Observation of a near-threshold $\omega J/\psi$ mass enhancement in exclusive $B \to K\omega J/\psi$ decays

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Abstract

We report the observation of a near-threshold enhancement in the $\omega J/\psi$ invariant mass distribution for exclusive $B \to K\omega J/\psi$ decays. The results are obtained from a 253 fb$^{-1}$ data sample that contains 275 million $B\bar{B}$ pairs that were collected near the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric energy $e^+e^-$ collider. The statistical significance of the $\omega J/\psi$ mass enhancement is estimated to be greater than 8\sigma.

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Recently there has been a revival of interest in the possible existence of mesons with a more complex structure than the simple $q \bar{q}$ bound states of the original quark model. There are long-standing predictions of four-quark $qqq\bar{q}$ meson-meson resonance states \[1\] and for $q\bar{q}$-gluon hybrid states \[2\]. Searches for these types of particles in systems that include a charmed-anticharmed quark pair ($c\bar{c}$) are particularly effective because for at least some of these cases, the states are expected to have clean experimental signatures as well as relatively narrow widths, thereby reducing the possibility of overlap with standard $c\bar{c}$ mesons.

$B$ meson decays are a prolific source of $c\bar{c}$ pairs and the large $B$ meson samples produced at $B$-factories are providing opportunities to search for missing $c\bar{c}$ charmonium mesons as well as more complex states. From studies of $K^0_S K^- \pi^+$ systems produced in exclusive $B \to KK^0_S K^- \pi^+$ decays with a 45 million $BB$ event sample, the Belle group made the first observation of the $\eta_c(2S)$ \[3\]. This state was subsequently seen in two-photon reactions by other experiments \[4\] and in the exclusive $e^+e^- \to J/\psi\eta_c(2S)$ production process by Belle \[5\]. With a larger sample of 152 million $BB$ events, Belle discovered the $X(3872)$ as a narrow peak in the $\pi^+\pi^-J/\psi$ mass spectrum from exclusive $B \to K\pi^+\pi^-J/\psi$ decays \[6\]. This observation has been confirmed by other experiments \[7\]. The properties of the $X(3872)$ do not match well to any $c\bar{c}$ charmonium state \[8\]. This, together with the close proximity of the $X(3872)$ mass with the $m_{D^0} + m_{D^{*0}}$ mass threshold, have led a number of authors to interpret the $X(3872)$ as a $D^0\bar{D}^{*0}$ resonant state \[9\].

In this Letter we report on a study of the $\omega J/\psi$ system produced in exclusive $B \to K\omega J/\psi$ decays. We observe a large enhancement in the $\omega J/\psi$ mass distribution near the $\omega J/\psi$ mass threshold. These results are based on a 253 fb$^{-1}$ data sample that contains 275 million $BB$ pairs collected with the Belle detector.

The Belle experiment observes $B$ mesons produced by the KEKB asymmetric energy $e^+e^-$ collider \[10\]. KEKB operates at the $\Upsilon(4S)$ resonance ($\sqrt{s} = 10.58$ GeV) with a peak luminosity of $1.39 \times 10^{34}$ cm$^{-2}$s$^{-1}$.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a 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.
The Belle detector is described in ref. [11].

We select events of the type $B \to K\pi^+\pi^-\pi^0J/\psi$, where we use both charged and neutral kaons [12]. We use the same charged kaon, pion and $J/\psi$ requirements as used in ref. [6]. For neutral kaons we use $\pi^+\pi^-$ pairs with invariant mass within 15 MeV of $m_{K_S}$ and a displaced vertex that is consistent with $K_S^0 \to \pi^+\pi^-$ decay. We identify a $\pi^0$ as a $\gamma\gamma$ pair that fits the $\pi^0 \to \gamma\gamma$ hypothesis with $\chi^2 < 6$. We further require the energy asymmetry $|E_{\gamma_1} - E_{\gamma_2}|/|E_{\gamma_1} + E_{\gamma_2}| < 0.9$ and the $\pi^0$ laboratory-frame momentum to be greater than 180 MeV. Events with a $\pi^+\pi^-J/\psi$ invariant mass within $3\sigma$ of $m_\psi'$ are rejected in order to eliminate $B \to K\pi^0\psi'$; $\psi' \to \pi^+\pi^-J/\psi$ decays.

At the $\Upsilon(4S)$, $BB$ meson pairs are produced with no accompanying particles. As a result, each $B$ meson has a total cms energy that is equal to $E_{\text{beam}}$, the cms beam energy. We identify $B$ mesons using the beam-constrained mass $M_{bc} = \sqrt{E_{\text{beam}}^2 - p_B^2}$ and the energy difference $\Delta E = E_{\text{beam}} - E_B$, where $p_B$ is the vector sum of the cms momenta of the $B$ meson decay products and $E_B$ is their cms energy sum. For the final state used in this analysis, the experimental resolutions for $M_{bc}$ and $\Delta E$ are approximately 3 MeV and 13 MeV, respectively.

We select events with $M_{bc} > 5.20$ GeV and $|\Delta E| < 0.2$ GeV for further analysis. For events with multiple $\pi^0$ entries in this region, we select the $\gamma\gamma$ combination with the best $\chi^2$ value for the $\pi^0 \to \gamma\gamma$ hypothesis. Multiple entries caused by multiple charged particle assignments are small ($\sim 4\%$) and are tolerated.

The signal region is defined as $5.2725 < M_{bc} < 5.2875$ GeV and $|\Delta E| < 0.030$ GeV, which is about $\pm 2.5\sigma$ from the central values. We identify three-pion combinations with $0.760 \text{ GeV} < M(\pi^+\pi^-\pi^0) < 0.805$ GeV as candidate $\omega$ mesons. To suppress events of the type $B \to K\pi J/\psi$; $K \to K\omega$, where $K$ denotes strange meson resonances such as $K_1(1270)$, $K_1(1400)$, and $K_2^*(1430)$ that are known to decay to $K\omega$, we restrict our analysis to events in the region $M(K\omega) > 1.6$ GeV.

Figure 1(a) shows the $M_{bc}$ distribution for selected events that are in the $\Delta E$ and $\omega$ signal regions. The curve in the figure is the result of a binned likelihood fit that uses a single Gaussian for the signal and an ARGUS function [14] for the background. The fit gives a signal yield of $219 \pm 23$ events. Figure 1(b) shows the $\Delta E$ distribution for events in the
FIG. 1: (a) $M_{bc}$ distributions for $B \rightarrow K \omega J/\psi$ candidates in the $\Delta E$ and $\omega \rightarrow \pi^+\pi^-\pi^0$ signal regions. (b) $\Delta E$ distribution for events in the $M_{bc}$ and $\omega$ signal regions. (c) $M(\pi^+\pi^-\pi^0)$ distribution for events in the $M_{bc}$ and $\Delta E$ signal regions. The curves are the results of fits described in the text; the arrows indicate the signal region for each quantity.

$M_{bc}$ and $\omega$ signal regions. Here the curve is the result of a fit that represents the signal with a single Gaussian and the background with a first-order polynomial. The signal yield is $196 \pm 21$ events. Figure 1(c) shows the $M(\pi^+\pi^-\pi^0)$ distribution for all events in the $M_{bc}$-$\Delta E$ signal region. The peak is well fitted with a Breit-Wigner with the mass and width of the $\omega(780)$, broadened by an experimental resolution of 8 MeV. Here the signal yield is $204 \pm 20$ events. The reasonable consistency in the signal yield from all three distributions indicates that $K\omega J/\psi$ is the dominant component of $B \rightarrow K\pi^+\pi^-\pi^0 J/\psi$ decays with $M(3\pi)$ in the $\omega$ mass range and $M(K\omega) > 1.6$ GeV. The arrows in the figures indicate the signal regions for the plotted quantity.

Figure 2 shows the Dalitz plot of $M^2(\omega J/\psi)$ (vertical) vs $M^2(\omega K)$ (horizontal) for $B \rightarrow K \omega J/\psi$ candidates in the signal regions. Here the $M(K\omega) > 1.6$ GeV requirement has been relaxed. The clustering of events near the left side of the plot are attributed to $B \rightarrow K_X J/\psi$; $K_X \rightarrow K \omega$ decays. There is an additional clustering of events with low $\omega J/\psi$ invariant masses near the bottom of the Dalitz plot. This clustering is the subject of the analysis reported here.

The fits to the $M_{bc}$ and $\Delta E$ distributions of Figs. 1(a) and (b) indicate that about half of the entries with $M(\omega K) > 1.6$ GeV in the Dalitz plot of Fig. 2 are background. To determine the level of $B \rightarrow K \omega J/\psi$ signal events, we bin the data into 40 MeV-wide bins of $M(\omega J/\psi)$ and fit for $B$ meson signals. The histograms in Figs. 3(a)-(l) show the $M_{bc}$ distributions for the twelve lowest $M(\omega J/\psi)$ bins for events in the $\Delta E$ and $\omega$ signal regions. Here there are
FIG. 2: Dalitz-plot distribution for $B \to K\omega J/\psi$ candidate events. The dotted line indicates the boundary of the $M(K\omega) > 1.6$ GeV selection requirement.

distinct $B \to K\omega J/\psi$ signals for low $\omega J/\psi$ invariant mass bins, especially those covered by Figs. 3(b) and (c). We establish the $B \to K\omega J/\psi$ signal level for each $M(\omega J/\psi)$ bin by performing binned one-dimensional fits to the $M_{bc}$ and $\Delta E$ distributions for events in that interval using the same signal and background functions that are used to fit the integrated distributions of Figs. 1(a) and (b). For these fits, the peak positions, resolution values and background shape parameters are all fixed at the values that are determined from the fits to the integrated distributions, and the areas of the $M_{bc}$ and $\Delta E$ signal functions are constrained to be equal. The curves in Fig. 3 indicate the results of the $M_{bc}$ fits.

The $B$-meson signal yields from the fits to the individual bins are plotted vs $M(\omega J/\psi)$ in Figs. 4(a) and (b). An enhancement is evident around $M(\omega J/\psi) = 3940$ MeV. The curve in Fig. 4(a) is the result of a fit with a threshold function of the form $f(M) = A_0 q^*(M)$, where $q^*(M)$ is the momentum of the daughter particles in the $\omega J/\psi$ restframe. This functional form accurately reproduces the threshold behavior of Monte Carlo simulated $B \to K\omega J/\psi$ events that are generated uniformly distributed over phase-space. The fit quality to the observed data points is poor ($\chi^2/d.o.f. = 115/11$), indicating a significant deviation from phase-space; the integral of $f(M)$ over the first three bins is 16.8 events, where the data total is 55.6 events.

In Fig. 4(b) we show the results of a fit where we include an $S$-wave Breit-Wigner (BW) function [15] to represent the enhancement. The fit, which has $\chi^2/d.o.f. = 15.6/8$ (CL =
FIG. 3: $M_{bc}$ distributions for $B^- \rightarrow K^- \omega J/\psi$ candidates in the $\Delta E$ signal region for 40 MeV-wide $\omega J/\psi$ invariant mass intervals. The curves are the results of fits described in the text.

FIG. 4: $B \rightarrow K \omega J/\psi$ signal yields vs $M(\omega J/\psi)$. The curve in (a) indicates the result of a fit that includes only a phase-space-like threshold function. The curve in (b) shows the result of a fit that includes an $S$-wave Breit-Wigner resonance term.

4.8%), yields a Breit-Wigner signal yield of $58 \pm 11$ events with mass $M = 3943 \pm 11$ MeV and width $\Gamma = 87 \pm 22$ MeV (statistical errors only). The statistical significance of the signal, determined from $\sqrt{-2 \ln(L_0/L_{\text{max}})}$, where $L_{\text{max}}$ and $L_0$ are the likelihood values for the
best-fit and for zero-signal-yield, respectively, is 8.1σ.

The $K\omega$ invariant mass distribution for $M_{bc}-\Delta E$ signal region events in the region of the $M(\omega J/\psi)$ enhancement are distributed uniformly across the available phase space and there is no evident $K\omega$ mass structure that might be producing the observed mass enhancement by a kinematic reflection. Nevertheless, the possibility that different high-mass $K\omega$ partial waves might interfere in a way that produces some peaking in the $\omega J/\psi$ mass distribution cannot be ruled out.

The $M(\pi^+\pi^-\pi^0)$ distributions for different $M(\omega J/\psi)$ mass regions exhibit $\omega \rightarrow \pi^+\pi^-\pi^0$ signals that track the $M_{bc}-\Delta E$ signal yields. The $\omega$ signal strength is used to infer that ($90 \pm 18$)% of the $B \rightarrow K\pi^+\pi^-\pi^0 J/\psi$ events in the $M = 3943$ MeV enhancement are produced via $\omega \rightarrow \pi^+\pi^-\pi^0$ decays.

We study potential systematic errors on the yield, mass and width by repeating the fits with different signal parameterizations, background shapes and bin sizes. For example, when we change the background function to include terms up to third order in $q^*$, the yield increases to $75 \pm 10$ events, the mass changes to $3948 \pm 9$ MeV, the width changes to $\Gamma = 100 \pm 23$ MeV and the fit quality improves: $\chi^2/d.o.f. = 10.0/6$ (CL=12.4%). However, the resulting background shape is very different from that of phase-space. For different bin sizes, fitting ranges, $M(K\omega)$ requirements, and signal line shapes we see similar variations.

For the systematic uncertainties we use the largest deviations from the nominal values for the different fits. In the following, we assume that all of the $3\pi$ systems are due to $\omega \rightarrow \pi^+\pi^-\pi^0$ decays and include the possibility of a non-resonant contribution in the systematic error. This is the main component of the negative-side systematic error; the change in yield for different background shapes contributes a positive-side error of comparable size. The effects of possible acceptance variation as a function of $M(\omega J/\psi)$ on the mass and width values are found to be negligibly small.

To determine a branching fraction, we use the BW fit shown in Fig. 4(b) to establish the event yield of the observed enhancement. Monte Carlo simulation is used to estimate detection efficiencies of $2.4 \pm 0.1\%$ and $0.42 \pm 0.02\%$ for $B \rightarrow K^+ \omega J/\psi$ and $K^0 \omega J/\psi$, respectively. We find a product branching fraction (here we denote the enhancement as $Y(3940)$)

$$B(B \rightarrow KY(3940))B(Y(3940) \rightarrow \omega J/\psi) = (7.1 \pm 1.3 \pm 3.1) \times 10^{-5},$$

(1)
where the second error is systematic. The latter includes uncertainties in the acceptance, and the shape of the function used to parameterize the background and the possibility of a non-ω component of the $\pi^+\pi^-\pi^0$ system added in quadrature. Here we have assumed that charged and neutral $B$ mesons are produced in equal numbers at the $\Upsilon(4S)$ and they have the same branching fractions to the observed enhancement [16].

In summary, we have observed a strong near-threshold enhancement in the $\omega J/\psi$ mass spectrum in exclusive $B \to K \omega J/\psi$ decays. The enhancement peaks well above threshold and is broad [17]; if treated as an $S$-wave BW resonance, we find a mass of $3943\pm11(\text{stat})\pm13(\text{syst})$ MeV and a total width $\Gamma = 87\pm22(\text{stat})\pm26(\text{syst})$ MeV. It is expected that a $c\bar{c}$ charmonium meson with this mass would dominantly decay to $D\bar{D}$ and/or $D\bar{D}^*$; hadronic charmonium transitions should have minuscule branching fractions [18].

The peak mass of the observed enhancement is very similar to that of a peak observed by Belle in the $J/\psi$ recoil mass spectrum for inclusive $e^+e^- \to J/\psi X$ events near $\sqrt{s} = 10.56$ GeV [19]. This latter peak is also seen to decay to $D\bar{D}^*$, and a search for it in the $\omega J/\psi$ channel is in progress. In addition, we are examining $B \to K D\bar{D}^*$ decays for a $D\bar{D}^*$ component of the enhancement reported here.

The properties of the observed enhancement are similar to those of some of the $c\bar{c}$-gluon hybrid charmonium states that were first predicted in 1978 [2] and are expected to be produced in $B$ meson decays [20]. It has been shown that a general property of these hybrid states is that their decays to $D^{(*)}\bar{D}^{(*)}$ meson pairs are forbidden or suppressed, and the relevant “open charm” threshold is $m_D + m_{D^{**}} \simeq 4285$ MeV [21, 22], where $D^{**}$ refers to the $J^P = (0,1,2)^+$ charmed mesons. Thus, a hybrid state with a mass equal to that of the peak we observe would have large branching fractions for decays to $J/\psi$ or $\psi'$ plus light hadrons [23]. Moreover, lattice QCD calculations have indicated that partial widths for such decays can be comparable to the width that we measure [24]. However, these calculations predict masses for these states that are between 4300 and 4500 MeV [25], substantially higher than our measured value.

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We use the form\[ \frac{\Gamma(q^*/q_0)}{(M^2-M_0^2)^2 + (M_0\Gamma(q^*/q_0))^2}, \]
where \( M_0 \) is the peak mass and \( q_0 = q^*(M = M_0) \).

The signal yields for the separate \( K^+\omega J/\psi \) and \( K_S\omega J/\psi \) channels are consistent.

The \( M(\omega J/\psi) \) mass resolution is \( \simeq 6 \) MeV and much narrower than the observed enhancement.

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