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GLUEBALL SPECTROSCOPY*

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The main features of the glueball spectrum is discussed.

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1. Introduction

The gluon is the fundamental particle of Yang–Mills theories. Quantum Chromodynamics (QCD) predicts the existence of purely gluonic bound states, the glueballs [1]. We review briefly here the properties of such states in Yang–Mills theories and their mixing with quarks in QCD.

2. Glueballs in Yang–Mills theories

The spectrum of pure gauge theories was investigated from various points of view [1]. The spectrum of low-lying glueballs was obtained by Morningstar and Peardon from a lattice study [2]. They restricted their study to low dimensional gluonic operators and states below four GeV. Although they did not draw any definitive conclusion concerning a 1^{++} state, they found a clear signal for a vector state but above the two-glueball molecule threshold.

It has been argued that no two-glueball vector state exists in agreement with Yang's theorem. This idea deserves clarification. A vector does exist for non-Abelian gauge group and appears in the decomposition of the tensor built out of two gluon field strength $G^a_{\mu\nu} D_\delta G^a_{\alpha\beta}$ [3]. This is not in contradiction with Yang's theorem saying that a vector meson cannot decay into two massless vector particles. One has just to keep in mind that (the non-Abelian part of) $G^a_{\mu\nu}$ involves more than one gluon operators. At the level

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of constituent model, it is not possible to construct of vector wave function out of two transverse gluons [4] and indeed the vector signal found in the lattice study [2] is a mass gap above the two-gluon glueballs.

Constituent models teach us that only two gluonic degrees of freedom are required by each gluon in the wave function to reproduce properly the lattice spectrum [4]. We learn also from this technique that instanton contributions play an important role in scalar and pseudoscalar correlators. This is supported by Forkel's analysis using QCD spectral sum rules [5]. Another support for the massive gluon propagator and the instanton importance for scalar operators comes by the recent analysis of Dudal *et al.* [6]. Using a massive gluon propagators fitted from lattice calculations, they computed the one loop gluonic operators for the lowest states (no instantons contributions included). After some subtractions, they found masses in perfect agreement with constituent models

$$M_{0^{++}} = 1.96 \text{ GeV}\,, \qquad M_{0^{-+}} = 2.19 \text{ GeV}\,. \tag{1}$$

Moreover, this is a clear indication that the fully dressed propagator can play the role of the condensates in the operator product expansion.

3. Scalar mesons

Three isoscalars would have been observed in central production [7]:

$$f_0(1370)\,, \qquad f_0(1500)\,, \qquad f_0(1710)\,. \tag{2}$$

Although no definitive conclusion about their existence can be drawn [7], three isoscalars would imply a mixing between the two conventional isoscalar $\bar{q}q$ and $\bar{s}s$ with a glueball (gg). We call mesons with a large glue content, *gluonic mesons*. With the discovery of the $f_0(1500)$, Close interpreted it as a glueball candidate and predict a third isoscalar gluonic meson to be discovered later on. With the discovery of the $f_0(1710)$ coupling stronger to $K\bar{K}$ than to $\pi\pi$, Close and Kirk proposed a mixing scheme, Fig. 1 (right), where the glueball is shared between the three isoscalars [8]. In this interpretation, the heaviest state is mainly a $\bar{s}s$ meson due to its coupling to $K\bar{K}$.

Fig. 1. Mixing schemes for isoscalar mesons from Cheng *et al.* [9] (left) and from Close and Kirk [8] (right); black (blue): $\bar{q}q$, dark grey (red): $\bar{s}s$, light grey (green): gg.

However, Chanowitz showed that the scalar glueball couples to $\bar{q}q$ with a strength proportional to the quark mass [10]. Using this chiral suppression argument and lattice inputs for the bare masses, Cheng *et al.* proposed another scheme, Fig. 1 (left), where the $f_0(1710)$ is mainly the glueball [9].

The situation is even more obscure in view of B factories (Belle and Babar) results [7]: The invariant K^+K^- mass shows a peak around 1500 MeV denoted with mass and width consistent with the standard $f_0(1500)$ state. An observation of $f_0(1500) \to K^+K^-$, but no signal in the decay to $\pi^+\pi^-$ is inconsistent with the standard $f_0(1500)$, which is expected to couple more strongly to the two-pion decay.

4. Pseudoscalar mesons

The first pseudoscalar glueball candidate was observed in J/ψ radiative decays by the Mark III Collaboration [7]. Actually, they observed two resonances denoted $\eta(1405)$ and $\eta(1475)$. Only the latter was observed in $\gamma\gamma$ fusion, leading to a possible large glue content in the former. The actual interpretation favours η and η' radial excitations for $\eta(1295)$ and $\eta(1475)$ and leave $\eta(1405)$ as the glueball candidate.

In addition to a pseudoscalar gluonic meson candidate, we have indication of a possible large glue content in the η' wave function. J/ψ radiative decay is a gluon rich environment and the experimental branching ratio shows a large coupling for the η'

$$\frac{\Gamma(J/\psi \to \eta'\gamma)}{\Gamma(J/\psi \to \eta\gamma)} = \left(\frac{\langle 0|G\tilde{G}|\eta'\rangle}{\langle 0|G\tilde{G}|\eta\rangle}\right)^2 \left(\frac{M^2_{J/\psi} - M^2_{\eta'}}{M^2_{J/\psi} - M^2_{\eta}}\right)^3 = 4.81 \pm 0.77\,. \qquad (3)$$

It could be, therefore, interesting to have a theoretical framework to study the mixing between the group theoretical states η_0 and η_8, and the pseudoscalar glueball η_g. The chiral Lagrangian in the large-N provides such tools. The singlet η_0 is included in the non linear parametrization for the Goldstone bosons $U = \exp\left(i\sqrt{2}\pi/f\right)$ with $\pi = \pi^a\lambda_a$ ($\lambda_0 \equiv \mathbf{1}_3/\sqrt{3}$) and, at each order in p^2, only the leading term in N is kept.

In order to investigate the mixing with glue, one has to couple it to Goldstone bosons. Such a coupling is provided by the anomaly since the anomalous operator $\tilde{G}_{\mu\nu}G^{\mu\nu}$ interpolates the pseudoscalar glueball. At the effective level, we add a kinetic term and a mass term for η_g coupled to η_0 *via* the anomaly [11,12] and we obtain at leading order

$$\begin{aligned}\mathcal{L}^{(p^2)} &= \frac{f^2}{8}\left\langle \partial_\mu U^\dagger \partial^\mu U + B\left(mU^\dagger + Um^\dagger\right)\right\rangle \\ &\quad -\frac{\alpha}{2}(\eta_0 + k\eta_g)^2 - \frac{1}{2}m^2_\theta \eta^2_g + \frac{1}{2}\partial_\mu\eta_g\partial^\mu\eta_g\,. \end{aligned} \qquad (4)$$

In the large-N approximation, the flavour basis is preferred [13] and the mass matrix reads in this basis

$$\mathcal{M}^2_{qsg} = \begin{pmatrix} m_\pi^2 + 2\alpha & \sqrt{2}\alpha & \sqrt{2}\beta \\ \sqrt{2}\alpha & 2m_K^2 - m_\pi^2 + \alpha & \beta \\ \sqrt{2}\beta & \beta & \gamma \end{pmatrix} . \tag{5}$$

This matrix can be diagonalized in terms of three physical masses [12]. Adding the leading order interacting Lagrangian for electromagnetic decays and J/ψ decays (ψ^α is the J/ψ field, Q the charge matrix, V the vector meson — the free Lagrangian for vector mesons is understood, $F_{\mu\nu}$ is field strength for the photon and $\alpha = 1/137$),

$$\begin{aligned} \mathcal{L}_\gamma &= g_\gamma \epsilon_{\alpha\beta\mu\nu} F^{\alpha\beta} \partial^\mu \left\langle Q(V^\nu\pi + \pi V^\nu)\right\rangle + g_\psi \epsilon_{\alpha\beta\mu\nu} \partial^\alpha \psi^\beta \partial^\mu \left\langle V^\nu \pi \right\rangle \\ &\quad - \frac{N\alpha}{4\pi} F_{\mu\nu} \tilde{F}^{\mu\nu} \left\langle Q^2 U \right\rangle , \end{aligned} \tag{6}$$

we can now test our framework on various processes (details have to be presented elsewhere [14]). We have only three free parameters that can equivalently be the three low energy constants (α, β, γ), the three mixing angles $(\theta, \varphi_G, \varphi)$ or, our choice, the three physical masses $(M_\eta, M_{\eta'}, M_{\eta''})$. Once one of the set of three parameters is given, branching ratios for various decays follow. Since we perform a leading order analysis, we would like to reproduce the two well-known η and η' up to 10%. A possible choice for the parameters lying in this range is

$$M_\eta = 530 \text{ MeV} , \qquad M_{\eta'} = 1030 \text{ MeV} . \tag{7}$$

The mass of the hypothetical third partner η'' is left undetermined. Surprisingly, we find an overall agreement for all decays (except the $J/\psi \to \omega\eta(')$ problematic even in the absence of glue) for $M_{\eta''} = 1400$–1500 MeV, see Fig. 2 for electromagnetic transitions and Fig. 3 for $J/\psi \to PV$ processes.

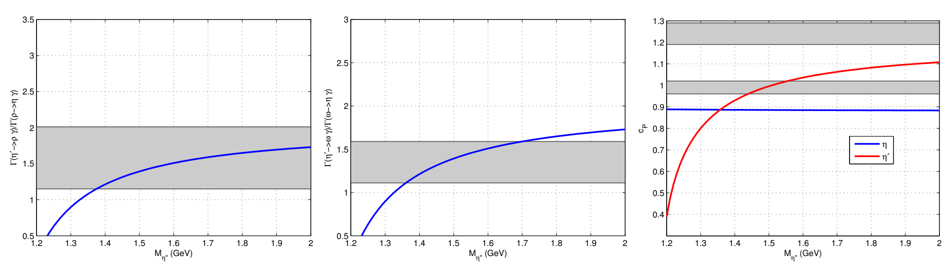

Fig. 2. Electromagnetic transitions and two photons decays.

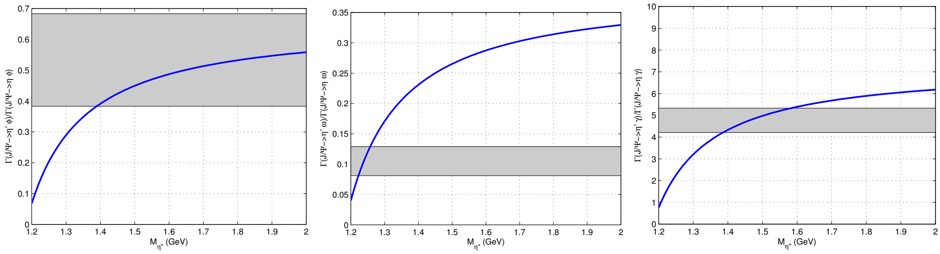

Fig. 3. J/ψ decays involving η and η' mesons.

This constatation encourages us to consider the possibility that our η'' is actually the $\eta(1405)$. This possibilities is strengthened by the process $J/\psi \to \eta''\gamma$ showed in Fig. 4. Nevertheless, the lack of data for other processes involving $\eta(1405)$ forbids us to draw definitive conclusion. However, it is still possible to predict branching ratios and hope they will be measure in the near future. Examples for decays involving ϕ and η'' is also displayed in Fig. 4.

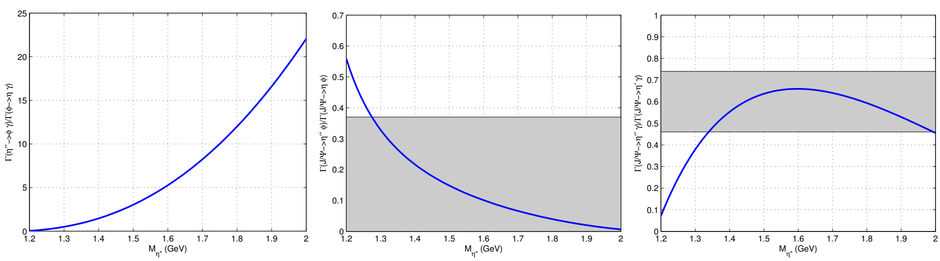

Fig. 4. Decays involving η''.

5. Conclusion

The present experimental and theoretical status of the glueball are still ambiguous. Although three isoscalars seem to be observed, no definitive conclusion can be drawn concerning the quark and glue content of those states. In the pseudoscalar sector, however, the situation is a little bit clearer with two well-established states η and η' and a glueball candidate $\eta(1405)$.

We presented a model based in the chiral Lagrangian to described the η–η'-glue system. Preliminary result favours $\eta(1405)$ to be the glueball partner of η and η'. Predictions are given for various processes involving this η''. The few data available supports the $\eta(1405)$ interpretation for our η'' and we hope that future measurements will confirm (or infirm!) our theoretical framework.

We hope that the analysis of data from Alice and Compass experiments at CERN, as well as the forthcoming Panda experiment [15], will shed some light on the experimental status of glueballs.

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