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Observation of $Y(3940) \to J/\psi\omega$ in $B \to \mathrm{J}/\psi\omega K$ at BABAR

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We report the results of a study of the decays $B^+ \to J/\psi\omega K^+$ and $B^0 \to J/\psi\omega K^0_S$ using 383 million $B\overline{B}$ events from $\Upsilon(4S)$ 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 product branching fractions $\mathcal{B}(B^+ \to YK^+, Y \to J/\psi\omega) = (4.9 \pm 1.0(stat) \pm 0.5(syst)) \times 10^{-5}$ and $\mathcal{B}(B^0 \to YK^0, Y \to J/\psi\omega) = (1.5^{+1.4}_{-1.2}(stat)^{+0.2}_{-0.2}(syst)) \times 10^{-5}$. The measured mass and width are $M(Y) = (3914.6^{+3.8}_{-3.4}(stat)^{+1.9}_{-1.9}(syst))$ MeV/c^2 and $\Gamma(Y) = (33^{+12}_{-8}(stat)^{+5}_{-5}(syst))$ MeV, respectively.

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Among the new particle discoveries from the B factories, the $Y(3940)$, discovered by the BELLE Collaboration [1] appears to be a puzzle, unexpected and unexplained by $q\overline{q}$ quark models of mesons. The mass ($3943 \pm 11 \pm 13$ MeV/c^2) and width ($87 \pm 22 \pm 26$ MeV) suggest a radially excited P-wave $c\bar{c}$ state, but the decay to $J/\psi\omega$ is not readily explained for a particle with a mass above open-charm threshold [2]. Unconventional explanations for the $Y(3940)$ include a hybrid charmonium-gluon bound state $\underline{c\bar{c}g}$ [3, 4], a charmonium-light quark molecule, $c\bar{c}(u\overline{u} + d\overline{d})$ [5–9], or a multi-quark state [10]. The $Y(3940)$ might also be connected to the $X(3872)$ [11], which has a small width, and is just below the $J/\psi\omega$ threshold.

In this Letter, we examine the decays $B^0 \to J/\psi\pi^+\pi^-\pi^0K^0_S$ and $B^+ \to J/\psi\pi^+\pi^-\pi^0K^+$ [12], where the $\pi^+\pi^-\pi^0$ system falls within the ω mass region. We provide experimental confirmation of a resonant $J/\psi\omega$ state, but obtain a lower mass and a smaller width than those from BELLE [1].

The data were collected with the *BABAR* detector [13] at the PEP-II asymmetric-energy e^+e^- storage rings operating at the $\Upsilon(4S)$ resonance. The integrated luminosity for this analysis is 348 fb^{-1}, which corresponds to the production of 383 million $B\bar{B}$ pairs.

The decays $B^0 \to J/\psi\pi^+\pi^-\pi^0K^0_S$ and $B^+ \to J/\psi\pi^+\pi^-\pi^0K^+$ are reconstructed using charged tracks and photon candidates [14]. A candidate $J/\psi \to e^+e^-$ ($\mu^+\mu^-$) decay is required to have an invariant mass in the J/ψ mass region (Table I). A mass constraint to the nominal J/ψ mass [15] is subsequently imposed. A neutral kaon decay candidate is constructed from a pair of oppositely charged tracks forming a vertex which yields a $\pi^+\pi^-$ invariant mass within 25 MeV/c^2 of the nominal K^0_S mass [15]. A π^0 candidate consists of a pair of photon candidates with invariant mass in the π^0 mass region (Table I). After applying a π^0 mass constraint, an $\omega \to \pi^+\pi^-\pi^0$ candidate must have three-pion invariant mass in the ω region (Table I). We form a B^+ $\left(B^0\right)$ decay candidate by combining a J/ψ and an ω candidate with a K^+ $\left(K^0_S\right)$ candidate, incorporating K^+ particle identification [16].

We define the B signal region using $\Delta E \equiv E^*_B - \sqrt{s}/2$, and $m_{ES} \equiv \sqrt{((s/2 + \vec{p}_i \cdot \vec{p}_B)/E_i)^2 - \vec{p}^{\,2}_B}$, where $(E_i, \vec{p}_i)$ is the initial state four-vector in the laboratory frame and $\sqrt{s}$ is the center-of-mass (c.m.) energy; E^*_B is the energy of the B candidate in the c.m. system, and $\vec{p}_B$ is its momentum in the laboratory frame. Signal events have ΔE 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 $B\overline{B}$ and continuum ($e^+e^- \to q\bar{q}$, $q = u, d, s, c$) events. The B helicity angle, θ_B, is the polar angle in the c.m. system between the B momentum vector and the e^+e^- collision axis. The distribution of $\cos\theta_B$ for $\Upsilon(4S) \to B\bar{B}$ decay is proportional to $\sin^2\theta_B$, whereas continuum background peaks toward ± 1, and combinatoric background is flat. The photon helicity angle, θ_γ, is the angle in the π^0 rest frame between the higher momentum photon and the direction of the π^0 in the laboratory frame. For π^0 decay the $\cos\theta_\gamma$ distribution is flat, whereas background peaks at 1. Events from $B \to \psi(2S)K\pi^0, \psi(2S) \to \pi^+\pi^-J/\psi$, are removed by the $\psi(2S)$ veto.

TABLE I: Principal criteria used to select B candidates.

Selection Category	Criterion
$J/\psi \to \mu^+\mu^-$ mass (GeV/c^2)	$3.06 < m_{\mu\mu} < 3.14$
$J/\psi \to e^+e^-$ mass (GeV/c^2)	$2.95 < m_{ee} < 3.14$
Photon helicity angle θ_γ	$\cos\theta_\gamma < 0.95$
π^0 mass (GeV/c^2)	$0.115 < m_{\gamma\gamma} < 0.150$
K_S mass (GeV/c^2)	$0.472 < m_{Ks} < 0.522$
$\psi(2S)$ veto (GeV/c^2)	$3.661 < M_{J/\psi\pi\pi} < 3.711$
ω signal region (GeV/c^2) (B^+)	$0.7695 < m_{3\pi} < 0.7965$
ω signal region (GeV/c^2) (B^0)	$0.7605 < m_{3\pi} < 0.8055$
B helicity angle θ_B	$\|\cos\theta_B\| < 0.9$
m_{ES} (GeV/c^2)	$5.274 < m_{ES} < 5.284$
ΔE (GeV) (B^+)	$\|\Delta E\| < 0.020$
ΔE (GeV) (B^0)	$\|\Delta E\| < 0.015$

The 3π invariant mass, m_{ES}, and ΔE distributions are shown in Fig. 1, where we apply all criteria listed in Table I except that for the variable plotted. The 3π mass distributions are fitted using an ω-meson Breit-Wigner (BW) lineshape with nominal ω 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 background function [17] with slope parameter free. The ΔE 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.

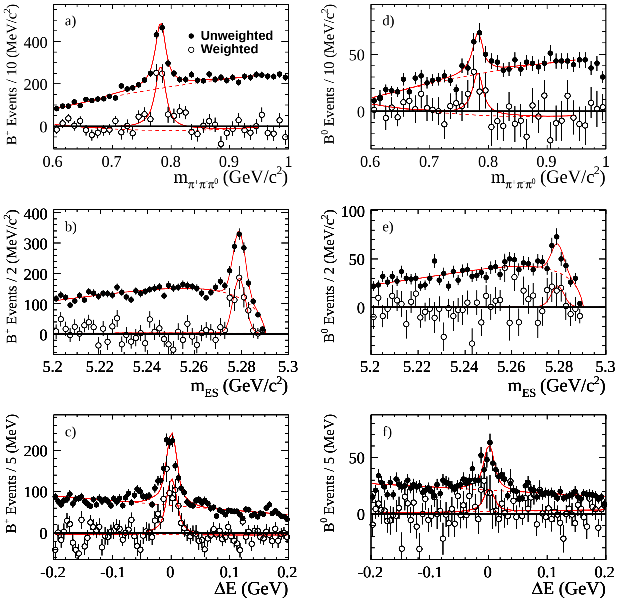

FIG. 1: The 3π mass, $m_{\rm ES}$, and ΔE distributions for the B^+ (B^0) mode are plotted in (a)-(c) ((d)-(f)). The solid dots are for unweighted events, and the open dots show the effect of the P_2 Legendre polynomial ω projection procedure. The solid (dashed) curves represent signal plus background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

There is a large ω-meson signal for the B^+ mode, and a smaller signal for B^0; the corresponding m_{ES} and ΔE distributions exhibit clear B meson signals of relative magnitude similar to that of the ω signals. The correlation between the ω and B meson signals is investigated using a projection procedure based on the ω decay angular distribution. We define the helicity angle, θ_h, as the angle between the π^+ and π^0 directions in the $\pi^+\pi^-$ rest frame. The $\cos\theta_h$ distribution is proportional to $\sin^2\theta_h$, and the ω signal can be projected in its entirety by giving the i^{th} event weight $w_i = \frac{5}{2}(1-3\cos^2\theta_h^i)$ $\sim -P_2(\cos\theta_h^i)$, 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 ω 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 ω signal and the B-meson signals in m_{ES} and ΔE, and that, at the present level of statistics, the 3π system in the ω mass region results entirely from ω decay for $B \to J/\psi\pi^+\pi^-\pi^0K$. The $\omega - m_{ES}$ (or ΔE) signal correlation is important to an analysis of the $J/\psi\omega$ threshold mass region. Near threshold, the 3π mass distribution above the ω mass is limited in range and distorted in shape, and this makes direct ω signal extraction unreliable, given the limited statistics. The m_{ES} distribution is not affected by this problem, and so we use m_{ES} fits to extract the $J/\psi\omega$ mass distribution. Consistent results are obtained from fits to the ΔE distributions.

For each B decay mode, after applying all criteria of Table I but that on m_{ES}, the m_{ES} distribution in each interval of $J/\psi\pi^+\pi^-\pi^0$ invariant mass is fitted to extract the $J/\psi\omega$ signal. The m_{ES} signal functions and ARGUS background functions are the same as for the $m_{\rm ES}$ 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 ~ 4 GeV/c^2, the $J/\psi\omega$ mass resolution varies from $\sim 5-8$ MeV/c^2, and so in this region the spectrum is investigated in ten $10\,{\rm MeV}/c^2$ intervals starting at 3.8825 GeV/c^2 in order to search for narrow structures. At higher mass, the resolution degrades to $\sim 10-12$ MeV/c^2. A search in 10 MeV/c^2 intervals reveals no evidence of structure, and so we present the spectrum in 50 MeV/c^2 intervals. Overall, satisfactory m_{ES} 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 $B \to YK$ and $Y \to J/\psi\omega$, but use the correct angular distribution for ω decay. Initially we used a relativistic S-wave BW lineshape with $M(Y) = 3.940$ GeV/c^2 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 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 $G(Y)$ 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/c^2 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.

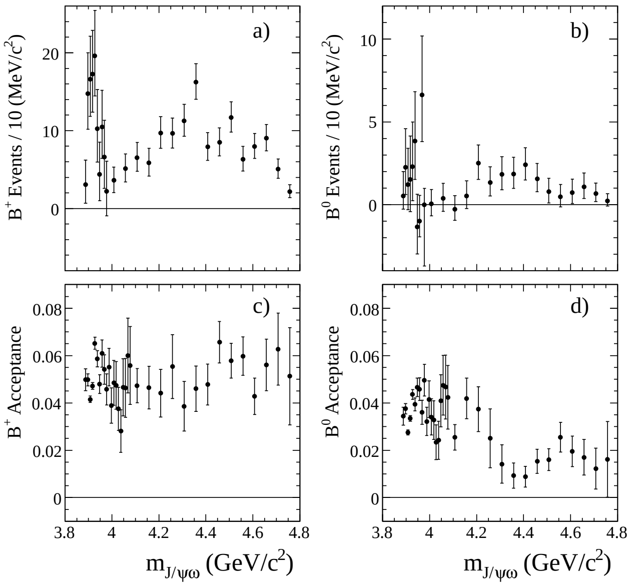

FIG. 2: The $J/\psi\omega$ mass distribution for (a) B^+, and (b) B^0 decay obtained from the m_{ES} fits described in the text. The acceptance as a function of $J/\psi\omega$ mass (c) for the B^+, and (d) for the B^0 mode.

Fig. 3 shows the mass distributions after acceptance correction. Up to $\sim$ 4 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 χ^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 $B\bar{B}$ 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 $B^0 \to YK^0$, $Y \to J/\psi\omega$

$$\begin{aligned}\mathcal{B}(B^+) &= (4.9^{+1.0}_{-1.0}(stat)^{+0.5}_{-0.5}(syst)) \times 10^{-5}\,,\\ \mathcal{B}(B^0) &= (1.5^{+1.4}_{-1.2}(stat)^{+0.2}_{-0.2}(syst)) \times 10^{-5}\,,\end{aligned}$$

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

$$\begin{aligned}\mathcal{B}(B^+_{tot}) &= (3.5^{+0.2}_{-0.2}(stat)^{+0.4}_{-0.4}(syst)) \times 10^{-4}\,,\\ \mathcal{B}(B^0_{tot}) &= (3.0^{+0.6}_{-0.6}(stat)^{+0.3}_{-0.3}(syst)) \times 10^{-4}\,.\end{aligned}$$

The combined (B^+ 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 $R_1 = 0.30^{+0.29}_{-0.24}(stat)^{+0.04}_{-0.01}(syst)$ and $R_2 = 0.94^{+0.23}_{-0.21}(stat)^{+0.03}_{-0.02}(syst)$; 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 ± 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 ± 0.044 for $B \to J/\psi K$ and 0.957 ± 0.106 for $B \to \psi(2S)K$ [15].

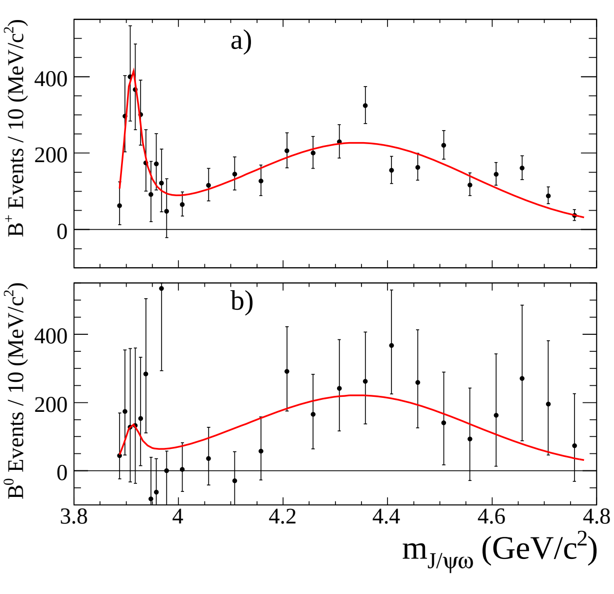

FIG. 3: The acceptance-corrected $J/\psi\omega$ mass distribution for (a) B^+ and (b) B^0 decay. The solid curves result from the fit described in the text.

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 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 3π 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

$$\begin{aligned} M(Y) &= (3914.6^{+3.8}_{-3.4}(stat)^{+1.9}_{-1.9}(syst))\ \mathrm{MeV/c}^2\,, \\ \Gamma(Y) &= (33^{+12}_{-8}(stat)^{+5}_{-5}(syst))\ \mathrm{MeV}\,. \end{aligned}$$

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 3π mass in the ω region (Table I).

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