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On the nature of the $a_0(980)$ and $f_0(980)$ scalar mesons

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Abstract. The unusual properties of the $a_0(980)$ and $f_0(980)$ scalar mesons are discussed in terms of the four-quark, two-quark, and molecular models. Arguments in favor of the four-quark model are given. Further studies needed to resolve the problem are discussed.

In August 1997, a report was made concerning the discovery of the electric dipole transitions $\phi \to \gamma\pi^0\pi^0$ and $\phi \to \gamma\pi^0\eta$ in the range of fairly soft (in relation to strong interactions) gamma photons with an energy $\omega < 200$ MeV, i.e. in the region of scalar $a_0(980)$ and $f_0(980)$ mesons $m_{\pi^0\pi^0} > 800$ MeV and $m_{\pi^0\eta} > 800$ 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 discovery was made on the spherical neutral detector (SND) attached to the accelerator – storage complex (VEPP-2M) in Novosibirsk, and the report took place at the HADRON-97 conference held at the Brookhaven National Laboratory (Upton, N.Y.). The preliminary data [1, 2] are as follows:

$$B(\phi \to \gamma\pi^0\pi^0\,;\, m_{\pi^0\pi^0} > 800\,\text{MeV}) = (1.1 \pm 0.2) \times 10^{-4}\,, \tag{1}$$

$$B(\phi \to \gamma\pi^0\eta\,;\, m_{\pi^0\eta} > 800\,\text{MeV}) = (1.3 \pm 0.5) \times 10^{-4}\,. \tag{2}$$

In this range of gamma-photon energies, the relative intensities of decays (1) and (2) are large and can be understood only if four-quark resonances are produced [3, 4].

Let us show that the values (1) and (2) really are large. Suppose we have a structural radiation with no resonance in the final state and with a spectrum normalized to the relative decay probability:

$$\frac{\mathrm{d}B(\phi \to \gamma\pi^0\pi^0(\eta))}{\mathrm{d}\omega} \sim \frac{\alpha}{\pi}\frac{1}{m_\phi^4}\omega^3\,.$$

(The reader will recall that the ω^3-law emerges due to gauge invariance. Indeed, the scattering amplitude is proportional to the electromagnetic field $F_{\mu\nu}$, which in our case is an electric field. This means that in the soft-photon region the amplitude is proportional to the photon energy ω.) Then at $\omega_0 = 200$ MeV the relative decay probability is

$$B\big(\phi \to \gamma\pi^0\pi^0(\eta)\big) \sim \frac{1}{4}\,\frac{\alpha}{\pi}\,\frac{\omega_0^4}{m_\phi^4} \simeq 10^{-6}\,.$$

It is quite easy to understand why (2) points to the four-quark model. Indeed, the ϕ meson is practically a pure isoscalar $s\bar{s}$ state, which decays into an isovector state $\pi^0\eta$ and an isovector photon. The isovector photon originates in the ρ meson, $\phi \to \rho a_0(980) \to \gamma\pi^0\eta$, whose structure in this energy range is well known:

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

The structure of the state [presumably the $a_0(980)$ meson] that produces the $\pi^0\eta$ system generally has the form

$$X = a_0(980) = \frac{c_1(u\bar{u} - d\bar{d})}{\sqrt{2}} + \frac{c_2 s\bar{s}(u\bar{u} - d\bar{d})}{\sqrt{2}} + \ldots \tag{4}$$

If we assume that the first term is predominant in the $a_0(980)$ meson, as it is in the ρ meson, then there are no strange quarks in the intermediate state. Thus, we would have a decay suppressed according to the Okubo – Zweig – Izuki (OZI) rule. The suppression factor in the decay probability would be of the order of 100, which leads to $B(\phi \to \gamma a_0(980) \to \gamma\pi^0\eta) \sim 10^{-6}$ due to the real part of the amplitude [5]. The imaginary part of the amplitude, due to intermediate K^+K^- states [$\phi \to \gamma K^+K^- \to \gamma a_0(980) \to \gamma\pi^0\eta$], violates the OZI rule and increases the decay intensity [3, 4] to 10^{-5}.

And so, if Eqn (2) is true, we are forced to assume that in the energy range considered here the four-quark state with the symbolic structure $s\bar{s}(u\bar{u} - d\bar{d})/\sqrt{2}$ is predominant in the structure of the $a_0(980)$ meson.

Note that J/ψ decays support this hypothesis. Indeed [6],

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

while [7]

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

The suppression

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

appears strange if we assume that the states $a_2(1320)$ and $a_0(980)$ are the tensor and scalar two-quark states of the same P-wave multiplet with the quark structure

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

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At the same time, the four-quark nature of the $a_0(980)$ meson with a symbolic quark structure

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

does not contradict suppression (7).

The reader will also recall that in Ref. [8] it was predicted that if the $a_0(980)$ meson is a four-quark state from the lightest nonet from the MIT bag [9], the intensity of production of such a meson in $\gamma\gamma$ collisions will be suppressed by a factor of ten greater than if the $a_0(980)$ meson were a two-quark P-wave state. The estimate obtained in Ref. [8] for the four-quark model was

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

and this result was corroborated by experiments [10, 11]:

$$\text{Crystal Ball} - \Gamma(a_0 \to \gamma\gamma) = \frac{\big(0.19 \pm 0.07^{+0.1}_{-0.07}\big)}{B(a_0 \to \pi\eta)}\ \text{keV}\,,$$

$$\text{JADE} - \Gamma(a_0 \to \gamma\gamma) = \frac{\big(0.28 \pm 0.04 \pm 0.1\big)}{B(a_0 \to \pi\eta)}\ \text{keV}\,. \tag{11}$$

In the two-quark model (8) it was expected [12, 13] that

$$\Gamma(a_0 \to \gamma\gamma) = (1.5 - 5.9)\Gamma(a_2 \to \gamma\gamma) = (1.5 - 5.9)(1.04 \pm 0.09)\ \text{keV}\,. \tag{12}$$

The spread in the predictions is due to different assumptions about the shape of the potential.

As for the $\phi \to \gamma f_0(980) \to \gamma\pi^0\pi^0$ decay, more complex reasoning is needed to explain it.

The structure of the isoscalar state [presumably the $f_0(980)$ meson] from which the $\pi^0\pi^0$ system is formed is, generally speaking, the following:

$$Y = f_0(980) = \tilde{c}_0 gg + \frac{\tilde{c}_1(u\bar{u} + d\bar{d})}{\sqrt{2}} + \tilde{c}_2 s\bar{s} + \frac{\tilde{c}_3 s\bar{s}(u\bar{u} + d\bar{d})}{\sqrt{2}} + \ldots \tag{13}$$

Let us first discuss the possibility of describing the $f_0(980)$ meson as a quark–antiquark state.

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

$$f_0 = \frac{u\bar{u} + d\bar{d}}{\sqrt{2}} \tag{14}$$

[which is suggested by the mass-degeneracy of the $f_0(980)$ and $a_0(980)$ state and the hasty assumption (8)] contradicts Eqn (1) in view of the OZI rule, in the same way as (8) contradicts (2) (see the above reasoning).

Furthermore, this assumption contradicts the following facts:

first, the strong coupling with the $K\bar{K}$ channel [4, 14],

$$1 < R = \left|\frac{g_{f_0K^+K^-}}{g_{f_0\pi^+\pi^-}}\right|^2 \lesssim 8\,, \tag{15}$$

since Eqn (14) implies that $|g_{f_0K^+K^-}/g_{f_0\pi^+\pi^-}|^2 = \lambda/4 \simeq 1/8$, where λ characterizes the suppression of the strange quark sea;

second, the weak coupling with gluons [15],

$$B\big(J/\psi \to \gamma f_0(980) \to \gamma\pi\pi\big) < 1.4 \times 10^{-5}\,, \tag{16}$$

in comparison to the expected coupling [16, 17] for Eqn (14),

$$B\big(J/\psi \to \gamma f_0(980)\big) \gtrsim \frac{B\big(J/\psi \to \gamma f_2(1270)\big)}{4} \simeq 3.4 \times 10^{-4}\,; \tag{17}$$

third, the weak coupling with photons [18, 19],

$$\text{Crystal Ball} - \Gamma(f_0 \to \gamma\gamma) = (0.31 \pm 0.14 \pm 0.09)\ \text{keV}\,,$$

$$\text{MARK II} - \Gamma(f_0 \to \gamma\gamma) = (0.24 \pm 0.06 \pm 0.15)\ \text{keV}\,, \tag{18}$$

in comparison to the expected coupling [12, 13] for Eqn (14),

$$\Gamma(f_0 \to \gamma\gamma) = (1.7 - 5.5)\Gamma(f_2 \to \gamma\gamma) = (1.7 - 5.5)(2.8 \pm 0.4)\ \text{keV}\,; \tag{19}$$

finally, the decays $J/\psi \to f_0(980)\omega$, $J/\psi \to f_0(980)\phi$, $J/\psi \to f_2(1270)\omega$, and $J/\psi \to f_2'(1525)\phi$ [6],

$$B(J/\psi \to f_0(980)\omega) = (1.4 \pm 0.5) \times 10^{-4}\,, \tag{20}$$

$$B(J/\psi \to f_0(980)\phi) = (3.2 \pm 0.9) \times 10^{-4}\,, \tag{21}$$

$$B(J/\psi \to f_2(1270)\omega) = (4.3 \pm 0.6) \times 10^{-3}\,, \tag{22}$$

$$B(J/\psi \to f_2'(1525)\phi) = (8 \pm 4) \times 10^{-4}\,. \tag{23}$$

The suppression

$$\frac{B\big(J/\psi \to f_0(980)\omega\big)}{B\big(J/\psi \to f_2(1270)\omega\big)} = 0.033 \pm 0.013 \tag{24}$$

appears to be as strange in this model as the suppression (7) in model (8).

On the other hand, the existence of the $J/\psi \to f_0(980)\phi$ decay, which is more intense than the $J/\psi \to f_0(980)\omega$ decay [cf. Eqns (20) and (21)] completely closes model (14), since in the case at hand the $J/\psi \to f_0(980)\phi$ decay must be suppressed in comparison to the $J/\psi \to f_0(980)\omega$ decay, according to the OZI rule.

Thus, we may assume that the $f_0(980)$ meson cannot have the quark structure (14).

Can the $f_0(980)$ meson be a state close to $s\bar{s}$?

Without a gluon component this is impossible. Indeed, for the scalar $s\bar{s}$ state, the first P-wave multiplet suggests [16, 17] that

$$B\big(J/\psi \to \gamma f_0(980)\big) \gtrsim \frac{B\big(J/\psi \to \gamma f_2'(1525)\big)}{4} \simeq 1.6 \times 10^{-4} \tag{25}$$

in comparison to the experimentally established upper bound (16), which actually requires that the $f_0(980)$ meson be the eighth component of the lowest P-wave scalar $SU_f(3)$-octet:

$$f_0(980) = \frac{u\bar{u} + d\bar{d} - 2s\bar{s}}{\sqrt{6}}\,. \tag{26}$$

Such a structure yields

$$\Gamma(f_0 \to \gamma\gamma) = \frac{3}{25}(1.7 - 5.5)\Gamma(f_2 \to \gamma\gamma)$$
$$= (0.57 - 1.9)(1 \pm 0.14)\ \text{keV}\,, \tag{27}$$

which is in poor agreement with Eqns (18).

Furthermore, such a structure predicts that

$$B\big(J/\psi \to f_0(980)\phi\big) = (2\lambda \approx 1) \times B\big(J/\psi \to f_0(980)\omega\big)\,, \tag{28}$$

which in the limit of two standard deviations contradicts the experimental data [cf. Eqns (20) and (21)].

The octet nature (26) contradicts the strong coupling of the $f_0(980)$ meson with the $K\bar{K}$ channel (15), since it suggests that

$$R = \left|\frac{g_{f_0K^+K^-}}{g_{f_0\pi^+\pi^-}}\right|^2 = \frac{(\sqrt{\lambda} - 2)^2}{4} \simeq 0.4\,. \tag{29}$$

Moreover, here the degeneracy in mass, $m_{f_0} \simeq m_{a_0}$, is accidental (if we assume that the a_0 meson is a four-quark state) or contradicts the hasty assumption (8).

The introduction of a gluon component, gg, into the structure of the $f_0(980)$ meson makes the solution of the problem of weak coupling with gluons [see Eqn (16)] very easy. Indeed, since [17]

$$B\big(R[q\bar{q}] \to gg\big) \simeq O(\alpha_s^2) \simeq 0.1 - 0.2\,,$$
$$B\big(R[gg] \to gg\big) \simeq O(1)\,, \tag{30}$$

an insignificant ($\sin^2\alpha \leqslant 0.08$) admixture of gluonium,

$$f_0 = gg\sin\alpha + \left[\frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\sin\beta + s\bar{s}\cos\beta\right]\cos\alpha\,,$$
$$\tan\alpha = -O(\alpha_s)\big(\sqrt{2}\,\sin\beta + \cos\beta\big)\,, \tag{31}$$

makes it possible to satisfy the inequalities (15) and (16) and to arrive at weak coupling with photons,

$$\Gamma\big(f_0(980) \to \gamma\gamma\big) < 0.22\ \text{keV} \tag{32}$$

at

$$-0.22 > \tan\beta > -0.52\,. \tag{33}$$

Thus, $\cos^2\beta > 0.8$ and the $f_0(980)$ meson is close to the $s\bar{s}$ state, as assumed, say, in Ref. [20].

Here, the prediction is that

$$0.1 < \frac{B\big(J/\psi \to f_0(980)\omega\big)}{B\big(J/\psi \to f_0(980)\phi\big)} = \frac{1}{\lambda}\tan^2\beta < 0.54 \tag{34}$$

as compared to the experimental value

$$\frac{B\big(J/\psi \to f_0(980)\omega\big)}{B\big(J/\psi \to f_0(980)\phi\big)} = 0.44 \pm 0.2\,, \tag{35}$$

whose refinement may serve as an effective means of judging the validity of the model.

If one assumes that the $a_0(980)$ meson is the two-quark state (8), such a scenario is fraught with the following difficulties:

first, there is no way in which one can explain the degeneracy in mass, $m_{f_0} = m_{a_0}$;

second, the result of such a scenario is only [3, 4]

$$B(\phi \to \gamma f_0 \to \gamma\pi^0\pi^0) \simeq 1.7 \times 10^{-5}\,,$$
$$B(\phi \to \gamma a_0 \to \gamma\pi^0\eta^0) \simeq 10^{-5}\,; \tag{36}$$

third, this scenario predicts that

$$\Gamma(f_0 \to \gamma\gamma) < 0.13\,\Gamma(a_0 \to \gamma\gamma)\,, \tag{37}$$

which in the limit of two standard deviations contradicts the experimental data [cf. Eqns (11) and (18)];

finally, this scenario also predicts that

$$B\big(J/\psi \to a_0(980)\rho\big) = \left(\frac{3}{\lambda} \approx 6\right) \times B\big(J/\psi \to f_0(980)\phi\big)\,, \tag{38}$$

which in the limit of two standard deviations contradicts the experimental data [cf. Eqns (6) and (21)].

Note that in the case being discussed the model-independent prediction (independent of λ)

$$\frac{B\big(J/\psi \to f_0(980)\phi\big)}{B\big(J/\psi \to f_2'(1525)\phi\big)} = \frac{B\big(J/\psi \to a_0(980)\rho\big)}{B\big(J/\psi \to a_2(1320)\rho\big)} \tag{39}$$

is excluded by the central value in

$$\frac{B\big(J/\psi \to f_0(980)\phi\big)}{B\big(J/\psi \to f_2'(1525)\phi\big)} = 0.4 \pm 0.23\,, \tag{40}$$

obtained from Eqns (21) and (23) [cf. (7)]. The error, however, is extremely large. An increase in accuracy in measuring (40) at least twofold could play a decisive role in the fate of this scenario.

The prospects of considering the $f_0(980)$ meson as a state close to $s\bar{s}$ (31) and the $a_0(980)$ meson as the four-quark state (9) with accidental mass degeneracy are not very promising, the more so that the four-quark model with the symbolic structure

$$f_0 = \frac{s\bar{s}(u\bar{u} + d\bar{d})\cos\theta}{\sqrt{2}} + u\bar{u}\,d\bar{d}\sin\theta\,, \tag{41}$$

based on the MIT bag model [9] provided a logical explanation of all the unusual properties of the $f_0(980)$ meson [14, 21].

Indeed, for $1/16 < \tan^2\theta < 1/2$ the strong-coupling problem (15) is solved [14]. When $\tan^2\theta < 1/3$, there are no problems with the mass degeneracy of the a_0 and f_0 mesons. A weak coupling with photons, (18), was predicted in Ref. [8]:

$$\Gamma\big(f_0(980) \to \gamma\gamma\big) \sim 0.27\ \text{keV}\,. \tag{42}$$

However, the problem of the weak coupling with gluons, (16), requires special treatment. The reader will recall that in the MIT bag model the $f_0(980)$ meson consists, so to say, of pairs of white pseudoscalar and vector two-quark mesons and pairs of colored pseudoscalar and vector two-quark mesons (see Refs [8, 9, 14]), including a pair of colored vectors singlets in the flavors. It is this last pair that transforms into two gluons in the lowest order in α_s.

The width of the decay of the $f_0(980)$ meson into two gluons, $f_0(980) \to gg$, can be calculated in the same way as the

width of the decay of a four-quark state into two photons [8]. Here

$$\Gamma(\mathrm{f}_0 \to \mathrm{gg}) = 0.03\left(\frac{4\pi\alpha_s}{\mathrm{f}_{\underline{V}}^2}\right)^2 \frac{g_0^2}{16\pi m_{\mathrm{f}_0}}(1+\tan\theta)^2\cos^2\theta\,, \tag{43}$$

where $g_0^2/4\pi \sim 10-20$ GeV is the coupling constant superallowed by the OZI rule; 0.03 is the fraction of the pair of colored vector two-quark flavor singlets in the wave function of the $\mathrm{f}_0(980)$ meson, which transforms into two massless gluons; $4\pi\alpha_s/f_{\underline{V}}^2$ is the probability of the colored vector two-quark flavor singlet becoming a gluon, $\underline{V} \leftrightarrow \mathrm{g}$. Since the spatial wave function of the colored vector two-quark flavor singlet is the same as of a ρ meson, we have $\mathrm{f}_{\underline{V}}^2/4\pi = \mathrm{f}_\rho^2/8\pi \approx 1$. Thus, it is predicted that

$$\Gamma(\mathrm{f}_0 \to \mathrm{gg}) = 15\alpha_s^2(1+\tan\theta)^2\cos^2\theta\ \mathrm{MeV}\,. \tag{44}$$

For $-1/\sqrt{2} < \tan\theta < -1/4$ we arrive at a width that in the worst possible case is ten times smaller than the decay width for a two-quark scalar meson [17], which does not contradict Eqn (16).

If we use only planar diagrams, in the four-quark model we get

$$B\big(\mathrm{J}/\psi \to \mathrm{a}_0^0(980)\rho\big) \approx B\big(\mathrm{J}/\psi \to \mathrm{f}_0(980)\omega\big) \approx 0.5B\big(\mathrm{J}/\psi \to \mathrm{f}_0(980)\phi\big)\,, \tag{45}$$

which does not contradict the experimental data [see Eqns (6), (20), and (21)].

Note that in the MIT bag model [9] almost all four-quark states are very wide, since they decay by channels superallowed by the OZI rule. Therefore there is no way these states can be isolated in the continuous spectrum. Only when these states are at the threshold or below the threshold of the decays superallowed by the OZI rule do they manifest themselves as narrow resonances. Possibly, such 'traces' of the MIT bag are the $\mathrm{a}_0(980)$ and $\mathrm{f}_0(980)$ mesons and resonance-interference phenomena discovered at the threshold of the reactions $\gamma\gamma \to \rho^0\rho^0$ and $\gamma\gamma \to \rho^+\rho^-$ (see Ref. [21]) and predicted in Ref. [8].

Up to this point nothing has been said about the rather attractive molecular model in which the $\mathrm{a}_0(980)$ and $\mathrm{f}_0(980)$ mesons are bound states of the $\mathrm{K}\bar{\mathrm{K}}$ system [22]. This model explains the degeneracy in mass of the states and their strong coupling with the $\mathrm{K}\bar{\mathrm{K}}$ channel. As in the four-quark problems, no questions arise with the suppressions (7) and (24) in the molecular model. Note that the relationships (45) are also valid in the model of $\mathrm{K}\bar{\mathrm{K}}$ molecules.

However, the predictions of this model for the two-photon width [13]

$$\Gamma\big(\mathrm{a}_0(\mathrm{K}\bar{\mathrm{K}}) \to \gamma\gamma\big) = \Gamma\big(\mathrm{f}_0(\mathrm{K}\bar{\mathrm{K}}) \to \gamma\gamma\big) \approx 0.6\ \mathrm{keV}\,, \tag{46}$$

in the limit of two standard deviations contradict the experimental data (11) and (18). More than that, the widths of $\mathrm{K}\bar{\mathrm{K}}$ molecules must be smaller (strictly speaking, much smaller) than the binding energy $\epsilon \approx 20$ MeV. Recent data [6], however, contradict this: $\Gamma_{\mathrm{a}_0} \sim 50-100$ MeV and $\Gamma_{\mathrm{f}_0} \sim 40-100$ MeV. The model of $\mathrm{K}\bar{\mathrm{K}}$ molecules also predicts [4] that

$$B(\phi \to \gamma\mathrm{f}_0) \approx B(\phi \to \gamma\mathrm{a}_0) \sim 10^{-5}$$

which contradicts (1) and (2).

Experiments in which $\mathrm{a}_0(980)$ and $\mathrm{f}_0(980)$ mesons were produced in the reactions $\pi^-\mathrm{p} \to \pi^0\eta\mathrm{n}$ [23] and $\pi^-\mathrm{p} \to \pi^0\pi^0\mathrm{n}$ [24] within a broad range of four-momentum transfer squares, $0 < -t < 1\ \mathrm{GeV}^2$, have shown that these states are compact, e.g. as two-quark ρ and other mesons and not as loose molecules with form factors determined by the wave functions. Clearly, these experiments have left no chances for the model of $\mathrm{K}\bar{\mathrm{K}}$ molecules. As for four-quark states, they are as compact as two-quark states.

Finally, there is still the standard problem that has to be resolved. Precisely, if the $\mathrm{a}_0(980)$ and $\mathrm{f}_0(980)$ mesons are four-quark states, where are the scalar two-quark states from the lowest P-wave multiplet with the quark structure (8) and (14)? Actually, there is no problem here: all the states (except scalar states) belonging to the lowest P-wave multiplet with such a quark structure have been established:

$$\begin{aligned}
&\mathrm{b}_1(1235)\,, \quad I^{\mathrm{G}}(J^{\mathrm{PC}}) = 1^+(1^{+-})\,, \quad \Gamma_{\mathrm{b}_1} \simeq 142\,\mathrm{MeV}\,,\\
&\mathrm{h}_1(1170)\,, \quad I^{\mathrm{G}}(J^{\mathrm{PC}}) = 0^-(1^{+-})\,, \quad \Gamma_{\mathrm{h}_1} \simeq 360\,\mathrm{MeV}\,,\\
&\mathrm{a}_1(1260)\,, \quad I^{\mathrm{G}}(J^{\mathrm{PC}}) = 1^-(1^{++})\,, \quad \Gamma_{\mathrm{a}_1} \simeq 400\,\mathrm{MeV}\,,\\
&\mathrm{f}_1(1285)\,, \quad I^{\mathrm{G}}(J^{\mathrm{PC}}) = 0^+(1^{++})\,, \quad \Gamma_{\mathrm{f}_1} \simeq 25\,\mathrm{MeV}\,,\\
&\mathrm{a}_2(1320)\,, \quad I^{\mathrm{G}}(J^{\mathrm{PC}}) = 1^-(2^{++})\,, \quad \Gamma_{\mathrm{a}_2} \simeq 107\,\mathrm{MeV}\,,\\
&\mathrm{f}_2(1270)\,, \quad I^{\mathrm{G}}(J^{\mathrm{PC}}) = 0^+(2^{++})\,, \quad \Gamma_{\mathrm{f}_2} \simeq 185\,\mathrm{MeV}\,.
\end{aligned} \tag{47}$$

We see that the forces responsible for mass splitting in the P-wave multiplet are either suppressed or balance each other. Hence we are justified to expect that there may be $\mathrm{a}_0(\approx 1300)$ and $\mathrm{f}_0(\approx 1300)$ states.

Indeed, the complete list of mesons [6] contains the state $\mathrm{a}_0(1450)$, $I^{\mathrm{G}}(J^{\mathrm{PC}}) = 1^-(0^{++})$, $\Gamma_{\mathrm{a}_0} \simeq 270$ MeV. What is interesting is that in several reports at the HADRON-97 conference the mass of this state was set by experimenters at 1300 MeV.

Furthermore, for several decades the final list of mesons [6] has contained the $\mathrm{f}_0(1370)$ state [formerly the $\mathrm{f}_0(1300)$ and $\epsilon(1300-1400)$ states], $I^{\mathrm{G}}(J^{\mathrm{PC}}) = 0^+(0^{++})$, $\Gamma_{\mathrm{f}_0} \simeq 300-500$ MeV.

It seems that there can be no doubt that the $\mathrm{a}_0(980)$ and $\mathrm{f}_0(980)$ mesons are foreign in the company of states (47).

Here is the latest news on the subject. The OPAL Collaboration has obtained two total inclusive rates of $\mathrm{f}_2(1270)$ and $\mathrm{f}_0(980)$ mesons in hadronic decays of the Z boson: $0.155 \pm 0.011 \pm 0.018$ and $0.141 \pm 0.007 \pm 0.011$, respectively [25]. If hypothesis (14) were true, simple statistical reasoning would suggest a 5-to-1 ratio of the $\mathrm{f}_2(1270)$- and $\mathrm{f}_0(980)$-meson rates. And if hypothesis (31) were true, the expected ratio of these rates would be 5-to-5 : $(\sin^2\beta + \lambda^2\cos^2\beta = 0.25-0.35)$. Thus the results of the OPAL Collaboration are a very strong argument against the two-quark nature of the $\mathrm{f}_0(980)$ meson. It would also be interesting to study the inclusive production of $\mathrm{a}_2(1320)$ and $\mathrm{a}_0(980)$ mesons in decays of Z bosons.

In conclusion we note once more that the study of the decays $\phi \to \gamma\mathrm{f}_0(980)$, $\gamma\mathrm{a}_0(980)$; $\mathrm{J}/\psi \to \mathrm{a}_0(980)\rho$, $\mathrm{f}_0(980)\omega$, $\mathrm{f}_0(980)\phi$, $\mathrm{a}_2(1320)\rho$, $\mathrm{f}_2(1270)\omega$, $\mathrm{f}_2'(1525)\phi$ and $\mathrm{a}_0(980) \to \gamma\gamma$, $\mathrm{f}_0(980) \to \gamma\gamma$ makes it possible to solve the problem of the origin of $\mathrm{a}_0(980)$ and $\mathrm{f}_0(980)$ mesons or at least close all the scenarios discussed above.

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