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SCALAR MESONS: A CHIRAL LAGRANGIAN FRAMEWORK FOR THEIR MIXING AND SUBSTRUCTURE

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Abstract

The highlights of studies of mixing among scalar mesons below and above 1 GeV within a nonlinear chiral Lagrangian framework is briefly presented. Two scalar meson nonets are introduced to explore the mass spectrum and decay properties of the I=1/2 and I=1 scalar states. For the I=0 states, in addition to these two nonets a scalar glueball component is also taken into account, and together with the constraints from the I=1/2 and I=1 sectors, their mass spectrum is studied. The fact that an ideally mixed $q\bar{q}$ scalar nonet has a mass ordering which is opposite to that of an ideally mixed four-quark scalar nonet is exploited to gain some insight into the quark substructure of the I=1/2, I=1 and I=0 states below and above 1 GeV. Consequently, numerical estimates of various components of these states (two quark and four quark components of I=1/2 and I=1 states, and two quark, four quark and glue component of I=0 states) are determined.

Scalar states below and above 1 GeV are shown in Fig. 1, and are all listed/discussed in PDG [1]. Not all of these states are well-established: Among these the $f_0(600)$ [or σ] and the $f_0(1370)$ have large uncertainties on their mass and decay widths, as well as the $K_0^*(800)$ [or κ] which has been particularly under a special scrutiny and debate. It is now generally believed that the states below 1 GeV are something other than pure $q\bar{q}$ states, as opposed to those above 1 GeV which have been the favored candidates for a $q\bar{q}$ nonet, even though some of their properties do not quite follow a $q\bar{q}$ assignment. Possible solutions for the status of the lowest-lying scalar states include the MIT bag model, $K\overline{K}$ molecule and unitarized quark model, as well as many recent investigations (see [2] for a selection of refs.). There are reasons to investigate the mixing between the scalar mesons below and above

1 GeV. First, intuitively this is not inconceivable as some of these states [such as $f_0(600)$ and $f_0(1370)$ as well as $K_0^*(800)$] are broad and their masses spread over a wide range, therefore one may expect that some of their properties may overlap. Second, the available experimental data may already be pointing to such mixings. For example, a close look at some of the properties of the $a_0(1450)$ and $K_0^*(1430)$ [which are expected to be two members of the same $q\bar{q}$ scalar meson nonet (see PDG [1])] shows surprising deviations from a $q\bar{q}$ nonet properties. Clearly, their masses are rather puzzling [1]: If these two states belong to the same $q\bar{q}$ nonet, then why should $a_0(1450)$ (which does not contain a strange quark) be heavier than $K_0^*(1430)$ (which does contain a strange quark)? There are also decay properties of these states that cannot be understood based on a pure $q\bar{q}$ picture. As a possible solution, a description of the $I = 1/2$ and $I = 1$ scalar states below and above 1 GeV in terms of two nonets of scalars and within a nonlinear chiral Lagrangian framework was explored in ref. [3]. In that work, it was shown that if an underlying "bare" four-quark nonet N lies beneath an underlying "bare" two-quark nonet N', then as a result of mixing of N and N' we can easily understand why $a_0(1450)$ becomes heavier than $K_0^*(1430)$ (in addition, the decay properties of these states can be understood in this scenario). Fig. 1 shows how this mechanism works. It was also found in [3] that the $I = 1$ states are close to equal admixtures of two and four-quark states, whereas the $I = 1/2$ states are less mixed, with $K_0^*(800)$ containing close to 75% four-quak and 25% two-quark [and vice versa for $K_0^*(1430)$]. What does this scenario say about the $I = 0$ states? This question was studied in [4] in which the implications of such underlying mixing of nonets N and N' on the $I = 0$ states was investigated. Fig. 1 summarizes the results and shows how the $I = 0$ states originate from the four-quark nonet N, two-quark nonet N' and a scalar glueball G. The mass part of the Lagrangian for N, N' and G is (in the leading order of mixing):

$$\begin{aligned}\mathcal{L}_{mass} = &-a\mathrm{Tr}(NN) - b\mathrm{Tr}(NN\mathcal{M}) - a'\mathrm{Tr}(N'N') - b'\mathrm{Tr}(N'N'\mathcal{M})\\ &-c\mathrm{Tr}(N)\mathrm{Tr}(N) - d\mathrm{Tr}(N)\mathrm{Tr}(N\mathcal{M}) - c'\mathrm{Tr}(N')\mathrm{Tr}(N') - d'\mathrm{Tr}(N')\mathrm{Tr}(N'\mathcal{M})\\ &-\gamma\mathrm{Tr}\,(NN') - \rho\mathrm{Tr}(N)\mathrm{Tr}(N') - gG^2 - eG\mathrm{Tr}\,(N) - fG\mathrm{Tr}\,(N') \qquad (1)\end{aligned}$$

in which $\mathcal{M}$ is the usual quark mass spurion. The mass of the $I = 1/2$ and $I = 1$ states involve terms a, b, a', b' and γ only. The mass of $I = 0$ states involve all 13 parameters. The mixing of $I = 0$ states is clearly much more complicated and amounts to 5×5 rotation matrices among N, N' and G. The result of the numerical analysis of [4] for the prediction of the substructure of the $I = 0$ states are given in Fig. 2, in which, in the middle, the dashed lines represent nonet N (that has a mass ordering consistent with an ideally mixed four-quark nonet), the solid lines represent nonet N' (that has a mass ordering consistent with an ideally mixed two-quark nonet) and the box represents the scalar glueball predicted in this model. Identifying the components of the two bare nonets with the corresponding members of an ideally mixed four-quark nonet and ideally mixed two-quark nonet results in conclusion that the bare masses in nonet N are (from bottom to top): $m(\overline{u}\overline{d}ud)$ = 0.83 GeV, $m(\overline{d}\overline{s}ud)$ = 1.06 GeV, $m\left[(\overline{s}\overline{d}ds + \overline{s}\overline{u}us)/\sqrt{2}\right]$ = 1.24 GeV; and the bare masses in nonet N' are (from bottom to top): $m\left[(\overline{u}u + \overline{d}d)/\sqrt{2}\right]$ = 1.24 GeV, $m(\overline{u}s) = 1.31$ GeV and $m(\overline{s}s) = 1.38$ GeV. The uncertainty of the glueball mass (shown by the height of the box, approximately between 1.5 GeV to 1.7 GeV) is due to the uncertainty of the input masses of $f_0(600)$ and $f_0(1370)$. In Fig. 1, on the right, the $I = 0$ physical states are shown, and the height of the two boxes represent the prediction of the present model for the uncertainties of the masses of $f_0(600)$ and $f_0(1370)$, which are (in this model) approximately in ranges $0.4 - 0.7$ GeV and $1.3 - 1.45$ GeV, respectively. On the left, the $I = 1/2$ and $I = 1$ physical states are shown [note the level-crossing that explains the properties of $a_0(1450)$ and $K_0^*(1430)$]. The arrows show the dominant component of each physical state. Finally, the detailed numerical analysis of [4] predicts the substructure of the $I = 0$ scalars (in terms of two quark, four quark and glueball components) which are given in Fig. 2.

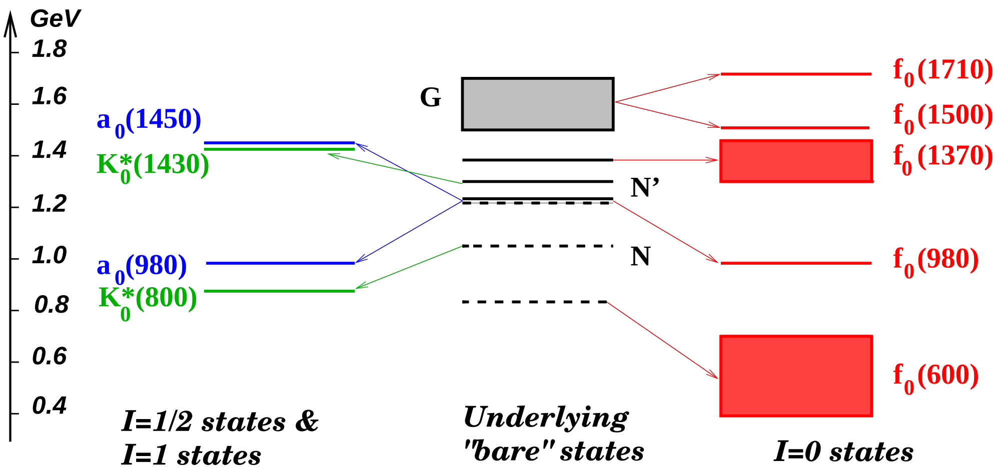

Figure 1: Prediction of the present model for the substructure of the $I = 1/2$, $I = 1$ scalar states below 2 GeV (left) and for the $I = 0$ scalar states below 2 GeV (right) in terms of the underlying “bare” states (middle).

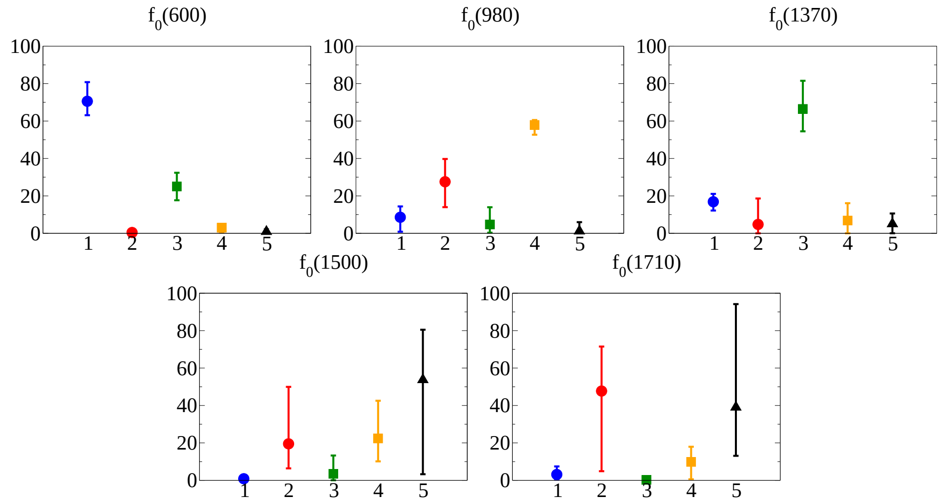

Figure 2: Components 1 to 5 respectively represent $\overline{u}\overline{d}ud$, $(\overline{s}\overline{d}ds+\overline{s}\overline{u}us)/\sqrt{2}$, $\overline{s}s$, $(\overline{u}u+\overline{d}d)/\sqrt{2}$, and glueball. The symbols represent the averaged values of each component and the error bars reflect the uncertainties of $m^{\rm exp.}[f_0(600)]$ and $m^{\rm exp.}[f_0(1370)]$.

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