Light scalar meson spectrum

Wolfgang Ochs

Föhringer Ring 6, D-80805 München, Germany

Abstract. We discuss the classification of the light scalar mesons with mass below 2 GeV into $q\bar{q}$ nonets and glueballs. The information on production and decay of these states, in particular recent information on the $f_0(980)$, $f_0(400−1200)$ (or $\sigma(600)$) and $f_0(1500)$ is considered. Although the data are not yet very precise the recent information is in favour of the previously developed scheme which includes $f_0(980)$, $a_0(980)$, $K^*_0(1430)$, $f_0(1500)$ into the lightest scalar nonet. The glueball in this approach appears as broad object around 1 GeV. Alternative schemes find the glueball at somewhat higher mass or suggest his mixing with $q\bar{q}$ states spread over a similar mass range. We do not see sufficient evidence yet for a light scalar nonet below 1 GeV around a $\sigma(600)$ resonance.

INTRODUCTION

Among the light mesons the scalars ($J^{PC} = 0^{++}$) are quite resistant against any classification which would be generally acceptable. In part this comes from the difficulty to identify very broad states, like $f_0(400−1200)$ and to determine their parameters or even to establish their presence, in part also from the possible existence of different types of mesons, namely besides the usual $q\bar{q}$ quarkonia, four quark or molecular states and glueballs. At the same time these possibilities are at the origin of the large interest in the scalar states as the lightest glueball is generally expected with these quantum numbers. It is therefore important to bring order into the scalar spectrum.

The existence of glueballs is confirmed by the nonperturbative QCD calculations and their discovery is a challenge for theory and experiment. In the quenched approximation of lattice QCD, i.e. neglecting sea quarks, one finds the mass of the scalar glueball in the range 1400-1800 MeV (recent reviews [2, 3]). There are still considerable uncertainties concerning the effects of sea quarks and the masses of the light quarks. The glueballs with tensor and pseudoscalar quantum numbers are next heavier in mass and already close to or above 2 GeV. At this higher mass it is certainly more difficult to establish the nature of the observed resonances, therefore the scalar glueball is the primary target for glueball searches. An alternative approach to glueball masses is based on QCD sum rules. In these calculations a light gluonic state near 1 GeV is demanded from a particular sum rule [4, 5]. According to these QCD results it seems plausible to search for the lightest scalar glueball in the range 1 - 2 GeV and not in a much narrower region.

In a first step it should be clarified which states with $J^{PC} = 0^{++}$ are really established and what their internal flavour structure is. Then one can attempt to group them into $q\bar{q}$ nonets. The existence of glueballs is indicated if there are supernumerary states. In the following we discuss in particular results from Ref. [6, 7] including new analyses [8] and compare with other approaches.
LIGHT SCALAR MESONS: EVIDENCE AND FLAVOUR STRUCTURE

First we attempt to identify the $q\bar{q}$ meson nonet(s). The scalar states listed by the Particle Data Group (PDG) are shown in Table 1. In this talk we concentrate our attention to the isoscalar ($f_0$) states of lowest mass and the construction of the lightest nonet.

In order to establish a resonance in a general environment with background, which case is relevant to our discussion, we request as necessary condition for a state to be acceptable a definite evidence for the movement of the partial wave amplitude in both magnitude and phase according to a local Breit Wigner representation, i.e. a pole in the complex energy plane in general above some background. We begin our discussion with two well established isoscalars where the debate concerns their intrinsic structure and continue with two others whose very existence we consider in doubt.

### The $f_0(980)$ meson

The existence of this state is well established by early phase shift analyses [9, 10]. There is a continuing debate on whether its internal structure corresponds to a quarkonia or rather to a 4-quark or molecular state. We follow here the standard quark model for simplicity as far as possible in the hope that some problems may disappear with improved calculations. The $q\bar{q}$ assumption is supported by various observations which are not natural for a complex 4q state: the close similarity in various production properties with other quarkonia of similar mass (like $\rho$, $\phi(1020)$, $a_0(980)$, $\eta'$, in both $e^+e^-$ annihilation [11] and $\nu p$ interactions [12], see recent review [13]); the dominance of $f_0(980)$ production at large momentum transfer $|t| \sim 0.5$ GeV$^2$ in $\pi p$ collisions [14] which suggests a $f_0\pi A_1$ coupling [6]; the strong production in $D, D_s$ decays (see below) through intermediate $d\bar{d}$ and $s\bar{s}$ states. This discussion will have to continue until a consistent description of all phenomena is achieved.

In the following we discuss the predictions from the quarkonium model for various ratios of observables, where the dependences on the less known intrinsic structures are expected to cancel. These ratios depend only on the mixing angle $\varphi_s$ in the scalar nonet which we define through the amplitudes into strange and non-strange components

$$ f_0(980) = \sin \varphi_s n\bar{n} + \cos \varphi_s s\bar{s} \quad \text{with} \quad n\bar{n} = (u\bar{u} + d\bar{d})/\sqrt{2}. $$

(1)

The results can ultimately be compared with corresponding predictions from molecular models if available. A consistent description of data in terms of only one parameter $\varphi_s$ is then a crucial test of the quarkonium model.

### TABLE 1. Scalar mesons below 2 GeV according to Particle Data Group [1]

| $I$ | $f_0(400 - 1200)$ (or $\sigma$) | $f_0(980)$ | $f_0(1370)$ | $f_0(1500)$ | $f_0(1710)$ | $f_0(2020)$? |
|-----|-------------------------------|------------|-------------|-------------|-------------|-------------|
| 0   |                               | $f_0(980)$ | $f_0(1370)$ | $f_0(1500)$ | $f_0(1710)$ | $f_0(2020)$? |
| $\frac{1}{2}$ | $K_0^*(1430)$ | $K^*(1950)$? |
| 1   |                               | $a_0(980)$ | $a_0(1450)$ |             |             |             |
The definition (1) is in analogy to the common definition for pseudoscalars

\begin{align}
\eta' &= \sin \phi_p n\bar{n} + \cos \phi_p s\bar{s} \\
\eta &= \cos \phi_p n\bar{n} - \sin \phi_p s\bar{s}.
\end{align}

A recent determination of the pseudoscalar mixing angle yielded [15]

\[ \phi_p = 39.3^\circ \pm 1.0^\circ. \]  

(4)

This result corresponds approximately to components \((u\bar{u}, d\bar{d}, s\bar{s})\)

\begin{align}
\eta' &= (1, 1, 2)/\sqrt{6} \quad \text{near singlet} \quad (1, 1, 1)/\sqrt{3} \quad \text{(5)} \\
\eta &= (1, 1, -1)/\sqrt{3} \quad \text{near octet} \quad (1, 1, -2)/\sqrt{6} \quad \text{(6)}
\end{align}

with mixing angle \(\phi_p = 35.3^\circ\) near singlet-octet angle \(\phi_p = 54.7^\circ\).

We consider here three ratios of branching ratios as in [6] but now express them in terms of the mixing angle \(\phi_p\). Then we can get a quantitative measure of the consistency of the approach. We summarize here only the final results in Table 2.

The experimental values for the ratios \(R_i\) are determined from the PDG results where available. The ratio \(R_1\) estimates the ratio of strange and nonstrange components of the \(f_0\). This ratio has been determined for the pseudoscalars and yielded a mixing angle consistent with all other determinations [15]. Remarkably the \(J/\psi\)-branching ratios entering \(R_1\) are very similar for \(\eta'\) and \(f_0(980)\) which gives the first hint towards the close similarity of the scalar and pseudoscalar multiplets. The ratio \(R_1 = 2\) would correspond to the quark composition \(\eta' = (1, 1, 2)/\sqrt{6}\) in (5). Accordingly, the mixing angle \(\phi_s \sim \phi_p\), in addition a second solution \(\phi_{s2}\) is possible.

The ratio \(R_2\) is calculated from the \(q\bar{q}\) annihilation amplitudes which are proportional to the squares of quark charges \(Q_q^2\). It is assumed here that the \(a_0(980)\) is a quarkonium as well with wave function \(a_0 = (u\bar{u} - d\bar{d})/\sqrt{2}\).

For the ratio \(R_3\) we assume a strange quark suppression amplitude \(S = 0.8 \pm 0.2\) close to Ref. [16]. The reduced branching ratio \(g_K^2/g_\pi^2\) is taken from determinations based on measurements of both \(K\bar{K}\) and \(\pi\pi\) final states in central production [17] and with low background in large \(t\pi p\) collisions [18].

The results for the mixing angles from the measured ratios are nicely compatible for the small angle solution (\(\chi^2 = 1.4\) with

\[ \phi_s = 35^\circ \pm 4^\circ \]  

(7)
whereas the large angle solution $\varphi_x = 154^\circ \pm 3^\circ$ closer to octet is disfavoured ($\chi^2 = 6.4$, Prob $\sim 1\%$). These results are based on three ratios and have little model dependence. Our favoured solution $\varphi_x$ is similar to the pseudoscalar mixing angle $\varphi_p$ in (4) as already suggested in [6].

Our two solutions are similar to those of Ref. [16] (using $g_2^2/\bar{g}_\pi^2 \sim 1.5$) whereas in Ref. [19] calculations based on two absolute rates yielded the small angle solution $\varphi_x = 4^\circ \pm 3^\circ$ which is rejected in favour of the large angle solution $\varphi_x = 138^\circ \pm 6^\circ$.

Independent information on the relative phase of the $s\bar{s}$ vs. $n\bar{n}$ components in the $f_0(980)$ wave function is accessible from $D$ and $D_s$ charmed meson decays. Consider first the decay $D^+_s \to \pi^+ K^+ K^-$ which shows a strong $\phi(1020)$ signal overlapping with $f_0(980)$. The dominant decay of $D^+_s$ proceeds through the emission of a $\pi^+$ and formation of an intermediate $s\bar{s}$ state subsequently decaying into $\phi$ and $f_0$ states with amplitudes $1$ and $\cos \varphi_x$ according to (1). The absolute phases of $\phi$ and $f_0$ have been determined by the E687 Collaboration [20] as $(178 \pm 20 \pm 24)^\circ$ and $(159 \pm 22 \pm 16)^\circ$, i.e. the relative phase is consistent with zero degrees. Therefore

$$ \cos \varphi_x > 0 \quad \Rightarrow \quad 0 < \varphi_x < 90^\circ \quad (8) $$

in agreement with the small phase solution (7).

The determination of the relative phases depends on the definition of the scattering angle. Under an exchange of the two particles of the decay the S-P wave interference term considered here would change sign. As a check we therefore studied a similar situation in the decay $D^+ \to \pi^+ \pi^- \pi^+$ with the relative phase between the amplitudes $D^+ \to \pi^+ \rho^0$ and $D^+ \to \pi^+ f_0(980)$. According to the dominant mechanism these resonances are produced through intermediate $d\bar{d}$ states with amplitudes $-1/\sqrt{2} < 0$ and $\sin \varphi_x/\sqrt{2} > 0$ respectively, so one expects a $180^\circ$ phase difference. This expectation is in fact verified by the measurements by both E687 [20] and E791 Collaborations [21, 22] which confirms that the standard definition of the angles yields consistent results.

Another interesting ratio is $R = (\phi \to a_0(980)\gamma)/(\phi \to f_0(980)\gamma)$. As the decays involve two decay mechanisms with or without $s\bar{s}$ annihilation we have no straightforward prediction. An explanation is possible in terms of $a_0 - f_0$ mixing [23].

### The $f_0(1500)$ meson

This state can be considered as well established by now also. In $p\bar{p} \to 3\pi$ the Dalitz plot has been fitted with some phase sensitivity and the S wave nature has been demonstrated (CBAR Collaboration [24]). Meanwhile various branching ratios became known.

The phase movement has also been seen in the Argand diagrams of $\pi\pi \to K\bar{K}$ and $\pi\pi \to \eta\bar{\eta}$ as obtained from the $\pi N$ production experiments which have been reconstructed using the data on $|S|$, $|D|$ and $\phi_{SD}$ together with Breit Wigner fits to the tensor mesons which provide the absolute phase [6]. The comparison of both reactions has also demonstrated through its interference with the tensor mesons that

$$ T(\pi\pi \to f_0(1500) \to K\bar{K}) = -T(\pi\pi \to f_0(1500) \to \eta\bar{\eta}) \quad (9) $$
which implies that the $f_0(1500)$ has an opposite sign of the $n\bar{n}$ and $s\bar{s}$ components [6]. A similar Argand diagram has been obtained for $\pi\pi \to K\bar{K}$ [25]; the opposite orientation of both amplitudes in (9) is also visible in the energy dependent fits in [26] although with different overall phase. Unfortunately, the elastic $\pi\pi$ scattering is not yet uniquely determined in this region.

Further interesting information on this meson can again be obtained from decays of $D$ and $D_s$ charmed mesons. In the decay $D_s \to \pi\pi\pi$ the scalars $f_0$ can be produced through the intermediate process $s\bar{s} \to \pi\pi$. This favours intermediate states with large $s\bar{s} - n\bar{n}$ mixing. One observes a strong signal from $f_0(980)$ which proves again its strong $s\bar{s}$ component and a higher mass state related to $f_0(1500)$ by E687 [20] and to $f_0(1370)$ by E791 [21]. The signal is strongest near the edge of phase space in the Dalitz plot where the two resonance bands cross but the mass and width appear to be closer to $f_0(1500)$. Ultimately the study of branching ratios of this state has to decide. For the time being we take this state as $f_0(1500)$.

An interesting feature common to both experiments is the large relative phase consistent with $180^\circ$ between the production amplitudes of $f_0(980)$ and “$f_0(1500)$” which we interpret as

$$T(s\bar{s} \to f_0(980)) = -T(s\bar{s} \to f_0(1500)).$$

This negative phase in the fit to the Dalitz plot obviously corresponds to a lack of enhancement at the off diagonal crossing point of the two resonance bands in this plot which contrasts the strong enhancement in the diagonal crossing points.

The mass of $f_0(1500)$ is close to the glueball mass obtained in quenched approximation of lattice QCD. This at first has lead to models with close connection between these two states [27]; further studies now prefer mixing models where the superposition of the glueball and nearby $q\bar{q}$ mesons correspond to the physical states $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ (for overview, see [13]). As an example we quote a recent result motivated by lattice calculations on mixing [28, 3]

$$f_0(1500) = -0.36 n\bar{n} + 0.91 s\bar{s} - 0.22 \text{ glueball}. \quad (11)$$

In this example the glueball component of the $f_0(1500)$ has a weight of only $\sim 5\%$.

Contrary to a single glueball which would mix with the flavour singlet we see in (11) $n\bar{n}$ and $s\bar{s}$ with opposite sign. This octet type flavour mixing is in line with our findings (9),(10) and appears as “robust result” in fits of the above kind [29]. On the other hand, our finding (9) not only requires an octet type flavour mixing but also provides an upper limit to the glueball contribution; this contribution would add with the same sign to all pairs of pseudoscalars. This is an important additional limitation to such fits not yet taken into account so far.

If we take these observations together, especially the large components of both $n\bar{n}$ and $s\bar{s}$ (suggested from $D_s$ decays) and their negative relative sign, then $f_0(980)$ and $f_0(1500)$ look like the orthogonal isoscalar members of the $q\bar{q}$ nonet. We will come back to this idea below.
**The $f_0(400–1200)$ and the $\sigma(600)$ meson**

This entry in the PDG refers to results from $\pi\pi$ phase shift analyses and from the observation of peaks in mass spectra around 400-600 MeV. We give a short account of these observations.

### $\pi\pi$ phase shifts and $f_0(400–1200)$

It is a common feature of fits to $\pi\pi$ scattering that there is one broad object where the width is comparable to the mass (see [6], for example). The $\pi\pi$ scattering amplitudes are rather well known by now up to $\sim 1.4$ GeV, from single pion production with and without polarized target. Recent studies have removed remaining ambiguities [30] below 1 GeV in favour of a slowly rising S wave phase shift in the $\rho$ region, excluding in particular a rapidly varying phase and resonance under the $\rho$, in essential agreement with the old results which were obtained using particular assumptions on the production mechanism [10]. A theoretical analysis [31] based on the constraints from S matrix theory provides a good description of the observed low energy (below 1 GeV) pion-pion interactions with slowly varying S wave.

The interpretation of the $I = 0$ S wave in terms of resonant states is less straightforward. The phase shifts pass through $90^\circ$ at $\sim 1000$ MeV once the $f_0(980)$ effects are subtracted. This suggests a state at 1000 MeV [32, 6] with a large width of 500-1000 MeV. With a negative background phase added the resonance position can be shifted towards lower values and this has been considered as state $\sigma(600)$ in [33]. Fits over a large mass region including a background term yield resonance poles in the scattering amplitude around 1300 MeV or higher, again with a large width [34]. With such broad states the determination of the resonance mass depends on the assumed background in an essential way. There is a strong $\pi\pi$ interaction around 1 GeV and beyond but not necessarily and exclusively a broad $\sigma(600)$.

### Peaks in mass spectra and $\sigma(600)$

There are a number of effects which have been related to $\sigma(600)$.

1. Decay $J/\psi \rightarrow \omega\pi\pi$

   There is a peak around 500 MeV in the $\pi\pi$ mass spectra besides a strong signal from $f_2(1270)$ [35]. For a Breit Wigner $\sigma$ resonance at 500 MeV the interference term $Re(SD^*)$ between the (almost real) D wave and the resonant S wave would change sign at the pole position and so the angular distribution $d\sigma/d\Omega \sim |S|^2 + (3\cos^2\theta - 1)Re(SD^*)/2 + O(|D|^2)$ would vary accordingly with a sign change of the $\cos^2\theta$ term (from + to −). The data [35] do not show any sign change below 750 MeV and therefore there is no indication for a Breit Wigner resonance below this mass.

2. $Y', Y'' \rightarrow Y\pi\pi$ and similar decays of $J/\psi$

   Mass peaks are observed here as well. Unfortunately the angular distributions are not measured as function of the mass. Hopefully such measurement will be provided in the
3. Central production $pp \rightarrow p(\pi\pi)p$

At small momentum transfers between the protons this process is assumed to be dominated by double Pomeron exchange. The centrally produced $\pi\pi$ system peaks shortly above threshold below 400 MeV [36, 37, 38, 39] and has been related to the $\sigma(600)$ as well [37]. There are some other remarkable features in this process. Quite unusually, there is a strong D wave near threshold as well which peaks near 500 MeV; the total D wave contributions $\sum |D_\lambda|^2$ at their peak are about five times larger than the $f_2(1270)$ contribution and about one third of the S wave contribution at its peak.

These observations are very similar to findings in $\gamma\gamma \rightarrow \pi\pi$ which suggest a close relation between the processes [8]

$$\text{Pomeron Pomeron} \rightarrow \pi\pi \quad \leftrightarrow \quad \gamma\gamma \rightarrow \pi\pi \quad (12)$$

In fact, the $I = 0$ S wave component obtained from a fit to $\gamma\gamma \rightarrow \pi\pi$ for charged and neutral pions [40] peaks below 400 MeV and the D wave near 500 MeV with similar ratio 1/3; the origin of this unusual behaviour is the contribution of one-pion-exchange to $\gamma\gamma \rightarrow \pi^+\pi^-$. Therefore we propose that one-pion-exchange dominates the double Pomeron reaction at small $\pi\pi$ masses as well [8]. It reproduces the main characteristics. As the pion pole is near the physical region the $\pi\pi$ angular distribution is very steep, steeper than in more typical interactions mediated by vector ($\rho$) exchange. Therefore one estimates that the D wave becomes important not at $m_{f_2}$ but already at $m_{f_2} \times (m_\pi/m_\rho) \sim 0.3$ GeV. This mechanism also explains the low mass peak of the S wave without associated phase variation. In fact, in the region of the peak no strong S-D phase variation is observed [38, 39] as would be expected for a $\sigma(600)$ resonance. The presence of the one-pion-exchange process does not exclude the presence of broad states as in $\pi\pi$ elastic scattering either from $\pi\pi$ rescattering or by direct formation, very much as it is discussed in the $\gamma\gamma$ process [40]; but there is no evidence for an additional low mass $\sigma(600)$ resonance near the peak.

4. Decay $D^+ \rightarrow \pi^-\pi^+\pi^+$

The $\pi^+\pi^-$ mass spectrum presented by the E791 Collaboration [21, 22] shows three prominent peaks, one just above $\pi\pi$ threshold, one related to $\rho$ and one to $f_0(980)$. Only fits including a light $\sigma$ particle have been found successful according to their analysis. In principle, the low mass peak could be due to the decays of resonances with higher spin $J \geq 1$ in the crossed channel.

Again, one would like to see the related Breit Wigner phase motion in a more direct way. There should be a large term $\text{Re}(SP^*)$ from the interference $\sigma - \rho$ which changes sign near the $\sigma$ resonance in $s_{12}(\pi^-\pi^+_1)$ and therefore changes sign of the forward backward asymmetry in the $\sigma$ decay angle $\cos\theta$ which is linearly related to the mass variable $s_{13}(\pi^-\pi^+_2)$ along the $\sigma$ resonance ($s_{12}$) band in the Dalitz plot. Such an effect is actually visible in the Dalitz plot at the $\rho$ resonance (presumably from the $(\rho - f_0(980)$ interference): the sign change of the asymmetry causes the appearance of the tails towards lower and higher mass ($s_{12}$) at the upper and lower part ($s_{13}$) of the $\rho$ band respectively. A study with sufficiently fine binning should reveal this effect for the $\sigma$

---

1 Some global properties of this process have been considered already long ago [41].
in the resonance Monte Carlo for the $\sigma + \rho$ superposition and prove or disprove the presence of the interference effect in the data (a sensitive observable is $\langle \cos \theta \rangle$ $d\sigma / ds_{12}$ together with $d\sigma / ds_{12}$).

The $f_0(1370)$ meson

There is strong interaction in $\pi\pi$ and other channels in this mass region but again the clear evidence for a localized Breit Wigner phase motion is missing to support the resonance hypothesis. The $f_0(1370)$ and $f_0(400 - 1200)$ look like parts of a broader state in the channels with two pseudoscalars [6]. The missing information could be provided by phase shift analysis of recent high statistics $\pi^0\pi^0$ data [14, 42]. Furthermore, the resonance interpretation is found not consistent [13] with the different branching ratios observed in the $4\pi$ channel; there could be a broad background state interfering with the narrow $f_0(1500)$ to cause a peak near 1370 MeV. Again a phase shift analysis is necessary to clarify the situation.

CONSTRUCTION OF THE LIGHTEST QUARK ANTI-QUARK NONET

For the time being neither the $\sigma(600)$ nor the $f_0(1370)$ are acceptable for us as genuine resonant states. There are peaks at these masses but the associated Breit Wigner phase variation has not yet been established. Then the most natural candidates for the lightest $q\bar{q}$ nonet are

$$f_0(980), \quad f_0(1500), \quad K_0^*(1430), \quad a_0(980)$$

with mixing pattern very similar to the one observed in the pseudoscalar nonet

$$f_0(980) \sim \eta' \sim \text{singlet} \quad f_0(1500) \sim \eta \sim \text{octet}. \quad (14)$$

A solution like this has been proposed on the basis of a renormalizable sigma model with instanton interactions [43]. It also has $f_0(1500)$ as octet member but would prefer $a_0(1450)$ over $a_0(980)$ as isovector. It explains why the octet state is above the singlet for the scalars and vice versa for the pseudoscalars. Similar models have been studied in [44, 45].

Independently, the correspondence (14) and the nonet (13) have been proposed on the basis of the phenomenological analysis [6]. These results were found consistent with a general QCD potential model for sigma variables; in this analysis the choice $m(a_0(980)) \approx m(f_0(980))$ is possible although not required or explained. Furthermore, it has been shown that the octet in (13),(14) fulfills approximately the Gell Mann Okubo formula, and from $a_0$ and $K_0^*$ one predicts

$$3(m_{f_8}^2 - m_{a}^2) = 4(m_{K_0^*}^2 - m_{a}^2) \quad \rightarrow \quad m_{f_8} = 1550 \text{ MeV} \quad (15)$$

a good result for the octet isoscalar.
In the low mass region we are now left with $f_0(400 - 1200)$ and $f_0(1370)$ to which we come back below. It is interesting to note that the remaining states in the PDG below 2 GeV (Table 1) can be grouped together into a second nonet which includes

$$f_0(1720), \quad f_0(2020), \quad K_0^*(1950), \quad a_0(1450). \quad (16)$$

In this case the Gell Mann Okubo formula predicts for the octet scalar $m_{f_8} = 2.080$ GeV which fits to the highest state in (16) and therefore this nonet would repeat the mixing pattern of the lowest nonet. However as there is little further information on these states this assignment is rather speculative.

CANDIDATE FOR LIGHTEST GLUEBALL

After having selected the lightest nonet from well established resonances we are left with $f_0(400 - 1200)$ and $f_0(1370)$. The $\pi\pi$ data are consistent with the view that both states correspond to the low and high mass tails of a single resonance ("red dragon" [6]) and this state we take as the glueball

$$f_0(400 - 1200) \quad \text{and} \quad f_0(1370) \rightarrow gb(1000). \quad (17)$$

This mass corresponds to a resonance fit of $\pi\pi$ elastic scattering without background, other fits have lead to higher masses with the option of a broad glueball near 1400 MeV [34]. These results are a bit lower than expected from the lattice results in quenched approximation but looking at the large width and the still approximate nature of QCD results there is not necessarily a contradiction.

Our detailed arguments in favour of this glueball assignment have been summarized elsewhere [7, 8], together with plausible arguments for a large width of an S wave binary glueball. Here we only recall the most relevant observations.

1. The state $gb(1000)$ is produced in most reactions which are considered as gluon rich: a. central production $pp \rightarrow pXp$; b. Decays of radially excited heavy quarkonia like $Y', Y'' \rightarrow Y(\pi\pi)$; c. $p\bar{p} \rightarrow 3\pi$

2. There is no prominent signal however in $J/\psi \rightarrow \gamma\pi\pi$ for $m_{\pi\pi} < 1$ GeV, this could possibly be due to instrumental problems at small masses.

Alternatively one may attempt to explain the strong $\pi\pi$ interaction in the 1 GeV region without direct channel resonance in terms of $\rho - f$ exchange processes ($\rho$ alone would not explain the strong $\pi^0\pi^0$ interaction) and to obtain the moving phase from a unitarization procedure (see review [13]). In considering this proposal we note that a t-channel analysis of $\pi\pi$ scattering [47] indicates a large component in the $I_t = 0$ channel which is not related to $q\bar{q}$ Reggeon exchange but indicates Pomeron exchange or gluonic interactions already for $m_{\pi\pi} < 1$ GeV [7, 8]. So in this explanation one has to take into account the presence of non-resonant effects and avoid double counting of direct and crossed channel exchanges where the fit has to be done to all isospin amplitudes.
SUMMARY AND CONCLUSIONS

We have presented the arguments to include the isoscalars $f_0(980)$ and $f_0(1500)$ in the lightest scalar nonet. Various ratios of branching fractions as well as new results on relative phases between different $q\bar{q}$ components and between the production amplitudes could be explained consistently in terms of one parameter, the scalar mixing angle $\phi_s = 35^\circ \pm 4^\circ$. This is found close to the pseudoscalar equivalent but very different from “ideal mixing” with $\phi_s = 0^\circ, 180^\circ$. The nonet (13) fulfills the Gell Mann Okubo formula which relates the masses of octet particles assuming symmetry breaking by quark mass terms. It will be important to improve the accuracy of these measurements as test of this classification scheme. Also it will be interesting to see whether the $K\bar{K}/4q$ model for $f_0/a_0(980)$ can explain the data discussed here.

We do not see evidence yet for the Breit-Wigner resonance nature of peaks related to $\sigma(600)$. It will be important to investigate the phase motion in $D \to \sigma\pi$. In some cases there is counter evidence for the expected phase motion (like $J/\psi \to \omega\pi\pi$ and $pp \to p(\pi\pi)p$). Therefore the existence of a meson multiplet below 1 GeV is not apparent. Also there is a lack of evidence for $f_0(1370)$ so far. There are data available which could be analysed in this respect (for example $\pi^- p \to \pi^0\pi^n$).

The PDG listing allows for a second scalar nonet below 2 GeV with similar mixing.

This leaves the broad state around 1 GeV (built from $f_0(400-1200)$ and $f_0(1370)+$ more (?)) with the large width of 500 - 1000 MeV as a candidate for the lightest scalar glueball. This assignment is in agreement with most phenomenological expectations. Also we do not see an obvious disagreement with QCD results taking into account the approximate nature of the calculations.

In alternative approaches a superposition of glueball and two neighbour scalar quarkonia (from nonet) builds up the physical states $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$. In effect this would imply that the glueball is not localized in a narrow mass interval but contributes to scattering processes in quite a large mass range of $\sim 500$ MeV as it happens in our “broad glueball” scheme. Major differences are in the $q\bar{q}$ sector, especially concerning the existence of $f_0(1370)$ and treating the left alone states $f_0, a_0(980)$ as molecules or forming an additional nonet around “$\sigma(600)$”. Therefore improved experimental data and analyses in the low energy region are of great importance.

Of course it would be nice to have a more direct evidence for the gluonic nature of a particular candidate. A promising tool is the comparative study of glueball candidates in the fragmentation region of both quark and gluon jets [48, 49]. First results [50] look promising in indicating an extra neutral component in the gluon jet. There is something to look forward to.

ACKNOWLEDGMENTS

I would like to thank Peter Minkowski for discussions and collaboration on the problems presented in this talk.
REFERENCES

1. Particle Data Group, D.E. Groom et al., Eur. Phys. J. C15, 1 (2000).
2. G.S. Bali, “Glueballs: Results and Perspectives from the Lattice”, hep-ph/0110254.
3. C.J. Morningstar, this conference.
4. S. Narison, Nucl. Phys. B 509 (1998) 312.
5. T.G. Steele and D. Harnett, “Two Topics in QCD Sum-Rules”, hep-ph/0108232.
6. P. Minkowski and W. Ochs, Eur. Phys. J. C 9, 283 (1999).
7. P. Minkowski and W. Ochs, Proc. Workshop on Hadron Spectroscopy, Frascati, March 1999, Italy, Eds. T. Bressani et al., Frascati Physics Series XV, p.245 (1999).
8. P. Minkowski and W. Ochs, in preparation.
9. S.D. Protopopescu et al., Phys. Rev. D 7, 1279 (1973).
10. B. Hyams et al., Nucl. Phys. B 64, 4 (1973); W. Ochs, thesis 1973 (unpublished).
11. OPAL Collaboration, K. Ackerstaff et al., Eur. Phys. J. C 4, 19 (1998).
12. S. Narison, Nucl. Phys. B 509 (1998) 312.
13. T.G. Steele and D. Harnett, “Two Topics in QCD Sum-Rules”, hep-ph/0108232.
14. P. Minkowski and W. Ochs, Eur. Phys. J. C 9, 283 (1999).
15. P. Minkowski and W. Ochs, Proc. Workshop on Hadron Spectroscopy, Frascati, March 1999, Italy, Eds. T. Bressani et al., Frascati Physics Series XV, p.245 (1999).
16. P. Minkowski and W. Ochs, in preparation.
17. S.D. Protopopescu et al., Phys. Rev. D 7, 1279 (1973).
18. B. Hyams et al., Nucl. Phys. B 64, 4 (1973); W. Ochs, thesis 1973 (unpublished).
19. OPAL Collaboration, K. Ackerstaff et al., Eur. Phys. J. C 4, 19 (1998).
20. S. Narison, Nucl. Phys. B 509 (1998) 312.
21. T.G. Steele and D. Harnett, “Two Topics in QCD Sum-Rules”, hep-ph/0108232.
22. P. Minkowski and W. Ochs, Eur. Phys. J. C 9, 283 (1999).
23. P. Minkowski and W. Ochs, Proc. Workshop on Hadron Spectroscopy, Frascati, March 1999, Italy, Eds. T. Bressani et al., Frascati Physics Series XV, p.245 (1999).
24. P. Minkowski and W. Ochs, in preparation.
25. S.D. Protopopescu et al., Phys. Rev. D 7, 1279 (1973).
26. B. Hyams et al., Nucl. Phys. B 64, 4 (1973); W. Ochs, thesis 1973 (unpublished).
27. OPAL Collaboration, K. Ackerstaff et al., Eur. Phys. J. C 4, 19 (1998).
28. S. Narison, Nucl. Phys. B 509 (1998) 312.
29. T.G. Steele and D. Harnett, “Two Topics in QCD Sum-Rules”, hep-ph/0108232.
30. P. Minkowski and W. Ochs, Eur. Phys. J. C 9, 283 (1999).
31. P. Minkowski and W. Ochs, Proc. Workshop on Hadron Spectroscopy, Frascati, March 1999, Italy, Eds. T. Bressani et al., Frascati Physics Series XV, p.245 (1999).
32. P. Minkowski and W. Ochs, in preparation.
33. S.D. Protopopescu et al., Phys. Rev. D 7, 1279 (1973).
34. B. Hyams et al., Nucl. Phys. B 64, 4 (1973); W. Ochs, thesis 1973 (unpublished).
35. OPAL Collaboration, K. Ackerstaff et al., Eur. Phys. J. C 4, 19 (1998).
36. S. Narison, Nucl. Phys. B 509 (1998) 312.
37. T.G. Steele and D. Harnett, “Two Topics in QCD Sum-Rules”, hep-ph/0108232.
38. P. Minkowski and W. Ochs, Eur. Phys. J. C 9, 283 (1999).
39. P. Minkowski and W. Ochs, Proc. Workshop on Hadron Spectroscopy, Frascati, March 1999, Italy, Eds. T. Bressani et al., Frascati Physics Series XV, p.245 (1999).
40. P. Minkowski and W. Ochs, in preparation.
41. S.D. Protopopescu et al., Phys. Rev. D 7, 1279 (1973).
42. B. Hyams et al., Nucl. Phys. B 64, 4 (1973); W. Ochs, thesis 1973 (unpublished).
43. OPAL Collaboration, K. Ackerstaff et al., Eur. Phys. J. C 4, 19 (1998).
44. S. Narison, Nucl. Phys. B 509 (1998) 312.
45. T.G. Steele and D. Harnett, “Two Topics in QCD Sum-Rules”, hep-ph/0108232.
46. P. Minkowski and W. Ochs, Eur. Phys. J. C 9, 283 (1999).
47. P. Minkowski and W. Ochs, Proc. Workshop on Hadron Spectroscopy, Frascati, March 1999, Italy, Eds. T. Bressani et al., Frascati Physics Series XV, p.245 (1999).
48. P. Minkowski and W. Ochs, in preparation.
49. S.D. Protopopescu et al., Phys. Rev. D 7, 1279 (1973).
50. B. Hyams et al., Nucl. Phys. B 64, 4 (1973); W. Ochs, thesis 1973 (unpublished).
51. OPAL Collaboration, K. Ackerstaff et al., Eur. Phys. J. C 4, 19 (1998).
52. S. Narison, Nucl. Phys. B 509 (1998) 312.
53. T.G. Steele and D. Harnett, “Two Topics in QCD Sum-Rules”, hep-ph/0108232.
54. P. Minkowski and W. Ochs, Eur. Phys. J. C 9, 283 (1999).
55. P. Minkowski and W. Ochs, Proc. Workshop on Hadron Spectroscopy, Frascati, March 1999, Italy, Eds. T. Bressani et al., Frascati Physics Series XV, p.245 (1999).
56. P. Minkowski and W. Ochs, in preparation.
57. S.D. Protopopescu et al., Phys. Rev. D 7, 1279 (1973).
58. B. Hyams et al., Nucl. Phys. B 64, 4 (1973); W. Ochs, thesis 1973 (unpublished).
59. OPAL Collaboration, K. Ackerstaff et al., Eur. Phys. J. C 4, 19 (1998).
60. S. Narison, Nucl. Phys. B 509 (1998) 312.
61. T.G. Steele and D. Harnett, “Two Topics in QCD Sum-Rules”, hep-ph/0108232.
62. P. Minkowski and W. Ochs, Eur. Phys. J. C 9, 283 (1999).
63. P. Minkowski and W. Ochs, Proc. Workshop on Hadron Spectroscopy, Frascati, March 1999, Italy, Eds. T. Bressani et al., Frascati Physics Series XV, p.245 (1999).
64. P. Minkowski and W. Ochs, in preparation.
65. S.D. Protopopescu et al., Phys. Rev. D 7, 1279 (1973).
66. B. Hyams et al., Nucl. Phys. B 64, 4 (1973); W. Ochs, thesis 1973 (unpublished).
67. OPAL Collaboration, K. Ackerstaff et al., Eur. Phys. J. C 4, 19 (1998).
68. S. Narison, Nucl. Phys. B 509 (1998) 312.