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

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We present a study of the decays $B^{0,+} \to J/\psi \omega K^{0,+}$ using 383×10^6 $B\bar{B}$ events obtained with the *BABAR* detector at PEP-II. We observe $Y(3940) \to J/\psi \omega$, with mass $3914.6^{+3.8}_{-3.4}(\text{stat}) \pm 2.0(\text{syst})$ MeV$/c^2$, and width $34^{+12}_{-8}(\text{stat}) \pm 5(\text{syst})$ MeV. The ratio of B^0 and B^+ decay to YK is $0.27^{+0.28}_{-0.23}(\text{stat})^{+0.04}_{-0.01}(\text{syst})$, and the relevant B^0 and B^+ branching fractions are reported.

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The BELLE Collaboration has reported evidence for the $X(3940)$ [1], the $Y(3940)$ [2], and the $Z(3930)$ [3]. The mass and width values are the same within error, the states have positive C parity, and spin-parity (J^P) 2^+ is favored for the Z, which may then be the first radial excitation of the $\chi_{c2}(3556)$, i.e., a charmonium state. The mass and width consistency with the X and Y suggests the possibility that these may be the Z in different production contexts. The Z was found in two-photon production of $D\bar{D}$, so that it may be a charmonium state. The X was observed in $e^+e^- \to J/\psi X$, and decays mainly to $D^*\bar{D}$, suggesting a charmonium interpretation. In contrast, the Y was found in $B \to YK$, $Y \to J/\psi\omega$, which is OZI suppressed for a charmonium state [4]. Also, an analysis of $B \to KD\bar{D}$ and $B \to KD^*\bar{D}$ [5] shows no evidence for the Y (nor for the X or Z), although $\psi(3770) \to D\bar{D}$ and $X(3872) \to D^*\bar{D}$ are observed. Other possibilities for the nature of this state, already suggested for the $X(3872)$, include a hybrid charmonium-gluon bound state, $c\bar{c}g$ [6,7], a molecular state of a $c\bar{c}(u\bar{u} + d\bar{d})$ system [8–12], or a multiquark state [13]. The S-wave molecule model [9] predicts a very small B^0/B^+ ratio for $B \to KX(3872)$. The previous low value has been confirmed [14], although the uncertainties are still large, so that a measurement of this ratio for the $Y(3940)$ may be important to an understanding of this state.

In this Letter, we examine the decays $B^{0,+} \to J/\psi\pi^+\pi^-\pi^0K^{0,+}$ [15], with $\pi^+\pi^-\pi^0$ mass in the ω region. We confirm the $Y(3940)$, improve the precision of the mass and width significantly, and measure the (B^0/B^+) production ratio for the first time. Branching fraction values for $B \to YK$, $Y \to J/\psi\omega$, and for $B \to J/\psi\omega K$ are obtained for B^0 and B^+ decay separately; each is a first measurement.

The data were collected with the *BABAR* detector [16] at the PEP-II asymmetric-energy e^+e^- storage rings operating at the $\Upsilon(4S)$ resonance. The integrated luminosity for this analysis is $348\ \text{fb}^{-1}$. The decays $B^{0,+} \to J/\psi\pi^+\pi^-\pi^0K^{0,+}$ are reconstructed as follows (Table I). A candidate $J/\psi \to e^+e^-$ ($\mu^+\mu^-$) decay has invariant mass in the J/ψ mass region, and is then constrained to the nominal mass [17]. A K_S^0 candidate has $\pi^+\pi^-$ invariant mass in the K_S^0 region. The J/ψ and K_S^0 distributions from the B signal region show no significant background. A π^0 candidate consists of a photon pair with invariant mass in the π^0 region. After a π^0 mass constraint, an $\omega \to \pi^+\pi^-\pi^0$ candidate has invariant mass in the ω region. We form a $B^+(B^0)$ candidate by combining J/ψ, ω and K^+ [18] (K_S^0) candidates.

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

We define the B signal region using the center of mass (c.m.) energy difference $\Delta E \equiv E_B^* - \sqrt{s}/2$, and the beam-energy substituted mass $m_{\rm ES} \equiv \sqrt{[(s/2 + \vec{p}_i \cdot \vec{p}_B)/E_i]^2 - \vec{p}_B^{\,2}}$ [16], where $(E_i, \vec{p}_i)$ is the initial state four-momentum vector in the laboratory frame (l.f.); $\sqrt{s}$ is the c.m. energy, E_B^* is the B meson energy in the c.m., and $\vec{p}_B$ is its l.f. momentum. Signal events have $\Delta E \sim$ zero and $m_{\rm ES} \sim m_B$; 12% of the events have multiple candidates, and for these the combination with the smallest $|\Delta E|$ is chosen.

The selection criteria were established by optimizing 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 $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) events.

The $\cos\theta_B$ distribution (θ_B is the c.m. polar angle of the B) is proportional to $\sin^2\theta_B$; since $e^+e^- \to q\bar{q}$ events peak toward ± 1, we require $|\cos\theta_B| < 0.9$. The variable $\cos\theta_\gamma$ is the normalized dot product between the higher momentum photon in the π^0 rest frame (r.f.) and the l.f. direction of the π^0. For π^0 decay this distribution is flat; background peaks at 1, hence we require $\cos\theta_\gamma < 0.95$. Events from $B \to \psi(2S)K\pi^0$, $\psi(2S) \to \pi^+\pi^-J/\psi$, are removed by the $\psi(2S)$ veto.

The 3π mass, $m_{\rm ES}$, and ΔE distributions are shown in Fig. 1, where we apply all Table I criteria except the requirement on the variable plotted. We fit the 3π mass distributions with an ω-meson Breit-Wigner (BW) line shape (nominal ω mass and width [17]) convolved with a MC-determined triple-Gaussian resolution function as signal, and a quadratic background function. We fit the $m_{\rm ES}$ distributions with a signal Gaussian with mass and width fixed from MC, and an ARGUS background function [19], and fit the ΔE distributions with a double-Gaussian signal function determined from MC, and a linear background function.

There is a large ω signal for the B^+ mode, and a smaller signal for B^0; the $m_{\rm ES}$ and ΔE distributions exhibit clear B signals. We establish the correlation between the ω and B signals with a projection procedure based on the ω decay angular distribution. The helicity angle θ_h is the angle between the π^+ and π^0 directions in the $\pi^+\pi^-$ r.f. The $\cos\theta_h$ distribution is proportional to $\sin^2\theta_h$, and the ω signal is projected by giving the ith event weight $w_i = \frac{5}{2} \times (1 - 3\cos^2\theta_h^i)$. The effect is shown in Fig. 1. For the B^+ mode, the omega signal survives, and background is re-

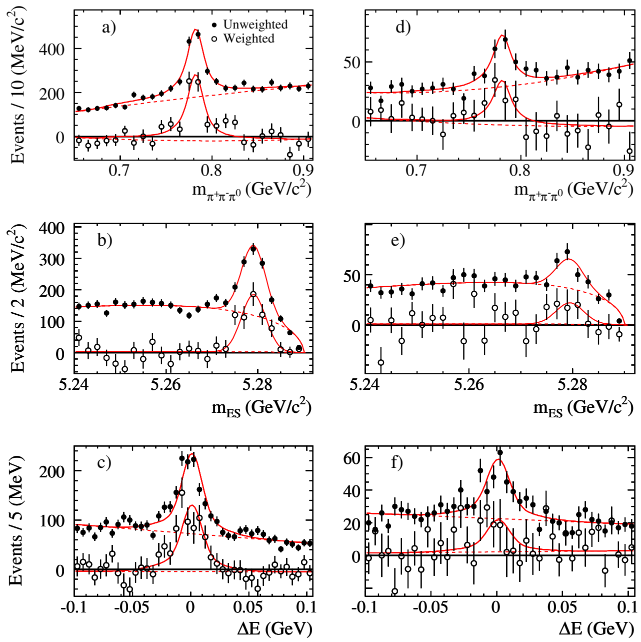

FIG. 1 (color online). (a)–(c) [(d)–(f)] The 3π mass, m_{ES}, and ΔE distributions for the B^+ (B^0) mode; solid (open) dots are for unweighted (weighted) events. The solid (dashed) curves represent signal plus background (background).

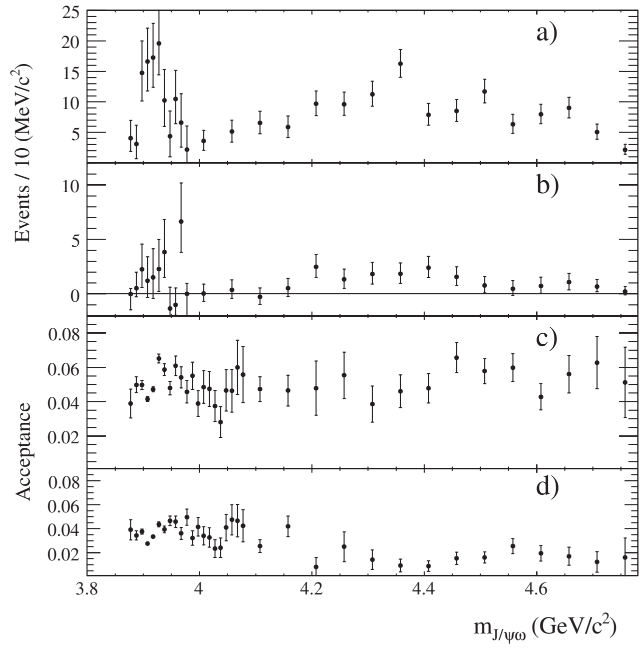

FIG. 2. The $J/\psi\omega$ mass distribution from the m_{ES} fits for (a) B^+ and (b) B^0 decay. The acceptance as a function of $J/\psi\omega$ mass (c) for the B^+, and (d) for the B^0 mode.

moved. For the B^0 mode the effect is qualitatively similar. Confirmation is obtained from a fit to the 3π mass distribution in each interval. We conclude that there is one-to-one correspondence between the ω and 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 $B \to J/\psi\pi^+\pi^-\pi^0 K$. 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. The m_{ES} distribution is not affected, and so we use m_{ES} fits to extract the $J/\psi\omega$ mass distribution.

For each B decay mode, 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, and ARGUS background, functions are those of Fig. 1; the fits use a binned Poisson likelihood function with signal and background normalizations free [20]. All fits converge properly and provide good descriptions of the data. From threshold to 4 GeV/c^2, the $J/\psi\omega$ mass resolution varies from 5–8 MeV/c^2, and so in this region the spectrum is investigated in 11 intervals of 10 MeV/c^2 starting at 3.8725 GeV/c^2. At higher mass, there is no evidence of narrow structure, and we show the results in 50 MeV/c^2 intervals. In Fig. 2, there is a clear enhancement near threshold for B^+ decay, while at higher mass no structure is apparent. The total B^+ (B^0) signal in Fig. 2 is 236^{+18}_{-15} (32^{+8}_{-7}) events of which 109^{+15}_{-13} (16^{+7}_{-6}) have $J/\psi\omega$ mass less than 4 GeV/c^2 (statistical errors only).

We 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 line shape with $M(Y) = 3.940$ GeV/c^2 and $\Gamma(Y) = 0.06$ GeV [2]. 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 events reconstructed in that interval to events generated in the interval; this accounts for efficiency and resolution effects. The acceptance-corrected spectrum is fit to a relativistic BW line shape without convolving resolution, since the acceptance correction takes this into account. We obtain values of $M(Y)$ and $\Gamma(Y)$ which are smaller than in the initial simulation, and so generate new MC samples with the new values in order to correctly reproduce resolution effects. This iterative procedure converges quickly, and the acceptance results in Figs. 2(c) and 2(d) are obtained with $M(Y) = 3.915$ GeV/c^2 and $\Gamma(Y) = 0.02$ GeV. The dip at $\sim$3.91 GeV/c^2 is due to net flow of events away from the resonance maximum because of mass resolution. At lower mass, the acceptance is slightly lower than at higher mass because of the proximity to threshold. Although the acceptance variation in the Y signal region is significant, the effect on the Y fit parameters, and on the corrected number of signal events, is small because of the large statistical uncertainties on the data.

The decrease in acceptance at high mass in Fig. 2(d) results from decreasing K^0_S l.f. momentum. The decay pion

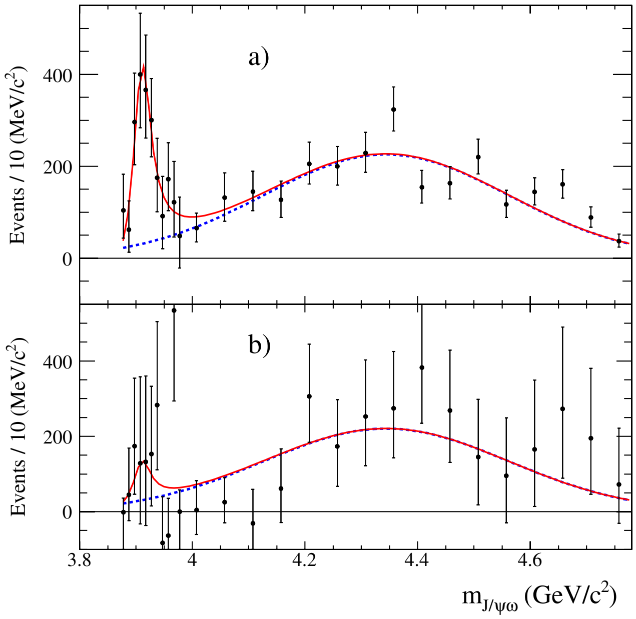

FIG. 3 (color online). The corrected $J/\psi\omega$ mass distribution for (a) B^+ and (b) B^0 decay. Each solid (dashed) curve represents the total fit function (the nonresonant contribution).

reconstruction probability decreases because its l.f. momentum is too small, or because the decay opening angle is so large that the pion does not intersect enough detector planes. Figure 3 shows the corrected mass distributions. Below ~ 4 GeV$/c^2$ we correct interval-by-interval, while for higher mass we use a linear fit to the $J/\psi\omega$ mass dependence. The B^0 data are corrected for K_L^0 and $K_S^0 \rightarrow \pi^0\pi^0$ decays.

We associate the near-threshold enhancement in Fig. 3(a) with Y production [2], and obtain the mass, width, and decay rate from χ^2 fits. The fit function consists of a relativistic S-wave BW describing the Y and a Gaussian nonresonant contribution. 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 [$\chi^2/\mathrm{NDF} = 45/44$ (NDF = number of degrees of freedom)], as shown in Fig. 3. In Fig. 3(a), the acceptance-corrected number of events with $J/\psi\omega$ mass less than 3.98 GeV$/c^2$ is 2140 ± 290(stat), while for the Gaussian it is 420 ± 90(stat). Our average efficiency of $\sim 5\%$ implies that a background fluctuation of ~ 19 standard deviations would be required to describe the near-threshold enhancement. This occurrence has negligible probability, and so we have instead a clear observation of the $Y(3940)$. The simultaneous fit yields a Y signal of 1980^{+396}_{-379}(stat) events (i.e., magnitude 5.2 standard deviations) for B^+ and 527^{+534}_{-454}(stat) for B^0.

Since the acceptance-correction procedure may depend on the input MC $Y(3940)$ line shape, we combine the first 11 mass intervals for data and MC and make an overall efficiency correction. The results differ by 1.9%, and we incorporate this as a systematic error associated with the MC line shape. Other 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 contribution is 10% due to m_{ES} mass variation; secondary branching fractions, particle identification, tracking, and K_S reconstruction efficiency contribute also. For both modes, there are uncertainties associated with the number of $B\bar{B}$ events produced, and with MC sample size. The product branching fraction for $B^+ \rightarrow YK^+$, $Y \rightarrow J/\psi\omega$ is $[4.9^{+1.0}_{-0.9}(\mathrm{stat}) \pm 0.5(\mathrm{syst})] \times 10^{-5}$, and that for $B^0 \rightarrow YK^0$, $Y \rightarrow J/\psi\omega$ is $[1.3^{+1.3}_{-1.1}(\mathrm{stat}) \pm 0.2(\mathrm{syst})] \times 10^{-5}$, with upper limit (95% C.L.) 3.9×10^{-5} for the latter. The corresponding branching fractions for $B \rightarrow J/\psi\omega K$ are $[3.5 \pm 0.2(\mathrm{stat}) \pm 0.4(\mathrm{syst})] \times 10^{-4}$, and $[3.1 \pm 0.6(\mathrm{stat}) \pm 0.3(\mathrm{syst})] \times 10^{-4}$, respectively.

We define R_Y and R_{NR} as the ratios between the number of B^0 and B^+ events (after all corrections) for the Y signal and for the nonresonant contribution, respectively. Simultaneous fits to Figs. 3(a) and 3(b) yield the values $R_Y = 0.27^{+0.28}_{-0.23}(\mathrm{stat})^{+0.04}_{-0.01}(\mathrm{syst})$ and $R_{\mathrm{NR}} = 0.97^{+0.23}_{-0.22}(\mathrm{stat})^{+0.03}_{-0.02}(\mathrm{syst})$; the upper limit (95% C.L.) on R_Y is 0.75. Although the uncertainty is large, the central value of R_Y is smaller than expected from isospin conservation. In comparison, R is 0.865 ± 0.044 for $B \rightarrow J/\psi K$ [17] and $0.81 \pm 0.05(\mathrm{stat}) \pm 0.01(\mathrm{syst})$ for $B \rightarrow \psi(2S)K$ [14].

The Y mass and width measurements are subject to additional systematic effects. When MC-generated signal events are fitted using the input line shape 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$/c^2$. This results from the limited 3π phase space near $J/\psi\omega$ threshold, and so we increase the fitted Y mass value by 1.6 MeV$/c^2$, and assign this as a systematic uncertainty. Also, we have used an S-wave BW line shape to describe the Y. We repeat the fit using a P-wave line shape. The fitted mass value decreases by 1 MeV$/c^2$, and the width increases by 5 MeV. We assign these as systematic uncertainties due to the choice of orbital angular momentum. Finally, a fit to the uncorrected distributions (Fig. 2) yields a mass value 1.4 MeV$/c^2$ larger, and a width 4 MeV larger, than obtained for the corrected distributions. The mass dependence of the acceptance depends on the MC line shape and so systematic uncertainties of 0.7 MeV$/c^2$ and 2 MeV, respectively, are associated with the MC line shape choice. These contributions dominate all other sources of systematic uncertainty, and the final mass and width values are $[3914.6^{+3.8}_{-3.4}(\mathrm{stat}) \pm 2.0(\mathrm{syst})]$ MeV$/c^2$ and $[34^{+12}_{-8}(\mathrm{stat}) \pm 5(\mathrm{syst})]$ MeV, respectively.

In summary, in the decays $B^{0,+} \to J/\psi\omega K^{0,+}$ we find a $J/\psi\omega$ mass enhancement at $\sim 3.915\ \mathrm{GeV}/c^2$, confirming the BELLE result [2], but obtain lower mass, smaller width, and reduce the uncertainty on each by a factor ~ 3. The mass is 2 standard deviations lower than the $Z(3930)$ mass, and 3 standard deviations lower than for the $X(3940)$; the width agrees with the $Z(3930)$ and $X(3940)$ values. The ratio of B^0 and B^+ decay to YK, R_Y, is measured for the first time and found to be ~ 3 standard deviations below the isospin expectation, but agrees with that for the $X(3872)$ [14]. The ratio for the nonresonant contribution R_{NR} agrees with the isospin expectation. We have obtained first measurements of the branching fractions for $B \to J/\psi\omega K$ and for $B \to YK$, $Y \to J/\psi\omega$, for B^0 and B^+ decays separately.

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