Observation of a Narrow Charmoniumlike State in Exclusive $B^\pm \to K^\pm \pi^+ \pi^- J/\psi$ Decays


(Belle Collaboration)

1Budker Institute of Nuclear Physics, Novosibirsk
2Chiba University, Chiba
3University of Cincinnati, Cincinnati, Ohio 45221
4University of Frankfurt, Frankfurt
5Gyeongsang National University, Chinju
6University of Hawaii, Honolulu, Hawaii 96822
7High Energy Accelerator Research Organization (KEK), Tsukuba
8Hiroshima Institute of Technology, Hiroshima
9Institute of High Energy Physics, Chinese Academy of Sciences, Beijing
10Institute of High Energy Physics, Vienna
11Institute for Theoretical and Experimental Physics, Moscow
12J. Stefan Institute, Ljubljana
13Kanagawa University, Yokohama
14Korea University, Seoul
15Kyungpook National University, Taegu
16Institut de Physique des Hautes Énergies, Université de Lausanne, Lausanne
17University of Ljubljana, Ljubljana
18University of Maribor, Maribor
19University of Melbourne, Victoria
20Nagoya University, Nagoya
21Nara Women's University, Nara
22National Kaohsiung Normal University, Kaohsiung
23National Lien-Ho Institute of Technology, Miaoli Li
24Department of Physics, National Taiwan University, Taipei
25H. Niewodniczanski Institute of Nuclear Physics, Krakow
26Nihon Dental College, Niigata
27Niigata University, Niigata
28Osaka City University, Osaka
29Osaka University, Osaka

PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2003
VOLUME 91, NUMBER 26 262001-1 0031-9007 = 03 = 91(26) = 262001(6)$20.00 C 2003 The American Physical Society 262001-1
We report the observation of a narrow charmoniumlike state produced in the exclusive decay process $B^+ \rightarrow K^\pm \pi^\mp J/\psi$. This state, which decays into $\pi^+ \pi^- J/\psi$, has a mass of 3872.0 ± 0.6(stat) ± 0.5(syst) MeV, a value that is very near the $M_{D^0} + M_{D^*0}$ mass threshold. The results are based on an analysis of 152 M $B\bar{B}$ events collected at the Y(4S) resonance in the Belle detector at the KEKB collider. The signal has a statistical significance that is in excess of 10σ.

A major experimental issue for the $c\bar{c}$ 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 $J^{PC} = 2^{-} + 1^{1}P_{11}$, and possibly the $n = 1$ singlet and triplet spin-2 $D$ states, i.e., the $J^{PC} = 2^{-} + 1^{1}D_{12}$ and $J^{PC} = 2^{-} - 1^{3}D_{12}$, all of which are narrow if their masses are below the $D\bar{D}$ threshold. The observation of these states and the determination of their masses provides useful information about the spin dependence of the charmonium potential.

In addition to charmonium states, some authors have predicted the existence of $D^{(*)}\bar{D}^{(*)}$ “molecular charmonium” states [1] and $c\bar{c}g$ “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 $c\bar{c}$ 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 $K_S^0 K^-\pi^+$ decay channel in exclusive $B \rightarrow KK_S^0 K^-\pi^+$ decays based on an analysis of 44.8 M $B\bar{B}$ events [3]. Strategies for finding the remaining missing states have been presented by Eichten, Lane, and Quigg [4]; they note that a narrow $3D_{c2}$ should have substantial decay branching fractions for $\gamma\chi_{c1}$ and $\pi^+ \pi^- J/\psi$ final states. In this Letter, we report on an experimental study of the $\pi^+ \pi^- J/\psi$ and $\gamma\chi_{c1}$ mass spectra from exclusive $B^+ \rightarrow K^+ \pi^+ \pi^- J/\psi$ and $K^+ \gamma\chi_{c1}$ decays [5] using a 152 M $B\bar{B}$ 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), and an electromagnetic calorimeter (ECL) composed 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 $K_L^0$ mesons and to identify muons (KLM). The detector is described in detail elsewhere [7].

Charged tracks are identified as pions or kaons using likelihood ratios based on the TOF and ACC responses as
and as the specific ionization in the CDC. 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 \( B \rightarrow K \pi^+ \pi^- J/\psi \) study we use events that have a pair of well identified oppositely charged electrons or muons with an invariant mass in the range \( 3.077 < M_{e^+e^-} < 3.117 \) GeV, a loosely identified charged kaon, and a pair of oppositely charged pions. In order to reject background from \( \gamma \) conversion products and curving tracks, we require the \( \pi^+ \pi^- \) invariant mass to be greater than 0.4 GeV. To reduce the level of \( e^+e^- \rightarrow q\bar{q} \) (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 \( B \rightarrow K^+ \pi^+ \pi^- J/\psi \) mesons are reconstructed using the energy difference \( \Delta E \equiv E_{CM}^B - E_{CM}^{beam} \) and the beam-energy constrained mass \( M_{bc} = \sqrt{(E_{CM}^{beam})^2 - (p_B^CM)^2} \), where \( E_{CM}^B \) is the beam energy in the CM system, and \( E_{CM}^B \) and \( p_{CM}^B \) are the CM energy and momentum of the \( B \) candidate. The signal region is defined as \( 5.271 \) GeV < \( M_{bc} < 5.289 \) GeV and \( |\Delta E| < 0.030 \) GeV.

Figure 1(a) shows the distribution of \( \Delta M = M(\pi^+ \pi^- \ell^+ \ell^-) - M(\ell^+ \ell^-) \) 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 \( B \rightarrow \bar{B} \) Monte Carlo (MC) events. Except for the prominent \( \psi' \) peak, the distribution is smooth and featureless. In the rest of this Letter we use \( M(\pi^+ \pi^- J/\psi) \) determined from \( \Delta M + M_{J/\psi} \), where \( M_{J/\psi} \) is the PDG [9] value for the \( J/\psi \) mass. The spike at \( \Delta M = 0.775 \) 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 \( M = 3872 \) 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 [10]. 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 composed of a narrow “core” and a broad “tail.” The background PDFs for \( \Delta E \) and \( M_{\pi^+ \pi^- J/\psi} \) are linear functions, and the \( M_{bc} \) background PDF is the ARGUS threshold function [11].

The signal PDF is a double Gaussian composed of a narrow “core” and a broad “tail.” The background PDFs for \( \Delta E \) and \( M_{\pi^+ \pi^- J/\psi} \) are linear functions, and the \( M_{bc} \) background PDF is the ARGUS threshold function [11]. 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 are consistent with MC-based expectations.

The results of the fits are presented in Table I. Figures 2(a)–2(c) show the \( M_{bc} \), \( M_{\pi^+ \pi^- J/\psi} \), and \( \Delta E \) signal-band projections for the \( M = 3872 \) 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 ± 0.8 events has a statistical significance of 10.3σ, determined from \( -2 \ln(L_0/L_{max}) \), where \( L_{max} \) 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 \( \psi' \) fit.

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

\[
M_X = M_X^{\text{meas}} - M_{\psi'}^{\text{meas}} + M_{\psi'}^{\text{PDG}} = 3872.0 \pm 0.6 \text{(stat)} \pm 0.5 \text{(syst)} \text{ MeV.}
\]

Since we use the precisely known value of the \( \psi' \) mass [9] 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 \( \pm 0.5 \) ± 0.2 MeV from its world-average value [12]. Variation of the mass scale from \( M_{\psi'} \) to \( M_X \) requires an extrapolation of only 186 MeV and, thus, the systematic shift in \( M_X \) 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 \( \psi' \) region.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>( \psi' ) region</th>
<th>( M = 3872 ) MeV region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal events</td>
<td>489 ± 23</td>
<td>35.7 ± 6.8</td>
</tr>
<tr>
<td>( M_{\pi^+ \pi^- J/\psi}^{\text{meas}} ) Peak</td>
<td>3685.5 ± 0.2 MeV</td>
<td>3871.5 ± 0.6 MeV</td>
</tr>
<tr>
<td>( \sigma_{M_{\pi^+ \pi^- J/\psi}} )</td>
<td>3.3 ± 0.2 MeV</td>
<td>2.5 ± 0.5 MeV</td>
</tr>
</tbody>
</table>
signal. To determine an upper limit on the total width, we repeated the fits using a resolution-broadened Breit-Wigner (BW) function to represent the signal. This fit gives a BW width parameter that is consistent with zero:

\[
\frac{\mathcal{B}(B^+ \to K^+ \chi_{c1}(3872)) \times \mathcal{B}(X(3872) \to \pi^+ \pi^- J/\psi)}{\mathcal{B}(B^+ \to K^+ \psi') \times \mathcal{B}(\psi' \to \pi^+ \pi^- J/\psi)} = 0.063 \pm 0.012({\text{stat}}) \pm 0.007({\text{syst}}).
\]

Here the systematic error is mainly due to the uncertainties in the efficiency for the \(X(3872) \to \pi^+ \pi^- J/\psi\) channel, which is estimated with MC simulations that use different models for the decay [13].

The decay of the \(3D_{2}\) 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 \(\Gamma(3D_{2} \to \gamma \chi_{c1}) > 5 \times \Gamma(3D_{2} \to \pi^+ \pi^- J/\psi)\). We searched for an \(X(3872)\) signal in the \(\gamma \chi_{c1}\) decay channel, concentrating on the \(\chi_{c1} \to J/\psi\) final state.

We select events with the same \(J/\psi \to \ell^+ \ell^-\) 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

\[
|\Gamma(3D_{2} \to \gamma \chi_{c1})| < 423 \text{ MeV} \quad (398 \text{ MeV} \leq (M_{\gamma} - M_{\pi^0}) < 423 \text{ MeV})
\]

in the likelihood fit. Instead, we perform 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 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 4(b), respectively, together with curves that show the results of the fit. The fitted signal yield is \(34.1 \pm 6.9 \pm 4.1 \text{ events}\), 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 \(26 \pm 4 \text{ events based on the known } B \to K \psi' \text{ and } \psi' \to \gamma \chi_{c1} \text{ branching fractions} [9]\) and the MC-determined acceptance.

The results of the application of the same procedure to the \(X(3872)\) mass region are shown in Figs. 4(c) and 4(d). Here, no signal is evident; the fitted signal yield is

\[
\Gamma = 1.4 \pm 0.7 \text{ MeV}.\]

From this we infer a 90% confidence level (C.L.) upper limit of \(\Gamma < 2.3 \text{ MeV}\).

The open histogram in Fig. 3(a) shows the \(\pi^+ \pi^-\) invariant mass distribution for events in a \(\pm 5 \text{ MeV}\) window around the \(X(3872)\) peak; the shaded histogram shows the corresponding distribution for events in the nonsignal \(\Delta E-M_{bc}\) 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 \(B^+ \to K^+ X(3872)\), \(X(3872) \to \pi^+ \pi^- J/\psi\) and \(B^+ \to K^+ \psi', \psi' \to \pi^+ J/\psi\) to be

\[
\mathcal{B}(B^+ \to K^+ X(3872)) \times \mathcal{B}(X(3872) \to \pi^+ \pi^- J/\psi) = 0.063 \pm 0.012({\text{stat}}) \pm 0.007({\text{syst}}).
\]
where the effects of systematic errors have been included. From these results, we determine a 90% C.L. upper limit on the ratio of partial widths of

\[
\frac{\Gamma(X(3872) \to \gamma_{\chi_{c1}})}{\Gamma(X(3872) \to \pi^+\pi^-J/\psi)} < 0.89 \quad (90\% \text{ C.L.}),
\]

where the effects of systematic errors have been included. This limit on the \(\gamma_{\chi_{c1}}\) decay width contradicts expectations for the \(3^3D_{12}\) charmonium state.

The mass of the observed state is higher than potential model expectations for the center of gravity (cog) of the \(1^3D_{12}\) states: the Cornell [14] and the Buchmüller-Tye [15] potentials both give \(M_{\text{cog}}(1D) = 3810\) MeV, which is 60 MeV below our measurement. A model by Godfrey and Isgur [16] gives a \(3^3D_{12}\) mass of 3840 MeV but also predicts a \(3^3D_{11}\) of 3820 MeV, which is higher than its observed value of 3770 MeV. Identification of the \(X(3872)\) with the \(3^3D_{12}\) state would imply a large \(3^3D_{2} - 3^3D_{11}\) splitting of \(\sim 100\) MeV. However, effects of coupling to real \(D\bar{D}\) and virtual \(D\bar{D}^*\) states may reduce the reliability of potential model calculations for these states [14].

The \(\pi^+\pi^-\) invariant masses for \(X(3872) \to \pi^+\pi^-J/\psi\) concentrate near the upper kinematic boundary as is also the case for \(\psi' \to \pi^+\pi^-J/\psi\) [see Figs. 3(a) and 3(b)]. For the \(X(3872)\), however, the boundary corresponds to the \(\rho\) meson mass. Charmonium decays to \(\rho J/\psi\) violate isospin, and are expected to be suppressed. More data will enable us to determine whether or not the \(\pi^+\pi^-\) system is coming from \(\rho\) meson decay [17] and thereby establish the \(C\) parity of the \(X(3872)\). Information about other possible decay channels, such as \(D\bar{D}, D\bar{D}\pi^0\), and \(D\bar{D}\gamma\), would be useful for determining other quantum numbers of this state [18].

In summary, we have observed a strong signal for a state that decays to \(\pi^+\pi^-J/\psi\) with

\[
M = 3872.0 \pm 0.6(\text{stat}) \pm 0.5(\text{syst}) \text{ MeV},
\]

\[
\Gamma < 2.3 \text{ MeV} \quad (90\% \text{ C.L.}).
\]

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 \(3^3D_{12}\) charmonium state. The mass is within errors at the \(D^0\bar{D}^0\) mass threshold (3871.1 \pm 1.0 MeV [9]), which is suggestive of a loosely bound \(D\bar{D}^*\) multiquark “molecular state,” as proposed by some authors [1,19].

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.

---

*a On leave from Fermi National Accelerator Laboratory, Batavia, IL 60510.

†On leave from Nova Gorica Polytechnic, Nova Gorica.


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


[10] We use the RooFit fitting package: W. Verkerke and D. Kirkby, physics/0306116. The fit extends over

FIG. 4 (color online). Signal-band projections of (a) \(M_{bc}\) and (b) \(M_{bc}\) for the \(\psi'\) region with the results of the unbinned fit superimposed. (c),(d) The corresponding results for the \(M = 3872\) MeV region.
5.2 GeV < M_{bc} < 5.29 GeV and −0.10 GeV < ΔE < 0.20 GeV.


[12] We use the PDG 2002 [9] average value of $M_{J/ψ} = 589.07 \pm 0.13$ MeV. A recent more precise measurement of $589.194 \pm 0.027 \pm 0.011$ MeV has recently been reported by KEDR Collaboration, V. M. Aulchenko et al., Phys. Lett. B 573, 63 (2003).

[13] We generate $X \rightarrow π^+ π^- J/ψ$ final states according to phase space and as a two-body $X \rightarrow ρJ/ψ$ process. For the acceptance we use the average, with the differences from the average as the error.


