Possible Hints and Search for Glueball Production in Charmless Rare $B$ Decays

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Recent data on $B \to ppK$, $K^0\pi\pi$ and $KK\bar{K}$ hint at a $\sim 2.3$ GeV object recoiling against a kaon. This could be the narrow state observed in $J/\psi \to \gamma \xi$. Nonobservation in $p\bar{p}$ annihilation implies $B(\xi \to p\bar{p}) \sim \sim 0.001 - 0.003$, consistent with $\eta_c$ and $J/\psi$ decays, but there are actual hints in $p\bar{p} \to \phi\phi$ and $pp \to \pi^+\pi^-\pi^\pm\pi^\mp p$. Simple modeling shows $B(B \to \xi K)B(\xi \to p\bar{p}) \sim 1 \times 10^{-6}$, appearing as a spike in the $p\bar{p}$ spectrum, with $\sim 30$ events per $100$ fb$^{-1}$; modes such as $KKK$, $K\phi\phi$, $K4\pi$ ($Kp\pi\pi\eta$) etc. should be explored. The underlying dynamics of $g^* \to g\xi$ is analogous to $g^* \to g\eta'$ or gluon fragmentation. Discovery of sizable $B \to \xi K$ could be useful for CP violation studies.

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The existence of glueballs as bound states of gluons, the gauge bosons of QCD, has been conjectured ever since the advent of QCD as the fundamental theory of the strong interaction. Alas, it is a unique feature of nonabelian gauge theories that has yet to be unequivocally tested. The main obstacle to identifying glueballs is their possible $\bar{q}q$ admixture, which allows the candidates to hide in the richness of $\bar{q}q$ resonances. Advances in lattice gauge theories suggest the lowest lying glueballs to be the $0^{++}$ scalar with $m_{\bar{q}q} \sim 1.4 - 1.8$ GeV and $2^{++}$ tensor with $m_{\bar{q}q} \sim 1.9 - 2.3$ GeV, while the $0^{+}$ glueball $P$ is another 150 MeV heavier $[3]$. Radiative $J/\psi \to \gamma gg \to \gamma +$hadrons decay is a prime hunting ground for glueballs. The narrow state $\xi$ with width 23 MeV, called $f_2(2220)$ by the Particle Data Group (PDG) $[3]$, was discovered $[3]$ by the MARK III experiment in such decays. The BES collaboration confirmed $[3]$ the $\xi$ signal in $J/\psi \to \gamma \pi^+\pi^-$, $\gamma K^+K^-$, $gK^0\bar{K}^0_\gamma$, $\gamma p\bar{p}$ at $(5.6 \pm 2.7) \times 10^{-5}$, $(3.3 \pm 2.0) \times 10^{-5}$, $(2.7 \pm 1.4) \times 10^{-5}$, $(1.5 \pm 0.8) \times 10^{-5}$, respectively, as well as $J/\psi \to \gamma \pi^0\pi^0 \sim (4.5 \pm 2.9) \times 10^{-5}$, where errors have been combined conservatively. Null results in $\gamma\gamma \to \xi$ search $[3]$ strengthen the glueball interpretation.

The $\xi \to p\bar{p}$ mode stimulated scans of $p\bar{p}$ annihilation around 2230 MeV, resulting in the limits of $p\bar{p} \to K^0\bar{K}^0_\gamma$, $\phi\phi$, $\pi^0\pi^0$, $\eta\eta \sim 7.5 \times 10^{-5}$, $6 \times 10^{-5}$ $[6]$, $6 \times 10^{-5}$, $4 \times 10^{-5}$ $[7]$, respectively. Combining with the BES result, one finds $[3]$ that $B(\xi \to p\bar{p}) \sim 5 \times 10^{-3}$, and

$$B(J/\psi \to \gamma \xi) \gtrsim 2.9 \times 10^{-3},$$

which seems to support the glueball interpretation. However, the nonobservation in quite a few $p\bar{p}$ annihilation modes has lead to doubt $[8]$ of the very existence of $\xi$.

With this impasse, it is desirable to open up new avenues for exploration. The charmless $b \to sg^*$ process could be $[8]$, $[9]$ a viable ground for glueball search. This was stimulated in part by the CLEO observation of large $B \to \eta'K \sim 2 \times 10^{-5}$ $[10]$ and $\eta'/X_s \gtrsim 6 \times 10^{-4}$ $[11]$, which were interpreted $[12]$, $[13]$ as related to the large glue content of $\eta'$ via the gluon anomaly. The $b \to sg^*$ transition, followed by the anomaly inspired effective $g^* \to g\eta'$ coupling, could account for $[14]$, $[15]$ the semi-inclusive $m_{\gamma\gamma}$ spectrum. Replacing $\eta'$ by a glueball may be even more effective $[16]$ $[17]$. In this Letter we point out possible hints for $B \to \xi K$ decay in the $B \to ppK$, $K\eta\pi\pi^-$ and $K^+K^-\eta\pi$ modes newly observed by Belle, and discuss directions for further study.

Let us first present the case for charmless $B$ decays. The $B \to ppK$ decay $[18]$ is the first ever charmless baryonic mode to be observed. While modeling the $m_{pp}$ spectrum by a QCD motivated threshold enhancement, we noted a hint for a $\sim 2.3$ GeV peak. The data (fitted $B$) and our modeling $[16]$ are plotted in Fig. 1(a). Threshold enhancement is apparent, in line with our prediction $[17]$.

![FIG. 1. Spectra for $B \to (a) ppK$; (b) $K\pi\pi$ ($m_{K\pi} > 2$ GeV); (c) $K_S\pi\pi$; (d) $KKK$; and (e), (f) for $KK\bar{K}$ vs. $m_{KK\bar{K}}$, $m_{KK\bar{K}}$ ($m_{KK\bar{K}} > 1.1$ GeV), respectively.](image-url)
for $B \to p\bar{p}n$ before the discovery of $B \to p\bar{p}K$. However, some excesses $\sim 7–10$ events is noticeable in the third, i.e., 2.2–2.4 GeV bin $[13]$, amounting to $\sim 0.6–1 \times 10^{-6}$ in rate, which we could not accommodate in our simple threshold model. Motivated by this, we find evidence in a few (but not all) other 3-body channels as well.

The $B \to K^+\pi^+\pi^−$ mode observed by Belle $[19]$ is plotted in Fig. 1(b), with a cut of $m_{K^+\pi^-} > 2$ GeV to suppress background. Despite some activity above 2 GeV, there is not much excess at 2.2–2.3 GeV.

The $B \to K_S\pi^+\pi^−$, $K_SK^+K^−$ modes, also observed by Belle $[20]$, are plotted in Figs. 1(c) and (d), respectively. The spectrum for $m_{\pi^+\pi^-} > 2$ GeV is very clean, with a striking cluster at 2.3 GeV, albeit with only 5 events. The $m_{K^+K^-}$ spectrum has $\sim 2$ events in the same region (but a prominent cluster at $\sim 1.95$ GeV). In all, $h^+h^−$ has about 7 events, and folding in efficiencies, we find the average over $K_S\pi^+\pi^−$, $K_SK^+K^−$ rates in the cluster region is $\sim 2.5 \times 10^{-6}$. The comparison with $p\bar{p}K$ case is consistent with the BES observation.

Turning to $B \to K^+K^+K^−$ $[12]$, we plot $m_{K^+K^-}$ and $m_{K^+K^+K^-}^\text{max}$ (for $m_{K^+K^-} > 1.1$ GeV) spectra in Figs. 1(e) and (f). The $m_{K^+K^-}$ spectrum above 2 GeV is quite sizable and rich with structure, like Fig. 1(b) amplified but with much less background. This decay is expected to arise solely from the $b \to s\bar{s}s$ penguin. One has $\sim 10$ events each at 2.3, 2.45 and 2.65 GeV, and $\sim 20$ events at 1.9–2.15 GeV, the latter similar to $K_SK^+K^−$. For $m_{K^+K^-}$ one has $\sim 11, 14, 6$ events respectively at 2.1, 2.45 and 2.65 GeV, but no 2.3 GeV cluster. Folding in efficiencies, we find a rate of 1.7 to $3.4 \times 10^{-6}$, again consistent with BES and with $K_S h^+h^−$. We caution, however, that identical particle effects, reflected in two possible $K^+K^−$ pairings, smear the plots.

To summarize, there is some evidence for a 2.2–2.3 GeV “state” recoiling against a kaon in $p\bar{p}K$, $K_S h^+h^−$ and $K^+K^+K^−$ channels, which could be the $\xi$ glueball candidate. The $\sim 2.45$ or 2.65 GeV objects might be the pseudoscalar $P$ (or a scalar excitation $[11]$); there is also some excess in these regions for $p\bar{p}K$ (Fig. 1(a)).

The absence in $\pi^+\pi^-\pi^±$ is worrisome, but, besides larger background (here extra cut), there are also amplitude level complications, such as a slower fall-off in $m_{\pi\pi}$ vs. $m_{p\bar{p}}$, the tree contribution (in contrast to $K_S h^+h^−$), and multiple interfering resonances. We conclude that glueballs may emerge in higher statistics studies of charmless rare $B$ decays, and wish to survey what we know about, and how to gain access to, such glueballs.

The $J/\psi \to \gamma K^0\bar{K}^0$, $\gamma K^0\bar{K}^0$ numbers from BES $[4]$ are slightly below MARK III results $[3]$, while the $p\bar{p}$ number is just below the bound of $2 \times 10^{-5}$. But the $\pi^+\pi^-\pi^±$ number is $\sim$ factor 3 above the MARK III bound of $2 \times 10^{-5}$. Since there are two structures adjacent to the $\pi^+\pi^-\pi^±$ peak in BES data, the actual rate is probably smaller. If the 2.2–2.3 GeV “signal” in $B \to p\bar{p}K$, $K_S h^+h^−$ and $K^+K^+K^−$ is due to the $\xi$, our discussion above indicates that $J/\psi \to \gamma \pi^+\pi^−$, $\gamma K^0\bar{K}^0 \sim (3–4) \times 10^{-5}$ would be more consistent, hence $J/\psi \to \gamma K^0\bar{K}^0 \sim (1.5–2) \times 10^{-5}$, slightly lower than BES. The BES result for $J/\psi \to \gamma \pi^0\pi^0$ $[4]$ is almost twice larger than implied by their $J/\psi \to \gamma \pi^+\pi^−$, and was not used in the PDG estimate $[2]$ of $J/\psi \to \gamma \pi^+\pi^−$.

An intriguing recent result has come from CLEO. Based on 61.3 pb$^{-1}$ data $\approx 1.45$ million $Y(1S)$ mesons, CLEO reports $[21]$ 1, 1, 2 events within $\pm 34$ MeV of 2234 MeV in $Y \to \pi^+\pi^-\pi^-$, $\gamma K^+ K^-$, $\eta p\bar{p}$, respectively, with background expected at 0.12, 0.21, 0.28; a lower bound of $Y \to \eta \xi \to \gamma p\bar{p} > 0.5 \times 10^{-6}$ is obtained. CLEO chose to drop this by allowing for larger background. However, scaling $[22]$ the BES $J/\psi \to \gamma p\bar{p}$ result by $(Q^2_{\psi}m^2_{\pi\pi}/Q^2_{\eta}m^2_{\pi\pi}) \sim 0.04$ gives $Y \to \eta p\bar{p} = (0.6 \pm 0.3) \times 10^{-6}$, right in the ballpark. We mention that CLEO has just finished $[22]$ taking 1.3 fb$^{-1}$ data on the $Y(1S)$, i.e. a 21-fold increase, and we may see the $\xi$ popping up in radiative $Y$ decays, with 10 to 40 events in the $\pi^+\pi^−$, $K^+K^−$ and $p\bar{p}$ (and other) modes in the near future.

It is the $p\bar{p}$ annihilation experiments which cast doubt on the existence of $\xi$. These experiments were stimulated by the BES observation of $\xi \to p\bar{p}$ to scan around 2230 MeV, before CERN Lower Energy Antiproton Ring (LEAR) shutdown in 1996. The results were all negative. The conservative conclusion is that $\xi \to \pi^+\pi^−$, $K^+K^−$, $K^0_S K^0_S$, $p\bar{p}$, $\phi\phi$, $\pi^0\pi^0$, $\eta\eta$ are all $\lesssim 1\%$. But, together with the narrow $\Gamma_\xi \sim 20$ MeV, the stated doubt $[8]$ grew with time. We offer a critique of the situation.

First, two body decays of $\xi \lesssim 1\%$ is not surprising. The $\eta_\xi$ and $J/\psi$ decays via $gg$ and $ggg$, and their $p\bar{p}$ rates are 0.12% and 0.21% $[2]$ respectively. If the $\xi$ is the $2^{++}$ two-gluon glueball, having $B(\xi \to p\bar{p}) \sim$ few $\times 10^{-3}$ seems just right. Second, a 20 MeV width for a lowest lying 2.2–2.3 GeV two-gluon glueball is also not unreasonable. On one hand, the “$\sqrt{Q^2}$” rule $[23]$, i.e. taking the geometric mean of the few MeV width of $\eta_\xi$ (scaled down to 2 GeV) and the few hundred MeV width of a typical 2 GeV meson gives 10–50 MeV. On the other hand, the near ideal mixing of $f_2(1270) - f_2^0(1525)$ system implies $[24]$ that the relevant lowest lying glueball, the $\xi$, would be relatively free of $q\bar{q}$ content, hence the above narrowness argument holds. Third, the lower bound of Eq. (1) is not unreasonable if $\xi$ is really a glueball, but the large $B(J/\psi \to \gamma \xi)$ is a bit overstated. It arises from combining the BES result on $J/\psi \to \pi^0\pi^0$ with the nonobservation of $p\bar{p} \to \pi^0\pi^0$. As we noted, the BES result for $\pi^0\pi^0$ is likely a factor of 2 to 3 too large.

With these points, it should be clear that $\xi$ is still viable. We now argue that there is in fact some evidence coming from $p\bar{p}$ annihilation or $p\bar{p}$ collisions.

Although the JETSET experiment did not observe a narrow $\xi$ in $p\bar{p} \to \phi\phi$ channel, they did find $[3]$ a broad structure just above threshold. In fact, further partial wave analysis $[25]$ found $2^{++}$ dominance, and a resonance
behavior in $2^+_D (D$-wave with $\phi \phi$ spin zero): a Breit-Wigner structure with phase vs. $2^+_D$, consistent with $m \cong 2231$ MeV and $\Gamma \cong 70$ MeV. From Fig. 6 of Ref. [29], comparing $2^+_D$ with $2^+_D$, $2^+_S$ waves, we note that it may be better to fit with two Breit-Wigner resonances (or one resonance with a broad underlying structure). We believe the JETSET data does not preclude a narrow resonance at 2.2 GeV.

There is another hint in central hadron production. The empirical “$dP_T$” glueball filter [28] is defined as the difference between the transverse momenta of the outgoing protons in $pp \rightarrow pXp$; $dP_T \rightarrow 0$ enhances glueball probability of $X$. Using data from WA102 experiment with $X = \pi^+\pi^-\pi^+\pi^-$, it was shown that the $f_1(1285)$ prominent for larger $dP_T$ all but disappeared for $dP_T < 0.2$ GeV, while the glueball candidate $f_0(1500)$ is retained. From Fig. 3(c) of Ref. [28], however, we find a remarkable single-bin (2320–2340 MeV) spike, absent for $dP_T > 0.2$ GeV, but popping up for $dP_T < 0.2$ GeV. With $\approx 100$ events on $\approx 360$, it constitutes a $>5\sigma$ fluctuation. The detector resolution is $\sim 12$ MeV [27] hence the spike seems genuine. A broader structure exists at 2430 MeV. Subsequent spin analysis (Fig. 3(f) of second paper of Ref. [28]) also show a “spike” at 2240–2280 MeV, and a broader structure at 2400 MeV, all in the $2^{++}$ channel of $f_2\pi\pi$. By analogy with the large $\eta_b \rightarrow \eta'(\pi \pi) \sim (4–5)\%$ [3], $\xi \rightarrow f_2\pi\pi$ could be a major decay mode. These features should be investigated further.

We now turn to simple modeling of the $B \rightarrow p \bar{p} K$ “bump” assuming a $2^{++}$ glueball state. That is, we have a $B \rightarrow \xi K(\pi)$ transition governed by

$$G_F \sqrt{2} V_{tb} V^{*}_{ts(\tau)} \int B \xi K(\pi) \varepsilon_{\mu \nu} P^\mu p^\nu, \quad (2)$$

where we factor out the quark mixing factor appropriate for the underlying $b \rightarrow s(d)$ penguin. The $\xi \rightarrow \bar{p}p$ transition is governed by $-g_1^{\bar{p}p} \varepsilon_{\mu \nu} \bar{u}\gamma^\mu p_\nu$, where a less effective $p_\mu p^\mu$ term is dropped. For given $\Gamma_\xi$, $g_1^{\bar{p}p}$ is fixed by $B(\xi \rightarrow \bar{p}p) \sim 5 \times 10^{-3}$. Together with the fits in Fig. 1(a), $f_{B \xi K}$ is fixed (its sign determines interference; we ignore relative strong phase) to reproduce $B(B \rightarrow \bar{p}p K) = 4.3 \times 10^{-6}$. The results for the

| $B(B \rightarrow \xi K^-)$ | $0.014 (0.015)$ | $-0.014 (-0.016)$ |
|--------------------------|----------------|------------------|
| $B(B \rightarrow \bar{p}p K^-)$ | $220 (260)$ | $240 (300)$ |

| $B(B \rightarrow \bar{p}p K^0)$ | $3.3 (0.5)$ | $4.1 (1.4)$ |
|--------------------------|----------------|------------------|
| $B(B \rightarrow \bar{p}p \pi^-)$ | $2.1 (2.1)$ | $2.1 (2.1)$ |

FIG. 2. Modeling of $B \rightarrow \bar{p}p K^0$, $p \bar{p} K^0$ and $p \bar{p} \pi^-$ spectra with $\xi$. For illustration we plot the $\Gamma_\xi = 70$ MeV case. The upper (lower) curves correspond to the upper (lower) one in Fig. 1 (a) (from Ref. [16]).
in gluon fragmentation. The $g^* \to g\xi$ process advocated here can be viewed as such, but at only a few GeV energy. This illustrates further the futility to discard the $g^*g\xi$ vertex by perturbative arguments.

One uniquely interesting feature for studying glueball production in charmless $B$ decays is the potential it offers for studying CP violation [14]. On one hand, the penguin loop implies sensitivity for new physics beyond the Standard Model, e.g., via the dipole $bsg$ coupling. On the other hand, if $B \to \xi K$ really is at a few $10^{-4}$ and $\xi$ is a narrow state, one could accumulate a large number of modes and gain in statistics. CP asymmetries could be at 10–30% level even if new physics contributes only 10% in amplitude [14].

From our survey, additional search modes are: $B \to KK_S K_S$, $K\phi\phi$, $K^4\pi$ (e.g., $Kf_2\pi\pi$), and perhaps $P p\bar{K}$, beyond the ones given in Fig. 1. Semi-inclusive studies, i.e., $B \to \xi(\to \rho\bar{\rho}\rho, \text{etc.}) + X$, can also be considered. One can also search for other glueballs such as $P$ and $G$, e.g., $B \to PK, GK$ via $P \to \eta(\pi\pi), K\bar{K}$. At the same time, the $\eta(\pi\pi)$ study, both exclusive and inclusive, including CP violation effects, should be pursued further.

In summary, we find indication for a narrow state in $B \to pp\bar{K}, K_S\pi\pi$ and $K^+K^-K^-$ recoiling against a kaon. This could be the $2^{+}$ glueball candidate found in radiative $J/\psi$ decays with mass supported by lattice calculations, and with tantalizing hints in $p\bar{p} \to \phi\phi$ and $pp \to \pi^+\pi^-\pi^+\pi^-\bar{p}$. Glueballs may emerge in the study of charmless rare $B$ decays, with confirming evidence from $Y \to \gamma\rho\bar{\rho}$. Search for $\xi$ (and $P$) in $B \to ppK, K^+K^+K^-, K_S h^+h^-, K^+K_S K_S, K\phi\phi, K^4\pi$ should be vigorously pursued, with an eye towards uncovering new physics sources of CP violation.

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