Observation of $Y(3940) \rightarrow J/\psi \omega$ in $B \rightarrow J/\psi \omega K$ at BABAR


Submitted to Physical Review Letters

Work supported in part by US Department of Energy contract DE-AC02-76SF00515

E. Di Marco, Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA

L. Vitale, N. Gagliardi, P. F. Harrison, P. F. Harrison, E. Di Marco, Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA

University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1

University of California at San Diego, La Jolla, California 92093, USA

University of California at Riverside, Riverside, California 92521, USA

University of California at San Diego, La Jolla, California 92093, USA

University of California at Santa Barbara, Santa Barbara, California 93106, USA

University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA

California Institute of Technology, Pasadena, California 91125, USA

University of Cincinnati, Cincinnati, Ohio 45221, USA

University of Colorado, Boulder, Colorado 80309, USA

Colorado State University, Fort Collins, Colorado 80523, USA

University of Oregon, Eugene, Oregon 97403, USA

University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA

University of Virginia, Charlottesville, Virginia 22903, USA

University of Washington, Seattle, Washington 98195, USA

University of Wisconsin, Madison, Wisconsin 53706, USA

Washington State University, Pullman, Washington 99164, USA

University of California at Los Angeles, Los Angeles, California 90024, USA

University of California at Riverside, Riverside, California 92521, USA

University of California at San Diego, La Jolla, California 92093, USA

University of California at Santa Barbara, Santa Barbara, California 93106, USA

University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA

California Institute of Technology, Pasadena, California 91125, USA

University of Cincinnati, Cincinnati, Ohio 45221, USA

University of Colorado, Boulder, Colorado 80309, USA

Colorado State University, Fort Collins, Colorado 80523, USA

(The BABAR Collaboration)
Universität Dortmund, Institut für Physik, D-44221 Dortmund, Germany
Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany
Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France
University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy
Laboratori Nazionali di Frascati dell’INFN, I-00044 Frascati, Italy
Università di Genova, Dipartimento di Fisica e INFN, I-16146 Genova, Italy
Harvard University, Cambridge, Massachusetts 02138, USA
Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany
Imperial College London, London, SW7 2AZ, United Kingdom
University of Iowa, Iowa City, Iowa 52242, USA
Iowa State University, Ames, Iowa 50011-3160, USA
Johns Hopkins University, Baltimore, Maryland 21218, USA
Universität Karlsruhe, Institut für Experimentelle Kernphysik, D-76021 Karlsruhe, Germany
Laboratoire de l’Accélérateur Linéaire, IN2P3/CNRS et Université Paris-Sud 11, Centre Scientifique d’Orsay, B. P. 34, F-91898 ORSAY Cedex, France
Lawrence Livermore National Laboratory, Livermore, California 94550, USA
University of Liverpool, Liverpool L69 7ZE, United Kingdom
Queen Mary, University of London, E1 4NS, United Kingdom
University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom
University of Louvain, Louvain-la-Neuve, Brussels, Belgium
University of Manchester, Manchester M13 9PL, United Kingdom
University of Maryland, College Park, Maryland 20742, USA
University of Massachusetts, Amherst, Massachusetts 01003, USA
Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA
McGill University, Montréal, Québec, Canada H3A 2T8
Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy
University of Mississippi, University, Mississippi 38677, USA
Mount Holyoke College, South Hadley, Massachusetts 01075, USA
Università di Napoli Federico II, Dipartimento di Scienze Fisiche e INFN, I-80126 Napoli, Italy
NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands
University of Notre Dame, Notre Dame, Indiana 46556, USA
Ohio State University, Columbus, Ohio 43210, USA
University of Oregon, Eugene, Oregon 97403, USA
Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy
Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6, Université Denis Diderot-Paris7, F-75252 Paris, France
University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
Università di Perugia, Dipartimento di Fisica and INFN, I-06100 Perugia, Italy
Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy
Prairie View A&M University, Prairie View, Texas 77446, USA
Princeton University, Princeton, New Jersey 08544, USA
Università di Roma La Sapienza, Dipartimento di Fisica e INFN, I-00185 Roma, Italy
Universität Rostock, D-18051 Rostock, Germany
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 OQX, United Kingdom
DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France
University of South Carolina, Columbia, South Carolina 29208, USA
Stanford Linear Accelerator Center, Stanford, California 94309, USA
Stanford University, Stanford, California 94305-4060, USA
State University of New York, Albany, New York 12222, USA
University of Tennessee, Knoxville, Tennessee 37996, USA
University of Texas at Austin, Austin, Texas 78712, USA
University of Texas at Dallas, Richardson, Texas 75083, USA
Università di Trieste, Dipartimento di Fisica Sperimentale and INFN, I-34125 Trieste, Italy
IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain
University of Victoria, Victoria, British Columbia, Canada V8W 3P6
Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom
University of Wisconsin, Madison, Wisconsin 53706, USA
Yale University, New Haven, Connecticut 06511, USA
(Dated: November 30, 2007)
We report the results of a study of the decays \( B^+ \to J/\psi \omega K^+ \) and \( B^0 \to J/\psi \omega K_S^0 \) using 383 million \( \bar{B}B \) events from \( T(4S) \) decays with the BABAR detector at the PEP-II asymmetric-energy \( e^+e^- \) storage rings. We observe evidence for \( Y(3940) \to J/\psi \omega \) with a mass above open-charm threshold [2]. Unconventional explanations for the \( J/\psi \omega \) is not readily explained for a particle near zero and \( m_{ES} \) close to the nominal \( B \) mass. In the final sample, 12% of the events have multiple candidates, and in such cases the combination with the smallest \(|\Delta E|\) is selected.

The selection criteria were obtained by optimizing the signal-to-background ratio using Monte Carlo (MC) simulated signal events. \( B \to YK \), \( Y \to J/\psi \omega \), and background \( B\bar{B} \) and continuum \((e^+e^- \to q\bar{q}, q = u, d, s, c)\) events. The \( B \) helicity angle, \( \theta_B \), is the polar angle in the \( B \) momentum vector and the \( e^+e^- \) collision axis. The distribution of \( \cos \theta_B \) for \( T(4S) \to BB \) decay is proportional to \( \sin \theta_B \), whereas continuum background peaks toward \( \pm 1 \), and combinatoric background is flat. The photon helicity angle, \( \theta_\gamma \), is the angle in the \( \pi^0 \) rest frame between the higher momentum photon and the direction of the \( \pi^0 \) in the laboratory frame. For \( \pi^0 \) decay the \( \cos \theta_\gamma \) distribution is flat, whereas background peaks at 1. Events from \( B \to \psi(2S)K^{*0} \), \( \psi(2S) \to \pi^- \pi^+ J/\psi \), are removed by the \( \psi(2S) \) veto.

The \( 3\pi \) invariant mass, \( m_{ES} \), and \( |\Delta E| \) distributions are shown in Fig. 1, where we apply all criteria listed in Table I except that for the variable plotted. The \( 3\pi \) mass distributions are fitted using an \( \omega \)-meson Breit-Wigner (BW) lineshape with nominal \( \omega \) mass and width [15] convolved with a MC-determined triple-Gaussian resolution function as signal, and a quadratic background function. The \( m_{ES} \) distributions are fitted with a signal Gaussian with mass and width fixed from MC, and an ARGUS

TABLE I: Principal criteria used to select \( B \) candidates.

<table>
<thead>
<tr>
<th>Selection Category</th>
<th>Criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>( J/\psi \to \mu^+\mu^- ) mass (GeV/c(^2))</td>
<td>3.06 &lt; ( m_{\mu\mu} ) &lt; 3.14</td>
</tr>
<tr>
<td>( J/\psi \to e^+e^- ) mass (GeV/c(^2))</td>
<td>2.95 &lt; ( m_{ee} ) &lt; 3.14</td>
</tr>
<tr>
<td>Photon helicity angle ( \theta_\gamma )</td>
<td>( \cos \theta_\gamma &lt; 0.95 )</td>
</tr>
<tr>
<td>( \pi^0 ) mass (GeV/c(^2))</td>
<td>0.115 &lt; ( m_{\pi^0} ) &lt; 0.150</td>
</tr>
<tr>
<td>( K_S ) mass (GeV/c(^2))</td>
<td>0.472 &lt; ( m_{K_S} ) &lt; 0.522</td>
</tr>
<tr>
<td>( \psi(2S) ) veto (GeV/c(^2))</td>
<td>3.661 &lt; ( M_{J/\psi}\omega ) &lt; 3.711</td>
</tr>
<tr>
<td>( \omega ) signal region (GeV/c(^2)) ((B^+))</td>
<td>0.7965 &lt; ( m_{\omega} ) &lt; 0.8055</td>
</tr>
<tr>
<td>( \omega ) signal region (GeV/c(^2)) ((B^0))</td>
<td>0.7965 &lt; ( m_{\omega} ) &lt; 0.8055</td>
</tr>
<tr>
<td>( B ) helicity angle ( \theta_B )</td>
<td>(</td>
</tr>
<tr>
<td>( m_{ES} ) (GeV/c(^2))</td>
<td>5.274 &lt; ( m_{ES} ) &lt; 5.284</td>
</tr>
<tr>
<td>( \Delta E ) (GeV) ((B^+))</td>
<td>(</td>
</tr>
<tr>
<td>( \Delta E ) (GeV) ((B^0))</td>
<td>(</td>
</tr>
</tbody>
</table>
background function [17] with slope parameter free. The $\Delta E$ distributions are fitted with a double-Gaussian signal function determined from MC, and a linear background function. The fit results are also shown in Fig. 1.

FIG. 1: The 3π mass, $m_{E_S}$, and $\Delta E$ distributions for the $B^+$ ($B^0$) mode are plotted in (a)-(c) ((d)-(f)). The solid dots are for unweighted events, and the open dots show the effect of the $P_2$ Legendre polynomial $\omega$ projection procedure. The solid (dashed) curves represent signal plus background (background) for the fits described in the text.

There is a large $\omega$-meson signal for the $B^+$ mode, and a smaller signal for $B^0$; the corresponding $m_{E_S}$ and $\Delta E$ distributions exhibit clear $B$ meson signals of relative magnitude similar to that of the $\omega$ signals. The correlation between the $\omega$ and $B$ meson signals is investigated using a projection procedure based on the $\omega$ decay angular distribution. We define the helicity angle, $\theta_h$, as the angle between the $\pi^+$ and $\pi^0$ directions in the $\pi^+\pi^-$ rest frame. The $\cos \theta_h$ distribution is proportional to $\sin^2 \theta_h$, and the $\omega$ signal can be projected in its entirety by giving the $i$th event weight $w_i = \frac{1}{2}(1 - 3 \cos^2 \theta_h) \sim -P_2(\cos \theta_h^o)$, where $P_2$ is the second order Legendre polynomial. If the background distribution contains no $P_2$ component, and the statistical level is sufficient, the weighting procedure causes the background to be zero on average. The results are shown in Fig 1, and for the $B^+$ mode, within the uncertainties, the entire $\omega$ signal survives, and background is removed. For the $B^0$ mode the effect is qualitatively similar, but less clear because of the lower statistics. Confirmation of this behavior is obtained by determining the $\omega$ signal from a fit to the 3π mass distribution in each interval. The results are consistent with those from the weighting procedure. We conclude that there is a one-to-one correspondence between the $\omega$ signal and the $B$-meson signals in $m_{E_S}$ and $\Delta E$, and that, at the present level of statistics, the 3π system in the $\omega$ mass region results entirely from $\omega$ decay for $B \rightarrow J/\psi\pi^+\pi^-\pi^0K$. The $\omega - m_{E_S}$ (or $\Delta E$) signal correlation is important to an analysis of the $J/\psi\omega$ threshold mass region. Near threshold, the 3π mass distribution above the $\omega$ mass is limited in range and distorted in shape, and this makes direct $\omega$ signal extraction unreliable, given the limited statistics. The $m_{E_S}$ distribution is not affected by this problem, and so we use $m_{E_S}$ fits to extract the $J/\psi\omega$ mass distribution. Consistent results are obtained from fits to the $\Delta E$ distributions.

For each $B$ decay mode, after applying all criteria of Table I but that on $m_{E_S}$, the $m_{E_S}$ distribution in each interval of $J/\psi\pi^+\pi^-\pi^0$ invariant mass is fitted to extract the $J/\psi\omega$ signal. The $m_{E_S}$ signal functions and ARGUS background functions are the same as for the $m_{E_S}$ fits in Fig. 1; because of the limited statistics, the fits use a binned Poisson likelihood function with the signal and background normalizations as free parameters [18]. From threshold to $\sim 4$ GeV/c², the $J/\psi\omega$ mass resolution varies from $\sim 5 - 8$ MeV/c², and so in this region the spectrum is investigated in ten 10 MeV/c² intervals starting at 3.8825 GeV/c² in order to search for narrow structures. At higher mass, the resolution degrades to $\sim 10 - 12$ MeV/c². A search in 10 MeV/c² intervals reveals no evidence of structure, and so we present the spectrum in 50 MeV/c² intervals. Overall, satisfactory $m_{E_S}$ fits are obtained. The results are shown in Fig. 2. For $B^+$ decay, there is a clear accumulation of events near threshold, while at higher mass no structure is apparent. For $B^0$ decay, the results are similar, but at a lower statistical level.

We next correct the mass distributions of Fig. 2 for efficiency and resolution. In the MC simulation of the $Y$ signal, we assume phase space decays of $B \rightarrow YK$ and $Y \rightarrow J/\psi\omega$, but use the correct angular distribution for $\omega$ decay. Initially we used a relativistic $S$-wave BW lineshape with $M(Y) = 3.940$ GeV/c² and $\Gamma(Y) = 0.06$ GeV [1]. Mass resolution effects result in a net flow of events away from the peak mass value. For a given mass interval we define acceptance as the ratio of genuine events to events reconstructed in that interval to events generated in the interval; this accounts for efficiency and resolution effects. The spectrum after acceptance correction is fit (as described below) to a relativistic BW lineshape without convolving resolution. We obtain values of $M(Y)$ and $\Gamma(Y)$ which are smaller than in the simulation, and so we generate new MC samples with the smaller values in order to correctly reproduce resolution effects. The acceptance results shown in Figs. 2(c), (d) are obtained using $M(Y) = 3.915$ GeV/c² and $\Gamma(Y) = 0.02$ GeV. The decrease at high mass in Fig. 2(d) is a consequence of $K_S$ acceptance: higher mass values correspond to lower $K_S$ laboratory momentum, and hence increased probability that a decay pion not be reconstructed.
Fig. 3(a) shows the mass distributions after acceptance correction. Up to \( \sim 4 \text{ GeV/c}^2 \) the correction is done interval-by-interval, while for higher mass the acceptance is taken from a linear fit to its \( J/\psi \omega \) mass dependence. The \( B^0 \) data are corrected for \( K^0_L \) and \( K^0_S \to \pi^0 \pi^0 \) decays in order to compare directly to Fig. 3(a).

We associate the near-threshold enhancement in Fig. 3(a) with \( Y \) production [1], and obtain the mass, width and decay rate from \( \chi^2 \) fits. The corrected \( B^+ \) and \( B^0 \) distributions are fitted simultaneously, with mass, width and Gaussian parameters as common free parameters. The fit describes the data well \( (\chi^2/NDF = 36.2/42) \), as shown in Fig. 3.

Systematic errors are estimated by repeating the entire process, separately varying by \( \pm 1\sigma \) the signal peak and width, and the ARGUS parameter, for the \( m_{ES} \) fits. The largest systematic uncertainty contributions to the \( B^+ \) branching fraction are 5–6% due to the uncertainties in the secondary branching fractions, tracking efficiency, and particle identification. For \( B^0 \), the largest systematic contribution is 10% due to the \( m_{ES} \) mass variation; secondary branching fractions, particle identification, tracking and \( K_S \) reconstruction efficiency contribute also. For both modes, there are additional uncertainties associated with the number of \( BB \) events produced, and with MC sample size. The total systematic errors are obtained by adding the individual contributions in quadrature. We determine product branching fractions for \( B^+ \to YK^+ \), \( Y \to J/\psi \omega \) and \( B^0 \to YK^0 \), \( Y \to J/\psi \omega \)

\[
\mathcal{B}(B^+) = (4.9^{+1.0}_{-0.5}(\text{stat})^{+0.5}_{-0.5}(\text{syst})) \times 10^{-5},
\mathcal{B}(B^0) = (1.5^{+1.4}_{-1.2}(\text{stat})^{+0.2}_{-0.2}(\text{syst})) \times 10^{-5},
\]

with upper limit (95% C.L.) \( 3.9 \times 10^{-5} \) for the latter, and total branching fractions for \( B^+ \to J/\psi \omega K^+ \) and \( B^0 \to J/\psi \omega K^0 \)

\[
\mathcal{B}(B^+_{tot}) = (3.5^{+0.2}_{-0.1}(\text{stat})^{+0.1}_{-0.1}(\text{syst})) \times 10^{-4},
\mathcal{B}(B^0_{tot}) = (3.0^{+0.6}_{-0.6}(\text{stat})^{+0.3}_{-0.3}(\text{syst})) \times 10^{-4}.
\]

The combined \( (B^+ \text{ and } B^0) \) branching fraction for \( B \to YK, Y \to J/\psi \omega \) agrees with that in Ref. [1].

We define the ratio of the corrected \( B^0 \) and \( B^+ \) decay rates as \( R_1 \) for the \( Y \) signal, and \( R_2 \) for the non-resonant contributions described by the Gaussian. Simultaneous fits to Figs. 3(a),(b) yield the values \( R_1 = 0.30^{+0.29}_{-0.22}(\text{stat})^{+0.04}_{-0.01}(\text{syst}) \) and \( R_2 = 0.94^{+0.23}_{-0.21}(\text{stat})^{-0.03}_{-0.02}(\text{syst}) \); the upper limit (95% C.L.) on \( R_1 \) is 0.79. We note that the value of \( R_1 \) for \( B \to X(3872)K \) is \( 0.50 \pm 0.31 \) [14]. Although the uncertainties are large for both, the central values of \( R_1 \) are smaller than expected from isospin conservation. In contrast, for charmonium states \( R_1 \) is \( 0.865 \pm 0.044 \) for \( B \to J/\psi K \) and \( 0.957 \pm 0.106 \) for \( B \to \psi(2S)K \) [15].

The \( Y \) mass and width measurements are subject to additional systematic effects. When MC-generated signal events are fitted using the input lineshape with mass and width as free parameters, the fitted value of the

![Fig. 2](image_url)  
**FIG. 2:** The \( J/\psi \omega \) mass distribution for (a) \( B^+ \), and (b) \( B^0 \) decay obtained from the \( m_{ES} \) fits described in the text. The acceptance as a function of \( J/\psi \omega \) mass (c) for the \( B^+ \), and (d) for the \( B^0 \) mode.

![Fig. 3](image_url)  
**FIG. 3:** The acceptance-corrected \( J/\psi \omega \) mass distribution for (a) \( B^+ \) and (b) \( B^0 \) decay. The solid curves result from the fit described in the text.
mass is 1.6 MeV/$c^2$ lower than the input value of 3.915 GeV/$c^2$; there is no significant change in width. This effect results from the limited $3\pi$ phase space near $J/\psi\omega$ threshold, and we account for it by increasing the fitted $Y$ mass value by 1.6 MeV/$c^2$, and conservatively assigning an additional systematic uncertainty of this magnitude. Furthermore, throughout the analysis we have used an $S$-wave BW lineshape to describe the $Y$ signal. We repeat the fits using a $P$-wave lineshape. The fitted mass value decreases by 1 MeV/$c^2$, and the width increases by 5 MeV. We assign these as systematic uncertainties associated with the choice of orbital angular momentum.

These contributions dominate all other sources of systematic uncertainty, and the final parameter values are

$$M(Y) = (3914.6^{+3.8}_{-3.4}(\text{stat})^{+1.9}_{-1.1}(\text{syst})) \text{ MeV}/c^2,$$

$$\Gamma(Y) = (33^{+12}_{-8}(\text{stat})^{+5}_{-5}(\text{syst})) \text{ MeV}.$$

In summary, we observe the decay $B^+ \to YK^+$, $Y \to J/\psi\omega$, and obtain qualitatively similar results for $B^0 \to YK$, $Y \to J/\psi\omega$; the combined branching fraction agrees with the previous measurement [1], however we measure a lower mass and smaller width. The mass value is well above $J/\psi\omega$ threshold. Simulation studies indicate that $X(3872) \to J/\psi\omega$ decay would yield a steeply decreasing mass distribution in the first two mass intervals of Fig. 3. The distribution in Fig. 3(a) behaves quite differently, indicating that the $X(3872)$ is not the source of the $Y$ signal which we observe. We see no evidence for $X(3872) \to J/\psi\omega$, nor for $X(3872) \to J/\psi 3\pi$ with $3\pi$ mass in the $\omega$ region (Table I).

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), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MIST (Russia), MEC (Spain), and STFC (United Kingdom). Individuals have received support from the Marie Curie EIF (European Union) and the A. P. Sloan Foundation.

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[12] The use of charge conjugate states is implied throughout this LETTER.