

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

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We report the observation of a narrow charmoniumlike 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  $M_{D^0} + M_{D^{*0}}$  mass threshold. The results are based on an analysis of 152M  $B\text{-}\bar{B}$  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  $10\sigma$ .

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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  $J^{PC} = 1^{+-}1^1P_{c1}$ , and possibly the  $n = 1$  singlet and triplet spin-2  $D$  states, i.e., the  $J^{PC} = 2^{-+}1^1D_{c2}$  and  $J^{PC} = 2^{-+}1^3D_{c2}$ , 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  $K_S K^- \pi^+$  decay channel in exclusive  $B \rightarrow K K_S K^- \pi^+$  decays based on an analysis of 44.8 M  $B\text{-}\bar{B}$  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  $B\text{-}\bar{B}$  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  $\Upsilon(4S)$  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) 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  $K_L$  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

well 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  $3.077 < M_{\ell^+\ell^-} < 3.117$  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  $e^+e^- \rightarrow q\bar{q}$  ( $q = u, d, s,$  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  $\Delta E \equiv E_B^{\text{CM}} - E_{\text{beam}}^{\text{CM}}$  and the beam-energy constrained mass  $M_{\text{bc}} \equiv \sqrt{(E_{\text{beam}}^{\text{CM}})^2 - (p_B^{\text{CM}})^2}$ , where  $E_{\text{beam}}^{\text{CM}}$  is the beam energy in the CM system, and  $E_B^{\text{CM}}$  and  $p_B^{\text{CM}}$  are the CM energy and momentum of the  $B$  candidate. The signal region is defined as  $5.271 \text{ GeV} < M_{\text{bc}} < 5.289 \text{ GeV}$  and  $|\Delta E| < 0.030 \text{ GeV}$ .

Figure 1(a) shows the distribution of  $\Delta M \equiv M(\pi^+\pi^-\ell^+\ell^-) - M(\ell^+\ell^-)$  for events in the  $\Delta E$ - $M_{\text{bc}}$  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 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  $\Delta M = 0.775 \text{ GeV}$  corresponds to a mass near 3872 MeV.

We make separate fits to the data in the  $\psi'$  ( $3580 \text{ MeV} < M_{\pi^+\pi^-J/\psi} < 3780 \text{ MeV}$ ) and the  $M =$

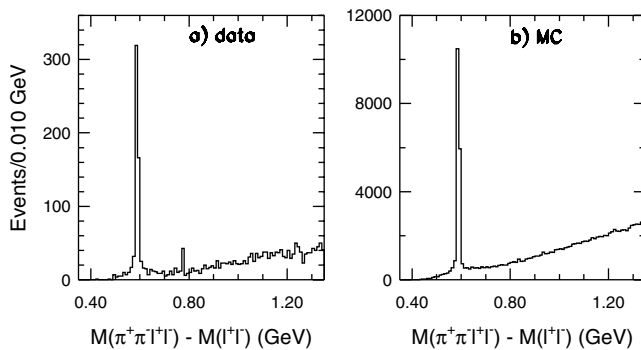


FIG. 1. Distribution of  $M(\pi^+\pi^-\ell^+\ell^-) - M(\ell^+\ell^-)$  for selected events in the  $\Delta E$ - $M_{\text{bc}}$  signal region for (a) Belle data and (b) generic  $B$ - $\bar{B}$  MC events.

3872 MeV ( $3770 \text{ MeV} < M_{\pi^+\pi^-J/\psi} < 3970 \text{ MeV}$ ) regions using a simultaneous unbinned maximum likelihood fit to the  $M_{\text{bc}}$ ,  $\Delta E$ , and  $M_{\pi^+\pi^-J/\psi}$  distributions [10]. For the fits, the probability density functions (PDFs) for the  $M_{\text{bc}}$  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  $M_{\text{bc}}$  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. For the fit to the  $M = 3872 \text{ MeV}$  region, the  $M_{\text{bc}}$  peak and width, as well as the  $\Delta E$  peak, widths, and core fraction (96.5%) are fixed at the values determined from the  $\psi'$  fit.

The results of the fits are presented in Table I. Figures 2(a)–2(c) show the  $M_{\text{bc}}$ ,  $M_{\pi^+\pi^-J/\psi}$ , 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  $\sqrt{-2 \ln(\mathcal{L}_0/\mathcal{L}_{\text{max}})}$ , where  $\mathcal{L}_{\text{max}}$  and  $\mathcal{L}_0$  are the likelihood values for the best-fit and for zero-signal yield, respectively. In the following we refer to this as the  $X(3872)$ .

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

$$\begin{aligned} M_X &= M_X^{\text{meas}} - M_{\psi'}^{\text{meas}} + M_{\psi'}^{\text{PDG}} \\ &= 3872.0 \pm 0.6(\text{stat}) \pm 0.5(\text{syst}) \text{ MeV}. \end{aligned}$$

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  $-0.5 \pm 0.2 \text{ MeV}$  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  $\sigma = 2.5 \pm 0.5 \text{ MeV}$ , which is consistent with the MC-determined resolution and the value obtained from the fit to the  $\psi'$

TABLE I. Results of the fits to the  $\psi'$  and  $M = 3872 \text{ MeV}$  regions. The errors are statistical only.

Quantity	$\psi'$ region	$M = 3872 \text{ MeV}$ region
Signal events	$489 \pm 23$	$35.7 \pm 6.8$
$M_{\pi^+\pi^-J/\psi}^{\text{meas}}$ peak	$3685.5 \pm 0.2 \text{ MeV}$	$3871.5 \pm 0.6 \text{ MeV}$
$\sigma_{M_{\pi^+\pi^-J/\psi}}$	$3.3 \pm 0.2 \text{ MeV}$	$2.5 \pm 0.5 \text{ MeV}$

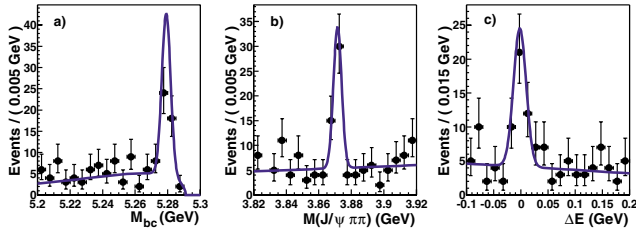


FIG. 2 (color online). Signal-band projections of (a)  $M_{bc}$ , (b)  $M_{\pi^+\pi^- J/\psi}$ , and (c)  $\Delta E$  for the  $X(3872) \rightarrow \pi^+\pi^- J/\psi$  signal region with the results of the unbinned fit superimposed.

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:

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

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 [13].

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  $\Gamma(^3D_{c2} \rightarrow \gamma\chi_{c1}) > 5 \times \Gamma(^3D_{c2} \rightarrow \pi^+\pi^- J/\psi)$ . We searched for an  $X(3872)$  signal in the  $\gamma\chi_{c1}$  decay channel, concentrating on the  $\chi_{c1} \rightarrow \gamma J/\psi$  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

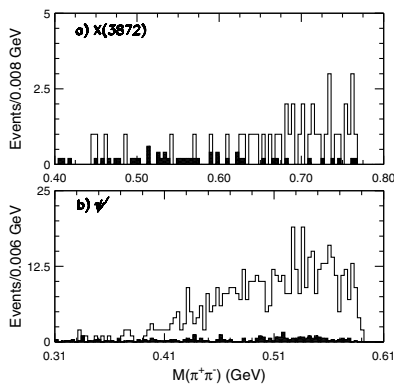


FIG. 3.  $M(\pi^+\pi^-)$  distribution for events in the (a)  $M(\pi^+\pi^- J/\psi) = 3872$  MeV signal region, and (b) the  $\psi'$  region. The shaded histograms are sideband data normalized to the signal-box area. Note the different horizontal scales.

$\Gamma = 1.4 \pm 0.7$  MeV. From this we infer a 90% confidence level (C.L.) 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 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  $B^+ \rightarrow K^+ X(3872)$ ,  $X(3872) \rightarrow \pi^+\pi^- J/\psi$  and  $B^+ \rightarrow K^+ \psi'$ ,  $\psi' \rightarrow \pi^+\pi^- J/\psi$  to be

$398 \text{ MeV} < (M_{\gamma\ell^+\ell^-} - M_{\ell^+\ell^-}) < 423 \text{ MeV}$  (corresponding to  $-15 \text{ MeV} < (M_{\gamma J/\psi} - M_{\chi_{c1}}) < 10 \text{ MeV}$ ). In the following we use  $M_{\gamma\chi_{c1}} \equiv M_{\gamma\ell^+\ell^-} - M_{\gamma\ell^+\ell^-} + M_{\chi_{c1}}^{\text{PDG}}$ , where  $M_{\chi_{c1}}^{\text{PDG}}$  is the PDG  $\chi_{c1}$  mass value [9].

The  $B \rightarrow K\gamma\chi_{c1}$ ,  $\chi_{c1} \rightarrow \gamma J/\psi$  decay processes have a large combinatoric background from  $B \rightarrow K\chi_{c1}$  decays plus an uncorrelated  $\gamma$  from the accompanying  $B$  meson. This background produces a peaking at positive  $\Delta E$  values that is well separated from zero and is removed by the  $\Delta E < 30$  MeV requirement. Because of the complicated  $\Delta E$  background shape and its correlation with  $M_{bc}$ , we do not include  $\Delta E$  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  $34.1 \pm 6.9 \pm 4.1$  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  $B \rightarrow K\psi'$  and  $\psi' \rightarrow \gamma\chi_{c1}$  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

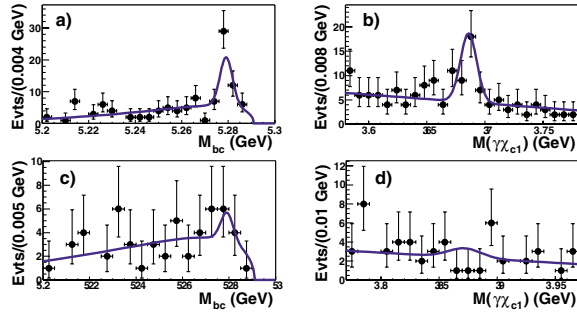


FIG. 4 (color online). Signal-band projections of (a)  $M_{bc}$  and (b)  $M_{\gamma\chi_{c1}}$  for the  $\psi'$  region with the results of the unbinned fit superimposed. (c), (d) The corresponding results for the  $M = 3872$  MeV region.

$3.7 \pm 3.7(\text{stat}) \pm 2.2(\text{syst})$  events, where the systematic error is determined by varying the input parameters to the fit over their allowed range. From these results, we determine a 90% C.L. upper limit on the ratio of partial widths of

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

where the effects of systematic errors have been included. This limit on the  $\gamma\chi_{c1}$  decay width contradicts expectations for the  $^3D_{c2}$  charmonium state.

The mass of the observed state is higher than potential model expectations for the center of gravity (cog) of the  $1^3D_{cJ}$  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  $^3D_{c2}$  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  $X(3872)$  with the  $^3D_{c2}$  state would imply a large  $^3D_{c2} - ^3D_{c1}$  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  $X(3872) \rightarrow \pi^+\pi^-J/\psi$  concentrate near the upper kinematic boundary as is also the case for  $\psi' \rightarrow \pi^+\pi^-J/\psi$  [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

$$\begin{aligned} M &= 3872.0 \pm 0.6(\text{stat}) \pm 0.5(\text{syst}) \text{ MeV}, \\ \Gamma &< 2.3 \text{ MeV} \quad (90\% \text{ C.L.}). \end{aligned} \quad (1)$$

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 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].

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