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Evidence for $X(3872) \to \gamma J/\psi$ and the sub-threshold decay $X(3872) \to \omega J/\psi$

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Abstract

We report evidence for the decay modes $X(3872) \to \gamma J/\psi$ and $X(3872) \to \pi^+\pi^-\pi^0 J/\psi$. In the latter, the $\pi^+\pi^-\pi^0$ invariant mass distribution has a strong peak between 750 MeV and the kinematic limit of 775 MeV, suggesting that the process is dominated by the sub-threshold decay $X \to \omega J/\psi$. These results establish the charge-conjugation parity of the $X(3872)$ as $C = +1$. The results are based on a study of $X(3872)$ mesons produced via exclusive $B^{\mp} \to K^{\mp} X(3872)$ decays in a 256 fb^{-1} data sample collected at the $\Upsilon(4S)$ resonance in the Belle detector at the KEKB collider. The $X(3872) \to \gamma J/\psi$ signal and $\pi^+\pi^-\pi^0 J/\psi$ signal each has a statistical significance that is greater than 4σ.

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The $X(3872)$ was discovered by Belle as a narrow $\pi^+\pi^- J/\psi$ mass peak in exclusive $B^- \to K^-\pi^+\pi^- J/\psi$ decays [1, 2]. The observed mass and the narrow width are not compatible with expectations for any of the as-yet unobserved charmonium states [3]. Moreover, the $\pi^+\pi^-$ invariant mass distribution peaks near the upper kinematic limit of $M(\pi^+\pi^-) = 775$ MeV, as expected for dipions that originate from $\rho \to \pi^+\pi^-$ decays. Charmonium decays to $\rho J/\psi$ final states violate isospin and are expected to be suppressed. The $X(3872)$ and its above-listed properties were confirmed by other experiments [4].

The $X(3872)$ mass (3871.9 ± 0.5 MeV [5]) is within errors of the $D^0\bar{D^{0*}}$ threshold (3871.3 ± 1.0 MeV [6]); the difference is 0.6 ± 1.1 MeV. This has led to speculation that the X might be a molecule-like $D^0\bar{D}^{0*}$ bound state [7, 8, 9]. According to Ref. [7], the preferred quantum numbers for such a bound state would be either $J^{PC} = 0^{-+}$ or 1^{++}. The decay of a $C = +1$ state to $\pi^+\pi^- J/\psi$ would proceed via an isovector $\rho^0 J/\psi$ intermediate state and produce a $\pi^+\pi^-$ mass spectrum that is concentrated at high masses, as is observed. In this meson-meson bound state interpretation, the close proximity of the X mass to $D^0\bar{D}^{0*}$ threshold compared to the $D^+\bar{D}^{*-}$-$D^0\bar{D}^{0*}$ mass splitting of 8.1 MeV produces a strong isospin violation.

Swanson proposed a dynamical model for the $X(3872)$ as a $D^0\bar{D}^{0*}$ hadronic resonance [8]. In this model, $J^{PC} = 1^{++}$ is strongly favored and the wave function has, in addition to $D^0\bar{D}^{0*}$, an appreciable admixture of $\omega J/\psi$ plus a small $\rho J/\psi$ component. The latter produces the $\pi^+\pi^- J/\psi$ decays that have been observed; the former gives rise to $\pi^+\pi^-\pi^0 J/\psi$ decays via a virtual ω that is enhanced because of the large $\omega J/\psi$ component to the wave-function. Swanson's model predicts that $X(3872) \to \pi^+\pi^-\pi^0 J/\psi$ decays should occur at about half the rate for $\pi^+\pi^- J/\psi$ and with a $\pi^+\pi^-\pi^0$ invariant mass spectrum that peaks near the upper kinematic boundary of 775 MeV (7.5 MeV below the ω peak). In a subsequent paper [10], Swanson emphasized the importance of searching for the radiative decay $X(3872) \to \gamma J/\psi$. The observation of this decay mode would unambiguously establish the charge-conjugation parity of the $X(3872)$ as $C = +1$.

In this Letter we report on a search for $B \to K\gamma J/\psi$ and $K\pi^+\pi^-\pi^0 J/\psi$ decays in a 275 million $B\bar{B}$ event sample collected in the Belle detector at the KEKB energy-asymmetric e^+e^- collider. The data were accumulated at a center-of-mass system (cms) energy of $\sqrt{s} = 10.58$ GeV, corresponding to the mass of the $\Upsilon(4S)$ resonance. KEKB is described in detail in ref. [11].

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a three-layer silicon vertex detector, a 50-layer cylindrical 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 [12].

For the $X(3872) \to \gamma J/\psi$ study we select events that contain a J/ψ, either a charged or neutral kaon and a γ with laboratory-frame energy greater than 40 MeV. We use the J/ψ and kaon selection criteria described in refs. [1] and [13]. The γ candidate is rejected if, when combined with any other photon in the event, fits a $\pi^0 \to \gamma\gamma$ hypothesis with $\chi^2 < 4$. 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 [14], and $|\cos\theta_B| < 0.8$, where θ_B is the polar angle of the B-meson direction in the cms.

Candidate $B \to K\gamma J/\psi$ mesons are identified by the energy difference $\Delta E \equiv E_B^{\rm cms} - E_{\rm beam}^{\rm cms}$

and the beam-energy constrained mass $M_{\rm bc} \equiv \sqrt{(E^{\rm cms}_{\rm beam})^2 - (p^{\rm cms}_B)^2}$, where $E^{\rm cms}_{\rm beam}$ is the cms beam energy, and $E^{\rm cms}_B$ and $p^{\rm cms}_B$ are the cms energy and momentum of the $K\gamma J/\psi$ combination. We select events with $M_{bc} > 5.20$ GeV and $|\Delta E| < 0.2$ GeV and among these define a signal region 5.2745 GeV $< M_{\rm bc} <$ 5.2855 GeV and $|\Delta E| < 0.035$ GeV, which correspond to $\simeq \pm 2\sigma$ from the central values for both variables.

There is prominent peak near 3510 MeV in the $M(\gamma J/\psi)$ distribution [15], due to $B \to K\chi_{c1}$; $\chi_{c1} \to \gamma J/\psi$. This is used as a calibration reaction to determine $M_{\rm bc}$, ΔE and $M(\gamma J/\psi)$ resolutions and shifts in the nominal peak positions.

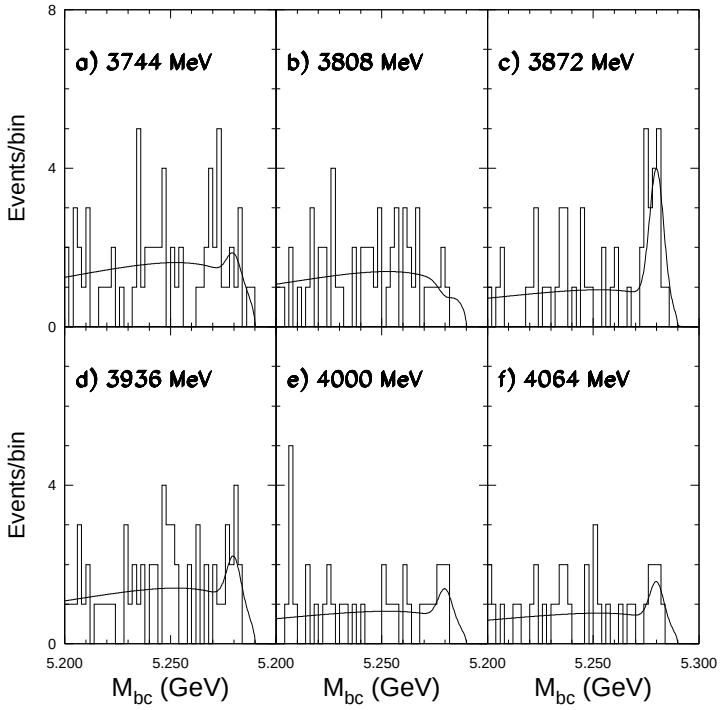

FIG. 1: The $M_{\rm bc}$ distributions for 64-MeV-wide $M(\gamma J/\psi)$ mass bins in the $X(3872)$ mass region. The curves are the results of fits described in the text.

Figures 1(a) through (f) show the $M_{\rm bc}$ distributions for six 64-MeV-wide $M(\gamma J/\psi)$ mass bins in the $X(3872)$ region. The 64 MeV bin-width corresponds to $\pm 2.5\sigma$, where σ is the $M(\gamma J/\psi)$ mass resolution determined by scaling the measured width of the χ_{c1} peak to the $X(3872)$ region using a MC-determined factor. The upper right-hand panel of Fig. 1, centered on 3872 MeV, is the only bin with a significant B meson signal. The ΔE distributions (not shown) also have a significant B meson signal in the 3872 MeV bin, and only there.

The curves in the figures are the results of binned likelihood fits that are applied simultaneously to the $M_{\rm bc}$ and ΔE distributions. The fit uses single Gaussians for the $M_{\rm bc}$ and ΔE signals with widths fixed at values determined from the $\chi_{c1} \to \gamma J/\psi$ event sample. The areas of the $M_{\rm bc}$ and ΔE signal Gaussians are constrained to be equal. For the backgrounds, an ARGUS function [16] is used for $M_{\rm bc}$ and a first-order polynomial for ΔE.

The results of the fits are plotted in Fig. 2. The signal yield in the 3872 MeV bin is 13.6 ± 4.4 events. We estimate the statistical significance of the excess signal in the $M = 3872$ MeV bin from $\sqrt{-2\ln[\mathcal{L}(n_{\rm bkg})/\mathcal{L}(n_{\rm max})]}$, where $\mathcal{L}(n)$ is the likelihood value for a signal of n events, $n_{\rm bkg}$ is the background level in the $X(3872)$ bin determined from a linear

fit to the event yields in the other bins (2.6 ± 0.6 events) inflated by 1σ, and $n_{\rm max}$ is the best-fit signal yield. The significance is 4.0σ.

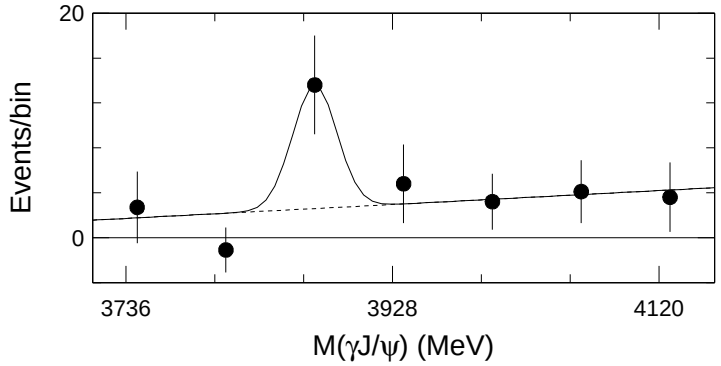

FIG. 2: The signal yields from fits to the $M_{\rm bc}$ and ΔE distributions in bins of $M(3872)$. The curves are results of fits described in the text.

Using a MC-determined efficiency of $(19 \pm 1)\%$, we determine the product branching fraction

$$\mathcal{B}(B \to KX)\mathcal{B}(X \to \gamma J/\psi) = (1.8 \pm 0.6 \pm 0.1) \times 10^{-6}, \quad (1)$$

where the first error is statistical and the second systematic. The latter includes effects of differences between data and MC resolutions for $M_{\rm bc}$ and ΔE (3%), tracking efficiency (3%), charged kaon identification (1%), K_S detection (3%) and γ detection efficiency (2%) added in quadrature. We assume that charged and neutral B mesons have the same branching fraction to $KX(3872)$. The product branching fraction of Eqn. 1 corresponds to the partial width ratio

$$\Gamma(X \to \gamma J/\psi)/\Gamma(X \to \pi^+\pi^- J/\psi) = 0.14 \pm 0.05. \quad (2)$$

For the $X \to \pi^+\pi^-\pi^0 J/\psi$ search we select events with a J/ψ, a kaon, and a $\pi^+\pi^-\pi^0$ combination. The J/ψ, kaon, R_2 and θ_B requirements are the same as for the $\gamma J/\psi$ search described above. For charged pions, we use any track that is not positively identified as a lepton. Neutral pions are reconstructed from pairs of gamma rays detected in the CsI calorimeter that fit a $\pi^0 \to \gamma\gamma$ hypothesis with a $\chi^2 < 6$. We require the π^0 cms momentum to be greater than 180 MeV. We eliminate events of the type $B \to K\pi^0\psi(2S)$; $\psi(2S) \to \pi^+\pi^- J/\psi$ by vetoing events where $M(\pi^+\pi^- J/\psi)$ is within 3σ of $m_{\psi(2S)}$.

In the case of multiple entries corresponding to different $\pi^0 \to \gamma\gamma$ assignments, we select the $\gamma\gamma$ combination with the best χ^2 value for the $\pi^0 \to \gamma\gamma$ hypothesis. For multiple entries caused by different charged particle assignments we select the track with the smallest impact parameter relative to the $J/\psi \to \ell^+\ell^-$ vertex. The signal region is defined as 5.2725 GeV $< M_{\rm bc} <$ 5.2875 GeV and $|\Delta E| < 0.035$ GeV. To select possible $X(3872) \to \pi^+\pi^-\pi^0 J/\psi$ events we require $|\Delta M| < 0.0165$ GeV, where $\Delta M \equiv M(3\pi J/\psi) - 3.872$ GeV; this corresponds to a $\pm 3\sigma$ requirement.

Figures 3(a) through (l) show the $M_{\rm bc}$ distributions for events in the ΔE and $X \to \pi^+\pi^-\pi^0 J/\psi$ signal regions for 25 MeV-wide $\pi^+\pi^-\pi^0$ invariant mass bins. There is a distinct B meson signal for the $M(\pi^+\pi^-\pi^0) > 750$ MeV bin (Fig. 3(l)), and no evident signals for any of the other 3π mass bins. The ΔE distributions (not shown) exhibit a similar pattern.

The curves in the figures are the results of binned likelihood fits that are applied simultaneously to the $M_{\rm bc}$ and ΔE distributions. The fit uses single Gaussians for the $M_{\rm bc}$ and

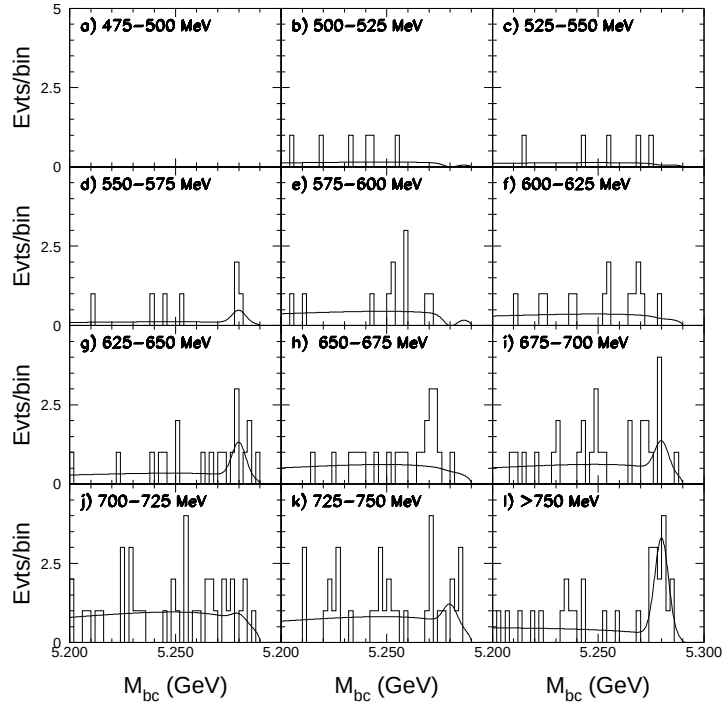

FIG. 3: $M_{\rm bc}$ distributions for $B^- \to K^-\pi^+\pi^-\pi^0 J/\psi$ candidates in the ΔE and $X \to \pi^+\pi^-\pi^0 J/\psi$ signal regions for 25 MeV-wide $\pi^+\pi^-\pi^0$ invariant mass bins.

ΔE signals with widths fixed at their MC-determined values. The areas of the $M_{\rm bc}$ and ΔE signal Gaussians are constrained to be equal. For the backgrounds, an ARGUS function [16] is used for $M_{\rm bc}$ and a second-order polynomial for ΔE.

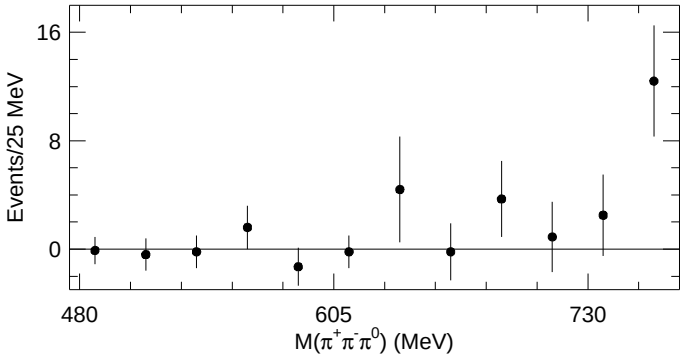

FIG. 4: The B-meson signal yield in bins of 3π invariant mass determined from fits to the $M_{\rm bc}$-ΔE distributions.

Figure 4 shows the fitted B-meson signal yields vs $M(\pi^+\pi^-\pi^0)$. All of the fitted yields are consistent with zero except for the $M(\pi^+\pi^-\pi^0) > 750$ MeV bin, where the fit gives 12.4 ± 4.1 events.

As possible backgrounds to the observed signal, we considered feed-across from $B \to K\omega J/\psi$ decays and non-resonant $B^- \to K^-\pi^+\pi^-\pi^0 J/\psi$ decays.

Belle has reported the observation of a near-threshold $\omega J/\psi$ mass enhancement in $B \to K\omega J/\psi$ decays [13]. Although the peak of the $\omega \to \pi^+\pi^-\pi^0$ resonance at 782.5 MeV is 7.5 MeV above the maximum possible 3π invariant mass value for $X \to \pi^+\pi^-\pi^0 J/\psi$ decays, there is some overlap in the tails of the kinematically allowed regions for the two processes that might result in some events from one signal feeding into the other. From the fit results to the $\omega J/\psi$ mass spectrum for $B \to K\omega J/\psi$ of ref. [13] we determine that this source contributes 0.75 ± 0.14 events to the overlap region. As an independent check, we determined the $X(3872) \to \pi^+\pi^-\pi^0 J/\psi$ signal yield with a more severe restriction on $M(\pi^+\pi^-\pi^0 J/\psi)$, namely $M_X - 3\sigma < M(\pi^+\pi^-\pi^0 J/\psi) < M_X + 1\sigma$, that has *no overlap* with the ω band. The $X \to \pi^+\pi^-\pi^0 J/\psi$ signal yield in the truncated region is 10.6 ± 3.6 events. For a Gaussian signal distribution with no feed-across background, we expect the truncation of the signal region to reduce the signal by 2.1 events (16%); the observed reduction of 1.8 events is consistent with a feed-across level that is less than one event.

To study possible contributions to the $X(3872) \to \pi^+\pi^-\pi^0 J/\psi$ signal from non-resonant $B^- \to K^-\pi^+\pi^-\pi^0 J/\psi$ decays, we defined two side-regions in the $[\Delta M, M(3\pi)]$ plane. The "upper" side-band is centered at $\Delta M = 0.033$ GeV (just above the $X(3872)$ signal region) and is ±0.0165 GeV wide, with 660 MeV $< M(3\pi) <$ 760 MeV. The "lower" sideband is ±0.0165 GeV wide centered at $\Delta M = -0.033$ GeV with $M(3\pi) > 640$ MeV. Each sideband has an area that is four times that of the $X \to \pi^+\pi^-\pi^0 J/\psi$ signal bin.

There is no evidence for significant signal yields in either sideband. Fits to the $M_{\rm bc}$-ΔE distributions give 4.3 ± 6.2 and 6.4 ± 5.6 signal events for the upper and lower bands, respectively. Normalizing by area, this gives an estimate of a possible non-resonant background level in the $X \to \pi^+\pi^-\pi^0 J/\psi$ signal bin of 1.3 ± 1.0 events.

The combined estimate for feed-across and non-resonant backgrounds is 2.1 ± 1.0. We inflate this by $+1\sigma$ and compute the significance with $n_{\rm bkg} = 3.1$ events and $n_{\rm max} = 12.4$ events. The resulting statistical significance is 4.3σ.

To determine the branching fraction for $B \to \pi^+\pi^-\pi^0 J/\psi$ we attribute all of the signal events with $M(\pi^+\pi^-\pi^0) > 750$ MeV to $X \to \pi^+\pi^-\pi^0 J/\psi$ decay. We compute the ratio of $\pi^+\pi^-\pi^0 J/\psi$ and $\pi^+\pi^- J/\psi$ branching fractions by comparing this to the number of $X \to \pi^+\pi^- J/\psi$ events in the same data sample, corrected by MC-determined relative detection efficiencies. The ratio of branching fractions is

$$\frac{\mathcal{B}(X \to \pi^+\pi^-\pi^0 J/\psi)}{\mathcal{B}(X \to \pi^+\pi^- J/\psi)} = 1.0 \pm 0.4({\rm stat}) \pm 0.3({\rm syst}), \qquad (3)$$

where the systematic error reflects the uncertainty in the relative acceptance, the level of possible feed-across and nonresonant background, and possible event loss due to the $M(3\pi) > 750$ MeV requirement, all added in quadrature.

In summary, we report strong evidence for the decays $X(3872) \to \gamma J/\psi$ and $X(3872) \to \pi^+\pi^-\pi^0 J/\psi$. These are the first measurements of an $X(3872)$ decay mode other than $\pi^+\pi^- J/\psi$. The $X(3872) \to \gamma J/\psi$ result unambiguously establishes the charge conjugation parity of the X as $C = +1$. This, in turn, would mean that the $\pi^+\pi^-$ system in $X \to \pi^+\pi^- J/\psi$ decay is from the decay of a ρ meson, as is suggested by the observed $\pi^+\pi^-$ invariant mass distribution

In the $X \to 3\pi J/\psi$ signal, the $\pi^+\pi^-\pi^0$ invariant masses are clustered above 750 MeV, near the upper kinematic boundary. This is suggestive of a sub-threshold decay to a virtual ω plus a J/ψ, and is further evidence for $C = +1$. This decay mode was predicted by Swanson to occur at about the observed strength based on a model where the $X(3872)$ is considered to be primarily a $D^0\bar{D}^{0*}$ hadronic resonance [8].

The large isospin violation implied by the near equality of the $\rho J/\psi$ and $\omega J/\psi$ decay widths is difficult to accomodate in a $c\bar{c}$ charmonium interpretation of the $X(3872)$, but a natural consequence of the meson-meson bound state model point of view [7, 8].

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