# QUARK–ANTIQUARK SYSTEMATICS AND THE GLUEBALL

V.V. Anisovich

*Institute of Nuclear Physics, Saint-Petersburg, Russia*

Current understanding of the meson ($IJ^{PC} = 00^{++}$)-states in the mass region below 2400 MeV is presented. I discuss *i)* resonances in the scalar sector, *ii)* $q\bar{q}$-nonet classification of scalar bare states, *iii)* accumulation of widths of the $q\bar{q}$ states by the glueball caused by overlapping of the $f_0$-resonances at 1200–1700 MeV, *iv)* systematics of the $q\bar{q}$ states in the $(n, M^2)$ plot and *v)* radiative decays of the $P$-wave $q\bar{q}$-resonances: $f_0(980)$, $a_0(980)$, $a_2(1320)$, $f_2(1270)$, $f_2(1525)$.

In Ref. [1], on the basis of experimental data of GAMS group [2], Crystal Barrel Collaboration [3] and BNL group [4], the $K$-matrix solution has been found for the waves $00^{++}, 10^{++}, 02^{++}, 12^{++}$ over the range 450–1900 MeV. Also the masses and total widths of resonances have been determined for these waves. The following states have been seen in the scalar-isoscalar sector:

$$00^{++}: \quad f_0(980),\ f_0(1300),\ f_0(1500),\ f_0(1530^{+\,90}_{-250}),\ f_0(1750)\ . \tag{1}$$

The broad state $f_0(1530^{+\,90}_{-250})$ has not been included into the compilation [5], the states $f_0(1300)$ and $f_0(1750)$ being referred in [5] as $f_0(1370)$ and $f_0(1710)$.

For the scalar-isovector sector, the analysis [1] points to the presence of the following resonances in the spectra:

$$10^{++}: \quad a_0(980),\ a_0(1520)\ . \tag{2}$$

In the compilation [5] the state $a_0(1520)$ was denoted as $a_0(1450)$.

As to tensor mesons, the following states have been seen:

$$12^{++}: \quad a_2(1320),\ a_2(1660); \qquad 02^{++}: \quad f_2(1270),\ f_2(1525)\ . \tag{3}$$

The $K$-matrix poles are not the amplitude poles, these latter being connected with physical resonances, but when the decays are switched off, the resonance poles turn into the $K$-matrix ones. In the states related to the $K$-matrix poles there is no cloud of real meson, that is due to the decay processes This was the reason to name them “bare states” [6]. Taking into consideration the $K$-matrix coupling constant values, the $q\bar{q}$-nonet classification of bare states has been established [1].

## 1. Resonances in the scalar-isoscalar sector

The $K$-matrix analysis [1] provides us a bulk of information on scalar-isoscalar sector at 450–1900 MeV. In this region the threshold singularities of the $00^{++}$ amplitude related to channels $\pi\pi, \pi\pi\pi\pi, K\bar{K}, \eta\eta, \eta\eta'$ have been correctly taken into account. This circumstance allowed us to reconstruct the amplitude in the region shown in Fig. 1 by dashed line. amplitude related to channels $\pi\pi, \pi\pi\pi\pi, K\bar{K}, \eta\eta, \eta\eta'$ have been correctly taken into account. In this area, with correctly restored analytical structure of the amplitude $00^{++}$, the amplitude poles corresponding to resonances (1) are located.

Below the mass scale of $K$-matrix analysis [1] there is a pole related to the low-mass $\sigma$-meson; its position is shown in Fig. 1 following the results of the dispersion-relation $N/D$-analysis [7] (the mass region validated by this analysis is also shown in Fig. 1). The pole near the $\pi\pi$ threshold has been seen in a number of papers [8, 9, 10, 11]. Above the mass region of the $K$-matrix analysis there are resonances $f_0(2030)$, $f_0(2100)$, $f_0(2340)$ [12, 13].

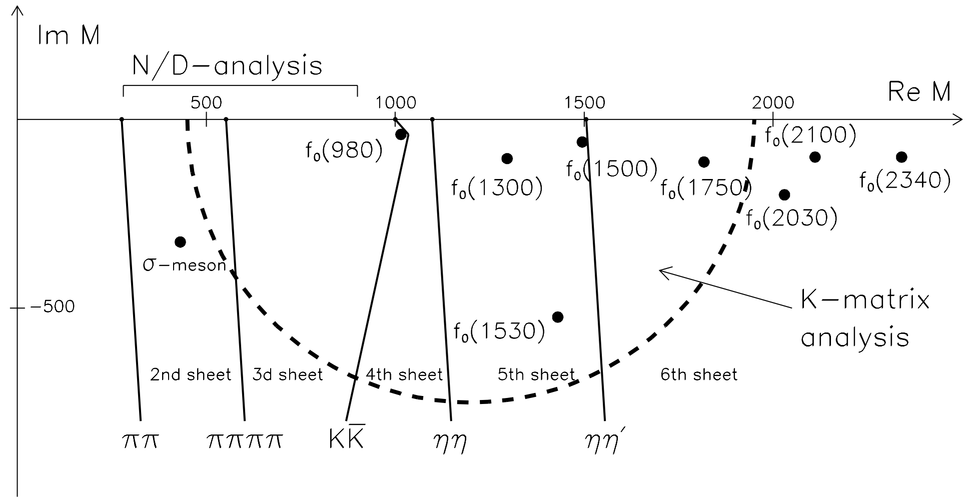


Figure 1: Complex $M$-plane in the $(IJ^{PC} = 00^{++})$ sector. Dashed line encircle the part of the plane where the $K$-matrix analysis [1] reconstructs the analytic $K$-matrix amplitude: in this area the poles corresponding to resonances $f_0(980)$, $f_0(1300)$, $f_0(1500)$, $f_0(1750)$ and the broad state $f_0(1530\,^{+90}_{-250})$ are located. Beyond this area the low-mass $\sigma$-meson is located (the position of pole found in the $N/D$ method is shown) as well as resonances $f_0(2030), f_0(2100), f_0(2340)$ Solid lines statnd for the cuts related to the thresholds $\pi\pi, \pi\pi\pi\pi, K\bar{K}, \eta\eta, \eta\eta'$.

**2. Classification of scalar bare states**

In Ref. [1], in terms of bare states, the quark-gluonium systematics of scalar particles has been established. The bare state being a member of the $q\bar{q}$ nonet imposes rigid restrictions on the $K$-matrix parameters. The $q\bar{q}$ nonet of scalars consists of two scalar-isoscalar states, $f_0^{bare}(1)$ and $f_0^{bare}(2)$, scalar-isovector meson $a_0^{bare}$ and scalar kaon $K_0^{bare}$. In the leading order of the $1/N$-expansion the decays of these four states into two pseudoscalars are determined by three parameters only, which are the common constant $g$, suppression parameter $\lambda$ for strange quark production (in the limit of a precise $SU(3)_{flavour}$ symmetry $\lambda = 1$) and mixing angle $\varphi$ for the $n\bar{n}$ ($n\bar{n} = (u\bar{u} + d\bar{d})/\sqrt{2}$) and $s\bar{s}$ components in $f_0^{bare}$: $n\bar{n}\cos\varphi + s\bar{s}\sin\varphi$. The mixing angle defines scalar–isoscalar nonet partners $f_0^{bare}(1)$ and $f_0^{bare}(2)$: $\varphi(1) - \varphi(2) = 90^\circ$ . Restrictions imposed on the coupling constants allow one to fix unambigously the basic scalar nonet:

$$1^3P_0 q\bar{q} : f_0^{bare}(720 \pm 100),\ a_0^{bare}(960 \pm 30),\ K_0^{bare}(1220^{+\,50}_{-150}),\ f_0^{bare}(1260 \pm 30)\ , \qquad (4)$$

as well as mixing angle for $f_0^{bare}(720)$ and $f_0^{bare}(1260)$: $\varphi(720) = -70^\circ\ ^{+5^\circ}_{-10^\circ}$. The nonet $1^3P_0q\bar{q}$ in the form (4) has been suggested in [14], where the $K$-matrix re-analysis of the $K\pi$ data [15] has been carried out (bare states and their couplings for the $00^{++}$ and $10^{++}$ waves have been found before, in [6, 16]).

To establish the nonet of first radial excitations, $2^3P_0q\bar{q}$, appeared to be more difficult task. The $K$-matrix analysis [1] gives us two scalar-isoscalar states at 1200–1650 MeV, $f_0^{bare}(1230^{+150}_{-\,30})$ and $f_0^{bare}(1600 \pm 50)$; the decay couplings for both of them satisfy the requirements imposed for the glueball. To solve this dilemma, we have performed a systematization of $q\bar{q}$ states on the $(n, M^2)$ plot [13] ($n$ is the radial quantum number of the meson and $M$ is the meson mass). Such a systematization definitely shows that $f_0^{bare}(1600 \pm 50)$ is an extra state for the $q\bar{q}$ trajectory. In this way, $f_0^{bare}(1230^{+150}_{-\,30})$ and $f_0^{bare}(1810 \pm 30)$ must be the $q\bar{q}$ states.

Below we present a set of arguments based on a more detailed consideration of the $(n, M^2)$ plot, while now on let us discuss the only variant of the $2^3P_0q\bar{q}$ nonet, which survives after taking into account the constraint given by $q\bar{q}$ trajectories.

The nonet $2^3P_0q\bar{q}$ looks as follows:

$$2^3P_0q\bar{q}:\ f_0^{bare}(1230^{+150}_{-\ 30}),\ f_0^{bare}(1810\pm 30),\ a_0^{bare}(1650\pm 50),\ K_0^{bare}(1885^{+\ 50}_{-100})\ . \quad (5)$$

The $K$-matrix analysis [1], together with the previous ones [6, 16], reveals the bare state in the scalar–isoscalar sector which is an extra one for the nonets $1^3P_0q\bar{q}$ and $2^3P_0q\bar{q}$. This is the $f_0^{bare}(1600)$-state. At the same time, the decay couplings of $f_0^{bare}(1600)$ to channels $\pi\pi, K\bar{K}, \eta\eta, \eta\eta'$ obey the requirements for the glueball decay. This gives us the reason to consider this state as the lightest scalar glueball:

$$0^{++}\ glueball: \qquad f_0^{bare}(1600\pm 50)\ . \quad (6)$$

The lattice calculations are in reasonable agreement with such a value of the lightest glueball mass [17].

After the onset of decay channels, the bare states transforme into real resonances. For the scalar–isoscalar sector we observe the transitions after switching-on the decay channels:

$$\begin{array}{rcl} f_0^{bare}(720)\pm 100) & \to & f_0(980)\ , \\ f_0^{bare}(1260\pm 30) & \to & f_0(1300)\ , \\ f_0^{bare}(1230^{+150}_{-\ 30}) & \to & f_0(1500)\ , \\ f_0^{bare}(1600\pm 50) & \to & f_0(1530^{+\ 90}_{-250})\ , \\ f_0^{bare}(1810\pm 30) & \to & f_0(1750)\ . \end{array} \quad (7)$$

The evolution of bare states into real resonances is illustrated by Fig. 2: the shifts of the amplitude poles on the complex-$M$ plane correspond to a gradual onset of the decay channels. Technically it is done by replacing the phase space $\rho_a$ for $a = \pi\pi, \pi\pi\pi\pi, K\bar{K}, \eta\eta, \eta\eta'$ in the $K$-matrix amplitude as follows: $\rho_a \to \xi\rho_a$, the parameter $\xi$ running in the interval $0 \le \xi \le 1$. At $\xi \to 0$ one has pure bare states, while the limit $\xi \to 1$ gives us the position of real resonance.

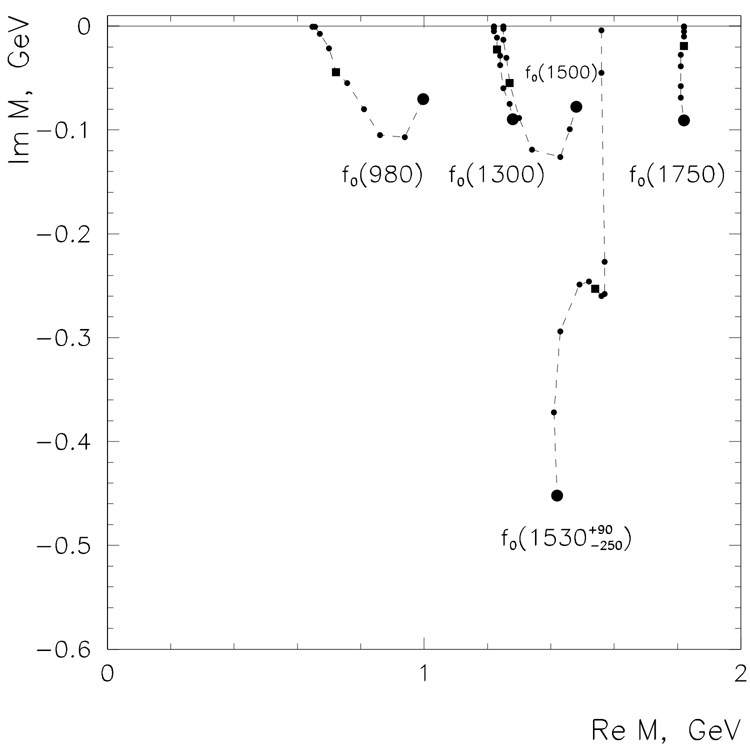


Figure 2: Complex $M$-plane: trajectories of the poles for $f_0(980)$, $f_0(1300)$, $f_0(1500)$, $f_0(1750)$, $f_0(1530\ ^{+\ 90}_{-250})$ during gradual onset of the decay processes.

## 3. Overlapping of the $f_0$-resonances at 1200–1700 MeV: accumulation of widths of $q\bar{q}$ states by the glueball

The appearance of a broad resonance is not at all an occasional phenomenon. It has originated as a result of a mixing of states which are due to the decay processes, namely, transitions $f_0(m_1) \to$ *real mesons* $\to f_0(m_2)$. These transitions result in a specific phenomenon, that is, when several resonances overlap, one of them accumulates the widths of neighbouring resonances and transforms into a broad state.

This phenomenon has been observed in [6, 16] for the scalar-isoscalar states, and the following scheme has been suggested in [18, 19]: the broad state $f_0(1530^{+90}_{-250})$ is a descendant of the pure glueball, which being in the neighbourhood of $q\bar{q}$ states accumulated their widths and transformed into a mixture of the gluonium and $q\bar{q}$ state. In [19] this idea has been applied for four resonances $f_0(1300)$, $f_0(1500)$, $f_0(1530^{+90}_{-250})$ and $f_0(1750)$, by using the language of the $q\bar{q}$ and $gg$ states for consideration of the decays $f_0 \to q\bar{q}, gg$ and mixing processes $f_0(m_1) \to q\bar{q}, gg \to f_0(m_2)$. Within the model [19], the gluonium component is mainly shared over three resonances, $f_0(1300)$, $f_0(1500)$, $f_0(1530^{+90}_{-250})$, so every state is a mixture of $q\bar{q}$ and $gg$ components, with roughly equal percentage of the gluonium (about 30–40%).

The accumulation of widths of overlapping resonances by one of them is a well-known effect in nuclear physics [20, 21, 22]. In meson physics this phenomenon can play an important role, in particular for exotic states which are beyond the $q\bar{q}$ systematics. Indeed, being among the $q\bar{q}$ resonances, the exotic state creates a group of overlapping resonances. The exotic state, which is not orthogonal to its neighbours, after having accumulated the "excess" of width turns into a broad state. This broad resonance should be accompanied by narrow states which are the descendants of states from which the widths have been taken off. In this way, the existence of a broad resonance accompanied by narrow ones may be a signature for exotics. This possibility, in context of searching for exotic states, has been discussed in [23, 24].

The broad state may be one of the components which form the confinement barrier: the broad states after accumulating the widths of neighbouring resonances play for these latter the role of locking states. Evaluation of the mean radii squared of the broad state $f_0(1530\ ^{+90}_{-250})$ and its neighbours-resonances, performed in [24] on the basis of the GAMS data [2], argues in favour of this idea, for the radius of $f_0(1530\ ^{+90}_{-250})$ is significantly larger than that of $f_0(980)$ and $f_0(1300)$, thus making it possible for $f_0(1530\ ^{+90}_{-250})$ to be the locking state.

## 4. Systematics of the $q\bar{q}$ states on the $(n, M^2)$ plot

As is stressed above, the systematics of $q\bar{q}$ states on the $(n, M^2)$ plot argues in favour of the fact that broad state $f_0(1530^{+90}_{-250})$ and its predecessor $f_0^{bare}(1600 \pm 50)$ are states beyond the $q\bar{q}$ classification. Following [13], we plot in Fig. 3a the $(n, M^2)$-trajectories for $f_0$, $a_0$ and $K_0$ states (the doubling of the $f_0$ trajectories is due to the two flavour components, $n\bar{n}$ and $s\bar{s}$). All trajectories are roughly linear, and they clearly represent the states with dominant $q\bar{q}$ component. It is seen that one of the states, either $f_0(1530^{+90}_{-250})$ or $f_0(1500)$, is superfluous for the $q\bar{q}$ systematics. Looking on the $(n, M^2)$-trajectories of bare states (Fig. 3b), one can see that just $f_0^{bare}(1600)$ does not fall onto any linear $q\bar{q}$ trajectory. So it would be natural to conclude that the state $f_0^{bare}(1600)$ is an exotic state, i.e. the glueball.

Relying on the systematics of $q\bar{q}$ states on the $(n, M^2)$ plot, we regard the classification presented in Eqs. (8) and (9) as endorsed one. Lattice calculations support the solution (8)–(9) giving the mass of the lightest glueball in the interval 1550–1750 MeV [17].

For resonances belonging to linear trajectories of Fig. 3a, the $q\bar{q}$ component is dominant. The scalar-isoscalar resonances $f_0(1300)$, $f_0(1500)$ contain a significant gluonium component, and certain gluonium admixture exists in $f_0(1750)$: gluonium components in these resonances result in a dominance of non-strange decay channels for $f_0(1300)$, $f_0(1500)$, $f_0(1750)$ [25].

The location of the $f_0(980)$ pole near $K\bar{K}$ threshold indicates the existence of some admixture of the $K\bar{K}$-component in this resonance. Concerning the dominance of the $q\bar{q}$ component, the estimation performed on the ground of quark combinatorics, by using hadronic decay couplings for $f_0(980) \to \pi\pi, K\bar{K}$ (with $g_K^2/g_\pi^2 \simeq 2$), point to a large $s\bar{s}$ component: the coupling values provide us $\varphi \sim -60^\circ$ or $\varphi \sim 50^\circ$ [26].

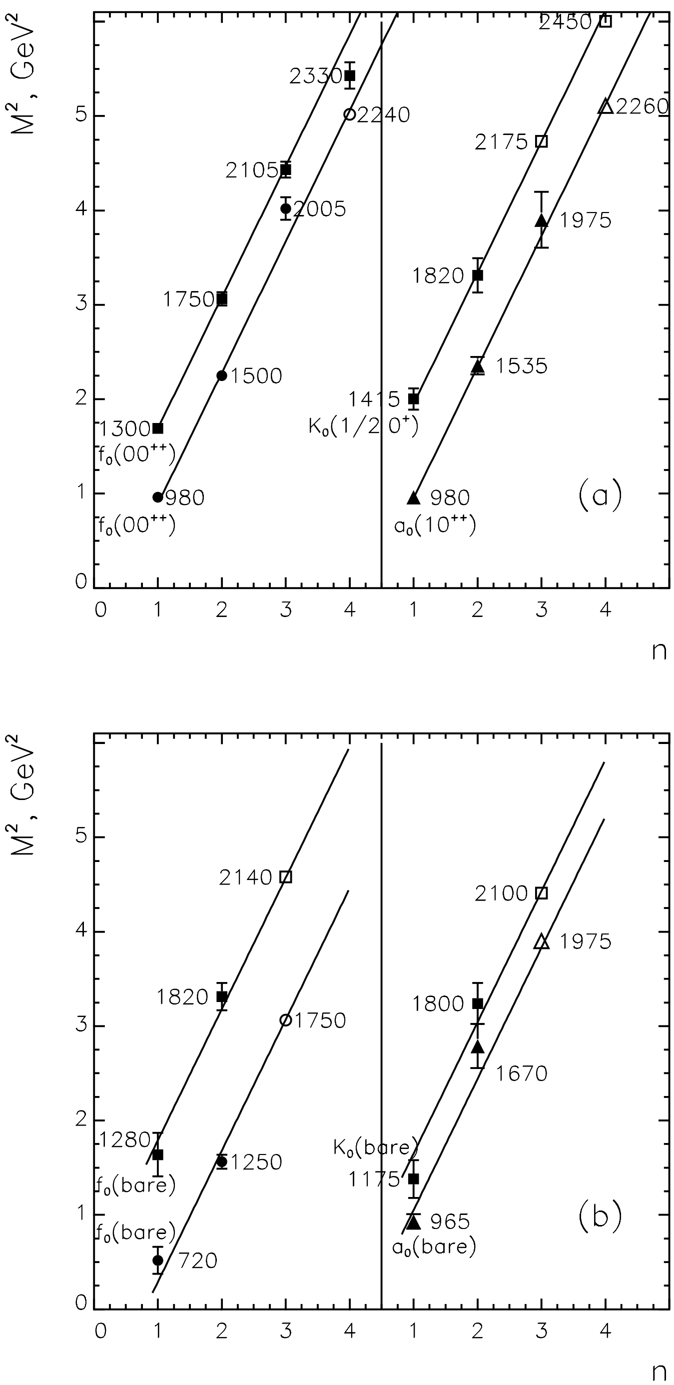


Figure 3: Linear trajectories in $(n, M^2)$-plane for scalar resonances (a) and scalar bare states (b). Open points stand for predicted states.

## 5. Radiative decays of the $P$-wave $q\bar{q}$-mesons

The investigation of radiative decays is a powerful tool for establishing the quark structure of hadrons. At the early stage of the quark model, the radiative decays of vector mesons provided strong arguments in favour of the idea of constituent quark, a universal object for mesons and baryons [27, 28, 29, 30]. To our opinion, radiative decays of the $1^3P_J q\bar{q}$ mesons are equally important for the verification of the $P$-wave multiplet.

In Ref. [31], partial widths of the decays $f_0(980) \to \gamma\gamma$ and $a_0(980) \to \gamma\gamma$ have been calculated assuming $f_0(980)$ and $a_0(980)$ to be dominantly $q\bar{q}$ states, that is, $1^3P_0 q\bar{q}$ mesons. The results of the calculation agree well with experimental data. In paper [32], on the basis of data [33] for the decay $\phi(1020) \to \gamma f_0(980)$ together with value for the partial width $f_0(980) \to \gamma\gamma$ obtained in the re-analysis [34], the flavour content of $f_0(980)$ has been studied. Assuming the flavour wave function in the form $n\bar{n}\cos\varphi + s\bar{s}\sin\varphi$, the experimental data were described with two possible values of mixing angle: either $\varphi = -48^\circ \pm 6^\circ$ or $\varphi = 85^\circ \pm 4^\circ$ (negative value is more preferable).

Although direct calculations of widths of radiative decays agree well with the hypothesis that the $q\bar{q}$ component dominates $f_0(980)$ and $a_0(980)$, to determine reliably these mesons as members of the $1^3P_0 q\bar{q}$ multiplet one more step is necessary. We have to prove that radiative decays of tensor mesons $a_2(1320)$, $f_2(1270)$, $f_2(1525)$ can be calculated within the same approach and the same technique as it was done for the calculation of the reactions with $f_0(980)$ and $a_0(980)$. Tensor mesons $a_2(1320)$, $f_2(1270)$, $f_2(1525)$ are basic members of the $P$-wave $q\bar{q}$ multiplet, and just the existence of tensor mesons had been used to suggest quark–antiquark classification for four $P$-wave nonets [35, 36]. Under this motivation, partial widths of the tensor $q\bar{q}$ states $a_2(1320) \to \gamma\gamma$, $f_2(1270) \to \gamma\gamma$ and $f_2(1525) \to \gamma\gamma$ have been calculated in [37]. The agreement with data has been reached for all calculated partial widths that indicates definitely that both scalar ($f_0(980)$, $a_0(980)$) and tensor ($a_0(1320)$, $f_2(1270)$, $f_2(1525)$) mesons belong to the same $P$-wave $q\bar{q}$ multiplet.

## 6. Exotics

The established $q\bar{q}$ systematics of scalar mesons based on the analysis of experimental data fix two nonets $1^3P_0 q\bar{q}$ and $2^3P_0 q\bar{q}$ in terms of bare states. The resonances which are the descendants of pure $q\bar{q}$ states are located on linear trajectories in the $(n, M^2)$-plane. The $q\bar{q}$ systematics reveal two extra states which are the light $\sigma$-meson, with mass about 300–450 MeV, and broad state $f_0(1530^{+90}_{-250})$. The broad state is the descendant of the pure glueball state which accumulated the widths of neighbouring $q\bar{q}$ resonances.

The nature of the exotic $\sigma$-meson is not quite clear, and various hypotheses have been suggested, for example, see [10, 11, 38] It is worth recollecting that a possibility for the existence of two extra states, which are superfluous from the point of view of the $q\bar{q}$ systematics, was discussed in the literature, see, for example, [39, 40, 41].

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