Eur. Phys. J. C 55, 417–421 (2008)
DOI 10.1140/epjc/s10052-008-0606-6

THE EUROPEAN
PHYSICAL JOURNAL C

Regular Article – Theoretical Physics

On two-body decays of a scalar glueball

K.T. Chao[1], Xiao-Gang He[1,2], J.P. Ma[1,3,a]

[1] Department of Physics, Peking University, Beijing, P.R. China
[2] Department of Physics and Center for Theoretical Sciences, National Taiwan University, Taipei, Taiwan, R.O.C.
[3] Institute for Theoretical Physics, Academia Sinica, P.O. Box 2735, Beijing, P.R. China

Received: 26 February 2008 /
Published online: 7 May 2008 –

Abstract. We study two-body decays of a scalar glueball. We show that in QCD a spin-0 pure glueball (a state with only gluons) cannot decay into a pair of light quarks if chiral symmetry holds exactly, i.e., the decay amplitude is chirally suppressed. However, this chiral suppression does not materialize itself at the hadron level such as in decays into $\pi^+\pi^-$ and K^+K^-. We show this explicitly in the two cases with the glueball much lighter and much heavier than the QCD scale using low-energy theorems and perturbative QCD. For a heavy glueball, using QCD factorization based on an effective Lagrangian, we find that the hadronization into $\pi\pi$ and KK leads to a large difference between $\mathrm{Br}(\pi^+\pi^-)$ and $\mathrm{Br}(K^+K^-)$; even the decay amplitude is not chirally suppressed. Our results can provide some understanding of the partonic contents if $\mathrm{Br}(\pi\pi)$ or $\mathrm{Br}(K\bar{K})$ is measured reliably.

It is believed that all hadrons are built with quarks and gluons, which are the dynamical degrees of freedom of QCD. So far all observed hadrons have been shown to contain quarks. In general, it is also possible to have hadrons that contain gluons only, the so called pure glueball states. Experimentally, the existence of glueballs has not been confirmed although there are some indications. Studies with lattice QCD indicate that the lowest lying glueball is a scalar, a 0^{++} state, having a mass in the range of 1.5–2.0 GeV [1–4]. The state $f_0(1710)$ is a promising candidate for a scalar glueball[5, 6].

In the framework of QCD a scalar glueball G_s is in general a superposition of many components containing gluons and quarks as partons a_i $(i = 1, \ldots, n)$, which can be schematically represented as

$$|G_\mathrm{s}\rangle = \sum_{n=2} \psi_{a_1\cdots a_n}|a_1, \ldots, a_n\rangle = \psi_{gg}|gg\rangle + \psi_{q\bar{q}}|q\bar{q}\rangle + \ldots , \quad (1)$$

where $\psi_{a_1\cdots a_n}$ is the probability amplitude for the component $|a_1, \ldots, a_n\rangle$. It is clear that a state should not be identified as a glueball state if it has a quark content larger than its gluon content – roughly speaking, if $|\psi_{gg}| < |\psi_{qq}|$. The decay products of a particle can be used to extract crucial information on whether a state is a glueball or not. In this letter we will show that two-body decays of a scalar glueball can reveal some important information and discuss possible experimental implications. Part of our results, in particular the result on the pQCD calculation of the leading contribution for glueball decays into two light mesons, has been discussed in [8]. Here we provide more details including some higher-twist effects and also discuss for the low-energy theorem the implications for light glueball decay into two light mesons.

We will first show in QCD, without any assumption, that a 0^{++} glueball G_s cannot decay into a light-quark pair $q\bar{q}$ if G_s is a pure glueball with exact chiral symmetry. The decay is chirally suppressed. Then we study two-body hadronic decays, such as $\pi\pi$ and KK, and show that the quark level chiral suppression does not materialize itself at hadron level, even for pure glueball decay. We will show this explicitly in the two cases with the glueball much lighter and much heavier than the QCD scale. In the case that the glueball is light, the decay products will have small momenta. One can use low-energy theorems to show that even in the chiral limit the glueball still can decay into $\pi\pi$. If the glueball is heavy, one can show based on QCD factorization even for a pure glueball that it will mainly couple to two quark pairs $q\bar{q}q\bar{q}$, which hadronize to two light mesons or so at long distances rather than just one quark pair $q\bar{q}$ at short distances (see Fig. 2a). Hence, there is no chiral suppression for the $\pi\pi$ mode compared with the KK mode. Taking $f_0(1710)$ as an example, we find that a small decay ratio $\mathrm{Br}(\pi^+\pi^-)/\,\mathrm{Br}(K^+K^-)$ does not necessarily imply that $f_0(1710)$ is a pure glueball. This is in contrast to the recent result in [7].

For the decay of a scalar glueball into $q\bar{q}$ all components in (1) may contribute. The contributions from those components only containing gluons can be represented by Fig. 1a, where the bulb with S can be defined as a n-point Green's function of gluon fields combined with gluon propagators in the free case, and the other bulb attached

[a] e-mail: majp@itp.ac.cn

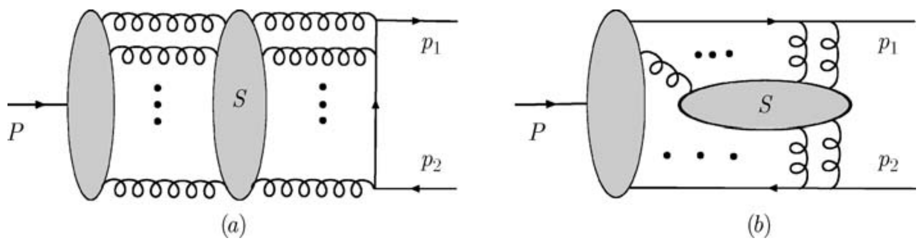

Fig. 1. A glueball decays into a $q\bar{q}$ pair. **a** The contribution from components containing gluons only. **b** The contribution from components containing a $q\bar{q}$ and gluons when mixing exists

with the glueball can be defined with gluon field operators sandwiched between the vacuum and the glueball state. Although a complete calculation for the diagram with the structure given in Fig. 1a is not possible at present, some general conclusions can be drawn by using properties of QCD and Lorentz covariance.

The decay amplitude from Fig. 1a for $G_s \to q(p_1)\bar{q}(p_2)$ can be written as a product of a spinor pair $\bar{u}(p_1)$ and $v(p_2)$ with a product of any number of γ matrices sandwiched between the spinors. Because the quark–gluon coupling in QCD is vector-like, the number of γ matrices is odd when the quark mass m_q is equal to zero. A product of an odd number of γ matrices can be reduced to just one γ matrix. Therefore the amplitude from Fig. 1a can always be written as

$$\mathcal{T}_g(G_s \to q\bar{q}) = \bar{u}(p_1)\gamma_u A^\mu v(p_2)\,. \tag{2}$$

Although we cannot obtain an explicit expression for A^μ, we know from Lorentz covariance that it can be written as $A^\mu(p_1,p_2) = a_1 p_1^\mu + a_2 p_2^\mu$. With this it is easy to find that in the chiral limit $m_q = 0$, the contribution to the decay amplitude $G_s \to q\bar{q}$ from the pure gluonic components is zero. The result also applies to pseudoscalar glueball decays into a $q\bar{q}$ pair.

It is clear that the contribution of these pure gluonic components to the decay amplitude in the limit $m_q \to 0$ is

$$\mathcal{T}_g(G_s \to q\bar{q}) \sim m_q + \mathcal{O}\left(m_q^3\right), \tag{3}$$

because the helicity of quarks can be flipped with a finite quark mass m_q. By assuming a specific form of the coupling for a scalar glueball with two gluons as given in (4), the result below for G_s is also obtained in [7], with other assumptions. We emphasize that the above results can be obtained in QCD without any assumption. The above result is obtained by an analysis in perturbative theory. It is well known that the chiral symmetry not only can be broken by finite quark masses but also can be broken spontaneously; the latter is a nonperturbative effect. Therefore the correct statement about the decay should be that the decay is not allowed if chiral symmetry holds. The m_q in (3) should not be understood as a current quark mass, but rather as the scale of chiral symmetry breaking. The effect of spontaneous breaking of the chiral symmetry on the decay can only be studied with nonperturbative methods; see, e.g., in [11] for this case. Combining nonperturbative effects the chiral suppression for the ratio $\mathcal{T}_g(G_s \to u\bar{u})/\mathcal{T}_g(G_s \to s\bar{s})$ will be not as strong as suggested by the current quark masses ratio m_u/m_s.

For contributions from components containing $q\bar{q}$ pairs with or without gluons, the situation will be different. The $q\bar{q}$ pair in the final state can come from one of the $q\bar{q}$ pairs through scattering from the already existing quark contents in the glueball state as shown in Fig. 1b. In this case one cannot conclude that the contribution from Fig. 1b is zero in the limit $m_q = 0$. The reason is that the glueball can have components with a $q\bar{q}$ pair and gluons. If these gluons are in a state like $J^{PC} = 1^{--}$, the $q\bar{q}$ pair must also be in a 1^{--} state. One can show that the contributions from those components are not zero in the chiral limit.

In the above, the results are obtained for the decay of G_s into a $q\bar{q}$ pair. For a real decay process one has to work with hadron states. Unfortunately at present the hadronization mechanism is not well understood. To study the hadronic decays we will therefore assume that a scalar glueball dominantly couples to gluons and quarks via the effective Lagrangian [7]:

$$L_s = G_s\left\{\frac{f_g}{M} G^{a,\mu\nu} G^a_{\ \mu\nu} + f_q \bar{q} q\right\} + \cdots\,, \tag{4}$$

where G_s is the extrapolation field of the scalar glueball, and M is its mass. f_g and f_q are dimensionless coupling constants. They are related to those probability amplitude in (1). If G_s is a pure glueball, the coupling f_q is chirally suppressed, i.e., $f_{u,d} \ll f_s$, or zero if the chiral symmetry is exact. These couplings are unknown, but important information on them can be extracted from experiment as we will show later.

If the glueball is light enough, it is easy to show with the above effective Lagrangian that there is no chiral suppression in the sense that in the chiral limit the decay of the glueball into $\pi^+\pi^-$ happens. The decay amplitude through the gluonic coupling f_g in (4) is given by

$$\mathcal{T}_g(G_s \to \pi^+\pi^-) = \frac{f_g}{M}\langle \pi^+(p_1)\pi^-(p_2)| G^{a,\mu\nu} G^a_{\ \mu\nu}|0\rangle\,. \tag{5}$$

This amplitude is nonperturbative. However, there exist some low-energy theorems that give information on the above amplitude. In the chiral limit one can show [12]

$$\begin{aligned}&\langle \pi^+(p_1)\pi^-(p_2)|\left(-\frac{\beta_0\alpha_s}{8\pi}\right) G^{a,\mu\nu} G^a_{\ \mu\nu}|0\rangle \\ &\quad = (p_1+p_2)^2 + \mathcal{O}(p^4)\,,\end{aligned} \tag{6}$$

where $\beta_0 = (11 - 2n_f/3)$ with n_f the number of light quarks. This result simply tells that the decay can happen in the chiral limit. Therefore, there is no chiral suppression if the glueball is light. Similarly, the direct transmission of $q\bar{q}$ into $\pi\pi$ can also be fixed [13, 14]. The same could also be obtained by using a chiral realization of L_s as described in [15–17]. One can also work out similar expressions for the $G_s \to KK$ amplitude.

To show that there is chiral suppression in $G_s \to \pi\pi$ compared with $G_s \to KK$, one needs to consider the direct hadronization of $G_s \to q\bar{q}$ to $G_s \to \pi\pi(KK)$ and also some other possible contributions [18]. The above discussion indicates that $G_s \to q\bar{q}$ direct hadronization will not produce chiral suppression.

We note that the glueball mass is expected to be around 2 GeV. Practically, the applicability of the low-energy theorems is questionable at this scale. At this energy scale, perturbative QCD may make some reliable predictions, such as those of the decay of the τ-lepton. Therefore, one can employ QCD factorization for exclusive processes suggested a long time ago in [9, 10], where the hadronization is parameterized with light-cone wave functions. In the following we will consider if there is chiral suppression from the pQCD point of view. We will use QCD factorization with L_s to study the decay $G_s \to \pi^+\pi^-$ in the following.

We first discuss the contributions from the coupling with gluons. To leading twist-2 order, the contribution comes from diagrams represented by Fig. 2a. Direct calculation gives

$$\mathcal{T}_g = -\alpha_s f_g \frac{8\pi}{9M} f_\pi^2 \int_0^1 \mathrm{d}u_1\,\mathrm{d}u_2 \phi_{\pi^+}(u_1)\phi_{\pi^-}(u_2) \times \left(\frac{1}{u_1 u_2} + \frac{1}{(1-u_1)(1-u_2)}\right)[1+\mathcal{O}(\alpha_s)+\mathcal{O}(\lambda/M)]\,, \tag{7}$$

where ϕ_π is the twist-2 light-cone wave function of π. u_i $(i=1,2)$ is the momentum fraction carried by the antiquark in the meson. In the above, λ can be any soft scale, such as the quark mass, Λ_{QCD} and m_π. The contribution from the coupling with quarks are nonzero if one takes $m_q \neq 0$. Clearly, $\mathcal{T}_g$ is not zero in the chiral limit $m_q = 0$.

The contribution from the coupling with quarks is given by diagrams represented in Fig. 2b. It is zero if we only take twist-2 light-cone wave functions. At twist-3 there are two wave functions, but only one leads to nonzero contributions. This gives

$$\begin{aligned}\mathcal{T}_q = &-\frac{4\pi}{9}\frac{f_\pi^2}{M^2}\alpha_s(\mu)\int_0^1 \mathrm{d}u_1\,\mathrm{d}u_2 \Bigg\{\phi_{\pi^+}(u_1)\phi_{\pi^-}(u_2) \\ &\times \Bigg[m_u f_u\left(\frac{1}{u_1^2(1-u_2)}+\frac{1}{u_1(1-u_2)^2}\right) \\ &+ m_d f_d\left(\frac{1}{(1-u_1)^2u_2}+\frac{1}{(1-u_1)u_2^2}\right)\Bigg] + \frac{m_\pi^2}{m_u+m_d} \\ &\times \Bigg[\left(\frac{3-u_2}{u_1(1-u_2)^2}f_u + \frac{2+u_2}{(1-u_1)u_2^2}f_d\right)\phi_{\pi^-}(u_2)\phi_{\pi^+}^{[p]}(u_1) \\ &+ \left(\frac{2+u_1}{u_1^2(1-u_2)}f_u + \frac{3-u_1}{(1-u_1)^2u_2}f_d\right)\phi_{\pi^-}^{[p]}(u_2)\phi_{\pi^+}(u_1)\Bigg]\Bigg\}\,.\end{aligned} \tag{8}$$

$\phi_\pi^{[p]}$ is the twist-3 light-cone wave function. Definitions of above light-cone wave functions can be found in [19]. It should be noted that the above integration is divergent because of end-point singularities. This is common in a higher-twist calculation for exclusive processes; examples can be found in B decay and form-factors [23–25]. These singularities can be regularized as usual by introducing a cut-off scale Λ_c or $\epsilon = \Lambda_c/M$ and by changing the integration range from $[0,1]$ to $[\epsilon, 1-\epsilon]$. In our later discussions we will use the QCD scale $\Lambda_c = 300$ MeV for illustration.

The amplitude for $G_s \to K^+K^-$ decay can be obtained by replacing the quantities related to π by those related to K correspondingly. We now apply the above results to analyze $\pi^+\pi^-$ and K^+K^- decays of $f_0(1710)$, which is a candidate for a scalar glueball. For numerical calculations we take the models for twist-2 light-cone wave functions at the energy scale 1 GeV in [20–22] and the asymptotic form of $\phi^{[p]}$, which is 1, and take $M = 1710$ MeV, $m_u = m_d = 4.5$ MeV, $m_s = 120$ MeV, $f_\pi = 132$ MeV and $f_k = 1.27 f_\pi$. We have the following amplitudes in units of GeV with $\Lambda_c = 300$ MeV:

$$\begin{aligned}\mathcal{T}(\pi^+\pi^-) &\approx (-1.062 f_g - 0.602 f_u - 0.602 f_d)\alpha_s\ (\mathrm{GeV})\,, \\ \mathcal{T}(K^+K^-) &\approx (-1.796 f_g - 1.674 f_u - 1.671 f_s)\alpha_s\ (\mathrm{GeV})\,.\end{aligned} \tag{9}$$

With a smaller cut-off, T_q becomes bigger. The qualitative features do not change very much.

We note the difference in the coefficients in front of f_g for the amplitude of $\pi\pi$ and $K\bar{K}$ in (9). This is mainly due to the difference between f_π and f_K. This tells us that the decays into $\pi\pi$ and $K\bar{K}$ are already significantly different, even if the glueball does not couple to $q\bar{q}$, i.e., $f_q = 0$. With $f_q = 0$ the ratio $R = \mathrm{Br}(\pi^+\pi^-)/\mathrm{Br}(K^+K^-) \approx f_\pi^4/f_K^4 = 0.48$, which is substantially different from 1. This suppression is much milder compared with the one at the quark level. It should be noted that the result $R \approx f_\pi^4/f_K^4$ can be derived without the effective Lagrangian in (4) if the glueball is purely composed of gluons and the pQCD contribution dominates. This is because that for a pure gluball state, the amplitude of the decay $G_s \to \pi^+\pi^-$ can always be written with QCD factorization as $T_{\pi\pi} = f_\pi^2 H_g \otimes \phi_{\pi^+} \otimes \phi_{\pi^-}$, where the higher-twist effects related to the π are neglected and H_g consists of some perturbative coefficient

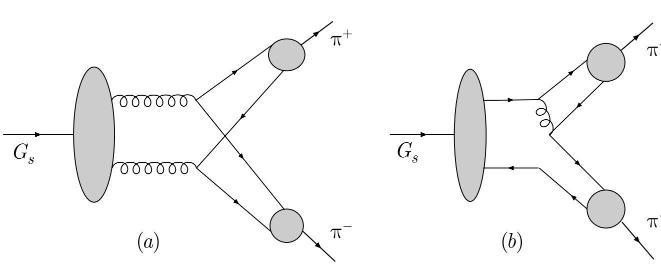

Fig. 2. a One of the two diagrams for the decay through the coupling with gluons. **b** One of the four diagrams for the decay through the coupling with quarks

functions and some quantities related to the structure of G_s. H_g does not depend on the hadrons in the final state. Although H_g is unknown, one can easily find the result of $R \approx f_\pi^4/f_K^4$. Hence, even the decay amplitude is not chirally suppressed, and the difference of hadronization for the G_s decays into $\pi\pi$ and KK already leads to a large difference between $\mathrm{Br}(\pi^+\pi^-)$ and $\mathrm{Br}(K^+K^-)$. It should be noted that $R \approx 0.48$ is close to the recent experimental central value $0.41^{+0.11}_{-0.17}$ obtained by BES [26]. From (9) the terms proportional to f_g are sizeable compared with the other terms if f_g and f_q are similar in size. Since a glueball should have a larger gluon content than quark content, f_q should not be too much larger than f_g if $f_0(1710)$ can be identified as a glueball.

If the ratio R is significantly smaller than f_π^4/f_K^4, it is an indication that there are other non-gluons in its contents. Previous measurements [5,6] gave smaller values compared with recent BES data [26]. We therefore also studied the influence of a nonzero f_q on R. In Fig. 3, we show the correlation of f_u/f_g and f_s/f_g for several given values of R, where we assume $f_u = f_d$. From Fig. 3 we can see that the measured ratio $R = 0.2$ does not necessarily imply $f_u/f_s \ll 1$, or the chiral suppression, as discussed after (4). The experimental data on R can be explained even if f_u is at the same order of magnitude as f_s, e.g., $f_s/f_g \approx 2f_u/f_g \approx 1$. Since the couplings f_q are determined by the quark contents, the current experimental data do not exclude the possibility that $f_0(1710)$ has large quark contents. Combining the experimental data of decay and production in radiative decay of J/ψ, the study in [27,28] also shows that $f_0(1710)$ not only has gluon content but also a large $s\bar{s}$-content and sizeable $u\bar{u}+d\bar{d}$-content. With the effective Lagrangian L_s one can also approximate the total decay width by $\Gamma = \Gamma(gg) + \sum_q \Gamma(q\bar{q})$. If we take the ratio R to be known, the branching ratio $\mathrm{Br}(K\bar{K})$ can be expressed as a function of f_s/f_g or f_u/f_g. In Fig. 4 we show the branching ratio as a function of f_s/f_g for several different R. Reliable experimental data on the branching ratios can provide crucial information on the constituent contents in $f_0(1710)$.

Our results are different from those in [7]. In [7] it is assumed that the decay of G_s into two light mesons goes

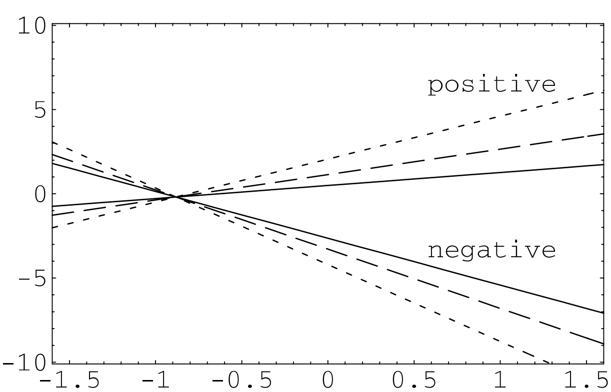

Fig. 3. The *solid*, *long-dashed*, and *short-dashed lines* are for f_s/f_g versus f_u/f_g with $R = 0.2$, 0.1, 0.05, respectively. *Lines* labeled 'positive' and 'negative' refer to the sign of $\mathcal{T}(\pi^+\pi^-)/\mathcal{T}(K^+K^-)$

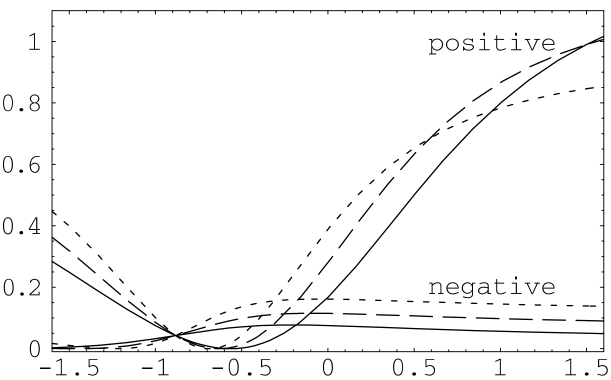

Fig. 4. The branching ratio of the decay into K^+K^- as a function of f_s/f_g with cut-off $\Lambda_c = 0.3$ GeV

like the following: G_s first decays into a $q\bar{q}$ pair and then the pair is hadronized into two light mesons. Because the decay amplitude into one $q\bar{q}$ pair is chirally suppressed, it can result in the chiral suppression at hadron level. The hadronization is a complicated process; one should not take directly the quark level picture. We have shown that if the glueball is light, the low-energy theorems tell us that there is no chiral suppression. For a heavy glueball, one can use pQCD to study its decay. In this case the two-quark decay picture is also problematic. In general one needs at least two $q\bar{q}$ pairs to form two light mesons. Perturbatively another $q\bar{q}$ pair can be produced, e.g., through emission of an extra gluon from the quark line in Fig. 1a and the gluon annihilates into the pair. In this case the decay amplitude into two $q\bar{q}$ pairs is not chirally suppressed.

Using the methods in previous discussions, the coupling of G_s to a proton–antiproton system can also be studied. The coupling is fixed at a certain level by the trace anomaly, the σ-term and the strange-quark content of proton. With this approximation we have considered the possibility if the enhancement in $J/\psi \to \gamma p\bar{p}$ at BES [29] is due to a glueball. We find that it is unlikely that the possible state $X(1876)$ causing the enhancement is a scalar glueball [29]. The coupling of a pseudoscalar glueball with $p\bar{p}$ can also be related to the spin content of the proton as an approximation [30]. A detailed analysis of the coupling to the $p\bar{p}$ system will be presented elsewhere.

In conclusion, we have studied several two-body decay modes of a scalar glueball. Without any assumption we have shown that a pure spin-0 glueball cannot decay into a $q\bar{q}$ pair in QCD if the chiral symmetry is exact. Hence the decay is chirally suppressed. However, this chiral suppression does not materialize itself at the hadron level such as in $G_s \to \pi^+\pi^-$ and $G_s \to K^+K^-$. This can be shown in the two cases with the glueball much lighter and much heavier than the QCD scale. One expects that the decay amplitude should not have drastic changes in between and therefore that the chiral suppression is unlikely materialized in some intermediate range of the glueball mass. Using QCD factorization based on an effective Lagrangian for scalar glueball coupling to two gluons and a quark pair, we have found that even if the decay amplitude is not chirally suppressed, only from the difference of hadronization into

$\pi\pi$ and KK, it already leads to a large difference between $\mathrm{Br}(\pi^+\pi^-)$ and $\mathrm{Br}(K^+K^-)$. The current experimental data of the small ratio $\mathrm{Br}(\pi^+\pi^-)/\mathrm{Br}(K^+K^-)$ for $f_0(1710)$ do not necessarily imply that $f_0(1710)$ is a pure glueball, but they also allow for a sizeable $q\bar{q}$ content. The gluon and quark contents of $f_0(1710)$ can be better understood if reliable $\mathrm{Br}(\pi^+\pi^-, K^+K^-)$ are measured.

Acknowledgements. We are grateful for helpful discussions with Profs. H.-Y. Cheng, X.D. Ji, H.Y. Jin, Y.P. Kuang and H.-N. Li. This work was supported in part by grants from NSC and NNSFC (10421003).

References

1. C. Morningstar, M.J. Peardon, Phys. Rev. D **56**, 3043 (1997)
2. C. Morningstar, M.J. Peardon, Phys. Rev. D **60**, 034 509 (1999)
3. C. Liu, Chin. Phys. Lett. **18**, 187 (2001)
4. C. Liu, Commun. Theor. Phys. **35**, 288 (2001)
5. Particle Data Group, S. Eidelman et al., Phys. Lett. B **592**, 1 (2004)
6. Particle Data Group, W.-M. Yao et al., J. Phys. G **33**, 1 (2006)
7. M.S. Chanowitz, Phys. Rev. Lett. **95**, 172 001 (2005) [hep-ph/0506125]
8. K.-T. Chao, X.-G. He, J.P. Ma, Phys. Rev. Lett. **98**, 149 103 (2007) [0704.1061 [hep-ph]]
9. S.J. Brodsky, G.P. Lepage, Phys. Rev. D **24**, 2848 (1981)
10. S.J. Brodsky, G.P. Lepage, Phys. Rev. D **22**, 2157 (1980)
11. Z.F. Zhang, H.Y. Jin, hep-ph/0511252
12. M.A. Shifman, Phys. Rep. **209**, 341 (1991)
13. X.D. Ji, Phys. Rev. Lett. **74**, 1071 (1995)
14. X.D. Ji, Phys. Rev. D **52**, 271 (1995)
15. J. Gunion, H. Habar, G. Kane, S. Dawson, The Higgs Hunter's Guide (Addison-Wesley, Reading, MA, 1990)
16. J. Donoghue, E. Golowich, B. Holstein, Dynamics of the Standard Model (Cambridge University Press, Cambridge, 1992)
17. X.-G. He, J. Tandean, G. Valencia, Phys. Lett. B **631**, 100 (2005) [hep-ph/0509041]
18. M. Chanowitz, Phys. Rev. Lett. **98**, 149 104 (2007)
19. V.M. Braun, I.B. Filyanov, Z. Phys. C **48**, 239 (1990)
20. P. Ball, JHEP **9901**, 010 (1999) [hep-ph/9812375]
21. P. Ball, M. Boglione, Phys. Rev. D **68**, 094 006 (2003) [hep-ph/0307337]
22. P. Ball, R. Zwicky, hep-ph/0510338
23. M. Beneke et al., Nucl. Phys. B **606**, 245 (2001)
24. Z.Z. Song, K.T. Chao, Phys. Lett. B **568**, 127 (2003) [hep-ph/0206253]
25. J.P. Ma, Z.G. Si, Phys. Rev. D **70**, 074 007 (2004) [hep-ph/0405111]
26. BES Collaboration, M. Ablikim et al., Phys. Lett. B **642**, 441 (2006)
27. F. Close, Q. Zhao, Phys. Rev. D **71**, 094 022 (2005)
28. S. Narison, hep-ph/0512256
29. BES Collaboration, J.Z. Bai et al., Phys. Rev. Lett. **91**, 022 001 (2003)
30. B.A. Li, Phys. Rev. D **74**, 034 019 (2006) [hep-ph/0510093]