Search for scalar glueballs from heavy meson decays

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Abstract. We investigate the transition form factors of $B$ meson decays into a scalar glueball in the light-cone formalism. Compared with form factors of $B$ to ordinary scalar mesons, the $B$-to-glueball form factors have the same power in the expansion of $1/m_B$. Taking into account the leading twist light-cone distribution amplitude, we find that they are numerically smaller than those form factors of $B$ to ordinary scalar mesons. In the presence of mixing between glueballs and ordinary scalar mesons, the possibility to extract the mixing parameters from semileptonic $B$ decays and nonleptonic $B$ decays are explored. We also point out a clean way to identify a glueball through $B_c$ decays.

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INTRODUCTION

Quark model has achieved a great success to describe hadronic states, while QCD also predicts the existence of mesons without any valence quark, which is called glueball. The confirmation of a glueball is one of the most important topics and this subject has received extensive interests [1]. Lattice QCD, which is almost the only method to do calculations from the fundamental QCD, predicted that the mass of the lowest-lying scalar glueball ($0^{++}$) is around 1.5–1.8 GeV [2]. Several different candidates have been observed around this mass region, but there is not any solid evidence on the existence of a pure glueball. For decades, people have tried to find a way to verify the existence of a glueball through its decay property. The glueball is quark flavor singlet, which should decay to $u\bar{u}, d\bar{d}$ and $s\bar{s}$ equally. However, the claimed “unique” feature of quark flavor singlet, is not unique, since the quark-antiquark state can also be flavor SU(3) singlet. Thus, it is not a firm evidence for a glueball. Furthermore, it is very likely that the glueball mix with the quark-antiquark scalar state and they together form several physical mesons. On the theoretical side, there are large ambiguities on the mixing mechanism [3]. This makes the study even more complicated.

Recently, another important direction to uncover the mysterious structure of scalar mesons, is discussed, which investigates the scalar meson production property through $B$ meson decays. In $B$ meson decays, the $O_{gg}$ operator has a large Wilson coefficient, which could produce a number of gluons. These gluons in the final state may have the tendency to form a glueball state, thus the glueball production in inclusive $B$ decays has attracted some theoretical interest [4, 5]. In a recent study [6], we calculate the transition form factors of $B$ meson decays into a scalar glueball in the light-cone formalism. Compared with form factors of $B$ to ordinary scalar mesons, the $B$-to-glueball form factors have the same power in the expansion of $1/m_B$. Taking into account the leading twist light-cone distribution amplitude, we find that they are numerically only a little smaller than those form factors of $B$ to ordinary scalar mesons. It means that the production rate of glueball in $B$ decays is quite copious.

The scalar meson can be produced in $B$ decays by two gluon (glueball) and also an isosinglet $q\bar{q}$ pair (ordinary meson). In this paper, we will propose a method for experiments to measure the mixing parameters between glueball and $q\bar{q}$ states by semileptonic and nonleptonic $D/B$ meson decays, so that to prove the existence of a scalar glueball effectively. We also find a possible clean way to prove the glueball existence, which will require the detection of scalar meson production from $B_c$ decays.
TRANSITION FORM FACTORS IN THE PERTURBATIVE QCD APPROACH

Up to the leading Fock state, a glueball is made up of two constituent gluons. In exclusive $B$ decays, these two gluons can be emitted from either the heavy $b$ quark or the light quark. In the expansion of $\alpha_s$, the lowest order Feynman diagrams for form factors of $B$ decays into a scalar glueball are depicted in Fig. 1 (a), (b) and (c). In Fig. 1 (d) and (e), the light antiquark in $B$ meson and the energetic quark from the electro-weak vertex also form an isospin or SU(3) singlet scalar meson. Usually, people believe that the form factor of $B$ decays to an ordinary scalar meson is larger than that of $D$ decays into a scalar glueball.

Momentum fractions of the light antiquark in $B$ meson and the upper (lower) gluon depicted in Fig 1 are denoted as $x_1$ and $x_2$ ($x_2 = 1 - x_2$), respectively. In the first diagram of Fig. 1, each of the two internal quark propagators is the sum of a collinear momentum (gluon) and a soft momentum (light quark). The virtualities of them are of order $\Lambda_{\text{QCD}}^2 m_b$, where $\Lambda_{\text{QCD}}$ is the hadronic scale. In the second and the third diagram, one or two light propagators become heavy $b$ quark propagators, whose virtualities become $m_b^2$ instead of $\Lambda_{\text{QCD}}^2 m_b$. Superficially, one may conclude that the power counting for the three diagrams obey the relation: $F(b) > F(c)$. But in fact, this relation is not exactly correct. The leading twist light-cone distribution amplitude is constructed in the case that the two gluons are transversely polarized. So the structures of the vertices attaching to these two gluons in the first diagram have the form: $\gamma^\mu$. Apparently, the numerator of the propagators commutes with the transverse Dirac matrix. So, the amplitude is proportional to $(\bar{x}_2 P_B^2 - x_1 P_B^2)(P_B^2 - x_1 P_B) \approx -x_1 P_B^2 x_2 - x_1 \bar{x}_2 P_B^2$. Neglecting the glueball’s mass square, there is a small momentum fraction $x_1$ in the numerator, which will cancel one of the momentum fraction of the denominator. The effective power for one light propagator in the first diagram becomes $m_b^2$, which is the same as a heavy propagator in the second diagram. It implies: $F(a) \sim F(b) > F(c)$. Adopting the power counting rule for the $B$ meson wave function and the scaling behaviors for the distribution amplitudes of collinear meson, given in Ref. [7], we directly obtain

$$F^{B \rightarrow G} \sim \alpha_s \left( \sqrt{m_b \Lambda_{\text{QCD}}} \right) \left( \frac{\Lambda_{\text{QCD}}}{m_b} \right)^{3/2},$$  

(1)

where the form factor is dominated by the first two diagrams. The $B \rightarrow G$ form factors have the same scaling rule with the $B$-to-light transition form factor. And we can expect that the gluonic $B \rightarrow \eta (\eta')$ form factors also obey this rule. While the light-cone distribution amplitude of a gluonic pseudo-scalar meson is normalized to zero, only the higher Gegenbauer moments contribute. The first effective Gegenbauer moment of $\eta$ and $\eta'$ is very small, so the gluonic contribution to $B \rightarrow \eta$ form factors is found to be numerically small [8].

Our detailed study shows [6] that the form factors of $B$ decays into a scalar glueball is numerically big enough for the experiments to observe it. Compared with our previous studies [9, 10] on the transition form factors of $B$ mesons decays into ordinary scalar mesons (denoted as $f_0$ with the mass around 1.5 GeV), the $B \rightarrow G$ form factors are at the same order of magnitude. The $B$-to-glueball form factors are only a factor of two smaller than the $B \rightarrow \pi$ form factors.
factors. In scenario II, where scalar mesons
large branching fractions offer a great opportunity to probe structures of scalar mesons. With the available data in the
final mesons in these channels are easy to reconstruct and these channels could have sizable branching fractions. Such
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another ideal probe to detect the internal structure of the scalar mesons. In
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THE STUDY OF MIXING BETWEEN GLUEBALL AND QUARK STATES

It is very likely that the glueball state mix with the ordinary quark-antiquark state and they form several physical mesons. In the mass region 1.5-1.8 GeV, there are three scalar mesons: f0(1370), f0(1500) and f0(1710), which might be the potential candidates. The mixing matrix can be set as

\[
\begin{pmatrix}
  f_0(1710) \\
  f_0(1500) \\
  f_0(1370)
\end{pmatrix} =
\begin{pmatrix}
  a_1 & a_2 & a_3 \\
  b_1 & b_2 & b_3 \\
  c_1 & c_2 & c_3
\end{pmatrix}
\begin{pmatrix}
  G \\
  \bar{s}s \\
  \bar{n}n
\end{pmatrix}.
\]

For each physical scalar meson for example f0(1370), which is a mixture of glueball and ordinary states, the coefficients c1, c2 and c3 satisfy the normalization condition

\[
\sqrt{|c_1|^2 + |c_2|^2 + |c_3|^2} = 1.
\]

A non-zero c3 would be a clear evidence for the existence of a glueball. Let us aim this to see if there is a way to settle it in B decays. The semileptonic B → f0J/ψ decays receive contributions from the \( \bar{n}n \) component but without \( \bar{s}s \) component (at least negligible), while the semileptonic B → f0π+π− channel only receive contributions from the \( \bar{s}s \) but without \( \bar{n}n \) component. Both of the decay channels can receive gluon component contributions. Thus from eq. (3), we notice that the two independent mixing parameters can be fitted from the above two experimental measurements, in principle. For the three kinds of f0’s, we have altogether 6 experiments, but only three real parameters in eq.(2) to be fixed. Since the branching fraction of Bs → f0π+π− is expected to have the order of \( 10^{-8} \) or even smaller, one needs to accumulate a large number of B decay events. This could be achieved on the future experiments such as the Super B factory.

For example, the B → J/ψf0 decay can filter out the glueball component and the \( \bar{n}n \) component of a scalar meson. Meanwhile in Bs → J/ψf0 decay, only the \( \bar{s}s \) and the gluon component contributes. Moreover, the final mesons in these channels are easy to reconstruct and these channels could have sizable branching fractions. Such large branching fractions offer a great opportunity to probe structures of scalar mesons. With the available data in the

These form factor results are collected in table 1 for comparison \(^1\). In fact, the main decay channel of a scalar glueball is \( \pi\pi \) or \( K\bar{K} \). Thus a scalar glueball is much easier to detect than the iso-singlet pseudoscalar meson such as \( \eta \). Thus the branching ratio of \( B \rightarrow G\ell \bar{\nu} \) \[^6\] is large enough to be observed on the ongoing B factories and the forthcoming Super B factory.

| \( B \rightarrow G \) | \( F_0(0) = F_1(0) \) |
| \( B \rightarrow \pi \) | \( F_0(0) = F_1(0) \) |
| \( B \rightarrow f_0 \) Scenario I | \( -0.30^{+0.08}_{-0.09} \) |
| \( B \rightarrow f_0 \) Scenario II | \( 0.63^{+0.23}_{-0.14} \) |

Table 1. B to glueball (G), B to ordinary scalar meson (f0) and B to pseudoscalar meson (π) transition form factors in the PQCD approach

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\(^1\) If these scalar mesons f0 are identified as \( \bar{q}q \) excited states, referred as scenario I, the decay constants of f0 are negative and so are B → f0 form factors. In scenario II, where scalar mesons f0 are identified as \( \bar{q}q \) ground state, the form factors are positive.
future, the mixing problem between the scalar mesons will be solvable and the glueball component can be projected out in principle.

If the power-suppressed annihilation diagrams are neglected, the charmful decays of $B$ meson, $B \rightarrow f_0D$, can also be used to constrain the mixing between scalar mesons. For instance in $B^- \rightarrow D^-\bar{f}_0$, the $\bar{u}u$ and gluon component contribute but the $\bar{s}s$ component does not, while in $B_1 \rightarrow D^0\bar{f}_0$, the $\bar{u}u$ component will not contribute. Thus the mixing coefficients can also be determined if these two channels are experimentally measured. It is necessary to point out that this method may suffer from sizable uncertainties of annihilation diagrams [9].

To be more specific, we will discuss two mixing mechanisms in detail. Because the decay width of $f_0(1500)$ is not compatible with the ordinary $\bar{q}q$ state. Amsler and Close claimed that $f_0(1500)$ is primarily a scalar glueball [12, 13]. Based on the SU(3) assumption for scalar mesons and the quenched lattice QCD results, Cheng et al. [14] reanalyze all existing experimental data and re-fit the mixing coefficient. It is found that the $f_0(1710)$ tends to be a primary glueball. This is very different from the first matrix of mixing coefficients by Close et al. The scalar meson production rates in $B$ meson decays can be used to distinguish these assignments, starting with the $B \rightarrow S$ form factors collected in Tab. 1. For example in scenario I if we use the mixing coefficients in Ref. [13], the production rates of $f_0(1710)$ and $f_0(1500)$ in $B$ decays are much smaller than that of $f_0(1370)$ but they have large and comparable production rates in $B_c$ decays; if we use the mixing coefficients in Ref. [14], $f_0(1710)$ has small production rates in both $B$ and $B_c$ decays but the other two mesons have large and comparable production rates in $B$ and $B_c$ decays. Based on our predictions on form factors [9, 10, 6], these differences in $B$ and $B_c$ decays are helpful to distinguish the two mixing matrix.

**GLUEBALL PRODUCTION IN $B_c$ DECAYS**

The ordinary light scalar meson is isospin singlet and/or flavor SU(3) singlet, while the glueball is flavor SU(6) singlet. Therefore it is difficult to distinguish them by the light $u$, $d$ and $s$ quark coupling. However, the light ordinary scalar meson has negligible $c\bar{c}$ component, while the glueball have the same coupling to $c\bar{c}$ as that to the $u\bar{u}, d\bar{d}$ or $s\bar{s}$. A clean way to identify a glueball is then through the $c\bar{c}$ coupling to the glueball [15].

In $B$ decays, the initial heavy meson contains a light quark, thus contributions of the gluon component always accompany with the quark content $\bar{u}u$ or $\bar{s}s$. It is not easy to isolate the gluon content. The situation in the doubly-heavy $B_c$ meson is different: it contains a heavy charm antiquark. The semileptonic $B_c \rightarrow f_0l\bar{\nu}$ decays would happen only through Fig. 1(a)(b) and (c) but not through Fig. 1(d) and (e). The observation of this decay channel in the experiments will surely establish the existence of a scalar glueball. Moreover the CKM matrix element in this channel is $V_{cb}$, thus the $B_c \rightarrow f_0l\bar{\nu}$ will have a sizable branching ratio. This channel will depend on the $B_c \rightarrow G$ transition form factor which requires the less-constrained $B_c$ meson’s light-cone distribution amplitude. But even if we assume the form factor of $B_c \rightarrow G$ is smaller than the $B_c \rightarrow \eta_c$ form factor by one order, branching ratios of $B_c \rightarrow G\nu(l\bar{\nu})$ are suppressed by two orders

$$\mathcal{B}(B_c \rightarrow G\nu,l\bar{\nu}) \sim 1\% \times 0.01 = 10^{-4}, \quad (4)$$

where the branching ratio of $B_c \rightarrow \eta_c(l\bar{\nu})$ has been taken as 1%. This branching ratio is large enough for the experiments. One only needs to reconstruct the $f_0$ scalar meson in the final state and also the $B_c$ meson mass in the intermediate state, so that to make sure that the scalar meson is produced from two gluons. That experiment is achievable even if the $f_0$ meson is not a pure glueball, but at least has a large portion of it. In fact, the glueball in eq.(4) is not necessary to be a scalar, for example, it also applies to a light pseudoscalar glueball.

$B_c \rightarrow f_0\pi^-$ is another potential mode to figure out the gluon content. But in this mode, the $\bar{n}n$ component also contributes through the annihilation diagrams. The $b$ and $c$ quark annihilates and the $d$ and $u$ quark are created. The CKM matrix element $V_{cb}$ and the Wilson coefficient $a_1$ are the same with the emission diagram for the $B_c$-to-glueball transition. The offshellness of the two internal particles in annihilation diagrams are of the order $m_{f_0}^2$. The electroweak vertex is the $V-A$ type and the decay amplitude is proportional to the light quark mass. Thus the decay amplitudes via annihilation diagram for the $\bar{n}n$ component are expected to be suppressed. As a result, the $B_c \rightarrow f_0\pi^-$ also filters out the gluon component of the scalar meson as an approximation[15].

**SUMMARY**

Although the $B$-to-glueball form factors are small, they can not be neglected and more interestingly these form factors may have different interferences with those for the quark content, according to different descriptions of scalar mesons.
If a scalar meson is a mixture of a glueball and an ordinary meson, we investigate the possibility to extract the mixing mechanism from semileptonic $B$ decays. Semileptonic $B \to f_0 l \bar{\nu}$ and $B_s \to f_0 l \bar{\nu}$ decays can be used to determine the internal structures. The nonleptonic $B \to J/\psi f_0$ and $B_s \to J/\psi f_0$ decays are also analyzed. To avoid the interference between the quark and the gluon component, we find that the $B_c \to f_0 l \bar{\nu}$ and $B_c \to f_0 \pi^-$ will project out the gluon component of a scalar meson cleanly. Our results can be generalized to the other glueball states.

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