A brief phenomenological review on the status of glueballs and hybrids is presented. Recent results for scalar mesons in hadronic reactions and in $\gamma\gamma$-collisions suggest that $f_0(1500)$ has a large glue content and forms the dominant component of the ground state scalar glueball, while $f_0(1710)$ is mainly $s\bar{s}$. The first excited glueball state, a tensor, has not been identified yet, although more tensor states have been reported than can be accommodated in the $q\bar{q}$ nonets. We have now evidence for two isovector mesons, $\pi_1(1400)$ and $\pi_1(1600)$, with quantum numbers incompatible with $q\bar{q}$ states, which could be hybrid mesons or four-quark states.

1. Light mesons

The ground state $1^1S_0(0^{-+})$ and $1^3S_1(1^{--})$ light quark mesons are well established\(^1\) and there are established states for the first orbital excitations $1^3P_1(1^{++})$, $1^3P_2(2^{++})$ and $1^1P_1(1^{+-})$, but the classification of scalar mesons $1^3P_0(0^{++})$, which we shall discuss below, remains controversial.

The states made of gluons only, the glueballs of QCD, are isoscalars. From lattice gauge theories the ground state glueball, a scalar $(0^{++})$, is predicted\(^2\) to lie at a mass of $1611 \pm 30 \pm 160$ MeV, while the first excited state, a tensor $(2^{++})$, has a mass of $2232 \pm 220 \pm 220$ MeV (the first error is statistical while the second error reflects the uncertainty on the mass scale). Lattice calculations also predict\(^3\) that glueballs with quantum numbers that cannot be generated with $q\bar{q}$ pairs $(0^{--}, 0^{+-}, 1^{-+}, 2^{++}, \text{etc})$ lie in the region above 3 GeV.

Hence the low mass glueballs lie in the same mass region as ordinary isoscalar $q\bar{q}$ states, that is in the mass range of the $1^3P_0(0^{++})$ and $2^3P_2$, $3^3P_2$, $1^3P_2(2^{++})$ isoscalar states which are made of $n\bar{m} \equiv 1/\sqrt{2}(u\bar{n} + d\bar{d})$ and $s\bar{\pi}$ pairs, or a mixture thereof. This is why a detailed understanding of the $q\bar{q}$ nonets is mandatory. Significant progresses were made recently for scalar mesons to identify the $0^{++}$ glueball, while much uncertainty remains.
Lattice calculations assume that the quark masses are infinite and therefore neglect $q\bar{q}$ loops. However, one expects that glueballs will mix with nearby $q\bar{q}$ states of the same quantum numbers. Nonetheless one would still find three isoscalar states in the regions of the $0^{++}$ and $2^{++}$ nonets, instead of only two.

Hybrids can be pictured as $q\bar{q}$ mesons with the binding gluons in a vibrating mode. In contrast to glueballs, they can have both isospin 0 and 1. The mass spectrum of hybrids was predicted in ref.\textsuperscript{5,6}. Exotic hybrids ($0^{+-}, 1^{-+}$ and $2^{+-}$) are expected around 1.9 GeV. Most of them are rather broad but some can be as narrow as 100 MeV. They prefer to decay into a pair of S- and P-wave mesons, like $\pi f_1(1285)$, $\pi b_1(1235)$ and $\pi f_0(1370)$. Lattice calculations predict\textsuperscript{7} that the hybrid with exotic quantum numbers $1^{-+}$ lies at a mass of $1.9 \pm 0.2$ GeV. Obviously, exotic hybrids do not mix with $q\bar{q}$ states.

Table 1. Classification of the low-mass scalar mesons showing the scattering resonances below 1 GeV and the ground state $q\bar{q}$ nonet $(1^3P_0)$ . The supernumerary $f_0(1500)$ (not shown) is dominantly glue.

<table>
<thead>
<tr>
<th>State</th>
<th>$\Gamma$ [MeV]</th>
<th>Isospin</th>
<th>Nature</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_0(980)$</td>
<td>$\sim 50$</td>
<td>1 $KK,qq\bar{q}\bar{q}$</td>
<td></td>
</tr>
<tr>
<td>$f_0(980)$</td>
<td>$\sim 50$</td>
<td>0 $KK,qq\bar{q}\bar{q}$</td>
<td></td>
</tr>
<tr>
<td>$f_0(600)$</td>
<td>$\sim 800$</td>
<td>0 meson-meson</td>
<td></td>
</tr>
<tr>
<td>$\kappa(800)?$</td>
<td>$\sim 600$</td>
<td>1/2 resonances</td>
<td></td>
</tr>
<tr>
<td>$a_0(1450)$</td>
<td>265</td>
<td>1 $\bar{u}\bar{d},\bar{d}\bar{u},\bar{d}\bar{d} - u\bar{u}$</td>
<td></td>
</tr>
<tr>
<td>$f_0(1370)$</td>
<td>$\sim 400$</td>
<td>0 $d\bar{d} + u\bar{u}$</td>
<td></td>
</tr>
<tr>
<td>$f_0(1710)$</td>
<td>125</td>
<td>0 $s\bar{s}$</td>
<td></td>
</tr>
<tr>
<td>$K_0^*(1430)$</td>
<td>294</td>
<td>1/2 $u\bar{s},d\bar{s},s\bar{u},s\bar{d}$</td>
<td></td>
</tr>
</tbody>
</table>

2. The $0^{++}$ glueball

There are too many scalar mesons to fit in the ground state $0^{++}$ $q\bar{q}$ nonet. Table 1 shows an increasingly popular classification scheme. The low mass nonet is made of four-quark states and/or meson-meson resonances. The ground state $(1^3P_0(0^{++})) q\bar{q}$ nonet lies in the 1400 MeV region. We shall argue below that $f_0(1500)$ contains a large fraction of glue and that $f_0(1710)$ is dominantly $s\bar{s}$. Let us deal first with the $a_0(980)$ and $f_0(980)$ mesons.
The $a_0(980)$ decays mainly into $\eta \pi$ while the $f_0(980)$ decays mainly into $\pi \pi$. However, their decay fractions to $K\bar{K}$ are large (e.g. 20% for the $a_0$) although this mode should be suppressed by the nearby $K\bar{K}$ threshold. This indicates that their wavefunctions contain a significant fraction of $s\bar{s}$. This is not possible for an isovector $qq$ state $a_0(980)$. The $a_0(980)$ and $f_0(980)$ are therefore often considered as four-quark states ($s\bar{s}(d\bar{d} - u\bar{u})$ and $s\bar{s}(d\bar{d} + u\bar{u})$, respectively)\(^8\), or as $K\bar{K}$ molecular states\(^9\).

The $\gamma\gamma$-widths of the $a_0(980)$ as a $K\bar{K}$ molecular state was predicted to be about 0.6 keV\(^{10}\). This is comparable to the predicted $\gamma\gamma$-width for $qq$ states\(^{11,12}\). Hence measurements of the $\gamma\gamma$-widths cannot distinguish between molecular and $qq$ states (the measured $a_0(980)$ and $f_0(980)$ $\gamma\gamma$ partial widths are $0.30 \pm 0.10$ and $0.39 \pm 0.11$ keV, respectively\(^1\)).

Decisive channels to study the internal structures of these mesons are radiative $\gamma$ decays into $a_0(980)$ and $f_0(980)$ (see ref.\(^{13}\)): $K\bar{K}$ molecules would be produced with a branching ratio of $10^{-5}$ in radiative $\gamma$ decay. For $q\bar{q}$ states the yield of $f_0(980)=s\bar{s}$ would be $5 \times 10^{-5}$. For $a_0(980)=n\bar{\pi}$ the rate should be much smaller since the process is OZI suppressed. However, four-quark states ($qqqq$) would be produced with a much larger rate of $10^{-4}$.

The first measurements made at the VEPP-2M ring at Novosibirsk\(^{14,15}\) were compatible with four-quark states, at least for the $f_0(980)$. More precise results from KLOE at DAΦNE now confirm the large radiative decay branching ratios: for $\phi \rightarrow f_0\gamma$ (where $f_0 \rightarrow \pi\pi$) KLOE\(^{16}\) reports $(4.47 \pm 0.21) \times 10^{-4}$ and for $\phi \rightarrow a_0\gamma$ (where $a_0 \rightarrow \eta\pi$) KLOE finds $(0.74 \pm 0.07) \times 10^{-4}$. For the first channel, the parametrization of the broad $f_0(600)$, which interferes destructively, is somewhat arbitrary in ref.\(^{16}\), but this does not affect the conclusion that the branching ratio is very large, compatible with that of four-quark states. However, the radiative decays, driven by the $K^+K^-$ loop, should be equal for $a_0$ and $f_0$, unless strong isospin mixing occurs\(^{17}\).

Note that $f_0(980)$ is strongly produced\(^{18}\) in the decay $D_s^+(c\bar{s}) \rightarrow \pi^+\pi^+\pi^-$. However, this does not point to a large $s\bar{s}$ component - as would be expected for Cabibbo favoured decays - since the $f_0(1370)$ - known to be mainly $n\bar{\pi}$ - is also strongly produced\(^{18}\). Hence other processes, e.g. $c\bar{s}$ annihilation in $D_s$ decay, must contribute significantly.

Let us now discuss the isoscalar states $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$. The $f_0(1370)$ and $f_0(1500)$ mesons were established by Crystal Barrel, first in their $\eta\eta$ and $\pi^0\pi^0$ decay modes\(^{19}\). The $f_0(1370)$ is broad ($\sim 400$ MeV) while the $f_0(1500)$ is rather narrow ($\sim 100$ MeV). Among others\(^{20}\), their $K\bar{K}$ decay rates were measured by Crystal Barrel\(^{21}\). They are small com-
pared to $\pi\pi$, indicating that neither state can have a large $s\bar{s}$ component\textsuperscript{22}.

The WA102 Collaboration at CERN observed the $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ decaying to $K\bar{K}$ and $\pi\pi$ in $pp$ central production at 450 GeV\textsuperscript{23}. For $f_0(1370)$ and $f_0(1500)$, the $\pi\pi$ decay mode was favoured over $K\bar{K}$. Hence both $f_0(1370)$ and $f_0(1500)$ do not have large $s\bar{s}$ components, in agreement with Crystal Barrel results. The spin of the $f_0(1710)$ meson was controversial ($J = 0$ or 2) and the issue was finally settled in favour of $0^{++}$ by the new data from WA102. However, for $f_0(1710)$, $K\bar{K}$ decay dominates by a large factor (5.5 \pm 0.8), suggesting that this state must be dominantly $s\bar{s}$.

There is no known mechanism suppressing the production of scalar mesons in $\bar{p}p$ annihilation and, in fact, scalar mesons dominate in the production of pseudoscalar pairs\textsuperscript{20}. However the OZI rule forbids the production of pure $s\bar{s}$ mesons in $\bar{p}p$ annihilation. The $f_0(1710)$ was searched for in $pp$ annihilation into three pseudoscalar mesons with 900 MeV/c antiprotons\textsuperscript{24}. For example, in $\bar{p}p \to \pi^0\eta\eta$ the $f_0(1710) \to \eta\eta$ is not observed, while $f_0(1500)$ is clearly seen. This is prima facie evidence that $f_0(1710)$ cannot have a large $n\bar{n}$ component.

![Figure 1](image.png)

Figure 1. Left: relative branching ratio $R_2 = B(K\bar{K})/B(\pi\pi)$ vs. $R_1 = B(\eta\eta)/B(\pi\pi)$ as a function of mixing angle $\alpha$ (in deg.); right: predicted $\gamma\gamma$-width for the $f_0(1500)$. The experimental upper limit is shown by the box (from ref.\textsuperscript{22}).

For a more quantitative statement, look at Figure 1 (left) which shows the ratio of branching ratios $R_2 = B(K\bar{K})/B(\pi\pi)$ vs. $R_1 = B(\eta\eta)/B(\pi\pi)$ for scalar mesons, apart from phase space factors. Data from Crystal Barrel and WA102 (2\sigma boundaries) on the $f_0(1500)$ and $f_0(1710)$ are compared with predictions from SU(3). The angle $\alpha$ describes the mixing of the two
nonet isoscalar mesons,

\[ |f_0\rangle = \cos \alpha \ |n\bar{u}\rangle - \sin \alpha \ |s\bar{s}\rangle \quad \text{with} \quad |n\bar{u}\rangle = \frac{u\bar{u} + d\bar{d}}{\sqrt{2}}. \]  

(1)

Hence for \( \alpha = 0 \), \( f_0 \) is pure \( n\bar{u} \) and for \( \alpha = 90^\circ \), pure \( s\bar{s} \) (ideal mixing). Full details can be found in ref.\textsuperscript{22}. Assuming that \( f_0(1500) \) and \( f_0(1710) \) are \( q\bar{q} \) states, we conclude from Figure 1 (left) that the former is mainly \( n\bar{u} \) \((-10^\circ \leq \alpha \leq 5^\circ)\) and the latter mainly \( s\bar{s} \) \((\alpha \simeq 117^\circ)\).  

Let us now deal with two-photon processes which are useful to probe the charge content of mesons through their electromagnetic couplings. Glue-balls do not couple directly to photons and their production should therefore be suppressed in \( \gamma\gamma \)-processes. New data in \( \gamma\gamma \)-collisions have been presented by the LEP collaborations. L3 observes three peaks below 2 GeV in the \( K_S^0K_S^0 \) mass distribution\textsuperscript{25} (Figure 2, left): \( f_2(1270) \) (interfering with \( a_2(1320) \)) and \( f'_0(1525) \), but the spin 0 \( f_0(1500) \) is not seen. The spin of the third peak, \( f_J(1710) \) around 1765 MeV, is determined to be mainly 2 but a large spin 0 component is also present\textsuperscript{26}. Since \( f_0(1500) \) does not couple strongly to \( KK \), its absence in Figure 2 (left) is perhaps not surprising. However, ALEPH studying the reaction \( \gamma\gamma \rightarrow \pi^+\pi^- \), does not observe \( f_0(1500) \) either\textsuperscript{27} (see Figure 2, right). An upper limit of 1.4 keV (95 \% CL) can be derived for its \( \gamma\gamma \)-width from the ALEPH result\textsuperscript{27}, using the known \( \pi\pi \) decay branching ratio of the \( f_0(1500) \)\textsuperscript{1}.  

\textsuperscript{a}Note that SU(3) predictions\textsuperscript{4} for branching ratios are in excellent agreement with data for tensor mesons for which the mixing angle is well known (\( \alpha = 82^\circ \)).
The $\gamma\gamma$-width of a $q\bar{q}$ state can be predicted from SU(3). Apart from an unknown nonet constant $C$ and for a meson of mass $m$:

$$\Gamma_{\gamma\gamma} = C(5\cos\alpha - \sqrt{2}\sin\alpha)^2m^3.$$  \hspace{1cm} (2)

The $\gamma\gamma$-width of a scalar meson is related to that of the corresponding tensor by

$$\Gamma_{\gamma\gamma}(0^{++}) = k \left(\frac{m_0}{m_2}\right)^3 \Gamma_{\gamma\gamma}(2^{++}),$$  \hspace{1cm} (3)

with obvious notations. Here the factor $k = 15/4$ arises from spin multiplicities in a non-relativistic calculation, while relativistically $k \approx 2$. Data on the charmonium states $\chi_{c2}$ and $\chi_{c0}$ are in excellent agreement with Eq. 3. The $\gamma\gamma$-width for scalar mesons can now be predicted as a function of $\alpha$ by first calculating the constant $C$ in Eq. 2 for tensor mesons, using their measured $\gamma\gamma$ partial widths$^4$ and then introducing into Eq. 3. Figure 1 (right) shows the prediction for the $\gamma\gamma$ partial width of the $f_0(1500)$ as a function of $\alpha$, together with the ALEPH upper limit$^{22}$. Assuming a $q\bar{q}$ structure, one concludes that $f_0(1500)$ is dominantly $s\bar{s}$ ($50^\circ \leq \alpha \leq 100^\circ$), at variance with the hadronic results discussed above.

This contradiction indicates that $f_0(1500)$ is not $q\bar{q}$ and the lack of $\gamma\gamma$-coupling points to a large gluonic content. Obviously, some mixing with nearby $q\bar{q}$ states is possible$^4$ but more accurate data in $\gamma\gamma$-collisions and theoretical guidance on the strength of $\gamma\gamma$-couplings to glueballs are needed for a more quantitative statement on mixing.

For the $f_0(1710)$, the ALEPH data are consistent with an $s\bar{s}$ state, although its $\pi\pi$ decay branching ratio is not known. In ref.$^{22}$ we argued that the spin 0 component in the $f_J$ region of Figure 2 (left) was consistent with an $s\bar{s}$ $f_0(1710)$, while the spin 2 contribution arose from the (isovector) $a_2(1320)$ radial excitation of the $a_2(1700)$.

3. Search for the $2^{++}$ glueball

The ground state tensor $q\bar{q}$ mesons ($1^3P_2(2^{++})$) are well established. Above the $f_2(1525)$ none of the nine reported isoscalars$^4$ can be definitely assigned to the six states expected in the $2^3P_2$, $3^3P_2$ and $1^3F_2$ nonets. A systematic study of the two-body channels $\pi\pi$, $K\bar{K}$, $\eta\eta$ and $\eta'\eta'$, similar to the one performed for scalar mesons at lower energy, has to be conducted. Three to four states appear to be solid, the $f_2(1565)$ observed in $pp$ annihilation at rest, the broad $f_2(1950)$ decaying to $4\pi$ and $\eta\eta$ and a broad structure (of perhaps several states) decaying to $\phi\phi$ around 2300 MeV.
The narrow ($\Gamma = 23 \text{ MeV}$) $f_{JJ}(2230)$, or $\xi$, was reported by BES at the $e^+e^-$ collider in Beijing. It was observed$^{28}$ to decay into $\pi^+\pi^-$, $K^+K^-$, $K_SK_S$, $\bar{p}p$ and $\pi^0\pi^0$ with a significance of about 4$\sigma$ in each decay mode. This state is an attractive candidate for the $2^{++}$ glueball as it is observed in the gluon rich environment of $J/\psi$ radiative decay, but not in $\gamma\gamma$-collisions.

If $\xi$ decays to $\bar{p}p$ then it would be observed in $\bar{p}p$ formation experiments. Crystal Barrel has searched for narrow states decaying to $\pi^0\pi^0$ and $\eta\eta$ as a function of $p$ momentum$^{29}$. The resolution was about $\pm 0.6 \text{ MeV}$ in the c.m. system. No structure was observed. Using the product of branching fractions $B(J/\psi \rightarrow \gamma\xi)B(\xi \rightarrow \bar{p}p, \pi^0\pi^0)$ measured by BES and the upper limit for $B(\bar{p}p \rightarrow \xi)B(\xi \rightarrow \pi^0\pi^0)$ from Crystal Barrel, one finds that the observed decays by BES amount to at most 4% of all $\xi$ decays, hence most $\xi$ decay channels have not been seen yet. Furthermore, $B(J/\psi \rightarrow \gamma\xi) > 3 \times 10^{-3}$ which is comparable to the branching ratio for the well known decay $J/\psi \rightarrow \gamma\eta'$, and could hardly have been missed in inclusive radiative decays. Hence the data are inconsistent: the $\bar{p}p$ decay width measured at BES appears to be too large or the $\xi$ does not exist.

3.1. Search for $1^{++}$ hybrids

A $1^{++}$ exotic meson with a mass of 1370 MeV and a width of 385 MeV was reported with 18 GeV pions in $\pi^-p \rightarrow \eta\pi^-p$ at the MPS in Brookhaven$^{30}$. It was observed as an interference between the $\eta\pi$ $L = 1$ and $L = 2$ $a_2(1320) \rightarrow \eta\pi$ amplitudes, leading to a forward/backward asymmetry in the $\eta\pi$ angular distribution. Crystal Barrel has searched for this resonance in the $\pi^-\pi^0\pi^0\eta$ in liquid deuterium at rest$^{31}$. The partial wave analysis required the inclusion of a resonant $1^{++}$ P-wave with mass 1400 and width 310 MeV, in agreement with ref.$^{30}$. This state was also observed$^{32}$ in the annihilation channel $\bar{p}p \rightarrow \pi^0\pi^0\eta$.

Another $1^{++}$ state at 1593 MeV with a width of 168 MeV and decaying into $\rho\pi$ was reported$^{33}$ at the MPS in the reaction $\pi^-p \rightarrow \pi^-\rho^0n$ at 18 GeV. It was also observed in its $\eta'\pi^-$ decay mode by the same collaboration in $\pi^-p \rightarrow \eta'\pi^-p$. Similar observations were made by the VES collaboration at Serpukhov with 37 GeV pions$^{35}$. The $\eta\pi$ decay mode was not observed for this high mass state. The dominance of an exotic $1^{++}$ P-wave in $\eta\pi$ around 1300 MeV and in $\eta'\pi$ around 1600 was reported much earlier by VES$^{36}$, but no resonance structure was claimed at that time.

Hence we now have two $1^{++}$ exotic states, $\pi_1(1400)$ and $\pi_1(1600)$. As isovectors, $\pi_1(1400)$ and $\pi_1(1600)$ cannot be glueballs. The coupling to $\eta\pi$
of the $\pi_1(1400)$ points to a four-quark state while the strong $\eta'\pi$ coupling of the $\pi_1(1600)$ is favoured by hybrid states$^{37}$. The mass of the latter is not far below lattice prediction$^7$.

References
20. For a review see C. Amsler, Rev. Mod. Phys. 70 (1998) 1293