Evidence of a Broad Structure at an Invariant Mass of 4.32 GeV/c² in the Reaction \( e^+e^- \rightarrow \pi^+\pi^- (2S) \) Measured at BABAR

3 California Institute of Technology, Pasadena, California 91125, USA
4 University of Cincinnati, Cincinnati, Ohio 45221, USA
5 University of Colorado, Boulder, Colorado 80309, USA
6 Colorado State University, Fort Collins, Colorado 80523, USA
7 Universität Dortmund, Institut für Physik, D-44221 Dortmund, Germany
8 Technische Universität Dresden, Institut für Kern-und Teilchenphysik, D-01062 Dresden, Germany
9 Ecole Polytechnique, Laboratoire Leprince-Ringuet, F-91128 Palaiseau, France
10 University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
11 Universität di Ferrara, Dipartimento di Fisica e INFN, I-44100 Ferrara, Italy
12 Laboratori Nazionali di Frascati dell’INFN, I-00044 Frascati, Italy
13 Universität di Genova, Dipartimento di Fisica e INFN, I-16146 Genova, Italy
14 Harvard University, Cambridge, Massachusetts 02138, USA
15 Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany
16 Imperial College London, London, SW7 2AZ, United Kingdom
17 University of Iowa, Iowa City, Iowa 52242, USA
18 Iowa State University, Ames, Iowa 50011-3160, USA
19 Johns Hopkins University, Baltimore, Maryland 21218, USA
20 Universität Karlsruhe, Institut für Experimentelle Kernphysik, D-76021 Karlsruhe, Germany
21 Laboratoire de l’Accélérateur Linéaire, IN2P3-CNRS et Université Paris-Sud 11, Centre Scientifique d’Orsay, B.P. 34, F-91898 ORSAY Cedex, France
22 Lawrence Livermore National Laboratory, Livermore, California 94550, USA
23 Queen Mary, University of London, E1 4NS, United Kingdom
24 University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom
25 McGill University, Montréal, Québec, Canada H3A 2T8
26 Università di Milano, Dipartimento di Fisica e INFN, I-20133 Milano, Italy
27 University of Mississippi, University, Mississippi 38677, USA
28 Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7
29 Mount Holyoke College, South Hadley, Massachusetts 01075, USA
30 Università di Napoli Federico II, Dipartimento di Scienze Fisiche e INFN, I-80126, Napoli, Italy
31 NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands
32 Ohio State University, Columbus, Ohio 43210, USA
33 University of Oregon, Eugene, Oregon 97403, USA
34 Università di Padova, Dipartimento di Fisica e INFN, I-35131 Padova, Italy
35 Université Paris VI et VII, Laboratoire de Physique Nucléaire et de Hautes Energies, F-75252 Paris, France
36 University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
37 Università di Perugia, Dipartimento di Fisica e INFN, I-06100 Perugia, Italy
38 Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore e INFN, I-56127 Pisa, Italy
39 Prairie View A&M University, Prairie View, Texas 77446, USA
40 Princeton University, Princeton, New Jersey 08544, USA
41 University of Roma La Sapienza, Dipartimento di Fisica e INFN, I-00185 Roma, Italy
42 Universitäts Rostock, D-18051 Rostock, Germany
43 Durham University, Durham, Durham DH1 3LE, United Kingdom
44 University of South Carolina, Columbia, South Carolina 29208, USA
45 Stanford Linear Accelerator Center, Stanford, California 94309, USA
46 Stanford University, Stanford, California 94305-4060, USA
47 State University of New York, Albany, New York 12222, USA
48 University of Texas at Austin, Austin, Texas 78712, USA
49 University of Texas at Dallas, Richardson, Texas 75083, USA
50 University of Wisconsin, Madison, Wisconsin 53706, USA
51 Yale University, New Haven, Connecticut 06511, USA
We present a measurement of the cross section of the process $e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$ from threshold up to 8 GeV center-of-mass energy using events containing initial-state radiation, produced at the PEP-II $e^+e^-$ storage rings. The study is based on 298 fb$^{-1}$ of data recorded with the BABAR detector. A structure is observed in the cross-section not far above threshold, near 4.32 GeV. We also investigate the compatibility of this structure with the $Y(4260)$ previously reported by this experiment.

PACS numbers: 14.40.Gx, 13.25.Gv, 13.66.Bc

Until recently, charmonium spectroscopy has been well described by potential models. Observations of the $X(3872)$ [1] and the $Y(4260)$ [2] decaying into $\pi^+\pi^- J/\psi$ complicate this picture, and have stimulated both experimental and theoretical interest in this area. The $Y(4260)$ can be produced by direct $e^+e^-$ annihilation and is therefore known to have $J^{PC} = 1^{--}$. Weak evidence for the $Y(4260)$ structure in $B$ decays was also reported by BaBar [3]. In addition, the $Y(4260)$ has been confirmed by the CLEO-c experiment in direct $e^+e^- \rightarrow Y(4260)$ interactions where the $Y(4260)$ is detected in decays to $\pi^+\pi^- J/\psi$ and $\pi^0\pi^0 J/\psi$ [4]; the observation of the latter mode and the measured ratio $B(Y(4260) \rightarrow \pi^0\pi^0 J/\psi)/B(Y(4260) \rightarrow \pi^+\pi^- J/\psi) \approx 0.5$ implies that the $Y(4260)$ has isospin zero, as expected for a charmonium state.

It is peculiar that the $Y(4260)$ is wide and yet has a large branching fraction into the charm quark-antiquark gluon hybrids [5] and hadronic molecules [6]. We undertook this study with the intent of clarifying the nature of the $Y(4260)$.

In this Letter we study the process $e^+e^- \rightarrow \pi^+\pi^- \psi(2S)$, $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$, for $e^+e^-$ center-of-mass (CM) energies from threshold up to 8 GeV using initial-state radiation (ISR) events. The ISR cross section for a particular hadronic final state $f$ is given by

$$\frac{d\sigma_f(s,x)}{dx} = W(s,x) \cdot \sigma_f(s(1-x)),$$

where $s$ is the square of the $e^+e^-$ CM energy, $x \equiv 2E_e/\sqrt{s}$ is the ratio of the photon energy to the beam energy in the $e^+e^-$ CM frame, and $W(s,x)$ is the spectrum for ISR photon emission for which we use a calculation good to $O(a^2)$; the effective CM energy $\sqrt{s'}$ is the invariant mass of the final state $m = \sqrt{s(1-x)}$.

We use data recorded with the BaBar detector [7] at the PEP-II asymmetric-energy $e^+e^-$ storage rings, located at the Stanford Linear Accelerator Center. These data represent an integrated luminosity of $272 \text{ fb}^{-1}$ recorded at $\sqrt{s} = 10.58$ GeV, near the $T(4S)$ resonance, and $26 \text{ fb}^{-1}$ recorded near $10.54$ GeV.

Charged-particle momenta are measured in a tracking system consisting of a five-layer double-sided silicon vertex tracker (SVT) and a 40-layer central drift chamber (DCH), both situated in a 1.5-T axial magnetic field. An internally reflecting ring-imaging Cherenkov detector (DIRC) provides charged-particle identification. A CsI(Tl) electromagnetic calorimeter (EMC) is used to detect and identify photons and electrons, while muons are identified in the instrumented magnetic-flux return system (IFR).

Optimized selection criteria are chosen based on a simulated sample of $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^-\psi(2S)$ events and a sample of $e^+e^- \rightarrow \gamma_{ISR}\psi(2S)$, $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$ candidates in data, which serves as a clean control sample [8]. A candidate $J/\psi$ meson is reconstructed via its decay to $e^+e^-$ or $\mu^+\mu^-$. The lepton tracks must be well reconstructed, and at least one must be identified as an electron or a muon candidate. An algorithm to recover energy lost to bremsstrahlung is applied to electron candidates. An $e^+e^-$ pair with its invariant mass within the interval of $(100,40)$ MeV/$c^2$ of the nominal $J/\psi$ mass is taken as a $J/\psi$ candidate. For a $\mu^+\mu^-$ pair, the interval is $(60,40)$ MeV/$c^2$. The $J/\psi$ candidate is then kinematically constrained to the nominal $J/\psi$ mass and combined with a pair of oppositely-charged tracks identified as pion candidates. The $\pi^+\pi^- J/\psi$ combinations with invariant mass within 10 MeV/$c^2$ of the nominal $\psi(2S)$ mass are taken as $\psi(2S)$ candidates. Another pair of oppositely-charged pion candidates (primary pions) is then combined with the $\psi(2S)$ candidate. The $\pi^+\pi^- \psi(2S)$ mass-resolution function is well described by a Cauchy distribution [9] with a FWHM of about 7 MeV/$c^2$. We do not require observation of the ISR photon ($\gamma_{ISR}$) as it is preferentially produced along the beam directions.

We select $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^-\psi(2S)$ events with the following criteria: (1) there must be no additional well-reconstructed charged tracks in the event; (2) there must be no well-reconstructed $\pi^0$ or $\eta \rightarrow \gamma\gamma$ in the event; (3) the transverse component of the visible momentum in the $e^+e^-$ CM frame, including that of the $\gamma_{ISR}$ when it is reconstructed, must be less than 2 GeV/$c$; (4) the difference $(\Delta p^*)$ between the measured $\pi^+\pi^-\psi(2S)$ momentum and the value expected for it in an ISR $\pi^+\pi^-\psi(2S)$ event, that is, $(s - m^2)/(2\sqrt{s})$, where $m$ is the $\pi^+\pi^-\psi(2S)$ invariant mass, must be within $[-0.10,0.06]$ GeV/$c$; (5) $\cos \theta_{\ell}$, where $\theta_{\ell}$ is the angle between the lepton $\ell^+$ momentum in the $J/\psi$ rest frame and the $J/\psi$ momentum
in the $e^+e^-$ CM frame, must satisfy $|\cos\theta_i| < 0.90$; and (6) the invariant mass of the $\pi^+\pi^-$ pair in $\psi(2S)$ decay must be greater than 0.4 GeV/$c^2$ in order to suppress the combinatorial $\pi^+\pi^- J/\psi$ background.

A clean $\psi(2S)$ signal is apparent in Fig. 1. An examination of the $\pi^+\pi^-\psi(2S)$ combinations reveals that about half the background results from recombinations within the same $2(\pi^+\pi^-) J/\psi$ system where at least one of the primary pions is combined with the $J/\psi$ to form a $\pi^+\pi^- J/\psi$ candidate. After subtracting the self-combinatorial background, we estimate $3.8 \pm 1.1$ non-$\psi(2S)$ background events in the final sample of 78 events within the $\psi(2S)$ mass window.

![FIG. 1: The invariant mass distribution for all $\pi^+\pi^- J/\psi$ candidates where more than one entry per event is allowed. The solid curve is a fit to the distribution in which the $\psi(2S)$ signal is described by a Cauchy function and the background by a quadratic function (represented by the dashed curve). The arrows indicate the $\psi(2S)$ mass window.](image)

In Fig. 2 the distributions of (a) $\Delta p^*$ and (b) $\cos\theta^*$ for $2(\pi^+\pi^-) J/\psi$ candidates, where $\theta^*$ is the angle between the positron beam and the $(\pi^+\pi^-\pi^+\pi^-) J/\psi$ momentum in the $e^+e^-$ CM frame, are shown and compared to expectations from simulations. There are 16 events that have a well reconstructed gamma with energy greater than 3 GeV, while the Monte Carlo simulation predicts 16.4 for the same total number of ISR $\pi^+\pi^- J/\psi(2S)$ candidates. Furthermore, all events within $|\cos\theta^*| < 0.9$ are accompanied by a reconstructed gamma with energy greater than 3.0 GeV. We find excellent agreement in the ISR characteristics between the data and signal Monte Carlo sample. The good agreement in the $\Delta p^*$ distribution rules out any significant feeddown from higher mass charmonia decaying to the $\psi(2S)$ with one or more undetected particles. As an example, the $\Delta p^*$ distribution for $\psi(4145) \rightarrow \pi^+\pi^- J/\psi(2S)$ events would peak around $-0.2$ GeV/$c$ with a long tail extending to well below $-0.2$ GeV/$c$. We estimate the non-ISRB $\pi^+\pi^- J/\psi(2S)$ background to be less than 1 event.

The track quality, particle identification information, and kinematic variables of all pion candidates are examined, and displays of the events are scanned visually to check for possible track duplications and other potential problems. No evidence for improper reconstruction or event quality problems is found.

The $2(\pi^+\pi^-) J/\psi$ invariant-mass spectrum up to 5.7 GeV/$c^2$ for the final sample is represented as data points in Fig. 3. A structure around 4.32 GeV/$c^2$ is observed in the mass spectrum.

To clarify the peaking structure observed in Fig. 3, we perform an unbinned maximum likelihood fit to the mass spectrum up to 5.7 GeV/$c^2$ in terms of a single resonance with the following probability density function (PDF):

$$P(m) = N \cdot \varepsilon(m) \cdot \left( \frac{W(s,x) \cdot 2m/s}{(W(s,x) \cdot 2m/s)^2 + (\frac{M \cdot \Gamma_{tot}(s,x)}{2m^2})^2} \right)$$

$$+ B(m),$$

where $M$, $\Gamma_{tot}$, $\Gamma_{ee}$, $\Gamma_f$, $N$ are the nominal mass, total width, partial width to $e^+e^-$, partial width to $\pi^+\pi^- J/\psi(2S)$, and yield for a resonance, respectively, and $m$ is the $2(\pi^+\pi^-) J/\psi$ invariant mass, $\varepsilon(m)$ is the mass-dependent efficiency, $\Phi(m)$ is the mass-dependent phase-space factor for a $S$-wave three-body $\pi^+\pi^- J/\psi(2S)$ system, $a$ is a normalization factor, and $B(m)$ is the PDF (the shaded histogram in Fig. 3) for the non-$\psi(2S)$ background. The shape of $B$ was obtained from $\psi(2S)$ sideband events with its integral fixed to 3.1 events corresponding to the mass region in the fit, where the total number of events is 68. The mass dependence of $\Gamma_{tot}$ is ignored in the fit.

We perform fits to the distribution in Fig. 3 to test hypotheses that the data are a result of the decay of the $Y(4260)$ (dashed curve) using resonance parameters fixed to those of Ref [2], and alternatively those of the $\psi(4415)$ (not shown) with the mass and width taken from Ref [10]. In the third fit (solid curve) we assume a single resonance whose mass and width are free parameters, which are then found to be $(4324 \pm 24)$ MeV/$c^2$ and $(172 \pm 33)$ MeV (after unfolding mass-resolution) by the fit. We calculate the $\chi^2$/dof value for each fit to test these hypotheses. In the calculation the events in Fig. 3 are regrouped so that at least seven events are expected in each
FIG. 5: The $2(\pi^+\pi^-)J/\psi$ invariant mass spectrum up to 5.7 GeV/$c^2$ for the final sample. The shaded histogram represents the fixed background and the curves represent the fits to the data (see text).

We extract the energy-dependent cross section for $e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$ up to 8 GeV for the final sample. The average cross section over a mass range of width $\Delta m$ is calculated as

$$\overline{\sigma}(m) \equiv \int_{m-\Delta m/2}^{m+\Delta m/2} \sigma(x) \, dx / \Delta m$$

$$\approx \frac{1}{\mathcal{L} \cdot B \cdot \Delta m} \sum_i \left( \frac{1}{2m_i/s \cdot W(s, 1 - m_i^2/s) \cdot \varepsilon_i} \right),$$

where $\mathcal{L}$ is the integrated luminosity, $B$ is the product of $B(\psi(2S) \rightarrow \pi^+\pi^-J/\psi)$ and $B(J/\psi \rightarrow \ell^+\ell^-)$, the sum is over all events within the mass range, $m_i$ is the $2(\pi^+\pi^-)J/\psi$ invariant mass, and $\varepsilon_i$ is the estimated efficiency at that mass. The measured cross section is shown in Fig. 5 and the numerical results can be found in [11], where the background has been subtracted from bins with non-zero content. The energy-dependent selection efficiency (solid histogram in Fig. 5) is determined from Monte Carlo events for which the $\psi(2S)$ polarization has been properly considered while the primary $\pi^+\pi^-$ is generated in $S$-wave phase-space. The uncertainty in the selection efficiency due to model dependence is estimated from the efficiency difference between $S$-wave phase-space model and multipole model [12] in the primary $\pi^+\pi^-$ generation. The main systematic uncertainties are listed in Table I, and are added in quadrature, resulting in a total systematic uncertainty of 12.3%.

In summary, we have used ISR events to study the exclusive process $e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$ and to measure its energy-dependent cross section from threshold to 8 GeV CM energy. A structure is observed at $\sim 4.32$ GeV/$c^2$ in the $\pi^+\pi^-\psi(2S)$ invariant mass spectrum that is not consistent with the decay $\psi(4115) \rightarrow \pi^+\pi^-\psi(2S)$. A fit to the mass spectrum with a single resonance yields a mass of $(4324 \pm 24)$ MeV/$c^2$ and a width of $(172 \pm 33)$ MeV,
FIG. 5: The measured CM energy dependence of the cross section (points with error bars) for $e^+e^-\rightarrow \pi^+\pi^-\psi(2S)$ after background subtraction. The solid histogram shows the energy-dependent selection efficiency.

TABLE I: Summary of main systematic uncertainties for the $e^+e^-\rightarrow \pi^+\pi^-\psi(2S)$ cross section measurements.

<table>
<thead>
<tr>
<th>Source</th>
<th>Systematic error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model-dependent acceptance</td>
<td>±9.0%</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>±7.6%</td>
</tr>
<tr>
<td>$B(\psi(2S)\rightarrow \pi^+\pi^- \Lambda(1S)) \cdot B(\Lambda(1S)\rightarrow e^+e^-)$</td>
<td>±3.5%</td>
</tr>
<tr>
<td>Total</td>
<td>±12.3%</td>
</tr>
</tbody>
</table>

where the errors are statistical only. The structure in Fig. 3 has a mass that differs somewhat from that reported for the $Y(4260)$ in Ref. [2]. However, the possibility that it represents evidence for a new decay mode for the $Y(4260)$ cannot be ruled out at this time.

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support BABAR. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), IHEP (China), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MIST (Russia), and PPARC (United Kingdom). Individuals have received support from the Marie Curie EIF (European Union) and the A. P. Sloan Foundation.

* Also at Laboratoire de Physique Corpusculaire, Clermont-Ferrand, France
† Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy
‡ Also with Università della Basilicata, Potenza, Italy
[11] See EPAPS Document No. E-PRLTA0-98-016722 for a supplementary table, corresponding to Fig. 5 in the Letter, which is a numerical representation of the cross section for $e^+e^-\rightarrow \pi^+\pi^-\psi(2S)$ at different center-of-mass energies using ISR events. For more information on EPAPS, see http://www.aip.org/pubservs/epaps.html.