Charmonium hadronic decays and the OZI rule violation effects

Qiang Zhao
Theory Division, Institute of High Energy Physics,
Chinese Academy of Sciences, Beijing 100049 P.R. China
and Department of Physics, University of Surrey, Guildford, GU2 7XH, United Kingdom

Received Day Month Year
Revised Day Month Year

We discuss the scalar meson mixing scenario and present an OZI rule violation mechanism for understanding the scalar productions in charmonium hadronic decays. We stress that the OZI violation could play a key role in disentangling the structure of the scalars: \( f_0(1370) \), \( f_0(1500) \) and \( f_0(1710) \).

Keywords: Glueball; \( J/\psi \) hadronic decay.

PACS numbers: 12.39.Mk, 13.30.Eg

1. About the scalars

The successful quark model classification for the pseudoscalar and vector nonet provides a natural reference for the expectation of masses of the scalar \( q\bar{q} \) nonet. Due to the orbital angular momentum excitation which combines the symmetric spin to form \( 0^{++} \), the quark model \( q\bar{q} \) nonet is expected to have masses heavier than their pseudoscalar and vector counterparts, i.e. above 1 GeV. In this sense, the existence of scalars below 1 GeV, i.e. \( \sigma(600) \) and \( f_0(980) \), is already a sign showing the non-trivial property of QCD. So far, more and more evidence suggests that \( \sigma(600) \), \( f_0(980) \), \( a_0(980) \) and \( \kappa(800) \) could be Jaffe’s four-quark nonet.\(^\text{[1]}\) Between 1~2 GeV, three scalars, \( f_0(1370) \), \( f_0(1500) \) and \( f_0(1710) \), were observed at DM2, MarkIII, WA102, Crystal Barrel.\(^\text{[2]}\) They were confirmed at BESII in \( J/\psi \) radiative and hadronic decays. Nonetheless, BES also reported signals of \( f_0(1790) \) in \( J/\psi \rightarrow \phi\pi\pi \) and \( f_0(1810) \) in \( J/\psi \rightarrow \gamma f_0(1810) \rightarrow \gamma\omega\phi \), which are different in decay modes. The over-crowded isospin-0 scalars thus bring difficulties to the interpretation and classification of the scalar spectrum and raise questions on the non-perturbative QCD dynamics.

In this proceeding, we will focus on \( f_0(1370) \), \( f_0(1500) \) and \( f_0(1710) \), for which more experimental information is available. An essential consideration is that the Lattice QCD predicts the lightest glueball to be \( 0^{++} \) with mass between 1.5~1.7 GeV.\(^\text{[3-5]}\) This makes the scalars in this energy region an natural candidate for the scalar glueball. However, due to possibly large glueball-\( q\bar{q} \) mixings, decisive evidence
is still unavailable. Recent data expose unexpected phenomena which could be a chance for us to gain deeper insights into this long-standing issue.

The systematic information from BES about these three states turned out to be out of expectations: i) $f_0(1370)$ which was seen in its strong decays into $\pi\pi$ and $4\pi$, and hence deduced to have a large $n\bar{n} \equiv (u\bar{u} + d\bar{d})/\sqrt{2}$, is found to be produced preferably via recoiling $\phi$ instead of $\omega$ in $J/\psi \rightarrow Vf_0$, where $V = \omega, \phi$; ii) $f_0(1710)$ which couples to $K\bar{K}$ strongly, is found produced preferably via recoiling $\omega$ instead of $\phi$. iii) $f_0(1500)$ is not directly seen in the invariant mass spectrum though it is needed in the partial wave analysis. The “scalar puzzle” arises from the OZI-rule expectation of the production of the scalars: it favors to occur via the singly OZI disconnected processes (SOZI) as illustrated by Fig. 1(a), while the doubly OZI disconnected process (DOZI, see Fig. 1(b)) should be strongly suppressed. In this sense, the puzzle also raises the question about the scalar production mechanism in $J/\psi$ hadronic decays. As follows, we will clarify the correlations between the scalar mixings and their production mechanisms. We will show that large OZI violations are expected in association with the scalars, and can be tested in experiment.

2. OZI-rule violation in charmonium hadronic decays

In Refs. [6, 7] a favor mixing scheme was proposed to accommodate those three scalars in a flavor-singlet basis of glueball and $q\bar{q}$. By fitting the data for $f_0 \rightarrow PP$, where $P$ stands for pseudoscalar mesons, a mixing pattern of the glueball and $q\bar{q}$ components is highlighted, and allows qualitative expectations of the scalar decays into other channels such as radiative and two-photon decays. In Ref. [8], an improved calculation for $f_0 \rightarrow PP$ is presented in association with the new data from $J/\psi \rightarrow Vf_0$ transitions [9]. It is found that $f_0(1370)$ has the largest $(u\bar{u} + d\bar{d})/\sqrt{2}$ component, while $f_0(1710)$ has the largest $s\bar{s}$. The glueball component in $f_0(1500)$ turns out to be the largest though it is also sizeable in $f_0(1710)$.

To be consistent with the $G-q\bar{q}$ mixing scheme, an essential question arising from
Charmonium hadronic decays and OZI rule violation effects

$J/\psi \rightarrow V f_0$, is on the role played by the DOZI processes. As shown in Ref. 8, a sizeable contribution from the OZI violation can explain the features observed in the production of those three scalars. Although the numerical results are qualitative, the interfering pattern among the SOZI and DOZI processes as a result of the $G$-$q\bar{q}$ mixings is rather stable. This naturally leads to the following concerns: i) What is the role played by the non-perturbative DOZI processes in $J/\psi \rightarrow V f_0$? ii) What is the correlation between the $G$-$q\bar{q}$ mixings and the DOZI processes in the scalar production?

Interestingly, the different considerations of the role played by the DOZI processes in $J/\psi$ hadronic decays seem to be one of the major divergences in different phenomenological approaches. To be specific, negligibly small DOZI contributions imply the dominance of pQCD transitions, and also small $G$-$q\bar{q}$ mixings. Based on this, a criteria pointed out by Carlson 10 and recently developed by Chanowitz 11 is the chiral suppression mechanism for $J = 0$ glueballs. Due to the fact that in pQCD the amplitude is proportional to the current quark mass in the final states, the $J = 0$ glueballs will have larger couplings into e.g. $K\bar{K}$ rather than $\pi\pi$. For $J \neq 0$, the decay amplitude is flavor symmetric. In association with the lattice QCD calculations, $f_0(1710)$ is thus proposed to be a glueball candidate. However, as pointed by Chao et al., the chiral suppression does not materialize itself in the hadronization process. Thus, the observation of relatively larger b.r. to $K\bar{K}$ for a candidate does not necessarily lead to its being a glueball 12, 13.

In contrast, the study of Isgur and Geiger by calculating hadronic loop contributions to meson propagators suggests that large OZI violations occur in the $0^{++}$ sector while systematic cancellations are found in other nonets 14. A general argument for the large OZI violations in $0^{++}$ is provided by Lipkin and Zou 15. QCD sum rule calculations also support large OZI-rule violations in the scalars 16, 17, 18. Unquenched lattice QCD calculations of the glueball spectrum should be crucial for clarifying the above two major scenarios.

In $J/\psi$ hadronic decays, some experimental evidence seems available for large OZI violation effects. The reaction, $J/\psi \rightarrow V f_0$, can occur via intermediate meson rescatterings, i.e. $J/\psi \rightarrow K^* K + c.c. \rightarrow V f_0$ and/or $J/\psi \rightarrow \rho \pi \rightarrow V f_0$. Since $J/\psi \rightarrow K^* K + c.c.$ and $J/\psi \rightarrow \rho \pi$ are two of the largest decay channels of $J/\psi$, the intermediate meson rescatterings as the dominant contributions to the DOZI processes may not be small. Theoretical study of such processes should be able to clarify the role played by the DOZI processes in $J/\psi \rightarrow V f_0$ and provide insights into the scalar structures.

### 3. Intermediate meson rescatterings

Following the meson exchange mechanisms, we calculate the meson loops in Fig. 2 as a leading contribution to the doubly disconnected process. The transition amplitude
can be written as

\[ M_{f1} = -i \int \frac{d^4 p_2}{(2\pi)^4} T_\nu^\beta \left( g_\nu \frac{p_1 \beta}{p_1^2} \right) T_0 \lambda T_a \frac{F(p_2)}{a_1 a_2 a_3} \delta^4(p_0 - p_v - P_s), \]  

where the vertex functions are

\[ T_\nu^\beta = ig_\nu \frac{\mu \nu \alpha \beta}{M_\nu} \rho_{\mu \nu} \epsilon_{f \nu} p_2 \alpha, \]
\[ T_\lambda = ig_0 \frac{\lambda \sigma \tau \delta}{M_0} \epsilon_{\sigma} \epsilon_{\tau} \epsilon_{\delta} p_3, \]
\[ T_0 = ig_s M_s, \]

and \( a_1 = p_1^2 + m_1^2 + i\epsilon, a_2 = p_2^2 - m_2^2 + i\epsilon, \) and \( a_3 = p_3^2 - m_3^2 + i\epsilon \) are the denominators of the meson propagators. The coupling constants \( g_\nu, g_s, \) and \( g_0 \) can be determined independently in meson decays. For the \( J/\psi \) hadronic decays, large branching ratios for \( J/\psi \to K^* \bar{K} + c.c. \) and \( \rho \pi + c.c. \) imply that the meson loop transitions may have significant contributions to those decays where the final state mesons have also large couplings to the exchanged mesons. This is indeed the case for \( J/\psi \to V f_0(1710) \), where the couplings for \( \phi K^* \bar{K}, \omega K^* K, \) and \( f_0(1710) K \bar{K} \) are significantly large. Therefore, this simple argument will allow us to consider only the dominant meson exchange loops in the calculations.

In the above equation, the coupling \( g_0 \) can be determined by the decays of \( J/\psi \to K^* \bar{K} + c.c. \) [Fig. 2(a) and (b)], or \( J/\psi \to \rho \pi + c.c. \) [Fig. 2(c)], of which large branching ratios are observed in experiment, e.g.

\[ g_0^2 = \frac{12\pi M_0^2}{|P_1|^3} \Gamma_{J/\psi \to V f_0} \]  

where \( \Gamma_{J/\psi \to K^* K + c.c.} = (9.2 \pm 0.8) \times 10^{-3} \) and \( \Gamma_{J/\psi \to \rho \pi + c.c.} = (1.27 \pm 0.09)\% \) are from the estimate of Particle Data Group [19].
For $f_0 \to K\bar{K}$ in the $f_0$ c.m. system, the coupling constant can be derived via $g_s^2 = 8\pi \Gamma_{f_0 \to K\bar{K}}^\text{exp}/|k|$, which is consistent with the studies of $f_0 \to PP$ in the determination of the mixing matrix elements\textsuperscript{8}, $|k|$ is the magnitude of the three momenta carried by the final-state kaon (anti-kaon). With the estimate of $b.r.f_0 \to K\bar{K} = 0.60\%$, and $\Gamma_T(1710) = 140$ MeV\textsuperscript{19}, we have $\Gamma_{f_0 \to K\bar{K}}^\text{exp} = 84$ MeV; the coupling $g_s$ can then be determined. We determine the $VPV$ couplings, i.e., $g_{\phi K^* K}$, $g_{\omega K^* K}$, and $g_{\omega\rho\pi}$, in the SU(3)-flavor-symmetry limit with $g_{\phi K^* K}^2 \rho_{\phi,0} \approx 84$ is determined in vector meson dominance (VMD) model in $\omega \to \pi^0 e^+ e^-$.\textsuperscript{19}

| Table 1. The intermediate meson exchange contributions to the decay of $J/\psi \to Vf_0 \to VPP$ with a dipole form factor. The data are from BES. |
|------------------|------------------|------------------|
|                  | $f_0(1710)$      | $f_0(1500)$      | $f_0(1370)$      |
| $b.r.(J/\psi \to \phi f_0)$ | 1.73             | 0.24             | 0.15             |
| $b.r.(J/\psi \to \phi f_0 \to \phi K\bar{K})$ | 1.04             | 0.02             | 0.00             |
| $b.r.(J/\psi \to \phi f_0 \to \phi K\bar{K})$ | (2.0 ± 0.7)      | (0.8 ± 0.5)      | (0.3 ± 0.3)      |
| $b.r.(J/\psi \to \omega f_0)$ | 1.43             | 0.19             | 0.11             |
| $b.r.(J/\psi \to \omega f_0 \to \omega K\bar{K})$ | 0.86             | 0.02             | 0.00             |
| $b.r.(J/\psi \to \omega f_0 \to \omega K\bar{K})$ | (13.2 ± 2.6)     | ...              | ...              |
| $b.r.(J/\psi \to \omega f_0)$ | 0.57             | 2.59             | 3.43             |
| $b.r.(J/\psi \to \omega f_0 \to \omega\pi\pi)$ | 0.04             | 0.90             | 0.69             |
| $b.r.(J/\psi \to \omega f_0 \to \omega\pi\pi)$ | ...              | ...              | ...              |

In Table\textsuperscript{11} the intermediate meson rescattering contributions to the branching ratios are listed. It shows some of those transitions play an important in $J/\psi \to Vf_0$, and can produce significant branching ratios compatible with the experimental data. This can be regarded as an instructive hint about the OZI violation effects in the $J/\psi$ hadronic decays.

The intermediate meson rescatterings can be compared with the “tree” diagram for $J/\psi \to V\bar{P} + c.c.$, e.g. $J/\psi \to K^* K + c.c.$ and $J/\psi \to \rho\pi + c.c.$ Since the $J/\psi V\bar{P}$ vertices are the same between the tree and loop transitions, the ratio between the intermediate meson rescattering loop and the tree process of $J/\psi \to V\bar{P} + c.c.$ will highlight the OZI violations in this dynamical process and can be related to the scalar flavor contents by measuring the following fraction\textsuperscript{20}

$$R_i^{OZI} = \frac{\Gamma_{J/\psi \to \phi f_0 \to \phi K\bar{K}}}{\Gamma_{J/\psi \to \omega f_0 \to \omega K\bar{K}}} = \frac{|p_{\phi i}| |x_i + y_i + \sqrt{2}z_i|^2}{|p_{\omega i}| 2[x_i + ry_i + \sqrt{2}z_i]^2},$$

where $x_i$, $y_i$, and $z_i$ are the mixing angles of $G$, $s\bar{s}$ and $(u\bar{u} + d\bar{d})/\sqrt{2}$ components for scalar $i$; Parameter $r$ denotes the relative strength between DOZI and SOZI transitions, which can be estimated by the ratio between the intermediate meson rescattering loop and the tree process. Since apart from the kinematic factors $|p_{\phi i}|$ and $|p_{\omega i}|$, the only energy-dependent factor in $R_i^{OZI}$ is $r$, one can thus measure
\( R^{OZI} \) in both \( J/\psi \to V f_0 \) and \( \Upsilon \to V f_0 \), where \( r \) is expected to change from a sizeable value in \( J/\psi \) decays to a smaller one in \( \Upsilon \) decays, to test the configuration of the scalars \(^{20}\).

4. Summary

In brief, we discussed a possible way to determine the scalar structures by clarifying the role played by the OZI-rule violation. The latter was correlated with the glueball-\( Q\bar{Q} \) mixings in \( J/\psi \to V f_i^0 \). Since the flavor wavefunctions for \( \omega \) and \( \phi \) are almost ideally mixed, the decay channels into \( \omega \) and \( \phi \) in association with the scalar mesons, respectively, serve as a flavor filter for probing the \( Q\bar{Q} \) contents of the scalars. This allows us to separate out the doubly OZI disconnected processes, of which the effects can be measured by the branching ratio fractions between \( \phi f_i^0 \) and \( \omega f_i^0 \), i.e. \( R^{OZI}_i \). Since the energy evolution of \( R^{OZI}_i \) is mostly determined by the energy evolution of the doubly disconnected processes relative to the singly disconnected ones, the suppression of the doubly disconnected process at higher energies, e.g. in \( \Upsilon \) decays, will lead to dramatic changes to \( R^{OZI}_i \) with certain patterns. Observation of such a change will provide direct information about the scalar meson structures.

Acknowledgement

The author thanks M. Chanowitz, K.T. Chao, L. Kisslinger, and K.F. Liu for many useful discussions. Collaborations with F.E. Close and B.S. Zou on relevant works are acknowledged.

References

1. R.L. Jaffe, Phys. Rev. D15, 267 (1977); ibid, D15, 281 (1977).
2. D.V. Bugg, Phys. Rept. 397, 257 (2004).
3. C. Morningstar and M. Peardon, Phys. Rev. D 56, 4043 (1997); Phys. Rev. D60, 034509 (1999).
4. G. Bali et al., UKQCD Collaboration, Phys. Lett. B 309, 378 (1993).
5. Y. Chen et al., Phys. Rev. D 73, 014516 (2005).
6. F.E. Close and C. Amsler, Phys. Lett. B 353, 385 (1995); Phys. Rev. D53, 295 (1996).
7. F.E. Close and A. Kirk, Phys. Lett. B 483, 345 (2000).
8. F.E. Close and Q. Zhao, Phys. Rev. D 71, 094022 (2005).
9. M. Ablikim et al. [BES Collaboration], Phys. Lett. B 607, 243 (2005); Phys. Lett. B 603, 138 (2004).
10. C. E. Carlson, J. J. Coyne, P. M. Fishbane, F. Gross and S. Meshkov, Phys. Lett. B 99, 353 (1981).
11. M. Chanowitz, Phys. Rev. Lett. 95, 172001 (2005) \[arXiv:hep-ph/0506125\].
12. K. T. Chao, X. G. He and J. P. Ma, \[arXiv:hep-ph/0512327\].
13. Z. F. Zhang and H. Y. Jin, \[arXiv:hep-ph/0511252\].
14. P. Geiger and N. Isgur, Phys. Rev. D 47, 5050 (1993).
15. H.J. Lipkin and B.S. Zou, Phys. Rev. D 53, 6693 (1996).
16. L.S. Kisslinger, J. Gardner and C. Vanderstraeten, Phys. Lett. B 410, 1 (1997).
17. F. Giacosa, T. Gutsche, V. E. Lyubovitskij and A. Faessler, Phys. Rev. D 72, 094006 (2005) [arXiv:hep-ph/0509247].
18. S. Narison, Phys. Rev. D 73, 114024 (2006).
19. S. Eidelman et al. (Particle Data Group), Phys. Lett. B 592, 1 (2004).
20. Q. Zhao, B.S. Zou and Z.B. Ma, Phys. Lett. B 631, 22 (2005).