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Experimental constraints on the possible J^{PC} quantum numbers of the $X(3872)$

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Abstract

We examine possible J^{PC} quantum number assignments for the $X(3872)$. Angular correlations between final state particles in $X(3872) \to \pi^+\pi^- J/\psi$ decays are used to rule out J^{PC} values of 0^{++} and 0^{-+}. The shape of the $\pi^+\pi^-$ mass distribution near its upper kinematic limit favors S-wave over P-wave as the relative orbital angular momentum between the final-state dipion and J/ψ, which strongly disfavors 1^{-+} and 2^{-+} assignments. The accumulated evidence strongly favors a $J^{PC} = 1^{++}$ assignment for the $X(3872)$, although the 2^{++} possibility is not ruled out by tests reported here. The analysis is based on a sample of $X(3872)$ mesons produced via the exclusive process $B \to KX(3872)$ in a 256 fb^{-1} data sample collected at the $\Upsilon(4S)$ resonance in the Belle detector at the KEKB collider.

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The $X(3872)$ was first observed by Belle in exclusive $B^- \to K^-\pi^+\pi^- J/\psi$ decays [1, 2]. The subsequent observation of the $X(3872) \to \gamma J/\psi$ decay mode [3] established the charge parity as $C = +1$. In the same paper, Belle also reported evidence for the decay $X \to \pi^+\pi^-\pi^0 J/\psi$, where 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 $X \to \omega J/\psi$. The partial widths for $3\pi J/\psi$ and $2\pi J/\psi$ decays are of comparable size, which implies a large violation of isospin symmetry.

Here we report on a study of $X(3872) \to \pi^+\pi^- J/\psi$ decays produced via the exclusive decay process $B \to KX(3872)$. We use a data sample that contains 275 million $B\bar{B}$ pairs 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. [4].

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 [5].

We select events that contain a J/ψ, either a charged or neutral kaon, and a $\pi^+\pi^-$ pair using criteria described in refs. [1] and [6]. 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 [7], and $|\cos\theta_B| < 0.8$, where θ_B is the polar angle of the B-meson direction in the cms.

Candidate $B \to K\pi^+\pi^- J/\psi$ mesons are identified by the energy difference $\Delta E \equiv E_B^{\text{cms}} - E_{\text{beam}}^{\text{cms}}$ and the beam-energy constrained mass $M_{\text{bc}} \equiv \sqrt{(E_{\text{beam}}^{\text{cms}})^2 - (p_B^{\text{cms}})^2}$, where $E_{\text{beam}}^{\text{cms}}$ is the cms beam energy, and E_B^{cms} and p_B^{cms} are the cms energy and momentum of the $K\pi^+\pi^- J/\psi$ combination. We select events with $M_{bc} > 5.20$ GeV and $|\Delta E| < 0.2$ GeV and among these define a signal region 5.2725 GeV $< M_{\text{bc}} <$ 5.2875 GeV and $|\Delta E| < 0.034$ GeV; this corresponds to $\pm 3\sigma$ from the central values for each variable.

We select events with a dipion invariant mass requirement of $M_{\pi^+\pi^-} > (M(\pi^+\pi^- J/\psi) - (m_{J/\psi} + 200\text{ MeV})$, which corresponds to $M_{\pi^+\pi^-} > 575$ MeV for the $X(3872)$. This reduces misidentified γ conversions and combinatoric backgrounds by 36% with an $X(3872)$ signal loss of 6%.

These selection criteria isolate a very pure sample of 696 ± 26 $B \to K\psi(2S)$, $\psi(2S) \to \pi^+\pi^- J/\psi$ events. These events are used as a calibration reaction to determine the M_{bc}, ΔE and $M(\pi^+\pi^- J/\psi)$ peak positions and resolution values, and for validating the Monte-Carlo (MC) acceptance calculations.

Figure 1 shows the $M(\pi^+\pi^- J/\psi)$ mass distribution near 3872 MeV for the selected events. Here the smooth curve is the result of a fit with a Gaussian function to represent the $X(3872)$ signal and a first-order polynomial to represent the background. The width of the Gaussian is fixed at $\sigma = 3.2$ MeV, the experimental resolution determined from the $\psi(2S) \to \pi^+\pi^- J/\psi$ event sample. The total signal yield is 49.1 ± 8.4 events. For subsequent analysis, we define an $X(3872)$ signal region to be ± 5 MeV around the signal peak. For background estimates, we use ± 50 MeV sidebands above and below the signal peak centered at 3837 MeV and 3907 MeV. There are a total 58 events in the signal region; the background content, determined from the scaled sidebands, is 11.4 ± 1.1 events.

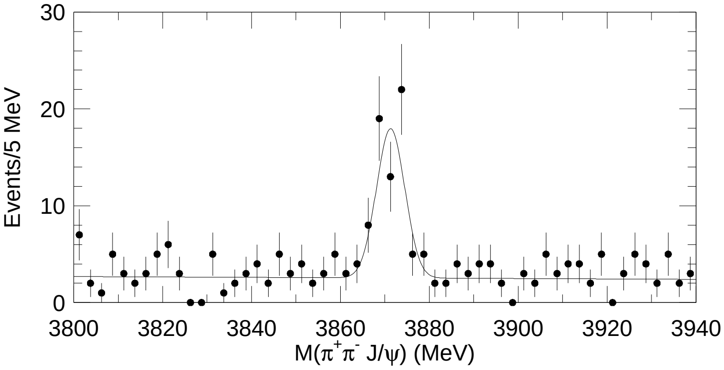

FIG. 1: The $M(\pi^+\pi^- J/\psi)$ mass distribution for the $X(3872)$ region.

Using a MC-determined acceptance, we determine the product branching fraction

$$\mathcal{B}(B \to KX(3872)) \times \mathcal{B}(X \to \pi^+\pi^- J/\psi) =$$

$$1.31 \pm 0.24(\text{stat}) \pm 0.13(\text{syst}) \times 10^{-5}. \tag{1}$$

where we have assumed equal $B \to KX$ branching fractions for charged and neutral B mesons, and that the dipion originates from $\rho \to \pi^+\pi^-$. The systematic error includes the effect of uncertainties in the $M(\pi^+\pi^-)$ shape for $X(3872)$ decay. This result agrees with, and supersedes, the results of ref. [1].

Since both the B and K mesons are scalar particles, $X(3872)$ mesons produced via exclusive $B \to KX$ decays cannot have a non-zero component of angular momentum along their momentum direction in the B rest frame. This provides useful limits on the number of independent partial-wave amplitudes needed to describe the decay [8, 9, 10].

With less than fifty signal events, any angular distribution will have, on average, only about five signal events per bin, which is not sufficient for a standard angular analysis. However, because the signal-to-noise ratio for the $X \to \pi^+\pi^- J/\psi$ signal is quite good ($S/N \simeq 4$), a typical distribution has, on average, only about one or two background events per bin. We exploit this good S/N and try to find, for a given J^{PC} hypothesis for the $X(3872)$, angular quantities that have distributions with a zero in some location. In the bins near the zero point, any observed events would have to be accounted for by upward fluctuations of the background [11].

For 0^{-+}, there is only one invariant amplitude corresponding to a ρ and J/ψ in a P-wave. The decay amplitude is proportional to the scalar triple product of the ρ and J/ψ polarizations and their relative momentum. As a result, the polarizations are perpendicular to each other and their relative momentum. We follow a suggestion by Rosner [9] and use a coordinate system where the x-axis is defined to be opposite the J/ψ direction in the ρ rest frame, the $x-y$ plane is defined by the π^+ and J/ψ directions and the z-axis is chosen so that it forms a right-handed coordinate system. We define θ as the angle between the ℓ^+ and the z axis in the J/ψ rest frame and ψ as the angle between the π^+ and the x axis in the dipion rest frame. The expected distribution for 0^{-+} is $d^2N/d(\cos\theta)d(\cos\psi) \propto \sin^2\theta \sin^2\psi$.

The $|\cos\theta|$ and $|\cos\psi|$ distributions for the $X(3872)$ signal region are shown in Figs. 2(a) and (b), respectively. The shaded histograms indicate the side-band determined background. The distributions for both variables show strong signals at the upper edge of each plot, in contrast to expectations for a $\sin^2\theta \sin^2\psi$ dependence. The open histogram shows the 0^{-+}

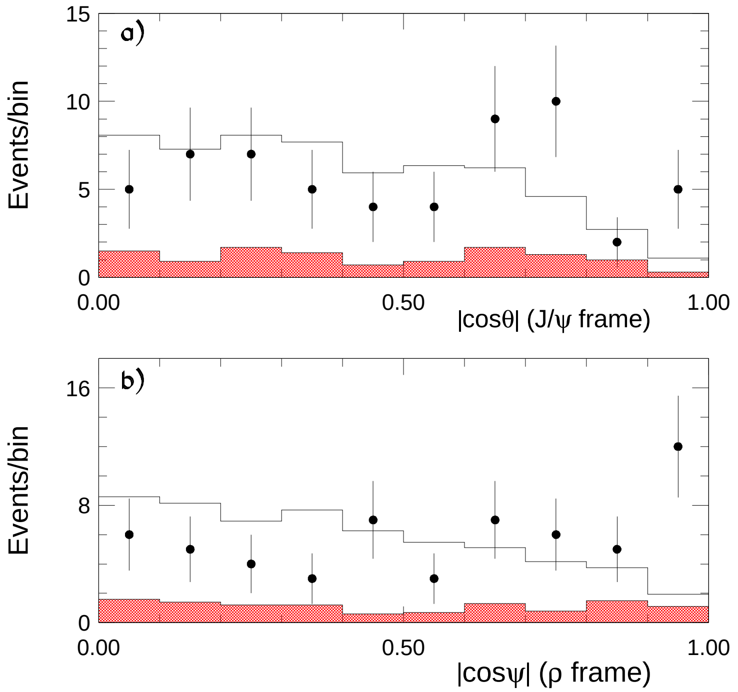

FIG. 2: The **(a)** $|\cos\theta|$ and **(b)** $|\cos\psi|$ distributions for events in the $X(3872)$ signal region (points with error bars). The open histogram is the expected distribution for a 0^{-+} assignment including background. The hatched histogram shows the scaled sideband.

MC expectations plus background, normalized to the observed number of events. Here the agreement is marginal for $\cos\theta$: $\chi^2/d.o.f. = 17.7/9$ but poor for $\cos\psi$: $\chi^2/d.o.f. = 34.2/9$. This latter distribution allows us to reject the 0^{-+} assignment with high confidence.

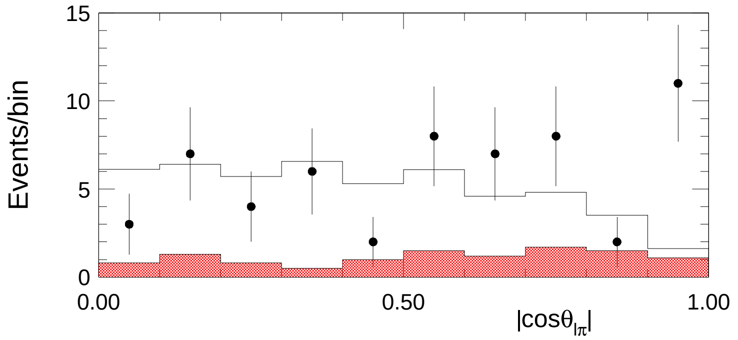

FIG. 3: The $|\cos\theta_{\ell\pi}|$ distribution for events in the $X(3872)$ signal region (points with error bars). The open histogram is the expected distribution for a 0^{++} assignment including background. The hatched histogram shows the scaled sideband.

For 0^{++}, two invariant amplitudes are possible, corresponding to the ρ and J/ψ in relative S- or D-waves. Because of the limited phase-space, the D-wave contribution can be expected to be strongly suppressed relative to the S wave term and is ignored. The amplitude is then proportional to the scalar product of the ρ and J/ψ polarizations. We define $\theta_{\ell\pi}$ as the angle between the ℓ^+ and the π^+ in the $X(3872)$ rest frame. In the limit where the $X(3872)$, J/ψ

and ρ rest frames coincide $dN/d(\cos\theta_{\ell\pi}) \propto \sin^2\theta_{\ell\pi}$. The kinematic smearing due to relative motion of the different frames is incorporated in the MC simulations that are used to compare data with expectations [13].

Figure 3 shows the $|\cos\theta_{\ell\pi}|$ distribution, computed in the ρ rest frame, for $X(3872)$ signal region events. The agreement with S-wave 0^{++} MC expectations is poor: $\chi^2/d.o.f. = 31.0/9$, and provides evidence against the 0^{++} assignment.

For 1^{++} the J/ψ and ρ can be in a relative S and/or D-wave. We use a coordinate system [9] where the x-axis is the negative of the kaon flight path, the $x-y$ plane is defined by the kaon and π^+ and the z axis completes a right-handed coordinate system. The angle between the π^+ direction and the x-axis is χ and the angle between the ℓ^+ direction and the z-axis is θ_ℓ. In the limit where the J/ψ and ρ are at rest in the X rest frame (and D-wave contributions can be neglected), the amplitude is proportional to the vector triple product of the X, ρ and J/ψ polarizations, and the choice of axes ensures that the X polarization is along the x direction [9, 10]. The expectation for 1^{++} is $d^2N/d(\cos\theta_\ell)d(\cos\chi) \propto \sin^2\theta_\ell \sin^2\chi$.

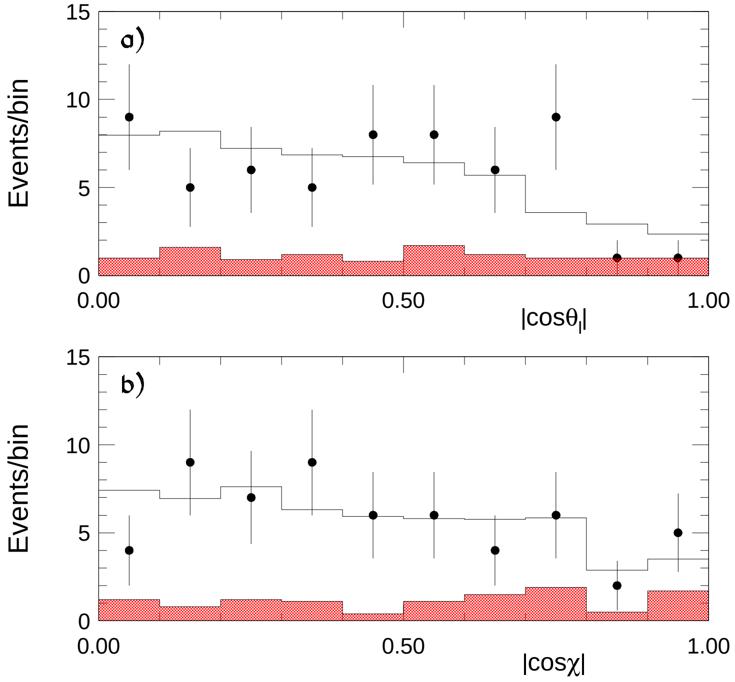

FIG. 4: The **a)** $|\cos\theta_\ell|$ and **b)** $|\cos\chi|$ distribution for events in the $X(3872)$ signal region (points with error bars). The open histogram is the expected distribution for a 1^{++} assignment including background. The hatched histogram shows the scaled sideband.

The $|\cos\theta_\ell|$ distribution for $X(3872)$ signal region events is shown in Fig. 4(a). The distribution tends toward zero at the upper edge of the plot, as expected for a $\sin^2\theta_\ell$ dependence. The open histogram shows the results of a comparison to normalized MC expectations for 1^{++} decaying to a ρ and J/ψ in an S-wave. The agreement is good: $\chi^2/d.o.f = 11.4/9$. The $|\cos\chi|$ distribution is shown in Figs. 4(b) together with the MC expectation for 1^{++}. The agreement here is also good: $\chi^2/d.o.f. = 5.0/9$.

For even-parity $C = +1$ states the $\pi^+\pi^- J/\psi$ final state would be a ρ and J/ψ primarily in a relative S-wave, with some possible D-wave component. For odd-parity states the ρ and J/ψ would be in a relative P-wave with some possible F-wave. The $M(\pi^+\pi^-)$ mass distribution near the upper kinematic boundary is suppressed by a $(q^*_{J/\psi})^{2\ell+1}$ centrifugal barrier, where $q^*_{J/\psi}$ is the J/ψ momentum in the $X(3872)$ rest frame, and ℓ is the orbital angular momentum. For the S-wave (*i.e.* $J^P = J^+$) cases, the upper-boundary is modulated by the available phase-space, which is proportional to $q^*_{J/\psi}$; for a P-wave the modulation is $(q^*_{J/\psi})^3$. Thus, the shape of the high-mass part of the $\pi^+\pi^-$ invariant mass distribution provides some J^{PC} information.

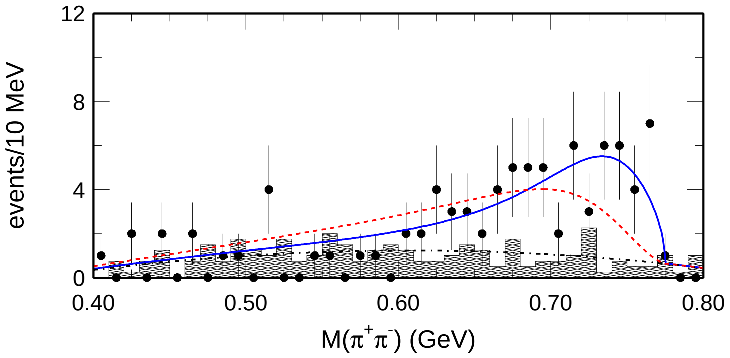

FIG. 5: $M(\pi^+\pi^-)$ distribution for events in the $X(3872)$ signal region; the histogram indicates the side-band determined background. The solid (dashed) curve shows the fit that uses a ρ Breit-Wigner line shape with the J/ψ and ρ in a relative S-wave (P-wave). The dot-dashed curve is a smooth parameterization of the background that is used in the fit.

Figure 5 shows the distribution for events in the $X(3872) \to \pi^+\pi^- J/\psi$ signal region with the $M(\pi^+\pi^-)$ requirement relaxed; the histogram indicates the side-band determined background, which is parameterized by the fourth-order polynomial shown in the figure as a dot-dashed curve. The solid curve in Fig. 5 shows the result of a fit to the $M(\pi^+\pi^-)$ distribution that uses the background function plus an acceptance-weighted ρ BW line-shape with an S-wave cut-off factor at the upper kinematic boundary [14]; the dashed curve shows the fit with a P-wave cut-off factor. The S-wave case fits the data well: $\chi^2/d.o.f. = 43.1/39$ (CL=28%). The P-wave fit is much poorer, $\chi^2/d.o.f. = 71.0/39$ (CL=0.1%), indicating that J^{++} is strongly favored over J^{-+}.

In summary, we find that with reasonable assumptions and a sample of 47 $X \to \pi^+\pi^- J/\psi$ signal events, we can rule out the $J^{PC} = 0^{-+}$ and 0^{++} assignments for the $X(3872)$ based on angular correlations among the final state particles. In addition, the $M(\pi^+\pi^-)$ distribution is inconsistent with all J^{-+} assignments.

The results reported here, taken together with the observation of the $X(3872) \to \gamma J/\psi$ decay mode [3], rule out all J^{PC} assignments with $J \leq 2$ other than 1^{++} and 2^{++}. The decay angular distributions and $\pi^+\pi^-$ invariant mass distribution agree well with expectations for the the 1^{++} assignment. The 2^{++} assignment is not seriously challenged by any of the tests reported here, but is made rather unlikely by Belle's recently reported evidence for the decay $X(3872) \to D^0\bar{D}^0\pi^0$ [15]. The formation of 2^{++} from three pseudoscalars requires at least one combination to be in a D-wave. Thus, the near-threshold production of $D^0\bar{D}^0\pi^0$ would be suppressed by an $\ell = 2$ centrifugal barrier.

The 1^{++} charmonium χ'_{c1} state is an unlikely assignment for the $X(3872)$. Potential model predictions for the χ'_{c1} mass range from 3953 MeV ~ 3990 MeV [16], well above the $X(3872)$ mass. The potential model masses are expected to be modified by coupling to open-charm states. A coupled-channel calculation of open-charm-induced splittings for the χ'_{c1} yields an upward mass shift of +28 MeV [17].

The decay $\chi'_{c1} \to \pi^+\pi^- J/\psi$ would proceed via $\rho J/\psi$ and violate isospin. The only well established isospin-violating hadronic transition in the charmonium system is $\psi(2S) \to \pi^0 J/\psi$, which has a measured partial width of $\Gamma(\psi(2S) \to \pi^0 J/\psi) = 0.27 \pm 0.06$ keV [12]. This is small compared to the expected total width of an $M = 3872$ MeV χ'_{c1} of more than 1 MeV [16, 17]. A decay mode with a partial width this small would thus have a branching fraction that is less than 0.1%. This contradicts the recent BaBar 90% confidence lower limit of $\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) > 4.3\%$ [18]. Godfrey and Barnes calculate a partial width for an $M = 3872$ MeV χ'_{c1} to be 11 KeV [16], more than an order-of-magnitude larger than that for the isospin violating $\psi(2S) \to \pi^0 J/\psi$ transition. Thus, one expects the $\gamma J/\psi$ decay to be stronger than $\rho J/\psi$. This is contradicted by our measurement: $\Gamma(X(3872) \to \gamma J/\psi)/\Gamma(X(3872) \to \pi^+\pi^- J/\psi) = 0.14 \pm 0.05$ [3].

The 1^{++} assignment is favored by models that treat the $X(3872)$ as a molecule-like $D^0\bar{D}^{*0}$ bound state [19, 20]. These models predict strong isospin violations and a $\gamma J/\psi$ branching fraction that is much less than that for $\pi^+\pi^- J/\psi$ [21], in agreement with observations.

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