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

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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 $J/\psi$, 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.

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The $X(3872)$ was first observed by Belle in exclusive $B^- \to K^-\pi^+\pi^-J/\psi$ decays \cite{1,2}. The subsequent observation of the $X(3872) \to \gamma J/\psi$ decay mode \cite{3} established the charge parity as $C = +1$. In the same paper, Belle also reported evidence for the decay $X \to \pi^+\pi^-\pi^0J/\psi$, 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 $BB$ 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. \cite{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 \cite{5}.

We select events that contain a $J/\psi$, either a charged or neutral kaon, and a $\pi^+\pi^-$ pair using criteria described in refs. \cite{1} and \cite{5}. 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 \cite{6}, and $|\cos \theta_B| < 0.8$, where $\theta_B$ 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 $M_{bc} \equiv \sqrt{(E_{\text{beam}}^{\text{cms}})^2 - (p_B^{\text{cms}})^2}$, where $E_{\text{beam}}^{\text{cms}}$ is the cms beam energy, and $E_B^{\text{cms}}$ and $p_B^{\text{cms}}$ 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 $< M_{bc} < 5.2875$ 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 $M_{\pi^+\pi^-} > (M(\pi^+\pi^-J/\psi) - m_{J/\psi} + 200$ MeV), which corresponds to $M_{\pi^+\pi^-} > 575$ MeV for the $X(3872)$. This reduces misidentified $\gamma$ conversions and combinatoric backgrounds by 36% with an $X(3872)$ signal loss of 6%.

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

Figure\cite{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 $49.1 \pm 8.4$ events. For subsequent analysis, we define an $X(3872)$ signal region to be $\pm 5$ MeV around the signal peak. For background estimates, we use $\pm 50$ 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 $11.4 \pm 1.1$ events.
Using a MC-determined acceptance, we determine the product branching fraction

$$B(B \to KX(3872)) \times B(X \to \pi^+\pi^-J/\psi) = 1.31 \pm 0.24\text{(stat)} \pm 0.13\text{(syst)} \times 10^{-5}. \hspace{1cm} (1)$$

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 $\rho$ and $J/\psi$ in a $P$-wave. The decay amplitude is proportional to the scalar triple product of the $\rho$ and $J/\psi$ 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 $J/\psi$ direction in the $\rho$ rest frame, the $x-y$ plane is defined by the $\pi^+$ and $J/\psi$ directions and the $z$-axis is chosen so that it forms a right-handed coordinate system. We define $\theta$ as the angle between the $\ell^+$ and the $z$ axis in the $J/\psi$ rest frame and $\psi$ as the angle between the $\pi^+$ 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 $\rho$ and $J/\psi$ 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 $\rho$ and $J/\psi$ polarizations. We define $\theta_{\ell \pi}$ as the angle between the $\ell^+$ and the $\pi^+$ in the $X(3872)$ rest frame. In the limit where the $X(3872)$, $J/\psi$
and $\rho$ 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 $\rho$ 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 $J/\psi$ and $\rho$ 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 $\pi^+$ and the $z$ axis completes a right-handed coordinate system. The angle between the $\pi^+$ direction and the $x$-axis is $\chi$ and the angle between the $\ell^+$ direction and the $z$-axis is $\theta_{\ell}$. In the limit where the $J/\psi$ and $\rho$ 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 $X$, $\rho$ and $J/\psi$ polarizations, and the choice of axes ensures that the $X$ polarization is along the $x$ direction [9, 10]. The expectation for $1^{++}$ is $d^2N/d(\cos \theta_{\ell})d(\cos \chi) \propto \sin^2 \theta_{\ell} \sin^2 \chi$.

![Figure 4](image.png)

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. 4a). 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 $\rho$ and $J/\psi$ in an $S$-wave. The agreement is good: $\chi^2/d.o.f. = 11.4/9$. The $|\cos \chi|$ distribution is shown in Figs. 4b) 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 $\rho$ and $J/\psi$ primarily in a relative $S$-wave, with some possible $D$-wave component. For odd-parity states the $\rho$ and $J/\psi$ 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 \(J/\psi\) momentum in the \(X(3872)\) rest frame, and \(\ell\) 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.

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

In summary, we find that with reasonable assumptions and a sample of 47 \(X \rightarrow \pi^+\pi^- J/\psi\) 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 \(X(3872) \rightarrow \gamma J/\psi\) decay mode, 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 \(1^{++}\) 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 \(X(3872) \rightarrow D^0\bar{D}^0\pi^0\). 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 \(\chi_{c1}'\) state is an unlikely assignment for the \(X(3872)\). Potential model predictions for the \(\chi_{c1}'\) mass range from 3953 MeV \(\sim\) 3990 MeV, 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 \( \chi'_c \) yields an upward mass shift of +28 MeV \(^{17}\).

The decay \( \chi'_c \rightarrow \pi^+\pi^-J/\psi \) would proceed via \( \rho J/\psi \) and violate isospin. The only well established isospin-violating hadronic transition in the charmonium system is \( \psi(2S) \rightarrow \pi^0J/\psi \), which has a measured partial width of \( \Gamma(\psi(2S) \rightarrow \pi^0J/\psi) = 0.27 \pm 0.06 \text{ keV}^{12} \). This is small compared to the expected total width of an \( M = 3872 \text{ MeV} \chi'_c \) 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 \( B(X(3872) \rightarrow \pi^+\pi^-J/\psi) > 4.3\%^{18} \). Godfrey and Barnes calculate a partial width for an \( M = 3872 \text{ MeV} \chi'_c \) to be 11 keV \(^{16}\), more than an order-of-magnitude larger than that for the isospin violating \( \psi(2S) \rightarrow \pi^0J/\psi \) transition. Thus, one expects the \( \gamma J/\psi \) decay to be stronger than \( \rho J/\psi \). This is contradicted by our measurement: \( \Gamma(X(3872) \rightarrow \gamma J/\psi) / \Gamma(X(3872) \rightarrow \pi^+\pi^-J/\psi) = 0.14 \pm 0.05^{3} \).

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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