

SPECTROSCOPY WITH GLUEBALLS AND THE ROLE OF $f_0(1370)^*$

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The existence of glueballs, bound states of gluons, is one of the basic predictions of QCD; the lightest state is expected to be a scalar. The experimental situation, however, is still ambiguous. The existence of $f_0(1370)$ would point to a supernumerous state within the nonet classification of scalars and would, therefore, provide a hint towards a glueball. In this paper, we summarise some arguments in favour and against the existence of $f_0(1370)$ and discuss schemes with and without this state included.

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1. Introduction

The existence of glueballs is a consequence of the self-interaction of gluons in QCD with consequences studied already about 40 years ago [1]. Today, within the lattice QCD approach, the mass of the lightest scalar glueball is found around 1700 MeV in the theory with gluons only, while in the full theory the mass is found to drop to ~ 1000 MeV [2] or to stay largely unchanged [3, 4]. QCD sum rules predict scalar gluonic mesons as well in the range 1000–1700 MeV [5–7]. The experimental search for a scalar glueball has lead to several scenarios for a spectroscopy with glueballs. A recent status of theoretical and experimental results on glueballs is found in [8].

One strategy to find glueballs is based on the identification of the scalar nonets lowest in mass and the search for super-numerous isoscalar states which could be related to the presence of a glueball in the spectrum. In addition, pure glueballs are characterised by flavour symmetric decays (with possible modifications [8]) and they are expected to be predominantly produced in “gluon-rich” processes. In general, glueballs could mix with isoscalar quarkonium states. An important example for such a supernumerous state is $f_0(1370)$ which we will discuss here in particular.

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2. Scalar meson spectrum with $f_0(1370)$

The states above 1 GeV listed by the Particle Data Group [9]

$$f_0(1370), \quad f_0(1500), \quad f_0(1710), \quad K_0^*(1430), \quad a_0(1450),$$

can be interpreted as being formed by a nonet of $q\bar{q}$ states and a glueball where the two $q\bar{q}$ isoscalars and the glueball mix into three isoscalar f_0 's. Such a scheme has been suggested originally by Amsler and Close [10]. At that time, the newly discovered $f_0(1500)$ meson has been related to the glueball with mass predicted near 1500 MeV by lattice theory with gluons only. The closer inspection of the decay branching ratios, however, suggested a mixing scheme for the three f_0 mesons. Other mixing schemes for the glueball are considered in [11–13], for a review, see [14].

The states below 1 GeV

$$f_0(500)/\sigma, \quad f_0(980), \quad K^*(900)/\kappa, \quad a_0(980)$$

can be grouped into a light meson nonet¹ formed by $q\bar{q}$ (as in [15–17]) or by diquark bound states (as in [18–20]).

3. Evidence for $f_0(1370)$ revisited

The crucial element in these schemes with glueball is the existence of $f_0(1370)$ and, therefore, we will reconsider the evidence. In the actual edition of the PDG, the rather wide ranges for mass and width are reported

$$M = 1200\text{--}1500 \text{ MeV}, \quad \Gamma = 200\text{--}500 \text{ MeV}. \quad (1)$$

There are 12 decay channels “seen”: $\pi\pi$, $K\bar{K}$, $\eta\eta$, 4π , $\gamma\gamma$ and various sub-channels of 4π , but no single experimental number on branching ratios nor ratios thereof has been determined because of conflicting results. This is quite different from the nearby $f_0(1500)$ with five well established branching ratios. Accordingly, supportive [21] and sceptical views [22] about $f_0(1370)$ have been presented in the past. A detailed discussion of various observations is given in [8]. Here, we present an overview and some details of two energy independent analyses.

3.1. Overview

The evidence for $f_0(1370)$ has been presented first in $p\bar{p}$ annihilation at rest by the Crystal Barrel Collaboration (CBAR) [23] and this state has been studied together with $f_0(1500)$ in the reactions (a) $p\bar{p} \rightarrow \pi^0\pi^0\pi^0$,

¹ The $K^*(900)/\kappa$ is not considered as established by the PDG at present.

(b) $p\bar{p} \rightarrow \pi^0\eta\eta$, (c) $p\bar{p} \rightarrow \pi^0\pi^0\eta$. Signal bands in the Dalitz plots related to $f_0(1500)$ are always clearly visible. A signal from $f_0(1370)$ can be seen in the $\eta\eta$ channel but there is an interference with the $\eta\pi$ resonances in crossed channels. The $f_0(1370)$ signal disappears immediately if the c.m.s. energy is increased above the $p\bar{p}$ threshold. So the evidence for $f_0(1370)$ relies on the proper global multi-channel fit with various interfering resonances present.

These problems are avoided if the S -wave amplitudes are reconstructed in an energy independent analysis in a sequence of mass bins with sufficiently high statistics. The resonant behaviour is then found from the characteristic behaviour of the complex amplitude. Such results are available for 2-body $\pi\pi \rightarrow ab$ scattering, which can be reconstructed from $\pi p \rightarrow ab + n$ processes. Proper care has to be taken in these analyses in the treatment of nucleon spins. Other high statistics results became available recently from $D \rightarrow 3\pi$ where the spin problems disappear or from $B \rightarrow J/\psi\pi\pi$ with only one spinning particle. In central production processes $pp \rightarrow p + X + p$, the measurements at SPS energies are difficult to analyse because of non-trivial superpositions from processes with different nucleon helicities [8].

A large fraction of $f_0(1370)$ decays goes into 4π channels ($\gtrsim 70\%$). Here, different experiments on central production and $p\bar{p}$ annihilation provide conflicting results; furthermore, no evidence for the existence of two resonances at 1370 and 1500 MeV has been found [22]. Here, some clarification is necessary. In this paper, we restrict ourselves to some 2-body processes where energy independent phase shifts are available.

3.2. Search in phase shift analysis of $\pi\pi$ scattering

Such data are extracted from the reaction $\pi p \rightarrow \pi\pi n(\Delta)$ in application of the one-pion-exchange model. Energy independent phase shift analyses of $\pi^+\pi^-$ scattering up to 1800 MeV have been carried out first by the CERN-Munich group [24, 25] (CM-I) using the assumptions of “spin and phase coherence” [26]; results above 1400 MeV are superseded by the more complete analyses based on CM-II data (see below). Above 1 GeV, there are, in general, multiple phase shift solutions which represent the same $\pi\pi$ angular distribution moments. Such multiple solutions up to 1800 MeV have been obtained first by Estabrooks and Martin [27]. Based on an improved data analysis, the CERN-Munich group obtained a similar set of results with some smaller errors [28] (CM-II). A unique solution has been found by combining with results from GAMS Collaboration [29] on the $\pi^0\pi^0$ final state [8, 30]. The isoscalar S -wave is shown in Fig. 1, where a clear signal from $f_0(1500)$ is seen: the resonance circle in the Argand diagram with related movements of the phase and inelasticity near 1500 MeV. The elastic $\pi\pi$ width is found as

$$f_0(1500) : \quad x_{\pi\pi} = 0.25 \pm 0.05 \text{ (CM-II)}, \quad x_{\pi\pi} = 0.349 \pm 0.023 \text{ (PDG)}, \quad (2)$$

where the first result (CM-II) is determined from $\text{Im } T_0$ of the resonant elastic partial wave amplitude (from Fig. 1) and the second one (PDG) from all inelastic channel cross sections; both should agree because of the optical theorem and they roughly do within 30%.

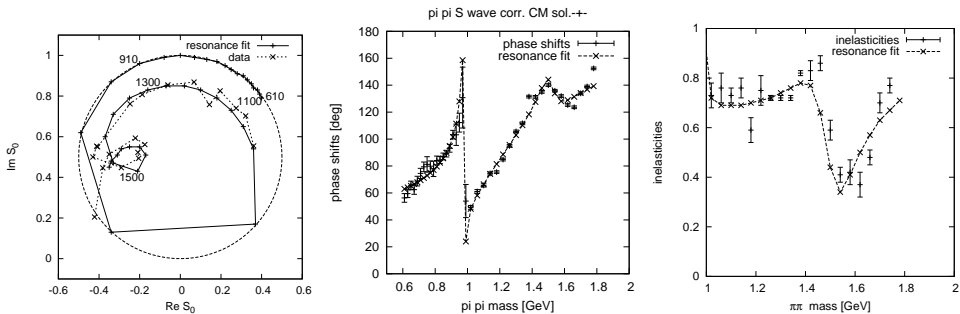


Fig. 1. Data in $\pi\pi$ S_0 wave (CERN-Munich data CM-I/II): Argand diagram for corrected S_0 wave, phase shifts δ_0^0 and inelasticities η_0^0 ; shown is also a preliminary resonance fit including $f_0(500)$, $f_0(980)$ and $f_0(1500)$.

There is no hint towards any resonance structure near 1370 MeV in any of the plots of Fig. 1 which leads to the limit

$$f_0(1370) : \quad x_{\pi\pi} < 0.1 \quad [\text{C.L.} = 95\%] \quad (\text{CM-II}). \quad (3)$$

The absence of $f_0(1370)$ is in agreement with the findings from an alternative phase shift analysis [31]. On the other hand, global multi-resonance fits to the angular momentum data (CM-I) with $f_0(1370)$ included have been presented in [21] showing an additional resonance circle. These results are in conflict with the energy-independent bin-by-bin phase shift data in Fig. 1.

3.3. Decays of D and B mesons

In the weak decays of heavy quark mesons, some well defined $q\bar{q}$ states evolve from the intermediate weak and strong interaction processes and they finally can form isoscalar f_0 mesons. Recent results from B factories and LHC have high statistical significance and they are well suited to find small branching ratios.

As an example, we report here the decay $D_s^+ \rightarrow \pi^+\pi^-\pi^+$, where the dominant subprocess is identified as $D_s^+ \rightarrow \pi^+ + s\bar{s}$; $s\bar{s} \rightarrow \pi^+\pi^-$ with possible intermediate $f_0(1370)$ and $f_0(1500)$. An energy-independent phase shift analysis carried out by the BaBar Collaboration [32] is shown in Fig. 2, see also [8]. One can see a strong movement of the amplitude related to $f_0(980)$ and $f_0(1500)$, while there is no effect visible in between where the phase movement becomes minimal. A similar process is $B_s^0 \rightarrow J/\psi + \pi^+\pi^-$

with subprocess $B_s^0 \rightarrow J/\psi + s\bar{s}$; $s\bar{s} \rightarrow \pi^+\pi^-$ which has been studied by the LHCb Collaboration [33]. Besides $f_0(980)$, one other resonance has been identified with parameters close to $f_0(1500)$ (see also [8]).

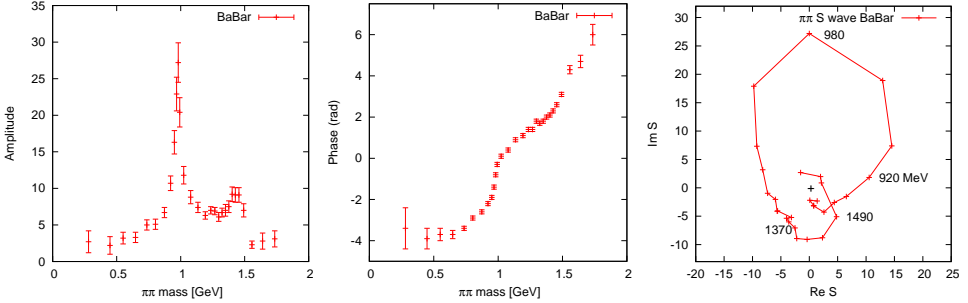


Fig. 2. $\pi\pi$ S -wave amplitude and phase extracted from decays $D_s^+ \rightarrow \pi^+\pi^-\pi^+$ (BaBar Collaboration [32]); right panel: Argand diagram for $\pi\pi$ amplitude (the phase is normalized to $\pi/2$ at the $f_0(980)$ peak).

4. Scalar meson spectrum without $f_0(1370)$

In view of the lacking evidence for $f_0(1370)$, alternative schemes for the scalar spectrum have been looked for. In the approach by Minkowski and Ochs [34], the lightest $q\bar{q}$ nonet includes

$$f_0(980), \quad a_0(980), \quad K^{*0}(1430), \quad f_0(1500), \quad (4)$$

whereas the glueball is represented by $f_0(500)/\sigma$. It is assumed that what is called $f_0(500)$ corresponds to the broad object centered at 1000 MeV with comparable width as observed in the $\pi\pi$ phase shift analysis of Fig. 1: the phase shift passes 90° near 1000 MeV after the effect from $f_0(980)$ is removed; so we call this state also $f_0(500\text{--}1000)$. An object at this mass is also found as lightest gluonic meson in the QCD sum rule approach [5]. A similar $q\bar{q}$ nonet including $f_0(980)$ and $f_0(1500)$ with a flavour mixing as for η, η' but with reversed mass ordering had been proposed before [35, 36]. No $K^{*0}(900)/\kappa$ is needed in this scheme; note that the phase movement in $K\pi$ scattering related to $K^{*0}(900)/\kappa$ is only about 40° [8].

Recently, an attempt has been presented to determine the constituent structure of the light f'_0 s from available branching fractions [8]. It is found that the $f_0(500)/\sigma$ decays are not “flavour blind” as expected for a glueball. The flavour composition of $f_0(980)$ is found similar to the one of η' confirming the earlier result [34]; the gluonic component is estimated as $\lesssim 25\%$. For $f_0(1500)$, a gluonic component is established as function of the scalar mixing angle ϕ_{sc} . Then, a minimal mixing scheme is proposed as

$$|f_0(500-1000)\rangle = \sin \phi_G |q\bar{q}\rangle - \cos \phi_G |gg\rangle, \quad (5)$$

$$|f_0(1500)\rangle = \cos \phi_G |q\bar{q}\rangle + \sin \phi_G |gg\rangle, \quad (6)$$

where $|q\bar{q}\rangle = \cos \phi_{sc} |n\bar{n}\rangle - \sin \phi_{sc} |s\bar{s}\rangle$ is near a flavour octet with the mixing angle $\phi_{sc} = (30 \pm 3)^\circ$, and $\phi_G \sim 35^\circ$ in the simplest model. For $\phi_G = 0$, we recover the model [34]. The strong mixing of the glueball into $f_0(500-1000)$ and $f_0(1500)$ is a feature also found in recent QCD lattice calculations [2] and QCD sum rules [7].

5. Concluding remarks

After 40 years of experimental and theoretical work, our knowledge on the scalar mesons has been considerably improved, but we have not yet succeeded ultimately to prove the existence of the scalar glueball and to determine its mass. The identification of a supernumerous state in the nonet classification of mesons depends on the knowledge of all nonet members. This is difficult if broad objects like $f_0(1370)$ are involved with small 2-body branching ratios if any.

Therefore, we have argued [8] not to rely only on establishing such difficult states like $f_0(1370)$ but to investigate other approaches as well.

1. Study of leading resonances in gluon jets (at large Feynman x).

Several LEP experiments observed a significant excess of neutral leading clusters beyond expectations from MC's as one expects from glueball production. The effect should be stronger at the LHC.

2. Study of decays of charmonium states like χ_c with primary gg decay. Pairs of scalar particles should be produced according to flavour symmetry if they belong to the same $q\bar{q}$ multiplet, but deviations are expected for gluonic states.

Such studies hopefully will provide new evidence for gluonic mesons if they exist.

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