SEARCH FOR A CHARMONIUM ASSIGNMENT FOR THE X(3872)

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We report recent results on the properties of the X(3872) produced via the $B^+ \rightarrow K^+ X(3872)$ decay process in the Belle detector. We compare these properties with expectations for possible charmonium-state assignments.

Keywords: X(3872); Charmonium

1. Introduction

The X(3872) is a narrow state that decays into $\pi^+\pi^- J/\psi$. Although its mass, a $M_X = 3871.9 \pm 0.5$ MeV, is well above the $D\bar{D}$ open-charm threshold, its width is narrow: the current experimental upper limit on its width is $\Gamma < 2.3$ MeV (90% CL) 1. It was first seen in exclusive $B \rightarrow KX(3872)$ decays by the Belle experiment 1 (see Fig. 1) and subsequently seen in inclusive $p\bar{p}$ collisions by CDF 2 and D0. 3 Recently, the BaBar group confirmed its production in exclusive $B$-meson decays. 4 Although it looks like a typical charmonium particle (i.e. a $c\bar{c}$ meson), its assignment to any of the as-yet unseen narrow charmonium states has proven to be problematic.

In this report I describe recent results on the X(3872) and compare its known properties with expectations for possible charmonium assignments.

2. Properties of the X(3872)

First I summarize the known properties of the X(3872):

(i) It decays to $\pi^+\pi^- J/\psi$.
(ii) Its mass is very close to the $M_{D^0} + M_{D^{*0}}$ mass threshold.
(iii) It is narrow ($\Gamma < 2.3$ MeV).
(iv) Although its mass is more that 140 MeV above the $D\bar{D}$ mass threshold, decays to $D\bar{D}$ are not seen; Belle 5 reports $\Gamma(X \rightarrow D\bar{D})/\Gamma(X \rightarrow \pi^+\pi^- J/\psi) < 7$ (90% CL). (The same ratio for the $\psi(3770)$, which is only about 30 MeV above

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*This mass value is a weighted average of the results from Refs. [1-4].
0.40
0.60
0.80
1.00
1.20

\[ M(p^+p^-J/\psi) - M(J/\psi) \text{ (GeV/c}^2) \]

200
400

Events/0.010 GeV/c^2

Fig. 1. \( M_{p^+p^-J/\psi} - M_{J/\psi} \) for \( B \to p^+p^-J/\psi \) decays seen in the Belle experiment. The large peak at 0.59 GeV corresponds to \( B \to K\psi'; \psi' \to p^+p^-J/\psi \) events. The peak at 0.776 GeV is the signal for \( X(3872) \to p^+p^-J/\psi \).

the \( D\bar{D} \) threshold, \( \Gamma_{DD} > 160 \).) The absence of \( D\bar{D} \) decays, taken together with fact that it is narrow indicates that \( D\bar{D} \) final states are probably not allowed. This suggests that the natural quantum number sequence \( J^P = 0^+, 1^-, 2^+, \text{ etc.} \) is ruled out.

(v) In the \( p^+p^-J/\psi \) decays, the dipion masses tend to concentrate near the mass of the \( \rho(770) \) meson. The decay of a \( c\bar{c} \) charmonium state to \( \rho J/\psi \) would violate isospin and isospin-violating charmonium transitions are strongly suppressed. If the dipions are in fact coming from \( \rho \to p^+p^- \) decays, the charge-conjugation parity of the \( X(3872) \) would be \( C = +1 \) and \( X \to \pi^3\pi^0 J/\psi \) decays would be forbidden. Otherwise, the \( X(3872) \) would have \( C = -1 \) and \( \Gamma(X \to \pi^3\pi^0 J/\psi) \approx \frac{1}{4} \Gamma(X \to p^+p^-J/\psi) \).

(vi) The decay \( X(3872) \to \gamma\chi_{c1} \) is not seen.\[1\]

\[ \Gamma(X \to \gamma\chi_{c1})/\Gamma(X \to p^+p^-J/\psi) < 0.89 \text{ (90\% CL)} \]

(vii) It is seen in exclusive \( B \to KX \) decays with the product branching fraction\[2\]

\[ B(B^+ \to K^-X) \times B(X \to p^+p^-J/\psi) = (1.3 \pm 0.3) \times 10^{-5} \] (1)

This suggests that high values of \( J \) are not likely (see Sect. 4.3 below).

3. Charmonium Possibilities

We consider as-yet unseen charmonium states with expected masses within \( \sim 200 \text{ MeV of } 3872 \text{ MeV} \), with unnatural quantum numbers (i.e. \( J^P = 0^-, 1^+, 2^- \), etc.), and with spin angular momentum \( J < 3 \). There are five candidate states that meet these criteria: the \( 1^3D_2, 2^1P_1, 2^3P_1, 1^1D_1, \text{ and } 3^1S_0 \). We also consider the \( 1^3D_3 \), even though it fails two of our criteria — it has \( J = 3 \) and decays to \( D\bar{D} \) are
allowed. This has been promoted to the candidate list because some authors have identified this as a candidate based primarily on the observation that $\psi_3 \rightarrow D\bar{D}$ decays are suppressed by an $L = 3$ angular momentum barrier.

Table 1. Some properties of the candidate charmonium states.

| State $D_2$ | nickname | $J^{PC}$ | $M_{predicted}$ (MeV) | $\Gamma_{predicted}$ (MeV) |
|-------------|----------|----------|------------------------|-----------------------------|
| $1^3D_2$    | $\psi_2$ | 2$^{--}$ | 3838                   | 0.7                         |
| $2^1P_1$    | $h_2^\prime$ | 1$^{++}$ | 3953                   | 1.6                         |
| $1^3D_3$    | $\psi_3$ | 3$^{+}$  | 3849                   | 4.8                         |
| $2^1P_1$    | $X_1'$   | 1$^{++}$ | 3956                   | 1.7                         |
| $1^1D_2$    | $\eta_{c2}$ | 2$^{--}$ | 3837                   | 0.9                         |
| $3^1S_0$    | $\eta_{c2}'$ | 0$^{+}$ | 4060                   | $\sim$ 20                   |

The six candidate states are summarized in Table 1 roughly in the order of their plausibility. We include in the Table the quantum numbers and a potential model prediction for the mass, and total width values that are from Ref. [8] and computed using a 3872 MeV mass value.

In the following I discuss each candidate assignment one-by-one in the context of measurements in progress that are intended to confirm or disallow that assignment.

4. $C = -1$ assignments

If the $X(3872)$ is a $C = -1$ state, the $\pi^+\pi^- J/\psi$ transition is isospin conserving and not suppressed. Thus, one of these assignments would seem to be more reasonable. For this case, the $X \rightarrow \pi^0\pi^0 J/\psi$ partial decay width would be about half of that for $\pi^+\pi^- J/\psi$. The $\pi^0\pi^0 J/\psi$ channel is more experimentally challenging than $\pi^+\pi^- J/\psi$ and there have been no results reported to date. Belle hopes to report a measurement of this channel in Summer 2004.

4.1. $X(3872) = \psi_2$?

In the charmonium model there are two states expected to have mass between $2M_D$ and $M_{D+D}$, for which $DD$ decays are forbidden: the $\psi_2$ and $\eta_{c2}$. Of these, the $\psi_2$ is expected to have an appreciable branching fraction for $\pi^+\pi^- J/\psi$ decays, making it a preferred assignment for the $X(3872)$. However, this assignment has some problems:

**Mass** In the charmonium picture, the $\psi_2$ mass differs from that of its multiplet partner, the $\psi''$ with $M = 3770$ MeV, by spin-orbit and tensor interactions plus coupled channel effects involving virtual $D\bar{D}^{(*)}$ states. The authors of Ref. [9] examined these effects and found a splitting of 66 MeV, well below the $X(3872)$-$\psi''$ mass difference: $\Delta M = 102$ MeV.

\[ \text{The predicted width for the } \eta_{c2}' \text{ is taken to be the same as the (poorly known) } \eta_{c} \text{ width.} \]
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The transition $\psi_2 \rightarrow \gamma \chi_{c1}$ is an allowed $E1$ transition with a partial width that is calculated in a potential model (for $M_{\psi_2} = 3872$ MeV) to be $\Gamma(X \rightarrow \gamma \chi_{c1}) \simeq 360$ keV. The inclusion of coupled-channel effects reduces this to $\simeq 210$ keV. The Wigner-Eckart theorem says that the widths for $\psi_2 \rightarrow \pi^+ \pi^- J/\psi$ and $\psi_3 \rightarrow \pi^+ \pi^- J/\psi$ should both be equal to $\Gamma(\psi(3770) \rightarrow \pi^+ \pi^- J/\psi)$. The latter has been recently measured by BESII \cite{6} and CLEO-c \cite{11} to be $80 \pm 38$ keV and $\leq 55$ keV (90\% CL), respectively. These results are in some contradiction with each other, but it is probably safe to say that $\Gamma(\psi(3770) \rightarrow \pi^+ \pi^- J/\psi) < 130$ keV. Thus, for the $X(3872) = \psi_2$ assignment, we can expect that $\Gamma(X \rightarrow \gamma \chi_{c1}) / \Gamma(X \rightarrow \pi^+ \pi^- J/\psi) > 1.6$, in contradiction with Belle's 90\% CL upper limit of 0.89. Belle continues to search for this decay mode with higher sensitivity.

4.2. $X(3872) = h'_c$ ?

The experimental situation for the $h_c$ is unsettled, but its mass is expected to be reasonably close to the center-of-gravity of its spin-triplet partners, the $\chi_{c0,1,2}$ states, and safely removed from 3872 MeV. It has been proposed \cite{12} that the $X(3872)$ might be its first radial excitation, the $h'_c$. If this were the case, the $h'_c$ has been discovered before its ground-state partner the $h_c$; stranger things have happened.

Mass The $h'_c$ cannot decay to $D\bar{D}$ and might be narrow if its mass were 3872 MeV. However, even with coupled-channel effects included, the $h'_c$ is expected to have a mass of $\sim 3950$ MeV, above the $D\bar{D}^*$ threshold and far from 3872 MeV.

Angular distribution In Belle, the $X(3872)$ is produced via $B \rightarrow KX$ decays. Since both the initial state $B$ and the accompanying $K$ mesons are spin zero, the angular properties of the final state are rather simple. \cite{12} We define $\theta_{J/\psi}$ as the angle...
between the $J/\psi$ and the negative of the $K$ momentum vectors in the $X(3872)$ rest frame (see Fig. 2). The $|\cos \theta_{J/\psi}|$ distribution for $X(3872)$ events with $m_{\pi^+\pi^-} > 0.65$ GeV is shown as data points in Fig. 2. For the case where the $X$ has $J^{PC} = 1^{-+}$, the $\cos \theta_{J/\psi}$ distribution would have a $\sin^2 \theta_{J/\psi}$ dependence. The distribution for a MC sample of events generated with $1^{-+}$ expectations plus (a small) sideband-determined background is shown in the figure as a histogram. The data tend to peak near $\cos \theta_{J/\psi} = 1$, where the $1^{-+}$ expectation is zero; the $\chi^2/\text{dof}$ is very poor at 75/9, and enables us to rule out any $1^{-+}$ assignment for the $X(3872)$ (including the $h_c'$) with high confidence.

4.3. $X(3872) = \psi_3$?

The authors of Refs. [8] and [9] have suggested that the $X(3872)$ may be the $\psi_3$, even though $\psi_3 \rightarrow D\bar{D}$ decays are allowed and the decay $B \rightarrow K\psi_3$ is likely highly suppressed. They argue that although $D\bar{D}$ decays are allowed, an $L = 3$ angular momentum barrier may suppress them to such an extent that the $\psi_3$ might appear to be “narrow.”

**Width** Predictions (from Ref. 8) for the total width and the rate for $D\bar{D}$ decays are above the Belle upper limits, but these calculations are probably not very reliable.

$\gamma \chi_{c2}$ partial width The transition $\psi_3 \rightarrow \gamma \chi_{c2}$ is a favored $E1$ transition with a partial width that is calculated to be $\sim 300$ keV, where suppression due to coupled-channel effects has been included. Thus, the partial width for $\psi_3 \rightarrow \gamma \chi_{c2}$ is expected to be more than twice that for $\psi_3 \rightarrow \pi^+\pi^-J/\psi$.

Belle searched for $X \rightarrow \gamma \chi_{c2}$ using a procedure that closely follows that used for the $\gamma \chi_{c1}$ limit reported in Ref. [1]. In a sample of $B \rightarrow K\gamma J/\psi$ event candidates, one of the $\gamma J/\psi$ combinations was required to be within $\pm 10$ MeV of the $\chi_{c2}$ mass, and the $\gamma \chi_{c2}$ mass was required to be within $\pm 20$ MeV of the $X(3872)$ mass. The results of an unbinned two-dimensional likelihood fit to the $B$-meson mass ($M_{bc}$) and the $\gamma \chi_{c2}$ mass distributions are shown in Fig. 3. There is no evidence for a signal; the fitted signal yield is $2.9 \pm 3.0 \pm 1.5$ events, where the first error is statistical and the second systematic. The latter is estimated by the changes that occur when the input parameters to the fit are varied over their allowed range of values. This yield translates into a 90% CL upper limit of $\Gamma(X \rightarrow \gamma \chi_{c2})/\Gamma(X \rightarrow \pi^+\pi^-J/\psi) < 1.1$, below expectations for the $\psi_3$.

**Spin** $B$-meson decays to a kaon plus a $c\bar{c}$ pair are expected to proceed via the diagram shown in Fig. 4. In the spectator picture, the $c\bar{s}s$ quark system has the same spin as the decaying $b$-quark (i.e. $J = \frac{1}{2}$). This implies $J = 0$ or 1 for

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\*\*\*We use the “beam constrained” mass: $M_{bc} = \sqrt{(E_{cm}/2)^2 - |\vec{p}_B|^2}$, where $\vec{p}_B$ is the candidate $B$ meson’s momentum in the center of mass frame.\*\*\*
Fig. 3. Signal-band projections of $B$-meson mass (left) and $M_{\gamma\chi^c_2}$ (right) distributions for events in the $X(3872)$ region with the results of the unbinned fit superimposed.

Fig. 4. The leading diagram for $B \to K(c\bar{c})$ decays.

the $c\bar{c}$ system. Higher values of $J$ can be accomplished via the exchange of hard gluons between the $c\bar{c}$ quarks and the "spectator" $\bar{q}$, but this is expected to be suppressed. Thus, it is expected that for $B \to K(c\bar{c})$ decays, $J = 0$ and $J = 1$ $c\bar{c}$ systems should dominate. The branching fractions for $B \to K\eta_c$, $KJ/\psi$ and $K\chi_{c1}$ (with $J_{c\bar{c}} = 0$, 1 and 1, respectively) are all about the same ($\mathcal{B} \approx 10^{-3}$); in contrast, the decay $B \to K\chi_{c2}$ (where $J_{c\bar{c}} = 2$) has yet to be observed (see Fig. 5 below). Reference 8 predicts a $\psi_3 \to D\bar{D}$ width of 4 MeV, more than an order of magnitude above that for $\pi^+\pi^-J/\psi$. According to Eq. 1 this would mean that for an $X(3872) = \psi_3$ assignment, the total branching fraction for $B \to K\psi_3$ would be $\simeq 10^{-3}$, comparable to that for $B \to K\eta_c$ or $KJ/\psi$. This seems unlikely for a $J_{c\bar{c}} = 3$ state.
5. $C = +1$ assignments

If the $X(3872)$ is a $C = +1$ state, the dipion system in the $\pi^+\pi^- J/\psi$ final states would be from a $\rho \to \pi^+\pi^-$ decay. This is supported by the dipion mass spectrum, which is concentrated near the $\rho$-meson mass. However, charmonium states all have zero isospin and, thus, decays to $\rho J/\psi$ are isospin violating and suppressed. Thus, $C = +1$ charmonium assignments seem rather implausible. Nevertheless, since some of these have been proposed as possibilities, we address them here.

5.1. $X(3872) = \chi'_{c1}$?

According to the authors of Ref. [8], if the $\chi'_{c1}$ mass were 3972 MeV, it would have a total width less than 2 MeV. However the isospin-violating decay $\chi'_{c1} \to \pi^+\pi^- J/\psi$ is not expected to be prominent. There is one well established isospin-violating hadronic charmonium transition: $\psi' \to \pi^0J/\psi$. This has a measured partial width of $\sim 0.3$ keV, which is a factor of $\sim 500$ smaller than the $\sim 150$ keV width for isospin-conserving $\psi' \to \pi\pi J/\psi$ process.

Mass  Potential models 8 prefer a $\chi'_{c1}$ mass in the range $3930 \sim 3990$ MeV and the coupled-channel corrections of Ref. [9] tend to shift this upwards, away from 3872 MeV.

$\gamma J/\psi$ partial width  A potential model estimate 8 for the $\gamma J/\psi$ partial width for a $\chi'_{c1}$ with a mass of 3872 MeV is 11 keV; coupled-channel effects may reduce this, but not by as much as an order of magnitude. If we assume that the partial width for the isospin-violating process $\chi'_{c1} \to \pi^+\pi^- J/\psi$ is similar to $\Gamma(\psi' \to \pi^0 J/\psi) \simeq 0.3$ keV, we can expect that $\chi'_{c1} \to \gamma J/\psi$ decays will be more common than $\pi^+\pi^- J/\psi$ decays by at least an order-of-magnitude.

Belle searched for $B \to KX; X \to \gamma J/\psi$ decays. Candidate $B^+ \to K^+\gamma J/\psi$ events were selected using the criteria described in Ref. [1]. Figure 5 shows the $\Delta M = M_{\gamma J/\psi} - M_{J/\psi}$ distribution for selected events. There is a large peak at $\Delta M = 0.414$ GeV corresponding to $B^+ \to K^+\chi_{c1}; \chi_{c1} \to \gamma J/\psi$ decays, but no sign of a signal at $\Delta M = 0.776$ GeV, the position of the $X(3872)$.

The $\chi_{c1}$ signal is a convenient calibration reaction. We perform a three-dimensional unbinned likelihood fit to the $M_{bc}, \Delta E$ and $\Delta M$ distributions for events in the $\chi_{c1}$ region; the fitted number of events is $470 \pm 24$. A similar fit to the events in the $X(3872)$ region using parameters for the $M_{bc}, \Delta E$ and $M_{\gamma J/\psi}$ signal functions that are derived from the results of the $\chi_{c1}$ fit scaled by MC-determined mass-dependent factors, gives a signal yield of $7.7 \pm 3.6$ events. When we include the effects of systematic errors, this yield translates into the limit

$$\frac{\Gamma(X \to \gamma J/\psi)}{\Gamma(X \to \pi^+\pi^- J/\psi)} < 0.40 \ (90\% CL),$$

which is considerably less than expectations for the $X(3872) = \chi'_{c1}$ assignment.
Fig. 5. The $M(\gamma\ell^+\ell^-) - M(\ell^+\ell^-)$ distribution for $B \to K\gamma J/\psi$ event candidates. The large ($\simeq 470$ event) peak near 0.414 GeV is due to $B \to K\chi_{c1}$. There are no evident signals for $B \to KX(3872)$, which would show up as a peak at 0.776 GeV (or $B \to K\chi_{c2}$, which would peak at 0.460 GeV).

5.2. $X(3872) = \eta_{c2}'$?

The isospin-conserving transition $\eta_{c2}' \to \pi^+\pi^-\eta_c$ is expected to be much more common than the isospin-violating $\pi^+\pi^-J/\psi$ decay. Thus, from Eqn. 1 we infer that if the $X(3872)$ is the $\eta_{c2}'$, the branching fraction $B(X \to \pi^+\pi^-J/\psi)$ would be very small, of order 1% or less, and the exclusive $B \to KX(3872)$ to a $c\bar{c}$ state with $J = 2$, would be comparable to, or even larger than, the branching fractions for the angular momentum-favored decays $B \to K\eta_c$ and $B \to KJ/\psi$.

For this assignment, $X(3872) \to \pi^+\pi^-\eta_c$ decays should be observable. Belle plans to report a result on this channel this summer.

5.3. $X(3872) = \eta''_c$ ?

The final candidate considered here is the $\eta''_c$. If the $\eta''_c$ mass were 3872 MeV, its dominant decay would be into two gluons. The $\pi^+\pi^-J/\psi$ decay would violate isospin and be suppressed.

Mass In 2002, Belle observed the $\eta''_c$ in exclusive $B \to KKsK\pi$ decays. This observation was subsequently confirmed by CLEO, BaBar and Belle. The average mass and width values are $M_{\eta''_c} = 3638 \pm 4$ MeV and $\Gamma_{\eta''_c} = 19 \pm 10$ MeV. The $\psi - \eta''_c$ mass splitting is $\simeq 48$ MeV, much smaller than the 117 MeV ground-state
The $J/\psi$-$\eta_c$ splitting; this decrease in splitting with increasing radial quantum number is expected in QCD-inspired potential models. Thus, one can reasonably expect that the $\psi(3S)$-$\eta_c''$ mass splitting will be less than 48 MeV. Since the mass of the $\psi(3S)$ is $4040 \pm 10$ MeV, the $\eta_c''$ mass must be far above 3872 MeV.

**Width** The dominant $\eta_c$ decay channel is via two gluons and the world-average width of the $\eta_c$ is $17 \pm 3$ MeV. It is expected that the $\eta_c''$, which also predominantly decays via two gluons, will be similar to that for the $\eta_c$. Existing measurements, while not conclusive, are consistent with this conjecture. It is, therefore, reasonable to expect that an $\eta_c''$ with mass below the $D\bar{D}$ threshold would have a total width similar to that of the $\eta_c$ and larger than the 2.3 MeV upper limit on the $X(3872)$ width.

6. Summary of possible charmonium assignments

Although our knowledge of the $X(3872)$ properties is still rather meager, none of the examined charmonium assignments naturally match the little we know about them. A summary of the discussion in the previous discussion is provided in Table 2.

| State | nickname | $JPC$ | comment |
|-------|----------|-------|---------|
| $1^3D_2$ | $\psi_2$ | $2^{--}$ | Mass wrong; $\Gamma_{\gamma \chi_c}$ too small |
| $2^1P_1$ | $\chi_c'$ | $1^{+-}$ | Ruled out by $|\cos \theta_{J/\psi}|$ distribution |
| $1^3D_3$ | $\psi_3$ | $3^{--}$ | $\Gamma_{\gamma \chi_c}$ too small; spin seems too high |
| $2^3P_1$ | $\chi_{c1}$ | $1^{++}$ | $\Gamma_{\gamma J/\psi}$ too small |
| $1^1D_2$ | $\eta_c$ | $2^{++}$ | $B(\pi^+ \pi^- J/\psi)$ expected to be very small |
| $3^1S_0$ | $\eta_c''$ | $0^{--}$ | Mass and width are wrong |

We conclude that if the $X(3872)$ is in fact a charmonium state, the standard quarkonium theory needs some considerable improvements.

7. Non-charmonium Possibilities

The absence of an obvious charmonium assignment naturally leads one to speculate about non-charmonium possibilities. In light of the close proximity of the $X(3872)$ to $M_{D^0} + M_{D^{*0}} (= 3871.5 \pm 1.0$ MeV)\[17\] an obvious candidate is a $D\bar{D}^*$ molecule-like bound state, and idea that has been around for some time \[18\] and has recently been resurrected\[11\][12][19][20][21]. An inter-mesonic force mediated by single pion exchange would be attractive for $J^{PC} = 1^{++}$ or $0^{-+}$.\[19\] This can be checked by measuring the $J^{PC}$ of the $X(3872)$, which can be done by a full angular analysis of the $\pi^+ \pi^- J/\psi$ system. However, this will require more data than are currently available.

Another, perhaps less likely, possibility is some kind of a $c\bar{c}g$ hybrid state.\[20][22\] These are found in lattice QCD, but generally with masses of 4400 MeV or so.
8. Conclusion
The $X(3872)$ particle is proving to be an interesting experimental and theoretical puzzle and a case where experiment appears to be way ahead of theory. As an experimentalist, the fun part about working on this is that I have no idea where it will lead.

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References
1. S.-K. Choi et al., (Belle Coll.), Phys. Rev. Lett 91, 262001 (2003).
2. G. Bauer et al., (CDF Coll.), hep-ex/0312021.
3. V.M. Abazov et al., (D0 Coll.), hep-ex/0405004.
4. B. Aubert et al., (BaBar Coll.), hep-ex/0406022.
5. R. Chistov et al., (Belle Coll.), hep-ex/0307061, to appear in Phys. Rev. Lett.
6. J.Z. Bai et al., (BESII Coll.), hep-ex/0307028v2.
7. S. Godfrey and N. Isgur, Phys. Rev. D 32, 189 (1985).
8. T. Barnes and S. Godfrey, Phys. Rev. D 69, 054008 (2004).
9. E.J. Eichten, K. Lane and C. Quigg, Phys. Rev. D 69, 094019 (2004).
10. M.B. Voloshin, Phys. Lett. B 579, 316 (2004).
11. T. Skwarnicki, hep-ph/0311243.
12. S. Pakvasa and M. Suzuki, Phys. Lett. B 579, 67 (2004).
13. S.-K. Choi et al., Belle Coll. Phys. Rev. Lett. 89, 102001 (2002); Erratum-ibid 89, 129901 (2002).
14. D.M. Asner et al., (CLEO Coll.), Phys. Rev. Lett. 92, 142001 (2004).
15. G. Wagner, (BaBar Coll.), hep-ex/0305083.
16. K. Abe et al., (Belle Coll.), hep-ex/0306015.
17. K. Hagibara et al., (Particle Data Group), Phys. Rev. D 66, 010001 (2002).
18. See, for example, M.B. Voloshin and L.B. Okun, JETP Lett. 23, 333 (1976); M. Bander, G.L. Shaw and P. Thomas, Phys. Rev. Lett. 36, 695 (1977); A. De Rujula, H. Georgi and S.L. Glashow, Phys. Rev. Lett. 38, 317 (1977); N.A. Törnqvist, Z. Phys. C 61, 525 (1994); and A.V. Manohar and M.B. Wise, Nucl. Phys. B 339, 17 (1993).
19. N.A. Törnqvist, Phys. Lett. B 590, 209 (2004).
20. F.E. Close and P.R. Page, Phys. Lett. B 578, 119 (2003).
21. C.-Y. Wong, Phys. Rev. C 69, 055202 (2004); E. Braaten and M. Kusunoki, Phys. Rev. D 69, 114012 2004; and E.S. Swanson, Phys. Lett. B 588, 189 (2004) and hep-ph/0406080.
22. See, for example, F.E. Close and S. Godfrey, Phys. Lett. B 574, 210 (2003); and G. Chiladze, A.F. Falk and A.A. Petrov, Phys.Rev. D 58, 034013 (1998).