the branching fraction of the recoil charmonium state into more than 2 charged tracks: \( \sigma \times B_{>2} \), where \( B_{>2} ((c\bar{c})_{\text{res}}) \equiv B((c\bar{c})_{\text{res}} \rightarrow > 2 \text{charged}) \). The cross-sections are given in Table I.

We perform a similar study with reconstructed \( \psi(2S) \rightarrow J/\psi \pi^+\pi^- \) decays to search for \( e^+e^- \rightarrow \psi(2S)(c\bar{c})_{\text{res}} \) processes. The recoil mass spectrum for the data is presented in Fig. 4: peaks corresponding to the \( \eta_c \), \( \chi_{c0} \), and \( \eta_c(2S) \) can be seen. The fit to the \( M_{\text{recoil}}(\psi(2S)) \) distribution is identical to the \( M_{\text{recoil}}(J/\psi) \) fit, but due to the limited sample in this case, the masses of the established charmonium states are fixed to their nominal values; the \( \eta_c(2S) \) mass is fixed to 3.630 GeV/c\(^2\) as found from the \( M_{\text{recoil}}(J/\psi) \) fit. The signal yields are listed in Table III. Significances for the individual \( \eta_c \), \( \chi_{c0} \), and \( \eta_c(2S) \) peaks are in the range 3 \~ 4\( \sigma \); the significance for \( e^+e^- \rightarrow \psi(2S)(c\bar{c})_{\text{res}} \), where \( (c\bar{c})_{\text{res}} \) is a sum
over \( \eta_c, \chi_{c0}, \) and \( \eta_c(2S) \), is estimated to be 5.3\( \sigma \). The significance is calculated as \( \sqrt{-2 \ln(\mathcal{L}_0/\mathcal{L}_{\text{max}})} \), where \( \mathcal{L}_0 \) and \( \mathcal{L}_{\text{max}} \) denote the likelihoods of the fit with all signal yields fixed at zero and at the best-fit value, respectively. In Fig. 4 the result of a fit with only \( \eta_c, \chi_{c0} \) and \( \eta_c(2S) \) contributions included is shown as a solid line; the dashed line shows the case where the \( J/\psi, \chi_{c1}, \chi_{c2}, \) and \( \psi(2S) \) contributions are set at their 90% confidence level upper limit values. The dotted line is the background function.

To estimate the efficiency we assume the \( \psi(2S) \) production and helicity angle distributions to be the same as those for the corresponding \( J/\psi (c\bar{c})_{\text{res}} \) final states. Finally, the calculated products of the Born cross-section and the branching fraction of the recoiling charmonium state into two or more charged tracks \( (\sigma \times B_{>0}) \), where \( B_{>0}((c\bar{c})_{\text{res}}) \equiv B((c\bar{c})_{\text{res}} \rightarrow \geq 0 \text{charged}) \) are presented in Table III.

| \( (c\bar{c})_{\text{res}} \) | \( N \)       | Signif. | \( \sigma_{\text{Born}} \times B_{>0} \) [fb] |
|-----------------|-------------|---------|--------------------------|
| \( \eta_c \)    | 36.7 ± 10.4 | 4.2     | 16.3 ± 4.6 ± 3.9         |
| \( J/\psi \)    | 6.9 ± 8.9   | —       | < 16.9 at 90% CL         |
| \( \chi_{c0} \) | 35.4 ± 10.7 | 3.5     | 12.5 ± 3.8 ± 3.1         |
| \( \chi_{c1} + \chi_{c2} \) | 6.6 ± 8.0 | —       | < 8.6 at 90% CL         |
| \( \eta_c(2S) \) | 36.0 ± 11.4 | 3.4     | 16.0 ± 5.1 ± 3.8         |
| \( \psi(2S) \)  | −8.3 ± 8.5  | —       | < 5.2 at 90% CL         |

The systematic error is dominated by the fitting systematics of the signal yields: 10% for \( J/\psi (c\bar{c})_{\text{res}} \) and 14% for \( \psi(2S)(c\bar{c})_{\text{res}} \). To estimate this contribution we vary the parameterizations of the signal (intrinsic widths of charmonium states, form-factor dependence on \( Q^2 \)) and background in the fit to the \( M_{\text{recoil}} \) spectra. Another large contribution is due to the reconstruction efficiency dependence on the angular distributions (7% for \( J/\psi (c\bar{c})_{\text{res}} \) and 15% for \( \psi(2S)(c\bar{c})_{\text{res}} \)). In the MC, the angular parameters \( \alpha \) are varied within the statistical errors of our angular analysis for \( e^+e^- \rightarrow J/\psi (c\bar{c})_{\text{res}} \) and in the full range \( -1 \leq \alpha_{\text{prod}}(\alpha_{\text{hel}}) \leq 1 \) for \( e^+e^- \rightarrow \psi(2S)(c\bar{c})_{\text{res}} \) to estimate the uncertainty in efficiencies. Other contributions for \( e^+e^- \rightarrow J/\psi (c\bar{c})_{\text{res}} (\psi(2S)(c\bar{c})_{\text{res}}) \) come from the multiplicity cut (3%(2%)), track reconstruction efficiency (3%(5%)) and lepton identification (3%(3%)).

In summary, using a larger data set we confirm our published observation of \( e^+e^- \rightarrow J/\psi \eta_c, J/\psi \chi_{c0} \) and \( J/\psi \eta_c(2S) \) and find no evidence for the process \( e^+e^- \rightarrow J/\psi J/\psi \). We have calculated the cross-sections for \( e^+e^- \rightarrow J/\psi \eta_c, J/\psi \chi_{c0}, \) and \( J/\psi \eta_c(2S) \) with better statistical accuracy and reduced sys-
tematic errors and set an upper limit for $\sigma(e^+e^- \rightarrow J/\psi J/\psi) \times B(J/\psi \rightarrow > 2 \text{ charged})$ of 9.1 fb at the 90\% CL. Although this limit is not inconsistent with the prediction for the $J/\psi J/\psi$ rate given in Ref. [3], the suggestion that a large fraction of the inferred $J/\psi \eta_c$ signal consists of $J/\psi J/\psi$ events is ruled out. We have measured the production and helicity angle distributions for $e^+e^- \rightarrow J/\psi \eta_c$, $J/\psi \chi_{c0}$, and $J/\psi \eta_c(2S)$; the distributions are consistent with expectations for these states, and disfavor a spin-0 glueball contribution to the $\eta_c$ peak. We observe $\psi(2S)(cc)_{\text{res}}$ production for the first time, and find that the production rates for these final states are of the same magnitude as the corresponding rates for $J/\psi (cc)_{\text{res}}$.

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* on leave from Fermi National Accelerator Laboratory, Batavia, Illinois 60510
† on leave from Nova Gorica Polytechnic, Nova Gorica

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