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Sh.S.EREMYAN, A.E.NAZARYAN

QUARK-GLUON MIXING IN SCALAR MESONS

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ՔՎԱՐԿ-ԳԼՅՈՒՈՆԱՅԻՆ ԽԱՌՆՈՒՅԹԸ ՍԿԱԼՅԱՐ ՄԵԶՈՆՆԵՐՈՒՄ

Քվարկ-գլյուոնային խառնման մոդելում դիտարկվում են սկալյար մեզոնները: Ցույց է տրված, որ գոյություն ունի սկալյար մասնիկների դեկուպլետ, կազմված $S^*(975)$, $\varepsilon(1400)$, $S^{*\prime}(1700)$, $\delta(980)$ և æ (1300) ռեզոնանսներից: Ընդ որում պարզվում է, որ վաղուց և լավ հայտնի $S^*(975)$ ռեզոնանսը գրեթե մաքուր գլյուբոլ է: Ստացված է սկալյար մասնիկների տրոհման վերաբերյալ բոլոր հայտնի փորձարարական տվյալների լավ նկարագրություն:

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Sh.S. EREMYAN, A.E. NAZARYAN

QUARK-GLUON MIXING IN SCALAR MESONS

Scalar mesons are considered within the quark-gluon mixing model. It is shown that there exists decouplet of scalar particles consisting of $S^*(975)$, $\varepsilon(1400)$, $S^{*\prime}(1700)$, $\delta(980)$ and æ (1350) resonances. It has turned out that the long ago known $S^*(975)$-resonance is a nearly pure glueball. A good description of all available experimental data on scalar meson decays is obtained.

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Ш.С.ЕРЕМЯН, А.Э.НАЗАРЯН

КВАРК-ГЛЮОННОЕ СМЕШИВАНИЕ В СКАЛЯРНЫХ МЕЗОНАХ

В модели кварк-глюонного смешивания рассмотрены скалярные мезоны. Показано, что существует декуплет скалярных частиц, состоящих из $S^*(975)$, $\varepsilon(1400)$ $S^{*\prime}(1700)$, $\delta(980)$ и $\ae(1350)$ резонансов. При этом оказывается, что давно и хорошо известный $S^*(975)$-резонанс является почти чистым глюболом. Получено хорошее описание всех известных экспериментальных данных по распадам скалярных мезонов.

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1. Introduction.

The nature of scalar mesons is one of most obscure and poorly studied aspects in the light meson spectroscopy, though a large number of theoretical papers were devoted to this problem (see, e.g. [1-7]). A seemingly natural effort to classify the light scalar resonances within the simple quark-antiquark scheme encounters great difficulties [2,3], this encouraging one to consider these resonances as bound states of more compound four-quark systems $q^2\bar{q}^2$ [2,4,6]. However this approach again faces great problems. For example, in [2] the strange 0^+ meson must be lighter than the isovector one. The naive method of the scalar meson mass determination, based on the $q\bar{q}$ model, also, leads to discrepancies in the mass spectra [3]. Besides, in the recent years, various glueball models were suggested to explain the 0^+ meson nature (see, e.g. [7]).

Consider the present-day experimental situation with 0^{++} mesons [8].

$-\delta = a_0(980)$ ($m_\delta = 983 \pm 2$ MeV, $\Gamma = 54 \pm 7$ MeV, $I^G(J^{PC}) = 1^-(0^{++})$)

is isotriplet. This particle decays mainly into $K\bar{K}$ and $\eta\pi$. Though the δ-meson mass is below the threshold of $K\bar{K}$ decay, the latter occurs due to the existence of finite width in δ. The existence of $K\bar{K}$ -channel nearly in the centre of the δ peak must bring, owing to the "cusp-effect", to the broadening of the real total width as compared to the 54-MeV one obtained from the $\eta\pi$ channel. Besides, this results in strong distortion of the shape of the Breit-Wiggner peak. Recently there appeared data on the decay width: $\Gamma(\delta^0 \to \gamma\gamma)\, BR(\delta \to \eta\pi) = 0.19 \pm 0.07 \pm 0.1$ keV and on photoproduction: $\sigma(\gamma p + \delta^{\pm} x \to \eta\pi^{\pm} x) = 400 \pm 100$ nb.

$- S^* = f_0(975)$ ($m_{S^*} = 975 \pm 4$ MeV, $\Gamma = 33 \pm 6$ MeV, $I^G(J^{PS}) = 0^+ (0^{++})$.

decays mainly to $\pi\pi$ (78±3)% and $K\bar{K}$ (22±3)%. This resonance is determined from the interference effects of S and P -wave π-π states and the direct production in the $\pi^- p \to \pi\pi n$ process. In addition, this particle was detected in $J/\Psi \to \varphi S^*$ and $J/\Psi \to \omega S^*$ decays. There exist also experimental restrictions on the width $\Gamma(S^* \to \gamma\gamma) < 0.8$ keV. Here again the crucial role must be played by the "cusp-effect" on the $\bar{K}K$ -channel threshold.

$- \varepsilon = f_0(1300)$ ($m_\varepsilon \sim 1300$-1500 MeV, $\Gamma \sim 160$-400 MeV, $I^G(J^{PC}) = 0^+(0^{++})$)

decays mainly into $\pi\pi$ (90 %) and $K\bar{K}$ (10 %). Ref. [7] cites 174 publications about observation of this particle; nevertheless its mass and width are known with very large errors. Precise determination of mass and width of this very wide resonance in ($\pi - \pi$) S -wave is highly complicated: it is difficult to discriminate between the S -wave contribution and the interference with the D -wave f and f' mesons; many other wide states are present in the S - wave; finally, the "cusp-effect" from $\pi\pi$, $\bar{K}K$ and $\eta\eta$ thresholds distorts violently the shape of the Breit-Wiggner peak.

These three resonances are regarded as established relatively reliably.

A total list of all available data on well-established scalar mesons δ, S^* and ε is given in Table 1.

$- æ = K_0^*(1350)$ ($m_æ \sim 1350$ MeV, $\Gamma \sim 250$ MeV, $I^G(J^P) = 1/2\ (0^+)$)

is the only known scalar strange resonance; it decays mostly into $K\pi$. The mass and width of this resonance in different experiments vary within 200 MeV. Again the parameters of this resonance are to be strongly affected by the "cusp-effect" from the $K\eta'$ threshold.

Here the "well"-established particles are over with, and the sphere of theoretical and experimental speculations begins.

$- G = f_0(1590)$ ($m_G = 1587 \pm 16$ MeV, $\Gamma = 287 \pm 50$ MeV, $I^G(J^{PC}) = 0^+ (0^{++})$).

It was observed by one experimental group only. It decays mostly into $\eta\eta$ and $\eta\eta'$. Possesses very strange properties. This resonance will be considered at greater length in Section 3.

$- g_s = f_0(1240)$ ($m_{g_s} = 1240 \pm 22$ MeV, $\Gamma = 140 \pm 22$ MeV, $I^G(J^{PC}) = 0^+(0^{++})$),

was observed by only one experimental group in decays into $K_S^0 \bar{K}_S^0$; besides, it is known that $BR(g_s \to \pi\pi)\ BR(g_s \to \bar{K}K) \leq (0.04)^2$. Experimental status of this resonance is highly doubtful.

$-S^{*\prime}(1730) = f_0(1730)$ ($m_{S^{*\prime}} = 1730 \pm 22$ MeV, $\Gamma = 200^{+156}_{-9}$ MeV, $I^G(J^{PC}) = 0^+ (0^{++})$). It was observed by two experimental groups in decays into $K_S^0 \bar{K}_S^0$. Its mass is determined sufficiently precisely, but its width varies from 50 to 300 MeV in different experiments. Besides, there exists $\xi = X(2220)$-meson with $m_\xi = 2220 \pm 20$ MeV and $\Gamma = 40 \pm 30$ MeV, whose spin is not precisely established but is known to be even.

The existence of such large number of resonances strongly complicates the construction of scalar meson multiplet. Various theoretical analyses of the S wave $\pi\pi$ and $\bar{K}K$ states bring to extraction of various new 0^+ states not coinciding to each other, displace the old well-known resonances. All these lead to nearly complete uncertainty of experimental status of 0^+ -mesons.

The isovector $\delta(980)$ as well as its isoscalar partner $S^*(980)$ are known pretty long ago. Their simplest interpretation within the naive quark model is that the $\delta(980)$ is considered as an analog of ρ -, while the $S^*(980)$ - as an analog of ω -mesons. But in this approach there immediately arise great difficulties, the most serious of them being, apparently, a too large decay width $\Gamma(S^* \to \pi\pi) \approx 400$ MeV as against the experimental value ≈ 25 MeV. Besides, it is unclear why the strange scalar meson $\varkappa$ (1350) is by 370 MeV heavier than δ. Experimentally, both S^* and δ seem to be connected with the strange particles more closely than with non-strange ones, contrary to the ordinary $\rho - \omega$ pair. Their relative rate of decay into $\bar{K}K$ is too high, though it is strongly suppressed by phase space. All these peculiarities make the interpretations of scalar states as usual quark-antiquark mesons doubtful.

The interpretation of scalar mesons as $q\bar{q}$ states mixed with the four-quark ones was proposed in Ref.[9], but the results of this work were criticized in Ref. [4].

In our work we suggest another, seemingly more natural explanation for unusual properties of scalar mesons. We assume that for 0^+ mesons there takes place a usual quark-gluon mixing that plays an essential part in 0^- and 2^+ mesons [10].

The mixing scheme considered is as follows: $\delta(980)$ is taken as isovector state, $\varkappa$ (1350) - as strange state. Two lowest singlet states are well determined - those are $S^*(980)$ and $\varepsilon(1300)$. The place of the third singlet state is vacant, it can be pretended on by the following resonances: $g_S(1240)$, $G(1592)$, $S^{*\prime}(1730)$ and $\xi(2220)$. We shall consider each of these particles separately and choose the most appropriate one.

In Section 2 we give the mixing model and formulae for the scalar particle decay widths.

In Section 3 we discuss the results obtained and compare them with experimental data.

2. Mixing Model.

Here just like in Refs. [10] we shall deal with an ideal basis containing vectors of states of normal $|N\rangle = \frac{1}{\sqrt{2}}|u\bar{u} + d\bar{d}\rangle$ and strange $|S\rangle = |s\bar{s}\rangle$ quarkonia and gluonium $|G\rangle = |gg\rangle$. The physical states $|\Psi\rangle$ are their linear combination:

$$|\Psi\rangle = x_\Psi|N\rangle + y_\Psi|S\rangle + z_\Psi|G\rangle, \qquad (1)$$

where $x_\Psi^2 + y_\Psi^2 + z_\Psi^2 = 1$ and $\Psi = S^*$, ε and one of the particles g_S, G, $S^{*\prime}$, ξ.

The reason of quark-gluon mixing in QCD is annihilation of $q\bar{q}$ -system into gluons, i.e. the annihilation terms λ_i ($i = N, S$ and G) corresponding to annihilation of quark-antiquark pair into two gluons must be added to the quadratic mass matrix of isoscalar mesons. We assume that the mixing parameters λ_i are energy-independent, i.e. we accept the orthogonal mixing model. The weights x, y and z of ideal states $|N\rangle$, $|S\rangle$ and $|G\rangle$ in physical states $|\Psi\rangle$ are functions of ideal- and physical-state masses and annihilation parameters. The physical states must satisfy the eigenvalue equations, owing to which we arrive at three equations that express the annihilation parameters through masses of ideal and physical states. As a result, only three free parameters remain in the model: m_N, m_S and m_G - the ideal state masses.

All experimental material availabe on scalar resonances is presented in Table 1. We can build up seven more or less satisfactory experimental ratios of decay widths from which we can determine parameters m_i with sufficient accuracy.

The formulae used in calculations were as follows:

$$\frac{\Gamma(S\to\gamma\gamma)}{\Gamma(\delta\to\gamma\gamma)} = \frac{25}{9}\left(\frac{m_S}{m_\delta}\right)^3\left(S_N + \frac{\sqrt{2}}{5}S_S\right)^2, \tag{2}$$

$$\frac{\Gamma(S\to\pi\pi)}{\Gamma(\delta\to\eta\pi)} = \frac{3}{x_\eta^2}\;\frac{P_S}{P_\delta}\left(\frac{m_\delta}{m_S}\right)^2 S_N^2, \tag{3}$$

$$\frac{\Gamma(S\to K\bar{K})}{\Gamma(\delta\to\eta\pi)} = \frac{1}{x_\eta^2}\;\frac{P_S}{P_\delta}\left(\frac{m_\delta}{m_S}\right)^2\left(S_N+\sqrt{2}\,S_S\right)^2, \tag{4}$$

$$\frac{\Gamma(S\to\eta\eta)}{\Gamma(\delta\to\eta\pi)} = \frac{1}{x_\eta^2}\;\frac{P_S}{P_\delta}\left(\frac{m_\delta}{m_S}\right)^2\left[x_\eta^2 S_N+\sqrt{2}\,y_\eta S_S+\sqrt{2}\,\lambda_G\alpha_S z_\eta^2 z_S\right]^2, \tag{5}$$

$$\frac{\Gamma(S\to\eta\eta')}{\Gamma(\delta\to\eta\pi)} = \frac{1}{x_\eta^2}\;\frac{P_S}{P_\delta}\left(\frac{m_\delta}{m_S}\right)^2\left[x_\eta x_{\eta'} S_N+\sqrt{2}\,y_\eta y_{\eta'} S_S+\sqrt{2}\,\lambda_G\alpha_S z_\eta z_{\eta'} z_S\right], \tag{6}$$

$$\frac{\Gamma(\delta\to K\bar{K})}{\Gamma(\delta\to\eta\pi)} = \left(\frac{P_{KK}}{m_\delta^2}\right)\frac{2m_\delta^2}{P_{\eta\pi}}\;\frac{1}{x_\eta^2}, \tag{7}$$

where $x_{\eta(\eta')}$, $y_{\eta(\eta')}$ and $z_{\eta(\eta')}$ are weights of $|N\rangle$, $|S\rangle$ and $|G\rangle$ states in $\eta(\eta')$ mesons, calculated in Refs. [10]. Here we used the following notations:

$$S_N = x_S + \sqrt{2}\,\lambda_N\alpha_S z_S,$$
$$S_S = y_S + \lambda_S\alpha_S z_S, \quad (S = S^*, \varepsilon, \ldots) \tag{8}$$

Decays of δ and S^* into $\bar{K}K$ and ε into $\eta\eta'$ can take place owing only to finite width of these resonances. The phase space of such decays was calculated by the approximate formula

$$\overline{\left(\frac{P}{m^2}\right)} = \frac{\Gamma_{tot}}{2\pi}\int_{m_1+m_2}^{\infty}\frac{\sqrt{(m_x^2-(m_1+m_2)^2)(m_x^2-(m_1-m_2)^2)}}{2m_x^3\left[(m_x-M)^2+\Gamma_{tot}^2/4\right]}\,dm_x$$

Ratios of decays of $J/\Psi\to S\gamma$ type were calculated by formula [10]

$$\frac{\Gamma(J/\Psi\to S\gamma)}{\Gamma(J/\Psi\to S^*\gamma)} = \left(\frac{P_S}{P_S^*}\right)^3\left(\frac{G(S)}{G(S^*)}\right)^2, \tag{9}$$

where

$$G(S) = \sqrt{2}\,\lambda_N x_S + \lambda_S y_S + \lambda_G z_S, \quad (S = S^*, \varepsilon \ldots) \tag{10}$$

Besides, there were considered decays of $J/\Psi\to SV$ type by formulae [10]

$$\Gamma(J/\Psi\to S\omega) = g_{\psi VS}^2 P_{S\omega}\left[S_N(1+e_N)+\sqrt{2}\,\xi\,G(S)\right]^2,$$
$$\Gamma(J/\Psi\to S\varphi) = g_{\psi VS}^2 P_{S\varphi}\left[R(S_S+\xi G(S))-2\mu e_N S_S\right]^2 \tag{11}$$

where the parameters R, ξ and e_N are determined in Ref. [19].

In formulae (2)-(6) and (8)-(11) the terms violating the quark count rules are taken into account in explicit form; they are proportional to $\lambda_i z$. The coefficient α_S before these terms has a dimension of GeV^{-1}. The comparison with experiment shows that $\alpha_S \approx 1$ GeV^{-1}, but the results are better at $\alpha_i = m_i^{-1}$ $(i = S^*, \varepsilon \ldots)$. For certainty we shall further fix $\alpha_i = m_i^{-1}$.

In formulae (5) and (6) the terms $\sim \lambda_G z_\eta z_{\eta'} z$ correspond to the triangular gluon diagrams derived by Gerstein et al. in [11] .

When determining the model parameters m_N , m_S and m_G the experimental data on decays into $\pi\pi$ and $K\bar{K}$ were used, while those on decays into two photons were not .

As a third isosinglet state four particles $g_S(1240)$, $G(1590)$, $S^*(1730)$ and $\xi(2220)$ were considered.

It turned out that for particles $g_S(1240)$ and $\xi(2220)$ there does not exist a satisfactory solution (at experimental data available). A more careful analysis of experimental situation shows that the resonance $g_S(1240)$ was observed by only one experimental group and was extracted from the S - wave $K_S^0 \bar{K}_S^0$ state by means of rather speculative theoretical considerations, and we are inclined to think that this resonance, most probably, does not exist at all. As to the $\xi(2220)$ meson, its spin apparently is 2^+ or 4^+ and it is not a scalar particle.

There are two particles left: $G(1590)$ and $S^{*\prime}(1730)$. For each of these resonances there exist two different solutions. One of them corresponds to that $S^*(980)$ is an almost pure $|S\rangle$ state, while the other brings to a pure glueball $|G\rangle$ state for this particle. All available experimental data on decays of S^* , ε and δ agree with theoretical predictions equally well in both cases.

In order to show preference to one of these versions, remind that not only in quark models but also in the quark-gluon mixing model [10] there works well the Gell-Mann-Okubo formula predicting mass m_S of state $S\bar{S}$:

$$m_S^2 = 4m_{æ}^2 - m_\delta^2 \tag{12}$$

In the first version it turns out from fitting that $m_S^2 \approx 0.6$ GeV^2, this leading to a mass of the scalar multiplet strange partner $m_{æ} \approx 870$ MeV. There is no such particle in Rosenfeld's tables [8] , so we shall not consider a version when $S^*(980)$ is a nearly pure $S\bar{S}$ state. A similar version was obtained in Ref. [7] and the same problems arose there.

There is left the second version of solution when $S^*(980)$ is a nearly pure glueball. In this case $m_S \approx 1.56$ GeV, this bringing to the strange partner mass $m_{æ} \approx 1300$ MeV, which agrees very well with experimental mass of the strange scalar meson $æ(1350)$.

To choose a proper version, a ratio

$$\frac{BR(J/\psi \to \varphi S^*)}{BR(J/\psi \to \omega S^*)} = ?.76 \pm 1.0$$

could have helped, but because of a too large error in experiment both versions agree with it sufficiently satisfactorily. The version with $S\bar{S}$ -quarks gives $\approx 3.4 \pm 0.6$, the one with glueball $\approx 1.5 \pm 0.5$.

We are left only to choose which of the two possible resonances, $G(1590)$ or $S^{*\prime}(1730)$, is the searched term of our multiplet.

From [8] we know that the $G(1590)$ possesses rather strange properties; the experiment gives the following ratios for decay widths of this particle:

$$\frac{\Gamma(G \to \pi\pi)}{\Gamma(G \to \eta\eta)} < 0.45; \qquad \frac{\Gamma(G \to K\bar{K})}{\Gamma(G \to \eta\eta)} < 0.6; \qquad \frac{\Gamma(G \to \eta\eta')}{\Gamma(G \to \eta\eta)} = 2.7 \pm 0.8$$

If $G(1590)$ is a term of our multiplet, it must possess the following properties:

$$\frac{\Gamma(G \to \pi\pi)}{\Gamma(G \to \eta\eta)} = 0.69 \pm 0.08; \quad \frac{\Gamma(G \to K\bar{K})}{\Gamma(G \to \eta\eta)} = 4.8 \pm 0.02; \quad \frac{\Gamma(G \to \eta\eta')}{\Gamma(G \to \eta\eta)} = 0.17 \pm 0.01$$

which contradicts strongly the experiment. Hence, either G -meson is not a term of the multiplet or the experimental data in [8] are wrong.

It was assumed [11] that the $G(1590)$ is a glueball just because it decays preferably into $\eta\eta$ and $\eta\eta'$. In this connection we shall consider at greater length the question of possible relations between decay widths of glueball. Suppose there is some particle G belonging to some multiplet and being a pure glueball. That is $X_G \approx Y_G \approx 0$ and $Z_G \approx 1$. From [10] it is known that $X_\eta \approx -Y_\eta \approx 0.7$, $Z_\eta Z_{\eta'} \lesssim -0.03$ and $Z_\eta^2 \lesssim 0.006$. Because of smallness of Z_η and $Z_\eta Z_{\eta'}$, the terms corresponding to the triangular gluon diagram (the mechanism of Ref. [11]) come to be very small; as a result we obtain from formulae (2)-(6) the following expressions to estimate constants of two-particle decays of possible glueball:

$$\frac{g_{GKK}}{g_{G\pi\pi}} \sim \frac{1}{\sqrt{3}}\left(1+\frac{\lambda_S}{\lambda_N}\right), \qquad (13.1)$$

$$g_{G\eta\eta}/g_{G\pi\pi} \approx \frac{X_\eta^2\lambda_N + Y_\eta^2\lambda_S + Z_\eta^2\lambda_G}{\lambda_N+\lambda_S} \sim X_\eta^2 \approx 0,5 \qquad (13.2)$$

$$g_{G\eta\eta'}/g_{GKK} \approx \frac{X_\eta X_{\eta'}\lambda_N + Y_\eta Y_{\eta'}\lambda_S + Z_\eta Z_{\eta'}\lambda_G}{\lambda_N+\lambda_S} \lesssim 0,5 \qquad (13.3)$$

One can see from (13.1) that the hypothetical glueball prefers decaying both into $\pi\pi$ and $K\bar{K}$, depending on the ratio of annihilation parameters, λ_S/λ_N, in a given multiplet. Contrary to the statement made in Ref. [11] we obtain that the particle decays into $\eta\eta$ and $\eta\eta'$ cannot be the grounds for the claim that the given particle is a glueball; moreover. as is seen from (13.2) and (13.3), decays of glueballs into $\eta\eta$ and $\eta\eta'$ are suppressed as compared to decay into $K\bar{K}$.

Hence, in the framework of the model suggested, with account of the existing scanty experimental information, the only claimant upon the place of the third isoscalar term in the scalar meson multiplet is the resonance $S^{*\prime}(1730)$. The experimental data fit gives in this case the following values

for the parameters:

$$m_N = 1.360 \pm 0.020 \text{ GeV}$$
$$m_S = 1.558 \pm 0.031 \text{ GeV} \qquad (14)$$
$$m_G = 0.881 \pm 0.031 \text{ GeV}$$

Substituting these values of ideal-state masses into Eq. (2) of Ref. [10] , we arrive at the following values for the annihilation parameters·

$$\lambda_N = 0.301 \pm 0.037 \text{ GeV}$$
$$\lambda_S = 0.640 \pm 0.076 \text{ GeV} \qquad (15)$$
$$\lambda_G = 0.508 \pm 0.078 \text{ GeV}$$

The resulting values of X, Y and Z are listed in Table 2.

3. Discussion of Results.

It turned out that nearly ideal mixing takes place in the scalar meson multiplet. The resonance $S^*(980)$ is a nearly pure glueball with very small admixture of $|N\rangle$ and $|S\rangle$ states and namely this latter circumstance accounts for all its paradoxical properties.

The resonance $\varepsilon(1300)$ turns out to be a nearly pure $|N\rangle$ state with small admixture of strange quarks; therefore it has very large width and decays mostly into $\pi\pi$. The resonance $S^{*\prime}(1730)$ is a nearly pure $S\bar{S}$ state with small admixture of normal quarks; therefore it is narrower than ε and decays into $K\bar{K}$.

The theoretical predictions resulting at such set of parameters are given in Table 1 together with existing experimental data.

Let us consider experimentally observed consequences following from the hypothesis that $S^*(980)$ is glueball. First, it will have a relatively small width $\Gamma^{tot}(S^*) \approx 38 \pm 11$ MeV, while in usual quark models its width is ≈ 500 MeV, in the four-quark models - ≈ 400 MeV, these have to be masked by means of various tricks (see, e.g. [9]). Besides, the smallness of $S^* \to \gamma\gamma$ decay width, which used to be a stumbling-stone for many models, is naturally explained.

Some objections can be raised concerning a too small ratio $\lambda_N/\lambda_S = 0.47 \pm 0.08$ obtained in our model, but here we can be supported by the results of the bag model (in which glueballs, and 4q-states, and hybrids were predicted). In this model the eigenmodes of gluons are classified as transverse-electrical (TE) with $P = (-1)^{L+1}$, and transverse-magnetic (TM) with $P = (-1)^L$. The TE-gluon in S-channel is connected with normal and strange quarks with a nearly equal strength, while the TM-gluons in S-channel are connected with the $s\bar{s}$-quarks more strongly than with $u\bar{u}$ and $d\bar{d}$ [12]. Ibidem it was claimed that glueballs consisting of the TM-gluons must decay mostly into states rich in S-quarks.

In our scheme $\lambda_N/\lambda_S \approx 0.5$, whence one can conlude that the state $|G\rangle$ in the scalar sector consists mainly of the TM-gluons which are just responsible for the greater values of the annihilation parameter λ_S and constant $g_{S^*K\bar{K}}$ that ensure the required decay width $BR(S^* \to K\bar{K}) = 0.21 \pm 0.09$.

For the ratio of $S^* \to K\bar{K}$ and $S^* \to \pi\pi$ decay constants we obtain

$$g^2_{S^*K\bar{K}} / g^2_{S^*\pi\pi} = 6.4 \pm 2.0 \qquad (16.1)$$

and for decays of δ

$$g^2_{\delta^\circ K^+K^-} / g^2_{\delta^\circ \pi\eta} = 0.63 \pm 0.22 \qquad (16.2)$$

The constant of $S^* \to \eta\eta$ decay also turns out sufficiently large:

$$g^2_{S^*\eta\eta} / g^2_{S^*\pi\pi} = 0.87 \pm 0.15$$

The ratios (16.1) and (16.2) are in good agreement with the results of the four-quark model [4]:

$$g^2_{S^*K\bar{K}} / g^2_{S^*\pi\pi} = 5 \div 13 \ ,$$

$$g^2_{\delta^\circ K^+K^-} / g^2_{\delta^\circ \pi\eta} = 3/4 \ .$$

Thus the assumption that $S^*(975)$ is a glueball explains well all peculiarities of this particle decays, which hitherto were explained within the four-quark models. In addition, this assumption is confirmed well by results of Refs. [12], where for the scalar $(TE)^2$-glueball there was obtained a mass value 650 MeV, while for the $(TM)^2$-glueball 1130 MeV. The mass $S^*(975)$ is between them and there must exist strong mixing between the $(TE)^2$ and $(TM)^2$ states in S^*. Therefore the suppression of $\pi\pi$-channel for S^* is not so strong as it could have been in case of a pure $(TM)^2$-state.

Our scheme predicts some enlargement in widths of δ and S^*-resonances, which is due to $K\bar{K}$-channel. A real width of δ will be $\Gamma^{tot}(\delta) \approx 78 \pm 19$ MeV and $\Gamma^{tot}(S^*) \approx 38 \pm 11$ MeV instead of the values [8] 54 ± 7 and 33 ± 6 MeV, respectively.

The only seeming contradiction in this picture is strong experimental upper restriction on the width of $J/\Psi \to S^*\gamma$ radiative decay. Indeed, a rather strong restriction, $BR(J/\Psi \to S^*(975)\gamma)\, BR(S^*(975) \to \pi\pi) < 7 \cdot 10^{-5}$ (90% C.L.), was obtained by MARK III group [13]. If taking the value of $BR(S^* \to \pi\pi)$ from Table 1, then $BR(J/\Psi \to S^*\gamma) < 7.8 \cdot 10^{-5}$ or $\Gamma(J/\Psi \to S^*\gamma) < 5$ GeV, which should be compared with $\Gamma(J/\Psi \to \eta'\gamma) = 263 \pm 46$ eV.

Consider this question at greater length: examine the ratio

$$R = \frac{\Gamma(J/\Psi \to S^*\gamma)}{\Gamma(J/\Psi \to \eta'\gamma)} < 0.021$$

In our scheme we have

$$R = \frac{g^2_{\Psi\gamma S}}{g^2_{\Psi\gamma P}} \left(\frac{P_{S*}}{P_{\eta'}}\right)^3 \left(\frac{\lambda^S_c}{\lambda^P_c}\right)^2 \left(\frac{G(S^*)}{G(\eta')}\right)^2,$$

where $G(A)$ is determined in Eq.(10), indices S and P denote a scalar and pseudoscalar sectors, respectively. $g^2_{\Psi\gamma S(P)}$ are normalization constants of $J/\Psi \to \gamma S(P)$ decay which are the same for each of multiplets S and P. $\lambda_c^{S(P)}$ are constants of $c\bar{c}$ -quark annihilation to a pair of gluons being in scalar or pseudoscalar state. In our model with addition of $c\bar{c}$ states we have

$$(\lambda^S_c)^2 = \frac{(m^2_{S*} - m^2_{cs})(m^2_{\epsilon} - m^2_{cs})(m^2_{S*'} - m^2_{cs})(m^2_{\chi_0} - m^2_{cs})}{(m^2_{NS} - m^2_{cs})(m^2_{ss} - m^2_{cs})(m^2_{GS} - m^2_{cs})} \approx 0.91(m^2_{\chi_0} - m^2_{cs}) \tag{17}$$

$$(\lambda^P_c)^2 = \frac{(m^2_{\eta} - m^2_{cp})(m^2_{\eta'} - m^2_{cp})(m^2_{\iota} - m^2_{cp})(m^2_{\eta_c} - m^2_{cp})}{(m^2_{Np} - m^2_{cp})(m^2_{sp} - m^2_{cp})(m^2_{Gp} - m^2_{cp})} \approx 0,87(m^2_{\eta_c} - m^2_{cp})$$

where m_{cs} and m_{cp} are masses of ideal $c\bar{c}$ states in S and P sectors. From Refs. [10] and Eqs. (14) and (15) we have

$$(G(S^*)/G(\eta'))^2 \approx 0.2 \quad ,$$

hence

$$R \approx 0.2 \frac{g^2_{\Psi\gamma S}}{g^2_{\Psi\gamma P}} \frac{m^2_{\chi_0} - m^2_{cs}}{m^2_{\eta_c} - m^2_{cp}} .$$

It is well known that $\chi_0(3415)$ and $\eta_c(2980)$ are practically pure $c\bar{c}$ states; therefore $\lambda^2_c \lesssim 10^{-2}$ (see, e.g. [14]). On the other hand, we know that $\Gamma(\eta_c \to hadr) > \Gamma(\chi_0 \to hadr)$, i.e. $\lambda^P_c > \lambda^S_c$.

Hence the quantity R can take any values, including very small ones, versus relative amounts of admixtures coming from $|N\rangle$, $|S\rangle$ and $|G\rangle$ states in $\chi_0(3415)$ and $\eta_c(2980)$ charmonia. In particular, the existing

experimental restriction brings to the condition

$$g^2_{\Psi\gamma S}(m^2_{\chi_0} - m^2_{cs}) < 0.125 g^2_{\Psi\gamma P}(m^2_{\eta_c} - m^2_{cp}) ,$$

i.e. the scalar charmonium $\chi_0(3415)$ is required to be a more pure $c\bar{c}$ - state taking into account that mixing in pseudoscalar sector is much stronger than in scalar one, and that mass of η_c is by 400 MeV less than that of χ_0.

Besides, in Ref. [15] , within the QCD sum rules it was obtained that $\Gamma(J/\Psi \to \sigma\gamma)\, BR(\sigma \to \pi\pi) \approx 25$ eV for scalar glueball σ with 750 MeV mass. Evidently, the accounting of mixing must reduce essentially this result (since the portion of gluons in σ decreases). If we assume the mixing parameters the same as in Table 1, this will result in reduction of the decay width by a factor of 2.5; if, in addition, we recount the phase space for transition to the 975 MeV mass, then we'll come to $\Gamma(J/\Psi \to \sigma\gamma) \approx 8.8$ eV, which already is not too far from experimental restriction.

That is, the hypothesis that $S^*(975)$ is a glueball does not necessarily guarantee the large decay width $\Gamma(J/\Psi \to S^*\gamma)$.

Consider the other experimental consequences of the scheme suggested.

For the resonance $\varepsilon(1300)$ the theory predicts the lower boundary of the total width $\Gamma^{tot}(\varepsilon) \gtrsim 324 \pm 79$ MeV obtained from the sum of widths over decay channels $\varepsilon \to \pi\pi$, $K\bar{K}$, $\eta\eta$ and $\eta\eta'$. In our model ε turned out to be a nearly pure $|N\rangle$ state with a small admixture of strange quarks. The main decay channel is $\Gamma(\varepsilon \to \pi\pi) = 290 \pm 70$ MeV. Theory has successfully predicted a recently measured [16] ratio $BR(\varepsilon \to \eta\eta) = 0.022 \pm 0.008$. In [16] $BR(\varepsilon \to \eta\eta) \approx 0.025$.

The resonance $S^{*\prime}(1730)$ has been inscribed into our scheme very successfully. It turned out to be a nearly pure $s\bar{s}$ state with small admixture of normal quarks and gluons. Namely because its mass is 1730 MeV, it turned out that m_s = 1.56 MeV, this, after being substituted to the Gell-Mann-Okubo formula (12), giving a correct value of the strange partner mass:

$$m_{\ae} = 1303 \pm 48 \text{ MeV},$$

which agrees well with experimental value $m_{\ae} \sim 1350$ MeV. The main decay channel of $S^{*\prime}$ is $\Gamma(S^{*\prime} \to K\bar{K})$ = 212 ± 51 MeV, but besides that, there must be well observed decays $\Gamma(S^{*\prime} \to \pi\pi)$ = 30.6 ± 8.8 MeV, $\Gamma(S^{*} \to \eta\eta)$ = = 45 ± 11 MeV and $\Gamma(S^{*\prime} \to \eta\eta')$ = 10.4 ± 2.6 MeV. The total width of $S^{*\prime}$ to be obtained from the sum over partial two-body widths will be $\Gamma^{tot}(S^{*\prime}) \gtrsim$ $\gtrsim$ 300 ± 74 MeV.

For the $\ae$-meson we obtain a very large decay width $\Gamma(\ae \to K\pi)$ = = 373 ± 6 MeV, which agrees well with results of other analyses [4,9,21] .

In our scheme the δ (980) meson consists of only normal quarks and is an analog of π-meson. In this assumption we obtain

$$\Gamma(\delta \to K\bar{K}) = 28 \pm 7 \text{ MeV}$$

$$\Gamma(\delta \to \eta\pi) = 55 \pm 1 \text{ MeV}$$

being in good agreement with experimental data [8] , $\Gamma(\delta \to K\bar{K}) \approx$ $\approx$ 35 ± 17 MeV and $\Gamma(\delta \to \eta\pi) \approx$ 50 ± 12 MeV.

Consider the two-photon decays of scalar particles at greater length. As was shown in [17] , it is quite unclear how much the decay width $\Gamma(\delta \to \gamma\gamma)$ is crucial for one to select between the $q\bar{q}$ and $4q$-models. Theoretical predictions strongly differ from each other: some authors obtain a large width if $\delta = q\bar{q}$ (4.8 keV [18]) and a small one if $\delta = 4q$ (0.27 keV [4]) or if δ is a $K\bar{K}$ molecule (0.6 keV [6]). Others, on the contrary, obtain a small width if $\delta = q\bar{q}$, $\Gamma(\delta \to \gamma\gamma) < 0.4$ keV [19] .

In Ref. [5] it was shown that all these calculations substantially depend on initial parameters of the models, so they nowise can serve as criteria for discrimination of the models.

In addition, as was shown in [9] , the experimental situation is pretty uncertain either. The experiment gives

$$\Gamma(\delta \to \gamma\gamma)\, BR(\delta \to \eta\pi) = 0.19 \pm 0.07^{+0.1}_{-0.07} \text{ keV}$$

i.e. the value of $\Gamma(\delta \to \gamma\gamma)$ substantially depends on $\Gamma^{tot}(\delta)$. If the real width of δ is appreciably larger than its table value, $\approx$ 54 MeV (as predicted in the 4q-models [4,9,21]), then $\Gamma(\delta \to \gamma\gamma)$ will increase respectively, and the question of the nature of δ meson will again remain open.

Unfortunately, staying within our scheme, one cannot directly calculate the decay width; instead, we come to ratios of widths given in Table 1. We have

$$\Gamma(\varepsilon \to \gamma\gamma)/\Gamma(\delta \to \gamma\gamma) = 5.73 \pm 0.28$$

In Ref. [20] , with account of the Euler-Heisenberg type diagrams it was obtained that the two-photon decay width of scalar quarkonia consisting of normal quarks (ε (1300)-meson in our scheme) is

$$\Gamma(\varepsilon \to \gamma\gamma) = 0.96 \left(\frac{m_\varepsilon}{1\,\text{ГэВ}}\right)^3 \text{ keV}$$

Substituting the mass m_ε we obtain

$$\Gamma(\varepsilon \to \gamma\gamma) \approx 2.11 \text{ keV},$$

hence

$$\Gamma(\delta \to \gamma\gamma) = 0.37 \pm 0.02 \text{ keV}.$$

Using the ratios

$$\Gamma(S^* \to \gamma\gamma)/\Gamma(\delta \to \gamma\gamma) = 0.11 \pm 0.05,$$

$$\Gamma(S^{*\prime} \to \gamma\gamma)/\Gamma(\delta \to \gamma\gamma) = 4.9 \pm 0.3$$

we arrive at the following values for the widths of two-photon decays of S^* and $S^{*\prime}$:

$$\Gamma(S^* \to \gamma\gamma) = 0.04 \pm 0.02 \text{ keV},$$

$$\Gamma(S^{*\prime} \to \gamma\gamma) = 1.82 \pm 0.15 \text{ keV}.$$

In the scheme under consideration $\Gamma^{tot}(\delta) \geqslant 78 \pm 19$ MeV; hence $\Gamma(\delta \to \gamma\gamma) \approx 0.29 \pm 0.10$ keV, this agreeing sufficiently well with the theoretical prediction. As to $S^* \to \gamma\gamma$ decay, there exists only the restriction $\Gamma(S^* \to \gamma\gamma)\, BR(S^* \to \pi\pi) < 0.8$ keV, which agrees well with our prediction. The account of $\delta^\circ - S^*$ mixing must even more reduce $\Gamma(\delta \to \gamma\gamma)$ and somewhat increase $\Gamma(S^* \to \gamma\gamma)$ and $\Gamma(S^{*\prime} \to \gamma\gamma)$ [6,21]. The results for the widths $\Gamma(S \to \gamma\gamma)$, where $S = \varepsilon, \delta, S^*, S^{*\prime}$, are somewhat speculative, and apparently should not be regarded as too serious ones (the same concerns the widths obtained in[4,6,18,19]. However they can at least indicate that it is possible to construct an independent scheme which contains both δ-meson built up of two quarks and S^* built up of gluons. The experimental data available do not at least indicate erroneousness of this assumption.

The values of X, Y, Z and λ_i obtained from the analysis of experiment can be used to predict widths of $J/\Psi \to SV$ decays. The additional parameters R, e_N and ξ required were determined in Ref. 10. The results are listed in Table 1.

Hitherto we presented only the arguments that favour a glueball nature of

S^* and a two-quark nature of other scalar resonances. However the analysis of formulae (2)-(11) shows that these ratios of decay widths would have the same form also in the case if the state $|G\rangle$ would be a 4q- or hybrid state. Then the parameters λ_i would be constants of transitions from 2q- to 4q-states. Unfortunately, the present experimental situation in the scalar sector, contrary to the pseudoscalar and tensor sectors, does not allow one to discriminate precisely between glueball, 4q-resonance and hybrid. The only thing that can be undoubtedly claimed is that the hypothesis that $|G\rangle$ is a glueball contradicts none of existing experiments.

If we admit that $|G\rangle$ is a four-quark state, then our analysis will be an analog of Tornqvist's analysis [9], i.e. will reduce to the description of scalar mesons as ordinary qq-mesons with large admixture of 4q-component without insertion of special 0^+ - 4q nonet. This approach was subjected in [4] to well-grounded criticism: it was shown that non-discrepant insertion of 4q states necessitates the existence of two 4q-nonets $(9,0^+)$ and $(9^*,0^+)$, otherwise there would arise strong violation in quark count rules, this leading to wrong predictions in other sectors.

If $|G\rangle$ is hybrid strongly mixed with ordinary quarks, this again must bring to the existence of two nonets of hybrid states with TE and TM-gluons [12].

On the other hand, experiment gives no grounds to postulate the simultaneous existence of two nonets of scalar mesons, so in both cases open is the question: where is a scalar $q\bar{q}$-nonet and which is a scalar glueball ?

We do not claim that we have managed to prove a glueball nature of S^* meson, but at least we have shown that this hypothesis contradicts none and has the same right for existence as other alternative hypotheses have (e.g. a 4q-model).

The main advantage of the glueball hypothesis is that it does not demand insertion of any additional assumptions or particles, it agrees with all available experimental data and gives lots of predictions which can be checked by future experiments. We can say that the glueball hypothesis is more economical against the others.

Moreover, this assumption inserts in a natural way 0^+ mesons to the family of ordinary qq-mesons (0^-, 1^-, 2^+ , etc.) and agrees well with various models (QCD sum rules [15] , bag model [12]) that predict scalar glueball mass $\lesssim$ 1 GeV.

In this approach scalar mesons form a multiplet with ideal mixing resembling a tensor meson multiplet. Resonance S^* is an analog of θ -meson, ε - analog of f , $S^{*\prime}$- analog of f' . Besides, these multiplets include isovectors δ and A_2 and strange particles æ and K^{**} , respectively. Pseudoscalar mesons, as usual, keep aloof since there occurs strong mixing between η , η' and ι mesons in them.

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Table 1

Comparison of experimental data with theoretical predictions for scalar meson decays.

Particle Mode	BR ($0^+ \to AB$) exp.	BR ($0^+ \to AB$) theor.	$\Gamma(0^+ \to AB)$ MeV exp.	$\Gamma(0^+ \to AB)$ MeV theor.
δ(980)	m_δ = 983 ± 2 MeV;	$\Gamma^{tot}_{exp} \gtrsim$ 54 ± 7 MeV;		$\Gamma^{tot}_{th} \gtrsim$ 78 ± 19 MeV
$\eta\pi$	0.92 ± 0.25	0.66 ± 0.01	50 ± 12	55 ± 1
$K\bar{K}$	0.65 ± 0.32	0.342 ± 0.007	35 ± 17	27.7 ± 6.6
S^*(975)	m_{S^*}= 975 ± 4 MeV;	$\Gamma^{tot}_{exp} \gtrsim$ 33 ± 6 MeV;		$\Gamma^{tot}_{th} \gtrsim$ 38 ± 11 MeV
$\pi\pi$	0.78 ± 0.03	0.80 ± 0.32	25.7 ± 4.8	30.3 ± 8.4
$K\bar{K}$	0.22 ± 0.03	0.21 ± 0.09	7.3 ± 1.7	7.9 ± 2.8
ε(1300)	m_ε 1300 - 1450 MeV;	$\Gamma^{tot}_{exp} \gtrsim$ 150 - 400 MeV;		$\Gamma^{tot}_{th} \gtrsim$ 324 ± 79 MeV
$\pi\pi$	0.9	0.89 ± 0.31	288 ± 48	290 ± 70
$K\bar{K}$	0.1	0.076 ± 0.028	23 ± 5	25 ± 7
$\eta\eta$	0.025	0.022 ± 0.008	8 ± 1	7.2 ± 1.9
$\eta\eta'$	?	0.0084 ± 0.0030	?	2.7 ± 0.7
$S^{*\prime}$(1730)	$m_{S^{*\prime}}$= 1730 ± 22 MeV;	$\Gamma^{tot}_{exp} \gtrsim$ 200^{+156}_{-9} MeV;		$\Gamma^{tot}_{th} \gtrsim$ 299 ± 74 MeV
$\pi\pi$	?	0.10 ± 0.04	?	30.6 ± 8.8
$K\bar{K}$	seen	0.71 ± 0.25	seen	212 ± 51
$\eta\eta$	?	0.15 ± 0.05	?	45 ± 11
$\eta\eta'$	?	0.035 ± 0.012	?	10.4 ± 2.6

(to be continued)

Table 1 (continuation)

Widths

$\Gamma(J/\psi \to \varepsilon\gamma)/\Gamma(J/\psi \to S^*\gamma) = 0.140 \pm 0.073$	$\Gamma(S^* \to \gamma\gamma)/\Gamma(\delta \to \gamma\gamma) = 0.11 \pm 0.05$
$\Gamma(J/\psi \to S^{*\prime}\gamma)/\Gamma(J/\psi \to S^*\gamma) = 0.69 \pm 0.25$	$\Gamma(\varepsilon \to \gamma\gamma)/\Gamma(\delta \to \gamma\gamma) = 5.7 \pm 0.3$
	$\Gamma(S^{*\prime} \to \gamma\gamma)/\Gamma(\delta \to \gamma\gamma) = 4.9 \pm 0.3$

	Experiment	Theory
$BR(J/\psi \to \rho\delta)\, BR(\delta \to \eta\pi)$	4.4 90% C.L.	5.0 ± 1.1
$BR(J/\psi \to \omega S^*)\, BR(S^* \to \pi\pi)$	0.095 ± 0.01 ± 0.022	0.124 ± 0.058
$BR(J/\psi \to \varphi S^*)\, BR(S^* \to \pi\pi)$	0.25 ± 0.074	0.19 ± 0.09

$BR(J/\psi \to \omega\varepsilon)$	2.74±0.58	$BR(J/\psi \to \ae^0 \bar{K}^0 + c.c.)$	3.2±0.7
$BR(J/\psi \to \varphi\varepsilon)$	0.088±0.020	$BR(J/\psi \to \rho^0 S^*)$	0.024±0.006
$BR(J/\psi \to \omega S^*)$	0.053±0.024	$BR(J/\psi \to \rho^0 \varepsilon)$	0.27±0.07
$BR(J/\psi \to \varphi S^{*\prime})$	0.46±0.11	$BR(J/\psi \to \rho^0 S^{*\prime})$	0.020±0.005
$BR(J/\psi \to \ae^+ K^{*-} + c.c.)$	4.7±1.0	$BR(J/\psi \to \omega\delta^0)$	0.34±0.09

Table 2

Weights of x, y and z for scalar mesons.

	S^* (975)	ε (1300)	$S^{*\prime}$ (1730)
x	0.159 ± 0.050	0.938 ± 0.013	-0.307 ± 0.019
y	0.145 ± 0.019	-0.330 ± 0.027	-0.933 ± 0.011
z	-0.9766 ± 0.0082	0.104 ± 0.045	-0.189 ± 0.025

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КВАРК-ГЛЮОННОЕ СМЕШИВАНИЕ В СКАЛЯРНЫХ МЕЗОНАХ

(на английском языке, перевод З.Н.Асланян)

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