

The identification of glueballs - further tests

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The indirect evidence for gluonic objects in gluon jets is recalled, more accurate tests at the LHC are possible. Estimates of gluonic and quarkonic components of scalar mesons are presented, which could be improved by further studies, in particular of B and B_s decays. The results are consistent with the scalar glueball mixing into $f_0(500)$ and $f_0(1500)$. The study of symmetry relations for 2-body decay rates of charmonium χ_c is suggested as crucial test in the identification of $q\bar{q}$ multiplets and glueballs. Further related results are discussed in the recent review [1].

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1. QCD expectations for glueballs

The identification of glueballs remains a challenge in meson spectroscopy ever since they have been discussed within QCD as bound states of the self-interacting gluons [2]. Today, on the theory side, lattice QCD aims at predictions from basic principles. There are converging results within the theory of gluons only (“quenched”) of a spectrum of gg bound states, “gluonium”, with the lightest state being a scalar $J^{PC} = 0^{++}$ of mass 1500 – 1700 MeV. In full QCD the gluonium state can mix with $q\bar{q}$ states. For the lightest scalar flavour singlet state there are conflicting results: most recently the full (“unquenched”) calculation yields comparable results to the purely gluonic calculation [3] while earlier studies suggested the lightest states are of mass around 1000 and 1500 MeV and they are mixed from $q\bar{q}$ and gg components [4].

An alternative path to spectroscopy is based on QCD sum rules which include some phenomenological parameters. Already long ago the lightest gluonium states have been located near 1000 MeV and 1500 MeV [5]. A more recent analysis finds that the states at these two masses should be viewed as mixtures of $q\bar{q}$ and gg components [6].

A commonly accepted view of these QCD results is still missing.

2. Indications of glueball production in gluon jets

While there is a clear evidence for glueballs in the theory of gluons, the evidence on the experimental side is still controversial; in particular, there are very different interpretations of the scalar meson spectrum. However, there is a remarkable effect which strongly points towards the existence of gluonic objects. In a well known phenomenology of “quark fragmentation” the most energetic hadrons are those which carry a valence quark in common with the initial quark of the jet, for example, the π^+ in a u -quark jet. In analogy one can hypothesize that glueballs are the leading objects in a gluon jet, an idea with a long history [7]. As a practical tool one may isolate leading clusters in jets by a rapidity gap: while in quark jets the charge of the leading $q\bar{q}$ object is $Q_q = 0, \pm 1$ the corresponding charge of (gg) in a gluon jet should be $Q_g = 0$ [8]. Remarkably, all the studies at LEP by the experiments ALEPH, DELPHI and OPAL [9] have shown consistently, that the “standard” Monte Carlo JETSET without glueballs included is able to reproduce the charge properties of quark jets but failed to describe the charge distribution of leading clusters in gluon jets: there was an excess of neutral charge Q_g . An example is shown in figure 1 for the ALEPH Collaboration with an excess at $Q_g = 0$ of about 40%. Such an effect is just what is expected for glueballs, so we take these observations as an indirect evidence for gluonic objects. Alternatively, the MC program has modeled the gluon jet incorrectly.

In any case it would be desirable to clarify this issue at the LHC [8, 1]. Here the higher jet energy allows for larger rapidity gaps and there is a high production rate of gluon jets to be compared with quark jets. Alternatively, one may compare the Feynman x -distribution of a resonance with composition in doubt (example $f_0(1500)$) with a known “test state” (examples $\rho(770)$, $f_2(1270)$, $\phi(1020)$). In a quark u, d jet the leading ρ would be “harder” than a glueball, whereas in a gluon jet the behaviour should be opposite.

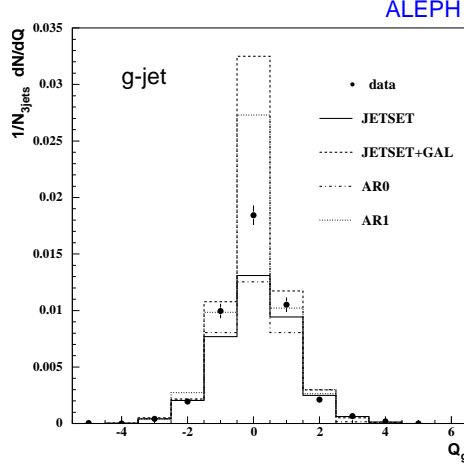


Figure 1: Distribution of the charge Q_g of the leading cluster in a gluon jet beyond a rapidity gap $\Delta y = 1.5$ showing a surplus of events at $Q_g = 0$ over the JETSET Monte Carlo prediction (full line) by 40%.

3. Scalar meson spectroscopy with glueballs

Most searches for glueballs have concentrated on the scalar sector as the lightest glueball is a scalar according to QCD. A scalar glueball could mix into the following states listed in [10]

$$f_0(500), f_0(980), f_0(1370), f_0(1500), f_0(1710) \dots \quad (3.1)$$

and there are various such mixing schemes. According to an early suggestion the heaviest three states in (3.1) are mixed from the two members of a $q\bar{q}$ nonet and a glueball centered around 1500 MeV [11]. Then there could be another nonet including the two f_0 states below 1 GeV together with $a_0(980)$ and the $K_0^*(900)/\kappa$ particle. A problem here is with $f_0(1370)$ whose existence is in doubt as there is no evidence found in the uniquely identified energy-independent phase shift solutions (for a recent review of the studied channels, see [1]); also the situation with κ is difficult to clarify [10, 1]. According to another suggestion the $q\bar{q}$ nonet includes $f_0(980)$ and $f_0(1500)$ while the broad $f_0(500)$ with “Breit-Wigner mass” $m_{BW} \sim 1000$ MeV, where the phase shifts pass 90° , is related to the glueball [12], related works in [5, 13, 14].

In [1] an attempt has been made to determine the gluonic component as given by the gluonic mixing angle ϕ_G and the flavour mixing angle ϕ_{sc} of scalars from experimental data, for example

$$|f_0(1500)\rangle = \cos \phi_G |q\bar{q}\rangle + \sin \phi_G |gg\rangle; \quad |q\bar{q}\rangle = \cos \phi_{sc} |n\bar{n}\rangle - \sin \phi_{sc} |s\bar{s}\rangle. \quad (3.2)$$

The following results have been obtained:

- $f_0(980)$: the scalar mixing angle (defined as in [1]) is found as $\phi_{sc} = (30 \pm 3)^\circ$ (similar to η' with $\phi_{ps} \sim 42^\circ$) from $\pi\pi \rightarrow \pi\pi/K\bar{K}$; $J/\psi \rightarrow (\omega/\phi)\pi\pi, D_s \rightarrow 3\pi, \gamma\gamma \rightarrow f_0(980)/a_0(980)$; there is no definitive evidence for a gluonic contribution ($\cos^2 \phi_G \approx 0.75 \pm 0.25$).
- $f_0(500)$: couplings $r_{K\pi} \equiv g_{K\bar{K}}^2/g_{\pi\pi}^2 = 0.3 - 0.6$ and $r_{\eta\pi} \equiv g_{\eta\eta}^2/g_{\pi\pi}^2 \sim 0.2$ based on model fits to $\pi\pi \rightarrow \pi\pi/K\bar{K}/4\pi/\eta\eta$ amplitudes [15, 16] suggest this state to be neither pure glue ($r_{K\pi} = 4/3$) nor pure nonstrange $qq\bar{q}\bar{q}$ ($r_{K\pi} = 0$).

- $f_0(1500)$: the 2-body branching ratios in [10] do not fix ϕ_{sc} ; given ϕ_{sc} the gluon component $r_G = r_G^0 \tan \phi_G$ is fixed where $r_G^0 = G_0/g_0$ refers to decay couplings G_0 , g_0 of (gg) and $(q\bar{q})$.

In a minimal mixing scheme [1] one assumes $f_0(980)$ without glue and with $\phi_{sc} = 30^\circ$, the glueball is mixed into $f_0(1500)$ and $f_0(500)$ with

$$|f_0(500)\rangle = \sin \phi_G |q\bar{q}\rangle - \cos \phi_G |gg\rangle; \quad |q\bar{q}\rangle = \cos \phi_{sc} |n\bar{n}\rangle - \sin \phi_{sc} |s\bar{s}\rangle. \quad (3.3)$$

With the above experimental results for $f_0(500)$ and $f_0(1500)$ we obtain

$$\phi_G \sim 50^\circ, \quad r_G^0 \approx 0.5 \quad (3.4)$$

i.e. a strongly mixed system. Note that for $\phi_G = 0$ we recover the model [12], while the composition of $f_0(1500)$ is similar to the model [11] but with a different $q\bar{q}$ multiplet. An interesting aspect of this mixing scheme is the compatibility with certain results obtained from lattice QCD and from QCD sum rules (see section 1).

Further tests on the flavour composition are possible from the decays $B \rightarrow J/\psi f_0$ and $B_s \rightarrow J/\psi f_0$ which allow for an isolation of the $d\bar{d}$ and the $s\bar{s}$ components of f_0 respectively. From B_s decays using equations (3.2, 3.3) one can obtain the ratio of the $s\bar{s}$ components as

$$r_{f_0'/f_0}^s = \frac{p^3 B(\bar{B}_s^0 \rightarrow J/\psi f_0(1500))}{(p')^3 B(\bar{B}_s^0 \rightarrow J/\psi f_0(980))}, \quad r_{f_0'/f_0}^s = \cos^2 \phi_G^{f_0'} \tan^2 \phi_{sc} \quad (3.5)$$

with $p(p')$ the respective momenta in the B_s cms. The LHCb results for $f_0 \rightarrow \pi\pi$ [17] yield two solutions of the phase shift analysis, from the recent data on the $f_0 \rightarrow K^+K^-$ decay mode [18] we conclude that the "alternate solution" is preferred with $r_{f_0'/f_0}^s = 0.15 \pm 0.05$; this supersedes our choice in [1]. Then we derive from (3.5) using $\phi_{sc} = 30^\circ$ the gluonic mixing angle $\phi_G^{f_0'} = 48^\circ \pm 10^\circ$ in good agreement with our result above in (3.4).

The flavour mixing angle ϕ_{sc} for a particular f_0 meson can be derived from the ratio of the $J/\psi f_0$ decays of B and B_s [1]. First indications of a $f_0(1500)$ signal in B_d decays become visible [19]. A measurement of these ratios for the light scalars f_0 would greatly advance our understanding of this sector. Note that $f_0(500)$ in our view is to be represented in a phase shift analysis as broad object centered at $m_{BW} \sim 1000$ MeV [12, 1].

4. Nonets and glueballs from symmetry relations

Another area of promising research are the decay rates of charmonia (or bottomonia). In the decay $\chi_c \rightarrow gg$ the pairs of hadrons from the same $q\bar{q}$ multiplet form a flavour singlet state. For pairs of pseudoscalars one expects for the phase space corrected decay rates

$$\gamma_{ij}^2(\chi_c \rightarrow \pi\pi : K\bar{K} : \eta\eta : \eta\eta' : \eta'\eta') = 3 : 4 : 1 : 0 : 1 \quad (4.1)$$

reflecting the $SU(3)_{fl}$ symmetry. These relations work rather well for decays of $\chi_{c0}(0^{++})$ and $\chi_{c2}(0^{++})$ within 10-20% [1]. Correspondingly, one may test this symmetry for decays into members of other multiplets, in particular of the scalar multiplet. The relations in analogy to (4.1) are expected to fail if the wrong members of the multiplet are chosen, furthermore, deviations are

expected for the isoscalar members in the presence of glueballs. The PDG results [10] (based on BES-II [20]) yield the ratio of decay rates after correction for phase space q and charge weight c

$$r_{f_0/K^*}^{\chi_{c0}} \equiv \frac{B(\chi_{c0}(3415) \rightarrow f_0(980)f_0(980))/(cq)}{B(\chi_{c0}(3415) \rightarrow K_0^*(1430)\bar{K}_0^*(1430))/(c'q')}, \quad r_{f_0/K^*}^{\chi_{c0}} = 1.64 \pm 0.73 \quad (4.2)$$

which is consistent with symmetry ($r_{f_0/K^*}^{\chi_{c0}} = 1$) and so with $f_0(980)$ and $K_0^*(1430)$ being in the same $q\bar{q}$ nonet [13, 12]. Higher accuracy and measurements of relations to other scalars like $a_0(980)$, $f_0(1500)$ and also to $f_0(500)$, $K_0^*(900)/\kappa$ could be decisive. The results also prefer $f_0(980)$ to be a $(q\bar{q})$ rather than a $(qq\bar{q}\bar{q})$ state according to [1] from a comparison with $p\bar{p}$ data.

5. Summary

QCD predicts the existence of glueballs; mass and mixing properties of the scalar glueball need further clarification. Experimental hints for glueballs come from the excess of neutral clusters in gluon jets. The intrinsic quark-gluon structure of mesons is accessible experimentally; the role of B , B_s data is stressed. Tests of symmetry relations for χ_c decays help identifying $q\bar{q}$ nonets.

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