Properties of the light scalar mesons face experimental data

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Abstract

The following topics are considered.

1. Confinement, chiral dynamics, and light scalar mesons
2. Chiral shielding of the $\sigma(600)$
3. The ϕ meson radiative decays about nature of light scalar resonances
4. The J/ψ decays about nature of light scalar resonances
5. The $a_0(980) \to \gamma\gamma$ and $f_0(980) \to \gamma\gamma$ decays about nature of light scalar resonances
6. New round in $\gamma\gamma \to \pi^+\pi^-$, the Belle data
7. The $a_0(980) - f_0(980)$ mixing: theory and experiment

Arguments in favor of the four-quark model of the $a_0(980)$ and $f_0(980)$ mesons are given.

1 INTRODUCTION

The scalar channel in the region up to 1 GeV became a stumbling block of QCD. The point is that not only perturbation theory does not work in these channels, but sum rules as well because there are not solitary resonances in this region. At the same time the question on the nature of the light scalar mesons is major for understanding the mechanism of the chiral symmetry realization, arising from the confinement, and hence for understanding the confinement itself. In the talk are discussed the chiral shielding of the $\sigma(600)$, $\kappa(800)$ mesons, a role of the radiative ϕ decays, the heavy quarkonia decays, the $\gamma\gamma$ collisions in decoding the nature of the light scalar mesons and evidence in favor of the four-quark nature of the light scalar mesons. New goal and objectives are considered also.

To discuss actually the nature of the nonet of the light scalar mesons: the putative $f_0(600)$ (or $\sigma(600)$) and $\kappa(700-900)$ mesons and the well-established $f_0(980)$ and $a_0(980)$ mesons, one should explain not only their mass spectrum, particularly the mass degeneracy of the $f_0(980)$ and $a_0(980)$ states, but answer the next real challenges.

1. The copious $\phi \to \gamma f_0(980)$ decay and especially the copious $\phi \to \gamma a_0(980)$ decay, which looks as the decay plainly forbidden by the Okubo-Zweig-Iizuka (OZI) rule in the quark-antiquark model of $a_0(980) = (u\bar{u} - d\bar{d})/\sqrt{2}$.

2. Absence of $J/\psi \to a_0(980)\rho$ and $J/\psi \to f_0(980)\omega$ with copious $J/\psi \to a_2(1320)\rho$, $J/\psi \to f_2(1270)\omega$ if $a_0(980)$ and $f_0(980)$ are P wave states of $q\bar{q}$ like $a_2(1320)$ and $f_2(1270)$ respectively.

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3. Absence of $J/\psi \to \gamma f_0(980)$ with copious $J/\psi \to \gamma f_2(1270)$ and $J/\psi \to \gamma f_2'(1525)\phi$ if $f_0(980)$ is P wave state of $q\bar{q}$ like $f_2(1270)$ or $f_2'(1525)$.

4. Suppression of $a_0(980) \to \gamma\gamma$ and $f_0(980) \to \gamma\gamma$ with copious $a_2(1320) \to \gamma\gamma$, $f_2(1270) \to \gamma\gamma$ if $a_0(980)$ and $f_0(980)$ are P wave state of $q\bar{q}$ like $a_2(1320)$and $f_2(1270)$ respectively.

As Experiment suggests, Confinement forms colourless observable hadronic fields and spontaneous breaking of chiral symmetry with massless pseudoscalar fields. There are two possible scenarios for QCD at low energy.

1. **Non-linear $\boldsymbol{\sigma}$-model**

$L = \frac{F_\pi^2}{2} Tr\left(\partial_\mu V(x) \partial^\mu V^+(x)\right) + ...$, where $V(x) = \exp\{2\imath\phi(x)/F_\pi\}$.

2. **Linear $\boldsymbol{\sigma}$-model**

$L = \frac{1}{2} Tr\left(\partial_\mu \mathrm{V}(x) \partial^\mu \mathrm{V}^+(x)\right) - W\left(\mathrm{V}(x)\mathrm{V}^+(x)\right)$, where $\mathrm{V}(x) = (\sigma(x) + \imath\pi(x))$.

The experimental nonet of the light scalar mesons [the putative $f_0(600)$ (or $\sigma(600)$) and $\kappa(700-900)$ mesons and the well-established $f_0(980)$ and $a_0(980)$ mesons] as if suggests the $U_L(3)\times U_R(3)$ linear σ model. Hunting the light σ and κ mesons had begun in the sixties already and a preliminary information on the light scalar mesons in Particle Data Group (PDG) Reviews had appeared at that time. But long-standing unsuccessful attempts to prove their existence in a conclusive way entailed general disappointment and an information on these states disappeared from PDG Reviews. One of principal reasons against the σ and κ mesons was the fact that both $\pi\pi$ and πK scattering phase shifts do not pass over 90^0 at putative resonance masses.

2 CHIRAL SHIELDING OF THE $\boldsymbol{\sigma}$(600) [2, 3, 4]

Situation changes when we showed that in the linear σ model [1],

$L = (1/2)\left[(\partial_\mu\sigma)^2 + (\partial_\mu \overrightarrow{\pi})^2\right] + (\mu^2/2)[(\sigma)^2 + (\overrightarrow{\pi})^2] - (\lambda/4)[(\sigma)^2 + (\overrightarrow{\pi})^2]^2$,

there is a negative background phase which hides the σ meson [2]. It has been made clear that shielding wide lightest scalar mesons in chiral dynamics is very natural. This idea was picked up and triggered new wave of theoretical and experimental searches for the σ and κ mesons. According the simplest Dyson equation for the $\pi\pi$ scattering amplitude with real intermediate $\pi\pi$ states only, see Fig. 1,

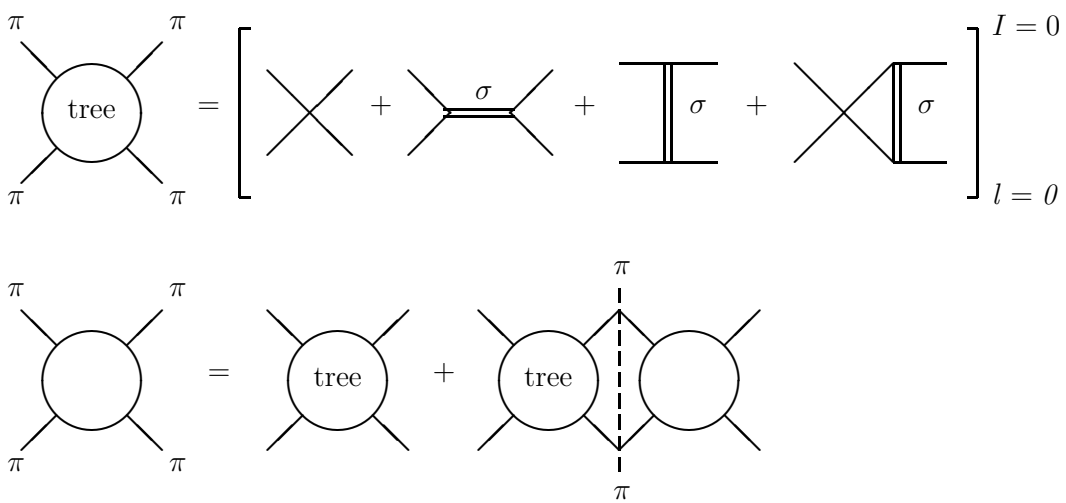


Figure 1: The graphical representation of the S wave $I = 0$ $\pi\pi$ scattering amplitude.

$$T_0^0 = \frac{T_0^{0(tree)}}{1 - \imath\rho_{\pi\pi} T_0^{0(tree)}} = \frac{e^{2\imath\delta_0^0} - 1}{2\imath\rho_{\pi\pi}} = \frac{e^{2\imath\delta_B^{\pi\pi}} - 1}{2\imath\rho_{\pi\pi}} + e^{2\imath\delta_B^{\pi\pi}} T_{res}\,,$$

$$\delta_0^0 = \delta_B^{\pi\pi} + \delta_{res}\,, \quad \rho_{\pi\pi} = \sqrt{1 - 4m_\pi^2/s}\,,$$

$$T_{res} = \frac{1}{\rho_{\pi\pi}} \left[\frac{\sqrt{s}\Gamma_{res}(s)}{M_{res}^2 - s + \Re(\Pi_{res}(M_{res}^2)) - \Pi_{res}(s)} \right] = \frac{e^{2\imath\delta_{res}} - 1}{2\imath\rho_{\pi\pi}}\,,$$

$$T_B = \frac{\lambda(s)}{1 - \imath\rho_{\pi\pi}\lambda(s)} = \frac{e^{2\imath\delta_B^{\pi\pi}} - 1}{2\imath\rho_{\pi\pi}}\,, \quad \lambda(s) = \frac{m_\pi^2 - m_\sigma^2}{32\pi F_\pi^2} \left[5 - 2\frac{m_\sigma^2 - m_\pi^2}{s - 4m_\pi^2} \ln\left(1 + \frac{s - 4m_\pi^2}{m_\sigma^2} \right) \right]\,,$$

$$\Re(\Pi_{res}(s)) = -3\frac{g_{res}^2(s)}{32\pi}\lambda(s)\rho_{\pi\pi}^2\,, \quad \Im(\Pi_{res}(s)) = \sqrt{s}\Gamma_{res}(s) = \frac{3}{2}\frac{g_{res}^2(s)}{16\pi}\rho_{\pi\pi}\,,$$

$$M_{res}^2 = m_\sigma^2 - \Re(\Pi_{res}(M_{res}^2))\,, \quad g_{res}(s) = \frac{g_{\sigma\pi^+\pi^-}}{\left|1 - \imath\rho_{\pi\pi}\lambda(s)\right|}\,,$$

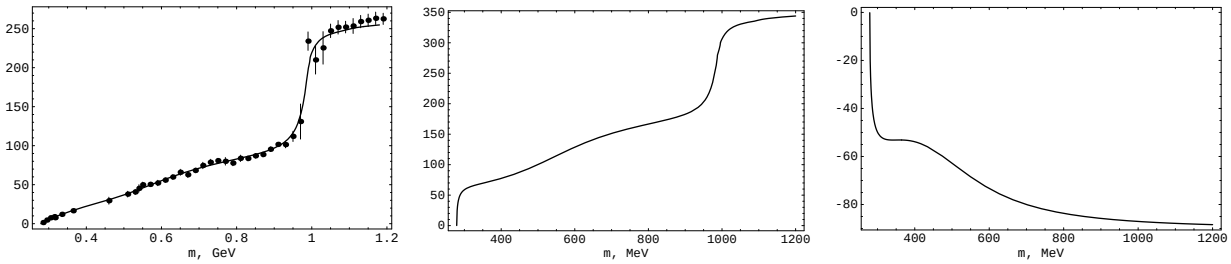
where $s = m^2$ and m is the invariant mass of the $\pi\pi$ system. These simple formulae show that the resonance contribution is strongly modified by the chiral background amplitude.

In theory the principal problem is impossibility to use the linear σ model in the tree level approximation inserting widths into σ meson propagators because such an approach breaks both unitarity and Adler self-consistency conditions. Strictly speaking, the comparison with the experiment requires the non-perturbative calculation of the process amplitudes. Nevertheless, now there are the possibilities to estimate odds of the $U_L(3) \times U_R(3)$ linear σ model to underlie physics of light scalar mesons in phenomenology. Really, even now there is a huge body of information about the S waves of different two-particle pseudoscalar states. As for theory, we know quite a lot about the scenario under discussion: the nine scalar mesons, the putative chiral shielding of the $\sigma(600)$ and $\kappa(700 - 900)$ mesons, the unitarity, analiticity and Adler self-consistency conditions. In addition, there is the light scalar meson treatment motivated by field theory. The foundations of this approach were formulated in our papers [3]. In particular, in this approach were introduced propagators of scalar mesons, satisfying the Källen-Lehmann representation. Recently [4], the comprehensive examination of the chiral shielding of the $\sigma(600)$ has been performed with a simultaneous analysis of the modern data on the $\phi \to \gamma\pi^0\pi^0$ decay and the classical $\pi\pi$ scattering data. Figs. 2 (a), 2 (b), and 2 (c) show an example of the fit to the data on the S wave $I = 0$ $\pi\pi$ scattering phase shift $\delta_0^0 = \delta_B^{\pi\pi} + \delta_{res}$, the resonance ($\delta_{res}$) and background ($\delta_B^{\pi\pi}$) components of δ_0^0, respectively (all the phases in degrees).

An example of the fit to the $\phi \to \gamma\pi^0\pi^0$ data in this case is shown in Fig. 6.

3 FOUR-QUARK MODEL

The nontrivial nature of the well-established light scalar resonances $f_0(980)$ and $a_0(980)$ is no longer denied practically anybody. In particular, there exist numerous evidences in favour of the $q^2\bar{q}^2$ structure of these states [5, 6]. As for the nonet as a whole, even a look at PDG Review gives an idea of the four-quark structure of the light scalar meson nonet, $\sigma(600)$, $\kappa(700 - 900)$,



(a) (b) (c)

Figure 2: (a) The S wave $I = 0$ $\pi\pi$ scattering phase shift δ_0^0. (b) The resonance phase shift δ_{res}. (c) The background phase shift $\delta_B^{\pi\pi}$.

$f_0(980)$, and $a_0(980)$, inverted in comparison with the classical P wave $q\bar{q}$ tensor meson nonet, $f_2(1270)$, $a_2(1320)$, $K_2^*(1420)$, $f_2'(1525)$. [1]

Really, while the scalar nonet cannot be treated as the P wave $q\bar{q}$ nonet in the naive quark model, it can be easy understood as the $q^2\bar{q}^2$ nonet, where $\sigma(600)$ has no strange quarks, $\kappa(700-900)$ has the s quark, $f_0(980)$ and $a_0(980)$ have the $s\bar{s}$ pair [7, 8]. The scalar mesons $a_0(980)$ and $f_0(980)$, discovered more than thirty years ago, became the hard problem for the naive $q\bar{q}$ model from the outset. Really, on the one hand the almost exact degeneration of the masses of the isovector $a_0(980)$ and isoscalar $f_0(980)$ states revealed seemingly the structure similar to the structure of the vector ρ and ω or tensor $a_2(1320)$ and $f_2(1270)$ mesons, but on the other hand the strong coupling of $f_0(980)$ with the $K\bar{K}$ channel as if suggested a considerable part of the strange pair $s\bar{s}$ in the wave function of $f_0(980)$. In 1977 R.L. Jaffe [7] noted that in the MIT bag model, which incorporates confinement phenomenologically, there are light four-quark scalar states. He suggested also that $a_0(980)$ and $f_0(980)$ might be these states with symbolic structures: $a_0^0(980) = (us\bar{u}\bar{s} - ds\bar{d}\bar{s})/\sqrt{2}$ and $f_0(980) = (us\bar{u}\bar{s} + ds\bar{d}\bar{s})/\sqrt{2}$. From that time $a_0(980)$ and $f_0(980)$ resonances came into beloved children of the light quark spectroscopy.

4 RADIATIVE DECAYS OF ϕ MESON ABOUT NATURE OF LIGHT SCALAR RESONANCES [9, 6, 10]

Ten years later we showed [9] that the study of the radiative decays $\phi \to \gamma a_0 \to \gamma\pi\eta$ and $\phi \to \gamma f_0 \to \gamma\pi\pi$ can shed light on the problem of $a_0(980)$ and $f_0(980)$ mesons. Over the next ten years before experiments (1998) the question was considered from different points of view. Now these decays have been studied not only theoretically, but experimentally as well by energies of the SND, CMD-2, and KLOE.

$$BR(\phi \to \gamma\pi^0\eta) = (0.83 \pm 0.05) \cdot 10^{-4}$$

$$BR(\phi \to \gamma\pi^0\pi^0) = (1.09 \pm 0.06) \cdot 10^{-4}$$

Note that $a_0(980)$ is produced in the radiative ϕ meson decay as intensively as $\eta'(958)$ containing $\approx 66\%$ of $s\bar{s}$, responsible for $\phi \approx s\bar{s} \to \gamma s\bar{s} \to \gamma\eta'(958)$. It is a clear qualitative argument for the presence of the $s\bar{s}$ pair in the isovector $a_0(980)$ state, i.e., for its four-quark nature.

[1] To be on the safe side, notice that the linear σ model does not contradict to non-$q\bar{q}$ nature of the low lying scalars because Quantum Fields can contain different virtual particles in different regions of virtuality.

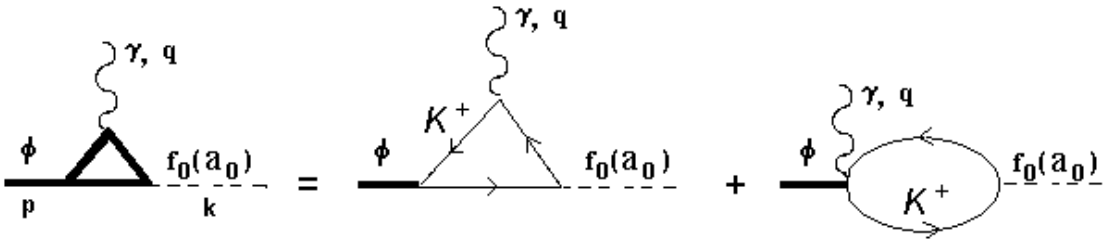
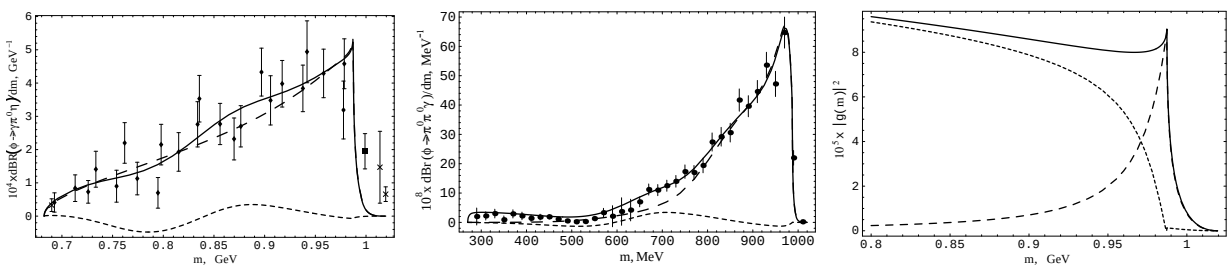


Figure 3: Diagrams of the K^+K^- loop model.

When basing the experimental investigations, we suggested one-loop model $\phi \to K^+K^- \to \gamma a_0(980)$ (or $f_0(980)$) [9], see Fig. 3.

This model is used in the data treatment and is ratified by experiment. Below we argue on gauge invariance grounds that the present data give the conclusive arguments in favor of the K^+K^- loop transition as the principal mechanism of $a_0(980)$ and $f_0(980)$ meson production in the ϕ radiative decays [6, 10]. The data are described in the model $\phi \to (\gamma a_0 + \pi^0\rho) \to \gamma\pi^0\eta$ and $\phi \to [\gamma(f_0+\sigma) + \pi^0\rho] \to \gamma\pi^0\pi^0$ [4, 10, 11]. The resulting fits to the KLOE data are presented in Figs. 4 (a) and 4 (b) [2].



(a) (b) (c)

Figure 4: (a) The fit to the KLOE data for the $\pi^0\eta$ mss spectrum in the $\phi \to \gamma\pi^0\eta$ decay. (b) The fit to the KLOE data for the $\pi^0\pi^0$ mss spectrum in the $\phi \to \gamma\pi^0\pi^0$ decay. (c) The universal in the K^+K^- loop model function $|g(m)|^2 = |g_R(m)/g_{RK^+K^-}|^2$ is shown by the solid curve. The contribution of the imaginary (real) part is shown by dashed (dotted) curve.

To describe the experimental spectra

$$S_R(m) \equiv dB(\phi \to \gamma R \to \gamma ab\,,\, m)/dm$$

$$= \frac{2m^2\Gamma(\phi \to \gamma R\,,\, m)\Gamma(R \to ab\,,\, m)}{\pi\Gamma_\phi |D_R(m)|^2} = \frac{4|g_R(m)|^2\omega(m)p_{ab}(m)}{\Gamma_\phi\, 3(4\pi)^3 m_\phi^2}\left|\frac{g_{Rab}}{D_R(m)}\right|^2$$

(where $1/D_R(m)$ and g_{Rab} are the propagator and coupling constants of $R = a_0, f_0$; $ab = \pi^0\eta$, $\pi^0\pi^0$) the function $|g_R(m)|^2$ should be smooth, almost constant, in the range $m \leq 0.99$ GeV. But the problem issues from gauge invariance which requires that

$$A[\phi(p) \to \gamma(k)R(q)] = G_R(m)[p_\mu e_\nu(\phi) - p_\nu e_\mu(\phi)][k_\mu e_\nu(\gamma) - k_\nu e_\mu(\gamma)].$$

Consequently, the function

$$g_R(m) = -2(pk)G_R(m) = -2\omega(m)m_\phi G_R(m)$$

[2]The last KLOE investigation [12] with the statistics corresponding to 450 pb$^-$1 supports our [4] analysis.

is proportional to the photon energy $\omega(m) = (m_\phi^2 - m^2)/2m_\phi$ (at least!) in the soft photon region. Stopping the function $(\omega(m))^2$ at $\omega(990\,\mathrm{MeV}) = 29$ MeV with the help of the form-factor $1/\left[1 + (R\omega(m))^2\right]$ requires $R \approx 100$ GeV^{-1}. It seems to be incredible to explain such a huge radius in hadron physics. Based on rather great $R \approx 10$ GeV^{-1}, one can obtain an effective maximum of the mass spectrum only near 900 MeV. To exemplify this trouble let us consider the contribution of the isolated R resonance: $g_R(m) = -2\omega(m)m_\phi G_R\,(m_R)$. Let also the mass and the width of the R resonance equal 980 MeV and 60 MeV, then $S_R(920\,\mathrm{MeV}) : S_R(950\,\mathrm{MeV}) : S_R(970\,\mathrm{MeV}) : S_R(980\,\mathrm{MeV}) = 3 : 2.7 : 1.8 : 1$. So stopping the $g_R(m)$ function is the crucial point in understanding the mechanism of the production of $a_0(980)$ and $f_0(980)$ resonances in the ϕ radiative decays. The K^+K^--loop model $\phi \to K^+K^- \to \gamma R$ solves this problem in the elegant way: fine threshold phenomenon is discovered, see Fig. 4 (c). So, the mechanism of production of $a_0(980)$ and $f_0(980)$ mesons in the ϕ radiative decays is established at a physical level of proof, see Refs. [6, 10] for details.

Both real and imaginary parts of the $\phi \to \gamma R$ amplitude are caused by the K^+K^- intermediate state, see Fig. 4 (c). The imaginary part is caused by the real K^+K^- intermediate state while the real part is caused by the virtual compact K^+K^- intermediate state, i.e., we are dealing here with the four-quark transition.

Needless to say, radiative four-quark transitions can happen between two $q\bar{q}$ states as well as between $q\bar{q}$ and $q^2\bar{q}^2$ states but their intensities depend strongly on a type of the transitions.

A radiative four-quark transition between two $q\bar{q}$ states requires creation and annihilation of an additional $q\bar{q}$ pair, i.e., such a transition is forbidden according to the Okubo-Zweig-Iizuka (OZI) rule, while a radiative four-quark transition between $q\bar{q}$ and $q^2\bar{q}^2$ states requires only creation of an additional $q\bar{q}$ pair, i.e., such a transition is allowed according to the OZI rule.

The four-quark transition constrains the large N_C expansion of the $\phi \to \gamma a_0(980)$ and $\phi \to \gamma f_0(980)$ amplitudes and gives the new strong (if not crucial) evidences in favor of the compact four-quark nature of $a_0(980)$ and $f_0(980)$ mesons: $a_0^0 = (u\bar{s}s\bar{u} - d\bar{s}s\bar{d})/\sqrt{2}$, $f_0^0 = (u\bar{s}s\bar{u} + d\bar{s}s\bar{d})/\sqrt{2}$, similar (but, generally speaking, not identical) the MIT-bag states [6].

5 THE J/ψ DECAYS AND THE $a_0(980) \to \gamma\gamma$, $f_0(980) \to \gamma\gamma$ DECAYS ABOUT NATURE OF LIGHT SCALAR RESONANCES [5]

The $a_0(980)$ in J/ψ decays. The following data is of very interest for our purposes: $B(J/\psi \to a_0(980)\rho) < 4.4 \cdot 10^{-4}$ and $B(J/\psi \to a_2(1320)\rho) = (109 \pm 22) \cdot 10^{-4}$. The suppression $B(J/\psi \to a_0(980)\rho)/B(J/\psi \to a_2(1320)\rho) < 0.04 \pm 0.008$ seems strange, if one considers the $a_2(1320)$ and $a_0(980)$ states as the tensor and scalar isovector states from the same P-wave $q\bar{q}$ multiplet. While the four-quark nature of the $a_0(980)$ meson is not contrary to the suppression under discussion. So, the improvement of the upper limit for $B(J/\psi \to a_0(980)\rho)$ and the search for the $J/\psi \to a_0(980)\rho$ decays are the urgent purposes in the study of the J/ψ decays!

Recall that twenty years ago the four-quark nature of $a_0(980)$ was supported by suppression of $a_0(980) \to \gamma\gamma$ as was predicted in our work based on the $q^2\bar{q}^2$ model, $\Gamma(a_0(980) \to \gamma\gamma) \sim 0.27\,\mathrm{keV}$. Experiment gives $\Gamma(a_0 \to \gamma\gamma) = (0.19 \pm 0.07^{+0.1}_{-0.07})/B(a_0 \to \pi\eta)$ keV, Crystal Ball, and $\Gamma(a_0 \to \gamma\gamma) = (0.28 \pm 0.04 \pm 0.1)/B(a_0 \to \pi\eta)$ keV, JADE. When in the $q\bar{q}$ model it was anticipated $\Gamma(a_0 \to \gamma\gamma) = (1.5 - 5.9)\Gamma(a_2 \to \gamma\gamma) = (1.5 - 5.9) \cdot (1.04 \pm 0.09)$ keV.

The $f_0(980)$ in J/ψ decays. The hypothesis that the $f_0(980)$ meson is the lowest two-quark P wave scalar state with the quark structure $f_0(980) = (u\bar{u} + d\bar{d})/\sqrt{2}$ contradicts the following facts. 1) The strong coupling with the $K\bar{K}$-channel, $1 < |g_{f_0K^+K^-}/g_{f_0\pi^+\pi^-}|^2 < 10$, for the prediction $|g_{f_0K^+K^-}/g_{f_0\pi^+\pi^-}|^2 = \lambda/4 \simeq 1/8$. 2) The weak coupling with gluons, $B(J/\psi \to \gamma f_0(980) \to \gamma\pi\pi) < 1.4 \cdot 10^{-5}$, opposite the expected one $B(J/\psi \to \gamma f_0(980)) \approx B(J/\psi \to \gamma f_2(1270))/4 = (3.45 \pm 0.35) \cdot 10^{-4}$. 3) The weak coupling with photons, predicted in our work

for the $q^2\bar{q}^2$ model, $\Gamma(f_0(980) \to \gamma\gamma) \sim 0.27\,\mathrm{keV}$, and supported by experiment, $\Gamma(f_0 \to \gamma\gamma) = (0.31\pm0.14\pm0.09)$ keV, Crystal Ball, and $\Gamma(f_0 \to \gamma\gamma) = (0.24\pm0.06\pm0.15)$ keV, MARK II. When in the $q\bar{q}$ model it was anticipated $\Gamma(f_0 \to \gamma\gamma) = (1.7-5.5)\Gamma(f_2 \to \gamma\gamma) = (1.7-5.5)\cdot(2.8\pm0.4)$ keV. 4) As is the case with $a_0(980)$ the suppression $B(J/\psi \to f_0(980)\omega)/B(J/\psi \to f_2(1270)\omega) = 0.033\pm0.013$ looks strange in the model under consideration. We should like to emphasize that from our point of view the DM2 Collaboration did not observed the $J/\psi \to f_0(980)\omega$ decay and should give a upper limit only. So, the search for the $J/\psi \to f_0(980)\omega$ decay is the urgent purpose in the study of theJ/ψ decays! 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 shuts down the $f_0(980) = (u\bar{u}+d\bar{d})/\sqrt{2}$ model. In the case under discussion the $J/\psi \to f_0(980)\phi$ decay should be strongly suppressed in comparison with the $J/\psi \to f_0(980)\omega$ decay by the OZI rule.

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 $B(J/\psi \to \gamma f_0(980)) \approx B(J/\psi \to \gamma f_2'(1525))/4 = (1.175^{+0.175}_{-0.125})\cdot 10^{-4}$ opposite experiment $< 1.4\cdot10^{-5}$, which requires properly that the $f_0(980)$-meson to be the 8-th component of the $SU_f(3)$ oktet $f_0(980) = (u\bar{u}+d\bar{d}-2s\bar{s})/\sqrt{6}$. But this structure gives $B(J/\psi \to f_0(980)\phi) = (2\lambda \approx 1)\cdot B(J/\psi \to f_0(980)\omega)$ which is on the verge of conflict with experiment. Here λ takes into account the strange sea suppression. The $SU_f(3)$ oktet case contradicts also the strong coupling with the $K\bar{K}$ channel $1 < |g_{f_0K^+K^-}/g_{f_0\pi^+\pi^-}|^2 < 10$ for the prediction $|g_{f_0K^+K^-}/g_{f_0\pi^+\pi^-}|^2 = (\sqrt{\lambda}-2)^2/4 \approx 0.4$. In addition, the mass degeneration $m_{f_0} \approx m_{a_0}$ is coincidental in this case if to treat the a_0-meson as the four-quark state or contradicts the two-quark hypothesis.

The introduction of a gluon component, gg, in the $f_0(980)$ meson structure allows the puzzle of weak coupling with two gluons and with two photons but the strong coupling with the $K\bar{K}$ channel to be resolved easily: $f_0 = gg\sin\alpha + [(1/\sqrt{2})(u\bar{u}+d\bar{d})\sin\beta + s\bar{s}\cos\beta]\cos\alpha$, $\tan\alpha = -O(\alpha_s)(\sqrt{2}\sin\beta+\cos\beta)$, where $\sin^2\alpha \le 0.08$ and $\cos^2\beta > 0.8$. So, the $f_0(980)$ meson is near to the $s\bar{s}$-state. It gives

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

As for the experimental value, $B(J/\psi \to f_0(980)\omega)/B(J/\psi \to f_0(980)\phi) = 0.44\pm0.2$, it needs refinement. Remind that in our opinion the $J/\psi \to f_0(980)\omega$ was not observed!

The scenario with the $f_0(980)$ meson near to the $s\bar{s}$ state and with the $a_0(980)$ meson as the two-quark state runs into following difficulties. 1) It is impossible to explain the f_0 and a_0-meson mass degeneration in a natural way. 2) It is predicted $\Gamma(f_0 \to \gamma\gamma) < 0.13\cdot\Gamma(a_0 \to \gamma\gamma)$, that means that $f_0(980)$ could not be seen practically in the $\gamma\gamma$ collision. 3) It is predicted $B(J/\psi \to a_0(980)\rho) = (3/\lambda \approx 6)\cdot B(J/\psi \to f_0(980)\phi)$, that has almost no chance from experimental point view. 4) The λ independent prediction $B(J/\psi \to f_0(980)\phi)/B(J/\psi \to f_2'(1525)\phi) = B(J/\psi \to a_0(980)\rho)/B(J/\psi \to a_2(1320)\rho) < 0.04\pm0.008$ is excluded by the central figure in $B(J/\psi \to f_0(980)\phi)/B(J/\psi \to f_2'(1525)\phi) = 0.4\pm0.23$. But, certainly, experimental error is too large. Even twofold increase in accuracy of measurement of could be crucial in the fate of the scenario under discussion.

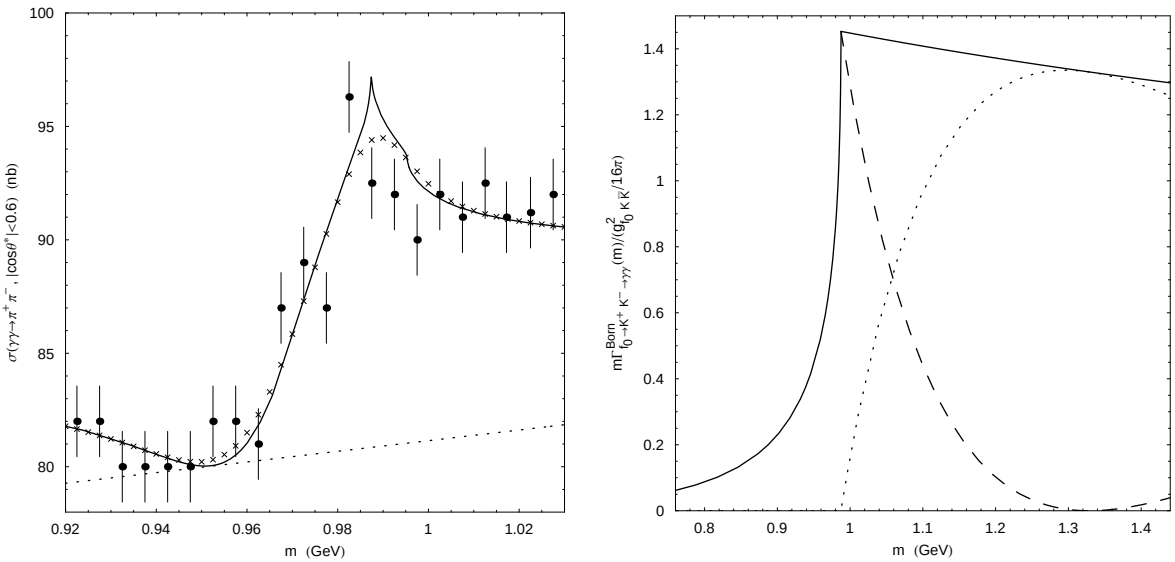
The prospects for the model of the $f_0(980)$ meson as the almost pure $s\bar{s}$-state and the $a_0(980)$-meson as the four-quark state with the coincidental mass degeneration is rather poor especially as the OZI-superallowed $(N_C)^0$ order mechanism $\phi = s\bar{s} \to \gamma s\bar{s} = \gamma f_0(980)$ [3] cannot explain the photon spectrum in $\phi \to \gamma f_0(980) \to \gamma\pi^0\pi^0$ [6], which requires the domination of the K^+K^- intermediate state in the $\phi \to \gamma f_0(980)$ amplitude: $\phi \to K^+K^- \to \gamma f_0(980)$! The $(N_C)^0$ order transition is bound to have a small weight in the large N_C expansion of the $\phi = s\bar{s} \to \gamma f_0(980)$ amplitude, because this term does not contain the K^+K^- intermediate state, which emerges only in the next to leading term of the $1/N_C$ order, i.e., in the OZI forbidden transition [6]. While the four-quark model with the symbolic structure $f_0(980) =$

[3] Such a mechanism is similar to the principal mechanism of the $\phi \to \gamma\eta'(958)$ decay: $\phi = s\bar{s} \to \gamma s\bar{s} = \gamma\eta'(958)$.

$(us\bar{u}\bar{s} + ds\bar{d}\bar{s})/\sqrt{2}\cos\theta + ud\bar{u}\bar{d}\sin\theta$, similar (but not identical) the MIT-bag state, reasonably justifies all unusual features of the $f_0(980)$-meson.

6 NEW ROUND IN $\gamma\gamma \to \pi^+\pi^-$, THE BELLE DATA [13]

Recently, the Belle Collaboration succeeded in observing a clear manifestation of the $f_0(980)$ resonance in the reaction $\gamma\gamma \to \pi^+\pi^-$, see Figure 5 . This has been made possible owing to the



(a) (b)

Figure 5: (a) The fit to the Belle data for the $\gamma\gamma \to \pi^+\pi^-$ process . (b) The energy (m) dependence of $f_0 \to K^+K^- \to \gamma\gamma$ width.

huge statistics and good energy resolution.

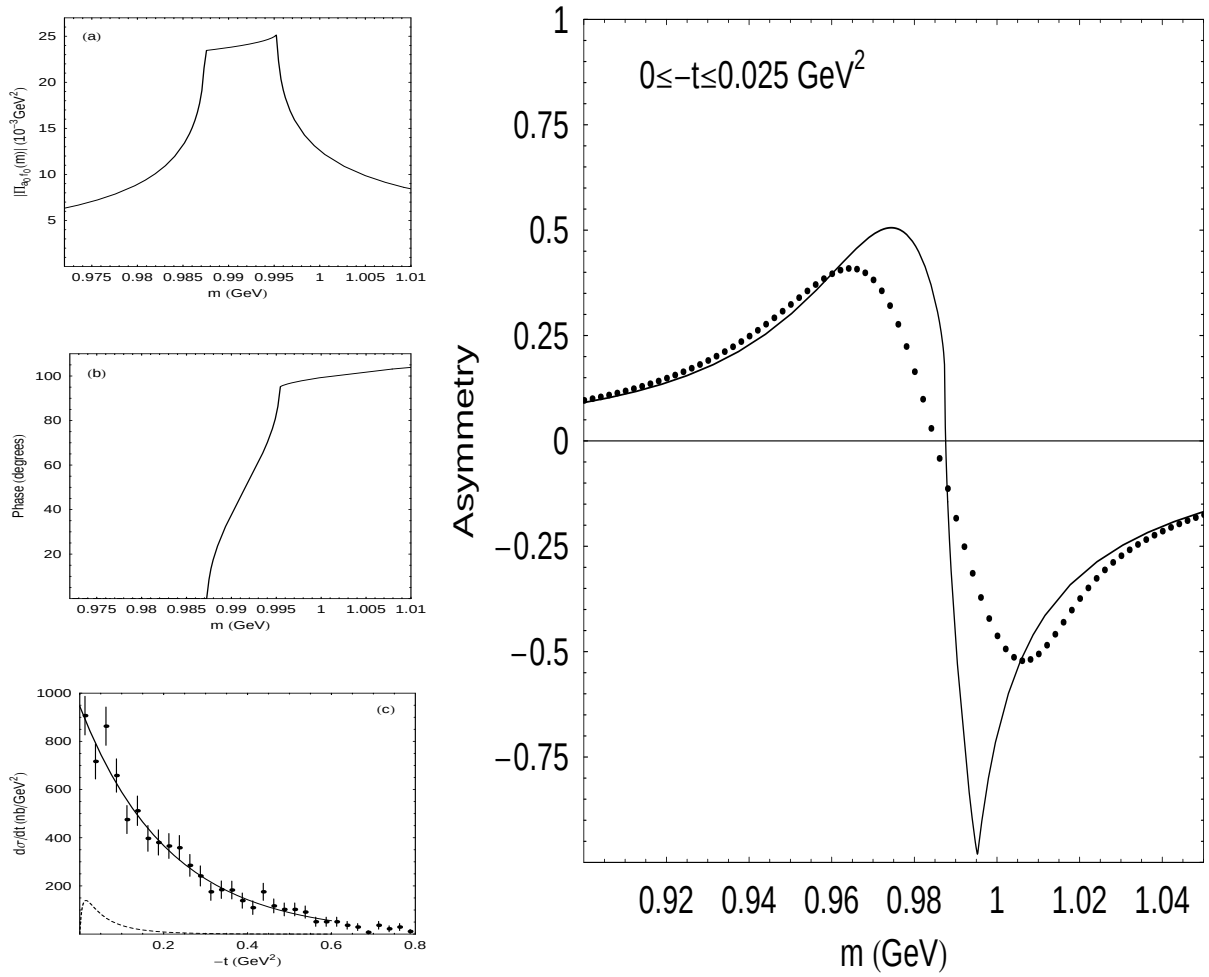
Analyzing these data we shown that the above K^+K^- loop mechanism provides the absolutely natural and reasonable scale of the $f_0(980)$ resonance manifestation in the $\gamma\gamma \to \pi^+\pi^-$ reaction cross sections as well as in $\gamma\gamma \to \pi^0\pi^0$ [4]. For the K^+K^- loop mechanism, we obtained the $f_0(980) \to \gamma\gamma$ width averaged by the resonance mass distribution in the $\pi\pi$ channel $\langle\Gamma^{Born}_{f_0\to K^+K^-\to\gamma\gamma}\rangle_{\pi\pi} \approx 0.15$ keV. Furthermore, the K^+K^- loop mechanism of the $f_0(980) \to \gamma\gamma$ coupling, see Figure 5, is one of the main factors responsible for the formation of the observed specific, steplike, shape of the $f_0(980)$ resonance in the $\gamma\gamma \to \pi^+\pi^-$ reaction cross section.

7 The $a_0(980) - f_0(980)$ mixing: theory and experiment [14]

The mixing between the $a_0^0(980)$ and $f_0(980)$ resonances was discovered theoretically as a threshold phenomenon in our work in the late 70s. Recently (last decade) interest in the $a_0^0(980) - f_0(980)$ mixing was renewed, and its possible manifestations in various reactions are intensively discussed, because its observation could give an exclusive information about the $a_0^0(980)$ and $f_0(980)$ coupling with the $K\bar{K}$ channel.

The amplitude of the $a_0^0(980) - f_0(980)$ transition is determined by the K^+K^- and $K^0\bar{K}^0$ intermediate states in the main, $a_0^0(980) \to K^+K^- + K^0\bar{K}^0 \to f_0(980)$,

[4]The $a_0^0(980)$ resonance manifestation in $\gamma\gamma \to \pi^0\eta$ is also described by the K^+K^- loop mechanism.



(d)

Figure 6: (a) The modulus of the $a_0 - f_0$ transition amplitude $\Pi_{a_0 f_0}(m)$. (b) The phase of the $a_0 - f_0$ transition amplitude $\Pi_{a_0 f_0}(m)$. (c) The solid curve describes the nonpolarized $d\sigma/dt(\pi^- p \to a_0 n \to \pi^0 \eta n)$ reaction without the $a_0 - f_0$ mixing, the dashed curve shows the π exchange contribution due to the $a_0 - f_0$ mixing. (d) The spin asymmetry due to the $a_0 - f_0$ mixing, the dotted curve shows the spin asymmetry smoothed with the Gaussian mass distribution with the dispersion of 10 MeV.

$$\Pi_{a_0 f_0}(m) = \frac{g_{a_0 K^+ K^-} g_{f_0 K^+ K^-}}{16\pi} \Bigg[i \left(\rho_{K^+K^-}(m) - \rho_{K^0\bar{K}^0}(m) \right) -$$

$$\frac{\rho_{K^+K^-}(m)}{\pi} \ln \frac{1 + \rho_{K^+K^-}(m)}{1 - \rho_{K^+K^-}(m)} + \frac{\rho_{K^0\bar{K}^0}(m)}{\pi} \ln \frac{1 + \rho_{K^0\bar{K}^0}(m)}{1 - \rho_{K^0\bar{K}^0}(m)} \Bigg]$$

$$\approx \frac{g_{a_0 K^+ K^-} g_{f_0 K^+ K^-}}{16\pi} \left[i \left(\rho_{K^+K^-}(m) - \rho_{K^0\bar{K}^0}(m) \right) \right],$$

where $m \geq 2m_{K^0}$, in the region $0 \leq m \leq 2m_K$, $\rho_{K\bar{K}}(m) = \sqrt{1 - 4m_K^2/m^2}$ should be replaced

by $i|\rho_{K\bar{K}}(m)|$. In the region between the K^+K^- and $K^0\bar{K}^0$ thresholds, which is 8 MeV wide,

$$|\Pi_{a_0 f_0}(m)| \approx \frac{|g_{a_0K^+K^-}g_{f_0K^+K^-}|}{16\pi}\sqrt{\frac{2(m_{K^0}-m_{K^+})}{m_{K^0}}}$$

$$\approx 0.127|g_{a_0K^+K^-}g_{f_0K^+K^-}|/16\pi \gtrsim 0.032\,\mathrm{GeV}^2.$$

This contribution dominates for two reason.
i) It has the $\sqrt{m_d - m_u}$ order. As for effects of the $m_d - m_u$ order, they are small. A clear idea of the magnitude of effects of the $m_d - m_u$ order gives $|\Pi_{a_0 f_0}(m)|$ at $m < 0.95$ and $m > 1.05$ in Fig. 6 (a). [5]
ii) The strong coupling of $a_0^0(980)$ and $f_0(980)$ to the $K\bar{K}$ channels $|g_{a_0K^+K^-}g_{f_0K^+K^-}|/4\pi \gtrsim 1\,\mathrm{GeV}^2$.

The "resonancelike" behavior of the $a_0^0(980) - f_0(980)$ mixing modulus and phase of the amplitude $\Pi_{a_0 f_0}(m)$ is clearly illustrated in Figs. 6 (a) and (b).

The phase jump suggest the idea to study the $a_0^0(980) - f_0(980)$ mixing in polarization phenomena. If a process amplitude with a spin configuration is dominated by the $a_0^0(980) - f_0(980)$ mixing then a spin asymmetry of a cross section jumps near the $K\bar{K}$ thresholds. An example is $\pi^- p \to \big(a_0^0(980) + f_0(980)\big)\, n \to \eta\pi^0\, n$.

$$\frac{d^3\sigma}{dtdmd\psi} = \frac{1}{2\pi}[\,|M_{++}|^2 + |M_{+-}|^2 + 2\,\Im(M_{++}M_{+-}^*)\,P\cos\psi\,]$$

The dimensionless normalized spin asymmetry

$$A(t,m) = 2\,\Im(M_{++}M_{+-}^*)/[\,|M_{++}|^2 + |M_{+-}|^2\,]\,, \quad -1 \le A(t,m) \le 1\,,$$

where M_{+-} and M_{++} are the s-channel helicity amplitudes with and without nucleon helicity flip, ψ is the angle between the normal to the reaction plain, formed by the momenta of the π^- and $\eta\pi^0$ system, and the transverse (to the π^- beam axis) polarization of the protons, P is a degree of this polarization.

As is seen from Fig. 6 (d), the effect of the $a_0^0(980) - f_0(980)$ mixing in the spin asymmetry is great, and its observation does not require the high-quality $\pi^0\eta$ mass resolution, that is very important in the problem under discussion.

8 Conclusion

Unfortunately, the majority of current investigations of the mass spectra in scalar channels does not study particle production mechanisms. Because of this, such investigations are essentially preprocessing experiments, and the derivable information is very relative. The progress in understanding the particle production mechanisms could essentially further our understanding the light scalar mesons.

Of fundamental importance is production of quark-antiquark pairs and hence virtual hadron pairs that forms both resonances and backgrounds in the light scalar meson region. Formally it appears in the necessity of taking into account loop diagrams and counter-terms essential for correct consideration high virtualities of intermediate particles in both non-linear and linear σ models. That is why a temptation by a potential approach is pregnant with artifacts.

Let us show for dessert that we observe the classic two-quark ρ meson state in its resonance region due to the four-quark component of the ρ meson field. Really, the imaginary part of the $\pi^+\pi^- \to \rho \to \pi^+\pi^-$ amplitude is defined by the real $\pi^+\pi^-$ intermediate state, i.e., by four-quark state. But, this amplitude is pure imaginary at $m = m_\rho$. Further still the four-quark

[5] Note that $|\Pi_{\rho^0\omega}| \approx |\Pi_{\pi^0\eta}| \approx 0.0036\,\mathrm{GeV}^2 \sim m_d - m_u$.

component of the ρ meson field dominates at $m_\rho - \Gamma_\rho/2 < m < m_\rho - \Gamma_\rho/2$. Let us dwell on this question. The amplitude

$$A(\pi^+\pi^- \to \rho \to \pi^+\pi^- \, , \, m) = \frac{g^2_{\rho\pi\pi} m^2 \rho^2_{\pi\pi}}{D_\rho(m)} \, , \tag{A}$$

where $1/D_\rho(m)$ is the ρ meson propagator to the evident Lorentz structures.

$$\frac{1}{D_\rho(m)} = \frac{1}{m^2_\rho - m^2} + \frac{1}{m^2_\rho - m^2} \Pi_\rho(m) \frac{1}{m^2_\rho - m^2} + ... \, , \tag{B}$$

where $\Pi_\rho(m)$ is the $\pi^+\pi^-$ loop contribution to the self-energy of the ρ meson ($\rho \to \pi^+\pi^- \to \rho$), but it is the four-quark intermediate state contribution. So, the first term in the right side of Eq. (B) is defined by the two-quark intermediate state, but the second and other terms mix two-quark and four-quark degrees of freedom. The infinite series in the right side of Eq. (B) lead to

$$\frac{1}{D_\rho(m)} = \frac{1}{m^2_\rho - m^2 - \Pi_\rho(m)} \, . \tag{C}$$

$\Re(\Pi_\rho(m_\rho)) = 0$, if the ρ meson mass is defined completely by two constituent quarks. As for $\imath\Im(\Pi_\rho(m_\rho) = \imath m \Gamma_\rho(m)$, it is defined completely by the real intermediate $\pi\pi$ state, i.e., by the four-quark state. Consequently, the four-quark component of the ρ meson field dominates in the ρ meson propagator when $m \approx m_\rho$.

But in case of the ρ coupling with the $\pi\pi$, $K\bar{K}$ channels, the $\rho \to \gamma\pi$, $\gamma\eta$ transitions and so on, the two-quark component of the ρ meson field works.

The $a_0(980)$ and $f_0(980)$ mesons are a different matter. As we have seen in Section 4, the $\phi \to \gamma a_0(980)$, $\gamma f_0(980)$ transitions are defined by the intermediate compact K^+K^- state, i.e., by the four-quark state.

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NB **References** contain mainly author's articles on basis of which the present talk has been written. Detailed references to other authors are in these articles.

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