

## Regarding the Ground Scalar Mesons<sup>\*</sup>

LI De-Min<sup>1)</sup> LIU Yun-Hu

(Department of Physics, Zhengzhou University, Zhengzhou 450052, China)

**Abstract** Based on the main assumption that the  $a_0(980)$  and  $D_{sJ}^*(2317)$  belong to the  $1^3P_0$   $q\bar{q}$  multiplet, the masses of the states belong to the  $1^3P_0$   $q\bar{q}$  multiplet are estimated in the quasi-linear Regge trajectory ansatz. In the framework of meson-meson mixing, it is suggested that the  $a_0(980)$ ,  $K_0^*(1052)$ ,  $f_0(1099)$  and  $f_0(530)$  constitute the ground scalar meson nonet, and that the  $f_0(1099)$  is composed mostly of  $s\bar{s}$  while the  $f_0(530)$  is mainly  $u\bar{u}+d\bar{d}$ . It is supposed that these states would likely correspond to the observed scalar states  $a_0(980)$ ,  $\kappa(900)$ ,  $f_0(980)$  and  $f_0(600)/\sigma$ , respectively. Also, in the glueball-dominance picture, the mass of the ground scalar glueball is estimated to be about 1340MeV. The agreement between the present findings and those given by other different approaches is satisfactory.

**Key words** scalar meson, Regge phenomenology, mixing

### 1 Introduction

The spectrum and structure of the scalar mesons are one of the most controversial subjects in hadron physics. In the recent issue of Review of Particle Physics<sup>[1]</sup>, too many light scalar mesons in the region below 2GeV 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  $K_0^*(800)/\kappa$ . Among these states, it is not yet clear which are the members of the ground scalar meson nonet.

With respect to the nature of the  $a_0(980)$ , although some possible interpretations such as  $K\bar{K}$  molecule<sup>[2]</sup>, four-quark state<sup>[3]</sup> were proposed in the literature, many results given by different approaches support the argument that the  $a_0(980)$  belongs to the ground scalar meson multiplet: (1) The K-matrix analysis of the  $K\pi$   $S$ -wave<sup>[4]</sup> showed the mass of the

$1^3P_0$  isovector state is about  $960\pm 30\text{MeV}$  and supported that the  $a_0(980)$  is dominantly  $q\bar{q}$  system; (2) The naive quark model predicts that the LS force makes lighter the  $J=0$  states with respect to the  $J=2$ , which favors that the  $a_0(980)$  rather than the  $a_0(1450)$  belongs to the the scalar member of the lowest  $^3P_J$  multiplet, because the  $a_2(1320)$  is well established as a  $q\bar{q}$  pair. The same behavior is evident in the  $c\bar{c}$  and the  $b\bar{b}$  spectra<sup>[5]</sup>; (3) Based on the theory of fine structure, it is suggested that it is the  $a_0(980)$  but not the  $a_0(1450)$  that could be a candidate for the ground  $^3P_0$  state<sup>[6]</sup>; (4) Most of the fits of the data using the nonrelativistic quark model strongly favored that the  $a_0(980)$  is the isovector member of the ground scalar nonet<sup>[7]</sup>; (5) The calculation of the partial width for the decay  $a_0(980)(f_0(980)) \rightarrow \gamma\gamma$ <sup>[8]</sup> based on the assumption that the  $a_0(980)$  and  $f_0(980)$  are the members of the  $1^3P_0$   $q\bar{q}$  multiplet is in reasonable agreement with the experimental data, which supports the idea of  $q\bar{q}$  origin of the scalar mesons

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1) E-mail: lidm@zzu.edu.cn

$a_0(980)$  and  $f_0(980)$ ; (6) The systematics of scalar  $q\bar{q}$  states on the linear trajectories in the  $(n, M^2)$  and  $(J, M^2)$  plane indicate the  $a_0(980)$  lays comfortable on the linear trajectory, together with other scalar states<sup>[9,10]</sup>; (7) The calculation within QCD sum rules method based on the argument that  $a_0(980)$  is considered as a  $q\bar{q}$  bound state is consistent with the existing experimental data<sup>[11]</sup>; (8) Some theoretical models such as  $U(3) \times U(3)$   $\sigma$  model<sup>[12]</sup>,  $SU(3)$   $\sigma$  model<sup>[13]</sup>, chiral quark model of Nambu-Jona-Lasinio type<sup>[14]</sup> also suggested the mass of the isovector member of the ground scalar nonet is close to that of the  $a_0(980)$ .

Recently, the experimental discovery of the low-lying charm-strange meson  $D_{sJ}^*(2317)$ <sup>[15]</sup> maybe open a new window to reveal the nature of the scalar states. All experimental findings, such as all the observed decay modes and angular distributions are consistent with the interpretation as  $P$ -wave states with spin-parity assignment  $J^P = 0^+$  for the  $D_{sJ}^*(2317)$ . On the one hand, the picture of the  $D_{sJ}^*(2317)$  composed of a heavy quark  $c$  and a light quark  $s$  fits well with the heavy-quark, chiral symmetries that predict parity doubling states  $(0^-, 1^-)$  and  $(0^+, 1^+)$ , with the inparity mass splittings in the chiral limit given by the Goldberger-Treiman relation, the subsequent observation of  $1^+$  state  $D_{sJ}^*(2460)$  strongly supports this picture<sup>[16]</sup>, and the assignment that the  $D_{sJ}^*(2317)$  is the  $c\bar{s}$  member of the  $1^3P_0$   $q\bar{q}$  multiplet has been suggested by Particle Data Group<sup>[1]</sup>. On the other hand, the  $c\bar{s}$  picture of this state does not play well with the potential model calculations, which generally predict substantially larger mass. For example, the measured mass of the  $D_{sJ}^*(2317)$  is  $2317.4 \pm 0.9\text{MeV}$ , while the prediction of the  $1^3P_0$   $c\bar{s}$  state by Isgur and Godfrey is  $2.48\text{GeV}$ <sup>[17]</sup> and that by Di Pierro and Eichten is  $2.487\text{GeV}$ <sup>[18]</sup>, which are about  $160\text{MeV}$  higher than the measured mass of the  $D_{sJ}^*(2317)$ . The substantially small observed mass led to many other interpretations on the nature of the  $D_{sJ}^*(2317)$ , such as the (DK) molecule, four-quark state,  $D\pi$  atom or baryonium. For the detailed review see e.g. Refs. [19,20]. However, it should be noted that the one loop chiral corrections for heavy-light

mesons in potential model<sup>[16]</sup> and the coupled channel effect<sup>[21]</sup> can naturally account for the unusually mass of the  $D_{sJ}^*(2317)$ , which confirms the  $q\bar{q}$  picture of the  $D_{sJ}^*(2317)$ . More recently, radiative decays of the  $D_{sJ}^*(2317)$  and  $D_{sJ}^*(2460)$  have been studied by Colangelo et al. within light-cone QCD sum rules, the results show that invoking nonstandard interpretations of the  $D_{sJ}^*(2317)$  and  $D_{sJ}^*(2460)$  is not necessary, and strongly favor the idea of ordinary  $c\bar{s}$  origin of the  $D_{sJ}^*(2317)$  and  $D_{sJ}^*(2460)$ <sup>[22]</sup>. The calculation of the pionic decay widths of  $D_{sJ}^*(2317)$  and  $D_{sJ}^*(2460)$  within the light-cone QCD sum rules performed by Zhu et al.<sup>[23]</sup> also support their interpretation as ordinary  $c\bar{s}$  mesons.

In the present work, we shall assume that the  $a_0(980)$  and  $D_{sJ}^*(2317)$  are the members of the  $1^3P_0$   $q\bar{q}$  multiplet, and discuss a possible assignment for the ground scalar  $q\bar{q}$  nonet in the framework of Regge phenomenology and meson-meson mixing.

## 2 Regge trajectories and the scalar meson spectrum

A series of recent papers<sup>[9, 10, 24]</sup> indicate that the quasi-linear 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 quasi-linear Regge trajectories for a meson multiplet, one can have

$$J = \alpha_{i\bar{i}'}(0) + \alpha'_{i\bar{i}'} M_{i\bar{i}'}^2, \quad (1)$$

where  $i$  ( $\bar{i}'$ ) refers to the quark (antiquark) flavor,  $J$  and  $M_{i\bar{i}'}$  are respectively the spin and mass of the  $i\bar{i}'$  meson,  $\alpha_{i\bar{i}'}(0)$  and  $\alpha'_{i\bar{i}'}$  are respectively the intercept and slope of the trajectory on which the  $i\bar{i}'$  meson lies. For a meson multiplet, the parameters for different flavors can be related by the following relations(see Ref. [24] and references therein)

(i) additivity of intercepts,

$$\alpha_{i\bar{i}}(0) + \alpha_{j\bar{j}}(0) = 2\alpha_{j\bar{i}}(0), \quad (2)$$

(ii) additivity of inverse slopes,

$$\frac{1}{\alpha'_{i\bar{i}}} + \frac{1}{\alpha'_{j\bar{j}}} = \frac{2}{\alpha'_{j\bar{i}}}. \tag{3}$$

In our estimate of the mass of the  $1^3P_0$   $n\bar{s}$  state, we adopt the assumption presented by Ref. [24] that the slopes of the parity partners' trajectories coincide. Under this assumption, the slopes of the scalar meson trajectories are the same as those of the vector meson trajectories. With the help of slopes of the vector meson trajectories extracted by Ref. [24], the slopes of the scalar meson trajectories used as input in this work are shown in Table 1. In the following,  $n$  denotes u- or d-quark.

From Eq. (1), one can have

$$0 = \alpha_{c\bar{c}}(0) + \alpha'_{c\bar{c}} M_{c\bar{c}}^2, \tag{4}$$

$$0 = \alpha_{b\bar{b}}(0) + \alpha'_{b\bar{b}} M_{b\bar{b}}^2, \tag{5}$$

$$0 = \alpha_{c\bar{s}}(0) + \alpha'_{c\bar{s}} M_{c\bar{s}}^2, \tag{6}$$

$$0 = \alpha_{n\bar{n}}(0) + \alpha'_{n\bar{n}} M_{n\bar{n}}^2. \tag{7}$$

Inserting the masses of the  $\chi_{c0}(1P)$ ,  $\chi_{b0}(1P)$ ,

$D_{sJ}^*(2317)$  and  $a_0(980)^{[1]}$  into Eqs. (4)—(7), with the help of Table 1 and Eqs. (2) and (3), one can extract all the intercepts of the  $1^3P_0$  trajectories as shown in Table 2. Based on these parameters, the estimated masses of states belong to the  $1^3P_0$   $q\bar{q}$  multiplet are shown in Table 3. Comparison of our predictions with those given by other references is also shown in Table 3. The masses used as input for our calculation are shown in boldface.

Table 1. The slopes of the  $1^3P_0$  trajectories of the form (1).

	$n\bar{n}$	$s\bar{s}$	$n\bar{s}$	$c\bar{c}$	$c\bar{n}$
$\alpha'/\text{GeV}^{-2}$	0.8830	0.8181	0.8493	0.4364	0.5841
	$c\bar{s}$	$b\bar{b}$	$n\bar{b}$	$s\bar{b}$	$c\bar{b}$
$\alpha'/\text{GeV}^{-2}$	0.5692	0.2049	0.3326	0.3277	0.2789

Table 2. The intercepts of the  $1^3P_0$  trajectories of the form (1).

	$n\bar{n}$	$s\bar{s}$	$n\bar{s}$	$c\bar{c}$	$c\bar{n}$
$\alpha(0)$	-0.8562	-1.0264	-0.9399	-5.0900	-2.9731
	$c\bar{s}$	$b\bar{b}$	$n\bar{b}$	$s\bar{b}$	$c\bar{b}$
$\alpha(0)$	-3.0568	-19.9199	-10.3880	-10.4718	-12.5049

Table 3. The masses of the states belong to the  $1^3P_0$   $q\bar{q}$  multiplet. All masses in GeV.

reference	$M_{n\bar{n}}$	$M_{s\bar{s}}$	$M_{n\bar{s}}$	$M_{c\bar{n}}$	$M_{c\bar{s}}$	$M_{n\bar{b}}$	$M_{s\bar{b}}$	$M_{c\bar{c}}$	$M_{b\bar{b}}$	$M_{c\bar{b}}$
present work	<b>0.9847</b>	1.118	1.052	2.256	<b>2.3174</b>	5.589	5.653	<b>3.41519</b>	<b>9.8599</b>	6.696
Exp.	0.9847 <sup>[1]</sup>			2.29 <sup>[25]</sup>	2.3174 <sup>[1]</sup>			3.41519 <sup>[1]</sup>	9.8599 <sup>[1]</sup>	
Ref. [26]				2.29	2.317					
Ref. [27]					2.303		5.643			
Ref. [28]				2.200	2.288	5.576	5.654			
Ref. [29]				2.217	2.317	5.627	5.718			
Ref. [30]					2.57		5.837			
Ref. [31]					2.304		5.71			
Ref. [32]				2.272	2.297					
Ref. [33]				2.20	2.357					
Ref. [34]				2.27	2.38	5.65	5.75	3.44	9.85	6.68
Ref. [35]	1.09		1.24	2.40	2.48	5.76	5.83	3.44	9.85	6.706
Ref. [36]				2.341	2.455	5.678	5.781	3.45		
Ref. [37]				2.377	2.487	5.700	5.804			
Ref. [38]				2.438	2.508	5.738	5.841			
Ref. [39]				2.278	2.378	5.689	5.810			
Ref. [40]								3.424	9.863	6.699
Ref. [41]								3.419	9.865	6.700
Ref. [42]								3.436	9.834	6.700
Ref. [43]								3.421	9.861	6.715
Ref. [44]								3.415	9.862	6.689
Ref. [45]								3.391	9.863	6.701
Ref. [46]										6.683
Ref. [47]										6.728
Ref. [48]										6.660
Ref. [49]										6.727
Ref. [50]										$\geq 6.639$

### 3 The $1^3P_0$ meson nonet in meson-meson mixing

It is well known that in a meson nonet, the pure isoscalar  $n\bar{n}$  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 below.

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<sup>[13, 51]</sup>

$$M^2 = \begin{pmatrix} M_N^2 + 2\beta & \sqrt{2}\beta X \\ \sqrt{2}\beta X & 2M_{n\bar{s}}^2 - M_N^2 + \beta X^2 \end{pmatrix}, \quad (8)$$

where  $M_N$  and  $M_{n\bar{s}}$  are the masses of the states  $N$  and  $n\bar{s}$ , respectively;  $\beta$  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 non-strange 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  $U$

$$UM^2U^\dagger = \begin{pmatrix} M_1^2 & 0 \\ 0 & M_2^2 \end{pmatrix}, \quad (9)$$

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

$$\begin{pmatrix} f_0(M_1) \\ f_0(M_2) \end{pmatrix} = U \begin{pmatrix} N \\ S \end{pmatrix}. \quad (10)$$

The constituent quark mass ratio can be determined within the nonrelativistic constituent quark model(NRCQM). In NRCQM<sup>[7, 52]</sup>, the mass of a  $q\bar{q}$  state with  $L=0$ ,  $M_{q\bar{q}}$  is given by

$$M_{q\bar{q}} = m_q + m_{\bar{q}} + \Lambda \frac{\mathbf{s}_q \cdot \mathbf{s}_{\bar{q}}}{m_q m_{\bar{q}}},$$

where  $m$  and  $\mathbf{s}$  are the constituent quark mass and spin,  $\Lambda$  is a constant. Since  $\mathbf{s}_q \cdot \mathbf{s}_{\bar{q}} = -3/4$  for spin-0 mesons and  $1/4$  for spin-1 mesons, in the  $SU(2)$  flavor symmetry limit, one can has

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

From Eq. (9), one can have

$$\begin{aligned} 2M_{n\bar{s}}^2 + (2 + X^2)\beta &= M_1^2 + M_2^2, \\ (M_N^2 + 2\beta)(2M_{n\bar{s}}^2 - M_N^2 + \beta X^2) - 2\beta^2 X^2 &= M_1^2 M_2^2. \end{aligned} \quad (11)$$

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

$$M_1^2 + M_2^2 \simeq 2(M_K^2 + M_{n\bar{s}}^2) - (M_n^2 + M_{n'}^2), \quad (12)$$

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<sup>[53]</sup>.

With the help of  $M_N = M_{a_0(980)}$  and  $M_{n\bar{s}} = 1052\text{MeV}$  estimated in section 2, from Eqs. (8)—(12), one can have

$$M_1 \simeq 1099\text{MeV}, \quad M_2 \simeq 530\text{MeV}, \quad (13)$$

and

$$\begin{pmatrix} f_0(M_1) \\ f_0(M_2) \end{pmatrix} \simeq \begin{pmatrix} 0.30 & -0.95 \\ 0.95 & 0.30 \end{pmatrix} \begin{pmatrix} N \\ S \end{pmatrix}. \quad (14)$$

Therefore, under the assumption that the  $a_0(980)$  and  $D_{sJ}^*(2317)$  belong to the  $1^3P_0$  meson multiplet, in the Regge phenomenology and meson-meson mixing, we suggest that the  $a_0(980)$ ,  $K_0^*(1052)$ ,  $f_0(1099)$  and  $f_0(530)$  constitute the ground scalar meson nonet.

### 4 The mass of the ground scalar glueball

After the masses as well as the mixing angle of the two isoscalar physical states of the  $1^3P_0$  meson nonet are estimated, we wish to estimate the mass of the ground scalar glueball by employing the following approximate formula derived by Brisudova et al.<sup>[54]</sup> in the glueball dominance picture

$$\beta^2 X^2 = \frac{f^2(M_{n\bar{n}}^2)}{M_{n\bar{n}}^2 - M_O^2} \frac{f^2(M_{s\bar{s}}^2)}{M_{s\bar{s}}^2 - M_O^2}, \quad (15)$$

where  $f(M_{q\bar{q}}^2) = \langle O | H | q\bar{q} \rangle |_{q^2=M_{q\bar{q}}^2}$ ,  $M_{s\bar{s}}^2 = 2M_{n\bar{s}}^2 - M_{n\bar{n}}^2$ . Under the assumption that  $f(M_{n\bar{n}}^2)f(M_{s\bar{s}}^2) \approx \text{const.}$  proposed by<sup>[54]</sup>, one can have

$$\begin{aligned} \beta_S^2 (M_{a_0}^2 - M_O^2) (2M_{K_0^*}^2 - M_{a_0}^2 - M_O^2) &\approx \\ \beta_T^2 (M_{a_2}^2 - M_G^2) (2M_{K_2^*}^2 - M_{a_2}^2 - M_G^2). & \end{aligned} \quad (16)$$

where  $a_0$ ,  $K_0^*$ ,  $a_2$  and  $K_2^*$  denote the  $1^3P_0$   $n\bar{n}$ ,  $1^3P_0$   $n\bar{s}$ ,  $1^3P_2$   $n\bar{n}$  and  $1^3P_2$   $n\bar{s}$  states, respectively;  $O$  and  $G$  denote the ground scalar and tensor glueballs, respectively;  $\beta_S = (M_1^2 + M_2^2 - 2M_{K_0^*}^2)/(2 + X^2)$ , and  $\beta_T = (M_{f_2(1270)}^2 + M_{f_2(1525)}^2 - 2M_{K_2^*}^2)/(2 + X^2)$ .

Taking  $M_G = 2.4\text{GeV}$  predicted by the lattice QCD calculation<sup>[55]</sup>, from Eq. (15), one can have<sup>1)</sup>

$$M_O \approx 1340\text{MeV}, \quad (17)$$

which is in excellent agreement with  $M_O = 1340 \pm 160\text{MeV}$  predicted by the lattice QCD calculation<sup>[56]</sup> for the ground scalar glueball.

Lattice QCD calculations in quenched approximation suggest that the mass of the ground scalar glueball is in the range  $1400\text{--}1800\text{MeV}$ <sup>[57]</sup>. Typically, present results on the glueball mass are about 20% lower than the quenched results<sup>[58]</sup>. Recent calculations of QCD sum rules<sup>[59]</sup> for the ground scalar glueball yield a mass consistent with the quenched lattice result but in addition require a gluonic state near  $1000\text{MeV}$ . At present, there is agreement in the QCD based calculations on the existence of the ground scalar glueball but the mass of the ground glueball is not yet certain and phenomenological searches should allow a mass range of about  $1000\text{--}1800\text{MeV}$ <sup>[60]</sup>. Therefore, we can conclude that our predicted  $M_O$  based on our predictions of the masses of the ground scalar mesons is consistent with the results given by lattice QCD and QCD sum rules.

## 5 Discussions

Obviously, the mass of the  $f_0(530)$  agrees with that of the observed scalar resonance  $f_0(600)/\sigma$  with a mass range of  $400\text{--}1200\text{MeV}$ , also, the picture that the  $f_0(530)$  is composed mostly of nonstrange quarkonia is consistent with the decay patterns of the  $f_0(600)/\sigma$ <sup>[1]</sup>. This suggests that the  $f_0(530)$  would correspond to the observed state  $f_0(600)/\sigma$ .

The K-matrix analysis of the  $K\pi$   $S$ -wave by Anisovich et al.<sup>[4]</sup> reveals the lowest scalar kaon with the pole position at  $1090 \pm 40\text{MeV}$ , which favors our es-

timated mass of the  $K_0^*(1052)$ . Comparison of the  $K_0^*(1052)$  and the observed scalar kaon states,  $\kappa$ ,  $K_0^*(1430)$  and  $K_0^*(1950)$ , indicates that if the  $\kappa$  really exists, the  $K_0^*(1052)$  would very likely correspond to the  $\kappa(900)$  with a mass of  $905_{-30}^{+65}\text{MeV}$ <sup>[61]</sup>.

With respect to the  $f_0(1099)$ , its estimated mass is close to the mass of the observed scalar state  $f_0(980)$  ( $980 \pm 10\text{MeV}$ ), also close to the mass of the observed scalar state  $f_0(1370)$  ( $1200\text{--}1500\text{MeV}$ ), and Eq. (14) clearly shows that the  $f_0(1099)$  is composed mostly of  $s\bar{s}$ . The results of analysis<sup>[62]</sup> for the two-meson spectra support the picture that the  $f_0(980)$  is composed mostly of  $s\bar{s}$  quarks. The transition  $\phi(1020) \rightarrow \gamma f_0(980)$  can be well described within the approach of additive quark model, with the dominant  $q\bar{q}$  component in the  $f_0(980)$ <sup>[63]</sup>, and the decay  $f_0(980) \rightarrow \gamma\gamma$  can be also treated in terms of the  $q\bar{q}$  structure of the  $f_0(980)$ <sup>[8, 64]</sup>. The values of partial widths in both decays ( $\phi(1020) \rightarrow \gamma f_0(980)$  and  $f_0(980) \rightarrow \gamma\gamma$ ) support the existence of a significant  $s\bar{s}$ -component in the  $f_0(980)$ . The study of the  $D_s^+ \rightarrow \pi^+ f_0(980)$  decay by many authors<sup>[65–68]</sup> also led to the conclusion about the  $s\bar{s}$  nature of the  $f_0(980)$ . The decay patterns of the  $f_0(1370)$ <sup>[1]</sup> implies that the  $f_0(1370)$  should be mainly non-strange. Therefore, the mass and the quarkonia content of the  $f_0(1099)$  strongly suggest that the  $f_0(1099)$  would correspond to the observed scalar state  $f_0(980)$  rather than the  $f_0(1370)$ .

Based on the above analysis, the results of the present work predict the ground scalar meson nonet consisting of the  $a_0(980)$ ,  $K_0^*(1052)$ ,  $f_0(1099)$  and  $f_0(530)$ . These states would correspond to the observed scalar states  $a_0(980)$ ,  $\kappa(900)$ ,  $f_0(980)$  and  $f_0(600)/\sigma$ , respectively.

The masses of the ground scalar meson nonet has been estimated by Volkov<sup>[14]</sup> in the framework of a nonlocal version of a chiral quark model of the Nambu-Jona-Lasinio type where the correct masses for the ground pseudoscalar meson nonet and vector meson nonet can be produced. The calculation of Volkov<sup>[14]</sup> shows that the ground scalar meson nonet

1) In our calculation, the masses of the scalar mesons are based on our predictions, and the masses of the tensor mesons are taken from PDG<sup>[1]</sup>.

is composed of the  $a_0(830)$ ,  $f_0(530)$ ,  $f_0(1070)$  and  $K_0^*(960)$ , these states correspond to the observed scalar states  $a_0(980)$ ,  $\sigma$ ,  $f_0(980)$  and  $K_0^*(930)$ <sup>1)</sup>, respectively.

Oller<sup>[69]</sup> has already suggested that the  $a_0(980)$ ,  $\kappa$ ,  $f_0(980)$  and  $\sigma$  resonances constitute the lightest scalar nonet in three different and complementary ways: (a) by establishing the continuous movement of the poles from the physical to a  $SU(3)$  limit, (b) by performing an analysis of the couplings of the scalar mesons to pairs of pseudoscalars and (c) by analysing the couplings of the scalars with meson-meson  $SU(3)$  scattering eigenstates. The results given by Oller<sup>[69]</sup> show

$$\begin{pmatrix} f_0(980) \\ \sigma \end{pmatrix} = \begin{pmatrix} 0.28 & -0.96 \\ 0.96 & 0.28 \end{pmatrix} \begin{pmatrix} N \\ S \end{pmatrix}. \quad (18)$$

Clearly, the agreement Eqs. (14) and (18) is good.

It is worth mention that our suggested  $q\bar{q}$  assignment for the ground scalar nonet is also favored by the results suggested by  $U(3) \times U(3)$   $\sigma$  model<sup>[12]</sup> and  $SU(3)\sigma$  model<sup>[13]</sup>.

Finally, we remark also that the masses of the  $f_0(1099)$  and  $f_0(530)$  predicted in the present work are below a typical range of 1400–1800MeV suggested by Lattice QCD calculation for the ground scalar glueball<sup>[57]</sup>. The masses of the two isoscalar scalar mesons may get shifted from the predicted values due to the possible mixture with the ground scalar glueball.

## 6 Concluding remarks

In the presence of the  $a_0(980)$  and  $D_{sJ}^*(2317)$  belonging to the  $1^3P_0$   $q\bar{q}$  multiplet, we estimate the masses of the members of the  $1^3P_0$   $q\bar{q}$  multiplet in the framework of the quasi-linear Regge trajectory. Our predictions on the masses of the heavy mesons are consistent with those suggested by many other different approaches listed in Table 3. It is noted that based on our predictions, the mass difference between  $c\bar{s}$  and  $c\bar{n}$  ( $s\bar{b}$  and  $n\bar{b}$ ) should roughly be the current strange quark mass. Then in the framework of the meson-meson mixing, we suggest the  $a_0(980)$ ,  $K_0^*(1052)$ ,  $f_0(1099)$  and  $f_0(530)$  constitute the ground scalar meson nonet. We find that the  $f_0(1099)$  is mostly strange while the  $f_0(530)$  is mainly non-strange. We suppose that the  $K_0^*(1052)$ ,  $f_0(1099)$  and  $f_0(530)$  would likely correspond to the observed scalar states  $\kappa(900)$ ,  $f_0(980)$  and  $f_0(600)/\sigma$ , respectively. Our suggested  $q\bar{q}$  assignment for the  $1^3P_0$  meson nonet is consistent with the assignments established by<sup>[12–14, 69]</sup> in different approaches. The fact that the agreement between the present findings and those given by other different approaches is satisfactory implies that the argument that the  $a_0(980)$  and  $D_{sJ}^*(2317)$  are ordinary  $1^3P_0$   $q\bar{q}$  states may be reasonable.

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## 关于标量介子的研究\*

李德民<sup>1)</sup> 刘云虎

(郑州大学物理系 郑州 450052)

**摘要** 基于  $a_0(980)$  和  $D_{sJ}^*(2317)$  属于  $1^3P_0$  介子多重态这个主要假定, 在准线性 Regge 轨迹方案下估计了  $1^3P_0$  介子多重态成员的质量. 在介子-介子混合的框架下, 建议  $a_0(980)$ ,  $K_0^*(1052)$ ,  $f_0(1099)$  和  $f_0(530)$  组成基态标量介子九重态, 并且  $f_0(1099)$  主要由  $s\bar{s}$  组成, 而  $f_0(530)$  主要是  $u\bar{u} + d\bar{d}$ . 这些态可能分别对应已观察到的标量态  $a_0(980)$ ,  $\kappa(900)$ ,  $f_0(980)$  和  $f_0(600)/\sigma$ . 另外, 在胶球为主的图像下, 估计基态标量胶球的质量大约为 1340 MeV. 给出的结果与其他不同方法给出的结果是一致的.

**关键词** 标量介子 Regge 唯象 混合

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1) E-mail: lidm@zzu.edu.cn