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A possible assignment for the ground scalar meson nonet

De-Min Li[1,2,a], Ke-Wei Wei[1], and Hong Yu[2]

[1] Department of Physics, Zhengzhou University, Zhengzhou, Henan 450052, PRC
[2] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100039, PRC

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Abstract. Based on the main assumption that $a_0(980)$ and $D^*_{sJ}(2317)$ belong to the $1\ ^3P_0$ $q\bar{q}$ multiplet, in the framework of Regge phenomenology and meson-meson mixing, it is suggested that $a_0(980)$, $K^*_0(1052)$, $f_0(1099)$ 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 a $u\bar{u}+d\bar{d}$ system. 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. The agreement between the present findings and those given by other different approaches is satisfactory.

PACS. 14.40.-n Mesons – 11.55.Jy Regge formalism

1 Introduction

The spectrum and structure of the scalar mesons are one of the most controversial subjects in hadron physics. In a recent issue of Review of Particle Physics [1], too many light scalar mesons 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 $K^*_0(800)/\kappa$. 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 the $K\bar{K}$ molecule [2], the four-quark state [3], 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 [4] shows that the mass of the $1\ ^3P_0$ isovector state is about 960 ± 30 MeV and supports the fact that the $a_0(980)$ is dominantly a $q\bar{q}$ system. 2) The naive quark model predicts that the LS force makes the $J = 0$ states lighter with respect to $J = 2$, which favors the fact that the $a_0(980)$ rather than the $a_0(1450)$ belongs to 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 [5]. 3) Based on the fine-structure theory, 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 [6]. 4) Most of the fits of the data using the nonrelativistic quark model strongly favor the fact that the $a_0(980)$ is the isovector member of the ground scalar nonet [7]. 5) The calculation of the partial width for the decay $a_0(980)(f_0(980)) \to \gamma\gamma$ [8] 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 $a_0(980)$ 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 indicates the $a_0(980)$ lies comfortably on the linear trajectory, together with other scalar states [9]. 7) The calculation within the 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 [10]. 8) Some theoretical models such as the $U(3) \times U(3)$ σ model [11], the $SU(3)$ σ model [12], the chiral quark model of Nambu–Jona-Lasinio type [13], also suggest that 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 $D^*_{sJ}(2317)$ [14] might open a new window to reveal the nature of the scalar states. All the experimental findings, such as all the observed decay modes and angular distributions are consistent with the interpretation of the $D^*_{sJ}(2317)$ as P-wave states with spin-parity assignment $J^P = 0^+$. 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 the parity doubling states (0^-, 1^-) and (0^+, 1^+), with the inerparity mass splittings in the chiral limit given by the Goldberger-Treiman relation; the subsequent observation of the 1^+ state $D^*_{sJ}(2460)$ strongly supports this picture [15], and the assignment of

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[a] e-mail: `lidm@zzu.edu.cn; lidm@mail.ihep.ac.cn`

the $D^*_{sJ}(2317)$ as the $c\bar{s}$ member of the $1\,^3P_0$ $q\bar{q}$ multiplet has been suggested by the Particle Data Group [1]. 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 ± 0.9 MeV, while the prediction of the $1\,^3P_0$ $c\bar{s}$ state by Isgur and Godfrey is 2.48 GeV [16] and that by Di Pierro and Eichten is 2.487 GeV [17], which are about 160 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, the four-quark state, the $D\pi$ atom or baryonium. For a detailed review see, *e.g.*, refs. [18,19]. However, it should be noted that the one-loop chiral corrections for heavy-light mesons in the potential model [15] and the coupled channel effect [20] can naturally account for the unusual 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 the 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 an ordinary $c\bar{s}$ origin of the $D^*_{sJ}(2317)$ and $D^*_{sJ}(2460)$ [21].

In the present work, we shall assume that $a_0(980)$ 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 The mass of the $1\,^3\mathrm{P}_0$ $\mathrm{n\bar{s}}$ state in Regge phenomenology

A series of recent papers [9,22,23] 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 been observed yet. By assuming the existence of the quasi-linear Regge trajectories for a meson multiplet, one can have

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

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. [23] and references therein):

i) additivity of intercepts,

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

ii) additivity of inverse slopes,

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

From relations (1)-(3), one can have

$$M^2_{n\bar{s}} = \frac{\alpha'_{n\bar{n}} M^2_{n\bar{n}} - \alpha'_{c\bar{c}} M^2_{c\bar{c}} + 2\alpha'_{c\bar{s}} M^2_{c\bar{s}}}{2\alpha'_{n\bar{s}}}, \tag{4}$$

where n denotes the u- or d-quark.

In our estimate of the mass of the $1\,^3P_0$ $n\bar{s}$ state, we adopt the assumption presented by ref. [23] 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. [23], we have $\alpha'_{n\bar{n}} = 0.8830\ \mathrm{GeV}^{-2}$, $\alpha'_{n\bar{s}} = 0.8493\ \mathrm{GeV}^{-2}$, $\alpha'_{c\bar{c}} = 0.4364\ \mathrm{GeV}^{-2}$ and $\alpha'_{c\bar{s}} = 0.5692\ \mathrm{GeV}^{-2}$. Inserting $M_{n\bar{n}} = M_{a_0(980)} = 984.7 \pm 1.2$ MeV, $M_{c\bar{c}} = M_{\chi_{c0}(1P)} = 3415.19 \pm 0.34$ MeV and $M_{c\bar{s}} = M_{D^*_{sJ}(2317)} = 2317.4 \pm 0.9$ MeV [1] into relation (4), one can have $M_{n\bar{s}} = 1051.99 \pm 1.48$ MeV.

3 The $1\,^3\mathrm{P}_0$ 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 [12,24]

$$M^2 = \begin{pmatrix} M_N^2 + 2\beta & \sqrt{2}\beta X \\ \sqrt{2}\beta X & 2M^2_{n\bar{s}} - M_N^2 + \beta X^2 \end{pmatrix}, \tag{5}$$

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,

$$UM^2U^\dagger = \begin{pmatrix} M_1^2 & 0 \\ 0 & M_2^2 \end{pmatrix}, \tag{6}$$

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

$$\begin{pmatrix} f_0(M_1) \\ f_0(M_2) \end{pmatrix} = U \begin{pmatrix} N \\ S \end{pmatrix}. \tag{7}$$

The constituent-quark mass ratio can be determined within the nonrelativistic constituent-quark model (NRCQM). In the NRCQM [7,25], 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, Λ 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 have[1]

$$X \equiv \frac{m_u}{m_s} = \frac{M_\pi + 3M_\rho}{2M_K + 6M_{K^*} - M_\pi - 3M_\rho} = 0.6298 \pm 0.00068\,.$$

From relation (6), one can have

$$\begin{aligned} &2M_{n\bar{s}}^2 + (2 + X^2)\beta = M_1^2 + M_2^2, \\ &(M_N^2 + 2\beta)(2M_{n\bar{s}}^2 - M_N^2 + \beta X^2) - 2\beta^2 X^2 = M_1^2 M_2^2. \end{aligned} \tag{8}$$

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

$$M_1^2 + M_2^2 \simeq 2(M_K^2 + M_{n\bar{s}}^2) - (M_\eta^2 + M_{\eta'}^2), \tag{9}$$

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 [26].

With the help of $M_N = M_{a_0(980)}$ and $M_{n\bar{s}} = 1051.99 \pm 1.48$ MeV estimated in sect. 2, from relations (5)-(9), we can obtain[2]

$$\begin{aligned} &M_1 \simeq 1099.86 \pm 2.71 \text{ MeV}, \quad M_2 \simeq 530.67 \pm 1.92 \text{ MeV}\,, \\ &\beta = -(301281.0 \pm 165.7) \text{ MeV}^2\,, \end{aligned} \tag{10}$$

and

$$\begin{pmatrix} f_0(M_1) \\ f_0(M_2) \end{pmatrix} \simeq \begin{pmatrix} 0.303 \pm 0.002 & -(0.953 \pm 0.001) \\ 0.953 \pm 0.001 & 0.303 \pm 0.002 \end{pmatrix} \begin{pmatrix} N \\ S \end{pmatrix}. \tag{11}$$

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

4 Discussion

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

The K-matrix analysis of the $K\pi$ S-wave by Anisovich *et al.* [4] reveals the lowest scalar kaon with the pole position at 1090 ± 40 MeV, which favors our estimated mass of the $K_0^*(1052)$. Comparison of the $K_0^*(1052)$ and the observed scalar kaon states, κ, $K_0^*(1430)$ and $K_0^*(1950)$, indicates that if the κ really existed, the $K_0^*(1052)$ would very likely correspond to the $\kappa(900)$ with a mass of 905^{+65}_{-30} MeV [27].

With respect to the $f_0(1099)$, its estimated mass is close to the mass of the observed scalar state $f_0(980)$ (980 ± 10 MeV), also close to the mass of the observed scalar state $f_0(1370)$ (1200–1500 MeV), and relation (11) clearly shows that the $f_0(1099)$ is composed mostly of $s\bar{s}$. The results of the analysis [28] for the two-meson spectra support the picture that the $f_0(980)$ is composed mostly of $s\bar{s}$-quarks. The transition $\phi(1020) \to \gamma f_0(980)$ can be well described within the approach of the additive quark model, with the dominant $q\bar{q}$-component in the $f_0(980)$ [29], and the decay $f_0(980) \to \gamma\gamma$ can be also treated in terms of the $q\bar{q}$-structure of the $f_0(980)$ [8, 30]. The values of the partial widths in both decays ($\phi(1020) \to \gamma f_0(980)$ and $f_0(980) \to \gamma\gamma$) support the existence of a significant $s\bar{s}$-component in the $f_0(980)$. The study of the $D_s^+ \to \pi^+ f_0(980)$ decay by many authors [31–34] also led to the conclusion about the $s\bar{s}$ nature of the $f_0(980)$. The decay patterns of the $f_0(1370)$ [1] implies that the $f_0(1370)$ should be mainly nonstrange. Therefore, the mass and the quarkonia content of the $f_0(1099)$ strongly suggest that the $f_0(1099)$ should correspond to the observed scalar state $f_0(980)$ rather than to the $f_0(1370)$.

Based on the above analysis, the results of the present work predict the ground scalar meson nonet consisting of $a_0(980)$, $K_0^*(1052)$, $f_0(1099)$ 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 [13] 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 [13] shows that the ground scalar meson nonet is composed of the $a_0(830)$, $f_0(530)$, $f_0(1070)$ and $K_0^*(960)$, and thereby suggests that these states correspond to the observed scalar states $a_0(980)$, σ, $f_0(980)$ and $K_0^*(930)$[3], respectively.

Oller [35] has already suggested that the $a_0(980)$, κ, $f_0(980)$ and σ 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 [35] show

$$\begin{pmatrix} f_0(980) \\ \sigma \end{pmatrix} = \begin{pmatrix} 0.28 & -0.96 \\ 0.96 & 0.28 \end{pmatrix} \begin{pmatrix} N \\ S \end{pmatrix}. \tag{12}$$

Clearly, the agreement between (11) and (12) is good.

It is worth mentioning that our suggested $q\bar{q}$ assignment for the ground scalar nonet is also favored by the

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[1] Here we take $M_\pi = 134.9766 \pm 0.0006$ MeV, $M_\rho = 775.8 \pm 0.5$ MeV, $M_K = 497.648 \pm 0.022$ MeV and $M_{K^*} = 896.10 \pm 0.27$ MeV [1].

[2] We take $M_\eta = 547.75 \pm 0.12$ MeV, $M_{\eta'} = 957.78 \pm 0.14$ MeV [1].

[3] It is supposed that it is possible for a wide strange resonance, $K_0^*(930)$, to exist in nature but yet not revealed in detectors as the ground scalar state, whereas the resonance $K_0^*(1430)$ is its radial excitation [13].

results suggested by the $U(3)\times U(3)$ σ model [11] and the $SU(3)$ σ model [12].

Finally, we remark also that the masses of $f_0(1099)$ and $f_0(530)$ predicted in the present work are below a typical range of 1730±50±80 MeV suggested by the Lattice QCD calculation for the ground scalar glueball [36]. 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.

5 Concluding remarks

In the presence of $a_0(980)$ and $D^*_{sJ}(2317)$ belonging to the $1\ ^3P_0$ $q\bar{q}$ multiplet, we estimate the mass of the $1\ ^3P_0$ kaon meson in the framework of the quasi-linear Regge trajectory. Then, in the framework of the meson-meson mixing, we suggest that $a_0(980)$, $K^*_0(1052)$, $f_0(1099)$ 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 nonstrange. We suppose that $K^*_0(1052)$, $f_0(1099)$ 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 [11–13,35] 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 $a_0(980)$ and $D^*_{sJ}(2317)$ are ordinary $1\ ^3P_0$ $q\bar{q}$ states may be reasonable.

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