Threshold effect and $\pi^\pm\psi(2S)$ peak\textsuperscript{1}

Jonathan L. Rosner\textsuperscript{2}

Enrico Fermi Institute and Department of Physics
University of Chicago, 5640 S. Ellis Avenue, Chicago, IL 60637

A resonance-like structure in the $\pi^\pm\psi(2S)$ mass spectrum arising in $B \to K\pi^\pm\psi(2S)$ has recently been reported. It is noted that the mass of this structure, $4433 \pm 4\pm1\text{ MeV}$, is not far from the threshold for production of $D^*\overline{D}_1(2420)$. A proposed mechanism for production of this state is suggested, and tests are suggested.

PACS Categories: 13.25.Gv, 13.25.Hw, 14.40.Gx, 14.40.Nd

A wealth of charmonium states have recently been reported in $B$ meson decays. (For one review, see Ref. [1].) Until recently, all such states were neutral, implying the possibility of at least some fraction of $c\bar{c}$ in their wave functions. Recently, however, the Belle Collaboration [2] has reported a state produced in $B \to K\pi^\pm\psi(2S)$ in which the $\pi^\pm\psi(2S)$ system displays a resonance-like structure with mass $M = 4433 \pm 4\pm1\text{ MeV}$ and width $\Gamma = 44^{+17+30}_{-13-11}\text{ MeV}$. This would be the first observation of a genuine tetraquark [3] charmonium configuration. The possibility of easily producing such configurations in $B$ decays was noted, for example, in Ref. [4].

The purpose of this Brief Report is to suggest a mechanism for production of this state which relies upon the proximity of its mass to the $D^*\overline{D}_1(2010)$ threshold. S-wave thresholds appear to be important in a wide variety of resonance-like behavior [5]. The $X(3872)$ state produced (for example) in $B \to KX$ and decaying to $\pi^+\pi^-J/\psi$ lies $0.6 \pm 0.6\text{ MeV}$ below $D^0\overline{D}^0$ c.c. threshold [6]. The $Y(4260)$, seen in the radiative return reaction $e^+e^- \to \gamma + Y(4260)$ and in a direct $e^+e^-$ scan, can be associated with the lowest threshold for which a $c\bar{c}$ pair with $J^{PC} = 1^{--}$ can materialize into a pair of mesons $D\overline{D}_1(2420)$ c.c. in a relative S-wave [5, 7].

The production mechanism we suggest for the $\pi^\pm\psi(2S)$ resonance-like state is based on the diagram of Fig. 1. The different charge states that can be involved in this process are summarized in Table I.

The quarks $q$ and $q'$ are independent. Isospin invariance implies $\mathcal{B}[B^0 \to K^+\pi^-\psi(2S)] = 2\mathcal{B}[B^0 \to K^0\pi^0\psi(2S)]$ and $\mathcal{B}[B^+ \to K^0\pi^+\psi(2S)] = 2\mathcal{B}[B^+ \to K^+\pi^0\psi(2S)]$.

The proposed mechanism operates by the production of an anti-charmed meson $\bar{c}q'$ and a charmed meson $cq$ which then rescatter into $c\bar{c} = \psi(2S)$ and $q'\bar{q} = \pi$. A key feature of the data not answered by the present mechanism is why rescattering into $J/\psi\pi$ is not observed. Perhaps the rescattering process is enhanced when the Q-values of the two sides are more nearly equal. The additional Q-value available in rescattering into states containing $J/\psi$ may favor higher pion multiplicities, e.g., $3\pi J/\psi$ or even $5\pi J/\psi$, over $\pi J/\psi$ [8]. [Here we have assumed a definite G-parity $G(Z) = \mp$.]

\textsuperscript{1}To be submitted to Phys. Rev. D.
\textsuperscript{2}rosner@hep.uchicago.edu
Figure 1: Diagram illustrating the production of a $\pi\psi(2S)$ state in $B$ decays. The weak subprocess $\bar{b} \rightarrow \bar{c}c\bar{s}$ is labeled by $\times$.

Table I: Possible charge states for production of a $\pi\psi(2S)$ state in $B$ decays.

| $q$ | $q'$ | $B$ | $K$ | $Z(4430)$ |
|-----|-----|-----|-----|-----------|
| $u$ | $d$  | $B^0$ | $K^+$ | $\pi^-\psi(2S)$ |
| $d$ | $u$  | $B^+$ | $K^0$  | $\pi^+\psi(2S)$ |
| $u$ | $u$  | $B^+$ | $K^+$  | $\pi^0\psi(2S)$ |
| $d$ | $d$  | $B^0$ | $K^0$  | $\pi^0\psi(2S)$ |

The $\bar{c}q'$ meson can be either $\bar{D}_1(2420)$ (the narrow P-wave charmed meson decaying to $\bar{D}\pi$) or $\bar{D}^*(2010)$ (the vector meson state decaying to $\bar{D}\pi$). The $c\bar{q}$ meson would then correspondingly be $D^*(2010)$ or $D_1(2420)$. In either case, the final state $D^*\bar{D}^*\pi$ should be visible, with a Dalitz plot showing a strong $\bar{D}_1(2420)$ and/or $D(2420)$ band. Which band is populated can shed light on details of the decay mechanism, such as whether relative orbital angular momentum of zero or one is favored between the $\bar{c}$ and the $q'$ in Fig. 1.

The S-wave states of $D^*(2010) + \bar{D}_1(2420)$ can have spin-parity $J^P = 0^-,1^-,2^-$. A $0^-$ or $1^-$ state would decay to $\pi\psi(2S)$ via a P-wave, while either P-wave or F-wave decay would be allowed for $2^-$. The calculation of acceptance in Ref. [2] assumed a relative S-wave between $\pi^\pm$ and $\psi(2S)$. The rather low Q-value for the decay $B \rightarrow KZ(4430)$ likely favors a low angular momentum $\ell$ between $K$ and $Z$. A low spin $J(Z)$ is then favored since one must have $J(Z) = \ell$ in this decay. For $J^P(Z) = 0^-$, the polarization vector of the $\psi(2S)$ in $Z \rightarrow \pi\psi(2S)$ must be parallel to the direction of the recoil $\pi$ in the rest frame of the $\psi(2S)$. If the polarization of the $J/\psi$ follows that of the $\psi(2S)$ (a good approximation), the leptons in $J/\psi \rightarrow \ell^+\ell^-$ will have a $\sin^2\theta$ distribution with respect to the recoil $\pi$ momentum.

If the $q\bar{q}$ pair in Fig. 1 is $s\bar{s}$ rather than $u\bar{u}$ or $d\bar{d}$, one will have final states such as $\phi D_s^{(*)}D^{(*)}$ or even (barely) $\phi D_s(2317)D$ [8]. The charm-anticharm pair could then
rescatter into $K\phi J/\psi$ or (for $D_s D$) $K\psi(2S)$. The decay $B^+ \rightarrow K^+ \phi J/\psi$ has been observed with a branching ratio of $(5.2 \pm 1.7) \times 10^{-5}$ (average of Ref. [9], based on Refs. [10] and [11]), and should be examined for bumps in the $K^+ J/\psi$ spectrum.

An anaglogue in charm decays, in which one would search for a $\phi \pi^-$ resonance, would be the Cabibbo-suppressed decay $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$. If the mechanism of Fig. 1 is responsible for a resonance through rescattering from a $K^{(*)}\overline{K}^{(*)}$ state, $D^0$ decays will yield a $\phi \pi^-$ resonance while $\overline{D}^0$ decays will yield a $\phi \pi^+$ resonance.

An alternative mechanism for production of a $c \bar{c} \pi$ state, distinct from that shown in Fig. 1, would involve a $\bar{b} \rightarrow \bar{s}$ penguin transition, leading to a similar diagram but with the $c \bar{c}$ pair produced from the vacuum rather than at the weak vertex. The presence of a signal in $\pi \psi(2S)$ and its absence in $\pi J/\psi$ would be even more puzzling in this picture. Moreover, the large product branching ratio \[ B[B \rightarrow KZ(4430)] \times B[Z(4430) \rightarrow \pi^+ \psi(2S)] = (4.1 \pm 1.0 \pm 1.3) \times 10^{-5}, \]
is larger than most $\bar{b} \rightarrow \bar{s}$ penguin-dominated processes without charmed pair production, so this alternative mechanism is highly unlikely to account for the observed signal. A similar statement applies to the case of the weak subprocess $\bar{b} \rightarrow \bar{u}u\bar{s}$ accompanied by charmed pair production from the vacuum, as this subprocess is even weaker than the $\bar{b} \rightarrow \bar{s}$ penguin process.

[Note added: subsequently to this work, a proposal appeared [12] that the $Z(4430)$, whose neutral member has charge conjugation eigenvalue $C = +$, is a tetraquark state representing a radial excitation of an as-yet-unseen $C = -$ state not far in mass from the $X(3872)$. (The $X(3872)$ is identified as having $C = +$ through its decay to $\gamma J/\psi$ [13, 14].) Even more recently, a proposal similar to ours [15] accounts for the apparent enhancement of the ratio $\Gamma[Z(4430) \rightarrow \pi \psi(2S)]/\Gamma[Z(4430) \rightarrow \pi J/\psi]$ via a rescattering model based on charm exchange, and concludes that $J^P[Z(4430)] = 1^-$ is favored.]

I thank Vera Luth, Luciano Maiani, and Art Snyder for discussions. Part of this work was performed at the Aspen Center for Physics. This work was supported in part by the United States Department of Energy through Grant No. DE FG02 90ER40560.

References

[1] E. Eichten, S. Godfrey, H. Mahlke and J. L. Rosner, arXiv:hep-ph/0701208

[2] K. Abe et al [Belle Collaboration], BELLE-CONF-0773, arXiv:0708.1790 [hep-ex], submitted to LP 2007

[3] L. Maiani, F. Piccinini, A. D. Polosa and V. Riquer, Phys. Rev. D 71, 014028 (2005);
L. Maiani, V. Riquer, F. Piccinini and A. D. Polosa, Phys. Rev. D 72, 031502 (2005);
I. Bigi, L. Maiani, F. Piccinini, A. D. Polosa and V. Riquer, Phys. Rev. D 72, 114016 (2005);
T. W. Chiu and T. H. Hsieh [TWQCD Collaboration], Phys. Lett. B 646, 95 (2007).

[4] J. L. Rosner, Phys. Rev. D 69, 094014 (2004).
[5] J. L. Rosner, Phys. Rev. D 74, 076006 (2006).

[6] C. Cawlfield et al. [CLEO Collaboration], Phys. Rev. Lett. 98, 092002 (2007).

[7] F. E. Close, Int. J. Mod. Phys. A 20, 5156 (2005).

[8] A. E. Snyder, private communication.

[9] Particle Data Group, http://pdg.lbl.gov/2007/listings/contents_listings.html

[10] C. P. Jessop et al. [CLEO Collaboration], Phys. Rev. Lett. 84, 1393 (2000).

[11] B. Aubert et al. [BaBar Collaboration], Phys. Rev. Lett. 91, 071801 (2003).

[12] L. Maiani, A. D. Polosa, and V. Riquer, arXiv:0708.3997v1 [hep-ph].

[13] B. Aubert et al. [BaBar Collaboration], Phys. Rev. D 74, 071101 (2006).

[14] K. Abe et al. [Belle Collaboration], Belle report BELLE-CONF-0541, arXiv:hep-ex/0505038, paper no. LP-2005-176, contributed to the XXII International Symposium on Lepton-Photon Interactions at High Energy, Uppsala, Sweden, June 30 – July 5, 2005.

[15] Ce Meng and Kuang-Ta Chao, arXiv:0708.4222v1 [hep-ph].