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 $\frac{B(B^0 \to X(3872)K^0_S)}{B(B^+ \to X(3872)K^+)} = 0.82 \pm 0.22 \pm 0.05$, 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 $B(B^0 \to X(3872)(K^+\pi^-)_{NR}) \times B(X(3872) \to J/\psi \pi^+ \pi^-) = (8.1 \pm 2.0^{+1.1}_{-1.4}) \times 10^{-6}$ and we set the 90% C.L. limit, $B(B^0 \to X(3872)K^*(892)^0) \times B(X(3872) \to J/\psi \pi^+ \pi^-) < 3.4 \times 10^{-6}$. 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 $B^+ \rightarrow X(3872)K^+$, $X(3872) \rightarrow J/\psi \pi^+ \pi^-$ 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 $B^+ \rightarrow X(3872)K^+$ has also been confirmed by the BaBar Collaboration [3]. The $X(3872)$ mass, combining all measurements in this final state, is [4]

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

which is at the threshold for the production of the charmed meson pair $D^0 D^{*0}$. 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 $D^0 D^{*0}$ threshold: $m_{D_0} + m_{D_0} = 3871.81 \pm 0.25 \text{MeV}$ [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 $B^0 \rightarrow X(3872)K^0$ to $B^+ \rightarrow X(3872)K^+$ 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 $\theta$ is a mixing angle that is near $\pm 20^\circ$.

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 $K^0_L$ 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 $152 \times 10^6 B \bar{B}$ pairs, a 2.0 cm radius beampipe and a 3-layer silicon vertex detector (SVD-I) were used; for the remaining $505 \times 10^6 B \bar{B}$ 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 \( R_{K/\pi} = \mathcal{L}_K / (\mathcal{L}_\pi + \mathcal{L}_K) \), 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 \( R_{K/\pi} > 0.6 \) that have an 88% efficiency and a 10% efficiency for pions. \( K_S^0 \) candidates are selected within the \( \pi^+\pi^- \) mass range \([0.4840, 0.5127]\) GeV/\( c^2 \). Requirements on the \( K_S^0 \) vertex displacement from the interaction point and on the difference between vertex and \( K_S^0 \) flight directions are applied. This selection is described in detail elsewhere \([20]\).

We reconstruct \( J/\psi \) mesons in the \( l^+l^- \) decay channel \((l = e \) or \( \mu)\) 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 \( J/\psi \) 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 \( J/\psi \) 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 \( J/\psi \) 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: \( M_{\pi^+\pi^-} > M(\pi^+\pi^0J/\psi) - (m_{J/\psi} + m_{\text{cut}}) \). For \( B \rightarrow J/\psi\pi^+\pi^-K \) modes \((B \rightarrow J/\psi\pi^+\pi^-K^{+}\pi^-)\), we apply the above requirement with \( m_{\text{cut}} = 0.2 \) GeV \((m_{\text{cut}} = 0.15 \) 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 \( e^+e^- \rightarrow q\bar{q} \) 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 \( \theta_B \) 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 \( K_S^0 \) or \( K^+\pi^- \) candidate with the \( J/\psi\pi^+\pi^- \) candidate. We select \( B \) candidates using two variables: the energy difference \( \Delta E = E_B - E_{\text{beam}}^* = \sum_i \sqrt{c^2p_i^2 + c^4m_i^2} - E_{\text{beam}}^* \), and the beam constrained mass \( M_{bc} = (1/c^2)\sqrt{E_{\text{beam}}^{*2} - c^2p_B^2} = (1/c^2)\sqrt{E_{\text{beam}}^{*2} - c^2(\sum_i p_i)^2} \), 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 \( \Delta E \) closest to zero is selected. Only \( B \) candidates with \(|\Delta E| < 30 \) MeV and \( M_{bc} < 5.27 \) GeV/\( c^2 \) are considered for further analysis.

RESULTS

From this point onwards, we correct the mass measurement using the known \( J/\psi \) 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 \( B \rightarrow \psi(2S)K, \psi(2S) \rightarrow J/\psi\pi^+\pi^- \) 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.

For $X(3872)$ 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 (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 $131.7 \pm 15.0$ and $27.6 \pm 6.6$ for the $X(3872)K^+$ and the $X(3872)K^0_S$ modes respectively. The significance is determined from $-2 \ln(\mathcal{L}_0/\mathcal{L}_{\text{max}})$ where $\mathcal{L}_0$ and $\mathcal{L}_{\text{max}}$ 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 $\chi^2(n_{\text{dof}} = 2)$, as two parameters are free for the signal. The calculated significance is then $12.8\sigma$ and $5.9\sigma$, respectively.

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

$$
\frac{B(B^0 \rightarrow X(3872)K^0)}{B(B^+ \rightarrow X(3872)K^+)} = 0.82 \pm 0.22 \pm 0.05,
$$
TABLE I: \(X(3872)\) results obtained in the fit described in the text.

| Mode | Yield      | \(\epsilon(\%)\) | Significance (\(\sigma\)) | \(B \times B(X(3872) \rightarrow J/\psi\pi^+\pi^-)\) |
|------|------------|-------------------|--------------------------|------------------------------------------------|
| \(B^+ \rightarrow X(3872)K^+\) | 131.7 ± 15.0 | 20.9             | 12.8                     | \((8.10 \pm 0.92 \pm 0.66) \times 10^{-6}\)     |
| \(B^0 \rightarrow X(3872)K^0\) | 27.6 ± 6.6   | 15.2             | 5.9                      | \((6.65 \pm 1.63 \pm 0.55) \times 10^{-6}\)     |

where we assume the \(B^0 \rightarrow X(3872)K^0\) transition rate to be equal to twice the \(B^+ \rightarrow X(3872)K^+\) 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                  | \(X(3872)K^+\) | \(X(3872)K^0\) | Ratio |
|-------------------------|----------------|----------------|-------|
| \(N_{\text{MC}}\)      | 1.4            | 1.4            | -     |
| Secondary \(B\)         | 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 \(B^+ \rightarrow \psi(2S)K^+\) and 559 ± 25 events for \(B^0 \rightarrow \psi(2S)K^0\), which gives \(\frac{B(B^0 \rightarrow \psi(2S)K^0)}{B(B^+ \rightarrow \psi(2S)K^+)} = 0.72 \pm 0.04\) (stat); the systematic error is the same as that for the \(X(3872)\) case, ±0.05. The ratio was also estimated using \(\psi(2S) \rightarrow l^+l^-\) decays in the same dataset, finding \(\frac{B(B^0 \rightarrow \psi(2S)K^0)}{B(B^+ \rightarrow \psi(2S)K^+)} = 0.88 \pm 0.05\) (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 \((3685.12 \pm 0.06)\) MeV/c\(^2\) (charged mode) and \((3685.23 \pm 0.14)\) MeV/c\(^2\) (neutral mode), we find \(\delta M = -(0.11 \pm 0.15)\) MeV/c\(^2\). There is thus no significant evidence of \(\delta M\) 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)\) 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:

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

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 $B^0 \rightarrow (J/\psi \pi^+\pi^-)K^+\pi^-$ mode (Fig. 2). The signal yield is $90 \pm 19$ events. A fit to the $M_{K\pi}$ distribution is then performed to disen-

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

- tangle the $B^0 \rightarrow X(3872)K^*(892)^0$ and 3-body $B^0 \rightarrow X(3872)K^+\pi^-$ contributions to the final state. We select the events within $\pm 7$ MeV around $m_{\psi(2S)}$ and $m_{X(3872)}$ and fit their $M_{K\pi}$ distributions (Fig. 3). For the $B^0 \rightarrow \psi(2S)K^+\pi^-$ mode, the PDF for the background is the sum of a function $(M(K\pi) - m_K - m_{\pi})^b (m_B - m_{\psi(2S)} - M(K\pi))^b$, representing phase space, and a Breit-Wigner function, to describe the $K^*(892)^0$ contribution, obtained from $M(J/\psi \pi^+\pi^-)$ sidebands ($|M(J/\psi \pi^+\pi^-) - m_{\psi(2S)}| \leq 0.030 < 0.014$ 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 $963 \pm 44$ events and corresponds to $B(\psi(2S)K^*(892)^0) = (5.4 \pm 0.3 \text{ (stat)}) \times 10^{-4}$. This result is in reasonable agreement with the PDG branching fraction $\left[14\right]$, $(7.2 \pm 0.8) \times 10^{-4}$.

For the $B^0 \rightarrow X(3872)K^+\pi^-$ 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 ($|M(J/\psi \pi^+\pi^-) - m_{X(3872)}| \leq 0.030 < 0.014$ 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 $8 \pm 10$ and $81 \pm 20$ events, respectively. The $K^*(892)^0$ contribution is not significant and we set the 90% C.L. limit, $B(B^0 \rightarrow X(3872)K^*(892)^0) \times B(X(3872) \rightarrow J/\psi \pi^+\pi^-) < 3.4 \times 10^{-6}$. A product branching fraction of $B(B^0 \rightarrow X(3872)(K^+\pi^-)_{NR}) \times B(X(3872) \rightarrow J/\psi \pi^+\pi^-) = (8.1 \pm 2.0^{+1.1}_{-1.4}) \times 10^{-6}$ is also obtained. For the systematic error contributions, in addition to those that enter for
In summary, we report the first statistically significant observation of $B^+ \rightarrow X(3872)K^+$ (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, ($+0.0, -1.0\%$).

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

In summary, we report the first statistically significant observation of $B^0 \rightarrow X(3872)K_S^0$ decay and measure the ratio of branching fractions to be $\frac{B(B^0 \rightarrow X(3872)K_S^0)}{B(B^+ \rightarrow X(3872)K^+)} = 0.82 \pm 0.22 \pm 0.05$, consistent with unity. The mass difference between the $X$ states produced in these two decay modes is found to be $\delta M \equiv M_{XK^+} - M_{XK^0} = (0.18 \pm 0.09 \pm 0.26)$ MeV/$c^2$, consistent with zero. In addition, we search for the $X(3872)$ in the decay $B^0 \rightarrow X(3872)K^+\pi^-$, $X(3872) \rightarrow J/\psi\pi^+\pi^-$. We measure $B(B^0 \rightarrow X(3872)(K^+\pi^-)_{NR}) \times B(X(3872) \rightarrow J/\psi\pi^+\pi^-) = (8.1 \pm 2.0_{-1.4}^{+1.1}) \times 10^{-6}$ and we set the 90% C.L. limit, $B(B^0 \rightarrow X(3872)K^*(892)^0) \times B(X(3872) \rightarrow J/\psi\pi^+\pi^-) < 3.4 \times 10^{-6}$.

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