Observation of a Resonancelike Structure in the $\pi^{+-}\psi'$ Mass Distribution in Exclusive $B \to K\pi^{+-}\psi'$ Decays

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A distinct peak is observed in the $\pi^{\pm}\psi'$ invariant mass distribution near 4.43 GeV in $B \to K\pi^{\pm}\psi'$ decays. A fit using a Breit-Wigner resonance shape yields a peak mass and width of $M = 4433 \pm 4(\mathrm{stat}) \pm 2(\mathrm{syst})$ MeV and $\Gamma = 45^{+18}_{-13}(\mathrm{stat})^{+30}_{-13}(\mathrm{syst})$ MeV. The product branching fraction is determined to be $\mathcal{B}(B^0 \to K^{\mp}Z^{\pm}(4430)) \times \mathcal{B}(Z^{\pm}(4430) \to \pi^{\pm}\psi') = (4.1 \pm 1.0(\mathrm{stat}) \pm 1.4(\mathrm{syst})) \times 10^{-5}$, where $Z^{\pm}(4430)$ is used to denote the observed structure. The statistical significance of the observed peak is 6.5σ. These results are obtained from a 605 fb^{-1} data sample that contains 657×10^6 $B\bar{B}$ pairs collected near the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric energy e^+e^- collider.

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An unexpected bonus from the B-factory experiments has been the discovery of a large number of charmoniumlike meson states [1–9]. While two of these have been identified as likely candidates for "missing" charmonium states, namely, the η_c' [1] and the χ_{c2}' [2], others have properties that are at odds with expectations of the charmonium model. These latter include the $X(3872)$ [3] and $Y(4260)$ [4], which are seen to decay to $\pi^+\pi^-J/\psi$, the $X(3940)$ [5], seen in $D^*\bar{D}$; the $Y(3940)$, seen in $\omega J/\psi$ [6]; and the $Y(4325)$ [7], seen in $\pi^+\pi^-\psi'$. Recently Belle reported a second $\pi^+\pi^-J/\psi$ mass enhancement below the $Y(4260)$ [8] and has shown that the $Y(4325) \to \pi^+\pi^-\psi'$ signal, reported by *BABAR* to have a width of $\Gamma = 172 \pm 33$ MeV, is better fitted with two narrower peaks, one at 4361 MeV with $\Gamma = 70 \pm 20$ MeV and a second at 4664 MeV, with $\Gamma = 40 \pm 17$ MeV [9].

Proposed assignments for these states have included multiquark states, either of the $(c\bar{q}, \bar{c}q)$ "molecular" type [10] or $[cq, \bar{c}\bar{q}]$ diquark-diantiquark type [11] (here c represents a charmed quark and q either a u, d, or s quark) hybrid $c\bar{c}$-gluon mesons [12]; or other missing charmonium states where the masses predicted by potential models are drastically modified by nearby $D^{(*)}\bar{D}^{(*)}$ thresholds [13,14]. A characteristic that clearly distinguishes multiquark states from hybrids or charmonia is the possibility to have charmoniumlike mesons with nonzero charge (e.g., $[cu\bar{c}\bar{d}]$), strangeness ($[cd\bar{c}\bar{s}]$) or both ($[cu\bar{c}\bar{s}]$) [15]. These considerations motivated a search for charmoniumlike mesons with nonzero electric charge.

Here we report the observation of a relatively narrow peak in the $\pi^+\psi'$ invariant mass distribution produced in exclusive $B \to K\pi^+\psi'$ decays [16]. The results are based on an analysis of a 657×10^6 $B\bar{B}$ event sample collected in the Belle detector operating at the KEKB asymmetric energy e^+e^- collider. The data were accumulated at a center-of-mass system (c.m.s.) energy of $\sqrt{s} = 10.58$ GeV, corresponding to the mass of the $\Upsilon(4S)$ resonance. KEKB is described in detail in Ref. [17].

The Belle detector, described in Ref. [18], is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector, a 50-layer cylindrical drift chamber, an array of aerogel threshold Cherenkov counters, a barrel-like arrangement of time-of-flight scintillation counters, and an electromagnetic calorimeter 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^0 mesons and to identify muons.

We select events of the type $B \to K\pi^+\psi'$, where the ψ' decays either to $\ell^+\ell^-$ or $\pi^+\pi^-J/\psi$ with $J/\psi \to \ell^+\ell^-$ ($\ell = e$ or μ). Both charged and neutral ($K_S^0 \to \pi^+\pi^-$) kaons are used. Charged tracks other than $K_S^0 \to \pi^+\pi^-$ secondaries are required to originate from the beam-beam interaction point. The charged kaon, lepton and pion selection requirements are described in Ref. [3]; those for neutral kaons are described in Ref. [6].

For $\psi'(J/\psi) \to \ell^+\ell^-$ candidates we require the invariant mass of the lepton pair to be within 20 MeV of the $\psi'(J/\psi)$ mass. For $\psi'(J/\psi) \to e^+e^-$ candidates, we include photons that are within 50 mrad of the e^+ or e^- tracks in the invariant mass calculation. For $\psi' \to \pi^+\pi^-J/\psi$ candidates, we require the $\pi^+\pi^-$ invariant mass to be greater than 0.44 GeV and $|M(\pi^+\pi^-\ell^+\ell^-) - M(\ell^+\ell^-) - 0.589\ \text{GeV}| < 0.0076$ GeV, which is $\pm 2.5\sigma$, where σ is the rms resolution.

We suppress continuum $e^+e^- \to q\bar{q}$ events, where $q = u, d, s$ or c, by requiring $R_2 < 0.4$, where R_2 is the second normalized Fox-Wolfram event-shape moment [19]. We also require $|\cos\theta_B| < 0.9$, where θ_B is the angle between the B meson and e^+ beam directions [20].

We identify B mesons using the beam-constrained mass $M_{\rm bc} = \sqrt{E^2_{\rm beam} - p^2_B}$ and the energy difference $\Delta E = E_{\rm beam} - E_B$, where $E_{\rm beam}$ is the c.m.s. beam energy, p_B is the vector sum of the c.m.s. momenta of the B meson decay products and E_B is their c.m.s. energy sum. We select events with $|M_{\rm bc} - m_B| < 0.0071$ GeV ($m_B = 5.279$ GeV, is the world-average B-meson mass [21]) and $|\Delta E| < 0.034$ GeV, which are $\pm 2.5\sigma$ windows around the nominal peak values.

The invariant mass of the selected $B \to K\pi\psi'$ candidate tracks is kinematically constrained to equal m_B. This improves the $\psi' \to \ell^+\ell^-$ ($J/\psi \to \ell^+\ell^-$) mass resolution to $\sigma = 4.4$ MeV (5.3 MeV). We require $M(\ell^+\ell^-)$ computed with the fitted lepton four-vectors to be within $\pm 2.5\sigma$ of $m_{\psi'}$ ($m_{J/\psi}$), the world-average ψ' (J/ψ) mass [21].

For the $\psi' \to \ell^+\ell^-$ mode we compute $M(\pi\psi')$ as $M(\pi\ell^+\ell^-) - M(\ell^+\ell^-) + m_{\psi'}$; for $\psi' \to \pi^+\pi^- J/\psi$ decays, we use $M(\pi\psi') = M(\pi\pi^+\pi^- J/\psi) - M(\pi^+\pi^- J/\psi) + m_{\psi'}$. Simulations of the two ψ' decay modes indicate that the experimental resolution for $M(\pi^+\psi')$ is $\sigma \simeq 2.5$ MeV for both modes.

Figure 1 shows a Dalitz plot of $M^2(K\pi^+)$ (horizontal) *vs.* $M^2(\pi^+\psi')$ (vertical) for the $B \to K\pi^+\psi'$ candidate events. Here, a distinct band at $M^2_{K\pi} \simeq 0.8\ \text{GeV}^2$, corresponding to $B \to K^*(890)\psi'$; $K^*(890) \to K\pi$, is evident. In addition, there are signs of a $K_2^*(1430)$ signal near $M^2_{K\pi} = 2.0\ \text{GeV}^2$. The $B \to K^*(890)\psi'$ events are used to calibrate the $M_{\rm bc}$ and ΔE peak positions and widths.

Some clustering of events in a horizontal band is evident in the upper half of the Dalitz plot near $M^2(\pi\psi') \simeq 20\ \text{GeV}^2$. To study these events with the effects of the known $K\pi$ resonant states minimized, we restrict our analysis to the events with $|M(K\pi) - m_{K^*(890)}| \geq 0.1$ GeV and $|M(K\pi) - m_{K_2^*(1430)}| \geq 0.1$ GeV. In the following, we refer to this requirement as the K^* veto.

The open histogram in Fig. 2 shows the $M(\pi^+\psi')$ distribution for selected events with the K^* veto applied. The bin width is 10 MeV. The shaded histogram shows the scaled distribution from ΔE sidebands ($|\Delta E \pm 0.070| < 0.034$ GeV). Here a strong enhancement is evident near $M(\pi\psi') \sim 4.43$ GeV.

We perform a binned maximum-likelihood fit to the $M(\pi\psi')$ invariant mass distribution using a relativistic S-wave Breit Wigner (BW) function to model the peak plus a smooth phase-space-like function $f_{\rm cont}(M)$, where $f_{\rm cont}(M) = \mathcal{N}_{\rm cont} q^*(Q^{1/2} + A_1 Q^{3/2} + A_2 Q^{5/2})$. Here q^* is the momentum of the π^+ in the $\pi\psi'$ rest frame and $Q = M_{\rm max} - M$, where $M_{\rm max} = 4.78$ GeV is the maximum $M(\pi\psi')$ value possible for $B \to K\pi\psi'$ decay. The normalization $\mathcal{N}_{\rm cont}$ and two shape parameters A_1 and A_2 are free parameters in the fit. This form for $f_{\rm cont}(M)$ is chosen because it mimics two-body phase-space behavior at the lower and upper mass boundaries. [Since the $M(\pi\psi')$

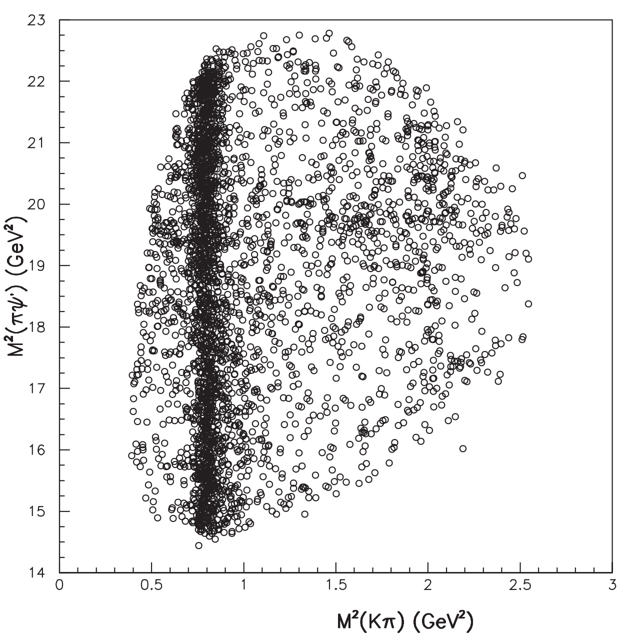

FIG. 1. The $M^2(K\pi)$ (horizontal) vs $M^2(\pi\psi')$ (vertical) Dalitz-plot distribution for $B^0 \to K^-\pi^+\psi'$ candidate events.

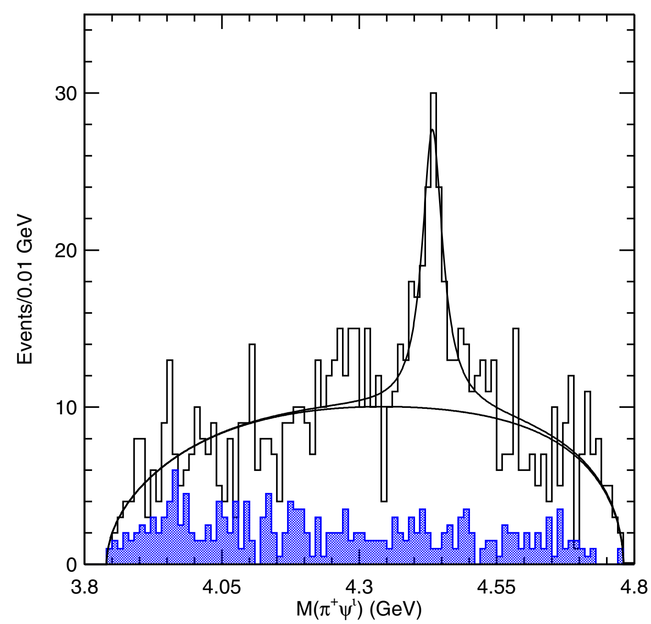

FIG. 2 (color online). The $M(\pi^+\psi')$ distribution for events in the $M_{\rm bc} - \Delta E$ signal region and with the K^* veto applied. The shaded histogram show the scaled results from the ΔE sideband. The solid curves show the results of the fit described in the text.

TABLE I. Results of the fit shown in Fig. 2.

N_{sig}	$\mathcal{N}_{cont}$	BW Mass (GeV)	Γ (GeV)
121 ± 30	766 ± 39	4.433 ± 0.004	$0.045^{+0.018}_{-0.013}$

distribution for the nonpeaking B-decay events and the ΔE sideband events have a similar shape, we represent them both with a single function.]

The results of the fit, shown as smooth curves in Fig. 2, are tabulated in Table I. The fit quality is $\chi^2 = 80.2$ for 94° of freedom. The significance of the peak, determined from the change in log likelihood when the signal and its associated degrees of freedom are removed from the fit, is 6.5σ.

We fit $M(\pi\psi')$ distributions for various subsets of the data. The results are summarized in Table II.

There are significant (i.e. significance of 4.5σ or more) signals with consistent mass values in both the $\psi' \to \pi^+\pi^- J/\psi$ and $\psi' \to \ell^+\ell^-$ subsamples. However, the width of the peak in the $\psi' \to \ell^+\ell^-$ subsample is substantially wider than that for the $\pi^+\pi^- J/\psi$ subsample. Fitting the two measured widths to a common value gives a $\chi^2 = 4.8$ for 1 degree of freedom. The corresponding confidence level is $\simeq 3\%$.

The fitted values for the signal yields are highly correlated with the widths. To compare the yields in each subchannel, we refit the distributions using a width that is fixed at the $\Gamma = 0.045$ GeV value determined from the common fit. These values are listed in the fifth column of Table II. The ratio of "constrained" signal yields for the $\pi^+\pi^- J/\psi$ and $\ell^+\ell^-$ subsamples (see Table II) is 1.09 ± 0.35, in good agreement with the MC-determined acceptance ratio of 1.23.

Table II also shows the results from dividing the data sample into $\ell^+\ell^- = e^+e^-$ and $\mu^+\mu^-$, and charged kaon and $K_S^0 \to \pi^+\pi^-$ subsets. We see signals in both the e^+e^- (3.5σ) and $\mu^+\mu^-$ modes (5.2σ) with consistent mass and width values, and with constrained yields that are consistent with the expected $e^+e^-/\mu^+\mu^-$ acceptance ratio of 0.61. There are too few events in the K_S^0 sample to enable a stable fit with yield, mass and width all allowed to vary. With the width fixed at the value found for the charged kaon sample, the fit returns a 19 ± 8 event signal with 2.0σ significance and a consistent mass value. The observed signal yield in the K_S^0 sample agrees with expectations [22] based on scaling the charged kaon signal by the $K_S^0/K^\pm$ acceptance ratio (0.19).

The last row of Table II shows the results of a fit to the $M(\pi\psi')$ distribution for the case where the K^* veto is replaced by a less stringent requirement that only eliminates the core of the $K^*(890)$ peak: $|M(K\pi) - m_{K^*(890)}| \geq 0.05$ GeV. Here the observed signal increases and its statistical significance improves to 7.1σ.

The $M(K\pi)$ distribution for events within ± 0.03 GeV of the peak at 4.43 GeV is shown in Fig. 3. Here the K^* veto, which excludes the regions indicated by the double-sided arrows in the figure, has been removed. The shaded histogram is the scaled ΔE sideband data. Aside from the $K^*(890)$ resonance events, which are removed by the K^* veto, no dramatic features are evident.

We considered the possibility that interference between S-, P- and D-waves in the $K\pi$ system might produce a structure similar to that which is observed. (There are F-wave and higher $K\pi$ resonances listed in the PDG tables; however, even the lowest mass F-wave entry, the $K_3^*(1780)$, is not kinematically accessible in $B \to K\pi\psi'$ decay.) We find that with only these three partial waves, it is not possible to produce a $\pi\psi'$ invariant mass peak near 4.43 GeV that is as narrow as the one we see without other, even more dramatic, accompanying structures.

We applied the same analysis to large MC samples of generic B meson decays and found no evidence of peaking in the $\pi\psi'$ invariant mass distribution.

The product branching fraction is determined using MC-computed acceptance values and world-average values for ψ' and J/ψ branching fractions [21]. For this calculation, we only use the signal yield from the $B^0 \to K^\mp\pi^\pm\psi'$ decay sample. The resulting product branching fraction is

$$\mathcal{B}(\bar{B}^0 \to K^- Z^+(4430)) \times \mathcal{B}(Z^+(4430) \to \pi^+\psi') = (4.1 \pm 1.0 \pm 1.4) \times 10^{-5}, \quad (1)$$

where $Z^+(4430)$ is used to denote the observed structure,

TABLE II. Results of fits to different subsamples of the data

Subset	Mass	Width	Significance	Constr. yield
	(GeV)	(GeV)	(σ)	($\Gamma = 0.045$ GeV)
$\pi^+\pi^- J/\psi$	4.435 ± 0.004	$0.026^{+0.013}_{-0.008}$	4.5	64 ± 15
$\ell^+\ell^-$	4.435 ± 0.010	$0.094^{+0.042}_{-0.030}$	4.7	59 ± 13
e^+e^-	4.430 ± 0.009	$0.056^{+0.028}_{-0.020}$	3.5	41 ± 12
$\mu^+\mu^-$	4.434 ± 0.004	$0.038^{+0.023}_{-0.013}$	5.2	80 ± 16
$K^\pm\pi^\mp\psi'$	4.434 ± 0.005	$0.048^{+0.019}_{-0.014}$	6.0	102 ± 18
$K_S^0\pi^\mp\psi'$	4.430 ± 0.009	0.048-fixed	2.0	19 ± 8
K^* veto	4.437 ± 0.005	$0.063^{+0.024}_{-0.017}$	7.1	170 ± 26

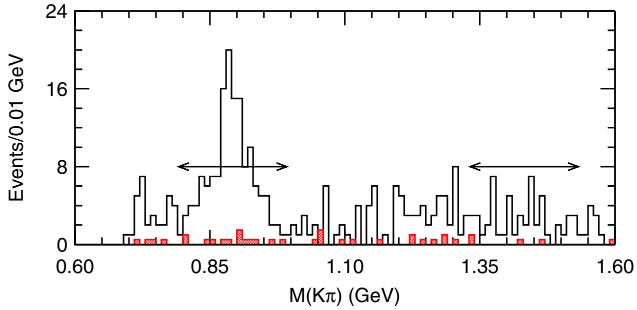

FIG. 3 (color online). The $M(K\pi)$ distribution for events within ± 0.03 GeV of the 4.43 GeV peak. Here the K^* veto, which excludes the regions indicated by double-sided arrows, has been removed. The shaded histogram indicates the ΔE-sideband-determined non-B background.

the first error is statistical and the second error is systematic (discussed below).

The values of the ψ' mass determined using events in the data agree within ± 1 MeV with the world-average value for both the $\psi' \to \pi^+\pi^- J/\psi$ and $\psi' \to \ell^+\ell^-$ decay modes. We find less than 1 MeV variation in the peak mass value for different fitting functions. Fits that include possible interference between the BW signal and the nonresonant $\pi\psi'$ continuum produce at most a 1.2 MeV shift in the fitted mass value. We assign a ± 2 MeV systematic error to the mass determination.

The systematic uncertainty on the width is mostly due to the uncertain effects of background fluctuations feeding into the fitted signal. We estimate the level of this effect from the range in width values determined from different subsets of the data to be $+29$ MeV and -10 MeV. Changes in the parameterization of $f_{\rm cont}(M)$ and variations in the range of $M(\pi\psi')$ values included in the fit produce ± 8 MeV changes in the width; using different BW forms produce ± 4 MeV width changes. Adding these sources in quadrature results in a total systematic error on the width of $+30$–13 MeV.

The largest systematic error on the product branching fraction measurement is due to the correlation between the fitted signal yield and the peak width. A $+30$ MeV (-13 MeV) change in the width produces a $+30\%$ (-17%) change in signal yield. Changes in the parameterization of $f_{\rm cont}(M)$ produce $+11\%$ and -18% variations in signal yield. Other systematic errors are smaller. These include: possible interference with the $\pi\psi'$ continuum; the choice of BW signal function; uncertainties in the acceptance calculation; uncertainties in the tracking and particle identification efficiencies; errors on the world-average ψ' decay branching fractions; MC statistics; and the error on the number of $B\bar{B}$ mesons in the sample. Combining these errors in quadrature gives a systematic error on the product branching fraction of 35%.

In summary, a study of $B \to K\pi^+\psi'$ decays reveals a peak in the $\pi^+\psi'$ invariant mass spectrum at $M = (4433 \pm 4({\rm stat}) \pm 2({\rm syst}))$ MeV. The measured width, $\Gamma = (45^{+18}_{-13}({\rm stat})^{+30}_{-13}({\rm syst}))$ MeV, is too narrow to be caused by interference effects in the $K\pi$ channel. The statistical significance of the observed peak is 6.5σ.

There have been a number of anomalous charmonium-like meson candidates reported in the literature [1–9]. The structure reported here is unique in that it is the first candidate to have a nonzero electric charge.

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