ON THE NATURE OF THE SCALAR $a_0(980)$ AND $f_0(980)$-MESONS

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It is presented a critical consideration of all unusual properties of the scalar $a_0(980)$ and $f_0(980)$-mesons in the four-quark, two-quark and molecular models. The arguments are adduced that the four-quark model is more preferable. It is discussed the complex of experiments that could finally resolve this issue.

Introduction

Spherical Neutral Detector (SND) from the e^+e^--collider VEPP-2M in Novosibirsk has discovered [1, 2] the electric dipole decays $\phi \to \gamma\pi^0\pi^0$ and $\phi \to \gamma\pi^0\eta$ in the region of the soft by strong interaction standard photons with the energy $\omega < 120\,\mathrm{MeV}$, i.e. in the region of the scalar $f_0(980)$ and $a_0(980)$-mesons, $m_{\pi^0\pi^0} > 900\,\mathrm{MeV}$ and $m_{\pi^0\eta} > 900\,\mathrm{MeV}$, $\phi \to \gamma f_0(980) \to \gamma\pi^0\pi^0$ and $\phi \to \gamma a_0(980) \to \gamma\pi^0\eta$. The final data [3, 4] are

$$\begin{aligned} & B(\phi \to \gamma\pi^0\pi^0\,;\, m_{\pi^0\pi^0} > 900\,\mathrm{MeV}) = \\ & = (0.559 \pm 0.06 \pm 0.053 \pm 0.025)\cdot 10^{-4} \\ & \text{at total}\;\; B(\phi \to \gamma\pi^0\pi^0) = (1.221 \pm 0.098 \pm 0.061)\cdot 10^{-4}\,, \qquad (1) \\ & B(\phi \to \gamma\pi^0\eta\,;\, m_{\pi^0\eta} > 900\,\mathrm{MeV}) \simeq (0.46 \pm 0.13)\cdot 10^{-4}\,, \\ & \text{at total}\;\; B(\phi \to \gamma\pi^0\eta) = (0.88 \pm 0.14 \pm 0.09)\cdot 10^{-4}\,. \qquad (2) \end{aligned}$$

Cryogenic Magnetic Detector-2 (CMD-2) from the e^+e^--collider VEPP-2M in Novosibirsk has confirmed these results [5].

The branching ratios in Eqs. (1) and (2) are great for this photon energy region and, probably, can be understood only if four-quark resonances are produced [6, 7, 8]. Note that the $a_0(980)$ meson is produced in the ϕ radiative decay as intensively as the containing strange quarks η' meson.

1. Evidences for strange quarks in the $f_0(980)$ and $a_0(980)$

To feel why numbers in Eqs. (1) and (2) are great, one can adduce the rough estimate. Let there be structural radiation without a resonance in the final state with the spectrum

$$\frac{d\Gamma(\phi \to \gamma\pi^0\pi^0(\eta))}{d\omega} \sim \frac{\alpha}{\pi}\cdot\delta_{OZI}\cdot\frac{1}{m_\phi^3}\omega^3\,,$$

where $\delta_{OZI} \sim 10^{-2}$ is a factor describing the suppression by Okubo-Zweig-Iizuka (OZI) rule. Recall that the ω^3 law follows from gauge invariance. Really, the decay amplitude is proportional to the electromagnetic field $F_{\mu\nu}$ (in our case to the electric field), i. e. to the photon energy ω in the soft photon region.

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Then one gets

$$\Gamma(\phi \to \gamma\pi^0\pi^0(\eta)) \sim \frac{1}{4}\cdot\frac{\alpha}{\pi}\cdot\delta_{OZI}\cdot\frac{\omega_0^4}{m_\phi^3} \simeq 10^{-6}\,\mathrm{MeV}\,,$$
$$\text{i.e. } B(\phi \to \gamma\pi^0\pi^0(\eta)) \sim 2\cdot 10^{-7}\,,$$

where $\omega_0 = 120\,\mathrm{MeV}$.

To understand, why Eq. (2) points to four-quark model, is particular easy. Really, the ϕ-meson is the isoscalar practically pure $s\bar{s}$-state, that decays to the isovector hadron state $\pi^0\eta$ and the isovector photon. The isovector photon originates from the ρ-meson, $\phi \to \rho a_0(980) \to \gamma\pi^0\eta$, the structure of which in this energy region is familiar

$$\rho \approx (u\bar{u} - d\bar{d})/\sqrt{2}\,. \tag{3}$$

The structure of the $a_0(980)$-meson , from which the $\pi^0\eta$-system originates, in general, is

$$X = a_0(980) = c_1(u\bar{u} - d\bar{d})/\sqrt{2} + c_2 s\bar{s}(u\bar{u} - d\bar{d})/\sqrt{2} + \dots\,. \tag{4}$$

The strange quarks, with the first term in Eq. (4) taken as dominant, are absent in the intermediate state. So, we would have the suppressed by OZI-rule decay with $B(\phi \to \gamma a_0(980) \to \gamma\pi^0\eta) \sim 10^{-6}$ owing to the real part of the decay amplitude [7]. The imaginary part of the decay amplitude, resulted from the K^+K^-- intermediate state ($\phi \to \gamma K^+K^- \to \gamma a_0(980) \to \gamma\pi^0\eta$), violates the OZI-rule and increases the branching ratio [6, 7] up to 10^{-5}.

The four-quark hypothesis is supported also by the J/ψ-decays. Really [9],

$$B(J/\psi \to a_2(1320)\rho) = (109 \pm 22)\cdot 10^{-4}\,, \tag{5}$$

while [10]

$$B(J/\psi \to a_0(980)\rho) < 4.4\cdot 10^{-4}\,. \tag{6}$$

The suppression

$$B(J/\psi \to a_0(980)\rho)/B(J/\psi \to a_2(1320)\rho) < 0.04 \pm 0.008 \tag{7}$$

seems strange, if one considers the $a_2(1320)$ and $a_0(980)$-states as the tensor and scalar two-quark states from the same P-wave multiplet with the quark structure

$$a_0^0 = (u\bar{u} - d\bar{d})/\sqrt{2}\quad,\quad a_0^+ = u\bar{d}\quad,\quad a_0^- = d\bar{u}\,. \tag{8}$$

While the four-quark nature of the $a_0(980)$-meson with the symbolic quark structure

$$a_0^0 = s\bar{s}(u\bar{u} - d\bar{d})/\sqrt{2}\quad,\quad a_0^+ = s\bar{s}u\bar{d}\quad,\quad a_0^- = s\bar{s}d\bar{u} \tag{9}$$

is not contrary to the suppression in Eq. (7).

Besides, it was predicted in [11] that the production vigor of the $a_0(980)$-meson, with it taken as the four-quark state from the lightest nonet of the MIT-bag [12], in the $\gamma\gamma$-collisions should be suppressed by the value order in comparison with the $a_0(980)$-meson taken as the two-quark P-wave state. In the four-quark model there was obtained the estimate [11]

$$\Gamma(a_0(980) \to \gamma\gamma) \sim 0.27\,\mathrm{keV}, \tag{10}$$

which was confirmed by experiment [13, 14]

$$\Gamma(a_0 \to \gamma\gamma) = (0.19 \pm 0.07^{+0.1}_{-0.07})/B(a_0 \to \pi\eta)\,\text{keV, Crystal Ball,}$$
$$\Gamma(a_0 \to \gamma\gamma) = (0.28 \pm 0.04 \pm 0.1)/B(a_0 \to \pi\eta)\,\text{keV, JADE.} \qquad (11)$$

At the same time in the two-quark model (8) it was anticipated [15, 16] that

$$\Gamma(a_0 \to \gamma\gamma) = (1.5 - 5.9)\Gamma(a_2 \to \gamma\gamma) = (1.5 - 5.9)(1.04 \pm 0.09)\,\text{keV}.$$

The wide scatter of the predictions is connected with different reasonable guesses of the potential form.

As for the $\phi \to \gamma f_0(980) \to \gamma\pi^0\pi^0$-decay, the more sophisticated analysis is required.

The structure of the $f_0(980)$-meson, from which the $\pi^0\pi^0$-system originates, in general, is

$$Y = f_0(980) = \tilde{c}_0 gg + \tilde{c}_1(u\bar{u} + d\bar{d})/\sqrt{2} + \tilde{c}_2 s\bar{s} + $$
$$+\tilde{c}_3 s\bar{s}(u\bar{u} + d\bar{d})/\sqrt{2} + \ldots \,. \qquad (12)$$

First we discuss a possibility to treat the $f_0(980)$-meson as the quark-antiquark state.

The hypothesis that the $f_0(980)$-meson is the lowest two-quark P-wave scalar state with the quark structure

$$f_0 = (u\bar{u} + d\bar{d})/\sqrt{2} \qquad (13)$$

contradicts Eq. (1) in view of OZI, much as Eq. (8) contradicts Eq. (2) (see the above arguments).

Besides, this hypothesis contradicts a variety of facts:

i) the strong coupling with the $K\bar{K}$-channel [17, 7]

$$1 < R = |g_{f_0 K^+K^-}/g_{f_0\pi^+\pi^-}|^2 \lesssim 8\,, \qquad (14)$$

for from Eq. (13) it follows that $|g_{f_0 K^+K^-}/g_{f_0\pi^+\pi^-}|^2 = \lambda/4 \simeq 1/8$, where λ takes into account the strange sea suppression;

ii) the weak coupling with gluons [18]

$$B(J/\psi \to \gamma f_0(980) \to \gamma\pi\pi) < 1.4 \cdot 10^{-5} \qquad (15)$$

opposite the expected one [19] for Eq. (13)

$$B(J/\psi \to \gamma f_0(980)) \gtrsim B(J/\psi \to \gamma f_2(1270))/4 \simeq 3.4 \cdot 10^{-4}\,; \qquad (16)$$

iii) the weak coupling with photons [20, 21]

$$\Gamma(f_0 \to \gamma\gamma) = (0.31 \pm 0.14 \pm 0.09)\,\text{keV, Crystal Ball,}$$
$$\Gamma(f_0 \to \gamma\gamma) = (0.24 \pm 0.06 \pm 0.15)\,\text{keV, MARK II} \qquad (17)$$

opposite the expected one [15, 16] for Eq. (13)

$$\Gamma(f_0 \to \gamma\gamma) = (1.7 - 5.5)\Gamma(f_2 \to \gamma\gamma) = (1.7 - 5.5)(2.8 \pm 0.4)\,\text{keV};$$

iv) the decays $J/\psi \to f_0(980)\omega$, $J/\psi \to f_0(980)\phi$, $J/\psi \to f_2(1270)\omega$, $J/\psi \to f_2'(1525)\phi$ [9]

$$B(J/\psi \to f_0(980)\omega) = (1.4 \pm 0.5) \cdot 10^{-4}\,. \qquad (18)$$

$$B(J/\psi \to f_0(980)\phi) = (3.2 \pm 0.9) \cdot 10^{-4}\,. \qquad (19)$$

$$B(J/\psi \to f_2(1270)\omega) = (4.3 \pm 0.6) \cdot 10^{-3}\,, \tag{20}$$

$$B(J/\psi \to f_2'(1525)\phi) = (8 \pm 4) \cdot 10^{-4}\,. \tag{21}$$

The suppression

$$B(J/\psi \to f_0(980)\omega)/B(J/\psi \to f_2(1270)\omega) = 0.033 \pm 0.013 \tag{22}$$

looks strange in the model under consideration as well as Eq. (7) in the model (8).

The existence of the $J/\psi \to f_0(980)\phi$-decay of greater intensity than the $J/\psi \to f_0(980)\omega$-decay (compare Eq. (18) and Eq. (19)) shuts down the model (13) for in the case under discussion the $J/\psi \to f_0(980)\phi$-decay should be suppressed in comparison with the $J/\psi \to f_0(980)\omega$-decay by the OZI-rule.

So, Eq. (13) is excluded at a level of physical rigor.

Can one consider the $f_0(980)$-meson as the near $s\bar{s}$-state?

It is impossible without a gluon component. Really, it is anticipated for the scalar $s\bar{s}$-state from the lowest P-wave multiplet that [19]

$$B(J/\psi \to \gamma f_0(980)) \gtrsim B(J/\psi \to \gamma f_2'(1525))/4 \simeq 1.6 \cdot 10^{-4} \tag{23}$$

opposite Eq. (15), which requires properly that the $f_0(980)$-meson be the 8-th component of the $SU_f(3)$-oktet

$$f_0(980) = (u\bar{u} + d\bar{d} - 2s\bar{s})/\sqrt{6}\,. \tag{24}$$

This structure gives

$$\Gamma(f_0 \to \gamma\gamma) = \frac{3}{25}(1.7 - 5.5)\Gamma(f_2 \to \gamma\gamma) = (0.57 - 1.9)(1 \pm 0.14)\,\text{keV},$$

that is on the verge of conflict with Eq. (17).

Besides, it predicts

$$B(J/\psi \to f_0(980)\phi) = (2\lambda \approx 1) \cdot B(J/\psi \to f_0(980)\omega)\,, \tag{25}$$

that also is on the verge of conflict with experiment, compare Eq. (18) with Eq. (19).

Eq. (24) contradicts Eq. (14) for the prediction

$$R = |g_{f_0 K^+K^-}/g_{f_0\pi^+\pi^-}|^2 = (\sqrt{\lambda} - 2)^2/4 \simeq 0.4\,. \tag{26}$$

Besides, in this case the mass degeneration $m_{f_0} \simeq m_{a_0}$ is coincidental, if to treat the a_0-meson as the four-quark state, or contradicts the light hypothesis (8).

The introduction of a gluon component, gg, in the $f_0(980)$-meson structure allows the weak coupling with gluons (15) to be resolved easy. Really, by [19],

$$\begin{aligned} &B(R[q\bar{q}] \to gg) \simeq O(\alpha_s^2) \simeq 0.1 - 0.2\,,\\ &B(R[gg] \to gg) \simeq O(1)\,, \end{aligned} \tag{27}$$

then the minor ($\sin^2\alpha \le 0.08$) dopant of the gluonium

$$\begin{aligned} &f_0 = gg\sin\alpha + \left[\left(1/\sqrt{2}\right)(u\bar{u} + d\bar{d})\sin\beta + s\bar{s}\cos\beta\right]\cos\alpha\,,\\ &\tan\alpha = -O(\alpha_s)\left(\sqrt{2}\sin\beta + \cos\beta\right)\,, \end{aligned} \tag{28}$$

allows to satisfy Eqs. (14), (15) and to get the weak coupling with photons

$$\Gamma(f_0(980)) \to \gamma\gamma) < 0.22\,\text{keV} \tag{29}$$

at

$$-0.22 > \tan\beta > -0.52\,. \tag{30}$$

So, $\cos^2\beta > 0.8$ and the $f_0(980)$-meson is near the $s\bar{s}$-state, as in [22]. It gives

$$0.1 < \frac{B(J/\psi \to f_0(980)\omega)}{B(J/\psi \to f_0(980)\phi)} = \frac{1}{\lambda}\tan^2\beta < 0.54\,. \tag{31}$$

As for the experimental value,

$$B(J/\psi \to f_0(980)\omega)/B(J/\psi \to f_0(980)\phi) = 0.44 \pm 0.2\,, \tag{32}$$

it needs refinement.

The scenario, in which with Eq. (28) the $a_0(980)$-meson is the two-quark state (8), runs into following difficulties:
i) it is impossible to explain the f_0 and a_0-meson mass degeneration;
ii) it is possible to get only [6, 7]

$$\begin{aligned} &B(\phi \to \gamma f_0 \to \gamma\pi^0\pi^0) \simeq 1.7\cdot 10^{-5}\,,\\ &B(\phi \to \gamma a_0 \to \gamma\pi^0\eta^0) \simeq 10^{-5}\,; \end{aligned} \tag{33}$$

iii) it is predicted

$$\Gamma(f_0 \to \gamma\gamma) < 0.13\cdot\Gamma(a_0 \to \gamma\gamma)\,, \tag{34}$$

that is on the verge of conflict with the experiment, compare Eqs. (11) and (17);
iv) it is also predicted

$$B(J/\psi \to a_0(980)\rho) = (3/\lambda \approx 6)\cdot B(J/\psi \to f_0(980)\phi)\,, \tag{35}$$

that has almost no chance, compare Eqs. (6) and (19).

Note that the λ independent prediction

$$\begin{aligned} &B(J/\psi \to f_0(980)\phi)/B(J/\psi \to f_2'(1525)\phi) =\\ &= B(J/\psi \to a_0(980)\rho)/B(J/\psi \to a_2(1320)\rho) \end{aligned} \tag{36}$$

is excluded by the central figure in

$$B(J/\psi \to f_0(980)\phi)/B(J/\psi \to f_2'(1525)\phi) = 0.4 \pm 0.23\,, \tag{37}$$

obtained from Eqs. (19) and (21), compare with Eq. (7). But, certainly, experimental error is too large. Even twofold increase in accuracy of measurement of Eq. (37) could be crucial in the fate of the scenario under discussion.

The prospects to consider the $f_0(980)$-meson as the near $s\bar{s}$-state (28) and the $a_0(980)$-meson as the four-quark state (9) with the coincidental mass degeneration is rather gloomy especially as the four-quark model with the symbolic structure

$$f_0 = s\bar{s}(u\bar{u} + d\bar{d})\cos\theta/\sqrt{2} + u\bar{u}d\bar{d}\sin\theta\,, \tag{38}$$

built around the MIT-bag [12], reasonably justifies all unusual features of the $f_0(980)$-meson [17, 23].

Really, the strong coupling with the $K\bar{K}$-channel is resolved at $1/16 < \tan^2\theta < 1/2$, see [17]. There is no problem of the a_0 and f_0-meson mass degeneracy at $\tan^2\theta < 1/3$. The weak coupling with photons was predicted in [11]

$$\Gamma(f_0(980) \to \gamma\gamma) \sim 0.27\,\text{keV}. \tag{39}$$

There is also no problem with the suppression (22).

But, it should be explained how the problem of the weak coupling with gluons is resolved. Recall that in the MIT-model the $f_0(980)$-meson "consists" of pairs of colorless and colored pseudoscalar and vector two-quark mesons [12, 11, 17]), including the pair of the flavorless colored vector two-quark mesons. It is precisely this pair that converts to two gluons in the lowest order in α_s.

The width of the $f_0(980)$-meson decay in two gluons can be calculated much as the width of a four-quark state decay in two photons [11]. It gives

$$\Gamma(f_0 \to gg) = \frac{g_0^2}{16\pi m_{f_0}} 0.03 \left(\frac{\alpha_s 4\pi}{f_{\underline{V}}^2}\right)^2 (1+\tan\theta)^2 \cos^2\theta\,, \tag{40}$$

where $g_0^2/4\pi \approx 10-20$ GeV is the OZI-superallowed coupling constant, 0.03 is the fraction of the pair of the flavorless colored vector two-quark mesons in the $f_0(980)$-meson wave function, that converts to two massless gluons, $\alpha_s 4\pi/f_{\underline{V}}^2$ is the probability of the transition of the flavorless colored vector two-quark meson in the massless gluon, $\underline{V} \leftrightarrow g$, $f_{\underline{V}}^2/4\pi = f_\rho^2/8\pi \approx 1$ for the space wave functions of the flavorless colored vector two-quark meson and the ρ-meson are the same. So,

$$\Gamma(f_0 \to gg) \approx 15\alpha_s^2(1+\tan\theta)^2\cos^2\theta \quad \text{MeV}. \tag{41}$$

At $-1/\sqrt{2} < \tan\theta < -1/4$ one gets the width that is at worst of order of magnitude less than in the two-quark scalar meson case [19] and does not contradict Eq. (15).

If to use only planar diagrams one can get in the four-quark model

$$\begin{aligned} &B(J/\psi \to a_0^0(980)\rho^0) \approx B(J/\psi \to f_0(980)\omega) \approx \\ &\approx 0.5B(J/\psi \to f_0(980)\phi)\,, \end{aligned} \tag{42}$$

that does not contradict experiment, see Eqs. (6), (18) and (19).

Recall that almost all four-quark states of the MIT-bag [12] are very broad for their decays into the OZI-superallowed channels. That is why it is impossible to extract them from the background independently on models. Only in the rare cases on or under the thresholds of the OZI-superallowed decay channels the "primitive" four-quark states should show up as narrow resonances. This sort evidences of the MIT-bag, probably, are the $a_0(980)$ and $f_0(980)$-mesons, as well as the resonance-interference phenomena discovered at the thresholds of the $\gamma\gamma \to \rho^0\rho^0$ and $\gamma\gamma \to \rho^+\rho^-$ reactions (see review [23]) and predicted in [11].

A few words on the attractive molecular model, wherein the $a_0(980)$ and $f_0(980)$-mesons are the bound states of the $K\bar{K}$-system [24, 25]. This model explains the mass degeneration of the states and their strong coupling with the $K\bar{K}$-channel. In the molecular model, as in the four-quark model, there is no problems with the suppressions (7) and (22). Note that Eq. (42) is also in the $K\bar{K}$-molecule model.

But its predictions for two-photon widths [16]

$$\Gamma(a_0(K\bar{K}) \to \gamma\gamma) = \Gamma(f_0(K\bar{K}) \to \gamma\gamma) \approx 0.6\,\text{keV} \tag{43}$$

is on the verge of conflict with the data (11) and (17). Besides, the $K\bar{K}$-molecule widths should be less bound energy $\epsilon \approx 20$ MeV. The current data [9], $\Gamma_{a_0} \simeq 50-100$ MeV and $\Gamma_{f_0} \simeq 40-100$ MeV, contradict this. The $K\bar{K}$-molecule model predicts also [26]

$$B(\phi \to \gamma f_0 \to \gamma\pi\pi) \simeq B(\phi \to \gamma a_0 \to \gamma\pi^0\eta) \simeq 10^{-5}, \tag{44}$$

that contradict Eqs. (1) and (2).

The studies of the $a_0(980)$ and $f_0(980)$-meson production in the $\pi^- p \to \pi^0 \eta n$ [27] and $\pi^- p \to \pi^0 \pi^0 n$ [28] reactions over a wide range of the four-momentum transfer square $0 < -t < 1\,\mathrm{GeV}^2$ show that these states are compact like the ρ and other two-quark mesons but not extended like the molecules with the form factors due to the wave functions. It seems that these experiments leave no chance to the $K\bar{K}$-molecule model. As for the four-quark states, they are compact like the two-quark ones.

Lastly, there is a need to answer to the traditional question. Where are the scalar two-quark states from the lowest P-wave multiplet with the quark structures (8) and (13)? We believe that there is no a tragedy with it now! All members of this multiplet are established [9]:

$$\begin{aligned}
& b_1(1235)\,, \quad I^G(J^{PC}) = 1^+(1^{+-})\,, \quad \Gamma_{b_1(1235)} \simeq 142\,\mathrm{MeV}, \\
& h_1(1170)\,, \quad I^G(J^{PC}) = 0^-(1^{+-})\,, \quad \Gamma_{h_1(1170)} \simeq 360\,\mathrm{MeV}, \\
& a_1(1260)\,, \quad I^G(J^{PC}) = 1^-(1^{++})\,, \quad \Gamma_{a_1(1260)} = 250\,\mathrm{to}\,600\,\mathrm{MeV}, \\
& f_1(1285)\,, \quad I^G(J^{PC}) = 0^+(1^{++})\,, \quad \Gamma_{f_1(1285)} \simeq 24\,\mathrm{MeV}, \\
& a_2(1320)\,, \quad I^G(J^{PC}) = 1^-(2^{++})\,, \quad \Gamma_{a_2(1320)} \simeq 107\,\mathrm{MeV}, \\
& f_2(1270)\,, \quad I^G(J^{PC}) = 0^+(2^{++})\,, \quad \Gamma_{f_2(1270)} \simeq 185\,\mathrm{MeV}, \\
& a_0(1450)\,, \quad I^G(J^{PC}) = 1^-(0^{++})\,, \quad \Gamma_{a_0(1450)} \simeq 265\,\mathrm{MeV}, \\
& m_{a_0(1450)} = 1300 \ \ \mathrm{to} \ \ 1500\,\mathrm{MeV}\,, \quad \Gamma_{a_0(1450)} = 100\,\mathrm{to}\,300\,\mathrm{MeV}, \\
& f_0(1370)\,, \quad I^G(J^{PC}) = 0^+(2^{++})\,, \quad \Gamma_{f_0(1370)} = 200\,\mathrm{to}\,500\,\mathrm{MeV}, \\
& m_{f_0(1370)} = 1200 \ \ \mathrm{to} \ \ 1500\,\mathrm{MeV}.
\end{aligned} \tag{45}$$

Certainly, one cannot consider the scalar members of Eq. (45) as much-established and it needs else the refinement of their masses and widths. Nevertheless, from Eq. (45) it will be obvious that forces, responsible for splitting of masses in the P-wave multiplet, are either small or compensate each other. That is why we rightfully expect the existence of the $a_0(\approx 1300)$ and $f_0(\approx 1300)$-states and it seems by far that the $a_0(980)$ and $f_0(980)$-mesons are foreigners in the company (45).

The statement of the OPAL Collaboration [29] on a consistency of the $f_0(980)$ inclusive production in hadronic Z^0 decay with the hypothesis (13) is not conclusive because any calculations of the inclusive production of four-quark states are absent. Nevertheless, from general point of view one can expect as copious multiquark state inclusive production as two-quark one because in both cases the primary production is the multiproduction of the vacuum $q\bar{q}$ pairs.

2. The theoretical grounds for the four-quark model

A few words on the theoretical grounds for the four-quark nature of the scalar $f_0(980)$ and $a_0(980)$ mesons. It was shown in the context of the MIT-bag [12] that the low-lying scalar four-quark nonet as bound state of diquarks ($T_a = \varepsilon_{abc}\bar{q}^b\bar{q}^c$ and $\bar{T}^a = \varepsilon^{abc}q_b q_c$, note that similar diquarks binding up with quarks to form the baryon octet) arises from the strong binding energy in such a configuration due to a hyperfine interaction Hamiltonian of the form

$$H_{hf} = -\Delta \sum_{i<j} \vec{s}_i \cdot \vec{s}_j \vec{F}_i \cdot \vec{F}_j\,, \quad \vec{s} = \frac{\vec{\sigma}}{2}\,,\ \vec{F} = \frac{\vec{\lambda}}{2}\,,$$

that obtained from one gluon exchange in QCD.

The result is [12]

$$\begin{aligned}
& \sigma = C^0 = ud\bar{u}\bar{d}\,; \quad \kappa^+ = C_{K^+} = ud\bar{d}\bar{s}\,, \quad \kappa^0 = C_{K^0} = ud\bar{u}\bar{s}\,, \\
& \kappa^- = C_{K^-} = ds\bar{u}\bar{d}\,, \quad \bar{\kappa}^0 = C_{\bar{K}^0} = us\bar{u}\bar{d}\,; \quad f_0 = C^s = \frac{(us\bar{u}\bar{s} + ds\bar{d}\bar{s})}{\sqrt{2}}\,;
\end{aligned}$$

$$a_0^+ = C^s_{\pi^+} = us\bar{d}\bar{s}\,, \quad a_0^0 = C^s_{\pi^0} = \frac{(us\bar{u}\bar{s} - ds\bar{d}\bar{s})}{\sqrt{2}}\,, \quad a_0^- = C^s_{\pi^-} = ds\bar{u}\bar{s}\,,$$
$$m(\sigma) = 650\text{MeV}\,, \quad m(\kappa) = 900\text{MeV}\,, \quad m(f_0) = m(a_0) = 1100\text{MeV}\,.$$

Certainly, the MIT-bag model is rather rough, so that one can consider its prediction only as a guide. As the σ and κ mesons lie considerably above their the OZI-superallowed channels their widths have of the 1 GeV order. That is why the information about them can be got only in a model dependent way.

In the last few years the true renaissance has been going in treatments of $\pi\pi$ and πK scattering with help of phenomenological linear σ models, see, for example, [30, 31, 32, 33, 34]. It has been argued on occasion that the corresponding σ mesons are quark-antiquark states. But in fact at the Lagrangian level there is no difference in the formulation of the two-quark and four-quark cases [35].

Conclusion

So, there are many reasons to consider the $a_0(980)$ and $f_0(980)$ mesons as the four-quark states. Nevertheless, in summary one emphasizes once again that the further study of the decays $\phi \to \gamma f_0$ and $\phi \to \gamma a_0$; $J/\psi \to a_0\rho$, $f_0\omega$, $f_0\phi$, $a_2\rho$, $f_2\omega$, and $f_2'\phi$; $a_0 \to \gamma\gamma$ and $f_0 \to \gamma\gamma$; $D_s \to f_0\pi$ and $D_s \to a_0\pi$ [36] will enable one to solve the question on the $a_0(980)$ and $f_0(980)$-meson nature, at any case to close the above scenarios.

The present work is supported in part by the grant RFBR-INTAS IR-97-232.

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