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QCD VACUUM IN QUARK MODELS AND $Q^2\bar{Q}^2$ MESONS

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I. Introduction

The aim of this paper is to investigate the $q^2\bar{q}^2$ meson spectrum in the frame work of the quark model which takes into account a nontrivial character of the QCD vacuum. Originally, four-quark states were considered by Jaffe et al. [1] on the basis of the MIT version of the bag model. From the results of this model it follows, in particular, that the scalar meson, S (980) and δ (980), are, most probably, $q^2\bar{q}^2$ states. That work has stimulated theoretical and experimental studies of multi-quark states ($q^m q^n$, $m+n>3$), which may possess quite exotic quantum numbers. So the data received by the groups JADE, TACCO, and CELLO [2,3,4,5] make one to believe that the resonances interpreted as $q^2\bar{q}^2$ mesons [16] are observed in $\gamma\gamma$-collisions. At the Serpukhov's accelerator the C-resonance of a mass ~ 1.5 GeV with exotic quantum numbers (I=1, $J^{PC}=1^{--}$) has been revealed in the $\varphi\pi^0$ system [7,8]. Being a 4-quark state, it must have a G-parity partner with I=0 [9]. Besides recently GAMS has reported on the $\eta\pi$-resonance of a mass ~1.4 GeV ($J^{PC}=1^{-+}$) which, it seems, is a G-partner of the C-resonance [10-12]. Further, in the vicinity of 3.1 GeV two groups [13,27] have observed several resonances with various electric charges and strangenesses, which possibly are the members of the same four-quark multiplet with orbital excitation of a diquark-antidiquark pair.

Along with extensive experimental search of multiquark states, theoretical studies within the various composite quark models [11,12,23,24], QCD sum rules [25,26], etc, are in progress. In these calculations attempts are made to obtain more accurate state characteristics, to use more reasonable assumptions and to estimate the role of certain effects. In this paper, we consider multi-quark states in the frame work of the quark model [16], in which the hadron characteristics are explicitly expressed via the QCD vacuum parameters.

The paper is organized as follows Sect.2 is devoted to basic assumptions of the model. The calculated results on the $q^2\bar{q}^2$ meson spectrum are presented in Sect.3, and in Sect.4 the conclusions are made.

2. Calculations on the QCD vacuum effects in the quark model

The QCD sum rules turned out to be extremely fruitful when describing various hadron properties. The results obtained by this technique point to an essential role of the quark-QCD vacuum field interaction.

In /16/ we formulated the quark model which was in qualitative agreement with the results of the QCD sum rules. For instance, the mass scale of hadrons, composed of light quarks, is determined by a quark condensate, while the interaction of quarks and vacuum fields substantially depends on hadron state quantum numbers. Within the model, the quark (ψ) and gluons (A_μ) fields are represented as sums of the valence fields q^{bag} , A_μ^{bag} , with characteristic frequencies $\omega \sim R^{-1}$ and vacuum fields Q^{vac}, A_μ^{vac} :

$$\begin{aligned} \psi &= q^{bag} + Q_{vac} \\ A_\mu &= A_\mu^{bag} + A_\mu^{vac}, \end{aligned} \qquad (I)$$

where q^{bag}, A_μ^{bag} are governed by the equality of the bag model /14,15/:

$$(\vec{\gamma}\vec{P} + m_i) q(\vec{r}) = \gamma_0 \varepsilon_i q(\vec{r}) \quad \text{in the bag} \qquad (2)$$
$$-\vec{\gamma}\vec{n}\, \psi(\vec{r})/_s = \psi(\vec{r})/_s \quad \text{on the bag surface .}$$

The quantities q^{vac}, A_μ^{vac} satisfy the QCD vacuum equations, their intensities being specified by the magnitudes of quark $<q^2>$ and gluon $< G^2 >$ condensates. The fields ψ , A_μ satisfy the total QCD equations. According to the basic assumption of the model, the QCD Lagrangian, as a result of the substitution (1), reduces to /16/:

$$\mathcal{L}^{QCD} = \mathcal{L}^{bag}_{QCD}(q^{bag}, A^{bag}) + \\ + \mathcal{L}_{int}(q^{bag}, A^{bag}; Q_{vac}, A_{vac}) + \mathcal{L}_{vac}(q^{vac}, A^{vac}), \qquad (3)$$

where $\mathcal{L}^{bag}$ is the bag model Lagrangian /14,15,17/ with $B_{bag} = 0$. It involves the boundary conditions imposed upon valence fields and perturbative quark-gluon interactions. So, the one-gluon exchange contribution to the hadron energy is determined by the expression /15/:

$$\Delta E_g = -\frac{\alpha_s}{4R} \sum_{i>j}^{N} \mu_{ij} < h | (\lambda^a \vec{\sigma})_i (\lambda^a \vec{\sigma})_j | h >, \qquad (4)$$

where N is the total number of quarks inside a hadron; $\vec{\sigma}_i$ (λ_i^a) are spin(color) operators of an i-th quark; μ_{ij} are interaction intensities; $| h >$ are states of the considered hadron. The Lagrangian $\mathcal{L}_{int}$ in (4) describes interactions of the bag fields and the vacuum ones. When applying the standard perturbation theory, we obtain the leading contribution to the energy of the quark-vacuum condensate interaction /16/:

$$\Delta E_{vac} = -\sum_{flav}^{u,d,s} N_a < \bar{q}_a q_a > R^2 b_a(m_a) + \dots , \qquad (5)$$

where summation is curried out over the flavour, $a = $ u,d,s; N_a is the number of quarks in a hadron; R is the bag radius; b_a are numerical coefficients. The interaction between quarks and long-wave vacuum fields dominates at distances of an order of the confinement radius ($R_0 \sim 1$ fm). At an intermediate distances ($\rho_c \sim 0.2 \div 0.3$ fm) the vacuum structure is characterised by high-frequency fluctuations approximated by instantons ($\omega_{inst} \sim 1/\rho_c \gg \omega_q$) /19,20/. The interactions via instantons are taken into consideration by t'Hooft's effective Lagrangian /18/, while the appropriate contribution to the energy /16/ is:

$$\Delta E_{inst} = - < h | H_{inst} | h > = \qquad (6)$$
$$= -\frac{4\pi^2}{3} \frac{\rho_c^2}{R^3} \sum_{a>b}^{u,d,s} I_{ab} < h | \left(\frac{2}{3} + \frac{1}{2} t_a t_b\right)\left(1 + \frac{3}{32} \lambda_a \lambda_b (1 + 3 \vec{\sigma}_a \vec{\sigma}_b\right) | h >,$$

where the coefficient of the sum is associated with the instanton density of the instanton liquid model /19/.

Thus, the hadron energy is composed of the quark kinetic energy determined by equations (2) and of the sum of interaction energies (4),(5),(6)

$$E(R) = \sum_i \varepsilon_i + \Delta E_{vac} + \Delta E_g + \Delta E_{inst} . \qquad (7)$$

The interaction with long-wave vacuum fields (5) induces dynamical stability of a bag at the bag constant equals to zero $B_{bag} = 0$ (the hypothesis on vacuum indestructibility inside a hadron):

$$\begin{cases} M^2 = E^2 - < P^2 > \\ \dfrac{d M^2}{d R^2} = 0 \end{cases} , \qquad (8)$$

Table I

State	c,s,f	ΔE_g $\mu\sim 15$ MeV	ΔE_{inst} $\rho\sim 40$ MeV	Example
$q\bar q$	1o, 1s, 8f	–16	-6ρ	π, η
	1c, 1s, 1f	–16	12ρ	η' $q^2\bar q^2$
	1c, 3s, 8f	$\frac{16}{3}$	0	ρ, ω
	1c, 3s, 1f	$\frac{16}{3}$	0	φ
	8c, 1s, 8f	2	$-3/8\rho$	
	8c, 1s, 1f	2	$3/4\rho$	$q^2\bar q^2$
	8c, 3s, 8f	–2/3	0	
	8c, 3s, 1f	–2/3	0	
qq	3c, 1s, 3f	–8	-3ρ	N
	3c, 3s, 6f	8/3	0	Δ $q^2\bar q^2$
	6c, 1s, 6f	4	0	
	6c, 3s, 3f	–4/3	0	

Table 2

The masses of $\eta\eta', \omega\varphi$ mesons and the expansion coefficients for the basis $SU_c(3)$ x $SU_s(2)$ x $SU_f(3)$

	m_{exp}	m_{theor}	8f	1f
η	550	525	0.952	0.307
η'	960	1200	–0.307	0.952
φ	I020	I070	–0.817	0.577
ω	783	760	0.577	0.817

where M is the hadron mass, $\langle P^2\rangle$ is the squared momentum of the quark mass center in a bag. The mass formula (8) has no parameters because the constants $\alpha_s, \rho_c, \langle\bar q q\rangle$ characterizing, various contributions have been chosen just as in the QCD sum rules /21,22/, $\alpha_s(\rho_c) = 0.7$, $\langle\bar q q\rangle = (-250\ \mathrm{MeV})^3$, and in the instanton liquid model /19/ $\rho_c = 2\ \mathrm{GeV}^{-1}$.

The model enables us not only to describe the mass spectra of the hadron ground states satisfactorily, but also to solve such known problems of the composite quark model as the problem of $\pi\rho$- and $\eta\eta'$ splitting (see Table I).

3. $Q^2\bar Q^2$ mesons

Pair forces acting within diquark (q^2) and quarkonium ($q\bar q$) systems occur due to the interaction via gluon exchange and instantons. In those channels, where instantons give attraction, compact quasibound systems arise (table 1). Just due to these effects π -mesons are lighter, than the ρ -meson while the Δ-N splitting is due to production of a light diquark (3_c , S=0, I=0) within a nucleon at the expense of the instanton interaction /16/. The stronger role of pair forces may be revealed in multi-quark systems where all the states presented in Table I are allowed. So, experimental and theoretical studies of such systems are extremely important for understanding the quark-vacuum field interactions.

In order to calculate the hadron spectrum within the quark model, we shall construct the state physical basis in which the hadron energy (7) is diagonal. The kinetic energy and the energy of interaction with a quark condensate depend on the quark masses ($m_u = m_d = 0$, $m_s = 0.2$ GeV), and so these contributions are diagonal in the basis of the states with a definite number of s -quarks (ideally mixed states, or an ideal basis). The quantity ΔE_{inst} in (7) is diagonal in the basis $SU_c(3)\times SU_s(2)\times SU_f(3)$ of the states with definite flavor - color - spin quantum numbers. When constructing the state physical basis for a four-quark system a situation occurs which is analogous, in many respects, to the one for system of the η, η' mesons. First these mesons have no definite number of s -quarks. Second, they do not enter into any irreducible representation of the flavor group but they are the mixture of the singlet 1_f and octet 8_f. The mesons are physical states, determined from the Hamiltonian diagonalisation (7). In Table 2, the results of this approach for $\eta\eta'$, ω, φ -mesons are presented.

In the MIT there are no reasons for occuring the basis, differing from the ideal one. So it is possible to classify particles with respect to the $SU_f(3)$-multiplets: 9f, 36f, 18f. As we shall see below, the general case the instanton interaction mixes irreducible representations of the $SU_f(3)$-group, and separation particles into flavour multiplets becomes meaningless.

3.1. Scalar $q^2\bar{q}^2$ mesons

A four-quark system may have three spin states: ($J^P = 0^+$, $1s$) ($J^P = 1^+$, 3_s) ($J^P = 2^+$, $5s$). Let us consider first scalar states. We shall construct the color – singlet, consistent with the Pauli principle, basis $q^2\bar{q}^2$ states with the combinations of diquark systems (Table 1):

$$\begin{aligned}
|1\rangle_{cs} &= |(6_c, 3_s, \bar{3}_f)(\bar{6}_c, 3_s, 3_f)\rangle = |(q^2)(\bar{q}^2)\rangle \\
|2\rangle_{cs} &= |(\bar{3}_c, 1_s, \bar{3}_f)(3_c, 1_s, 3_f)\rangle \\
|3\rangle_{cs} &= |(6_c, 1_s, 6_f)(\bar{6}_c, 1_s, \bar{6}_f)\rangle \\
|4\rangle_{cs} &= |(\bar{3}_c, 3_s, 6_f)(3_c, 3_s, \bar{6}_f)\rangle .
\end{aligned} \tag{9}$$

Separatly the total irreducible flavor representation

$$\begin{aligned}
3_f \times 3_f &= 9_f = 1_f(9) + 8_f(9) \\
6_f \times 6_f &= 36_f = 1_f(36) + 8_f(36) + 27_f
\end{aligned} \tag{IO}$$

for scalar $q^2\bar{q}^2$ mesons we obtain ten candidates for the basis states with a definite flavour:

$$\begin{aligned}
&|1\rangle_{cs}\, 1_f(9),\ |2\rangle_{cs}\, 1_f(9),\ |3\rangle_{cs}\, 1_f(36),\ |4\rangle_{cs}\, 1_f(36),\ |1_{cs}\rangle\, 8_f(36), \\
&|2\rangle_{cs}\, 8_f(9),\ |3\rangle_{cs}\, 8_f(36),\ |4\rangle_{cs}\, 8_f(36),\ |3\rangle_{cs}\, 27_f,\ |4\rangle_{cs}\, 27_f .
\end{aligned} \tag{11}$$

In this basis, we calculate the contributions of the instanton interaction (6). The kinetic energy and vacuum energy (5) are computed in the most simple way in the ideal basis which is connected with the basis (IO) by the well-known transformations /1/. Due to the connection between the basis, the instanton contribution may be rewrite in the ideal basis while the kinetic energy may be put down in the basis (IO). The physical states are defined by the requirement that the total energy (7) be diagonal. In Tables 3.1–13.1 present the results of decomposition of physical states over the ideal basis, in order to show how the mesons revealed by Jaffe /1/ are mixed.

Table 3.1

Masses of $q^2\bar{q}^2$ $0^+(J^P)$ mesons (I = 1) and the expansion ooeffioients for the ideal basis acoording to (9)

	m MeV	$c^S_\pi(9)$ $\|1\rangle_{cs}$	$c^S_\pi(9)$ $\|2\rangle_{cs}$	$c_\pi(36)$ $\|3\rangle_{cs}$	$c_\pi(36)$ $\|4\rangle_{cs}$	$c^S_\pi(36)$ $\|3\rangle_{cs}$	$c^S_\pi(36)$ $\|4\rangle_{cs}$
I.	II00	0.674	0.457	0.356	0.455	0.026	0.043
2.	1700	–0.222	0.746	–0.I52	–0.357	0.30I	0.391
3.	1700*	0.069	–0.121	0.787	–0.600	0.036	0.001
4.	1800	–0.615	0.373	0.361	0.3I0	–0.272	–0.428
5.	2050	0.026	–0.014	–0.033	0.009	0.8I0	–0.585
6.	1350	–0.336	–0.283	0.315	0.458	0.422	0.565

Table 3.2

The recouplings of $q^2\bar{q}^2$ $0^+(J^P)$ mesons (I=1) with the pair $(q\bar{q})(q\bar{q})$ mesons according to (12),(13)

	m	f \\ cs	$\|I\rangle_{cs}$	$\|II\rangle_{cs}$	$\|III\rangle_{cs}$	$\|IV\rangle_{cs}$
I	II00	$\|I\rangle_f$	–0.408	0.037	0.123	–0.388
		$\|II\rangle_f$	–0.453	0.029	0.090	–0.345
		$\|III\rangle_f$	0.373	0.121	0.219	–0.364
2	1700	$\|I\rangle_f$	0.184	–0.257	–0.159	–0.547
		$\|II\rangle_f$	–0.267	–0.398	–0.428	–0.I09
		$\|III\rangle_f$	–0.241	–0.005	–0.208	0.222
3	1700*	$\|I\rangle_f$	0.00I	0.080	0.053	0.033
		$\|II\rangle_f$	–0.021	0.045	0.066	0.059
		$\|III\rangle_f$	0.021	0.730	–0.651	–0.149
4	1800	$\|I\rangle_f$	0.00I	–0.358	–0.484	0.158
		$\|II\rangle_f$	0.461	–0.261	–0.167	–0.281
		$\|III\rangle_f$	0.302	0.166	0.115	–0.307
5	2050	$\|I\rangle_f$	0.016	0.537	–0.445	–0.116
		$\|II\rangle_f$	–0.037	–0.512	0.471	0.119
		$\|III\rangle_f$	–0.009	–0.026	0.016	0.013
6	1350	$\|I\rangle_f$	0.548	0.099	0.159	–0.I02
		$\|II\rangle_f$	–0.096	–0.093	–0.234	0.522
		$\|III\rangle_f$	0.358	0.091	0.233	–0.345

Table 4.1

Masses of $q^2\bar{q}^2$ $0^+(J^P)$ mesons (I=1/2) and the expansion coefficients for the ideal basis according to (9)

N°	m MeV	$C_k(9)$ $\|1\rangle_{cs}$	$C_k(9)$ $\|2\rangle_{cs}$	$C_k(36)$ $\|3\rangle_{cs}$	$C_k(36)$ $\|4\rangle_{cs}$	$C_k^S(36)$ $\|3\rangle_{cs}$	$C_k^S(56)$ $\|4\rangle_{cs}$
I	970	0.780	0.557	0.170	0.212	0.061	0.071
2	1550	–0.573	0.80I	0.007	0.068	–0.I03	–0.II9
3	1900	–0.016	0.023	0.788	–0.611	–0.062	–0.0I8
4	1400	–0.071	–0.214	0.485	0.663	–0.312	–0.420
5	2200	–0.019	0.006	0.040	–0.014	0.813	–0.580
6	2000	–0.241	–0.045	0.336	0.370	0.471	0.684

Table 4.2

The recouplings of $q^2\bar{q}^2$ $0^+(J^P)$ mesons (I=1/2) with the pair $(q\bar{q})(q\bar{q})$ mesons according to (12), (13)

	m	cs f	$\|I\rangle_{cs}$	$\|\overline{II}\rangle_{cs}$	$\|\overline{III}\rangle_{cs}$	$\|\overline{IV}\rangle_{cs}$
I	970	$\|V\rangle_f$	0.704	–0.005	0.091	0.450
		$\|VI\rangle_f$	–0.204	0.071	0.168	–0.458
		$\|VII\rangle_f$	0.060	0.022	0.033	–0.059
2	1550	$\|V\rangle_f$	–0.132	0.542	0.555	0.332
		$\|VI\rangle_f$	0.119	–0.330	–0.267	–0.228
		$\|VII\rangle_f$	–0.I02	–0.039	–0.054	0.I00
3	1900	$\|V\rangle_f$	0.004	0.383	–0.315	–0.062
		$\|VI\rangle_f$	0.016	0.626	–0.580	–0.131
		$\|VII\rangle_f$	–0.034	–0.039	0.006	0.038
4	1400	$\|V\rangle_f$	0.168	0.008	0.119	–0.405
		$\|VI\rangle_f$	0.514	0.170	0.311	–0.359
		$\|VII\rangle_f$	–0.338	–0.099	–0.207	0.328
5	2200	$\|V\rangle_f$	–0.006	0.026	–0.000	–0.008
		$\|VI\rangle_f$	0.014	0.022	–0.025	–0.012
		$\|VII\rangle_f$	0.042	0.743	–0.645	–0.170
6	2000	$\|V\rangle_f$	0.002	0.131	0.171	–0.247
		$\|VI\rangle_f$	0.371	0.075	0.092	–0.226
		$\|VII\rangle_f$	0.535	0.136	0.347	–0.515

Table 5.1

Masses of q^2q^2 $0^+(J^P)$ mesons (I=0) and the expansion coefficients for the ideal basis according to (9)

m MeV	$C^0(9)$ $\|1\rangle_{cs}$	$C^0(9)$ $\|2\rangle_{cs}$	$C^0(36)$ $\|3\rangle_{cs}$	$C^0(36)$ $\|4\rangle_{cs}$	$C^S(9)$ $\|1\rangle_{cs}$	$C^S(9)$ $\|2\rangle_{cs}$	$C^S(36)$ $\|3\rangle_{cs}$	$C^S(56)$ $\|4\rangle_{cs}$	$C^{SS}(36)$ $\|3\rangle_{cs}$	$C^{SS}(56)$ $\|4\rangle_{cs}$
800	0.754	0.535	–0.228	–0.267	–0.041	–0.021	0.043	0.129	0.018	0.029
1350	–0.537	0.818	0.088	–0.021	0.123	0.086	0.020	–0.087	–0.027	–0.057
1700	0.162	0.021	0.898	–0.098	–0.029	0.149	0.224	0.291	–0.004	–0.005
1600	0.059	0.130	–0.I08	0.795	0.080	–0.067	0.065	0.550	–0.049	0.126
1140	–0.025	–0.149	–0.202	–0.215	0.720	0.493	0.164	0.264	–0.120	–0.130
1700*	0.043	0.0I8	–0.088	0.179	–0.480	0.842	–0.091	–0.I00	0.027	0.003
1950	0.152	0.0II	–0.016	0.306	0.068	–0.015	0.737	–0.492	0.026	–0.302
2I00	–0.224	–0.043	–0.192	–0.247	–0.184	0.009	0.535	0.216	0.369	0.589
2350	–0.042	–0.004	–0.036	–0.007	–0.021	–0.021	–0.093	0.215	0.808	–0.537
2600	0.191	0.044	0.190	0.230	0.434	0.114	–0.264	–0.417	0.438	0.486

Table 5.2

The recouplings of q^2q^2 $0^+(J^P)$ mesons (I=0) with the pair $(q\bar q)(q\bar q)$ mesons according to (12),(13)

m	cs / f	$\|I\rangle_{cs}$	$\|II\rangle_{cs}$	$\|III\rangle_{cs}$	$\|IV\rangle_{cs}$	m	$\|I\rangle_{cs}$	$\|II\rangle_{cs}$	$\|III\rangle_{cs}$	$\|IV\rangle_{cs}$
	$\|VIII\rangle_f$	0.709	0.007	-0.075	0.405		0.004	0.050	-0.088	0.036
	$\|IX\rangle_f$	0.147	-0.093	-0.186	0.491		0.064	-0.103	0.125	-0.013
800	$\|X\rangle_f$	0.033	-0.000	0.064	-0.071	1700*	-0.129	0.411	0.381	0.384
	$\|XI\rangle_f$	-0.083	0.009	-0.047	0.034		-0.005	0.461	0.444	0.262
	$\|XII\rangle_f$	0.022	0.004	0.016	-0.021		0.013	0.018	-0.006	-0.015
	$\|VIII\rangle_f$	-0.137	0.510	0.542	0.385		0.023	0.001	-0.173	0.103
	$\|IX\rangle_f$	-0.050	0.373	0.266	0.181		0.183	-0.115	0.156	-0.076
1350	$\|X\rangle_f$	0.054	0.023	-0.066	0.086	1950	0.069	0.444	-0.425	-0.112
	$\|XI\rangle_f$	0.104	-0.032	0.029	0.050		-0.008	0.494	0.368	0.125
	$\|XII\rangle_f$	-0.040	-0.003	-0.032	0.037		-0.140	0.106	-0.221	0.110
	$\|VIII\rangle_f$	-0.054	-0.380	0.101	0.258		-0.047	0.093	0.142	-0.181
	$\|IX\rangle_f$	0.335	0.546	-0.320	-0.323		-0.260	-0.021	-0.056	0.123
1700	$\|X\rangle_f$	0.184	0.114	0.153	-0.095	2100	0.140	0.280	0.067	-0.284
	$\|XI\rangle_f$	-0.152	0.008	-0.047	0.232		-0.321	-0.167	0.069	0.218
	$\|XII\rangle_f$	-0.004	-0.001	-0.002	0.004		0.445	0.091	0.310	-0.425
	$\|VIII\rangle_f$	-0.108	0.188	-0.276	0.229		-0.018	0.025	0.014	-0.023
	$\|IX\rangle_f$	0.346	-0.244	0.526	-0.180		-0.031	-0.013	0.015	0.011
1600	$\|X\rangle_f$	0.240	-0.127	0.214	-0.199	2350	0.035	-0.092	0.128	-0.044
	$\|XI\rangle_f$	-0.187	0.033	-0.309	0.165		-0.064	0.089	-0.125	0.015
	$\|XII\rangle_f$	0.043	-0.071	0.104	-0.027		0.061	0.725	-0.613	-0.185
	$\|VIII\rangle_f$	0.042	-0.015	0.005	-0.192		0.032	-0.083	-0.121	0.169
	$\|IX\rangle_f$	-0.195	-0.102	-0.105	0.107		0.241	0.031	0.054	-0.120
1140	$\|X\rangle_f$	0.602	-0.005	-0.014	0.259	2600	0.017	-0.132	-0.275	0.359
	$\|XI\rangle_f$	0.320	-0.052	-0.211	0.528		0.464	-0.038	0.034	-0.068
	$\|XII\rangle_f$	-0.114	-0.047	-0.058	0.113		0.422	0.169	0.217	-0.417

Table 6.1

Masses of $q^2\bar q^2$ $0^+(J^P)$ exotic mesons and the expansion coefficients for the basic $SU_c(3)\times SU_s(2)\times SU_f(3)$ according to (9)

		27_f $\|3\rangle_{cs}$	27_f $\|4\rangle_{cs}$
27f $\|3\rangle'$	$E_{\pi\pi}$ m=1100, $E_{\pi K}$ M=1250, $E_{\pi K}$ M=1450	0.594	0.804
27f $\|4\rangle'$	$E_{\pi\pi}$ m=1700, $E_{\pi K}$ M=1850, $E_{\pi K}$ M=2050	0.804	-0.594

Table 6.2

The recouplings of $q^2\bar q^2$ $0^+(J^P)$ exotic mesons with the pair $(q\bar q)(q\bar q)$ mesons according to (12)

		$\|I\rangle_{cs}$	$\|II\rangle_{cs}$	$\|III\rangle_{cs}$	$\|IV\rangle_{cs}$
27f	$E_{\pi\pi}$, $E_{\pi K}$, E_{KK}	0.031	0.740	-0.652	-0.160
27f	$E_{\pi\pi}$, $E_{\pi K}$, E_{KK}	0.645	0.187	0.397	-0.625

Table 7.1

Masses of $q^2\bar q^2$ $1^+(J^P)$ mesons ($I = 1/2, 18_f$) and the expansion coefficients for the ideal basis according to (14)

m	$c_{\bar K}(\bar{18})$ $c_K(18)$ $\|1\rangle_{cs}$	$c_{\bar K}(\bar{18})$ $c_K(18)$ $\|2\rangle_{cs}$	$c_{\bar K}(18)$ $c_K(\bar{18})$ $\|3\rangle_{cs}$	$c_{\bar K}(18)$ $c_K(\bar{18})$ $\|4\rangle_{cs}$	$c^s_{\bar K}(18)$ $c^s_K(\bar{18})$ $\|3\rangle_{cs}$	$c^s_{\bar K}(18)$ $c^s_K(\bar{18})$ $\|4\rangle_{cs}$
1760	0.669	0.468	-0.387	-0.270	0.228	-0.242
1550	-0.375	0.721	0.216	-0.416	-0.241	0.250
1740	0.397	0.304	0.688	0.526	0.000	0.000
1400	-0.304	0.397	-0.526	0.688	-0.000	0.000
2100	-0.132	0.038	0.076	-0.022	0.883	0.442
1900	0.379	-0.101	-0.219	0.058	-0.333	0.827

Table 7.2

The recouplings of $q^2\bar{q}^2$ $0^+(J)$ mesons (I=1/2,18f) with the pair $(q\bar{q})(q\bar{q})$ mesons according to (16),(13)

m, MeV	cs f	$\|I\rangle_{cs}$	$\|II\rangle_{cs}$	$\|III\rangle_{cs}$	$\|IV\rangle_{cs}$
1760	$\|V\rangle_f$	–0.578	0.003	–0.000	0.000
	$\|VI\rangle_f$	0.333	–0.002	–0.628	0.226
	$\|VII\rangle_f$	0.033	–0.233	–0.047	–0.230
1550	$\|V\rangle_f$	–0.078	–0.569	–0.000	0.000
	$\|VI\rangle_f$	0.045	0.328	–0.304	–0.589
	$\|VII\rangle_f$	–0.037	0.242	0.046	0.241
1740	$\|V\rangle_f$	0.353	0.013	0.675	–0.210
	$\|VI\rangle_f$	0.612	0.023	–0.000	–0.000
	$\|VIII\rangle_f$	0.000	–0.000	0.000	–0.000
1400	$\|V\rangle_f$	–0.013	0.353	0.210	0.675
	$\|VI\rangle_f$	–0.023	0.612	–0.000	–0.000
	$\|VII\rangle_f$	–0.000	0.000	0.000	0.000
2100	$\|V\rangle_f$	0.061	–0.076	–0.000	0.000
	$\|VI\rangle_f$	–0.035	0.044	0.037	–0.106
	$\|VII\rangle_f$	0.690	–0.105	0.616	–0.329
1900	$\|V\rangle_f$	–0.178	0.213	0.000	–0.000
	$\|VI\rangle_f$	0.103	–0.123	–0.111	0.301
	$\|VII\rangle_f$	0.145	0.613	0.341	0.530

To analyse the decay properties of the $q^2\bar{q}^2$ mesons, the basis composed of the meson pairs $(q\bar{q})(q\bar{q})$ must also be considered. In Table 3.2–6.2 the expansion coefficients of the physical states in the basis states of mesons pairs $|(q\bar{q})(q\bar{q})\rangle$ are listed. The following color – spin basis is possible:

$$
\begin{aligned}
|I\rangle_{cs} &= |(1_c, 1_s)(1_c\, 1_s)\rangle = |(q\bar{q})(q\bar{q})\rangle\\
|II\rangle_{cs} &= |(1_c, 3_s)(1_c\, 3_s)\rangle\\
|III\rangle_{cs} &= |(8_c, 1_s)(8_c\, 1_s)\rangle\\
|IV\rangle_{cs} &= |(8_c, 3_s)(8_c\, 3_s)\rangle\ .
\end{aligned}
\qquad (12)
$$

For exotic mesons their masses (Table 6.1) as well as the decomposition in the basis (12) (Table 6.2) practically coincide with the results of /1/. For the rest of mesons $0^+(J)$ one must extend the determination of the basis (12) to the flavor decomposition:

$$
\begin{aligned}
|I\rangle_f &= (K\bar{K})^{I=1} & |VIII\rangle_f &= (\pi\pi)^{I=0}\\
|II\rangle_f &= (\pi\eta_s)^{I=1} & |IX\rangle_f &= (\eta_0\eta_0)^{I=0}\\
|III\rangle_f &= (\pi\eta_0)^{I=1} & |X\rangle_f &= (K\bar{K})^{I=0}\\
|IV\rangle_f &= (\pi\pi)^{I=1} & |XI\rangle_f &= (\eta_0\eta_s)^{I=0}\\
|V\rangle_f &= (K\pi)^{I=1/2} & |XII\rangle_f &= (\eta_s\eta_s)^{I=0}\\
|VI\rangle_f &= (K\eta_0)^{I=1/2} & \eta_0 &= \frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d})\\
|VII\rangle_f &= (K\eta_s)^{I=1/2} & \eta_s &= s\bar{s}\ .
\end{aligned}
\qquad (13)
$$

Expressions (12),(13) form, in general, bases states of the $(q\bar{q})(q\bar{q})$ meson pairs with a definite flavor . As is seen from the presented data, we have isolated the $0^+(J^P)$ mesons (exceptions are exotic mesons) with isospins I=1,1/2,0.

3.2. Vector $q^2\bar{q}^2$ mesons

Analogous results are obtained for the $q^2\bar{q}^2$ $1^+(J^P)$ mesons (Tables 7-11) . The basis for the vector mesons consistent with the Pauli principle and composed of diquark systems (Table 1) is as follows:

$$
\begin{aligned}
|1\rangle_{cs} &= |(6_c, 1_s, 6_f)(\bar{6}_c, 3_s, 3_f)\rangle = |(qq)(\bar{q}\bar{q})\rangle\\
|2\rangle_{cs} &= |(\bar{3}_c, 3_s, 6_f)(3_c, 1_s, 3_f)\rangle\\
|3\rangle_{cs} &= |(6_c, 3_s, \bar{3}_f)(\bar{6}_c, 1_s, \bar{6}_f)\rangle\\
|4\rangle_{cs} &= |(\bar{3}_c, 1_s, \bar{3}_f)(3_c, 3_s, \bar{6}_f)\rangle\\
|5\rangle_{cs} &= |(6_c, 3_s, \bar{3}_f)(\bar{6}_c, 3_s, 3_f)\rangle\\
|6\rangle_{cs} &= |(\bar{3}_c, 3_s, 6_f)(3_c, 3_s, \bar{6}_f)\rangle\ .
\end{aligned}
\qquad (14)
$$

Combining it with the total irreducible SU (3) representations

$$
\begin{aligned}
6_f \times 3_f &= 18_f = 8_f + 10_f\\
\bar{6}_f \times \bar{3}_f &= \overline{18}_f = \bar{8}_f + \overline{10}_f\\
\bar{3}_f \times 3_f &= 9_f = 1_f + 8_f\\
6_f \times \bar{6}_f &= 36_f = 1_f + 8_f + 27_f
\end{aligned}
\qquad (15)
$$

we obtains for vector mesons 13 basis states with a definite flavor.

Table 8.I

Masses of $q^2\bar{q}^2$ $1^+(J^P)$ meson ($I = 1, 18_f, \overline{18}_f$) and the expansion coefficients for the ideal basis according to (14)

m	$c_\pi(18)$ $\vert 1\rangle_{cs}$	$c_\pi(18)$ $\vert 2\rangle_{cs}$	$c_\pi(\overline{18})$ $\vert 3\rangle_{cs}$	$c_\pi(\overline{18})$ $\vert 4\rangle_{cs}$	$c^s_\pi(18)$ $\vert 1\rangle_{cs}$	$c^s_\pi(18)$ $\vert 2\rangle_{cs}$	$c^s_\pi(\overline{18})$ $\vert 3\rangle_{cs}$	$c^s_\pi(\overline{18})$ $\vert 4\rangle_{cs}$
1550	0.561	0.429	0.562	0.430	0.000	0.000	-0.000	0.000
1200	-0.430	0.562	-0.430	0.561	0.000	-0.00I	0.00I	-0.00I
1600	-0.560	-0.374	0.558	0.373	0.153	-0.158	-0.153	0.157
1350	0.304	-0.594	-0.304	0.594	-0.164	0.168	0.163	-0.168
1950	0.I02	-0.030	-0.I02	0.030	0.626	0.318	-0.621	-0.314
1750	-0.291	0.086	0.291	-0.086	-0.247	0.589	0.247	-0.589
1900	-0.000	0.000	0.000	-0.000	0.559	0.428	0.564	0.432
1570	-0.00I	0.00I	-0.00I	0.00I	-0.430	0.561	-0.430	0.561

Table 8.2

The recouplings of $q^2\bar{q}^2$ $0^+(J^P)$ mesons (I=1,18f) with the pair $(q\bar{q})$ $(q\bar{q})$ mesons according to (16),(13)

m MeV	cs f	$\vert I\rangle_{cs}$	$\vert II\rangle_{cs}$	$\vert III\rangle_{cs}$	$\vert IV\rangle_{cs}$	m	$\vert I\rangle_{cs}$	$\vert II\rangle_{cs}$	$\vert III\rangle_{cs}$	$\vert IV\rangle_{cs}$
	III	0.707	0.027	0.00I	-0.000		-0.000	0.000	-0.034	0.I00
1550	IV	0.00I	-0.000	0.675	-0.2I0	1950	-0.066	0.083	0.000	0.000
	I	-0.000	0.000	-0.000	-0.000		-0.692	0.I02	0.003	-0.00I
	II	-0.000	-0.000	0.000	0.000		0.003	0.000	-0.618	0.327
	III	-0.027	0.707	-0.000	-0.000		0.000	-0.000	-0.098	-0.287
	VI	-0.000	-0.000	-0.2I0	0.675		0.188	-0.238	-0.000	-0.000
1200	I	0.000	0.000	-0.00I	-0.00I	1750	-0.138	-0.624	0.000	-0.000
	II	-0.000	-0.002	0.000	-0.000		0.000	-0.000	-0.338	-0.542
	III	-0.00I	0.000	0.628	-0.241		0.000	0.000	-0.000	-0.000
	VI	0.672	-0.018	-0.00I	0.000		-0.000	-0.000	-0.000	0.000
1600	I	-0.034	0.217	0.000	-0.000	1900	0.003	-0.000	0.675	-0.2I0
	II	0.000	-0.000	0.040	0.216		0.707	0.027	0.003	-0.00I
	I	-0.000	0.000	0.309	0.591		0.000	0.002	0.000	-0.000
	VI	0.094	0.660	0.000	0.000		0.000	-0.000	0.00I	0.00I
1350	I	0.036	-0.232	0.000	0.000	1570	0.000	-0.000	0.2I0	0.675
	II	-0.000	0.000	-0.043	-0.230		-0.027	0.707	0.000	-0.000

Table 9.I

Masses of $q^2\bar{q}^2$ $1^+(J^P)$ mesons (I=0,18f) and the expansion coefficients for the ideal basis according to (14)

m MeV	$c^s(8)$ $\vert 1\rangle_{cs}$	$c^s(8)$ $\vert 2\rangle_{cs}$	$c^s(\bar{8})$ $\vert 3\rangle_{cs}$	$c^s(\bar{8})$ $\vert 4\rangle_{cs}$
2000	0.704	0.071	-0.703	-0.070
1550	-0.430	0.561	-0.430	0.561
1900	0.561	0.430	0.562	0.430
1800	0.071	-0.704	-0.071	0.704

Table 9.2

The recouplings of $q^2\bar{q}^2$ $1^+(J^P)$ mesons (I=0) with the pair $(q\bar{q})(q\bar{q})$ mesons according to (16),(13)

m MeV	cs f	$\vert I\rangle_{cs}$	$\vert II\rangle_{cs}$	$\vert III\rangle_{cs}$	$\vert IV\rangle_{cs}$
	$\vert XI\rangle_f$	0.000	0.000	-0.464	0.534
2000	$\vert X\rangle_f$	-0.615	0.348	0.000	-0.000
1550	$\vert XI\rangle_f$	-0.027	0.707	0.000	0.000
	$\vert X\rangle_f$	0.000	0.000	0.2I0	0.675
1900	$\vert XI\rangle_f$	0.707	0.027	0.000	-0.000
	$\vert X\rangle_f$	0.00I	-0.000	0.675	-0.2I0
I800	$\vert XI\rangle_f$	-0.000	-0.000	0.534	0.464
	$\vert X\rangle_f$	0.348	0.615	-0.000	-0.000

Table IO.I

Masses $q^2\bar{q}^2$ $1^+(J^P)$ mesons (I=0) and the expansion coefficients for the ideal basis according to (14)

m MeV	$c^0(9)$ $\vert 5\rangle_{cs}$	$c^0(36)$ $\vert 6\rangle_{cs}$	$c^s(9)$ $\vert 5\rangle_{cs}$	$c^s(36)$ $\vert 6\rangle_{cs}$	$c^{ss}(36)$ $\vert 6\rangle_{cs}$
1250	0.931	-0.351	-0.099	0.022	0.014
1600	0.226	0.772	-0.582	0.060	0.I03
1700	0.181	0.352	0.608	0.689	-0.005
2000	-0.218	-0.389	-0.467	0.670	0.365
2400	0.048	0.075	0.254	-0.268	0.925

Table I0.2

The recouplings of $q^2\bar{q}^2$ $1^+(J^P)$ mesons (I=0) with the pair $(q\bar{q})(q\bar{q})$ mesons according to (16),(13)

m	1250		1600		1700		2000		2400	
f \ cs	$\vert\bar{V}\rangle_{cs}$	$\vert\bar{VI}\rangle_{cs}$	$\vert\bar{V}\rangle_{cs}$	$\vert\bar{VI}\rangle_{cs}$	$\vert\bar{V}\rangle_{cs}$	$\vert\bar{VI}\rangle_{cs}$	$\vert\bar{V}\rangle_{cs}$	$\vert\bar{VI}\rangle_{cs}$	$\vert\bar{V}\rangle_{cs}$	$\vert\bar{VI}\rangle_{cs}$
VIII	-0.322	0.759	-0.428	-0.063	-0.234	0.026	0.268	-0.042	-0.055	0.012
IX	-0.517	0.205	0.481	0.478	0.196	0.250	-0.212	-0.284	0.039	0.057
X	0.054	-0.048	0.272	-0. 311	0.150	0.632	0.578	0.004	-0.259	0.037
XI	0.028	-0.067	0.203	-0.360	-0.646	0.070	-0.196	-0.543	0.051	0.256
XII	0.0II	0.008	0.084	0.059	-0.004	-0.003	0.298	0.211	0.755	0.534

Table 11.1

Masses of $q^2\bar{q}^2$ $1^+(J^P)$ mesons (I=1) and the expansion coefficients for the ideal basis according to (14)

m (MeV)	$c_\pi(36)$ $\vert 6\rangle_{cs}$	$c^{\xi}_{\pi}(36)$ $\vert 6\rangle_{cs}$	$c^{s}_{\pi}(9)$ $\vert 5\rangle_{cs}$
1500	0.863	0.132	0.488
1850	-0.309	0.902	0.302
1650	-0.40I	-0.412	0.819

Table 12.1

Masses of $q^2\bar{q}^2$ $1^+(J^P)$ mesons (I=1/2) and the expansion coefficients for the ideal basis according to (14)

m (MeV)	$c_K(9)$ $\vert 5\rangle_{cs}$	$c_K(36)$ $\vert 6\rangle_{cs}$	$c^{s}_{K}(36)$ $\vert 6\rangle_{cs}$
1400	0.968	0.243	0.065
1700	-0.213	0.928	-0.304
2050	-0.134	0.281	0.950

Table 11.2

The recouplings of $q^2\bar{q}^2$ $1^+(J^P)$ mesns (I=1) with the pair $(q\bar{q})(q\bar{q})$ mesons according to (16),(13)

m	f \ cs	$\vert\bar{V}\rangle_{cs}$	$\vert\bar{VI}\rangle_{cs}$
1500	$\vert III\rangle_f$	-0.498	0.704
	$\vert I\rangle_f$	-0.206	-0.146
	$\vert II\rangle_f$	-0.358	-0.253
1850	$\vert III\rangle_f$	0.178	-0.252
	$\vert I\rangle_f$	0.346	0.245
	$\vert II\rangle_f$	-0.695	-0.492
1650	$\vert III\rangle_f$	0.231	-0.327
	$\vert I\rangle_f$	-0.710	-0.502
	$\vert II\rangle_f$	-0.235	-0.166

Table 12.2

The recouplings of $q^2\bar{q}^2$ $1^+(J^P)$ mesons (I=1/2) with the pair $(q\bar{q})(q\bar{q})$ mesons according to (16),(13)

m	f \ cs	$\vert\bar{V}\rangle_{cs}$	$\vert\bar{VI}\rangle_{cs}$
1400	$\vert V\rangle_f$	-0.384	0.754
	$\vert VI\rangle_f$	0.451	-0.273
	$\vert VII\rangle_f$	0.053	0.037
1700	$\vert V\rangle_f$	0.486	0.117
	$\vert VI\rangle_f$	0.595	0.551
	$\vert VII\rangle_f$	-0.248	-0.176
2050	$\vert V\rangle_f$	0.182	-0.014
	$\vert VI\rangle_f$	0.160	0.195
	$\vert VII\rangle_f$	0.776	0.549

Table 13

Masses of $q^2\bar{q}^2$ $1^+(J)$ exotic mesons $(18f,\overline{18f})$, the expansion coefficients for the basis (14) and recouplings with the pair $(q\bar{q})(q\bar{q})$ mesons according to (16)

		$10_f(\overline{10}_f)$	$10_f(\overline{10}_f)$	$(q\bar{q})(q\bar{q})$			
		$\vert 3\rangle_{cs}$	$\vert 4\rangle_{cs}$	$\vert I\rangle_{cs}$	$\vert\bar{II}\rangle_{cs}$	$\vert\bar{III}\rangle_{cs}$	$\vert\bar{IV}\rangle_{cs}$
$E_{\bar{K}\bar{K}}$, m=1900	$E^{*}_{\pi K}$, m=1750	0.794	0.608	0.707	0.027	-0.675	0.21
$E_{\bar{K}\bar{K}}$, m=1550	$E_{\pi K}$, m=1400	-0.608	0.794	-0.027	0.707	-0.21	-0.675
E_{KK}, m=1900	$E^{*}_{\pi\bar{K}}$, m=1750	0.794	0.608	0.707	0.027	0.675	-0.21
E_{KK}, m=1550	$E_{\pi\bar{K}}$, m=1400	-0.608	0.794	-0.027	0.707	0.21	0.675

Table 14

Masses of exotic mesons $1^+(J^P)$, 36f and the expansion according to (14)

	27f $\vert 5\rangle_{cs}$	27f $\vert 6\rangle_{cs}$
$E_{\pi\pi}$, m = 1400; $E_{\pi K}$, m=1600; E_{KK}, m = 1750	0.816	0.577

Table 15

Masses of $q^2\bar{q}^2$ $2^+(J^P)$ mesons

36f	C^0, C_π, $E_{\pi\pi}$	1650
	C_K, $E_{\pi K}$	1800
	C^s, C^s_π, E_{KK}	2000
	C^s_K	2150
	C^{ss}	2300
9f	C^0	1650
	C_K	1800
	C^s, C^s_π	2000

Instanton interactions in bases (14),(15) lead to mixing of the 18- and $\overline{18}_f$- plets (Tables 7,8,9) and 9f - and 36_f-plets (Tables 10, 11,12). The coefficients of transition from to $q^2\bar{q}^2$ $1^+(J^P)$ physical states to the basis states of the mesons pairs $(q\bar{q})$ $(q\bar{q})$

$$\begin{aligned}
|I\rangle_{cs} &= |(1_c, 3_s)(1_c, 3_s)\rangle = |(q\bar{q})(q\bar{q})\rangle \\
|II\rangle_{cs} &= |(8_c, 3_s)(8_c, 3_s)\rangle \\
|III\rangle_{cs} &= \frac{1}{\sqrt{2}}\left(|(8_c\, 3_s)(8_c\, 1_s)\rangle - |(8_c\, 1_s)(8_c\, 3_s)\rangle\right) \\
|IV\rangle_{cs} &= \frac{1}{\sqrt{2}}\left(|(1_c\, 3_s)(1_c\, 1_s)\rangle - |(1_c\, 1_s)(1_c\, 3_s)\rangle\right) \\
|V\rangle_{cs} &= \frac{1}{\sqrt{2}}\left(|(8_c\, 3_s)(8_c\, 1_s)\rangle - |(8_c\, 1_s)(8_c\, 3_s)\rangle\right) \\
|VI\rangle_{cs} &= \frac{1}{\sqrt{2}}\left(|(1_c\, 3_s)(1_c\, 1_s)\rangle - |(1_c\, 1_s)(1_c\, 3_s)\rangle\right)
\end{aligned} \tag{16}$$

are reported in Tables 7.2-12.2.

3.3. Tensor $q^2\bar{q}^2$ mesons

The instanton contributions for tensor mesons equal zero. So, the results (Table 15) practically coincide with those obtained in the MIT-model /1/.

4. Conclusions

The quark-vacuum condensate interaction energy (5) depends on the number of quarks inside a hadron while in the MIT version the term proportional to R^3 does not depend on N_q. This leads to a faster growth of the characteristic mass scale with increasing N. As a result, our $q^2\bar{q}^2$ meson mass spectrum, as a whole, lies higher than in the MIT-model /1/. For several states high masses are associated with the fact that the strong coupling α_s in our model is one third of that in the MIT-version. So, the negative contributions in ΔE_g (4) reduce meson masses less than in the MIT-version.

Taking into account of the instanton contribution changes the total pair interaction strength in many channels (Table 1) while in particular two channels ($1_c\, 1_s\, 8_f$ and $8_c\, 1_s\, 8_f$) the sign is also changed. As a result, a number of consequences arise. First, the spectrum dependence on the flavor representation of the quark system occurs, forcing us to refuse the ideal bases as a physical one (η, η' mesons, $q^2\bar{q}^2$ $0^+, 1^+(J^P)$ mesons). Second, a number of states degenerated in mass have been splitted. Third, rather a high degree of mixing for scalar and vector mesons does not allow us to classify them over the $SU_f(3)$ multiplets. Fourth, taking into account the instanton interaction changes the decay properties of the four-quark states. In particular, if the isoscalar to f_0(975) (it was S^*(975)) 0^{++} meson is interpreted as a $q^2\bar{q}^2$ meson /1/ (Table 5.1, 5.2, m = 1140 MeV), then, along with $K\bar{K}$, $\eta\eta$ channels /1/, the non-zero coupling with the $\pi\pi$ channel will arise.

Thus, we see a number of the experimentally testable consequences of nonperturbative QCD effects in multiquark hadrons.

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