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Scalar mesons and the search for the 0^{++} glueball

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Abstract. The possibility that gluonic excitations of hadronic matter or of the QCD vacuum may exist is perhaps one of the most fascinating topics in hadron spectroscopy. Glueballs are predicted by many models; in particular, present-day lattice gauge calculations require their existence. All these models agree that the lightest glueball should have scalar quantum numbers and a mass around 1.6 GeV, which corresponds to the mass region where the scalar $q\bar{q}$-mesons are expected. Therefore, mixing effects can complicate the search for the glueball. Experiments indeed show an overpopulation of states, for which many different interpretations exist. This reflects the complexity of the situation. New data from various experiments on scalar states give hints toward an interpretation of the scalar states. But still many questions remain.

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1 Introduction

Quantum chromodynamics is believed to be the correct theory of strong interactions. The theoretical understanding of QCD is limited to two regimes: at high momentum transfer, where perturbative methods can be applied, and at very low energies in the realm of chiral perturbation theory. At medium energies, where perturbative methods fail, our present understanding is very limited. This is the energy regime of meson and baryon resonances, and one of the key issues is to identify the relevant degrees of freedom and the effective forces between them. This is strongly related to the question of whether gluonic degrees of freedom play a role in the hadronic spectrum. Do bound states of gluons (glueballs) or bound states of a $q\bar{q}$-pair and a gluon (hybrids) exist? Glueballs and hybrids are predicted by many models and by lattice gauge calculations; a whole spectrum of glueballs and hybrids is expected to exist. The lowest-mass glueball is predicted to have scalar quantum numbers and a recent lattice calculation [1] predicts a mass of about 1730 MeV. This corresponds to the mass region of the scalar $\bar{q}q$-mesons. So mixing between the pure scalar glueball and the nearby $q\bar{q}$ states can occur. A good understanding of all scalar states is therefore absolutely necessary, in order to identify the scalar glueball. There are some hints, how a glueball should reveal its existence, apart from the expected overpopulation of states. Glueballs are supposed to be produced preferentially in gluon-rich processes and should be suppressed in gluon-poor reactions: Radiative J/Ψ decays is, *e.g.*, such a gluon-rich process. The OZI rule suppresses decays of the $c\bar{c}$ system into light quarks and the $D\bar{D}$ threshold is far above the mass of the J/Ψ. Thus, the J/Ψ has the chance to decay into two gluons and a photon. The two gluons can interact with each other and must form glueballs —if they exist. Central production is another process in which glueballs should be produced abundantly. In central production two hadrons pass by each other "nearly untouched" and are scattered diffractively in the forward direction. No valence quarks are exchanged. The absence of valence quarks in the production process makes central production a good place to search for glueballs. In addition, $\bar{p}p$ annihilation is a gluon-rich environment; quark-antiquark pairs annihilate into gluons. These gluons can interact and can form a glueball. On the other hand, the situation is quite different in photon-photon collisions. Photons couple to the electric charges of the quarks and the production of glueballs should be suppressed. This reaction is often called "anti-glueball filter". Of course, this picture is rather naive. Glueballs couple to hadrons and glueballs can in general be produced in every reaction where hadrons occur. The reactions discussed above can provide only a rough hint toward the interpretation of the observed states.

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2 The scalar resonances

For the tensor $J^{PC} = 2^{++}$-states a clear nonet consisting of the $K_2^*(1430)$, the $a_2(1320)$, the $f_2(1270)$ and the $f_2(1525)$ exists [2]. In contrast, the situation for the scalar states is rather unclear. Here the number of known states exceeds the number of expected states by far. Most people agree that the $K_0^*(1430)$ belongs to the scalar nonet, while all other states are controversially discussed. Possible candidates are $a_0(980)$, and $a_0(1450)$ for the isovector state, and for the two isoscalar nonet states five candidates exist: the $f_0(400–1200)$, $f_0(980)$, $f_0(1370)$, $f_0(1500)$, and the $f_0(1710)$, if its existence is established. The reasons for the uncertainties in the assignment of the scalar mesons to the $^3P_0$ $q\bar{q}$ nonet are manyfold: the scalar mesons couple strongly to their decay channels, their production rates are weak in many processes and the scalar glueball may play a role in the spectrum. In contrast to the scalar glueball, the tensor glueball is expected to have a mass well above the ground-state tensor mesons.

2.1 Possible interpretations

For the scalar states several very different interpretations exist, some of them will be discussed briefly in this section. The assignment given, *e.g.*, by the PDG [3] is based on the interpretation of $f_0(980)$, $a_0(980)$, and $f_0(400–1200)$ as non-$q\bar{q}$ states, with a possible interpretation of the $f_0(980)$, and the $a_0(980)$ as $K\bar{K}$-molecules, and of the $f_0(400–1200)$ as a background structure, which could, *e.g.*, be explained by t-channel exchanges [4]. Excluding these three states from the list of scalar resonances, three isoscalar states remain. The states $f_0(1370)$, $f_0(1500)$, and $f_0(1710)$ cannot possibly belong to the same nonet. Since the $f_0(1370)$ is dominantly a $u\bar{u} + d\bar{d}$ state (it decays only weakly into $K\bar{K}$), one would expect ideal mixing and an $s\bar{s}$ state at 1620 MeV. This state cannot be the $f_0(1500)$, which has a weak $K\bar{K}$ decay mode only. The expected mass is not too far from the $f_0(1710)$. This leads to an assignment in which the $f_0(1370)$ and $f_0(1710)$ belong to the $1\,^3P_0$ nonet, while there is no space for the $f_0(1500)$, which is then discussed as glueball candidate.

A distinctive property of glueballs is their decay. Being a flavor singlet, glueballs should decay with flavor symmetry: thus the decay into $\pi\pi$, $\eta\eta$, $\eta\eta'$ and $K\bar{K}$ should scale as $3:1:0:4$, after correcting for phase space. This decay pattern is inconsistent with the decay pattern of the $f_0(1500)$, but also with the decay pattern of all other scalar states [5]. So none of the observed states seems to be a pure glueball. This leads to the suggestion that the glueball mixes with the nearby $q\bar{q}$ states. Several authors suggested different mixing scenarios [6–8], which lead to a different distribution of glue over the f_0-states. The unproven assumption made in these mixing schemes is that $a_0(980)$, $f_0(980)$, and $f_0(400–1200)$ are non-$q\bar{q}$ states.

These assumptions are not made by Anisovich *et al.* [9], who believe 5 states to exist below 1.8 GeV. They develop from the $1\,^3P_0$ and $2\,^3P_0$ $q\bar{q}$ states and the scalar glueball. Through mixing the glueball strength distributes between the $f_0(1370)$, the $f_0(1500)$, and a broad underlying component. Of course, these mixing schemes can only be valid, if an $f_0(1710)$ exists.

A phenomenological analysis by Minkowski and Ochs [10] results in a different interpretation. Here the $a_0(980)$ and the $f_0(980)$ as well as the $f_0(1500)$ are interpreted as $q\bar{q}$ states. They claim that the $f_0(1370)$ is not a genuine resonance, but part of a broader object, which they call "red dragon". Both the $f_0(400–1200)$, and $f_0(1370)$ belong to this broad structure, that is interpreted as scalar glueball. As last interpretation, we discuss the results of a relativistic quark model which takes instanton-induced forces into account [11]. Within this model the spectrum of pseudoscalar mesons is reproduced properly; the η-η' mass splitting is described correctly. For the scalar sector the instanton interaction changes sign. Using the same parameters as for the pseudoscalar states, the model predicts a low-lying singlet state, which can be identified with the $f_0(980)$, and two octet states of higher mass. These can be identified with the $f_0(1500)$, the $a_0(1450)$, and the $K_0^*(1430)$. The $a_0(980)$ and $f_0(1370)$ remain unexplained. Other interpretations exist, but will not be discussed here. The different interpretations mentioned above raise important questions which must be answered, if we want to understand the spectrum of scalar states:

- What is the nature of the $a_0(980)$ and the $f_0(980)$?
- Is the existence of the $f_0(1370)$ and of the $f_0(1710)$ established?
- What are the production and decay properties of the scalar states ?

These questions will be discussed in the following.

Table 1. Branching ratios for radiative $\phi(1020)$ decays from CMD2, SND, and KLOE [12–14]. The CMD2 branching fraction given in the $\phi \to a_0\gamma$ column corresponds to $\phi \to \gamma\pi\eta$.

	$\phi \to f_0\gamma$	$\phi \to a_0\gamma$
CMD2	$(2.9 \pm 0.21 \pm 1.54)10^{-4}$	$(0.90 \pm 0.24 \pm 0.10)10^{-4}$
SND	$(3.5 \pm 0.3^{+1.3}_{-0.5})10^{-4}$	$(0.88 \pm 0.14 \pm 0.09)10^{-4}$
KLOE	$(4.47 \pm 0.21)10^{-4}$	$(0.74 \pm 0.07)10^{-4}$

2.2 The nature of the $a_0(980)$ and the $f_0(980)$

Data on ϕ decays into $\gamma\pi\pi$ and $\gamma\pi\eta$ have been taken by CMD2 [12], SND [13] and, more recently, by KLOE [14]. The results are given in table 1. The big difference in the branching ratio for $\phi \to \gamma f_0$ from KLOE and CMD2/SND is due to the introduction of the $\phi \to \gamma\sigma$-channel in the KLOE analysis, which leads to a strong destructive interference with the γf_0-contribution, thus increasing the $\phi \to \gamma f_0$ branching ratio. Of course, the reliability of this $\sigma\gamma$ contribution can be questioned.

The measured ϕ radiative decay rates are surprisingly large. Early predictions [15] assuming different structures for the $f_0(980)$, $q\bar{q}$, $K\bar{K}$ or four-quark were all well below the recent experimental value. Recently, the reaction was studied by Markushin [16]. It was found that kaonic loops play a decisive role and that, including these, rate and $\pi\pi$ invariant mass distributions are well reproduced. The $f_0(980)$-resonance corresponds to a T-matrix pole close

Table 2. Yield of light mesons per hadronic Z^0 decay; (from [22,23]).

π^0: $9.55 \pm 0.06 \pm 0.75$	η: $0.97 \pm 0.03 \pm 0.11$
η': $0.14 \pm 0.01 \pm 0.02$	$a_0^{\pm}(980)$: $0.27 \pm 0.04 \pm 0.10$
$f_0(980)$: $0.141 \pm 0.007 \pm 0.011$	$\phi(1020)$: $0.091 \pm 0.002 \pm 0.003$
$f_2(1270)$: $0.155 \pm 0.011 \pm 0.018$	

to the $K\bar{K}$ threshold; a good description of the data is achieved assuming that the pole is of dynamical origin and represents a molecular-like $K\bar{K}$ state. An underlying $q\bar{q}$ component is possible but not required. This seems to be in disagreement with the rate for $\phi \to \gamma a_0(980)$ being smaller than the rate for $\phi \to \gamma f_0(980)$ by a factor of ~ 4 or even ~ 6. This appears to be difficult to reproduce if both mesons are $K\bar{K}$ molecules. In this case their rates should be equal [15]. Other authors claim that the measured branching ratios favor a four-quark structure of these states, *e.g.* [17]. Oset, on the other hand, using a chiral unitary approach, finds that these states are generated dynamically [18].

We conclude that the predictions for the branching ratios differ significantly from one work to another; they cannot all be correct.

The same is also true for the two-photon widths [19] of the $f_0(980)$ and $a_0(980)$. These are quite often used to argue that these states are $K\bar{K}$-molecules [20]. But there exist also calculations which show that the f_0 and the a_0 are consistent with a $q\bar{q}$ nature [21].

At LEP, the inclusive production of mesons in the Z^0 decay has been studied [22]. In particular, the investigation of the $f_0(980)$ and $a_0(980)$ provides new insight into their internal structure. The OPAL Collaboration searched for these and other light-meson resonances in hadronic Z^0 decays. The total inclusive rates (table 2) for the η', the $f_0(980)$ and the $a_0(980)$ —which have very similar masses— are nearly identical (with the two charge modes of the $a_0(980)^{\pm}$ taken into account). This points to an identical internal structure of these states. This conclusion can be substantiated by further studies [23], which investigate the production characteristics of $f_0(980)$, $f_2(1270)$ and $\phi(1020)$. Their fragmentation functions have been measured as well as their production as a function of the event multiplicity and of the rapidity gap. In all these measurements the three states show an almost identical behavior, which is, in addition, in good agreement with the Lund string model of hadronization in which the $f_0(980)$ is treated as a conventional meson. This again supports the hypothesis that these states have the same nature. Results on ν_μ-charged current interactions hint in the same direction. The NOMAD Collaboration has studied the inclusive production of the $\rho(770)$, the $f_0(980)$, and the $f_2(1270)$ [24]. Also here the $f_0(980)$ shows the same behavior as the two $q\bar{q}$ states $\rho(770)$, and $f_2(1270)$.

From these experiments one can conclude that:

$\Rightarrow$ the $f_0(980)$ and $a_0(980)$ seem to be $q\bar{q}$ states.

This interpretation cannot be disproven by the data from radiative $\phi(1020)$ decays or by the measurement of their two-photon width.

If the $f_0(980)$ and $a_0(980)$ are $q\bar{q}$ states, the f_0 wave function can be written as

$f_0(980) = \sin\varphi_s \cdot 1/\sqrt{2}(u\bar{u} + d\bar{d}) + \cos\varphi_s \cdot s\bar{s}$.

Using the measured ratios

$$R_1 = \frac{J/\Psi \to \phi f_0(980)}{J/\Psi \to \omega f_0(980)},\ R_2 = \frac{f_0 \to \gamma\gamma}{a_0 \to \gamma\gamma},\ R_3 = \frac{f_0 \to K\bar{K}}{f_0 \to \pi\pi},$$

one can show that they are consistent with a mixing angle φ_s of about 35° [25]. The measured ratios R_i are therefore also in agreement with a $q\bar{q}$ nature of the $f_0(980)$.

2.3 The existence of an $f_0(1710)$

Radiative J/Ψ-decays

Three scalar resonances are observed at BES in radiative J/Ψ-decays into $2\pi^+2\pi^-$ [26]. The results of a partial wave analysis show a slowly rising instrumental background and 3 important contributions with scalar, pseudoscalar, and tensor quantum numbers. The scalar part contains three resonances, at 1500, 1740, and 2100 MeV, a pattern of states as already suggested in a reanalysis of MARKIII data [27]. The $f_0(1500), f_0(1710)$, and the $f_0(2100)$ have a similar production and decay pattern. Neither a $f_0(1370)$ nor a "background" intensity is assigned to the scalar isoscalar partial wave. The mass and width given for the $f_0(1710)$ is $m = 1740^{+30}_{-25}$ MeV, $\Gamma = 120^{+50}_{-40}$ MeV [26]. Additional evidence for a scalar state has been found by the BES Collaboration in $J/\Psi \to \gamma K^+K^-$. Here a scalar contribution was observed around a mass of 1710 MeV [28].

Central production

Clear evidence for an $f_0(1710)$ was also found in central production. The WA102 experiment investigated several final states like $\pi\pi$, $\eta\eta$, $\eta\eta'$, $K\bar{K}$, and 4π to search for scalar states and especially for the $f_0(1710)$ [29]. The $f_0(1710)$ was observed in its decay into $\pi\pi$, $K\bar{K}$, and $\eta\eta$. For the other two channels upper limits have been derived. They find for the relative decay rates $\pi\pi : \eta\eta : \eta\eta' : K\bar{K} : 4\pi = 1 : 2.4 \pm 0.6 : < 0.8 : 5.0 \pm 0.7 :< 5.4$. Surprisingly, they do not observe a 4π-decay mode. This is in contradiction to the BES results, where this decay was clearly observed.

From the experiments discussed above, one can conclude that

$\Rightarrow$ An $f_0(1710)$ exists ($m \approx 1713$ MeV, $\Gamma \approx 125$ MeV [2]).

2.4 Production and decay properties

$\pi\pi$-scattering

Data on $\pi^- p_\uparrow \to \pi^+\pi^- n$ at 17.2 GeV/c (CERN-Cracow-Munich Collaboration) were analysed by Kaminski *et* *al.* [30]. The phase of the $\pi\pi$-scattering amplitude rises slowly, then there is a sudden phase increase at 980 MeV indicating the presence of the $f_0(980)$. The modulus of the amplitude shows a dip at the mass of the $f_0(980)$: intensity is taken from $\pi\pi$ scattering to the $K\bar{K}$ inelastic channel. A second dip together with a phase motion is observed at 1500 MeV. This indicates evidence for two resonances, the $f_0(980)$, and the $f_0(1500)$.

D_s decays into three pions

D_s decays into three pions provide further insight into the spectrum of isoscalar scalar resonances. The comparatively large rate for three-pion production is surprising [31, 32]; consider the reaction $D_s^+ \to 2\pi^+\pi^-$. The quark content of the D_s^+ is $c\bar{s}$. In the decay, the c can undergo a transition to an s and the produced W^+ converts into a π^+. Hence a $s\bar{s}$ state is produced which decays into $\pi^+\pi^-$. This violates the OZI rule, and the OZI violation is strong. In the three-pion Dalitz plots the $f_0(980)$ is clearly seen [31, 32]. E687 finds in a partial wave analysis a second scalar state at 1470 MeV which we identify with the $f_0(1500)$. E791 finds a scalar state with a mass of about 1434 MeV and a width of about 173 MeV. The latter could in principle be produced by the $f_0(1370)$, and the $f_0(1500)$. For the time being we assume that the observed state is the $f_0(1500)$. We note two aspects: first, the two states $f_0(980)$, $f_0(1500)$ are produced in a similar way and —taking phase space into account— with similar couplings. Second, if produced by the process described above, both mesons do not respect the OZI rule. Then the wave functions of both, $f_0(980)$ and $f_0(1500)$, must contain $1/\sqrt{2}(u\bar{u}+d\bar{d})$ and $s\bar{s}$ components. In principle, the states can also be produced over a graph, where the $\bar{s}$- and c-quark of the D_s^+ annihilate into an W^+, which then converts into a $\bar{d}$- and an u-quark. Producing an $u\bar{u}$-pair out of the vacuum, the f_0 states might then also be produced via their $u\bar{u}$ component. In general, it is believed, that the process described first is the dominant one. This would hint to an $f_0(980)$ and $f_0(1500)$ which contain a $1/\sqrt{2}(u\bar{u}+d\bar{d})$ and a $s\bar{s}$ component.

Radiative J/Ψ decays

As discussed before in $J/\Psi \to 4\pi\gamma$ (BES) three peaks due to an $f_0(1500)$, an $f_0(1710)$, and an $f_0(2100)$ are observed.

$\bar{p}p$ in flight

In the $\bar{p}p \to \pi^0\eta\eta$ data of E760 at a CMS energy of 3 GeV/3.5 GeV, three peaks are observed at masses corresponding to the same three scalar states [33]. The data were not decomposed in partial waves, so the peaks could have $J^{PC} = 0^{++}$ or 2^{++}. If the states have $J^{PC} = 2^{++}$, their decay into $\eta\eta$ would be suppressed by the angular-momentum barrier. The fact that they are so clearly seen might suggest that they have indeed scalar quantum numbers.

In the Crystal Barrel data $\bar{p}p \to \pi^0\eta\eta$ at an antiproton momentum of 1.94 GeV/c the $f_0(1500)$ and an $f_J(2100)$ were clearly observed while no $f_0(1710)$ was needed to describe the data.

From the discussed data sets one can conclude that

$\Rightarrow$ $f_0(980)$, $f_0(1500)$, $f_0(1710)$ and $f_0(2100)$ show very similar production and decay characteristics.

The $f_0(980)$ and the $f_0(1500)$ have both been observed in $\pi\pi$ scattering and probably also in D_s decays, where the $f_0(980)$ is clearly observed, while the parameters for a second scalar state found by E687 and E791 differ significantly. Future data, taken, *e.g.*, by the BarBar experiment, might help to clarify the situation. The $f_0(1500)$, the $f_0(1710)$ and the $f_0(2100)$ have all been observed in radiative J/Ψ decays.

Table 3. Partial widths Γ_i (in MeV) of $f_0(1370)$ and $f_0(1500)$ (from [35]), $\Gamma_{tot}(f_0(1370)) = 275 \pm 55$ MeV, $\Gamma_{tot}(f_0(1500)) = 130 \pm 30$ MeV. σ is used as an shortcut for the $\pi\pi$-S wave.

	$\sigma\sigma$ / $\pi\pi$	$\rho\rho$ / $\eta\eta$	$\pi(1300)\pi$ / $\eta\eta'$	$a_1\pi$ / $K\bar{K}$
$f_0(1370)$	120.5 ± 45.2	62.2 ± 28.8	41.6 ± 22.0	14.1 ± 7.2
	21.7 ± 9.9	0.41 ± 0.27		(7.9 ± 2.7) to (21.2 ± 7.2)
$f_0(1500)$	18.6 ± 12.5	8.9 ± 8.2	35.5 ± 29.2	8.6 ± 6.6
	44.1 ± 15.3	3.4 ± 1.2	2.9 ± 1.0	8.1 ± 2.8

The $f_0(1370)$

One of the scalar particles is obviously missing on this list, the $f_0(1370)$. The $f_0(1370)$ has not been observed in radiative J/Ψ decays, there is no clear evidence for its existence in D_s decays and in $\bar{p}p$ annihilation in flight. On the other hand, there exists evidence for this particle in $\pi\pi$ scattering [2], in $\bar{p}p$ annihilation at rest, and in central production. The evidence in the two latter reactions will be discussed using recent results of the Crystal Barrel and the WA102 experiment.

$\bar{p}p$ at rest (data from Crystal Barrel)

The decays of the $f_0(1370)$, and the $f_0(1500)$ into two pseudoscalar mesons have been measured by the Crystal Barrel (CB) experiment and are summarized in [5]. In order to gain additional information on the two states, their decays into 4π have been investigated by analysing four different 5π final states: $\bar{p}p \to 5\pi^0$, $\bar{p}n \to \pi^-4\pi^0$, $\bar{p}p \to \pi^+\pi^-3\pi^0$ and $\bar{p}n \to \pi^+2\pi^-2\pi^0$ [34,35]. The data demand two scalar states, the $f_0(1370)$ with $m = 1395 \pm 40\,\mathrm{MeV}/c^2$, $\Gamma = 275 \pm 55\,\mathrm{MeV}/c^2$ and the $f_0(1500)$ with mass and width compatible with previous findings. Using the determined 4π branching ratios together with the known ratios into two pseudoscalar mesons the partial widths of the two states can be determined, assuming that all decay modes of the particles are known. These are given in table 3.

Central production (data from WA102)

Not only the Crystal Barrel, but also the WA102 experiment has investigated the decay of scalar resonances into two pseudoscalar particles and into 4π [36]. The relative decay rates found by WA102 for the $f_0(1370)$, the $f_0(1500)$, and the $f_0(1710)$ are as follows [29]:

	$\pi\pi$:	$K\bar{K}$:	$\eta\eta$:	$\eta\eta'$:	4π
$f_0(1370)$	1	: 0.46±0.19	: 0.16±0.07	: –	: 34.0^{+22}_{-9}
$f_0(1500)$	1	: 0.33±0.07	: 0.18±0.03	: 0.096±0.026	: 1.36±0.15
$f_0(1710)$	1	: 5.0±0.7	: 2.4±0.6	: < 0.18	: < 5.4

In the following the 4π decays will be discussed in more detail. The partial wave analysis decomposes the observed structures into several scalar resonances, the $f_0(1370)$, $f_0(1500)$, and a new $f_0(2000)$. We note that the partial wave analysis finds that the $f_0(1370)$ decays into $\rho\rho$ but not into $\sigma\sigma$, while the $f_0(1500)$ shows both decay modes. This is in contradiction to the Crystal Barrel results, where a strong $\sigma\sigma$ decay mode of the $f_0(1370)$ was found (table 3). WA102 gives an upper limit for the $\sigma\sigma$ decay modes, which is $< 25\%$ of its $\rho\rho$ decay mode. In addition, WA102 did not observe a decay into $a_1\pi$ or $\pi(1300)\pi$ for the states, which is again in disagreement with the Crystal Barrel experiment.

The results of the two experiments can be compared qualitatively. One finds that the $4\pi/2\pi$ rates for the $f_0(1500)$ are in good agreement in both experiments (WA102: 1.36±0.15, CB: 1.62±0.7). WA102 finds a $\rho\rho/\sigma\sigma$ ratio for the $f_0(1500)$ of about 3, Crystal Barrel finds, adding up all decay modes which include a ρ, a very similar value: $(\rho\rho + a_1\pi + \pi(1300)\pi)/\sigma\sigma \approx 2.9$. So one could argue that the results are consistent, if one ignores the different isobar decomposition in the 4π decay modes. This is no longer the fact for the $f_0(1370)$. Here the $4\pi/2\pi$ rate differs substantially: WA102 finds 34^{+22}_{-9} and CB: 11 ± 3.2. A further disagreement is the $\sigma\sigma/\rho\rho$ rate; while WA102 gives an upper limit for $\sigma\sigma$, Crystal Barrel finds that $\sigma\sigma$ is the strongest decay mode of this particle. It should be noted that it is impossible to describe the $4\pi^0$-invariant mass of the $5\pi^0$ and $\pi^-4\pi^0$ Crystal Barrel data by the $f_0(1500)$ alone. This difference is so far not understood, but may be related to processes like, *e.g.*, t-channel exchange [37]. Such effects are not included in the analyses and should have a different influence on central production and in $\bar{p}p$ annihilation.

$\gamma\gamma$-collisions

As mentioned in the beginning, the observation or non-observation of states in $\gamma\gamma$-collisions may give hints concerning the nature of the states. While there is evidence for a $\gamma\gamma$-coupling of the $f_0(400–1200)$, $f_0(980)$, and maybe also of the $f_0(1370)$ [2], the L3 experiment investigated $\gamma\gamma \to K_sK_s$ to search for the $f_J(1710)$. In the mass region around 1700 MeV a dominant contribution from a 2^{++} wave, but also some evidence for a 0^{++} contribution of 24±16% at 84%CL was found [38]. If the existence of an $f_0(1710)$ in $\gamma\gamma$-collisions could be confirmed, this would be rather interesting. It discriminates between models, where the state has a big or small gluonic contribution. This result would indicate, that the gluonic component (if there is one) of the $f_0(1710)$ is smaller than that of the $f_0(1500)$, which was so far not observed in $\gamma\gamma$-collisions.

Table 4. Observation (√) or non-observation (–) of the scalar states in different reactions. First three reactions: "gluon-rich processes"; last one: "anti-glueball filter".

	$f_0(400–1200)$	$f_0(980)$	$f_0(1370)$	$f_0(1500)$	$f_0(1710)$
$\bar{p}p$	√	√	√	√	?
$J/\Psi \to \gamma X$	–	–	–	√	√
$pp \to p_f X p_s$	–	√	√	√	√
$\gamma\gamma$	√	√	√ ?	–	(√) ?

3 Conclusions

Table 4 summarizes the production properties of the scalar states. The $f_0(1500)$ is the only state which is produced in all "gluon rich" processes, but was so far not observed in $\gamma\gamma$-collisions, if the L3 result is confirmed. Otherwise, the $f_0(1710)$ would be the second candidate. If a scalar glueball exists and mixes with the $q\bar{q}$ states, this would support a mixing scenario, where the $f_0(1500)$ has a sizable gluonic component. On the other hand, the results from OPAL (and NOMAD) show that the most probable interpretation of the $a_0(980)$ and the $f_0(980)$ is that of $q\bar{q}$ states. This questions the validity of the glueball-meson mixing schemes [6–8]. Not only the $1\,^3P_0$ but also the $2\,^3P_0$ must then be included in the mixing scenario as done in the analysis by Anisovich *et al.* [9].

The $f_0(400–1200)$ and the $f_0(1370)$ should be produced in radiative J/Ψ decays, if they are indeed part of the scalar glueballs as claimed by Minkowski and Ochs [10]. That is not the case; this makes the interpretation of the scalar background as glueball unlikely.

Not understood at present is why the $f_0(1370)$ is not observed in J/Ψ decays, where it should not only be produced if it is a glueball but also if it is a $q\bar{q}$ state. The same is true for its non-observation in $\bar{p}p$ annihilation in flight and probably also in D_s decays. From this observation one could argue that the $f_0(1370)$ is a non-$q\bar{q}$ state [37].

The scalar states are an exciting topic; not all of them can be $q\bar{q}$ states. But we certainly have to admit that so far not everything is understood. The question, whether a scalar glueball exists and how the glue is distributed over the observed states, still remains without a generally accepted answer [39,40].

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