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Regarding the scalar mesons

Yun-Hu Liu,[1,*] De-Min Li,[2] Jian-Xin Shao,[1] Xiao-Gang Wang,[1] and Zi-Ying Zhang[1]

[1]*Key Laboratory of Ecophysics and Department of Physics, Teachers College, Shihezi University, Shihezi Xinjiang 832003, People's Republic of China*

[2]*Department of Physics, Zhengzhou University, Zhengzhou Henan 450052, People's Republic of China*

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Based on the main assumption that the $D_{sJ}(2860)$ belongs to the 2^3P_0 $q\bar{q}$ multiplet, the masses of the scalar meson nonet are estimated in the framework of the relativistic independent quark model, Regge phenomenology, and meson-meson mixing. We suggest that the $a_0(1005)$, $K_0{}^*(1062)$, $f_0(1103)$, and $f_0(564)$ constitute the ground scalar meson nonet; it is supposed that these states would likely correspond to the observed states $a_0(980)$, $\kappa(900)$, $f_0(980)$, and $f_0(600)/\sigma$, respectively. Also $a_0(1516)$, $K_0{}^*(1669)$, $f_0(1788)$, and $f_0(1284)$ constitute the first radial scalar meson nonet, it is supposed that these states would likely correspond to the observed states $a_0(1450)$, $K_0{}^*(1430)$, $f_0(1710)$, and $f_0(1370)$, respectively. The scalar state $f_0(1500)$ may be a good candidate for the ground scalar glueball. The agreement between the present findings and those given by other different approaches is satisfactory.

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I. INTRODUCTION

In a recent issue of Review of Particle Physics [1], too many light scalar states in the region below 2 GeV are claimed to exist experimentally: two isovectors $a_0(980)$ and $a_0(1450)$; five isoscalars $f_0(600)/\sigma$, $f_0(980)$, $f_0(1370)$, $f_0(1500)$, and $f_0(1710)$; and three isodoublets $K_0^*(1430)$, $K_0^*(1950)$, and $K_0^*(800)/\kappa$. Though some papers have discussed the possible members of the ground scalar meson nonet, the identification of the scalar mesons is ever a long-standing puzzle. The following reasons are the main difficulties to resolve these problems. First, scalar resonances are difficult to resolve because of their large decay widths which cause a strong overlap between resonances and background, and also because several decay channels open up with a short mass interval. In addition, the $\bar{K}K$ and $\eta\eta$ thresholds produce sharp cusps in the energy dependence of the resonant amplitude. Furthermore, one expects non-$\bar{q}q$ scalar objects, like glueballs and multiquark states in the mass range below 1800 MeV. The meson nonets of 1^3P_1 and 1^3P_2, $c\bar{c}$ and $b\bar{b}$ states of 1^3P_0, 1^3P_1, and 1^3P_2 and $b\bar{b}$ state of 2^3P_0, 2^3P_1, and 2^3P_2 have established well [1], these states maybe open a new window to reveal the nature of the scalar states.

II. PHENOMENOLOGICAL MASS FORMULA FOR ISOVECTOR $q\bar{q}'$-MESONS

In the framework of the relativistic independent quark model, a mass formula for $q\bar{q}'$-mesons has a structure which differs from structures of mass formula in other types of potential models. The following mass formula has been considered in Ref. [2],

$$M(n^{2s+1}L_J) = E_1(n_1^r, j_1, c, x) + E_2(n_2^r, j_2, c, x), \tag{1}$$

where the mass terms (mass or energy spectral functions) $E_i(n_i^r, j_i, c, x)$ $(i = 1, 2)$ for a quark and an antiquark are defined as

$$E(n^r, j, c, x) = \begin{cases} c + x\sqrt{2n^r + L + j - \frac{1}{2}}, & \text{for } L + j - \frac{1}{2} = 2k, k = 0, 1, 2, \cdots, \\ x\sqrt{2n^r + L + j - \frac{1}{2}}, & \text{for } L + j - \frac{1}{2} = 2k + 1, k = 0, 1, 2, \cdots. \end{cases} \tag{2}$$

In order to exclude superfluous meson states, the following selection rules for $q\bar{q}'$-mesons with given J^{PC} values, quark masses m_1 and m_2, and quantum numbers j_1 and j_2 are used

$$j_1 = j_2 = J + \tfrac{1}{2}, \quad \text{if } J = L + S;$$
$$j_1 = j_2 + 1 = J + \tfrac{3}{2}, \quad \text{if } J \neq L + S, \qquad m_1 \leq m_2, \tag{3}$$

while the radial quantum numbers $n_1^r = n_2^r = n - 1$ for the $n^{2S+1}L_J$-state. The values of two parameters c and x can be obtained by fitting the mass values of experimentally observed meson states. From relations (1) and (2) and the selection rules (3), we can have

$$M(1^1S_0) = 2c; \tag{4}$$

$$M(1^3S_1) = 2x. \tag{5}$$

*liuyunhu20@tom.com

TABLE I. Isovector meson masses of 1^3P_0, 1^3P_1, 1^3P_2, 2^3P_0, 2^3P_1, and 2^3P_2 states, all in GeV.

	$M(1^3P_0)$	$M(1^3P_1)$	$M(1^3P_2)$	$M(2^3P_0)$	$M(2^3P_1)$	$M(2^3P_2)$
This work	1.0048	1.2887	1.3434	1.5159	1.7113	1.7343
Expt. [1]		1.23 ± 0.04	1.3183 ± 0.0006			

For isovector states, $M(1^1S_0) = 0.1373$ GeV, $M(1^3S_1) = 0.7755$ GeV,[1] the values of c and x given by Eqs. (4) and (5) are 0.0686 GeV and 0.3878 GeV, respectively. For all the correlative isovector meson states, we can have

$$M(1^3P_0) = c + (\sqrt{2} + 1)x, \tag{6}$$

$$M(1^3P_1) = c + (\sqrt{2} + \sqrt{3})x, \tag{7}$$

$$M(1^3P_2) = 2\sqrt{3}x, \tag{8}$$

$$M(2^3P_0) = c + (\sqrt{3} + 2)x, \tag{9}$$

$$M(2^3P_1) = c + (2 + \sqrt{5})x, \tag{10}$$

$$M(2^3P_2) = 2\sqrt{5}x. \tag{11}$$

We take the values of c and x into relations (6)–(11), masses of mesons are shown in Table I.

III. REGGE PHENOMENOLOGY

Regge theory is concerned with the particle spectrum, the forces between particles and the high energy behavior of scattering amplitudes [3]. One of the most distinctive features of Regge theory is the Regge trajectory by which the mass and the spin of a hadron are related. A series of recent papers [4–6] indicate that the quasilinear Regge trajectory can, at least at present, give a reasonable description for the meson spectroscopy, and its predictions may be useful for the discovery of the meson states which have not yet been observed. By assuming the existence of the quasilinear Regge trajectories for a meson multiplet, one can have

$$J = \alpha_{i\bar{i}'(N)}(0) + \alpha'_{i\bar{i}'(N)} M^2_{i\bar{i}'(N)}, \tag{12}$$

where i ($\bar{i}'$) refers to the quark (antiquark) flavor, $i\bar{i}'$ (N) denotes the meson $i\bar{i}'$ with radial quantum number N ($N = 1, 2, 3, \ldots$), J and $M_{i\bar{i}'(N)}$ are, respectively, the spin and mass of the $i\bar{i}'(N)$ meson, $\alpha_{i\bar{i}'(N)}$ (0) and $\alpha'_{i\bar{i}'(N)}$ are, respectively, the intercept and slope of the trajectory on which the $i\bar{i}'(N)$ meson lies. For a meson multiplet, the parameters for different flavors can be related by the following relations (see Ref. [6] and references therein):

(1) additivity of intercepts

$$\alpha_{i\bar{i}'(N)}(0) + \alpha_{j\bar{j}'(N)}(0) = 2\alpha_{j\bar{i}'(N)}(0), \tag{13}$$

(2) additivity of inverse slopes

$$\frac{1}{\alpha'_{i\bar{i}'(N)}} + \frac{1}{\alpha'_{j\bar{j}'(N)}} = \frac{2}{\alpha'_{j\bar{i}'(N)}}. \tag{14}$$

In the following text, we shall adopt two assumptions: (a) the slopes of the parity partners' trajectories coincide, as proposed by Ref. [7], and (b) $\alpha'_{i\bar{i}'(N)} = \alpha'_{i\bar{i}'(1)}$, as adopted by Ref. [4]. Under these assumptions, the slopes of the scalar meson trajectories are the same as those of the vector meson trajectories.

IV. MESON-MESON MIXING SCHEME

It is well known that in a meson nonet, the pure isoscalar $n\bar{n}$ (here and following, n denotes u- or d-quark) and $s\bar{s}$ states can mix to produce the physical isoscalar states $f_0(M_1)$ and $f_0(M_2)$. In order to understand the physical scalar states, we shall discuss the mixing of the $n\bar{n}$ and $s\bar{s}$ states.

In the $N = (u\bar{u} + d\bar{d})/\sqrt{2}$, $S = s\bar{s}$ basis, the mass-squared matrix describing the mixing of the $f_0(M_1)$ and $f_0(M_2)$ can be written as [8,9]

$$M^2 = \begin{pmatrix} M_N^2 + 2\beta & \sqrt{2}\beta X \\ \sqrt{2}\beta X & 2M^2_{n\bar{s}} - M_N^2 + \beta X^2 \end{pmatrix}, \tag{15}$$

where M_N and $M_{n\bar{s}}$ are the masses of the states N and $n\bar{s}$, respectively; β denotes the total annihilation strength of the $q\bar{q}$ pair for the light flavors u and d; X describes the $SU(3)$-breaking ratio of the nonstrange and strange quark propagators via the constituent quark mass ratio m_u/m_s. The masses of the two physical scalar states $f_0(M_1)$ and $f_0(M_2)$, M_1 and M_2, can be related to the matrix M^2 by the unitary matrix U

$$UM^2U^\dagger = \begin{pmatrix} M_1^2 & 0 \\ 0 & M_2^2 \end{pmatrix}, \tag{16}$$

[1] $M_\pi = (M_{\pi^0} + M_{\pi^\pm})/2$. Here and following, all the masses used as input for our calculation are taken from PDG 2006 [1].

and the physical states $f_0(M_1)$ and $f_0(M_2)$ can be expressed as

$$\begin{pmatrix} f_0(M_1) \\ f_0(M_2) \end{pmatrix} = U \begin{pmatrix} N \\ S \end{pmatrix}. \tag{17}$$

The constituent quark mass ratio can be determined within the nonrelativistic constituent quark model (NRCQM). In NRCQM [10,11], the mass of a $q\bar{q}$ state with $L = 0$, $M_{q\bar{q}}$ is given by

$$M_{q\bar{q}} = m_q + m_{\bar{q}} + \Lambda \frac{s_q \cdot s_{\bar{q}}}{m_q m_{\bar{q}}},$$

where m and s are the constituent quark mass and spin, Λ is a constant, since $s_q \cdot s_{\bar{q}} = -3/4$ for spin-0 mesons and $1/4$ for spin-1 mesons. In the $SU(2)$ flavor symmetry limit, one can have

$$X \equiv \frac{m_u}{m_s} = \frac{M_\pi + 3M_\rho}{2M_K + 6M_{K^*} - M_\pi - 3M_\rho} = 0.6298.$$

From Eq. (16), one can have

$$\begin{gathered} 2M_{n\bar{s}}^2 + (2 + X^2)\beta = M_1^2 + M_2^2; \\ (M_N^2 + 2\beta)(2M_{n\bar{s}}^2 - M_N^2 + \beta X^2) - 2\beta^2 X^2 = M_1^2 M_2^2. \end{gathered} \tag{18}$$

V. THE GROUND SCALAR MESON NONET

For the mass of the $c\bar{s}$ member of the ground scalar meson nonet, the recent result predicted by the QCD sum rule is 2.31 ± 0.03 GeV [12], which is in good agreement with 2.331 GeV predicted by Regge phenomenology [13], the average value is only 3.2 MeV higher than the experimental result. Those analyses support the conclusion that the $D_{s0}(2317)$ can be identified as a conventional 1^3P_0 $c\bar{s}$ state. From relations (12)–(14), one can have

$$M_{n\bar{s}}^2 = \frac{\alpha'_{n\bar{n}}(0)M_{n\bar{n}}^2 - \alpha'_{c\bar{c}}(0)M_{c\bar{c}}^2 + 2\alpha'_{c\bar{s}}(0)M_{c\bar{s}}^2}{2\alpha'_{n\bar{s}}(0)}. \tag{19}$$

With the help of slopes of the vector meson trajectories extracted by Ref. [6], inserting the parameters into relation (19), one can have $M_{n\bar{s}} = 1.0620$ GeV.

For the scalar meson nonet, the masses of two isoscalar physical states satisfy the following approximate sum rule:

$$M_1^2 + M_2^2 \simeq 2(M_K^2 + M_{n\bar{s}}^2) - (M_\eta^2 + M_{\eta'}^2), \tag{20}$$

which is derived by Dmitrasinovic in the framework of the Nambu-Jona-Lasinio model with a $U_A(1)$ symmetry-breaking instanton-induced 't Hooft interaction [14]. With the help of $M_N = 1.0048$ GeV estimated in Sec. II and $M_{n\bar{s}} = 1.0620$ GeV, from relations (15)–(18) and (20), we can obtain

$$\begin{gathered} M_1 = 1.1026 \text{ GeV}, \qquad M_2 = 0.5639 \text{ GeV}, \\ \beta_1 = -0.3013 \text{ GeV}^2, \end{gathered} \tag{21}$$

and

$$\begin{pmatrix} f_0(M_1) \\ f_0(M_2) \end{pmatrix} = \begin{pmatrix} 0.3144 & -0.9494 \\ 0.9494 & 0.3144 \end{pmatrix} \begin{pmatrix} N \\ S \end{pmatrix}. \tag{22}$$

Therefore, in the framework of a relativistic independent quark model and under the assumption that the $D_{s0}^*(2317)$ belongs to the ground scalar meson multiplet, we suggest that the $a_0(1005)$, $K_0^*(1062)$, $f_0(1103)$, and $f_0(564)$ constitute the ground scalar meson nonet.

VI. THE FIRST RADIAL SCALAR MESON NONET

However, the $c\bar{s}$ member of the 2^3P_0 has not been decided. The prediction of the mass of the $c\bar{s}$ member of the 2^3P_0 is 2.838 GeV in Regge phenomenology [13]; this is in good agreement with the experimental data 2.8566 GeV. The suggestion that the $D_{sJ}(2860)$ can be identified as the 2^3P_0 $c\bar{s}$ state has been given by [15,16]. In this paper, we shall assume that the $D_{sJ}(2860)$ is the first radial state of $D_{s0}(2317)$.

Though the $c\bar{c}$ state of 2^3P_0 has not been observed experimentally, many papers have given the predictions of the mass of this state: 3.875 GeV [13], 3.92 GeV [17], 3.94 GeV [18], 3.854 GeV [19], 3.867 GeV [20], and 3.86 GeV [21]. These results are in good agreement; we take the average of these results 3.886 GeV as the mass of $c\bar{c}$ state of 2^3P_0.

With the help of $M_{n\bar{n}}(2^3\mathrm{P}_0) = 1.5159$ GeV predicted in Sec. II and relation (19), one can have $M_{n\bar{s}}(2^3P_0) = 1.6685$ GeV.

From relations (15)–(18) and (20), one can have

$$\begin{gathered} M_1 = 1.7884 \text{ GeV}, \qquad M_2 = 1.2835 \text{ GeV}, \\ \beta_2 = -0.3013 \text{ GeV}^2, \end{gathered} \tag{23}$$

and

$$\begin{pmatrix} f_0(M_1) \\ f_0(M_2) \end{pmatrix} = \begin{pmatrix} 0.1753 & -0.9846 \\ 0.9846 & 0.1753 \end{pmatrix} \begin{pmatrix} N \\ S \end{pmatrix}. \tag{24}$$

Therefore, in the framework of the relativistic independent quark model and under the assumption that the $D_{sJ}(2860)$ belongs to the first radial scalar meson multiplet, we suggest that the $a_0(1516)$, $K_0^*(1669)$, $f_0(1788)$, and $f_0(1284)$ constitute the first radial scalar meson nonet.

VII. DISCUSSIONS

In the recent literature, there is not yet a consensus on the $1^3P_0 n\bar{n}(n = 1)$ mass given by lattice stimulations. For example, both $M_{a_0}(1^3P_0) \sim 1$ Gev [22–24] and $M_{a_0}(1^3P_0) \sim 1.4\text{-}1.6$ Gev [25–27] are predicted recently. Considering that the naive quark model predicts that the spin-orbit force makes lighter the $a_0(1^3P_0)$ with respect to the $a_2(1^3P_2)$ and the same behavior is evident in the $c\bar{c}$ and $b\bar{b}$ spectra [28], our prediction is in good agreement with $M_{a_0}(1^3P_0) \sim 1$ GeV. Obviously, the mass of $a_0(1005)$

agrees with that of the observed scalar resonance $a_0(980)$, and there are many results given by different approaches that support the argument that the $a_0(980)$ is dominantly a $q\bar{q}$ system [11,29–31]. This suggests that the $a_0(1005)$ would correspond to the observed state $a_0(980)$.

With respect to the $f_0(1103)$, we can find that it is composed mostly of $s\bar{s}$ from relation (22). Although its estimated mass is close to the masses of the observed scalar state $f_0(980)$ and $f_0(1370)$, the studies of $f_0(980)$ indicate that the $f_0(980)$ is composed mostly of $s\bar{s}$ quarks [32–36] and the $f_0(1370)$ should be mainly nonstrange [1]. Therefore, the $f_0(1103)$ would correspond to the observed scalar state $f_0(980)$ rather than the $f_0(1370)$.

Obviously, the mass of the $f_0(564)$ agrees with that of the observed scalar resonance $f_0(600)/\sigma$ with a mass range of 0.4–1.2 GeV. Also, from relation (22), one can have that $f_0(564)$ is composed mostly of nonstrange quarkonia which is consistent with the decay patterns of the $f_0(600)/\sigma$ [1]. This suggests that the $f_0(564)$ would correspond to the observed state $f_0(600)/\sigma$. With respect to the $a_0(1516)$, its estimated mass is close to the mass of the observed scalar state $a_0(1450)$, and a measurement of the $a_0(1450)$ decays at the predicted level favors the $q\bar{q}$ structure for the $a_0(1450)$ [37,38]. This suggests that the $a_0(1516)$ would correspond to the observed scalar state $a_0(1450)$.

Obviously, the mass of the $f_0(1284)$ agrees with that of the observed scalar state $f_0(1370)$, and one can find that the $f_0(1284)$ is composed mostly of nonstrange quarkonia from relation (24), which coincides with the decay patterns of the $f_0(1370)$ [1]. The mass and quarkonia content of the $f_0(1284)$ strongly suggest that the $f_0(1284)$ would correspond to the observed scalar state $f_0(1370)$.

From relation (24), one can find that the $f_0(1788)$ is mainly $s\bar{s}$ and the estimated mass of $f_0(1788)$ is close to that of the $f_0(1710)$. The decay patterns [1] of the $f_0(1710)$ imply that the $f_0(1710)$ should be mainly $s\bar{s}$. These results show that the $f_0(1788)$ would very likely correspond to the observed scalar state $f_0(1710)$.

The lattice studies suggest the mass of the ground scalar kaon would be 100–130 MeV heavier than the a_0 mass [24], and the K-matrix analysis of the $K\pi S$-wave by Anisovich *et al.* reveals the lowest scalar kaon with the pole position at 1.09 ± 0.04 GeV [29], which favors our estimated mass of the $K_0^*(1062)$ within errors. The estimated mass of its first radial state is 1.6685 GeV. Comparison of the $K_0^*(1062)$ and $K_0^*(1669)$ and the observed scalar kaon states: κ, $K_0^*(1430)$, and $K_0^*(1950)$, indicates that if the κ really exists, the $K_0^*(1062)$ and $K_0^*(1669)$ would correspond to the κ with a mass of 905^{+65}_{-30} MeV and the $K_0^*(1430)$. However, the estimated masses of the $K_0^*(1062)$ and $K_0^*(1669)$ are 100–200 MeV higher than those of the corresponding observed states. The masses of the scalar mesons may get shifted from the predicted values due to some unclear reasons.

VIII. CONCLUDING REMARKS

Based on the main assumption that the $D_{sJ}(2860)$ belongs to the 2^3P_0 $q\bar{q}$ multiplet, the masses of the scalar meson nonet are estimated in the framework of the relativistic independent quark model, Regge phenomenology, and meson-meson mixing. We suggest that the $a_0(1005)$, $K_0^*(1062)$, $f_0(1103)$, and $f_0(564)$ constitute the ground scalar meson nonet, $f_0(1103)$ is composed mostly of strange quarkonia, and $f_0(564)$ is mainly nonstrange. It is supposed that these states would likely correspond to the observed states $a_0(980)$, $\kappa(900)$, $f_0(980)$, and $f_0(600)/\sigma$, respectively. Also $a_0(1516)$, $K_0^*(1669)$, $f_0(1788)$, and $f_0(1284)$ constitute the first radial scalar meson nonet, $f_0(1788)$ is composed mostly of strange quarkonia, and $f_0(1284)$ is mainly nonstrange. It is supposed that these states would likely correspond to the observed states $a_0(1450)$, $K_0^*(1430)$, $f_0(1710)$, and $f_0(1370)$, respectively. The agreement between the present findings and those given by other different approaches is satisfactory [39]. From relations (21) and (23), one can find that the total annihilation strength of the $q\bar{q}$ pair for the light flavors u and d is equal between the ground scalar meson nonet and the first radial scalar meson nonet. Lattice QCD calculations in quenched approximation suggest that the mass of the ground scalar glueball is in the range 1400–1800 MeV [40]. In this range, there is only one scalar state $f_0(1500)$ which is excluded from the scalar meson nonet, it may be a good candidate for the ground scalar glueball.

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