THE STRUCTURE OF THE LIGHT SCALAR MESONS AND QCD SUM RULES *

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The structure of the light scalar mesons is elucidated by the investigation of the S-matrix poles and the $q\bar{q}$ spectral density in a coupled channel model that includes $\pi\pi$, $K\bar{K}$ and $q\bar{q}$ channels. It is shown that the dynamical origin of the σ and $f_0(980)$ mesons is consistent with the observed spectrum of the scalar states. The $K\bar{K}$ molecular picture of the $f_0(980)$ is in good agreement with recent experimental data on the decay $\varphi \to \gamma\pi\pi$ from Novosibirsk.

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1. Introduction

The structure of the light scalar mesons addresses different problems in hadron spectroscopy: strong channel coupling, the OZI rule violation, exotic states (glueballs, $q^2\bar{q}^2$), and the properties of the QCD vacuum. Recent theoretical studies (see [1–4] and references therein) have demonstrated that the appearance of dynamical states can naturally explain the striking difference of the observed spectrum of the $J^{PC} = 0^{++}$ states [5] from the other multiplets. The goal of this paper is to investigate the properties of the light scalar mesons in a coupled channel model where both the σ meson and the $f_0(980)$ arise as dynamical states due to strongly attractive interactions in the $\pi\pi$ and $K\bar{K}$ channels.

2. The $\pi\pi - K\bar{K} - q\bar{q}$ coupled channel model

Our approach is based on an exactly solvable Coupled Channel Model (CCM), which is an extended version of the one studied in [2]; it contains the $\pi\pi$, $K\bar{K}$, and $q\bar{q}$ channels ($J^{PC} = 0^{++}$, $I^G = 0^+$), and the interactions

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are approximated by separable potentials. The model parameters were determined by fitting the $\pi\pi$ scattering amplitude together with the $\pi\pi$ mass distribution in the decay $\varphi \to \gamma(\pi\pi)_{J=0}$ [6,7]. The detailed description of the model is given in [8].

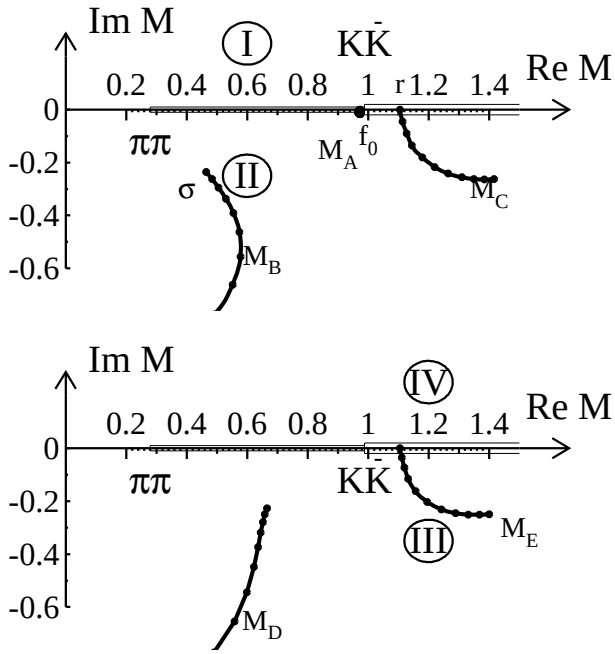


Fig. 1. The trajectories of the S-matrix poles in the complex mass plane (GeV) on the sheets II and III for the $K\bar{K} - \pi\pi$ and $q\bar{q} - \pi\pi$ couplings increasing from zero to the physical values.

The poles of the S-matrix in the complex mass plane are shown in Fig. 1. The $f_0(980)$ resonance corresponds to *one* S-matrix pole $M_A = (0.975 - i0.017)$ GeV close to the $K\bar{K}$ threshold; this pole has a dynamical origin and represents the molecular-like $K\bar{K}$ state. There are two poles corresponding to the σ meson: $M_B = (0.46 - i0.24)$ GeV on sheet II and $M_D = (0.67 - i0.23)$ GeV on sheet III. The dynamical origin of the σ meson is related to the attractive character of the effective $\pi\pi$ interaction which has a partial contribution from the coupling via the intermediate scalar $q\bar{q}$ states. Two poles at $M_C = (1.42 - i0.26)$ GeV (sheet II) and $M_E = (1.40 - i0.25)$ GeV (sheet III) originate from the bare $q\bar{q}$ state. The pole trajectories plotted in Fig. 1 were calculated for the $K\bar{K} - \pi\pi$ and $q\bar{q} - \pi\pi$ couplings changing from zero (the decoupled channels) to their physical values.

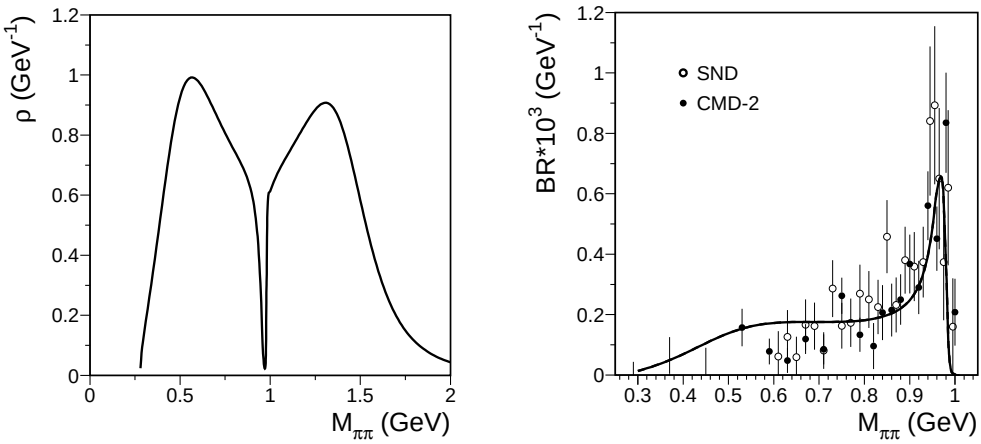


Fig. 2. (a) The spectral density of the $q\bar{q}$ state. (b) The $\pi\pi$ invariant mass distribution in the decay $\varphi \to \gamma\pi^0\pi^0$. The curve is the result of our CCM model. The experimental points are from [6] and [7].

The mixing between the $q\bar{q}$ and the two–meson channels is illustrated in Fig. 2(a) showing the calculated spectral density $\rho(M)$ of the $q\bar{q}$ state. In the weak–coupling limit, there would be a single peak corresponding to the bare $q\bar{q}$ state with mass $M^{(0)}_{q\bar{q}} = 1.11$ GeV. As a result of the strong $\pi\pi - q\bar{q}$ coupling a substantial fraction of the $q\bar{q}$ spectral density is present in the σ meson region. The peak around 1.3 GeV corresponds to the broad resonance originating from the $q\bar{q}$ state. This peak and the corresponding poles M_C and M_E can be associated with the $f_0(1370)$ meson.

The molecular picture of the $f_0(980)$ meson was found to be fully consistent with the data on the $\varphi \to \gamma\pi\pi$ decay. Fig. 2(b) shows the result of the CCM calculations of $\pi\pi$ invariant mass distribution in the decay $\varphi \to \gamma\pi^0\pi^0$ (see [8] for detailed discussion). The calculated branching ratio $\mathrm{BR}(\varphi \to \gamma\pi^0\pi^0) = 0.5\ BR(\varphi \to \gamma(\pi^+\pi^-)_{J=0}) = 1.2\ 10^{-4}$ is in good agreement with the experimental data $\mathrm{BR}(\varphi \to \gamma\pi^0\pi^0) = (1.14 \pm 0.10 \pm 0.12)10^{-4}$ [6] and $\mathrm{BR}(\varphi \to \gamma\pi^0\pi^0) = (1.08 \pm 0.17 \pm 0.09)\ 10^{-4}$ [7] and with the recent calculation in chiral perturbation theory $\mathrm{BR}(\varphi \to \gamma\pi^0\pi^0) = 0.8\ 10^{-4}$ [9].

3. Conclusion

The structure of the S–matrix poles in our coupled channel model shows the dynamical origin of the σ and $f_0(980)$ mesons: both of them are produced by strongly attractive interactions in the $\pi\pi$ and $K\bar{K}$ channels. The distinction between genuine $q\bar{q}$ states and dynamical resonances, σ and $f_0(980)$, can be demonstrated in the limit $N_c \to \infty$, which implies vanishing meson–

meson interaction, where the $q\bar{q}$ states turn into infinitely narrow resonances while the dynamical states disappear altogether. Our calculation of the decay $\varphi \to \gamma\pi\pi$ shows that the $K\bar{K}$ molecular picture of the $f_0(980)$ is in good agreement with the recent experimental data.

The structure of the $q\bar{q}$ state embedded into the mesonic continuum has been analyzed using the calculated $q\bar{q}$ spectral density $\rho(M)$. While the high–energy part of $\rho(M)$ is related to the $f_0(1370)$ resonance, there is also a significant contribution to $\rho(M)$ in the region of σ meson, which demonstrates the strong coupling between the $\pi\pi$ and $q\bar{q}$ channels. The same approach can also be used for studying the QCD sum rules related to the gluon condensate by including the mixing with the scalar glueballs in an extended coupled channel model. The results of these studies will be published elsewhere.

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