Observation of a narrow charmonium-like state in exclusive
$B^\pm \rightarrow K^\pm \pi^+\pi^- J/\psi$ decays

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Abstract

We report the observation of a narrow charmonium-like state produced in the exclusive decay process $B^\pm \rightarrow K^\pm \pi^+\pi^- J/\psi$. This state, which decays into $\pi^+\pi^- J/\psi$, has a mass of $3872.0 \pm 0.6\text{(stat)} \pm 0.5\text{(syst)}$ MeV, a value that is very near the $M_D + M_{D^*}$ mass threshold. The results are based on an analysis of 152M $B$-$\bar{B}$ events collected at the $\Upsilon(4S)$ resonance in the Belle detector at the KEKB collider. The signal has a statistical significance that is in excess of $10\sigma$.

PACS numbers: 14.40.Gx,12.39.Mk,13.20.He
A major experimental issue for the $\psi$ charmonium particle system is the existence of as yet unestablished charmonium states that are expected to be below threshold for decays to open charm and, thus, narrow. These include the $n = 1$ singlet $P$ state, the $J^{PC} = 1^{++} 1^{1}P_{11}$, and possibly the $n = 1$ singlet and triplet spin-2 $D$ states, i.e. the $J^{PC} = 2^{++} 1^{1}D_{12}$ and $J^{PC} = 2^{−−} 1^{3}D_{21}$, all of which are narrow if their masses are below the $DD^*$ threshold. The observation of these states and the determination of their masses would provide useful information about the spin dependence of the charmonium potential.

In addition to charmonium states, some authors have predicted the existence of $D^{(*)}D^{(*)}$ “molecular charmonium” states [1] and $\psi g$ “hybrid charmonium” states [2]. If such states exist with masses below the relevant open charm threshold, they are expected to be narrow and to have large branching fractions to low-lying $\psi$ charmonium states.

The large $B$ meson samples produced at $B$-factories provide excellent opportunities to search for new charmonium states. The Belle group recently reported the first observation of the $\eta_c(2S)$ via its $K_S K^- \pi^+$ decay channel in exclusive $B \to K K_S K^- \pi^+$ decays based on an analysis of 44.8M $B\bar{B}$ events [3]. Strategies for finding the remaining missing states have been presented by Eichten, Lane and Quigg [4]; they note that a narrow $3D_{12}$ should have substantial decay branching fractions for $\gamma \chi_{c1}$ and $\pi^+ \pi^- J/\psi$ final states. In this paper, we report on an experimental study of the $\pi^+ \pi^- J/\psi$ and $\gamma \chi_{c1}$ mass spectra from exclusive $B^+ \to K^+ \pi^+ \pi^- J/\psi$ and $K^+ \gamma \chi_{c1}$ decays [5] using a 152M $B\bar{B}$ event sample. The data were collected in the Belle detector at the KEKB energy-asymmetric $e^+e^-$ collider, which operates at a center-of-mass (CM) energy of $\sqrt{s} = 10.58$ GeV, corresponding to the mass of the $Y(4S)$ resonance. KEKB is described in detail in ref. [6].

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a three-layer silicon vertex detector, 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 of the coil is instrumented to detect $K_L$ mesons and to identify muons (KLM). The detector is described in detail elsewhere [7].

The identity of each charged track is determined by a sequence of likelihood ratios that determine the hypothesis that best matches the available information. Tracks are identified as pions or kaons based on the specific ionization in the CDC as well as the TOF and ACC responses. This classification is superseded if the track is identified as a lepton: electrons are identified by the presence of a matching ECL cluster with energy and transverse profile consistent with an electromagnetic shower; muons are identified by their range and transverse scattering in the KLM.

For the $B \to K \pi^+ \pi^- J/\psi$ study we use events that have a pair of well identified oppositely charged electrons or muons with an invariant mass in the range $3.077 < M_{\ell^+\ell^-} < 3.117$ GeV, a loosely identified charged kaon and a pair of oppositely charged pions. In order to reject background from $\gamma$ conversion products and curling tracks, we require the $\pi^+ \pi^-$ invariant mass to be greater than 0.4 GeV. To reduce the level of $e^+e^- \to q\bar{q}$ ($q = u, d, s$ or $c$-quark) continuum events in the sample, we also require $R_2 < 0.4$, where $R_2$ is the normalized Fox-Wolfram moment [8], and $|\cos \theta_B| < 0.8$, where $\theta_B$ is the polar angle of the $B$-meson direction in the CM frame.

Candidate $B^+ \to K^+ \pi^+ \pi^- J/\psi$ mesons are reconstructed using the energy difference $\Delta E \equiv E_{CM}^B - E_{CM}^{beam}$ and the beam-energy constrained mass $M_{bc} \equiv \sqrt{(E_{CM}^{beam})^2 - (p_B^{CM})^2}$, where $E_{CM}^{beam}$ is the beam energy in the CM system, and $E_{CM}^B$ and $p_B^{CM}$ are the CM energy
and momentum of the $B$ candidate. The signal region is defined as $5.271 \text{ GeV} < M_{bc} < 5.289 \text{ GeV}$ and $|\Delta E| < 0.030 \text{ GeV}$.

![Distribution of $M(\pi^+\pi^-\ell^+\ell^-) - M(\ell^+\ell^-)$ for selected events in the $\Delta E$-$M_{bc}$ signal region for (a) Belle data and (b) generic $B$-$\bar{B}$ MC events.](image)

**FIG. 1:** Distribution of $M(\pi^+\pi^-\ell^+\ell^-) - M(\ell^+\ell^-)$ for selected events in the $\Delta E$-$M_{bc}$ signal region for (a) Belle data and (b) generic $B$-$\bar{B}$ MC events.

Figure 1(a) shows the distribution of $\Delta M \equiv M(\pi^+\pi^-\ell^+\ell^-) - M(\ell^+\ell^-)$ for events in the $\Delta E$-$M_{bc}$ signal region. Here a large peak corresponding to $\psi' \rightarrow \pi^+\pi^- J/\psi$ is evident at 0.589 GeV. In addition there is a significant spike in the distribution at 0.775 GeV. Figure 1(b) shows the same distribution for a large sample of generic $B$-$\bar{B}$ Monte Carlo (MC) events. Except for the prominent $\psi'$ peak, the distribution is smooth and featureless.

In the rest of this paper we use $M(\pi^+\pi^- J/\psi)$ determined from $\Delta M + M_{J/\psi}$, where $M_{J/\psi}$ is the PDG value for the $J/\psi$ mass. The spike at $\Delta M = 0.775 \text{ GeV}$ corresponds to a mass near 3872 MeV.

We make separate fits to the data in the $\psi'$ (3580 MeV < $M_{\pi^+\pi^- J/\psi}$ < 3780 MeV) and the $M = 3872 \text{ MeV}$ (3770 MeV < $M_{\pi^+\pi^- J/\psi}$ < 3970 MeV) regions using a simultaneous unbinned maximum likelihood fit to the $M_{bc}$, $\Delta E$, and $M_{\pi^+\pi^- J/\psi}$ distributions. For the fits, the probability density functions (PDFs) for the $M_{bc}$ and $M_{\pi^+\pi^- J/\psi}$ signals are single Gaussians; the $\Delta E$ signal PDF is a double Gaussian comprised of a narrow “core” and a broad “tail”. The background PDFs for $\Delta E$ and $M_{\pi^+\pi^- J/\psi}$ are linear functions, the $M_{bc}$ background PDF is the ARGUS threshold function. For the $\psi'$ region fit, the peak positions and widths of the three signal PDFs, the $\Delta E$ core fraction, as well as the parameters of the background PDFs are left as free parameters. The values of the resolution parameters that are returned by the fit, listed in Table I, are consistent with MC-based expectations. For the fit to the $M = 3872 \text{ MeV}$ region, the $M_{bc}$ peak and width, as well as the $\Delta E$ peak, widths and core fraction are fixed at the values determined from the $\psi'$ fit.

The results of the fits are presented in Table I. Figures 2(a), (b) and (c) show the $M_{bc}$, $M_{\pi^+\pi^- J/\psi}$, and $\Delta E$ signal-band projections for the $M = 3872 \text{ MeV}$ signal region, respectively. The superimposed curves indicate the results of the fit. There are clear peaks with consistent yields in all three quantities. The signal yield of $35.7 \pm 6.8$ events has a statistical significance of $10.3\sigma$, determined from $\sqrt{-2 \ln(L_0/L_{\text{max}})}$, where $L_{\text{max}}$ and $L_0$ are the likelihood values for the best-fit and for zero-signal-yield, respectively. In the following we refer to this as the $X(3872)$. 

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TABLE I: Resolution values from the fits to the $\psi'$ signal region. The errors are statistical only.

| Quantity          | Fitted value     |
|-------------------|------------------|
| $\sigma_{M_{bc}}$ | 2.6 $\pm$ 0.1 MeV |
| $\sigma_{\Delta E(\text{core})}$ | 11.6 $\pm$ 0.4 MeV |
| $\sigma_{\Delta E(\text{tail})}$ | 130 $\pm$ 130 MeV |
| Core fraction     | 0.965 $\pm$ 0.015 |

FIG. 2: Signal-band projections of (a) $M_{bc}$, (b) $M_{\pi^+\pi^-J/\psi}$ and (c) $\Delta E$ for the $X(3872) \rightarrow \pi^+\pi^-J/\psi$ signal region with the results of the unbinned fit superimposed.

We determine the mass of the signal peak relative to the well measured $\psi'$ mass:

$$M_X = M_{X}^{\text{meas}} - M_{\psi'}^{\text{meas}} + M_{\psi'}^{\text{PDG}} = 3872.0 \pm 0.6 \pm 0.5 \text{ MeV}. $$

Here the first error is statistical and the second systematic. Since we use the precisely known value of the $\psi'$ mass as a reference, the systematic error is small. The $M_{\psi'}$ measurement, which is referenced to the $J/\psi$ mass that is 589 MeV away, is $-0.5 \pm 0.2$ MeV from its world-average value. Variation of the mass scale from $M_{\psi'}$ to $M_X$ requires an extrapolation of only 186 MeV and, thus, can safely be expected to be less than this amount. We assign 0.5 MeV as the systematic error on the mass.

The measured width of the $X(3872)$ peak is $\sigma = 2.5 \pm 0.5$ MeV, which is consistent with the MC-determined resolution and the value obtained from the fit to the $\psi'$ signal. To determine an upper limit on the total width, we repeated the fits using a resolution-

TABLE II: Results of the fits to the $\psi'$ and $M = 3872$ MeV regions. The errors are statistical only.

| Quantity          | $\psi'$ region | $M = 3872$ MeV region |
|-------------------|----------------|-----------------------|
| Signal events     | 489 $\pm$ 23   | 35.7 $\pm$ 6.8        |
| $M_{\pi^+\pi^-J/\psi}^{\text{meas}}$ | 3685.5 $\pm$ 0.2 MeV | 3871.5 $\pm$ 0.6 MeV |
| $\sigma_{M_{\pi^+\pi^-J/\psi}}$ | 3.3 $\pm$ 0.2 MeV | 2.5 $\pm$ 0.5 MeV |
broadened Breit-Wigner (BW) function to represent the signal. This fit gives a BW width parameter that is consistent with zero: $\Gamma = 1.4 \pm 0.7$ MeV. From this we infer a 90% confidence level (CL) upper limit of $\Gamma < 2.3$ MeV.

The open histogram in Fig. 3(a) shows the $\pi^+\pi^-$ invariant mass distribution for events in a $\pm 5$ MeV window around the $X(3872)$ peak; the shaded histogram shows the corresponding distribution for events in the non-signal $\Delta E-M_{bc}$ region, normalized to the signal area. The $\pi^+\pi^-$ invariant masses tend to cluster near the kinematic boundary, which is around the $\rho$ mass; the entries below the $\rho$ are consistent with background. For comparison, we show the $\pi^+\pi^-$ mass distribution for the $\psi'$ events in Fig. 3(b), where the horizontal scale is shifted and expanded to account for the different kinematically allowed region. This distribution also peaks near the upper kinematic limit, which in this case is near 590 MeV.

We determine a ratio of product branching fractions for $B^+ \rightarrow K^+ X(3872)$, $X(3872) \rightarrow \pi^+\pi^- J/\psi$ and $B^+ \rightarrow K^+\psi'$, $\psi' \rightarrow \pi^+\pi^- J/\psi$ to be

$$\frac{\mathcal{B}(B^+ \rightarrow K^+ X(3872)) \times \mathcal{B}(X(3872) \rightarrow \pi^+\pi^- J/\psi)}{\mathcal{B}(B^+ \rightarrow K^+\psi') \times \mathcal{B}(\psi' \rightarrow \pi^+\pi^- J/\psi)} = 0.063 \pm 0.012({\text{stat}}) \pm 0.007({\text{syst}}).$$

Here the systematic error is mainly due to the uncertainties in the efficiency for the $X(3872) \rightarrow \pi^+\pi^- J/\psi$ channel, which is estimated with MC simulations that use different models for the decay $[14]$.

The decay of the $^3D_{c2}$ charmonium state to $\gamma\chi_{c1}$ is an allowed $E1$ transition with a partial width that is expected to be substantially larger than that for the $\pi^+\pi^- J/\psi$ final state; e.g. the authors of Ref. [4] predict $\Gamma(^3D_{c2} \rightarrow \gamma\chi_{c1}) > 5 \times \Gamma(^3D_{c2} \rightarrow \pi^+\pi^- J/\psi)$. Thus, a measurement of the width for this decay channel can provide important information about the nature of the observed state. We searched for an $X(3872)$ signal in the $\gamma\chi_{c1}$ decay channel, concentrating on the $\chi_{c1} \rightarrow J/\psi$ final state.

We select events with the same $J/\psi \rightarrow \ell^+\ell^-$ and charged kaon requirements plus two photons, each with energy more than 40 MeV. We reject photons that form a $\pi^0$ when
combined with any other photon in the event. We require one of the $\gamma J/\psi$ combinations to satisfy $398 \text{ MeV} < (M_{\gamma e^+e^-} - M_{\ell^+\ell^-}) < 423 \text{ MeV}$ (corresponding to $-15 \text{ MeV} < (M_{\gamma J/\psi} - M_{\chi_{c1}}) < 10 \text{ MeV}$). In the following we use $M_{\gamma\chi_{c1}} \equiv M_{\gamma e^+e^-} - M_{\ell^+\ell^-} + M_{\chi_{c1}}^{PDG}$, where $M_{\chi_{c1}}^{PDG}$ is the PDG $\chi_{c1}$ mass value [9].

The $B \to K\gamma\chi_{c1}$, $\chi_{c1} \to \gamma J/\psi$ decay processes have a large combinatoric background from $B \to K\chi_{c1}$ decays plus an uncorrelated $\gamma$ from the accompanying $B$ meson. This background, which tends to peak in the $M_{bc}$ signal region, produces a peaking in $\Delta E$ at positive values that is well separated from zero, and is removed by the $\Delta E < 30 \text{ MeV}$ requirement. Because of the complicated $\Delta E$ background shape and its correlation with $M_{bc}$, we do not include $\Delta E$ in the unbinned likelihood fit. Instead we do an unbinned fit to the $M_{\gamma\chi_{c1}}$ and $M_{bc}$ distributions with the same signal and background PDFs for $M_{bc}$ and $M_{\gamma\chi_{c1}}$ that are used for the $\pi^+\pi^- J/\psi$ fits. We fix the values of the Gaussian widths at their MC values, and the $\psi'$ and $X(3872)$ masses at the values found from the fits to the $\pi^+\pi^- J/\psi$ channels. The signal yields and background parameters are allowed to float.

The signal-band projections of $M_{bc}$ and $M_{\gamma\chi_{c1}}$ for the $\psi'$ region are shown in Figs. 4(a) and (b), respectively, together with curves that represent the results of the fit. The fitted signal yield is $34.1 \pm 6.9 \pm 4.1$ events, where the first error is statistical and the second is a systematic error determined by varying the $M_{bc}$ and $M_{\gamma\chi_{c1}}$ resolutions over their allowed range of values. The number of observed events is consistent with the expected yield of $26 \pm 4$ events based on the known $B \to K\psi'$ and $\psi' \to \gamma\chi_{c1}$ branching fractions [9] and the MC-determined acceptance.

The results of the application of the same procedure to the $M = 3872$ MeV region are shown in Figs. 4(c) and (d). Here, no signal is evident; the fitted signal yield is $3.7 \pm 3.7 \pm 2.2$ events, where the first error is statistical and the second is a systematic error determined by varying the input parameters to the fit over their allowed range. From these results, we
determine a 90% CL upper limit on the ratio of partial widths of
\[
\frac{\Gamma(X(3872) \to \gamma \chi_{c1})}{\Gamma(X(3872) \to \pi^+ \pi^- J/\psi)} < 0.89 \quad (90\% \text{ CL}),
\]
where the effects of systematic errors have been included. This limit on the $\gamma \chi_{c1}$ decay width contradicts expectations for the $^3D_{c2}$ charmonium state.

The mass of the observed state is higher than potential model expectations for the center-of-gravity (cog) of the $^3D_{cJ}$ states: the Cornell \cite{15} and the Buchmüller-Tye \cite{16} potentials both give $M_{\text{cog}}(1D) = 3810$ MeV, which is 60 MeV below our measurement. A model by Godfrey and Isgur \cite{17} gives a $^3D_{c2}$ mass of 3840 MeV but also predicts a $^3D_{c1}$ of 3820 MeV, which is higher than its observed value of 3770 MeV. Identification of the observed state with the $^3D_{c2}$ state would imply a $^3D_{c2} - ^3D_{c1}$ splitting of $\sim 100$ MeV. On the other hand, complications due to effects of coupling to real $D \bar{D}$ and virtual $D \bar{D}^*$ states may reduce the validity of potential model calculations for these states \cite{15}.

The $\pi^+ \pi^-$ invariant masses for the $M = 3872$ MeV signal region concentrate near the upper kinematic boundary as is also the case for $\psi' \to \pi^+ \pi^- J/\psi$ (see Figs. 3(a) and (b)). For the $M = 3872$ MeV signal region, however, the boundary corresponds to the mass of the $\rho$. The decay of a $c \bar{c}$ charmonium state to $\rho J/\psi$ is an isospin-violating process, and these are strongly suppressed in $\psi' \to J/\psi$ transitions. With more data, we will be able to determine whether or not the $\pi^+ \pi^-$ system is coming from $\rho$ meson decay \cite{18} and thereby establish the $C$ parity of the $X(3872)$. Information about other possible decay channels, such as $D \bar{D}$, $DD^0$ and $D \bar{D} \gamma$, would be useful for determining other quantum numbers of this state \cite{19}.

In summary, we have observed a strong signal for a state that decays to $\pi^+ \pi^- J/\psi$ with
\[
M = 3872.0 \pm 0.6 \pm 0.5 \ (\text{stat}) \pm 0.5 \ (\text{syst}) \text{ MeV}
\Gamma < 2.3 \text{ MeV} \ (90\% \text{ CL}).
\]
This mass value and the absence of a strong signal in the $\gamma \chi_{c1}$ decay channel are in some disagreement with potential model expectations for the $^3D_{c2}$ charmonium state. The mass is within errors of the $D^0 \bar{D}^*$ mass threshold ($3871.1 \pm 1.0$ MeV \cite{4}), which is suggestive of a loosely bound $D \bar{D}^*$ multiquark “molecular state,” as proposed by some authors \cite{1, 20}.

We thank E. Eichten, K. Lane, C. Quigg, J. Rosner and T. Skwarnicki for useful comments. We acknowledge support from the Ministry of Education, Culture, Sports, Science, and Technology of Japan and the Japan Society for the Promotion of Science; the Australian Research Council and the Australian Department of Industry, Science and Resources; the National Science Foundation of China under contract No. 10175071; the Department of Science and Technology of India; the BK21 program of the Ministry of Education of Korea and the CHEP SRC program of the Korea Science and Engineering Foundation; the Polish State Committee for Scientific Research under contract No. 2P03B 01324; the Ministry of Science and Technology of the Russian Federation; the Ministry of Education, Science and Sport of the Republic of Slovenia; the National Science Council and the Ministry of Education of Taiwan; and the U.S. Department of Energy.

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[1] See, for example, M. Bander, G.L. Shaw and P. Thomas, Phys. Rev. Lett. 36, 695 (1977); M.B. Voloshin and L.B. Okun, JETP Lett. 23, 333 (1976); A. De Rujula, H. Georgi and S.L. Glashow, Phys. Rev. Lett. 38, 317 (1977); N.A. Törnqvist, Z. Phys. C61, 525 (1994); and A.V. Manohar and M.B. Wise, Nucl. Phys. B339, 17 (1993).

[2] See, for example, S. Godfrey and J. Napolitano, Rev. Mod. Phys. 71, 1411 (1999), and reference cited therein.

[3] S.K. Choi et al. (Belle Collaboration), Phys. Rev. Lett. 89, 102001 (2002).

[4] E.J. Eichten, K. Lane, and C. Quigg, Phys. Rev. Lett. 89, 162002 (2002). See also P. Ko, J. Lee and H.S. Song, Phys. Lett. B395, 107 (1997) and F. Yuan, C.-F. Qiao and K.-T. Chao, Phys. Rev. D56, 329 (1997).

[5] In this paper, the inclusion of charge conjugate states is always implied.

[6] S. Kurokawa and E. Kikutani, Nucl. Inst. Meth. A499, 1 (2003).

[7] A. Abashian et al. (Belle Collaboration), Nucl. Inst. Meth. A479, 117 (2002).

[8] G.C. Fox and S. Wolfram, Phys. Rev. Lett. 41, 1581 (1978).

[9] K. Hagiwara et al. (Particle Data Group), Phys. Rev. D66, 10001 (2002).

[10] We use the RooFit fitting package: W. Verkerke and D. Kirkby, physics/0306116. In addition to the $M_{\pi^+\pi^-J/\psi}$ regions listed in the text, the fit extends over $5.2 < M_{bc} < 5.29$ GeV and $-0.10 < \Delta E < 0.20$ GeV.

[11] There are potential peaking backgrounds in $M_{bc}$ and $\Delta E$. Measurements using $M_{\pi^+\pi^-J/\psi}$ sidebands indicate that they are small and have a negligible effect on the signal yield at the current level of statistics.

[12] H. Albrecht et al. (ARGUS Collaboration), Phys. Lett. B241, 278 (1990).

[13] We use the PDG 2002 [9] average value of $M_{\psi'} - M_{J/\psi} = 589.07 \pm 0.13$ MeV. A recent more precise measurement of $589.194 \pm 0.027 \pm 0.011$ MeV has recently been reported by V.M. Aulchenko et al. (KEDR Collaboration), hep-ex/0306050.

[14] As extreme models we generate $X \to \pi^+\pi^-J/\psi$ final states according to phase space and as a two-body $X \to \rho J/\psi$ process. For the acceptance we use the average, with the differences from the average taken as the error.

[15] E. Eichten, K. Gottfried, T. Kinoshita, K.D.Lane and T.M. Yan, Phys. Rev. D21, 203 (1980).

[16] W. Buchmüller and S-H.H. Tye, Phys. Rev. D24, 132 (1981).

[17] S. Godfrey and N. Isgur, Phys. Rev. D32, 189 (1985).

[18] S. Pakvasa and M. Suzuki, hep-ph/0309294.

[19] M.B. Voloshin hep-ph/0309307.

[20] N.A. Törnqvist, hep-ph/0308277; and F.E. Close and P.R. Page, hep-ph/0309253.