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Study of $X(3872)$ in B meson decays

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Abstract

We present results on the $X(3872)$, produced in $B^+ \to X(3872)K^+$ and $B^0 \to X(3872)K^0_S$ decays where $X(3872) \to J/\psi\pi^+\pi^-$. We report the first statistically significant observation of $B^0 \to X(3872)K^0_S$ and measure the ratio of branching fractions to be $\frac{\mathcal{B}(B^0\to X(3872)K^0)}{\mathcal{B}(B^+\to X(3872)K^+)} = 0.82\pm0.22\pm0.05$, consistent with unity. The mass difference between the $X(3872)$ states produced in B^+ and B^0 decay is found to be $\delta M \equiv M_{XK^+} - M_{XK^0} = (+0.18 \pm 0.89 \pm 0.26)$ MeV/c^2, consistent with zero. In addition, we search for the $X(3872)$ in the decay $B^0 \to X(3872)K^+\pi^-$, $X(3872) \to J/\psi\pi^+\pi^-$. We measure $\mathcal{B}(B^0 \to X(3872)(K^+\pi^-)_{NR}) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (8.1 \pm 2.0^{+1.1}_{-1.4}) \times 10^{-6}$ and we set the 90% C.L. limit, $\mathcal{B}(B^0 \to X(3872)K^*(892)^0) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) < 3.4 \times 10^{-6}$. The analysis is based on a 605 fb^{-1} data sample collected at the $\Upsilon(4S)$ with the Belle detector at the KEKB collider.

INTRODUCTION

The $X(3872)$ was first observed in the charged B-meson decay $B^+ \to X(3872)K^+$, $X(3872) \to J/\psi\pi^+\pi^-$ by the Belle Collaboration [1]. Its existence has been confirmed by the CDF and D0 Collaborations [2] through its inclusive production in proton-antiproton collisions. The discovery mode $B^+ \to X(3872)K^+$ has also been confirmed by the BaBar Collaboration [3]. The $X(3872)$ mass, combining all measurements in this final state, is [4]

$$m_X = (3871.2 \pm 0.5)\text{MeV} \tag{1}$$

which is at the threshold for the production of the charmed meson pair $\overline{D}^0 D^{*0}$. Recent studies from Belle and CDF that combine angular information, and kinematic properties of the $\pi^+\pi^-$ pair, strongly favor a $J^{PC} = 1^{++}$ or 2^{-+} assignment [6, 7, 8]. The $X(3872)$ does not appear to be a simple quark model $q\bar{q}$ meson state: different models have been proposed to explain the nature of the $X(3872)$ including S-wave $D^0 D^{*0}$ molecule models [9, 10] and various diquark-antidiquark models [11, 12]. The DD^* molecule proposal is motivated by the proximity of the $X(3872)$ to the $\overline{D}^0 D^{*0}$ threshold: $m_{D^0} + m_{D^{*0}} = 3871.81 \pm 0.25$ MeV [13, 14].

In the molecular model, the $X(3872)$ is a $J^P = 1^+$ state. Some authors have argued [10] that this model, together with factorization, heavy-quark and isospin symmetries, implies that the ratio of $B^0 \to X(3872)K^0$ to $B^+ \to X(3872)K^+$ decays is smaller than 0.1; this claim has recently been challenged [15]. This ratio is expected to be unity for charmonium as well as for hybrids ($c\bar{c}g$) and glueballs (gg).

The diquark anti-diquark model of Maiani *et al.* [11] predicts that the observed $X(3872)$ is one component of a doublet of states. In this model, the $X(3872)$ produced in charged B meson decays will have a mass that is different from its counterpart in neutral B meson decays by $\delta M = (7 \pm 2)/\cos(2\theta)$ MeV, where θ is a mixing angle that is near $\pm 20°$.

In order to test the predictions of these models, we compare branching fraction and $X(3872)$ mass measurements in charged and neutral B decays. A previous study performed by BaBar [16] using 413 fb^{-1} was not conclusive on these points; this analysis uses a larger sample, 605 fb^{-1} ($657 \times 10^6 B\bar{B}$ pairs), collected with the Belle detector at the KEKB asymmetric-energy e^+e^- (3.5 GeV on 8 GeV) collider [17] operating at the $\Upsilon(4S)$ resonance.

THE BELLE DETECTOR

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM). The detector is described in detail elsewhere [18]. Two different inner detector configurations were used. For the first sample of 152×10^6 $B\overline{B}$ pairs, a 2.0 cm radius beampipe and a 3-layer silicon vertex detector (SVD-I) were used; for the remaining 505×10^6 $B\overline{B}$ pairs, a 1.5 cm radius beampipe, a 4-layer silicon detector (SVD-II), and a small-cell inner drift chamber were used [19].

SELECTION

Charged tracks are required to originate from the interaction point. A likelihood ratio $\mathcal{R}_{K/\pi} = \mathcal{L}_K/(\mathcal{L}_\pi+\mathcal{L}_K)$, where $\mathcal{L}_\pi$ ($\mathcal{L}_K$) is the likelihood value for the pion (kaon) hypothesis, is built using ACC, TOF and CDC (dE/dx) measurements. For charged kaons, we impose $\mathcal{R}_{K/\pi} > 0.6$ that have an 88% efficiency and a 10% efficiency for pions. K^0_S candidates are selected within the $\pi^+\pi^-$ mass range [0.4840, 0.5127] GeV/c^2. Requirements on the K^0_S vertex displacement from the interaction point and on the difference between vertex and K^0_S flight directions are applied. This selection is described in detail elsewhere [20].

We reconstruct J/ψ mesons in the l^+l^- decay channel ($l = e$ or μ) and include bremsstrahlung photons that are within 50 mrad of either the e^+ or e^- tracks (denoted as $e^+e^-(\gamma)$). The invariant mass of the J/ψ candidates is required to be within -0.150 GeV/c^2 $< M_{e^+e^-(\gamma)} - m_{J/\psi} < +0.036$ GeV/c^2 and -0.060 GeV/c^2 $< M_{\mu^+\mu^-} - m_{J/\psi} < +0.036$ GeV/c^2, where $m_{J/\psi}$ denotes the J/ψ nominal mass [14], and $M_{e^+e^-(\gamma)}$ and $M_{\mu^+\mu^-}$ are the reconstructed invariant masses from $e^+e^-(\gamma)$ and $\mu^+\mu^-$, respectively. The J/ψ candidate is then combined with a $\pi^+\pi^-$ pair for further analysis: both the $X(3872)$ and the $\psi(2S)$, which is used for calibration, decay to this final state. More than one $J/\psi\pi^+\pi^-$ combination may be possible at this stage. An additional cut is applied on the $M_{\pi^+\pi^-}$ variable: $M_{\pi^+\pi^-} > M(\pi^+\pi^-J/\psi) - (m_{J/\psi} + m_{\rm cut})$. For $B \to J/\psi\pi^+\pi^-K$ modes ($B \to J/\psi\pi^+\pi^-K^+\pi^-$), we apply the above requirement with $m_{\rm cut} = 0.2$ GeV ($m_{\rm cut} = 0.15$ GeV). For the former case, this cut corresponds to $M_{\pi^+\pi^-} > 389$ MeV/c^2 for the $\psi(2S)$ region and $M_{\pi^+\pi^-} > 575$ MeV/c^2 for the $X(3872)$ region and reduces significantly the combinatorial background ($\sim$ 46% in the charged mode) for a reasonable loss of efficiency ($\sim$ 9%). It also has the property of making the background flat in the $M(J/\psi\pi^+\pi^-)$ variable.

To reduce the combinatorial background from $e^+e^- \to q\overline{q}$ continuum events, we require $R_2 < 0.4$ where R_2 is the ratio of the second to zeroth normalized Fox-Wolfram moments [5], and $|\cos\theta_B| < 0.8$, where θ_B is the polar angle of the B meson momentum in the center-of-mass (CM) system, relative to the e^+ beam direction.

B candidates are obtained by combining a K^+, a K^0_S or $K^+\pi^-$ candidate with the $J/\psi\pi^+\pi^-$ candidate. We select B candidates using two variables: the energy difference $\Delta E = E_B - E^*_{\rm beam} = \sum_i \sqrt{c^2p_i^2 + c^4m_i^2} - E^*_{\rm beam}$, and the beam constrained mass $M_{\rm bc} = (1/c^2)\sqrt{E^{*2}_{\rm beam} - c^2p_B^2} = (1/c^2)\sqrt{E^{*2}_{\rm beam} - c^2(\sum_i p_i)^2}$, where the summation is over all particles from the B candidate (p_i and m_i are their CM three-momenta and masses respectively) and p_B is the B candidate momentum in the CM frame. If more than one candidate is obtained at this stage of the analysis, the candidate with ΔE closest to zero is selected. Only B candidates with $|\Delta E| < 30$ MeV and $M_{\rm bc} < 5.27$ GeV/c^2 are considered for further analysis.

RESULTS

From this point onwards, we correct the mass measurement using the known J/ψ mass, redefining $M(J/\psi\pi^+\pi^-)$ as $M(J/\psi\pi^+\pi^-)-M(J/\psi)+m_{J/\psi}$. The selection cuts isolate a very pure sample of $B \to \psi(2S)K$, $\psi(2S) \to J/\psi\pi^+\pi^-$ decays. These events are used to calibrate the $M(J/\psi\pi^+\pi^-)$ resolution and estimate the systematic uncertainty for the $X(3872)$ mass difference. Figure 1 shows the $M(J/\psi\pi^+\pi^-)$ distributions for data near 3686 MeV and

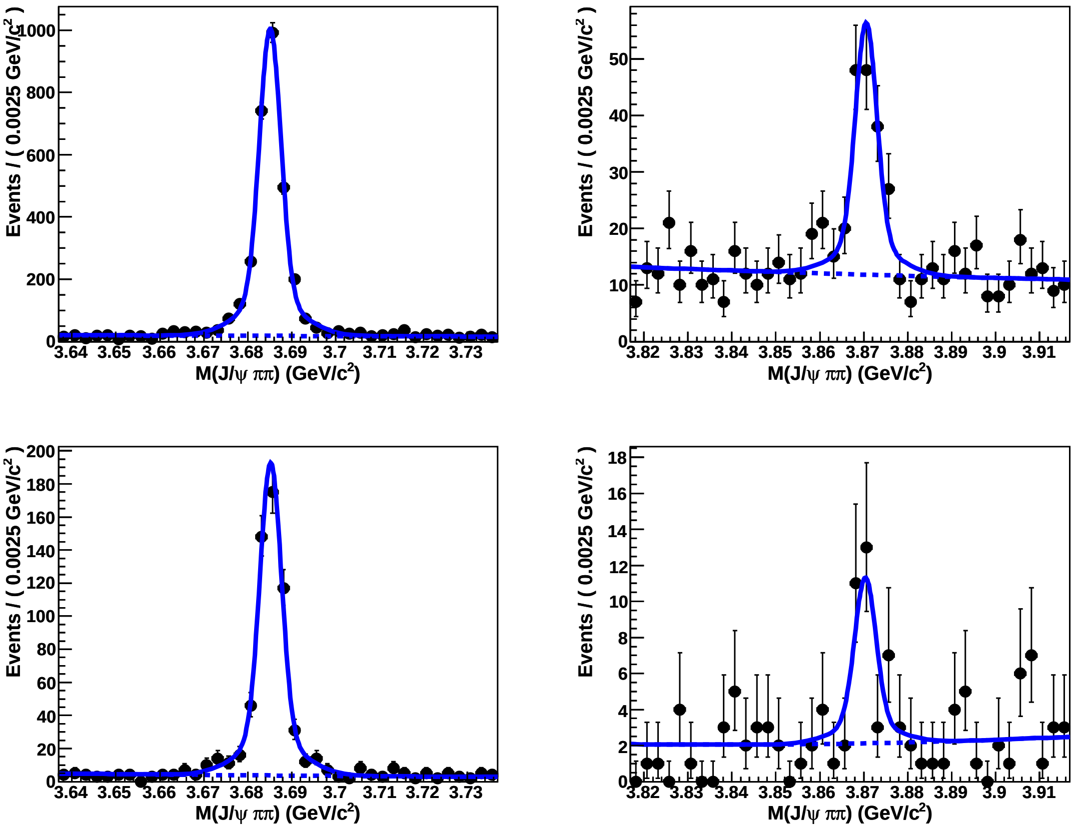

FIG. 1: The $M(J/\psi\pi^+\pi^-)$ distribution for the $\psi(2S)$ (left) and $X(3872)$ (right) region for charged (top) and neutral (bottom) B decays. The curve is the result of the fit described in the text.

3872 MeV for the charged and neutral B modes. We perform a fit to the $M(J/\psi\pi^+\pi^-)$ distribution to determine the $\psi(2S)$ and $X(3872)$ yields, and the signal shape. This fit is performed in the region $[m_{J/\psi} + 0.54,\ m_{J/\psi} + 0.82]$ GeV/c^2. We use the same probability density function (PDF) for each signal: a sum of two Gaussians with a common mean. We first perform the fit for the charged mode, with the $\psi(2S)$ and $X(3872)$ masses and the two Gaussian widths as free parameters. The width parameters (mostly determined by the large $\psi(2S)$ peak) are then fixed, and we perform the fit for the neutral mode, with only the masses as free parameters. This procedure allows a clean comparison of the masses in charged and neutral B decay, for both the $X(3872)$ and the $\psi(2S)$ control sample. The signal yields are 131.7 ± 15.0 and 27.6 ± 6.6 for the $X(3872)K^+$ and the $X(3872)K^0_S$ modes respectively. The significance is determined from $-2\ln(\mathcal{L}_0/\mathcal{L}_{\max})$ where $\mathcal{L}_0$ and $\mathcal{L}_{\max}$ denote the likelihoods returned by the fits with the signal yield fixed at zero and at the fitted value, respectively. This quantity should be distributed as $\chi^2(n_{dof} = 2)$, as two parameters are free for the signal. The calculated significance is then 12.8σ and 5.9σ, respectively.

Using a Monte Carlo (MC) determined acceptance (ϵ), the results are summarized in Table I and the ratio of branching fractions can then be calculated:

$$\frac{\mathcal{B}(B^0 \to X(3872)K^0)}{\mathcal{B}(B^+ \to X(3872)K^+)} = 0.82 \pm 0.22 \pm 0.05,$$

TABLE I: $X(3872)$ results obtained in the fit described in the text.

Mode	Yield	$\epsilon(\%)$	Significance (σ)	$\mathcal{B}\times\mathcal{B}(X(3872)\to J/\psi\pi^+\pi^-)$
$B^+\to X(3872)K^+$	131.7 ± 15.0	20.9	12.8	$(8.10\pm0.92\pm0.66)\times10^{-6}$
$B^0\to X(3872)K^0$	27.6 ± 6.6	15.2	5.9	$(6.65\pm1.63\pm0.55)\times10^{-6}$

where we assume the $B^0 \to X(3872)K^0$ transition rate to be equal to twice the $B^0 \to X(3872)K^0_S$ rate. In this ratio, most of the systematic uncertainties cancel. Therefore only the uncertainties due to the $\Upsilon(4S)$ branching fractions [14] (2.4%), Monte Carlo statistics and MC/data differences are included (Table II). The latter source dominates: the differences are due to kaon identification (2.2%) and K^0_S reconstruction efficiency (4.5%).

TABLE II: Summary of the systematic errors in %.

Source	$X(3872)K^+$	$X(3872)K^0_S$	Ratio
$N_{B\overline{B}}$	1.4	1.4	-
Secondary $\mathcal{B}$	1.4	1.4	2.4
MC statistics	0.2	0.2	0.2
MC decay model	2.0	2.0	-
Kaon ID	2.2	-	2.2
Lepton ID	4.2	4.2	-
Tracking	6.0	4.8	1.2
K^0_S reconstruction	-	4.5	4.5
Total (quadrature)	8.1	8.3	5.7

As a check, the ratio was estimated for modes with $\psi(2S)$. The signal yields are 2916 ± 61 events for $B^+ \to \psi(2S)K^+$ and 559 ± 25 events for $B^0 \to \psi(2S)K^0_S$ which gives $\frac{\mathcal{B}(B^0\to\psi(2S)K^0)}{\mathcal{B}(B^+\to\psi(2S)K^+)} = 0.72 \pm 0.04$ (stat); the systematic error is the same as that for the $X(3872)$ case, ±0.05. The ratio was also estimated using $\psi(2S) \to l^+l^-$ decays in the same dataset, finding $\frac{\mathcal{B}(B^0\to\psi(2S)K^0)}{\mathcal{B}(B^+\to\psi(2S)K^+)} = 0.88 \pm 0.05$ (stat). These two results are in reasonable agreement with the ratio calculated from the PDG branching fractions [14], 0.96 ± 0.11.

The difference between the masses in the charged and neutral B modes for $X(3872)K$ is found to be $\delta M \equiv M_{XK^+} - M_{XK^0} = (+0.18 \pm 0.89)$ MeV/c^2 in data. The same calculation is performed for the $\psi(2S)$: from measured masses of (3685.12 ± 0.06) MeV/c^2 (charged mode) and (3685.23 ± 0.14) MeV/c^2 (neutral mode), we find $\delta M = -(0.11 \pm 0.15)$ MeV/c^2. There is thus no significant evidence of δM bias; we assign a conservative systematic error of ±0.26 MeV/c^2 by adding the central value and one-sigma error for the $\psi(2S)$, and taking the result as a symmetric error. The mass difference between the $X(3872)$ states produced in B^+ and B^0 decay is then

$$\delta M = (+0.18 \pm 0.89 \pm 0.26)\ \mathrm{MeV}/c^2$$

which is consistent with zero.

Combining the charged and neutral B samples, we perform a fit to the $J/\psi\pi^+\pi^-$ invariant mass. We correct the fitted $X(3872)$ mass by the difference between the $\psi(2S)$ world average [14] and the mass we measure. The corrected mass is:

$$M(X(3872)) = (3871.46 \pm 0.37 \pm 0.07)\ \mathrm{MeV}/c^2$$

where the first error is statistical and the second systematic (from the $m_{\psi(2S)}$ fit and the nominal mass $m_{\psi(2S)}$).

A similar fit is performed to $M(J/\psi\pi^+\pi^-)$ for the $B^0 \to (J/\psi\pi^+\pi^-)K^+\pi^-$ mode (Fig. 2). The signal yield is 90 ± 19 events. A fit to the $M_{K\pi}$ distribution is then performed to disentangle the $B^0 \to X(3872)K^*(892)^0$ and 3-body $B^0 \to X(3872)K^+\pi^-$ contributions to the final state. We select the events within ±7 MeV around $m_{\psi(2S)}$ and $m_{X(3872)}$ and fit their $M_{K\pi}$ distributions (Fig. 3). For the $B^0 \to \psi(2S)K^+\pi^-$ mode, the PDF for the background is the sum of a function $(M(K\pi) - m_K - m_\pi)^a\ (m_B - m_{\psi(2S)} - M(K\pi))^b$, representing phase space, and a Breit-Wigner function, to describe the $K^*(892)^0$ contribution, obtained from $M(J/\psi\pi^+\pi^-)$ sidebands ($|M(J/\psi\pi^+\pi^-) - m_{\psi(2S)} \pm 0.030| < 0.014$ GeV). The PDFs for the signal are a Breit-Wigner PDF with a free mean and width to represent the $K^*(892)^0$ component and a histogram PDF obtained from MC to represent the $K_2^*(1430)^0$ component. The signal yield obtained for the $\psi(2S)K^*(892)^0$ component is 963 ± 44 events and corresponds to $\mathcal{B}(\psi(2S)K^*(892)^0) = (5.4 \pm 0.3\ (\mathrm{stat})) \times 10^{-4}$. This result is in reasonable agreement with the PDG branching fraction [14], $(7.2 \pm 0.8) \times 10^{-4}$.

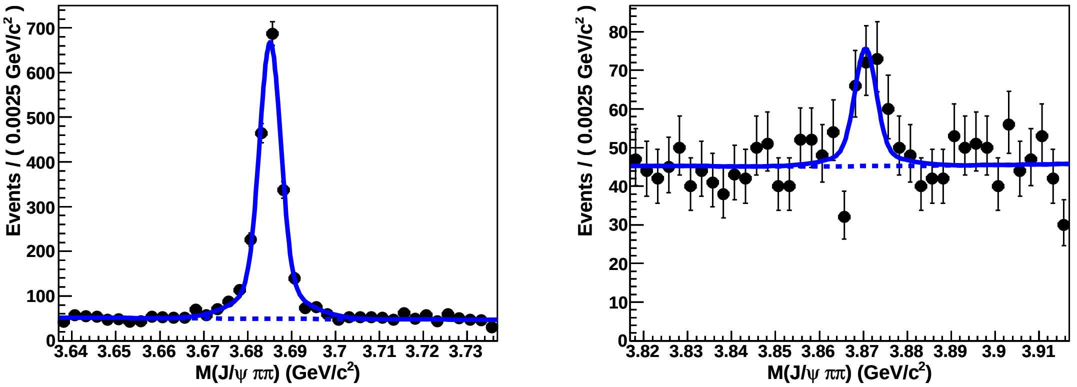

FIG. 2: The $M(J/\psi\pi^+\pi^-)$ distribution for the $\psi(2S)$ (left) and $X(3872)$ (right) region for $B^0 \to J/\psi\pi^+\pi^-K^+\pi^-$. The curve is the result of the fit described in the text.

For the $B^0 \to X(3872)K^+\pi^-$ mode, the PDF for the background is the sum of a phase space function and a Breit-Wigner PDF obtained from $M(J/\psi\pi^+\pi^-)$ sidebands ($|M(J/\psi\pi^+\pi^-) - m_{X(3872)} \pm 0.030| < 0.014$ GeV). The background yield is fixed from these sidebands. The signal is represented by two components: a $K^*(892)^0$ Breit-Wigner PDF and a phase space function obtained from MC. The signal yields are 8 ± 10 and 81 ± 20 events, respectively. The $K^*(892)^0$ contribution is not significant and we set the 90% C.L. limit, $\mathcal{B}(B^0 \to X(3872)K^*(892)^0) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) < 3.4 \times 10^{-6}$. A product branching fraction of $\mathcal{B}(B^0 \to X(3872)(K^+\pi^-)_{NR}) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (8.1 \pm 2.0^{+1.1}_{-1.4}) \times 10^{-6}$ is also obtained. For the systematic error contributions, in addition to those that enter for

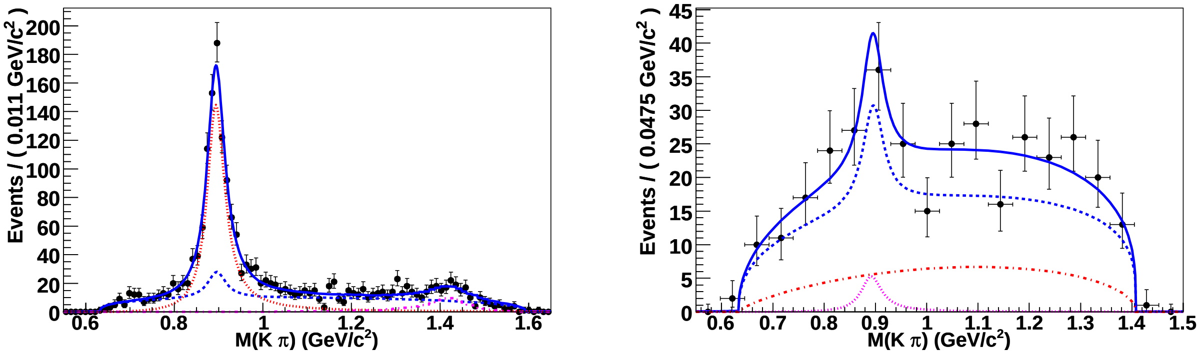

FIG. 3: The $K\pi$ mass spectrum for the $B \to \psi(2S)K\pi$(left) and $B \to X(3872)K\pi$ (right) candidates. Left: $B \to \psi(2S)K^*(892)^0$ is shown by the dotted red curve, $B \to \psi(2S)K_2^*(1430)^0$ by the dash-dot magenta curve, and the background by the dashed blue curve. Right: $B \to X(3872)(K^+\pi^-)_{NR}$ is shown by the dash-dot red curve, $B \to X(3872)K^*(892)^0$ by the dotted magenta curve, and the background by the dashed blue curve.

$B^+ \to X(3872)K^+$ (Table II), we have one more track in the final state, limited statistics to fix the background in $M_{K\pi}$ ($\pm 10\%$), and possible peaking background contributions in $M(J/\psi\pi^+\pi^-)$, based on a study of the $\psi(2S)K^+\pi^-$ calibration mode, $(^{+0.0}_{-10.6}\%)$.

The result for the $X(3872)$ case is in marked contrast to the $\psi(2S)$ case, where the non resonant $B \to \psi(2S)K\pi$ component is small and the $B^0 \to \psi(2S)K^*(892)^0$ and $B^+ \to \psi(2S)K^+$ branching fractions are of comparable size. K^* dominance is also found for $B \to J/\psi K\pi$ and $\chi_{c1}K\pi$ [14].

In summary, we report the first statistically significant observation of $B^0 \to X(3872)K^0_S$ decay and measure the ratio of branching fractions to be $\frac{\mathcal{B}(B^0 \to X(3872)K^0)}{\mathcal{B}(B^+ \to X(3872)K^+)} = 0.82 \pm 0.22 \pm 0.05$, consistent with unity. The mass difference between the X states produced in these two decay modes is found to be $\delta M \equiv M_{XK^+} - M_{XK^0} = (+0.18 \pm 0.89 \pm 0.26)$ MeV$/c^2$, consistent with zero. In addition, we search for the $X(3872)$ in the decay $B^0 \to X(3872)K^+\pi^-$, $X(3872) \to J/\psi\pi^+\pi^-$. We measure $\mathcal{B}(B^0 \to X(3872)(K^+\pi^-)_{NR}) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (8.1 \pm 2.0^{+1.1}_{-1.4}) \times 10^{-6}$ and we set the 90% C.L. limit, $\mathcal{B}(B^0 \to X(3872)K^*(892)^0) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) < 3.4 \times 10^{-6}$.

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