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

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

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  $e^+e^- \rightarrow J/\psi X$ , and decays mainly to  $D^*\bar{D}$ , suggesting a charmonium interpretation. In contrast, the  $Y$  was found in  $B \rightarrow YK$ ,  $Y \rightarrow J/\psi\omega$ , which is OZI suppressed for a charmonium state [4]. Also, an analysis of  $B \rightarrow K\bar{D}\bar{D}$  and  $B \rightarrow K\bar{D}^*\bar{D}$  [5] shows no evidence for the  $Y$  (nor for the  $X$  or  $Z$ ), although  $\psi(3770) \rightarrow D\bar{D}$  and  $X(3872) \rightarrow D^*\bar{D}$  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  $B \rightarrow KX(3872)$ . 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  $B^{0,+} \rightarrow J/\psi\pi^+\pi^-\pi^0K^{0,+}$  [15], with  $\pi^+\pi^-\pi^0$  mass in the  $\omega$  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  $B \rightarrow YK$ ,  $Y \rightarrow J/\psi\omega$ , and for  $B \rightarrow J/\psi\omega K$  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  $Y(4S)$  resonance. The integrated luminosity for this analysis is  $348 \text{ fb}^{-1}$ . The decays  $B^{0,+} \rightarrow J/\psi\pi^+\pi^-\pi^0K^{0,+}$  are reconstructed as follows (Table I). A candidate  $J/\psi \rightarrow e^+e^-$  ( $\mu^+\mu^-$ ) decay has invariant

mass in the  $J/\psi$  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  $J/\psi$  and  $K_S^0$  distributions from the  $B$  signal region show no significant background. A  $\pi^0$  candidate consists of a photon pair with invariant mass in the  $\pi^0$  region. After a  $\pi^0$  mass constraint, an  $\omega \rightarrow \pi^+\pi^-\pi^0$  candidate has invariant mass in the  $\omega$  region. We form a  $B^+(B^0)$  candidate by combining  $J/\psi$ ,  $\omega$  and  $K^+$  [ $K_S^0$ ] candidates.

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  $m_{\text{ES}} \equiv \sqrt{[(s/2 + \vec{p}_i \cdot \vec{p}_B)/E_i]^2 - \vec{p}_B^2}$  [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  $m_{\text{ES}} \sim m_B$ ; 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,  $B \rightarrow YK$ ,  $Y \rightarrow J/\psi\omega$ , and background  $B\bar{B}$  and  $e^+e^- \rightarrow q\bar{q}$  ( $q = u, d, s, c$ ) events.

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

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

There is a large  $\omega$  signal for the  $B^+$  mode, and a smaller signal for  $B^0$ ; the  $m_{\text{ES}}$  and  $\Delta E$  distributions exhibit clear  $B$  signals. We establish the correlation between the  $\omega$  and  $B$  signals with a projection procedure based on the  $\omega$  decay angular distribution. The helicity angle  $\theta_h$  is the angle between the  $\pi^+$  and  $\pi^0$  directions in the  $\pi^+\pi^-$  r.f. The  $\cos\theta_h$  distribution is proportional to  $\sin^2\theta_h$ , and the  $\omega$  signal is projected by giving the  $i$ th 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-

TABLE I. Principal criteria used to select  $B$  candidates.

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

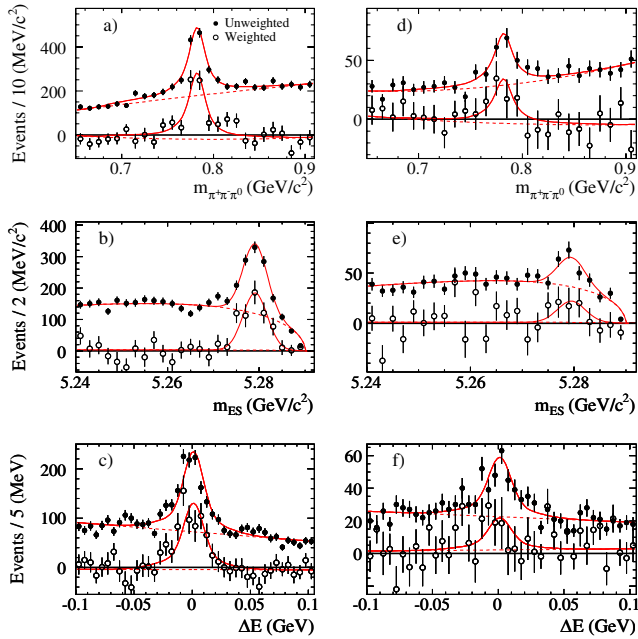


FIG. 1 (color online). (a)–(c) [(d)–(f)] The  $3\pi$  mass,  $m_{ES}$ , and  $\Delta E$  distributions for the  $B^+$  ( $B^0$ ) mode; solid (open) dots are for unweighted (weighted) events. The solid (dashed) curves represent signal plus background (background).

moved. For the  $B^0$  mode the effect is qualitatively similar. Confirmation is obtained from a fit to the  $3\pi$  mass distribution in each interval. We conclude that there is one-to-one correspondence between the  $\omega$  and  $B$ -meson signals in  $m_{ES}$  and  $\Delta E$ , and that, at the present level of statistics, the  $3\pi$  system in the  $\omega$  mass region results entirely from  $\omega$  decay for  $B \rightarrow J/\psi\pi^+\pi^-\pi^0K$ . The  $\omega - m_{ES}$  (or  $\Delta E$ ) signal correlation is important to an analysis of the  $J/\psi\omega$  threshold mass region. Near threshold, the  $3\pi$  mass distribution above the  $\omega$  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  $4 \text{ GeV}/c^2$ , the  $J/\psi\omega$  mass resolution varies from  $5\text{--}8 \text{ MeV}/c^2$ , and so in this region the spectrum is investigated in 11 intervals of  $10 \text{ MeV}/c^2$  starting at  $3.8725 \text{ GeV}/c^2$ . At higher mass, there is no evidence of narrow structure, and we show the results in  $50 \text{ MeV}/c^2$  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  $4 \text{ GeV}/c^2$  (statistical errors only).

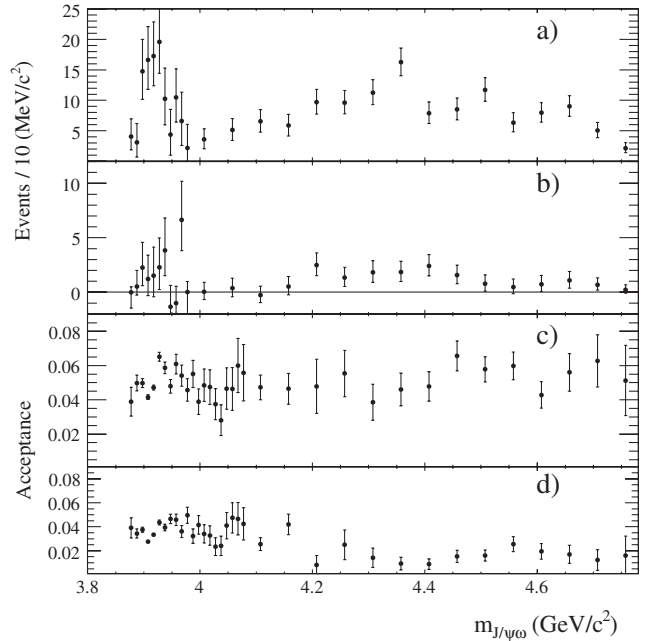


FIG. 2. The  $J/\psi\omega$  mass distribution from the  $m_{ES}$  fits for (a)  $B^+$  and (b)  $B^0$  decay. The acceptance as a function of  $J/\psi\omega$  mass (c) for the  $B^+$ , and (d) for the  $B^0$  mode.

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  $B \rightarrow YK$  and  $Y \rightarrow J/\psi\omega$ , but use the correct angular distribution for  $\omega$  decay. Initially we used a relativistic  $S$ -wave BW line shape with  $M(Y) = 3.940 \text{ GeV}/c^2$  and  $\Gamma(Y) = 0.06 \text{ GeV}$  [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  $M(Y) = 3.915 \text{ GeV}/c^2$  and  $\Gamma(Y) = 0.02 \text{ GeV}$ . The dip at  $\sim 3.91 \text{ GeV}/c^2$  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  $K_S^0$  l.f. momentum. The decay pion

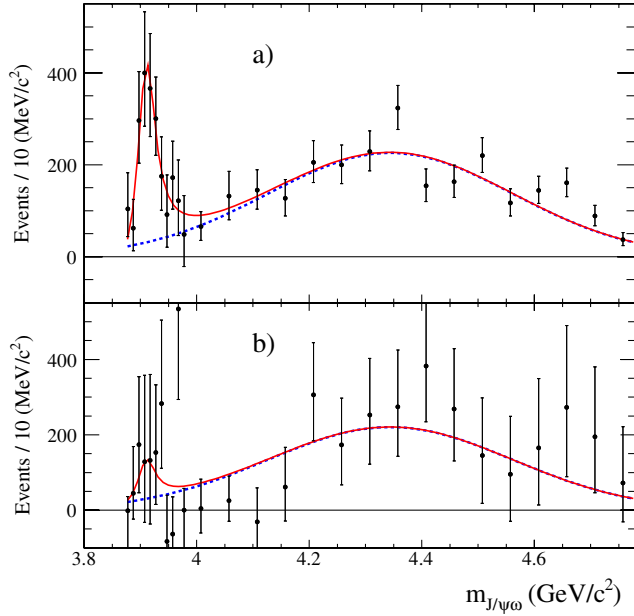


FIG. 3 (color online). The corrected  $J/\psi\omega$  mass distribution for (a)  $B^+$  and (b)  $B^0$  decay. Each solid (dashed) curve represents the total fit function (the nonresonant contribution).

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  $\sim 4$   $\text{GeV}/c^2$  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  $\chi^2$  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 [ $\chi^2/\text{NDF} = 45/44$  (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  $3.98$   $\text{GeV}/c^2$  is  $2140 \pm 290(\text{stat})$ , while for the Gaussian it is  $420 \pm 90(\text{stat})$ . Our average efficiency of  $\sim 5\%$  implies that a background fluctuation of  $\sim 19$  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  $1980^{+396}_{-379}(\text{stat})$  events (i.e., magnitude 5.2 standard deviations) for  $B^+$  and  $527^{+534}_{-454}(\text{stat})$  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  $[4.9^{+1.0}_{-0.9}(\text{stat}) \pm 0.5(\text{syst})] \times 10^{-5}$ , and that for  $B^0 \rightarrow YK^0$ ,  $Y \rightarrow J/\psi\omega$  is  $[1.3^{+1.3}_{-1.1}(\text{stat}) \pm 0.2(\text{syst})] \times 10^{-5}$ , with upper limit (95% C.L.)  $3.9 \times 10^{-5}$  for the latter. The corresponding branching fractions for  $B \rightarrow J/\psi\omega K$  are  $[3.5 \pm 0.2(\text{stat}) \pm 0.4(\text{syst})] \times 10^{-4}$ , and  $[3.1 \pm 0.6(\text{stat}) \pm 0.3(\text{syst})] \times 10^{-4}$ , 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  $R_Y = 0.27^{+0.28}_{-0.23}(\text{stat})^{+0.04}_{-0.01}(\text{syst})$  and  $R_{NR} = 0.97^{+0.23}_{-0.22}(\text{stat})^{+0.03}_{-0.02}(\text{syst})$ ; 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  $0.865 \pm 0.044$  for  $B \rightarrow J/\psi K$  [17] and  $0.81 \pm 0.05(\text{stat}) \pm 0.01(\text{syst})$  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  $1.6$   $\text{MeV}/c^2$  lower than the input value of  $3.915$   $\text{GeV}/c^2$ . This results from the limited  $3\pi$  phase space near  $J/\psi\omega$  threshold, and so we increase the fitted  $Y$  mass value by  $1.6$   $\text{MeV}/c^2$ , 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  $1$   $\text{MeV}/c^2$ , and the width increases by  $5$   $\text{MeV}$ . 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  $1.4$   $\text{MeV}/c^2$  larger, and a width  $4$   $\text{MeV}$  larger, than obtained for the corrected distributions. The mass dependence of the acceptance depends on the MC line shape and so systematic uncertainties of  $0.7$   $\text{MeV}/c^2$  and  $2$   $\text{MeV}$ , 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  $[3914.6^{+3.8}_{-3.4}(\text{stat}) \pm 2.0(\text{syst})] \text{MeV}/c^2$  and  $[34^{+12}_{-8}(\text{stat}) \pm 5(\text{syst})] \text{MeV}$ , respectively.

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

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