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THE STATUS OF SCALAR MESONS: EVIDENCE FOR GLUEBALLS*

Eberhard Klempt

Institut für Strahlen– und Kernphysik der Universität Bonn
Nußallee 14–16, D-53115 Bonn, Germany

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A series of new scalar and tensor mesons has been discovered at LEAR, mostly in the Crystal Barrel experiment. One of these states, the $f_0(1500)$, has unusual properties: a comparatively narrow width and a decay pattern which seems incompatible with SU(3) relations based on the OZI rule. In a naive quark model a $s\bar{s}$ state should be expected at this mass but the $f_0(1500)$ partial decay width to $\bar{K}K$ is small. This leads to the conclusion that the state is supernumerous and must interpreted as the ground-state scalar glueball mixing with nearby quarkonia. Alternative interpretations are however not yet ruled out.

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1. Introduction

The central theme of meson spectroscopy is the test of a most striking prediction of QCD in the low energy domain: that glueballs should exist, bound states of gluons without constituent quarks [1]. Lattice gauge calculations give us a precise mass where they should be expected: the scalar glueball is predicted to have a mass of 1.61 ± 0.15 GeV, the tensor of 2.26 ± 0.22 and pseudoscalar glueball of 2.19 ± 0.32 GeV [2]. Mixing with ordinary quarkonium states may change their properties and makes it more difficult to find glueballs. Mesonic molecules, opening thresholds, multiquark or hybrid states may lead to further complications and to uncertainties in the interpretation of results. This is particularly difficult for scalar mesons which remain mysterious for a long time. Hence a precise understanding of the scalar mesons is required before the scalar glueball and its properties can be determined.

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2. The spectrum of scalar mesons

In the recent years the Crystal Barrel Collaboration recorded high-statistics high-quality data sets on $\bar{p}p$ annihilation at rest and in flight. In particular all-neutral final states proved to be very sensitive to scalar resonances and three new states, two scalar isoscalar mesons, the $f_0(1370)$ and $f_0(1370)$, and one scalar isovector meson, the $a_0(1450)$, were uncovered. The following final states have been analysed; the Dalitz plots (shown at the conference) demonstrate the large role of statistics in the interpretation of data. The plots can be found in the references given below.

$\bar{p}p \to 3\pi^0$	[3]	$\bar{p}p \to 2\pi^0\eta$	[4]	$\bar{p}p \to 2\pi^0\eta'$	[5]
$\bar{p}p \to \pi^0 2\eta$	[6]	$\bar{p}p \to \pi^0\eta\eta'$	[7]	$\bar{p}p \to \pi^0\eta\omega$	[8]
$\bar{p}p \to \mathrm{K}_l\mathrm{K}_l\pi^0$	[9]	$\bar{p}p \to \bar{K}K\pi$	[10]	$\bar{p}p \to 5\pi^0$	[11]
$\bar{p}p \to \pi^+\pi^-3\pi^0$	[12]	$\bar{p}n \to \pi^-4\pi^0$	[13]	$\bar{p}n \to \pi^+2\pi^-2\pi^0$	[13]

In these data a large number of scalar and tensor mesons is observed. They are listed in Table I. (The $\mathrm{K}_2(1950)$ is listed for convenience.) It is worthwhile to mention that 5 of the 10 scalar and tensor states below 1.7 GeV were discovered at LEAR in $\bar{p}p$ annihilation at rest.

Before entering a detailed discussion of possible interpretations of the $f_0(1500)$ I should like to emphasize its outstanding properties. The $K_0^*(1430)$ and the $a_0(1450)$ have widths of 286 MeV and 260 MeV, respectively. Using SU(3) relations, the width of the $f_0(1500)$ should be 700 MeV if it is an octet state. Its observed width of 150 MeV is much narrower; its $\pi\pi$ partial width is 25 MeV only, which is an extremely low value. This can also be seen when we compare the partial width to that of the $f_2(1270)$. The latter is about 150 MeV even though the centrifugal barrier should make the $f_2(1270)$ narrower than the $f_0(1500)$. This fact makes the $f_0(1500)$ a good glueball candidate.

3. The lowest scalar meson nonet

3.1. The glueball scenario

First we should notice that not all s-channel resonances are necessarily originating from truely resonating systems: t-channel exchanges may also generate phase shifts in the s-channel which are then interpreted as s-channel resonances. For the low-energy $\pi\pi$ mass spectrum this is most convincingly demonstrated by Speth and collaborators [14], by Zou and Bugg [15] or by Locher and collaborators [16]. We thus assume that the $f_0(400-1200)$ of the Particle Data Group (and the former $f_0(1300)$) are generated by t-channel exchanges and do not correspond to a true $\bar{q}q$ resonances.

TABLE I

The isoscalar and isovector S- and D-wave resonances as observed in the Crystal Barrel experiment at LEAR

$f_0(400-1200)$:			$\pi\pi$			
$f_0(975)$:	$M=$	(980 ± 20)MeV	$\pi\pi$	$\bar{K}K$		
	$\Gamma=$	(100 ± 20)MeV				
$f_0(1300)$:	$M=$	(1365 ± 50)MeV	$\pi\pi$	$\bar{K}K$	$\eta\eta$	4π
	$\Gamma=$	$(200-1000$MeV				
$f_0(1500)$:	$M=$	(1500 ± 15)MeV	$\pi\pi$	$\bar{K}K$	$\eta\eta$	$\eta\eta'$
	$\Gamma=$	(150 ± 20)MeV	$\sigma\sigma$	$\pi\pi(1300)$	$\rho\rho$	
$f_0(1710)$:	$M=$	(1750 ± 15)MeV	$\sigma\sigma$			
	$\Gamma=$	(150 ± 20)MeV				
$a_0(975)$:	$M=$	(985 ± 5)MeV	$\pi\eta$	$\bar{K}K$		
	$\Gamma=$	(54 ± 5)MeV				
$a_0(1450)$:	$M=$	(1450 ± 40)MeV	$\pi\eta$	$\bar{K}K$	$\pi\eta'$	
	$\Gamma=$	(270 ± 40)MeV				
$f_2(1270)$:	$M=$	(1265 ± 10)MeV	$\pi\pi$	$\bar{K}K$		
	$\Gamma=$	(54 ± 5)MeV				
$f_2(1565)$:	$M=$	(1565 ± 50)MeV	$\pi\pi$	$\eta\eta$		
	$\Gamma=$	(170 ± 50)MeV				
$a_2(1320)$:	$M=$	(1316 ± 5)MeV	$\pi\eta$	$\bar{K}K$		
	$\Gamma=$	(113 ± 4)MeV				
$a_2(1650)$	$M=$	(1650 ± 50)MeV	$\pi\eta$			
	$\Gamma=$	(220 ± 50)MeV				
$K_2(1430)$:	$M=$	(1430 ± 7)MeV		$\bar{K}K$		
	$\Gamma=$	(287 ± 24)MeV				
$K_2(1950)$	$M=$	(1945 ± 17)MeV	$\pi\eta$			
	$\Gamma=$	(201 ± 80)MeV				

The $f_0(980)$ and $a_0(980)$ are also mostly considered as non-$\bar{q}q$ states. Isgur and Weinstein argue that their unusual properties can be understood if they are $\bar{K}K$ molecules [17]. Speth and coworkers show that scattering and production data on the $f_0(980)$ and $a_0(980)$ can be fitted by a sum of s-channel and t-channel exchanges without the need for genuine resonances at the $\bar{K}K$ threshold [14]. Törnquist interprets the two states as conventional $\bar{q}q$ states; their unusual properties arise from the $\bar{K}K$ threshold in a unitarised quark model [18]. In any case there are reasons to exclude these two states from a discussion of the scalar meson nonet. We are thus left with the following states:

$a_0(1450)$	$f_0(1370)$	$f_0(1750)$	$K_0^*(1430)$	$f_0(1500)$

This is a redundancy of states: when counting the number of low-mass scalar $\bar{q}q$ states, the $f_0(1500)$ is supernumerous. Even worse, the decay pattern of none of the isoscalar mesons identifies a $s\bar{s}$ state in a straightforward way. So the $s\bar{s}$ state could even be missing, it might however also be the $f_0(1750)$. Assuming the $f_0(1370)$ to be the isoscalar partner of the $a_0(1450)$ we expect the $s\bar{s}$ state at 1600 to 1700 MeV and to decay dominantly into $\bar{K}K$; these facts exclude an interpretation of the $f_0(1500)$ as quarkonium state.

Yet the $f_0(1500)$ can also not be a pure glueball. A glueball should decay flavor-blind, hence $\pi\pi$, $\eta\eta$, $\eta\eta'$ and $\bar{K}K$ should be seen with couplings 3 : 1 : 0 : 4. This is not the case; instead we find $1 : 0.25 \pm 0.11 : 0.35 \pm 0.15 : 0.24 \pm 0.09$. Hence mixing with ordinary $\bar{q}q$ states is required.

Amsler and Close analysed the $f_0(1500)$ decays and found that its decay pattern is incompatible with both a glueball interpretation and an interpretation as $\bar{q}q$ state for any scalar mixing angle [1] [19]. However, the decay pattern can be reproduced when mixing of the $f_0(1500)$ with the $f_0(1370)$ and a $f_0(\bar{s}s)$ is introduced. In this scenario the $f_0(1500)$ is a glueball mixing with closeby scalar isoscalar states but with a large glueball component. The $f_0(1370)$ and the $f_0(s\bar{s})$ are mainly $q\bar{q}$ states with some glueball content.

Other mixing schemes have been proposed since then: in Weingarten's scheme the $f_0(1710)$ has more glue than $f_0(1500)$ [20]; Anisovich, Anisovich, and Sarantsev find 5 scalars below 1800 MeV, one glueball and two nonets (1^3P_0 and 2^3P_0) which are all mixed [21]. Narison allows the $f_0(1370)$, $f_0(1500)$, and the $f_0(1710)$ to share glue democratically [24]. So even when the precise mixing is not yet well understood, the analyses agree that a scalar glueball has intruded into the spectrum of scalar mesons. Most authors find a mass of the bare glueball at about 1600 MeV.

When the $f_0(1500)$ is a glueball then it must be produced in radiative J/ψ decays. Its appearant non-observation in those experiments was therefore an intruiging argument against the possibility that it should contain at least a large glueball component. A closer look at the J/ψ data reveals the possibility that the $f_0(1500)$ is produced in radiative J/ψ decays but escaped unobserved.

Data on radiative J/ψ decays into 4π show a distinct peak at 1500 MeV to which pseudoscalar quantum numbers had been assigned. In a recent reanalysis [25] it was shown that the data prefer scalar quantum numbers. The analysis has an important consequence: it demonstrates that likely the $f_0(1500)$ is produced in radiative J/ψ decays. A careful inspection of data on $J/\psi \to \pi\pi$, $\eta\eta$ and into 4π evidences small peaks at 1500 MeV in all three

[1] The statement is no longer strictly true since the $f_0(1500) \to \bar{K}K$ decay branching ratio seems to be larger than the upper limit given in a bubble chamber analysis.

mass projections. The data provide certainly no conclusive evidence for a scalar resonance at this mass, but they can also not be used as an argument against production of the $f_0(1500)$ in radiative J/ψ decays. Close has argued recently that the production rate of scalar glueballs in J/ψ decays should be small, in the order of 10^{-3} [26]. This value is not incompatible with the experimental findings.

Central production is believed to be a good place for a glueball search. It is known that no mesons or quark lines are exchanged in Central Production, the process is mediated by the exchange of Pomerons, particles which incorporate a large fraction of glue. It was therefore exciting when the WA91 collaboration reported observation of a narrow structure at 1450 MeV which was produced in central collisions but which disappeared when the two scattered protons were scattered with significant momentum transfers [27]. This fact argued in favor of a glueball interpretation but it seemed unlikely that two scalar states, the $f_0(1450)$ and the $f_0(1500)$, should exist in such a small mass interval. A reanalysis demonstrated that the data are also compatible in mass and width with the Crystal Barrel values once interference with the $f_0(1370)$ was taken into account [28].

Close and Kirk noticed that the resonance pattern in Central Production depends significantly on the transerve momentum balance [29]: the two protons may collide and be scattered into opposite directions so that the difference of the two transverse momenta p_T becomes large. This is a configuration in which well-established $\bar{q}q$ mesons are observed with large production cross sections. With a cut excluding large differences between transverse momenta — a configuration in which gluons from Pomerons might fuse into glueballs — production of conventional $\bar{q}q$ states is suppressed while the $f_0(980)$ and the $f_0(1500)$ remain as strong structures in the data [30]. Close and Kirk suggest that this mechanism provides strong evidence for the non-$\bar{q}q$ nature of these two states; they propose to use the cut on p_T as a filter to discriminate glueballs against conventional states. Of course, with vanishing relative linear momenta also the relative orbital angular momentum vanishes, and one might expect enhancement of scalar states.

3.2. Alternative interpretations of the scalar meson nonet

The interpretation of the $f_0(980)$ as $\bar{K}K$ bound state seems to contradict results of the GAMS collaboration investigating the reaction $\pi^- p \rightarrow \pi^0\pi^0 n$ as a function of the momentum transfer to the $\pi^0\pi^0$ system, *i.e.* with different spatial resolution. With moderate resolution there is a large background with a superimposed $f_0(980)$ which is seen to transfer intensity from the $\pi\pi$ background to $\bar{K}K$ due to strong $\pi\pi \rightarrow \bar{K}K$ coupling. With high spatial resolution the background disappears and the $f_0(980)$ shows up as clear peak. The q^2-dependence of the production of the $f_0(980)$ at sufficiently high resolution is that of a normal $\bar{q}q$ resonance while it is distinctively different for the background. This observation supports the idea that the background should originate from t-channel exchanges rather than from s-channel resonances while the $f_0(980)$ is of different character. A $\bar{q}q$ nature of the $f_0(980)$ is also suggested by recent findings of the OPAL collaboration comparing $f_0(980)$, $f_2(1270)$, and $\Phi(1020)$ production characteristics in Z^0 decays [31].

Once this concept is accepted, one has to allow for other t-channel effects. This could result in a coupling from $\pi\pi$ scattering to $\sigma\sigma$ and to $\rho\rho$ via pion exchange (with σ representing the $\pi\pi_{S-\mathrm{wave}}$) or to $\eta\eta$ via ρ exchange. Since the $\pi\pi$ scattering amplitude reaches a maximum at 1300 MeV, a maximum intensity at the same mass can also be expected in the 4π or 2η mass spectrum. Also the phase increases by 180° from 980 to 1500 MeV if these are 2 adjacent resonances. Without a proper treatment of t-channel exchanges I do not believe that the existence of the $f_0(1370)$ as $\bar{q}q$ resonance can be extracted from data with confidence. The number of scalar $\bar{q}q$ states, in particular the redundancy of the states, depends crucially on the existence of this supernumerous state.

It is well known that most quark models are not capable of describing the pseudoscalar nonet. In the limit of vanishing quark masses an octet of (pseudoscalar) Goldstone bosons is expected; with finite quark masses the symmetry is broken spontaneously and the Goldstone particles acquire masses. In SU(3) the η' should have a small mass, too. This is obviously not the case. This fact led 't Hooft to introduce a chiral invariant but γ_5-violating effective interaction which is OZI violating. With these instanton-induced interactions, the pseudoscalar mass spectrum can be reproduced accurately. In non-relativistic quark models, instanton interactions influence only the pseudoscalar nonet. Relativistically, they become also important for the scalar nonet. In this case alternative interpretations of the scalar meson spectrum are possible.

In [32] the mass spectrum of scalar mesons was calculated using the Bethe–Salpeter equation with a linear confinement potential. The parameters of the potential and the quark masses were adjusted to fit tensor mesons and higher orbital excitations. When the strength of instanton interactions is adjusted to fit the pseudoscalar meson masses, scalar meson masses are predicted as

$a_0(1320)$	$f_0(980)$	$f_0(1470)$	$K_0^*(1430)$

Remarkably, the $f_0(980)$ is the mainly singlet state, the $f_0(1470)$ the mainly octet state.

This interpretation has important implications: the $f_0(1500)$ as octet state has small coupling to $\bar{K}K$, the $s\bar{s}$ strength is predicted to be close to the $\bar{K}K$ threshold. There is thus no need for an extra unobserved $f_0(s\bar{s})$ state as postulated by Amsler and Close. The $f_0(980)$ is assumed to be a quarkonium state. One should remember that in J/ψ decays it is seen to be produced in $J/\psi{\to}\omega f_0(980)$ and to decay into $\bar{K}K$. This anomalous behaviour follows directly from its SU(3) isosinglet character.

Similar conclusions as those discussed in [32] have been obtained by Dmitrasinovic [33] using a Nambu–Jona-Lasinio model with instanton interactions, and by Burakovsky [34] who derived linear mass relations between scalar and pseudoscalar mesons. Both agree that the isosinglet meson should be lower in mass than the octet state and predict a mass for the isosinglet meson of about 1 GeV.

4. Summary and conclusions

The scalar meson nonet has changed its face. New information is available largely based on analyses of Crystal Barrel data. But also other experiments continue to make substantial contributions. There are two important issues:

First, I believe that the approaches based on instanton-induced interactions reflect a new perception of the scalar meson nonet. The organisation of the nonet with the low-mass isoscalar state as mainly-singlet state and with the high-mass isoscalar state as member of the meson octet expects the low-mass state to couple to $\bar{K}K$ and to $\pi\pi$ while the high-mass state should have a small branching ratio for kaonic decays (because of the negative sign between $u\bar{u}{+}d\bar{d}$ and $2s\bar{s}$). The observation in J/ψ decays of the $f_0(980)$ in its $\pi\pi$ decay mode recoiling against a Φ evidences the two facets of the $f_0(980)$: it has both components, $s\bar{s}$ and $(u\bar{u}{+}d\bar{d})$. This picture is, however, different from the findings of other groups which interprete the $f_0(980)$ as $\bar{K}K$ molecule.

Most important is, of course, the possibility that the $f_0(1500)$ is the long-awaited ground-state scalar glueball. There are several convincing arguments favoring this interpretation. The state is seen in $\bar{p}p$ annihilation at rest and in flight, in radiative J/ψ decays and in central production. Its width is incompatible with our expectation for the ${}^3P_0$ light-quark state while the $f_0(1370)$ fits nicely into a scalar nonet. The $f_0(1500)$ passes "the glueball filter" of Close and Kirk. Its mass agrees well with lattice gauge theory calculations.

Thus we are led to the conclusion that, likely, the $f_0(1500)$ is a glueball or contains at least a sizable glueball component. This conclusion depends however crucially on the interpretation of the $f_0(1370)$ as genuine $\bar{q}q$ resonance. This decisive question has to explored with scrutiny.

REFERENCES

[1] H. Fritzsch, U. Gell-Mann, XVI Int. Conf. on HEP, Vol 2 (1972), p. 135.

[2] M. Teper, Oxford U., HEP 97, Jerusalem, hep-ph/9711299.

[3] C. Amsler *et al.*, Crystal Barrel Collab., *Phys. Lett.* **B342**, 433 (1995).

[4] C. Amsler *et al.*, Crystal Barrel Collab., *Phys. Lett.* **B333**, 277 (1994).

[5] A. Abele *et al.*, Crystal Barrel Collab., *Phys. Lett.* **B404**, 179 (1997).

[6] C. Amsler *et al.*, Crystal Barrel Collab., *Phys. Lett.* **B353**, 571 (1995).

[7] C. Amsler *et al.*, Crystal Barrel Collab., *Phys. Lett.* **B340**, 259 (1994).

[8] C. Amsler *et al.*, Crystal Barrel Collab., *Phys. Lett.* **B327**, 425 (1994).

[9] C. Amsler *et al.*, Crystal Barrel Collab., *Phys. Lett.* **B385**, 425 (1996).

[10] A. Abele *et al.*, Crystal Barrel Collab., *Phys. Rev.* **D57**, 3860 (1998).

[11] C. Amsler *et al.* Crystal Barrel Collab., *Phys. Lett.* **B380**, 453 (1996).

[12] C. Amsler *et al.*, Crystal Barrel Collab., *Phys. Lett.* **B322**, 431 (1994).

[13] U. Thoma *et al.*, Crystal Barrel Collab., *Nucl. Phys.* **56A**, 216 (1997).

[14] G. Jansson, B.C. Pearce, K. Holinde, J. Speth, *Phys. Rev.* **D52**, 2690 (1994).

[15] B.S. Zou, D.V. Bugg, *Phys. Rev.* **D50**, 591 (1994).

[16] M.P. Locher, V.E. Markushin, H.Q. Zheng, *Eur. Phys. J.* **C4** 317 (1998).

[17] J. Weinstein, N. Isgur, *Phys. Rev.* **D41**, 2236 (1990).

[18] N. Tornquist, *Phys. Rev. Lett.* **49**, 624 (1982).

[19] C. Amsler, F.E. Close, *Phys. Rev.* **D53**, 295 (1996).

[20] H. Chen *et al.*, *Nucl. Phys.* **B34**, 357 (1994).

[21] A. Anisovich, V. Anisovich, A. Sarantsev, *Phys. Lett.* **B353**, 378 (1994).

[22] R.M. Barnett *et al.*, Particle Data Group, *Phys. Rev.* **D54**, 1 (1996).

[23] C. Amsler *et al.*, Crystal Barrel Collab., *Phys. Lett.* B355, 425 (1995).

[24] S. Narison, Masses, Decays and Mixings of Gluonia in QCD, hep-ph/9612448.

[25] D.V. Bugg *et al.*, *Phys. Lett.* **B353**, 378 (1994).

[26] F.E. Close G. Farrar, Z.P.Li, *Phys. Rev.* **D55**, 5749 (1997).

[27] S. Abatzis *et al.*, *Phys. Lett.* **B324**, 509 (1994).

[28] F. Antinori *et al.*, *Phys. Lett.* **B353**, 589 (1995).

[29] F.E. Close, A. Kirk, *Phys. Lett.* **B397**, 333 (1997).

[30] D. Barberis *et al.*, *Phys. Lett.* **B397**, 339 (1997).

[31] G. D. Lafferty, contribution to Hadron '97, BNL.

[32] E. Klempt, B.C. Metsch, C.R. Münz, H.R. Petry, *Phys. Lett.* **B361**, 160 (1995).

[33] V. Dmitrasinovic, *Phys. Rev.* **C53**, 1383 (1996).

[34] L. Burakovsky, *Phys. Lett.* **B427**, 361 (1998).