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THE $J^{PC} = 0^{++}$ SCALAR MESON NONET AND GLUEBALL OF LOWEST MASS

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ABSTRACT

The evidence for the low mass $J^{PC} = 0^{++}$ states is reconsidered. We suggest classifying the isoscalars $f_0(980)$ and $f_0(1500)$ as members of the 0^{++} nonet, with a mixing rather similar to that of the pseudoscalars η' and η. The broad state called $f_0(400-1200)$ or "sigma" and the state $f_0(1370)$ are considered as different signals from a single broad resonance, which we take to be the lowest-lying 0^{++} glueball. The main arguments in favor of these hypotheses are presented and compared with theoretical expectations.

1 Introduction

This session of the workshop is devoted to the study of the "sigma" particle, which is related to the large S-wave $\pi\pi$ scattering amplitude; it peaks around 800 MeV and again near 1300 MeV. The nature of this S wave enhancement was under discussion since the very beginning of $\pi\pi$ interaction studies[1] and the interpretation is still developing. Its role in S-matrix and Regge theory, chiral theories and $q\overline{q}$ spectroscopy is considered since; after the advent of QCD the possibility of glueball spectroscopy [2)] has opened up as well which is in the focus of our attention. In

[1] For a summary of the early phase of studies in the seventies, see [1)].

order to obtain the proper interpretation of the "sigma", a classification of all low lying $J^{PC} = 0^{++}$ states into the $q\overline{q}$ nonet and glueball states appears necessary. To this end we first discuss the evidence for the low mass scalar states ($\leq$ 1600 MeV) and then proceed with an attempt of their classification as quarkonium or glueball states from their properties in production and decay. We will argue that the "sigma" is actually the lightest glueball. The main arguments for our classifications will be presented, further details of this study can be found in the recent publication. [3]

2 Evidence for light 0^{++} states with $I = 0$

The Particle Data Group [4] lists the following $I = 0$ scalar states: $f_0(400-1200)$ which is related to the "sigma", $f_0(980)$, $f_0(1370)$ and $f_0(1500)$, not all being firmly established. The existence of a resonance is not only signaled by a peak in the mass spectrum but it requires in addition that the scattering amplitude moves along a full circle in the complex plane ("Argand diagram").

The first two states have been studied in detail in the phase shift analysis of elastic $\pi^+\pi^-$ scattering. As discussed by K. Rybicki [5], the results from high statistics experiments with unpolarized [6] and polarized target [7] have led to an almost unique solution up to 1400 MeV out of the total of four. On the other hand, recent data on the $\pi^0\pi^0$ final state from GAMS [8] show a different behaviour of the S-D wave phase differences above 1200 MeV. A complete phase shift analysis would provide an important consistency check with the previous $\pi^+\pi^-$ results. Another experiment on $\pi^0\pi^0$ pair production is in progress (BNL–E852 [9]), the preliminary mass spectrum is shown in fig.1a. One can see a broad spectrum with two or three peaks (which we refer to as the "red dragon"). There is no question about the existence of $f_0(980)$ which causes the first dip near 1 GeV by its interference with the smooth "background".

More controversial is the interpretation of the second peak which appears in the region 1200-1400 MeV in different experiments. If we remove the $f_0(980)$ from a global resonance fit of the spectrum the remaining amplitude phase shift moves slowly through 90° near 1000 MeV and continues rising up to 1400 MeV where it has largely completed a full resonance circle (see also [11]). A local Breit-Wigner approximation to these phase shifts yields

$$\text{"sigma"}: \qquad m \sim 1000 \text{ MeV}, \qquad \Gamma \sim 1000 \text{ MeV}. \tag{1}$$

In this interpretation the second peak does not correspond to a second resonance – $f_0(1370)$ – but is another signal from the broad object. A second resonance would

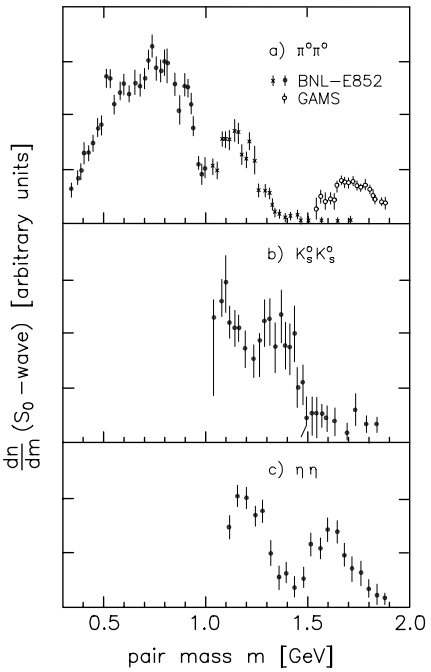

Figure 1: *Isoscalar S-wave components of the mass spectra of pseudoscalar pairs produced in πp-collisions at small momentum transfers t, (a) $\pi^0\pi^0$ spectrum, recent results* [9, 12]*; (b) $K_s^0 K_s^0$ spectrum* [13] *and (c) $\eta\eta$ spectrum.* [14]

require a second circle which is not seen. [6, 7] Therefore, a complete phase shift analysis of the $\pi^0\pi^0$ data in terms of resonances is important for consolidation.

We also investigated whether the state $f_0(1370)$, instead, appears with sizable coupling in the inelastic channels $\pi\pi \to K\overline{K}$, $\eta\eta$ where peaks in the considered mass region occur as well, although not all at the same position, see fig.1b,c. To this end we constructed the Argand diagrams for these channels in fig.2. A similar result for $K\overline{K}$ has been found already from earlier data. [15]

The movement of the amplitudes in the complex plane (fig.2) can be interpreted in terms of a superposition of a resonance and a slowly varying background. We identify the circles with the $f_0(1500)$ state which has been studied in great detail by Crystal Barrel. [16] This resonance can be seen to interfere with opposite sign in the two channels in figs.2a,b with the background and this also explains the shift of the peak positions in fig.1b,c. Thus, the structures in the 1300 MeV region do not correspond to additional circles, therefore no additional Breit-Wigner resonance $f_0(1370)$ is associated with the respective peaks.

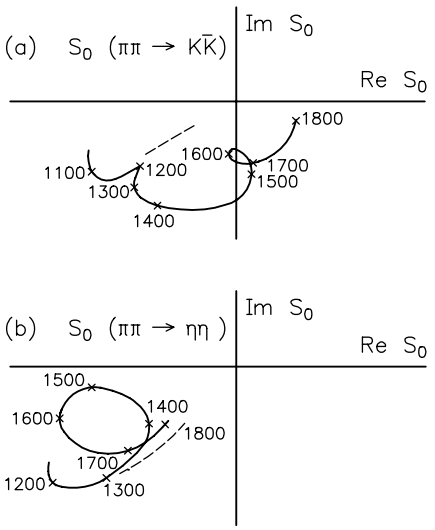

Figure 2: *Argand diagrams of the isoscalar S-wave amplitudes constructed* [3] *from data on the mass spectra shown in fig.1 and the relative phases between S and D-waves,* [13, 14] *assuming a Breit-Wigner form for the latter. The numbers indicate the pair masses in MeV, the dashed curves give an estimate of the background.*

3 The $J^{PC} = 0^{++}$ nonet of lowest mass

As members of the nonet we take the two isoscalars $f_0(980)$ and $f_0(1500)$ which are mixtures of flavor singlet and octet states. Furthermore we include the isovector $a_0(980)$ and the strange $K^*(1430)$. Then the only scalar states with mass below $\sim$ 1600 MeV left out up to now are the broad "sigma" to which we come back later and the $a_0(1450)$, which could be a radially excited state.

We find the mixing of the f_0 states like the one of the pseudoscalars, namely, with flavour amplitudes $(u\overline{u}, d\overline{d}, s\overline{s})$, approximately as

$$\begin{array}{lcll} f_0(980) & \leftrightarrow \; \eta'(958) & \sim \; \frac{1}{\sqrt{6}}(1,\ 1,\ 2) & \text{(near singlet)} \\ f_0(1500) & \leftrightarrow \; \eta(547) & \sim \; \frac{1}{\sqrt{3}}(1,\ 1,\ -1) & \text{(near octet)} \end{array} \qquad (2)$$

We have been lead to this classification and mixing by a number of observations:
1. $J/\psi \to \omega, \varphi + X$ decays
The branching ratios of J/ψ into $\varphi\ \eta'(958)$ and $\varphi\ f_0(980)$ are of similar size and about twice as large as $\omega\ \eta'(958)$ and $\omega\ f_0(980)$ which is reproduced by the above flavor composition.

2. Gell-Mann-Okubo mass formula

This formula predicts the mass of the octet member $f_0^{(8)}$. With our octet members a_0 and K_0^* as input one finds $m(f_0^{(8)}) = 1550$ MeV, or, with the η-η' type mixing included $m(f_0^{(8)}) = 1600$ MeV. The small deviation of $\sim$10% in m^2 from the mass of the $f_0(1500)$ is tolerable and can be attributed to strange quark mass effects.

3. Two body decays of scalars

Given the flavor composition eq.(2) we can derive the decay amplitudes into pairs of pseudoscalars whereby we allow for a $s\overline{s}$ relative amplitude S (for a similar analysis, see [17]). In particular, the branching ratios

$$f_0(980) \to \pi\pi, K\overline{K}; \qquad f_0(1500) \to \pi\pi, K\overline{K}, \eta\eta, \eta\eta'; \qquad a_0(980), f_0(980) \to \gamma\gamma \quad (3)$$

are found in satisfactory agreement with the data for values S around 0.5.

4. 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 $s\overline{s}$ component, see eq.(2), the sign of the $K\overline{K}$ 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.2a,b which show circles pointing in upward and downward directions, respectively. If $f_0(1500)$ were a glueball, then both circles should have positive sign as in fig.2b, but the experimental results are rather orthogonal to such an expectation.

Further tests of our classification are provided by the predictions on the decays $J/\psi \to \varphi/\omega + f_0(1500)$ and the $\gamma\gamma$ decay modes of the scalars.

4 The lightest 0^{++} glueball

In the previous analysis we have classified the scalar mesons in the PDG tables below 1600 MeV with the exception of $f_0(400-1200)$ and also of $f_0(1370)$ which we did not accept as standard Breit-Wigner resonance. We consider the broad spectrum in fig.1a with its two or three peaks as a single very broad object which interferes with the f_0 resonances. This "background" with slowly moving phase appears also in the inelastic channels (see fig.2). It is our hypothesis that this very broad object with parameters eq.(1) is the lightest glueball. We do not exclude some mixing with the scalar nonet states but it should be sufficiently small such as to preserve the main characteristics outlined before. We discuss next, how this glueball assignment fits with phenomenological expectations. [18, 3]

1. The large width

The unique feature of this state is its large width. There are two qualitative arguments [3] why this is natural for a light glueball:

a) For a heavy glueball one expects a small width as the perturbative analysis involves a small coupling constant α_s at high masses ("gluonic Zweig rule [2]). For a light glueball around 1 GeV this argument doesn't hold any more and a large α_s could yield a large width.

b) The light 0^{++} states are coupled mainly to pairs of pseudoscalar particles. Then, for a scattering process through a 0^{++} channel the external particles are in an S-wave state; an intermediate $q\overline{q}$ resonance will be in a P-wave state but an intermediate gg system in an S-wave again. Therefore the overlap of wave functions in the glueball case is larger and we expect

$$\Gamma_{gb_0} \gg \Gamma_{q\overline{q}-hadron}. \tag{4}$$

2. Reactions favorable for glueball production

a) The "red dragon" shows up also in the centrally produced systems in high energy pp collisions [19] which are dominated by double Pomeron exchange, with new results presented by A. Kirk. [20] Because of the gluonic nature of the Pomeron, this strong production coincides with the expectations.

b) The broad low mass $\pi\pi$ spectrum is also observed in decays of radially excited states $\psi' \to \psi(\pi\pi)_s$ and $Y', Y'' \to Y(\pi\pi)_s$ which are expected to be mediated by gluonic exchanges.

c) The hadrons in the decay $J/\psi \to \gamma$+hadrons are expected to be produced through 2-gluon intermediate states which could form a scalar glueball. However, in the low mass region $m < 1$ GeV only little S-wave in the $\pi\pi$ channel is observed.

3. Flavour properties

The branching ratios of the $f_0(1370)$ – which we consider as part of the glueball – into $K\overline{K}$ and $\eta\eta$ compare favorably with expectations.

4. 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, a very small cross section in the low mass region around 600 MeV. This could be partially due to hadronic rescattering and absorption, partly due to the smallness of the 2 photon coupling of the intermediate states. Unfortunately, the data in the f_2 region leave a large uncertainty on the S-wave fraction ($< 19\%$ [21]). In a fit to the data which takes into account the one-pion-exchange Born terms and $\pi\pi$ rescattering the two photon width of the states

$f_2(1270)$ and $f_0(400-1200)$ have been determined [22] as 2.84±0.35 and 3.8± 1.5 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, but we find (in units of 10^{-6})

$$R_2 = \frac{\Gamma(f_2(1270) \to \gamma\gamma)}{\Gamma(f_2(1270) \to \pi\pi)} \sim 15; \quad R_0 = \frac{\Gamma(f_0(400-1200) \to \gamma\gamma)}{\Gamma(f_0(400-1200) \to \pi\pi)} \sim 4-6, \quad (5)$$

thus, for the scalar state, this ratio is 3-4 times smaller, and it could be smaller by another factor 3 at about the 2σ level.[2] A more precise measurement of the S-wave cross section in the f_2 region would be very important for this discussion.

At present, we conclude that the 2γ width of the scalar state is indeed surprisingly small. In this model [22] an intermediate glueball would couple to photons through the intermediate $\pi^+\pi^-$ channel.

5. Quark-antiquark and gluonic components in $\pi\pi$ scattering

In the dual Regge picture the $2 \to 2$ scattering amplitude is built either from the sequence of s-channel resonances or from the sequence of t-channel Regge poles. There is a second component ("two component duality" [23]) which corresponds to the Pomeron in the t-channel and is dual to a "background" in the direct s-channel. If the Pomeron is related to glueballs, then one should have, by crossing, a third component with a glueball in the direct s-channel, dual to exotic exchange. [3]

The existence of the "background" process can be demonstrated by constructing the amplitudes for definite t-channel isospin I_t. Such an analysis has been carried out by Quigg [24] for $\pi\pi$ scattering and is shown in fig.3. Similar to what has been found in πN scattering [25] there are essentially background-free resonance circles for $I_t \neq 0$, but in the $I_t = 0$ amplitude (Pomeron exchange) the background rises with energy and is sizable already below 1 GeV. We take this result as a further hint that low energy $\pi\pi$ scattering is not dominated by $q\overline{q}$ resonances alone.

5 Theoretical expectations

5.1 QCD results on glueballs

1. Lattice QCD

In the calculation without sea-quarks ("quenched approximation") one finds the lightest glueball in the 0^{++} channel at masses 1500-1700 MeV (recent review [26]). These results have motivated various recent searches and scenarios for the lightest glueball. The identification with the well established $f_0(1500)$ state, either with or

[2] We thank Mike Pennington for the discussions about their analysis.

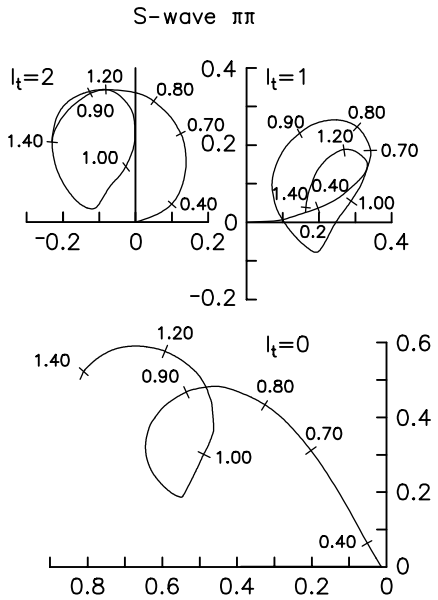

Figure 3: *Amplitudes for the $\pi\pi$ S-wave for definite t-channel Isospin I_t determined by Quigg* [24]*. The $I_t = 0$ amplitude has a large background which is not related to the $q\overline{q}$ resonances in the dual model approach.*

without mixing with other states, has some phenomenological difficulties, especially the negative amplitude sign into $K\overline{K}$ (fig.2a).

Some changes of these QCD predictions may occur if the full unquenched calculation is carried out. The first results by Bali et al. [27] indicate a decrease of the glueball mass with the quark masses; the latter are still rather large and correspond to $m_\pi \sim 700 \ldots 1000$ MeV. For the moment we conclude that our light glueball hypothesis is not necessarily in conflict with the lattice QCD results.

2. QCD sum rules

The saturation of the sum rules for the 0^{++} glueball was found impossible with a single state near 1500 MeV alone in a recent analysis. [28] Rather, the inclusion of a light glueball component was required and assumed to be coupled to states $\sigma_B(1000)$ and $\sigma_{B'}(1370)$. Already before, a sum rule solution with a light glueball ~ 500 MeV was proposed. [29]

3. Bag model

In a model which consideres quarks and gluons to be confined in a bag of comparable size and with radiative QCD corrections included, [30] the lightest glueball was suggested for 0^{++} at around 1 GeV mass.

5.2 Scalar nonet and effective Sigma variables

An important precondition for the assignment of glueball states is the understanding of the low mass $q\overline{q}$ spectroscopy.

1. Renormalizable linear sigma models

These models realize the spontaneous chiral symmetry breakdown and represent an attractive theoretical approach to the scalar and pseudoscalar mesons. An example is the approach by Törnqvist [31] which starts from a "bare" nonet respecting the OZI rule while the observed hadron spectrum is strongly distorted by unitarization effects.

In an alternative approach, [32] one starts from a 3-flavor Nambu-Jona-Lasinio model but includes a renormalizable effective action for the sigma fields with an instanton induced axial $U(1)$ symmetry-breaking term along the suggestion by t'Hooft. [33] In this model $f_0(1500)$ is near the octet and the light isoscalar near the singlet state; different options are pursued [32] for $f_0(980)$ and $a_0(980)$, at least one of them should be a non-$q\overline{q}$ state. This suggestion of a large singlet-octet mixing and the classification of the $f_0(1500)$ is close to our phenomenological findings in sect.3.

2. General effective QCD potential

In our approach [3] we do not restrict ourselves to renormalizable interaction terms. In this way the consequences of chiral symmetry in different limits for the quark masses can be explored in a general QCD framework. [34] In particular, it is possible to keep both $f_0(980)$ and $a_0(980)$ as $q\overline{q}$ states. Their degeneracy in mass can be obtained, although not predicted. An expansion to first order in the strange quark mass is investigated. The Gell-Mann-Okubo formula is obtained in this approximation; with an η-η' type mixing the observed states discussed in sect.3, with $f_0(1500)$ as the heaviest member of the nonet near the octet state, can be realized.

6 Conclusions

We found a classification of the low lying $J^{PC} = 0^{++}$ states which explains a large body of experimental and phenomenological results. The $q\overline{q}$ nonet includes $f_0(980)$ and $f_0(1500)$ with mixing similar to the pseudoscalars η' and η, furthermore $a_0(980)$ and $K^*(1430)$; η' and $f_0(980)$ appear as genuine parity doublet.

The lightest glueball is identified with the broad "sigma" corresponding to $f_0(400-1200)$ and $f_0(1370)$ of the PDG. The basic triplet of light binary glueballs is completed [3] by the states $\eta(1440)$ with 0^{-+} and $f_J(1710)$ with 2^{++}, not discussed here.

It will be important to further study production and decay of the states under discussion. Some particular questions we came across here include: a) unique phase shift solution for $\pi\pi$ scattering above 1 GeV for both charge modes ($+-$ and 00), b) production of $f_0(1500)$ in J/ψ decays, c) S-waves in radiative J/ψ decays and d) $\gamma\gamma$ widths of the scalar particles.

It remains an open question in this approach, though, what the physical origin of the $a_0 - f_0$ mass degeneracy is and where the mirror symmetry of the mass patterns in the scalar and pseudoscalar nonets comes from. A possible explanation for the latter structure is suggested by a renormalizable model with an instanton induced $U_A(1)$-breaking interaction.

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