Quarkonium studies at BABAR

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We present a selection of recent quarkonium measurements at BABAR: the observation of $X(3872) \to J/\psi\,\omega$ decays, the confirmation of the $\chi_{c2}(2P)$ state in $\gamma\gamma$ fusion, and the study of $\Upsilon(1^3D_J)$ states 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]. They 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 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 the BABAR experiment of record samples at center of mass energies corresponding to the $\Upsilon(3S)$ and $\Upsilon(2S)$ resonances. The bottomonium spectrum is less known than charmonium, and several predicted states below the open-flavor threshold still await an unambiguous experimental verification.

2. OBSERVATION OF $X(3872) \to J/\psi\,\omega$

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 $B \to K J/\psi\,\pi^+\pi^-\pi^0$ 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/ψ [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 $X(3872) \to J/\psi\,\omega$, with the $\omega \to \pi^+\pi^-\pi^0$ 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 ω. 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 on 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.

The background-subtracted $m_{3\pi}$ and $J/\psi\,\omega$ invariant mass ($m_{J/\psi\omega}$) 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 of 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 $X(3872)$ signal is observed with a statistical significance of 4.0σ at $3873.0^{+1.8}_{-1.6}(\text{stat.}) \pm 1.3(\text{syst.})\,\text{MeV}/c^2$ (Fig. 1).

In the ω region, the signal $m_{3\pi}$ distribution extends from $0.74\,\text{GeV}/c^2$ to $0.80\,\text{GeV}/c^2$. To justify the ω meson interpretation, we project away non-ω events by applying an ω-Dalitz-plot weight $\frac{5}{2}(1 - 3\cos^2\theta_h)$ to each event, where θ_h is the angle between the π^+ and the π^0 directions in the $\pi^+\pi^-$ rest frame. The sum of weights for the $B^\pm$
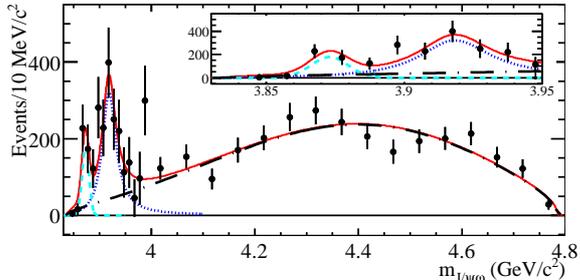
Figure 1. The corrected $m_{J/\psi\,\omega}$ distribution for B^+ decays: the $Y(3940)$ (dotted) and $X(3872)$ (dashed) emerge over a nonresonant component (dash-dotted). Inset: zoom in the signal region.

events in the $3.8425 < m_{J/\psi\,\omega} < 3.8925\,\mathrm{GeV}/c^2$ region (41 ± 13) is consistent with the result of the m_{ES} fit $(42.4^{+7.8}_{-7.2})$, thus establishing a clear correlation between the B-signal and the ω signal.

As shown by the analysis of the mass and angular distributions in $X(3872) \to \pi^+\pi^- J/\psi$ decays by CDF [10], the $X(3872)$ can be $J^P = 1^+$ or 2^-, so that the $J/\psi\,\omega$ 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 $q^2/(1+R^2q^2)$ that suppresses the $m_{3\pi}$ spectrum near the upper kinematic limit. A χ^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 $J^P = 2^-$ $(P(\chi^2) = 61.9\%)$ over $J^P = 1^+$ $(P(\chi^2) = 7.1\%)$, although the latter is not ruled out.

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

Belle discovered the $Z(3930)$ resonance in $\gamma\gamma \to D\bar{D}$ events with $395\,\mathrm{fb}^{-1}$ and interpreted it as the $\chi_{c2}(2P)$ [11]. With $384\,\mathrm{fb}^{-1}$ data, BABAR has reconstructed the $\gamma\gamma \to D\bar{D}$ reaction in final states with at most one π^0 and less than seven charged particles [12], with $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-$ and $D^+ \to K^-\pi^+\pi^+$.

Only positive C-parity states can result from $\gamma\gamma$ interactions, where the interacting virtual photons are emitted by the two incoming lep-

tons. 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 $e^+e^- \to K^+K^-\pi^+\pi^- X$ 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 $D\bar{D}$ production is characterized by large values of the missing mass squared $m^2_{\mathrm{miss}} \equiv (p_{e^+} + p_{e^-} - p_D - p_{\bar{D}})^2$, 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 main selection criteria $m^2_{\mathrm{miss}} > 10\,(\mathrm{GeV}/c^2)^2$, $p_t(D\bar{D}) < 50\,\mathrm{MeV}/c$, $E_{EMC} < 400\,\mathrm{MeV}$ greatly enhance $\gamma\gamma$-production events over ISR, continuum events, and combinatorial background.

The contribution to the combined $D\bar{D}$ invariant mass $(m(D\bar{D}))$ spectrum due to D candidates from combinatorial background is estimated using sidebands in the D and $\bar{D}$ masses. The study of the $p_t(D\bar{D})$ distribution prior to the p_t selection shows that the candidates in the signal region are mostly due to $\gamma\gamma$ events.

The reconstruction efficiency $\epsilon_i(m(D\bar{D}))$, including the product branching fraction, is evaluated using MC events for each final state i. 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 a fit to the $m(D\bar{D})$ distribution (Fig. 2 left), 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 Breit-Wigner to model the signal structure around $3.93\,\mathrm{GeV}/c^2$. The signal lineshape includes centrifugal barrier factors (assuming $J = 2$ in the nominal fit), and is convolved with a mass- and decay-mode-dependent resolution model. A significance of 5.8σ is obtained for a resonance with a mass $3926.7 \pm$
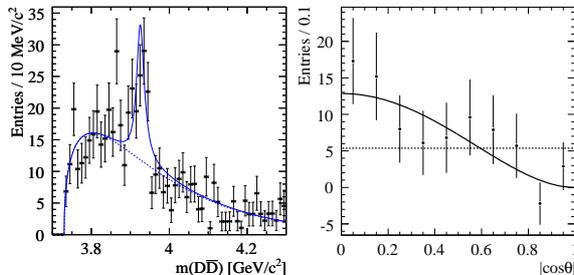
Figure 2. Left: $m(D\bar{D})$ distribution with fit; the dashed curve is the background lineshape. Right: $|\cos\theta|$ distribution in the signal region ($3.91 < m(D\bar{D}) < 3.95\,\text{GeV}/c^2$) compared to the $J = 0$ (dotted line) and $J = 2$ (solid line) hypotheses.

$2.7(\text{stat.}) \pm 1.1(\text{syst.})\,\text{MeV}/c^2$ 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 decay distribution in the angle θ, 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 (Fig. 2 right) 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 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 obtained by CLEO in the $\Upsilon(1^3D_J) \rightarrow \gamma\gamma\Upsilon(1S)$ 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 $10161.1 \pm$

$0.6(\text{stat.}) \pm 1.6(\text{syst.})\,\text{MeV}/c^2$ 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 very good $\Upsilon(1^3D_J)$ mass resolution in the $\Upsilon(1^3D_J) \rightarrow \pi^+\pi^-\Upsilon(1S)$ decays may allow to separate the members of the triplet. 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 range from 0.2% to 40% [15–17], while an experimental upper limit (UL) $\mathcal{B} < 4\%$ at 90% confidence level (CL) exists [14].

$B\textsc{A}B\textsc{AR}$ has searched for the $\Upsilon(1^3D_J)$ in a sample of 122×10^6 $\Upsilon(3S)$ 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 assuming 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 dominant decay paths, and a systematic uncertainty is introduced.

Signal yields and masses are extracted from a 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 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 $\Upsilon(3S) \rightarrow \gamma\gamma\Upsilon(2S) \rightarrow$

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. (σ)	$\mathcal{B}$ (%)	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

$\gamma\gamma\pi^+\pi^-\Upsilon(1S)$ decay chain serves for mass calibration. Results are shown in Table 1.

The $\pi^+\pi^-$ mass distribution in the $\Upsilon(1^3D_J)$ signal region ($[10.140, 10.178]\,\text{GeV}/c^2$) 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 ($10.155 < m_{\pi^+\pi^-\ell^+\ell^-} < 10.168\,\text{GeV}/c^2$) we analyze the background-subtracted and efficiency-corrected distributions in the angle χ between the $\pi^+\pi^-$ and $\ell^+\ell^-$ planes, and in the helicity angle θ_π, where θ_π is the angle of the π^+ 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 $X(3872) \to J/\psi\,\omega$ 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 interpretation of this state as the $\chi_{c2}(2P)$ ($J^{PC} = 2^{++}$).

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

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