Lightest glueball and scalar meson nonet
in production and decay†

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Abstract
Recent results concerning the evidence and classification of the $J^{PC} = 0^{++}$ states, obtained with P. Minkowski, are presented: The isoscalars $f_0(980)$ and $f_0(1500)$ are classified as members of the $0^{++}$ nonet, while the broad state called $f_0(400−1200)$ and the state $f_0(1370)$ are considered as different components of a single broad resonance, the lowest-lying $0^{++}$ glueball. Furthermore, we propose the investigation of glueball production in the fragmentation region of gluon jets.

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1. Introduction
A longstanding problem in hadron spectroscopy is the existence of gluonic mesons or “glueballs”. Despite many experimental efforts not a single such state is generally accepted in the community until now.

On the theoretical side the existence of such states is considered a necessary consequence of the QCD dynamics [1] and in most considerations it is concluded that the state of lowest mass should have the quantum numbers $J^{PC} = 0^{++}$.

Some convergence of the numerical results from lattice QCD has been reached in recent years in the application of the quenched approximation, i.e. neglecting fermion loops, with mass values for the $0^{++}$ glueball in the range 1600-1700 MeV (for a recent review, see Teper [2]). This prediction has also influenced the experimental searches in the last years. On the other hand, recent lattice calculations which include two light quark flavors [3] suggest the glueball mass to decrease with the quark mass; the ultimate conclusion from this approach has therefore to await the final results from the unquenched calculations.

An alternative approach to the properties of hadrons are the QCD sum rules [4]. In a recent application by Narison [5] it was found impossible to saturate the relevant sum rules with a single $0^{++}$ glueball at a mass around 1500 MeV alone. Rather, the inclusion of a light gluonic component in the mass region around 1 GeV was required. The role of a light glueball in the saturation of the QCD sum rules was already pointed out some years ago by Bagan and Steele [6].

In view of this situation we have reconsidered the spectroscopy of the light $0^{++}$ hadrons and we do not exclude the states below 1500 MeV as candidates for the lightest glueball or for a state with large gluonic admixture [7].

2. Evidence for light scalar isoscalar states
The Particle Data Group (PDG [8]) lists the following states below 1600 MeV mass: $f_0(400−1200)$, $f_0(980)$, $f_0(1370)$ and $f_0(1500)$. To establish the resonance it is important to observe the characteristic variation of the scattering amplitude: it moves locally around a circle in the complex plane. In elastic and inelastic 2-body scattering additional constraints are provided by unitarity.

Therefore, we have concentrated on the appearence of the above states in $\pi\pi$ scattering processes into final states $\pi\pi$, $K\bar{K}$, $\eta\eta$ which can be obtained from the analysis of peripheral pion exchange processes.

There is no controversy about the existence of the narrow $f_0(980)$ which appears as a dip in the elastic $\pi\pi$ cross section. The construction of the scattering amplitudes for $\pi\pi \rightarrow K\bar{K}$, $\eta\eta$ in the complex plane (“Argand diagram”) reveals in both channels a Breit-Wigner resonance centered around 1500 MeV above a slowly moving background with negative ($K\bar{K}$) or positive sign ($\eta\eta$) relative to $f_2(1270)$, see Fig. 1. These amplitudes correspond to mass spectra which produce peaks around 1300-1400 MeV in the $K\bar{K}$ and 1600 MeV in the $\eta\eta$ channels. Only the state $f_0(1500)$ associated with
the full circle is considered a genuine resonance; the other structures, especially the \( f_0(1370) \) we take -together with the \( f_0(400 - 1200) \) - as components of a single broad state which extends from 400 up to 1500 MeV or beyond and only in this large mass interval the elastic \( \pi\pi \) amplitude describes a full circle as required for a Breit Wigner resonance. The mass and width of this state is estimated as

\[
m \sim 1000 \text{ MeV}, \quad \Gamma \sim 1000 \text{ MeV}
\]

(1)

3. The \( 0^{++} \) \( q\bar{q} \) nonet

As members of the nonet we take the isoscalars \( f_0(980) \) and \( f_0(1500) \), in addition the isovector \( a_0(980) \) and the strange \( K^*(1430) \). The mixing pattern is close to the one found in the pseudoscalar sector with flavour amplitudes \( \{u\bar{u}, d\bar{d}, s\bar{s}\} \):

\[
\begin{align*}
f_0(980) &\leftrightarrow \eta'(958) \sim \frac{1}{\sqrt{2}}(1, 1, 2) \\
f_0(1500) &\leftrightarrow \eta(547) \sim \frac{1}{\sqrt{3}}(1, 1, -1)
\end{align*}
\]

(2)

i.e. the \( f_0(980) \) is near the singlet, the \( f_0(1500) \) is near the octet state. This classification has been suggested and is supported by the following observations:

1. \( J/\psi \rightarrow \omega, \varphi + X \) decays

The branching ratios of \( J/\psi \) into \( \varphi, \eta' \) and \( \varphi, \eta \) of similar size and about twice as large as \( \omega, \eta' \) and \( \omega, \eta \). These observations are reproduced by the flavor composition (2).

2. Two body decays of \( f_0 \) states

Given the flavor composition (2), we can derive the decay amplitudes for \( f_0(980) \rightarrow \pi\pi, K\bar{K} \), as well as for \( f_0(1500) \rightarrow \pi\pi, K\bar{K}, \eta\eta, \eta'\eta' \). The available data are reasonably well reproduced if we allow for a \( s\bar{s} \) relative amplitude in the range \( S = 0.5 \ldots 1.0 \). The decays \( f_0(980) \rightarrow \gamma\gamma \) and \( a_0(980) \rightarrow \gamma\gamma \) are important but not yet very decisive.

3. Relative signs of decay amplitudes

A striking prediction is the relative sign of the decay amplitudes of the \( f_0(1500) \) into pairs of pseudoscalars: because of the negative sign in the \( s\bar{s} \) component, see eq. (2), the sign of the \( K\bar{K} \) decay amplitude is negative with respect to \( \eta\eta \) decay and also to the respective \( f_2(1270) \) and glueball decay amplitudes. This prediction is indeed confirmed by the amplitudes in Fig.1 which show circles pointing in upward and downward directions, respectively. If \( f_0(1500) \) were a glueball, then both circles should have the same sign, but the experimental results are rather orthogonal to such an expectation.

4. The lightest \( 0^{++} \) glueball

The remaining states in the PDG tables, the \( f_0(400 - 1200) \) and \( f_0(1370) \), are not accepted as distinct Breit-Wigner resonances because of a lack of sufficient phase variation of the amplitude. Rather, they are considered as two components of a yet broader state with parameters (3) which also has an inelastic coupling, visible as slowly moving “background” in the reactions shown in Fig.1. It is our hypothesis that this broad state is the lightest glueball \( gb(1000) \). A mixing with the nonet states is not excluded but it is expected to be sufficiently small such that the structures outlined before are not destroyed. The following observations support the identification of this state with the glueball:

1. Reactions favorable for glueball production

The broad object \( gb(1000) \) is observed in the “gluon rich” processes: the central production in hadron-hadron collisions which are expected to
proceed through double-Pomeron exchange; in the
decays of radially excited Onia \( \psi' \to \psi(\pi\pi) \) and
\( Y', Y'' \to Y(\pi\pi) \), which are expected to proceed
gthrough gluonic exchanges. On the other hand, no
prominent signal is observed in the radiative \( J/\psi \)
decays as expected, but the statistics is rather low.

2. Suppression in \( \gamma\gamma \) collisions

If the mixing of the glueball with charged particles
is small it should be weakly produced in \( \gamma\gamma \) collisions.
In the process \( \gamma\gamma \to \pi^0\pi^0 \) there is a dominant peak
related to \( f_2(1270) \) but, in comparison to elastic \( \pi\pi \)
scattering, a very small cross section in the low mass
region around 600 MeV. In a fit to the data which
takes into account the one-pion-exchange Born
terms and \( \pi\pi \) rescattering Boglione and Pennington
have determined the two photon width of the
states \( f_2(1270) \) and \( f_0(400-1200) \) as \( 2.84\pm0.35 \) and
\( 3.8\pm1.5 \) keV, respectively. If the \( f_0 \) were a light
quark state like the \( f_2 \) we might expect comparable
ratios of \( \gamma\gamma \) and \( \pi\pi \) decay widths \( R(f) = \Gamma(f \to \gamma\gamma)/\Gamma(f \to \pi\pi) \),
but we find
\[
R(f_2) \sim 15 \times 10^{-6}; \quad R(f_0) \sim 4 \ldots 6 \times 10^{-6},
\]
thus, for the scalar state, this ratio is 3-4 times
smaller, and it could be smaller by another factor 3
at about the \( 2\sigma \) level. So, the two photon coupling
of the \( gb(1000) \) is indeed smaller than one would
anticipate for a \( q\bar{q} \) state.

Further support for the glueball hypothesis is
drawn from the large width of \( gb(1000) \), certain
branching ratios of “\( f_0(1370) \)” and the non-\( q\bar{q} \)
component in elastic \( \pi\pi \) scattering.

5. Gluon fragmentation into glueballs

The observations reported above and others in
\[ ] are largely consistent with the proposed
identification of the scalar states. We suggest
studying further the quark and gluon constituent
nature of these states. An attractive environment
not yet explored is the fragmentation region of
 gluon and quark jets, respectively, with resonances
produced at large energy fractions, say with
\[
z = E_{\text{resonance}}/E_{\text{jet}}, \quad z \gtrsim 0.5.
\]
The production of color singlet clusters in gluon jets
has been considered already in \[ ] but the idea
applied to glueballs has not been pursued further.

In the mass spectra of particles at large total \( z \)
the resonances should show up clearly with little
combinatorial background; of particular interest
for the glueball search are the \( \pi\pi \) and \( K\bar{K} \) pairs,
especially in the neutral mode to select \( 0^{++} \) and
\( 2^{++} \) states.

It is well established that a quark fragments
at large \( z \) predominantly into a hadron with the
primary quark as valence quark. Similarly, a gluon
at large \( z \) might fragment into a glueball with
the primary gluon as valence gluon. Then it will
be interesting to compare resonance production in
quark and glueon jets at large \( z \): a gluonic state like
\( gb(1000) \) or any higher mass glueball state should
be produced with larger rate in the gluon jet at large
\( z \) than in the quark jet and vice versa for \( q\bar{q} \) states
like \( f_0(980) \) or \( f_0(1500) \).

A large number of gluon and quark jets should
be available for such studies in \( e^+e^- \to 3 \) jets and
in high \( p_T \) production of quark and glueon jets at \( pp \)
or \( ep \) colliders.

6. Conclusions

Our analysis of the low lying scalar isoscalar
particles \[ ] suggests including \( f_0(980) \) and \( f_0(1500) \)
in the \( q\bar{q} \) nonet with mixing similar to the
 pseudoscalars \( \eta' \) (near singlet) and \( \eta \) (near octet),
respectively. We concluded the \( f_0(1370) \) not to be
a genuine Breit-Wigner resonance and the \( f_0(1500) \)
not to be a glueball or anything close to it.

The states in the PDG called \( f_0(400-1200) \) and
\( f_0(1370) \) are components of a single broad
Breit-Wigner resonance which is a respectable candidate
for the lightest glueball: \( gb(1000) \). The basic
triplet of light binary glueballs is completed in our
approach \[ ] by the states \( \eta(1440) \) with \( 0^- \) and
\( f_1(1710) \) with \( 2^{++} \), not discussed here.

A promising field of further glueball studies is in
the fragmentation region of quark and glueon jets.

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