LIGHT EXOTIC MESONS

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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 ± 30 ± 160 MeV, while the first excited state, a tensor (2^{++}), has a mass of 2232 ± 220 ± 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^{+-}, 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, $1^3F_2(2^{++})$ isoscalar states which are made of $n\overline{n} \equiv 1/\sqrt{2}(u\overline{u} + d\overline{d})$ and $s\overline{s}$ 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 for the 2^{++} assignment.

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[4]. 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.[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[7] that the hybrid with exotic quantum numbers 1^{-+} lies at a mass of 1.9 ± 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.

State	Γ [MeV]	Isospin	Nature
$a_0(980)$	~ 50	1	$K\overline{K}, qq\bar{q}\bar{q}$
$f_0(980)$	~ 50	0	$K\overline{K}, qq\bar{q}\bar{q}$
$f_0(600)$	~ 800	0	meson-meson
$\kappa(800)$?	~ 600	1/2	resonances
$a_0(1450)$	265	1	$u\bar{d}, d\bar{u}, d\bar{d} - u\bar{u}$
$f_0(1370)$	~ 400	0	$d\bar{d} + u\bar{u}$
$f_0(1710)$	125	0	$s\bar{s}$
$K_0^*(1430)$	294	1/2	$u\bar{s}, d\bar{s}, s\bar{u}, s\bar{d}$

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 $s\overline{s}$. This is not possible for an isovector $q\overline{q}$ state $a_0(980)$. The $\mathrm{a}_0(980)$ and $\mathrm{f}_0(980)$ are therefore often considered as four-quark states ($s\overline{s}(d\overline{d}-u\overline{u})$ and $s\overline{s}(d\overline{d}+u\overline{u})$, respectively)[8], or as $K\overline{K}$ molecular states[9].

The $\gamma\gamma$-widths of the $a_0(980)$ as a $K\overline{K}$ molecular state was predicted to be about 0.6 keV[10]. This is comparable to the predicted $\gamma\gamma$-width for $q\overline{q}$ states[11,12]. Hence measurements of the $\gamma\gamma$-widths cannot distinguish between molecular and $q\overline{q}$ states (the measured $\mathrm{a}_0(980)$ and $\mathrm{f}_0(980)$ $\gamma\gamma$ partial widths are 0.30 ± 0.10 and 0.39 ± 0.11 keV, respectively[1]).

Decisive channels to study the internal structures of these mesons are radiative ϕ decays into $a_0(980)$ and $f_0(980)$ (see ref.[13]): $K\overline{K}$ molecules would be produced with a branching ratio of 10^{-5} in radiative ϕ decay. For $q\overline{q}$ states the yield of $f_0(980)$=$s\overline{s}$ would be 5×10^{-5}. For $a_0(980)$=$n\overline{n}$ the rate should be much smaller since the process is OZI suppressed. However, four-quark states ($qq\bar{q}\bar{q}$) 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 $\phi \to f_0\gamma$ (where $f_0 \to \pi\pi$) KLOE[16] reports $(4.47 \pm 0.21) \times 10^{-4}$ and for $\phi \to a_0\gamma$ (where $a_0 \to \eta\pi$) 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 $D_s^+(c\overline{s}) \to \pi^+\pi^+\pi^-$. However, this does not point to a large $s\overline{s}$ component - as would be expected for Cabibbo favoured decays - since the $f_0(1370)$ - known to be mainly $n\overline{n}$ - is also strongly produced[18]. Hence other processes, e.g. $c\overline{s}$ 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 compared to $\pi\pi$, indicating that neither state can have a large $s\bar{s}$ component[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[23]. For $f_0(1370)$ and $f_0(1500)$, the $\pi\pi$ decay mode was favoured over $K\overline{K}$. 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 $\pi\pi$ by a large factor (5.5 ± 0.8), suggesting that this state must be dominantly $s\bar{s}$.

There is no known mechanism suppressing the production of scalar mesons in $\overline{p}p$ annihilation and, in fact, scalar mesons dominate in the production of pseudoscalar pairs[20]. However the OZI rule forbids the production of pure $s\bar{s}$ mesons in $\overline{p}p$ annihilation. The $f_0(1710)$ was searched for in $\overline{p}p$ annihilation into three pseudoscalar mesons with 900 MeV/c antiprotons[24]. For example, in $\overline{p}p \to \pi^0\eta\eta$ 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 $n\overline{n}$ component.

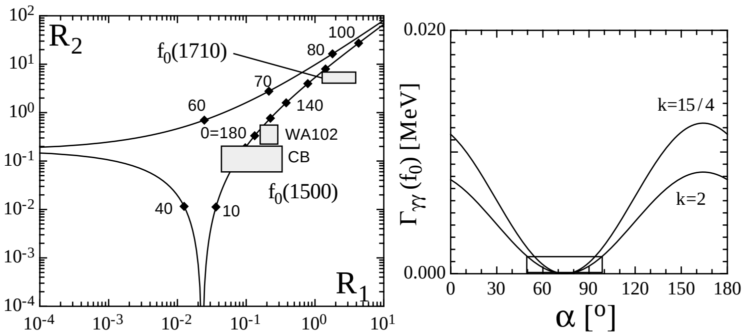

Figure 1. Left: relative branching ratio $R_2 = B(K\overline{K})/B(\pi\pi)$ vs. $R_1 = B(\eta\eta)/B(\pi\pi)$ as a function of mixing angle α (in deg.); right: predicted $\gamma\gamma$-width for the $f_0(1500)$. The experimental upper limit is shown by the box (from ref.[22]).

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

$$|f_0\rangle = \cos\alpha\ |n\overline{n}\rangle - \sin\alpha\ |s\overline{s}\rangle \quad \text{with} \quad |n\overline{n}\rangle \equiv \frac{u\overline{u} + d\overline{d}}{\sqrt{2}}\ . \tag{1}$$

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

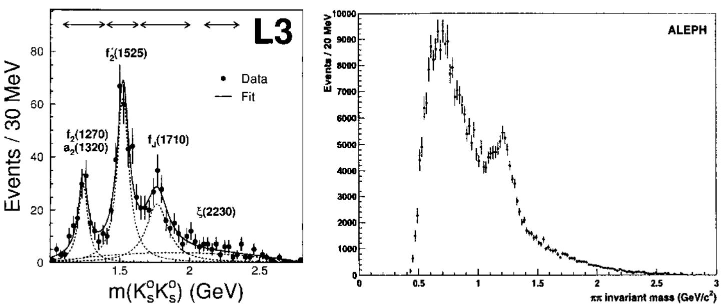

Figure 2. Left: K_SK_S mass distribution in $\gamma\gamma$-collisions at LEP/L3 (from ref.[25]); right: $\pi^+\pi^-$ mass distribution from LEP/ALEPH showing only the $f_2(1270)$ (from ref.[27]).

Let us now deal with two-photon processes which are useful to probe the charge content of mesons through their electromagnetic couplings. Glueballs 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_SK_S mass distribution[25] (Figure 2, left): $f_2(1270)$ (interfering with $a_2(1320)$) and $f_2'(1525)$, 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[26]. Since $f_0(1500)$ does not couple strongly to $K\bar{K}$, its absence in Figure 2 (left) is perhaps not surprising. However, ALEPH studying the reaction $\gamma\gamma \to \pi^+\pi^-$, does not observe $f_0(1500)$ either[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[27], using the known $\pi\pi$ decay branching ratio of the $f_0(1500)$[1].

[a]Note that SU(3) predictions[4] for branching ratios are in excellent agreement with data for tensor mesons for which the mixing angle is well known ($\alpha = 82°$).

The $\gamma\gamma$-width of a $q\overline{q}$ state can be predicted from SU(3). Apart from an unknown nonet constant C and for a meson of mass m:

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

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

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

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

This contradiction indicates that $f_0(1500)$ is not $q\overline{q}$ and the lack of $\gamma\gamma$-coupling points to a large gluonic content. Obviously, some mixing with nearby $q\overline{q}$ 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 $s\overline{s}$ 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 $s\overline{s}$ $f_0(1710)$, while the spin 2 contribution arose from the (isovector) $a_2(1700)$ radial excitation of the $a_2(1320)$.

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

The ground state tensor $q\overline{q}$ mesons ($1^3P_2(2^{++})$) are well established. Above the $f_2'(1525)$ none of the nine reported isoscalars[1] 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 $\pi\pi$, $K\overline{K}$, $\eta\eta$ 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 $\overline{p}p$ annihilation at rest, the broad $f_2(1950)$ decaying to 4π and $\eta\eta$[24] and a broad structure (of perhaps several states) decaying to $\phi\phi$ around 2300 MeV.

The narrow ($\Gamma = 23$ MeV) $f_J(2230)$, or ξ, 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, $\overline{p}p$ and $\pi^0\pi^0$ with a significance of about 4σ 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/ψ radiative decay, but not in $\gamma\gamma$-collisions.

If ξ decays to $\overline{p}p$ then it would be observed in $\overline{p}p$ formation experiments. Crystal Barrel has searched for narrow states decaying to $\pi^0\pi^0$ and $\eta\eta$ as a function of $\overline{p}$ momentum[29]. The resolution was about $\pm$ 0.6 MeV in the c.m. system. No structure was observed. Using the product of branching fractions $B(J/\psi \to \gamma\xi)B(\xi \to \overline{p}p, \pi^0\pi^0)$ measured by BES and the upper limit for $B(\overline{p}p \to \xi)B(\xi \to \pi^0\pi^0)$ from Crystal Barrel, one finds that the observed decays by BES amount to at most 4% of all ξ decays, hence most ξ decay channels have not been seen yet. Furthermore, $B(J/\psi \to \gamma\xi) > 3 \times 10^{-3}$ which is comparable to the branching ratio for the well known decay $J/\psi \to \gamma\eta'$, and could hardly have been missed in inclusive radiative decays. Hence the data are inconsistent: the $\overline{p}p$ decay width measured at BES appears to be too large or the ξ 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 $\pi^-p \to \eta\pi^-p$ at the MPS in Brookhaven[30]. It was observed as an interference between the $\eta\pi$ $L = 1$ and $L = 2$ $a_2(1320) \to \eta\pi$ amplitudes, leading to a forward/backward asymmetry in the $\eta\pi$ angular distribution. Crystal Barrel has searched for this resonance in the $\eta\pi$ P-wave with $\overline{p}n \to \pi^-\pi^0\eta$ 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 $\overline{p}p \to \pi^0\pi^0\eta$.

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 $\pi^-p \to \pi^-\rho^0n$ at 18 GeV. It was also observed in its $\eta'\pi^-$ decay mode by the same collaboration in $\pi^-p \to \eta'\pi^-p$[34]. 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].

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