

# Quarkonium studies at *BABAR*

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We present a selection of the latest measurements in quarkonium physics at *BABAR*: the observation of  $X(3872) \rightarrow \omega J/\psi$  decays, the confirmation of the  $\chi_{c2}(2P)$  state in two-photon fusion, and the study of  $\Upsilon(1^3D_J)$  states produced in  $\Upsilon(3S)$  decays.

## 1. INTRODUCTION

Several newly discovered charmonium-like states above the open-charm threshold are not easily accommodated within the phenomenological model describing the bound state of the charm and anti-charm quark system [1]. If not experimental artifacts, these new states could be an indication of *exotic* states, such as tetraquarks (tightly bound four-quark states) [2], molecules (loosely bound states of two mesons) [3], hybrids ( $c\bar{c}g$  states with excited gluonic degrees of freedom) [4], or hadro-charmonium (a charmonium resonance bound inside an excited state of light hadronic matter) [5]. Kinematic thresholds for decays to pairs of charm mesons can lead to resonance-like enhancements, whose interplay with a nearby  $c\bar{c}$  state may shift its mass [6].

The interest in bottomonium spectroscopy has recently been renewed by the accumulation by *BABAR* of record samples at center of mass energies corresponding to the  $\Upsilon(3S)$  and  $\Upsilon(2S)$  resonances. The bottomonium spectrum is far less known than charmonium, and several predicted states below the open-flavor threshold still await an unambiguous experimental verification.

## 2. OBSERVATION OF $X(3872) \rightarrow \omega J/\psi$

The currently best established exotic candidate is the  $X(3872)$ . The large variety of proposed interpretations calls for a thorough study of its decay modes and spin-parity ( $J^P$ ) assignment.

A hint of the  $X(3872)$  decays to the  $J/\psi \pi^+ \pi^- \pi^0$  final state has been found by Belle

in  $B \rightarrow K J/\psi \pi^+ \pi^- \pi^0$  decays, with  $256 \text{ fb}^{-1}$ , as an enhancement between 750 and 775  $\text{MeV}/c^2$  in the spectrum of the invariant mass  $m_{3\pi}$  of the three pions recoiling against the  $J/\psi$  [7]. *BABAR* previously analyzed this final state using  $348 \text{ fb}^{-1}$  to study the  $Y(3940)$  state [8]. The analysis reported no evidence of  $X(3872) \rightarrow \omega J/\psi$ , with the  $\omega \rightarrow \pi^+ \pi^- \pi^0$  mass region defined as  $[0.7695, 0.7965] \text{ GeV}/c^2$  [8].

The updated *BABAR* analysis [9] we present here, based on the full sample ( $\sim 426 \text{ fb}^{-1}$ ), assumes a broader  $m_{3\pi}$  region  $[0.5, 0.9] \text{ GeV}/c^2$  around the  $\omega$ . The discrimination of the  $B$  meson signal from the background is achieved by means of a selection on the energy difference  $\Delta E = E_B^* - \sqrt{s}/2$ , and the beam-energy substituted mass  $m_{ES} = \sqrt{s/4 - |\vec{p}_B^*|^2}$ , where  $(E_B^*, \vec{p}_B^*)$  is the  $B$  meson four-momentum vector in the CM frame, and  $\sqrt{s}$  is the CM energy. In each event, the candidate with the smallest  $|\Delta E|$  is chosen.

The background-subtracted  $m_{3\pi}$  and  $J/\psi 3\pi$  invariant mass ( $m_{J/\psi 3\pi}$ ) distributions are obtained by extracting the signal fraction from a fit to  $m_{ES}$  in each bin. The fit comprises a Gaussian and a phase-space motivated ARGUS distribution, for signal and background respectively. The parameters for the Gaussian and the ARGUS function are obtained from a fit to  $m_{ES}$  for all selected events (separately for  $B^0$  and  $B^\pm$ ).

The  $m_{J/\psi 3\pi}$  distribution after background subtraction shows two peaking structures (corresponding to the  $Y(3940)$  and  $X(3872)$ ) over a nonresonant component. The  $X(3872)$  signal is observed with a statistical significance of  $4.0\sigma$ . The extracted mass  $3873.0^{+1.8}_{-1.6}(\text{stat.}) \pm$

1.3(syst.) MeV/ $c^2$  is consistent with the  $X(3872)$ .

In the  $\omega$  region, the signal  $m_{3\pi}$  distribution extends from 0.74 GeV/ $c^2$  to 0.80 GeV/ $c^2$ . In order to justify the  $\omega$  meson interpretation, we project away non- $\omega$  events by applying an  $\omega$ -Dalitz-plot weight  $\frac{5}{2}(1 - 3\cos^2\theta_h)$  to each event, where  $\theta_h$  is the angle between the  $\pi^+$  and the  $\pi^0$  directions in the  $\pi^+\pi^-$  rest frame. The sum of weights for the  $B^\pm$  events in the  $3.8425 < m_{J/\psi 3\pi} < 3.8925$  GeV/ $c^2$  region is  $41 \pm 13$  and is consistent with the number resulting from the  $m_{ES}$  fit ( $42.4^{+7.8}_{-7.2}$ ), thus establishing a clear correlation between the  $B$ -signal and the  $\omega$  signal.

As shown by the analysis of the mass and angular distributions in  $X(3872) \rightarrow \pi^+\pi^-J/\psi$  decays by CDF [10], the  $X(3872)$  can be  $J^P = 1^+$  or  $2^-$ , so that the  $\omega J/\psi$  system can be either in a  $S$ -wave (if  $J^P = 1^+$ ) or  $P$ -wave (if  $J^P = 2^-$ ) state. In the latter case, one unit of angular momentum introduces a centrifugal barrier factor  $q^2/(1 + R^2q^2)$  (with Blatt-Weisskopf radius  $R = 3$  GeV $^{-1}$ ) that suppresses the  $m_{3\pi}$  spectrum near the upper kinematic limit. The  $\omega$  lineshape is therefore sensitive to the  $J^P$  assignment. A  $\chi^2$  test between the combined  $B^\pm$  and  $B^0$  data and the MC  $m_{3\pi}$  distributions in the  $S$ - and  $P$ -wave hypotheses favors the  $P$ -wave description ( $P(\chi^2) = 61.9\%$ ) against the  $S$ -wave one ( $P(\chi^2) = 7.1\%$ ), although the latter is not ruled out.

### 3. CONFIRMATION OF THE $\chi_{c2}(2P)$

Several charmonium-like states have been observed in the mass region around 3940 MeV/ $c^2$  in different decay final states and production processes. Belle discovered the  $Z(3930)$  resonance in  $\gamma\gamma$  production of the  $D\bar{D}$  system with  $395\text{ fb}^{-1}$  integrated luminosity and interpreted it as the  $\chi_{c2}(2P)$  charmonium state [11].

With  $384\text{ fb}^{-1}$  data, BABAR has reconstructed the  $\gamma\gamma \rightarrow D\bar{D}$  reaction in several exclusive final states with at most one  $\pi^0$  and less than seven charged particles [12]. The  $D$  mesons are reconstructed in the  $D^0 \rightarrow K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-$  and  $D^+ \rightarrow K^-\pi^+\pi^+$  decay modes, and different  $D$  mass windows are used for different channels.

Only positive  $C$ -parity states can result from

$\gamma\gamma$  interaction, where the interacting virtual photons are emitted by the two incoming leptons. The analysis is performed in the “no tag” mode, meaning that the outgoing leptons are not detected. Since the photons are predominantly emitted along the beampipe, they are almost on-shell, and the Yang-Landau theorem [13] forbids  $J = 1$  states from being produced.

The  $e^+e^- \rightarrow K^+K^-\pi^+\pi^-X$  events, where  $X$  contains no additional charged particles and the  $K^+K^-\pi^+\pi^-$  invariant mass is below the region of interest, are studied to establish the selection criteria. Since the scattered electrons have high momentum and small angles with respect to the beam, two-photon production of the final state  $f$  is characterized by large values of the missing mass squared  $m_{\text{miss}}^2 \equiv (p_{e^+} + p_{e^-} - \sum_{i \in f} p_i)^2$ , small transverse momentum  $p_t(D\bar{D})$  and, as only the outgoing  $e^+$  and  $e^-$  are undetected, small total energy deposits  $E_{EMC}$  in the calorimeter that are unmatched to any charged-particle track. The three main selection criteria  $m_{\text{miss}}^2 > 10 (\text{GeV}/c^2)^2$ ,  $p_t(D\bar{D}) < 50 \text{ MeV}/c$ ,  $E_{EMC} < 400 \text{ MeV}$  significantly enhance  $\gamma\gamma$ -production events over ISR, continuum events, and combinatorial background. A clear structure around 3.93 GeV/ $c^2$  emerges in the combined  $D\bar{D}$  invariant mass ( $m(D\bar{D})$ ) distribution.

The contribution to the  $D\bar{D}$  mass spectrum due to  $D$  candidates from combinatorial background is estimated using sidebands in the two-dimensional space spanned by the invariant masses of the  $D$  and  $\bar{D}$  candidates. Furthermore the study of the  $p_t(D\bar{D})$  distribution previous to the  $p_t$  selection shows that the  $D\bar{D}$  candidates in the signal region ( $3.91 < m(D\bar{D}) < 3.95 \text{ GeV}/c^2$ ) are for the most part due to  $\gamma\gamma$  events.

The reconstruction efficiency  $\epsilon_i(m(D\bar{D}))$  for each final state  $i$  is evaluated using MC events as a function of  $m(D\bar{D})$ , and includes the product branching fraction  $\mathcal{B}_i$  for the  $i$ th  $D\bar{D}$  channel. A mean efficiency  $\bar{\epsilon}(m(D\bar{D}))$  is obtained as the average of the efficiencies for each channel, weighted by the number of  $D\bar{D}$  candidates in the data mass spectrum for each decay mode.

The signal contribution is extracted from an unbinned maximum likelihood fit to the  $m(D\bar{D})$

distribution, corrected event-by-event for the mean efficiency  $\bar{\epsilon}(m(D\bar{D}))$ . The fit includes a threshold function for the background and a relativistic Breit-Wigner to model the signal structure around  $3.93 \text{ GeV}/c^2$ . The signal lineshape includes centrifugal barrier factors (we assume spin  $J = 2$  for the resonance in the nominal fit), and is convolved with a mass- and decay-mode-dependent resolution model. A significance of  $5.8\sigma$  is obtained for a resonance with a mass  $3926.7 \pm 2.7(\text{stat.}) \pm 1.1(\text{syst.}) \text{ MeV}/c^2$  and a total width  $21.3 \pm 6.8(\text{stat.}) \pm 3.6(\text{syst.}) \text{ MeV}$ , consistent with the previous observation by Belle.

The  $Z(3930)$   $J^{PC}$  assignment is derived from the study of the decay distribution in the angle  $\theta$ , defined as the angle of the  $D$  meson in the  $D\bar{D}$  system relative to the  $D\bar{D}$  laboratory momentum vector. The efficiency-corrected, background-subtracted  $|\cos\theta|$  distribution in the  $Z(3930)$  signal region is obtained by extracting the signal yield from fits to the  $m(D\bar{D})$  spectrum for ten regions of  $|\cos\theta|$ , after weighting each event by a  $\cos\theta$ -dependent efficiency. Parity and  $C$ -parity conservation for the production and decay mechanisms restricts the possible  $J^{PC}$  assignments to  $L^{++}$ , where the orbital angular momentum  $L$  is even. Only the  $J = 0$  and  $J = 2$  hypotheses are compared to data, as higher spin values are expected to be unlikely because of the small available phase space for the decay. The data favor the  $J^{PC} = 2^{++}$  assignment, consistent with the results by Belle and with the predictions for the  $\chi_{c2}(2P)$  state.

#### 4. STUDY OF $\Upsilon(1^3D_J) \rightarrow \pi^+\pi^-\Upsilon(1S)$

Evidence for the  $\Upsilon(1^3D_J)$  states was first obtained by CLEO in the  $\Upsilon(1^3D_J) \rightarrow \gamma\gamma\Upsilon(1S)$  decay channel, where the  $\Upsilon(1^3D_J)$  is produced through the  $\Upsilon(3S) \rightarrow \gamma\chi_{bJ'} \rightarrow \gamma\gamma\Upsilon(1^3D_J)$  decay chain [14]. CLEO observed a single state at a mass of  $10161.1 \pm 0.6(\text{stat.}) \pm 1.6(\text{syst.}) \text{ MeV}/c^2$  and interpreted it as the  $J = 2$  member of the  $\Upsilon(1^3D_J)$  triplet. The quantum numbers  $J$ ,  $L$  and  $P$  were not verified, and the  $J = 1, 3$  states remained unobserved.

The study of the  $\Upsilon(1^3D_J) \rightarrow \pi^+\pi^-\Upsilon(1S)$  decays may allow to separate the members of the

triplet thanks to the very good  $\Upsilon(1^3D_J)$  mass resolution ( $3 \text{ MeV}/c^2$ ). Furthermore, the  $\pi^+\pi^-$  mass and angular distributions convey relevant information for the  $J^P$  and  $L$  assignment. Theoretical predictions for the branching fraction  $\mathcal{B}$  of these decays span two orders of magnitude, from 0.2% to 40% [15–17], while an experimental upper limit (UL) at 90% confidence level (CL) by CLEO exists,  $\mathcal{B} < 4\%$  [14].

BABAR has searched for the  $\Upsilon(1^3D_J)$  in a sample of  $122 \times 10^6$   $\Upsilon(3S)$  decays [18]. The final state is exclusively reconstructed in the full decay chain. Exactly four charged particles are required in each event, corresponding to two pions from the  $\Upsilon(1^3D_J) \rightarrow \pi^+\pi^-\Upsilon(1S)$  transition and two leptons ( $\ell = e, \mu$ ) from the  $\Upsilon(1S)$  decay. Two photons with energy  $E_{\gamma_1} \in [86, 122] \text{ MeV}$  and  $E_{\gamma_2} \in [80, 117] \text{ MeV}$  are combined with the  $\Upsilon(1^3D_J)$  candidate to yield a  $\Upsilon(3S)$ . Each pair of photons can be combined in up to six ways, corresponding to the decay paths allowed by angular momentum conservation. Whenever multiple photon combinations are present, the one that minimizes  $\chi^2 = \sum_{i=1}^2 (E_{\gamma_i} - E_{\gamma_i}^{(exp)})^2 / \sigma_{E_i}^2$  is chosen, where  $\sigma_{E_i} \approx 7 \text{ MeV}$  is the measured resolution and  $E_{\gamma_i}^{(exp)}$  is the expected photon energy for one of the transition paths (results do not depend on the choice of  $E_{\gamma_i}^{(exp)}$  within a wide range).

Efficiencies are estimated from MC samples in which the photon transitions are simulated according to the detailed angular distributions, calculated under the assumption of pure electric dipole (E1) transitions. The difference in efficiency due to different photon combinations can be as large as 7.5%. Efficiencies are calculated for the predicted dominant decay paths, and a systematic uncertainty is introduced.

Signal yields and masses are extracted from an unbinned maximum likelihood fit to the  $\pi^+\pi^-\ell^+\ell^-$  invariant mass  $m_{\pi^+\pi^-\ell^+\ell^-}$  in the interval  $[10.11, 10.28] \text{ GeV}/c^2$ , including the three  $J = 1, 2, 3$  signal components, and several background components, among which the main ones are the decays  $\Upsilon(3S) \rightarrow \gamma\chi_{bJ'}(2P)$ , with  $\chi_{bJ'}(2P) \rightarrow \omega_{\pi^+\pi^-}\Upsilon(1S)$ , and  $\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$  with final state radiation. The  $\Upsilon(3S) \rightarrow \gamma\gamma\Upsilon(2S) \rightarrow \gamma\gamma\pi^+\pi^-\Upsilon(1S)$  decay chain

Table 1

Results of the fit to the  $\pi^+\pi^-\ell^+\ell^-$  invariant mass spectrum in [18].

$\Upsilon(1^3D_J)$	Mass (MeV/ $c^2$ )	Event yield	Sign. ( $\sigma$ )	$\mathcal{B}$ (%)	90% $CL$ UL (%)
$J = 1$	$10151.6^{+1.3}_{-1.4} \pm 0.5$	$10.6^{+5.7}_{-4.9}$	1.8	$0.42^{+0.27}_{-0.23} \pm 0.10$	$< 0.82$
$J = 2$	$10164.5 \pm 0.8 \pm 0.5$	$33.9^{+8.2}_{-7.5}$	5.8	$0.66^{+0.15}_{-0.14} \pm 0.06$	
$J = 3$	$10172.9 \pm 1.7 \pm 0.5$	$9.4^{+6.2}_{-5.2}$	1.6	$0.29^{+0.22}_{-0.18} \pm 0.06$	$< 0.62$

serves for mass calibration purposes. Results are displayed in Table 1.

The  $\pi^+\pi^-$  mass distribution in the  $\Upsilon(1^3D_J)$  signal region ( $[10.140, 10.178]$  GeV/ $c^2$ ) is compared, after background subtraction and efficiency correction, to the expectations [19,20] for the decay of a  $D$  ( $P(\chi^2) = 84.6\%$ ),  $S$  (3.1%), or  $^1P_1$  (0.3%) bottomonium state to  $\pi^+\pi^-\Upsilon(1S)$  and strongly favors the  $D$  hypothesis. For the dominant member of the triplet ( $10.155 < m_{\pi^+\pi^-\ell^+\ell^-} < 10.168$  GeV/ $c^2$ ) we analyze the background-subtracted and efficiency-corrected distributions in the angle  $\chi$  between the  $\pi^+\pi^-$  and  $\ell^+\ell^-$  planes, and in the helicity angle  $\theta_\pi$ , where  $\theta_\pi$  is the angle of the  $\pi^+$  in the  $\pi^+\pi^-$  rest frame with respect to the boost from the  $\Upsilon(1^3D_J)$  frame: they are consistent with the  $J = 2$  and  $P = -1$  assignments for a  $D$  state [21].

## 5. CONCLUSIONS

*BABAR* has established a clear evidence for the  $X(3872) \rightarrow \omega J/\psi$  decay. Among conventional charmonium interpretations, a spin-parity analysis of this decay favors the  $\eta_{c2}(1D)$  ( $J^{PC} = 2^{-+}$ ).

*BABAR* observation of  $\gamma\gamma$ -production of the  $Z(3930)$  and the study of the angular distribution of its decay products support Belle's interpretation of this state as the  $\chi_{c2}(2P)$  ( $J^{PC} = 2^{++}$ ).

The  $\Upsilon(1^3D_2)$  state has been observed by *BABAR* in  $\Upsilon(1^3D_J) \rightarrow \pi^+\pi^-\Upsilon(1S)$  decays, and its quantum numbers have been determined for the first time. The measured branching fractions will help resolve decades-old issues in models of dipion transitions among quarkonium states.

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