Scalar mesons and glueball in $B$-decays and gluon jets\textsuperscript{1}

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Abstract

We discuss the recent observation of $f_0(980)$ in charmless $B$-decays and in gluon jets which hints toward a gluonic coupling of this meson similar to $\eta'$. Further predictions on $B$-decays into scalar particles are presented. Charmless $B$ decays also show a broad $K\bar{K}$ (and possibly $\pi\pi$) $S$-wave enhancement which we relate to the $0^{++}$ glueball. These gluonic mesons represent a sizable fraction of the theoretically derived decay rate for $b \rightarrow sg$.

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1 Introduction

There is still no general consensus about the lightest scalar $q\bar{q}$ nonet, neither about its members nor about the mixing between strange and nonstrange components, also the existence and mixing properties of the $J^{PC} = 0^{++}$ glueball are in doubt. A central role for the nonet is played by $f_0(980)$ which has been considered not only as standard $q\bar{q}$ meson but also as $K\bar{K}$-molecule or as 4-quark state.

The spectroscopic data often have not been precise enough to arrive at unique conclusions. New results on $D$ and $B$ decays of high statistics are now providing additional information. In this paper we discuss some recent experimental results and their implications on these problems:

1. The observation by the BELLE collaboration of charmless decays $B \to Khh$ with $h = \pi, K$ \cite{1} which show a significant signal of $f_0(980)$; this has been observed recently also by the BaBar collaboration \cite{2}.

2. In the same channel BELLE has also observed a broad enhancement in $K\bar{K}$ mass spectrum in the range 1000-1700 MeV with spin $J = 0$ and a smaller effect in $\pi\pi$ around 1000 MeV. Preliminary results from BaBar \cite{4} confirm this effect but there is no quantitative analysis yet.

3. A significant signal of $f_0(980)$, larger than expected, has also been observed in a first analysis of the leading system in gluon jets obtained by DELPHI at LEP \cite{5}.

The interest in charmless $B$-decays with strangeness has been stimulated through the observation by CLEO \cite{6,7} of large inclusive and exclusive decay rates $B \to \eta'X$ and $B \to \eta'K$, which have been confirmed by more recent measurements \cite{8,9,10}. These processes have been related to the decay $b \to sg$ of the $b$-quark which could be a source of mesons with large gluon affinity \cite{11,12,13,14}. In consequence, besides $\eta'$ also other gluonic states, in particular also scalar mesons or glueballs could be produced in a similar way.

The total rate $b \to sg$ has been calculated perturbatively in leading \cite{15} and next-to-leading order \cite{16}

$$
\text{Br}(b \to sg) = \begin{cases} 
(2 - 5) \times 10^{-3} & \text{in LO (for } \mu = m_b \ldots m_b/2) \\
(5 \pm 1) \times 10^{-3} & \text{in NLO}
\end{cases}
$$

(1)

The energetic massless gluon in this process could turn entirely into gluonic mesons by a nonperturbative transition after colour neutralization by a second gluon. Alternatively, colour neutralization through $q\bar{q}$ pairs is possible as well. This is to be distinguished from the short distance process $b \to s\bar{q}g$ with
virtual intermediate gluon which has to be added to the CKM-suppressed decays $b \to q_1 \bar{q}_2 q_2$. These quark processes with $s$ have been calculated and amount to branching fractions of $\sim 2 \times 10^{-3}$ each \cite{17,18,16}. The question then arises which hadronic final states correspond to the decay $b \to sg$.

Here we discuss how the above new results and further measurements can clarify the low mass spectroscopy of scalar particles and their contribution to the gluonic $B$ decays. In a previous study \cite{19} we have performed a detailed phenomenological analysis of production and decay of low mass scalar mesons, which led us to identify the scalar nonet with the states $a_0(980)$, $f_0(980)$, $K_0^*(1430)$ and $f_0(1500)$ with large flavour mixing, just as in the pseudoscalar nonet. The near flavour singlet states are the parity partners $\eta'$ and $f_0(980)$ whereas near flavour octet states are $\eta$ and $f_0(1500)$. This scalar nonet fulfills the Gell Mann-Okubo mass formula and is also consistent with a general QCD potential model. The left over states $f_0(400 - 1200)$ (also called $\sigma(600)$) and $f_0(1370)$ seen in $\pi\pi$ and other channels have been interpreted as signals from a single broad object centered around 1 GeV with a large width of 500-1000 MeV which we take as the $0^{++}$ glueball. In this paper we discuss how this scheme compares with the new data and how further measurement could clarify the structure of the scalar sector.

There are alternative schemes for low mass $q\bar{q}$ and glueball spectroscopy which include: light $q\bar{q}$ nonet like ours, except for $a_0(980)$ but no glueball \cite{20}; QCD sum rule analysis \cite{21} with $f_0(980)$ and broad $\sigma$ around 1000 MeV, both mixed in equal parts from glueball and light quark scalar; a broad glueball in the range 1000-1600 MeV from overlapping $f_0$ states in $K$ matrix analyses (recent results \cite{22}) but with $f_0(980)$ near flavour octet. $B$ decays may clarify these alternatives.

## 2 Charmless $B$ decays with $K$ and $K^*(890)$

Two-body decays into pseudoscalar and vector mesons $PP$ and $PV$

We begin by reconsidering the decays $B \to K\eta'$, $K^*\eta'$ together with other final states related by $U(3)$ symmetry. Subsequently we wish to extend these considerations to the inclusion of scalar particles. The large branching fraction $B \to K\eta'$ confirms the special role of $\eta'$ in these decays and it has been related \cite{11,12,13,14} to the gluon affinity of $\eta'$, especially through the QCD axial anomaly which affects only the flavour singlet component. However, it appears difficult to explain the $K\eta'$ rate entirely by quark final states and the QCD anomaly within a perturbative framework \cite{23}, a factor 2 remains unexplained. An improvement is possible by inclusion of radiative corrections \cite{24} but with considerable uncertainties.
Alternatively, one may introduce a phenomenological flavour singlet amplitude which allows also for non-perturbative effects \[14\]. This amplitude is added to the dominant penguin amplitudes, the small tree amplitudes and electroweak penguins. Different decays are related by flavour $U(3)$ symmetry. Recent applications \[25\] of this scheme to 2-body $B$ decays with strange and nonstrange pseudoscalar and vector particles yield a good overall agreement with the data in terms of a few phenomenological input amplitudes.

Here we discuss first the 2-body $B$ decays with $K$ and $K^*$ in this way \[25\] to understand the pattern of the observed rates and then extend the analysis to the scalar sector. For this purpose we restrict ourselves to a simple approximation and at short distances we keep only the dominant QCD penguin amplitudes $T_q$ for $b \to u s\bar{s}, d\bar{d}s, s\bar{s}s$ with $T_u = T_d = T_s$. The hadronic penguin amplitude $p_{AB}$ for the 2-body $B$ decay into particles from $U(3)$ multiplets $A$ and $B$ are then proportional to the superposition of short distance amplitudes $T_q$ corresponding to the quark composition of the final hadrons; in addition, there is the contribution from the flavour singlet amplitude which we write as $\gamma_{AB}p_{AB}$. The quark mixing in the pseudoscalar sector is taken as $\eta = (u\bar{u} + d\bar{d} - s\bar{s})/\sqrt{3}$ and $\eta' = (u\bar{u} + d\bar{d} + 2s\bar{s})/\sqrt{6}$, see Table 1.

If the two particles belong to two different multiplets then $p_{AB}$ is the amplitude for the $A$ particle carrying the $s$ quark from $b \to sg$ decay and the $B$ particle carrying the spectator quark $q_s$. The amplitude for both particles interchanged, i.e. $s \to B$, $q_s \to A$, is written as $\beta_{AB}p_{AB}$. In case of $B$-decays into mesons with $s\bar{s}$ component ($\eta, \eta', \phi \ldots$) both amplitudes contribute and interfere with full amplitude $p_{AB}(1 + (-1)^L\beta_{AB})$ where the second term with $\beta' = (-1)^L\beta$ refers to the 2-particle state with reflected momenta ($\vec{p} \to -\vec{p}$) for orbital angular momentum $L$ \[26\]. In particular, for $B \to VP$ decays there is a relative $(-)$ sign for the interchange amplitude.

Concerning our leading penguin approximation we note the following: the decay rates at the quark level including penguin and tree amplitudes have been calculated \[18,16\] and the quark decays of interest to us are found with relative fractions \[18\] 22\% ($b \to u\bar{u}s$), 18\% ($b \to d\bar{d}s$) and 15\% ($b \to s\bar{s}s$) of all charmless $B$ decays. So the nonleading weak decay amplitudes which we neglect here modify the leading result from penguins by about $\pm 20\%$. Effects of that size are also found in the phenomenologically determined hadronic non-penguin amplitudes \[25\].

The results in our leading approximation are given in Table 1. There are two adjustable (penguin) amplitudes, chosen real, for both multiplets $p_{PP}$ and $p_{VP}$ ($\alpha = p_{VP}/p_{PP}$), the flavour singlet amplitudes $\gamma p_{PP}$ and $\gamma' p_{VP}$ ($\gamma \equiv \gamma_{PP}$, $\gamma' \equiv \gamma_{VP}$) and the interchange amplitude in case of $VP$ decay $\beta p_{VP}$. First we try the simplest approximation with equal strength for both
Table 1: Branching ratios for $B^+$ and $B^0$ decays into pseudoscalar (P) and vector (V) particles (col. 4-6) in terms of amplitudes $T_q$ (col. 2) for decays $b \to s \bar{q} q, \gamma, \gamma'$ and $\beta$ for gluonic and interchange processes, col. 3: $p_{AB}$ set to 1, col. 5: $\alpha = 0.67, \gamma = 0.53$ (always $\beta = -\beta' = 1, \gamma = \gamma'$), see also text.

| $B \to PP$ amplitudes | $T_q = 1$ | $\gamma = 0$ | $\alpha, \gamma$ | $\text{Br}_{\text{exp}}[10^{-6}]$ |
|------------------------|-----------|--------------|------------------|------------------|
| $K^0\pi^+$ | $T_d$ | 1 | input | 17.9$^{+2.7}_{-2.4}$ |
| $K^+\pi^0$ | $\frac{1}{\sqrt{2}} T_u$ | $\frac{1}{\sqrt{2}}$ | 8.7 | 8.7 | 12.1$^{+1.6}_{-1.6}$ |
| $K^+\eta$ | $\frac{1}{\sqrt{3}} (T_u - T_s + \gamma T_d)$ | $\frac{\gamma}{\sqrt{3}}$ | 0.0 | 1.6 | $< 6.9$ |
| $K^+\eta'$ | $\frac{1}{\sqrt{6}} (T_u + 2T_s + 4\gamma T_d)$ | $\frac{3+4\gamma}{\sqrt{6}}$ | 26.0 | input $\gamma$ | 75$^{+7}_{-7}$ |
| $K^+\pi^-$ | $T_u$ | 1 | 15.9 | 15.9 | 17.4$^{+1.5}_{-1.5}$ |
| $K^0\pi^0$ | $\frac{1}{\sqrt{2}} T_d$ | $\frac{1}{\sqrt{2}}$ | 8.0 | 8.0 | 10.7$^{+2.7}_{-2.5}$ |
| $K^0\eta$ | $\frac{1}{\sqrt{3}} (T_d - T_s + \gamma T_d)$ | $\frac{\gamma}{\sqrt{3}}$ | 0.0 | 1.5 | $< 9.3$ |
| $K^0\eta'$ | $\frac{1}{\sqrt{6}} (T_d + 2T_s + 4\gamma T_d)$ | $\frac{3+4\gamma}{\sqrt{6}}$ | 23.9 | 69.4 | 58$^{+14}_{-13}$ |

| $B \to VP$ amplitudes | $\alpha = 1$ | $\alpha = 1$ |
|------------------------|--------------|--------------|
| $K^{*0}\pi^+$ | $\alpha T_d$ | 1 | 17.3 | 7.9 | 19$^{+6}_{-8}$ |
| $K^{*+}\pi^0$ | $\frac{\alpha}{\sqrt{2}} T_u$ | $\frac{1}{\sqrt{2}}$ | 8.7 | 3.9 | $< 31$ |
| $K^{*+}\eta$ | $\frac{\alpha}{\sqrt{3}} (T_u - \beta T_s + \gamma T_d)$ | $\frac{2+\gamma}{\sqrt{3}}$ | 23.1 | 36.9 | 26$^{+10}_{-9}$ |
| $K^{*+}\eta'$ | $\frac{\alpha}{\sqrt{6}} (T_u + 2\beta T_s + 4\gamma T_d)$ | $\frac{1+4\gamma}{\sqrt{6}}$ | 2.9 | 3.6 | $< 35$ |
| $\rho^+ K^0$ | $\alpha \beta T_d$ | 1 | 17.3 | 7.9 | $< 48$ |
| $\rho^0 K^+$ | $\frac{\alpha}{\sqrt{2}} T_u$ | $\frac{1}{\sqrt{2}}$ | 8.7 | 4.0 | $< 12$ |
| $\omega K^+$ | $\frac{\alpha}{\sqrt{2}} T_u$ | $\frac{1}{\sqrt{2}}$ | 8.7 | 4.0 | $< 4$ |
| $\phi K^+$ | $-\alpha T_s$ | 1 | 17.3 | input $\alpha$ | 7.9$^{+2.0}_{-1.8}$ |
| $K^{*+}\pi^-$ | $\alpha T_u$ | 1 | 15.9 | 7.3 | $< 72$ |
| $K^{*0}\pi^0$ | $\frac{\alpha}{\sqrt{2}} T_d$ | $\frac{1}{\sqrt{2}}$ | 8.0 | 3.6 | $< 3.6$ |
| $K^{*0}\eta$ | $\frac{\alpha}{\sqrt{3}} (T_d - \beta T_s + \gamma T_d)$ | $\frac{2+\gamma}{\sqrt{3}}$ | 21.3 | 15.7 | 14$^{+6}_{-6}$ |
| $K^{*0}\eta'$ | $\frac{\alpha}{\sqrt{6}} (T_d + 2\beta T_s + 4\gamma T_d)$ | $\frac{1+4\gamma}{\sqrt{6}}$ | 2.6 | 1.5 | $< 24$ |
| $\rho^- K^+$ | $\alpha \beta T_u$ | 1 | 15.9 | 7.3 | $< 32$ |
| $\rho^0 K^0$ | $\frac{\alpha}{\sqrt{2}} T_d$ | $\frac{1}{\sqrt{2}}$ | 8.0 | 3.6 | $< 3.9$ |
| $\omega K^0$ | $\frac{\alpha}{\sqrt{2}} T_d$ | $\frac{1}{\sqrt{2}}$ | 8.0 | 3.6 | $< 13$ |
| $\phi K^0$ | $-\alpha T_s$ | 1 | 15.9 | 7.3 | 7.6$^{+1.4}_{-1.3}$ |
multiplets \((\alpha = 1)\) and equal recombination \(\beta = 1\), also \(\gamma = 0\). Then all branching ratios are given in terms of one overall normalization parameter \((p_{PP})\). The corresponding predictions are given in column 3 (in units of \(p_{PP}\) and \(p_{VP}\)) and 4 of Table 1. The predictions for \(B^0\) are obtained after multiplying \(|p_{AB}|^2\) by the ratio \(\tau_{B^0}/\tau_{B^+} = 0.921\). We compare with experimental data compiled by the PDG [27] which includes \(\eta\) and \(\eta'\) decays [8,9,10].

One can see that for \(PP\) decays the overall pattern is reproduced, except for \(K\eta'\) which is observed significantly too large by a factor \(\sim 3\). In this scheme this conclusion is derived from flavour symmetry, the neglect of nonleading short distance terms was only about 20%. Agreement with data can be obtained by adding the flavour singlet amplitude with \(\gamma' = 0\). 53 which predicts also effects for \(\eta\).

With this choice the model can also reproduce the decay pattern of \(B \rightarrow K^*(890) + (\pi, \eta, \eta')\) with reversed abundances of \(\eta\) and \(\eta'\). This is a consequence of the different sign of \(\beta'\) in the PP and VP amplitudes [26,25], a feature also present in other analyses [23,24] for the same reason. One can estimate the gluonic part of the \(\eta'K^+\) production alone (without interference) from contributions \(\sim |\gamma|^2\) to \(\eta K^+\) and \(\eta'K^+\) rates and obtains

\[
\text{Br}(B^+ \rightarrow \eta'K^+)|_{\text{gluonic}} = (8/3) |\gamma p_{PP}|^2 \sim (15 \ldots 35) \times 10^{-6} \quad (2)
\]

where the smaller number refers to real \(\gamma = 0.53\) and the second one to arbitrary gamma with \(|\gamma| = 0.88\) (see also 25), \(Re\gamma < 0\) would be in conflict with the \(K^+\eta\) rate.

At this level of approximation, accurate to \(\sim 20\%\), there are no major discrepancies encountered. We conclude that the main effects are reproduced by 3 parameters, the two penguin amplitudes \(p_{PP}\) and \(p_{VP}\) and the gluonic amplitude with \(\gamma\), furthermore we have chosen \(\beta = 1\) and \(\gamma' = \gamma \equiv \gamma_p\).

**Decay \(B \rightarrow f_0(980)K\) and expectations for scalar particles**

A remarkably strong signal is observed for the scalar meson \(f_0(980)\) by the BELLE Collaboration 1 in the decay \(B^+ \rightarrow K^+\pi^+\pi^-\) where almost one half of the total rate above background falls into this sub-channel with

\[
\text{Br} (B^+ \rightarrow K^+f_0(980); f_0(980) \rightarrow \pi^+\pi^-) = (9.6^{+2.5+1.5+3.4}_{-2.3-1.5-0.8}) \times 10^{-6}. \quad (3)
\]

The preliminary result by BaBar 3 reads

\[
\text{Br} (B^+ \rightarrow K^+f_0(980); f_0(980) \rightarrow \pi^+\pi^-) = (9.2 \pm 1.2^{+2.1}_{+2.4}) \times 10^{-6}. \quad (4)
\]

This large fraction of \(f_0(980)\) (3 times larger than \(\rho^0\)) is a first hint for the gluonic affinity of this meson as well.
It is clear that a more definitive answer requires an analysis similar to the one with \( \eta' \) for scalar (S) particles as well. To this end we have written down in Table 2 the amplitudes for the decays \( B \to PS \) and \( B \to VS \) in the approximation as above, keeping only the QCD penguin and gluonic amplitudes \( p_{PS}, p_{VS} \) and \( \gamma_S p_{PS}, \gamma_S p_{VS} \) (\( \gamma_S \equiv \gamma_{PS} \equiv \gamma_{VS} \)). We assume the scalar nonet with states as in Ref. [19]. Because of the large phase space in \( B \) decays there is a good chance to identify the scalar particles belonging to the nonet of lowest mass with little background from crossed decay channels.

In order to determine the gluonic production amplitude \( \gamma_S \) for \( f_0(980) \) one needs to identify additional channels, in particular with \( a(980) \) and \( K^*(1430) \), the suggested partners of pion and kaon, respectively. The latter state has apparently been observed by BELLE [11] (called \( K_X(1400) \)) albeit with large error (\( \text{Br}(B^+ \to K_{sc}^0 \pi^+) \approx (21.7_{-11.1}^{+7.6}) \times 10^{-6} \)). Measurements together with \( K^*(890) \) can reveal the different effects the gluonic amplitude has on \( f_0(980) \)

| \( B^0 \to B^+ \to \) | \( B^0 \to B^+ \to \) |
|---|---|
| normalization to | normalization to |
| \( P + S \) | \( P + S \) |
| \( p_{PS} \) | \( V + S \) |
| \( V + S \) | \( p_{VS} \) |
| \( K^+ a^- \) | \( K^0 a^+ \) |
| \( K^0 a^0 \) | \( K^0 a^0 \) |
| \( K^0 a^0 \) | \( K^0 a^0 \) |
| \( K^0 f_0 \) | \( K^0 f_0 \) |
| \( \frac{1}{\sqrt{2}} (1 + 2\gamma_S) \cos \varphi_S \) | \( \frac{1}{\sqrt{2}} (1 + 2\gamma_S) \cos \varphi_S \) |
| \( \frac{1}{\sqrt{2}} (1 + 2\gamma_S) \sin \varphi_S \) | \( \frac{1}{\sqrt{2}} (1 + 2\gamma_S) \sin \varphi_S \) |
| \( K^0 f_0 \) | \( K^0 f_0' \) |
| \( \frac{1}{\sqrt{2}} (1 + 2\gamma_S) \sin \varphi_S \) | \( \frac{1}{\sqrt{2}} (1 + 2\gamma_S) \sin \varphi_S \) |
| \( \beta \) | \( \beta \) |
| \( \rho^0 K_{sc}^+ \) | \( \rho^0 K_{sc}^+ \) |
| \( \rho^0 K_{sc}^+ \) | \( \rho^0 K_{sc}^+ \) |
| \( \eta' K_{sc}^+ \) | \( \eta' K_{sc}^+ \) |
| \( \frac{1}{\sqrt{3}} (2 + \beta + 4\gamma_P) \) | \( \phi K_{sc}^+ \) |
| \( \phi K_{sc}^+ \) | \( \phi K_{sc}^+ \) |
| \( \phi K_{sc}^+ \) | \( \phi K_{sc}^+ \) |
| \( \phi K_{sc}^+ \) | \( \phi K_{sc}^+ \) |

It is clear that a more definitive answer requires an analysis similar to the one with \( \eta' \) for scalar (S) particles as well. To this end we have written down in Table 2 the amplitudes for the decays \( B \to PS \) and \( B \to VS \) in the approximation as above, keeping only the QCD penguin and gluonic amplitudes \( p_{PS}, p_{VS} \) and \( \gamma_S p_{PS}, \gamma_S p_{VS} \) (\( \gamma_S \equiv \gamma_{PS} \equiv \gamma_{VS} \)). We assume the scalar nonet with states as in Ref. [19]. Because of the large phase space in \( B \) decays there is a good chance to identify the scalar particles belonging to the nonet of lowest mass with little background from crossed decay channels.

In order to determine the gluonic production amplitude \( \gamma_S \) for \( f_0(980) \) one needs to identify additional channels, in particular with \( a(980) \) and \( K^*(1430) \), the suggested partners of pion and kaon, respectively. The latter state has apparently been observed by BELLE [11] (called \( K_X(1400) \)) albeit with large error (\( \text{Br}(B^+ \to K_{sc}^0 \pi^+) \approx (21.7_{-11.1}^{+7.6}) \times 10^{-6} \)). Measurements together with \( K^*(890) \) can reveal the different effects the gluonic amplitude has on \( f_0(980) \)
and \( f_0(1500) \), the suggested partners of \( \eta' \) and \( \eta \). Given several rates for pure quark states the scalar mixing angle \( \varphi_S \) defined through

\[
f_0(980) = n\pi \sin \varphi_S + s\pi \cos \varphi_S, \quad f_0(1500) = n\pi \cos \varphi_S - s\pi \sin \varphi_S
\]  

(5)

with \( n\pi = (u\bar{u} + d\bar{d})/\sqrt{2} \) can be determined as well. Our choice \[\text{[12]}\] is \( \sin \varphi_S = 1/\sqrt{3} \) as in the pseudoscalar nonet, i.e. \( \varphi_P \approx \varphi_S \).

The strong appearance of \( f_0(980) \) in the final state with intermediate gluons points toward a flavour singlet component. As further test we note that in the approximation of Table 2 the decay \( B \to K f_0(1500) \) should be suppressed in analogy to \( K \eta \). Indeed, there is no signal from \( \pi^+ \pi^- \) or \( K^+ K^- \) at this mass in the BELLE data \[\text{[1]}\] (assuming \( f_0(1500) \) is the partner in the same nonet), however, there is a large branching ratio of \( f_0(1500) \) also into 4\( \pi \).

On the other hand, \( f_0(1500) \) should show up together with \( K^* \). Furthermore we note that \( f_0(980) \) could interfere destructively with the background which would result in a much larger decay rate. This occurs for the amplitude \( T_B + T_6 e^{2i\phi_B} \) in case of background phase \( \phi_B \sim \pi/2 \) \(|T_B| \ll |T_6| \) here, \( T = |T|^e^{i\phi} \) as we expect for our glueball interpretation below.

Next we consider a possible mechanism for the \( B \to f_0(980) K \) decay similar to \( B \to \eta' K \) assuming a direct coupling to a two gluon state. Then we expect that the gluonic couplings of \( \eta' \) and \( f_0 \) are proportional to the corresponding processes with photons. In consequence, the ratios

\[
R_1 = \frac{\text{Br}(B \to f_0(980) K)_{\text{gluonic}}}{\text{Br}(B \to \eta' K)_{\text{gluonic}}} = \frac{|\gamma_{\pi \gamma\pi \gamma}|^2}{|\gamma_{\pi \gamma\pi \gamma}|^2}, \quad R_2 = \frac{\Gamma(f_0(980) \to \gamma\gamma)}{\Gamma(\eta' \to \gamma\gamma)}
\]

(6)

should be of comparable size if indeed the mixing angles \( \varphi_P \approx \varphi_S \), then the quark charge factors cancel in \( R_2 \). Taking \( \Gamma(\eta' \to \gamma\gamma) = (4.29 \pm 0.15) \) keV and \( \Gamma(f_0(980) \to \gamma\gamma) = (0.39^{+0.10}_{-0.13}) \) keV \[\text{[27]}\] we obtain \( R_2 \sim 0.09 \pm 0.03 \).

With the assumption \( R_1 \approx R_2 \) and together with the decay rate \[\text{[3]}\] or \[\text{[11]}\] using Table 3 for \( \eta' K \) we can actually determine \( \gamma_S \) and \( p_{\pi\gamma} \) taken as real parameters. With \( \text{Br}(B^+ \to f_0(980) K^+) \sim (14 \pm 4) \times 10^{-6} \) after correction for \( \pi^0\pi^0 \) decay of \( f_0 \) and neglecting \( K\bar{K} \) we find two solutions

\[
\text{A:} \quad \gamma_S = -0.17, \quad p_{\pi\gamma}^2 = 15 \times 10^{-6}; \quad \text{B:} \quad \gamma_S = 0.3, \quad p_{\pi\gamma}^2 = 5 \times 10^{-6}
\]

(7)

According to Table 2 the \( K^o_{sc} \pi^\pm \) and \( K a^\pm \) rates are of order \( p_{\pi\gamma}^2 \). If we take the quoted BELLE result on \( K^o_{sc} \pi^+ \) into account, then Solution A is favoured. In this solution the rates for \( K^* f_0, K^* f_0' \) are \( 7\alpha_S^2 \times 10^{-6} \) and \( 17\alpha_S^2 \times 10^{-6} \) resp. whereas the same rates in Solution B are \( 0.0 \times 10^{-6} \) and \( 9\alpha_S^2 \times 10^{-6} \) where \( \alpha_S = p_{\pi\gamma}/p_{\pi\gamma} \).

**Total rate for gluonic decays**

Next we compare the rates for \( f_0 \) and \( \eta' \) production with the total rate \( b \to sg \)
CLEO \cite{7} has measured the inclusive non-charm decay $\text{Br}(B \to \eta' + X) = (6.2^{+2.1}_{-2.0}) \times 10^{-4}$, where the signal refers to the region $2.0 < p_{\eta'} < 2.7$ GeV of the $\eta'$ momentum. Identifying the non-charm rate with $X_s$ according to the SM and adding the exclusive $\eta'K$ rate we obtain the inclusive rate $\text{Br}(B \to \eta' + X_s) \sim 7.0 \times 10^{-4}$, so the total inclusive $\eta'/X_s$ rate is about 9 times larger than the exclusive $\eta'K$ rate. We take the gluonic part as in \cite{2} and add a gluonic contribution for $f_0(980)$ of fraction $R_2 \sim 10\%$. Then we find for the fully inclusive contribution of these decays

$$\text{Br}(B \to \eta', f_0(980))|_{\text{gluonic}} \sim (1.5 \ldots 3.5) \times 10^{-4}. \quad (8)$$

Hence, these decays cannot contribute more than $\sim (3 - 7)\%$ of the expected $b \to sg$ rate of $5 \times 10^{-3}$ \cite{16}. We will argue below that glueball production does provide the dominant part of the $b \to sg$ decay with “real” gluon.

## 3 Gluon jet fragmenting into $f_0(980)$

Gluonic mesons should also be found as leading particles in gluon jets \cite{28,12,29,30,31}. Following the proposal in ref. \cite{30} the 3-jet events obtained by DELPHI at LEP have been used to isolate the leading component in gluon jets. Events have been selected with a rapidity gap in this jet and first results have been presented \cite{5}. The charge of the leading component of the gluon jet beyond the rapidity gap has been compared with the MC simulation. Whereas the quark jets showed good agreement with this calculation the gluon jets had an excess of jets with charge $Q = 0$ as expected for an extra gluonic component. The $\pi^+\pi^-$ mass spectrum showed the $Q = 0$ excess spread over a large mass range with considerable fluctuations, but in the low mass region a significant peak is found for $f_0(980)$, absent in quark jets. This is a strong hint at the gluonic affinity of $f_0(980)$, i.e. its flavour singlet nature.

Results are desirable from energetic jets with large gaps and good separation from neighbour jets to minimize background. Such jets with high $p_T$ are produced also in hadronic or $ep$ collisions.

## 4 Glueball production in $B$ decays

Besides the observation of the strong $f_0(980)$ signal in charmless $B$ decays, there is another interesting feature in the decays $B^+ \to K^+\pi^+\pi^-$ and $B^+ \to K^+K^-\pi^+$ observed by the BELLE collaboration \cite{11}. The latter channel shows a broad enhancement in the $K^+K^-$ mass spectrum in the region $1.0 - 1.7$ GeV. The flat distribution in the Dalitz plot of these events suggests
this object to be produced with spin $J = 0$. Its contribution has been parametrized as scalar state $f_X(1500)$ with mass $M = 1500$ MeV and $\Gamma = 700$ MeV. There is no sign of a particular narrow resonance such as $f_0(1500)$ with width of about 100 MeV; this latter state should be seen more clearly in the $\pi\pi$ spectrum, given the small ratio $\Gamma(K\bar{K})/\Gamma(\pi\pi) = 0.19 \pm 0.07$ \[^{32}\] but there is no sign here either in the same experiment.

In the $\pi\pi$ mass spectrum in $B^+ \to K^+\pi^+\pi^-$ there are enhancements around $f_0(980)$ in the region 0.7-1.4 GeV. In this case, because of high background and smaller statistics, the spin is not so obvious but at least some $J = 0$ component is apparently present. The enhancement above 1 GeV has been related to $f_0(1370)$. Similar results have been reported by BaBar \[^{3}\].

In our earlier study of low mass scalars \[^{19}\] we interpreted the $\pi\pi$ S wave as being dominated by a very broad scalar state which interferes destructively with narrow $f_0(980)$ and $f_0(1500)$ (“red dragon”) and extends in mass up to about 1600 MeV. This broad object, corresponding to $f_0(400 - 1200)$ and $f_0(1370)$ listed by the PDG, we classified as scalar glueball $gb(1000)$ after the other low mass scalar states have been filled into the $q\bar{q}$ nonet. We argued that the Breit Wigner phase motion for $f_0(1370)$ has not been demonstrated clearly enough to require an extra state.

We consider the enhancements in $\pi\pi$ and $K\bar{K}$ observed by BELLE as a new, very clear manifestation of this broad scalar glueball. Whereas the center of the peak in $\pi\pi$ is closer to 1 GeV, it is shifted to higher mass in the $K\bar{K}$ channel. Because of the large width the branching ratios into different channels vary strongly with mass depending on the respective thresholds. The shape of the mass spectrum is also expected to vary from one reaction to another because different kinematic and dynamic factors may apply.

In order to relate different channels and to obtain an estimate of the total glueball production rate we consider the following decay scheme. The glueball decays first into $q\bar{q}$ pairs (possibly glueballs)

$$gb \rightarrow u\pi + d\bar{d} + s\bar{s} \quad (+gb \ gb)$$

subsequently, each of these $q\bar{q}$ pairs recombines with a newly created pair $u\bar{u}$, $d\bar{d}$ or $s\bar{s}$ where $s\bar{s}$ is produced with amplitude $S$ ($|S| < 1$). In this way the 2-body channels $gb \rightarrow q\bar{q}' + q'\bar{q}'$ are opened, at low energies just pairs of pseudoscalars. They are produced with probabilities

$$\begin{array}{cccccccc}
\pi^+\pi^- & \pi^0\pi^0 & K^+ K^- & K^0\bar{K}^0 & \eta\eta & \eta'\eta' \\
2 & 1 & 2 & 2 & 1 & 1 \\
2 & 1 & \frac{1}{2}|1 + S|^2 & \frac{1}{2}|1 + S|^2 & \frac{1}{3}|2 + S|^2 & \frac{1}{3}|1 + 2S|^2 \\
\end{array} \quad (10)$$
Table 3: Observed and corrected/expected branching ratios for $B \rightarrow K^+ gb(0^{++})$ decays for different 2-body channels (with $S = 0.8$).

| mass range $\times 10^{-6}$ | corr./exp. Br $\times 10^{-6}$ | comments |
|-----------------------------|-------------------------------|----------|
| [GeV] | $\times Br_{R \rightarrow h+h^-}$ | $K K^+ K^-$ |
| 1.0 − 1.7 | 27.6 ± 4.9 | 55.2 ± 9.8 | factor 2 (isospin) |
| | | $\eta \eta$ 17.3 | $K K^\mp/\eta \eta = 3.2$ (Eq.10) |
| | | "$\pi \pi$" 51.8 | $K K^\mp/\pi \pi = 1.08$ (Eq.10) |
| all | 124 ± 37 | |
| 1.0 − 1.3 | 11.1 $^{+8.0}_{-4.5}$ | 16.7 $^{+12.0}_{-6.7}$ | factor 3/2 (isospin) |
| all | $\sim 64^{+65}_{-36}$ | $\pi \pi/\text{all} = 0.26 \pm 0.09$ |
| 0.7 − 1.0 | $\sim 8$ | estimate |
| 0.7 − 1.7 | 132 | $B \rightarrow K^+ gb(0^{++})$ total |

The first row corresponds to $U(3)$ symmetry ($S = 1$), the second row to arbitrary $S$; $\eta, \eta'$ mixing is assumed as above. With increasing glueball mass the $q\bar{q}$ pairs can decay also into pairs of vector mesons or of other states but the total rates in (10) are assumed to remain unaltered.

We study first the mass region 1.0-1.7 GeV. In this region the pseudoscalars alone saturate the $K K^+$ rate in (10) as $K^+ K^+$ is forbidden by parity and $K^\pi K^\pi$ is kinematically suppressed. Another possible decay is $\eta \eta$, contributions from higher mass isoscalars ($\omega \omega$) are only possible at the upper edge of the considered mass interval. The decay $\eta' \eta'$ is kinematically forbidden. On the other hand, the $\pi \pi$ channel can get contributions from higher states, in particular $\rho \rho$ which becomes effective in the mass region above 1300 MeV.

Next we estimate the total glueball rate. In Table 3 we start from the observed $K K^+$ rate in the mass interval 1.0-1.7 GeV and derive using (11) the rates for $\eta \eta$ and "$\pi \pi$" where the latter includes $\rho \rho$. This yields the rate $(124 \pm 37) \times 10^{-6}$. We may compare the prediction for "$\pi \pi$" with the observed $\pi \pi$ rate in the region around $f_0(1370)$ which we consider as part of the glueball. Its decay properties are not well known, but there is a considerable fraction into $4\pi$, in particular $\rho \rho$. If the result from the extrapolation of $\pi \pi$ alone ($\sim 64 \times 10^{-6}$) is multiplied by factor 2 in order to account for the larger mass interval of $K K^+$, then both results (predicted and extrapolated) are consistent within the very large errors (Table 3).

Finally, from the total rate $B^+ \rightarrow K^+ gb(0^{++}) \sim 132 \times 10^{-6}$ in Table 3.
obtained by adding the low mass interval we may estimate the total inclusive rate by applying the same factor 9 as in case of $\eta'$ in the extrapolation $K^+ \to X_s$ and find

$$\text{Br}(B^+ \to gb(0^{++]}) + X_s) \sim 1.2 \times 10^{-3}$$ (11)

If we add the gluonic $\eta'X_s$ and $f_0(980)X_s$ contributions in (8) then we estimate the total production of observed gluonic mesons as

$$\text{Br}(B^+ \to gb(0^{++]}) + f_0 + \eta' + X_s) \sim (1.5 \pm 0.5) \times 10^{-3}$$ (12)

which is of the same size as the leading order result for the process $b \to sg$ in (1) and about 1/3 of the full rate obtained in NLO.

Besides the scalar glueball other glueballs should be produced as well. For orientation, it is plausible to assume

$$\text{Br}(B \to gb(0^{++}) + X_s) \approx \text{Br}(B \to gb(0^{-+}) + X_s)$$ (13)

This is obtained if one assumes a symmetry under chromoelectric-magnetic rotation $F \to \tilde{F}$ for the operators $F^2$ and $F\tilde{F}$ and approximately neglects the breaking of this symmetry. In this case the scalar and pseudoscalar gluonic mesons would add up to about $B \to (J = 0)$ glue mesons $\sim 3 \times 10^{-3}$ which is close to the total gluonic decay rate $b \to sg$. Given the errors in these estimates the counted decays could actually saturate the total rate, alternatively, there is room for glueballs with higher spin or hybrid states.

5 Conclusions

The large decay rate $B \to f_0(980)K$ and the excess of $f_0(980)$ in the leading part of the gluon jet suggest the gluonic affinity of this meson similar to $\eta'$ and therefore its flavour singlet nature. The further study of $B$ decays into scalar particles could be of invaluable help in establishing the members of the still controversial $0^{++}$ multiplet and its mixing. We also remark that the large exclusive decay rate for $f_0(980)$ makes a 4-quark or molecular hypothesis unpalausible as formfactors are expected rather to suppress this decay at the high energy of the $B$ meson. Similarly, measurements of $f_0(980)$ (also $\eta'$) in gluon jets with larger rapidity gaps for background suppression are desirable, possibly also from $pp$ and $ep$ collisions.

Our interpretation of $B \to K\bar{K}K$ decays in terms of glueball production should be tested by observing the predicted missing channels ($\eta\eta$ and $4\pi$) with the rates expected for the flavour singlet (Table 3).
The flavour singlet nature of \( f_0(980) \) does not necessarily imply a large mixing with a scalar glueball, such a large mixing is absent also in case of \( \eta' \). The near singlet flavour mixing of \( \eta' \) and \( f_0(980) \) is intrinsically due to their gluonic couplings. In fact, taking the results of our glueball analysis for granted with rate \( 132 \times 10^{-6} \) then an upper limit for mixing results by assuming the full rate of \( f_0(980) \) production \( (14 \times 10^{-6}) \) to be due to mixing with glueball; then the mixing angle would be \( \sin^2 \varphi_g < (14/132) \) or \( \varphi_g < 20^\circ \).

Ultimately there is the question of how the \( b \rightarrow sg \) decay is realized by hadronic final states. The large rate for the \( 0^{++} \) glueball we obtain suggests the intriguing possibility that it could be saturated by gluonic mesons. In the next step it will be interesting to search for the \( 0^{-+} \) glueball which could decay into \( \eta \pi \pi \) and \( K\overline{K} \pi \). The candidate of lowest mass would be \( \eta(1440) \) which is strongly produced in radiative \( J/\psi \) decays.

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