ON THE EXISTENCE OF LIGHT-SCALAR MESONS
\( \kappa(800) \) and \( \kappa'(1150) \):
THE \( \tilde{U}(12) \) SCHEME AND BES II DATA

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Abstract

We present that there should exist a light strange-scalar meson \( \kappa' \), in addition to the \( \kappa(800) \), which has a mass around 1.1-1.2 GeV, a rather narrow width, and couples strongly to \( \kappa(800)\sigma(600) \) (K\( \pi\pi\)) but weakly to K\( \pi \), based upon the \( \tilde{U}(12) \)-classification scheme of hadrons and BES II data on \( J/\psi \rightarrow K(892)^0K^+\pi^- \) decay.

1 Introduction

Recently, the existence of the light-scalar mesons, \( \sigma(600) \) and \( \kappa(800) \), has been confirmed by showing the presence of respective poles in the \( \pi\pi \) \(^1\), \(^2\) and K\( \pi \) \(^2\), \(^3\) scattering amplitudes, in addition to results of Breit-Wigner fits to D- and J/\( \psi \)-decay data, respectively, from the E791 \(^4\) and BES \(^5\), \(^6\) collaborations. However, the nature of these resonances, together with the
f_0(980) and a_0(980), has been a long-standing problem in controversy, where it is not obvious how these light-scalar mesons are understood in terms of quarks and gluons in QCD.

Here we focus on the strange scalar mesons and discuss the existence of an extra κ’ meson, in addition to the normal κ(800), and their strong decay properties.

2 Existence of the extra κ’ meson

2.1 The \(\tilde{U}(12)\)-classification scheme of hadrons

The \(\tilde{U}(12)\)-classification scheme of hadrons, \(^7,^8\) which has a manifestly covariant framework of \(\tilde{U}(12)_{SF} \times O(3,1)_{L}\), generalized covariantly from nonrelativistic \(SU(6)_{SF} \times O(3)_{L}\) by boosts, separating the spin and space degrees of freedom, gives covariant quark representations for composite hadrons with definite Lorentz and chiral transformation properties. The \(\tilde{U}(12)\)-classification scheme has a “static” unitary \(U(12)_{SF}\) spin-flavor symmetry in the rest frame of hadrons, embedded in the covariant \(\tilde{U}(12)\)-representation space, where \(\tilde{U}(12)\) has as its subgroups the pseudounitary homogeneous Lorentz group for Dirac spinors and unitary symmetry group for light-quark flavors,

\[
\tilde{U}(12)_{SF} \supset U(4)_D \times U(3)_F.
\]

Since

\[
U(12)_{SF} \supset U(4)_D \times U(3)_F, \quad (2a)
\]

\[
U(4)_D \supset SU(2)_\rho \times SU(2)_\sigma, \quad (2b)
\]

the static \(U(12)_{SF}\) symmetry includes both the nonrelativistic spin-flavor \(SU(6)_{SF}\) and chiral \(U(3)_L \times U(3)_R\) symmetry\(^1\) as

\[
U(12)_{SF} \supset SU(6)_{SF} \times SU(2)_\rho, \quad (3a)
\]

\[
U(12)_{SF} \supset U(3)_L \times U(3)_R \times SU(2)_\sigma, \quad (3b)
\]

\(^1\)Hadron states are classified, aside from flavors, by the quantum numbers \(\rho,S,L,J,P\), where \(\rho\) is the net quark \(\rho\)-spin concerning \(SU(2)_\rho\), \(S\) the ordinary net quark \(\sigma\)-spin, \(L\) the total quark orbital angular momentum, and \(J\) and \(P\) the total spin and parity of hadrons.
where \( SU(2)_\rho \) and \( SU(2)_\sigma \) are the Pauli-spin groups concerning the boosting and intrinsic spin rotation, respectively, of constituent quarks, being connected with decomposition of Dirac \( \gamma \)-matrices, \( \gamma = \rho \times \sigma \). This implies that the \( \bar{U}(12) \)-classification scheme is able to incorporate effectively, according to dynamical consequences of QCD, the effects of chiral symmetry and its spontaneous breaking, essential for understanding of properties of the low-lying hadrons, into what is called a constituent quark model.

In the \( \bar{U}(12) \)-classification scheme there are two light-scalar meson multiplets, normal \( S^{(N)} \) and extra \( S^{(E)} \) with \( J^{PC} = 0^{++} \) and \( 0^{+-} \), respectively, in the ground level \( (L = 0) \). These \( N \)- and \( E \)-scalar multiplets are the chiral partners, respectively, of the \( N \)- and \( E \)-pseudoscalar multiplets and they form linear representations of the \( U(3)_L \times U(3)_R \) chiral symmetry. Concerning the strange scalar mesons, now we have two \( \kappa \) mesons, \( \kappa^{(N)}(0^{++}) \) and \( \kappa^{(E)}(0^{+-}) \). Note that the observed \( \kappa(800) \) and missing \( \kappa' \) are generally mixtures of them. 9)

2.2 The BES II data

The \( K^+\pi^- \) mass spectrum in \( J/\psi \to K^*(892)^0 K^+\pi^- \) decay observed by the BES II experiment 6) is shown in fig.1 where there seems to be a visible bump structure at 1.1-1.2 GeV. If this structure is attributed to the existence of a new \( K\pi \) resonance, its spin-parity will likely be \( 0^+ \) or \( 1^- \), since higher spins are unfavorable for such a low-mass state, and also its width is supposed to be narrow, judging from the data structure.

We hereafter refer to the strange scalar meson mentioned above as the \( \kappa'(1150) \).2

3 Strong decays of the \( \kappa(800) \) and \( \kappa'(1150) \) mesons

We examine strong two-body decays of the \( \kappa(800) \) and \( \kappa'(1150) \) as mixtures of the \( \kappa^{(N)} \) and \( \kappa^{(E)} \) in the \( \bar{U}(12) \)-classification scheme as follows:

\[
\kappa(800) \to K + \pi
\]  

2A recent lattice-QCD study on light-scalar mesons by the UKQCD collaboration 10) suggests that the \( a_0(980) \) is predominantly a conventional \( \bar{q}q \) state, while the \( \kappa(800) \) is too light to be assigned to the \( \bar{q}q \) state, which is expected to have a mass about 100-130 MeV heavier than the \( a_0(980) \).
Figure 1: The $K^+\pi^-$ invariant mass spectrum in $J/\psi \to \bar{K}^*(892)^0K^+\pi^-$ decay from BES II. The dark shaded histograms show contribution from the $\kappa(800)$.

and

\[ \kappa'(1150) \to K + \pi, \]  
\[ \to K + \eta, \]  
\[ \to \kappa(800) + \sigma(600) \rightarrow K\pi\pi\pi. \] (5c)

In the actual calculations of decay matrix elements we treat the strange mesons $K$, $\kappa$ and $\kappa'$ as quark-composite $n\bar{s}$ states, while $\pi$, $\eta$ and $\sigma$ as external local fields.

3.1 Quark-pseudoscalar and quark-scalar couplings

For the effective quark-pseudoscalar coupling inside hadrons we assume the two independent interactions of the forms

\[ g_{ps}\bar{q}(\gamma_5)q\phi \] for pseudoscalar type, \hspace{1cm} (6a)
\[ g_{pv}\bar{q}(\gamma_5\gamma_\mu)q\partial_\mu\phi \] for pseudovector type. \hspace{1cm} (6b)

The effective quark-scalar coupling is simply related to the quark-pseudoscalar coupling, assuming the $\sigma$ meson is a chiral partner of the $\pi$ meson in the linear
representation of chiral symmetry,\textsuperscript{3} and given as
\begin{equation}
g_{ps}\bar{q}q\phi_{\sigma},\tag{7a}
\end{equation}
\begin{equation}
g_{pv}\bar{q}\gamma_{\mu}\gamma_{\mu}\phi_{\sigma}.
\tag{7b}
\end{equation}
Then the matrix elements for the pseudoscalar($\pi,\eta$)-emitted processes are generally given by
\begin{equation}
T^{(P)} = T_{ps}^{(P)} + T_{pv}^{(P)}
\tag{8a}
\end{equation}
with
\begin{equation}
T_{ps}^{(P)} = g_{ps}\langle \overline{W}(v')(-i\gamma_{5}\phi_{p})W(v)i\nu\gamma\rangle I_{G}^{(P)}(q^2) + \text{c.c.}
\tag{8b}
\end{equation}
\begin{equation}
T_{pv}^{(P)} = g_{pv}\langle \overline{W}(v')(-\gamma_{5}\gamma_{\mu}q_{\mu}\phi_{p})W(v)i\nu\gamma\rangle I_{G}^{(P)}(q^2) + \text{c.c.}
\tag{8c}
\end{equation}
where \(\overline{W}(v')\) and \(W(v')\) are the spin wave functions of initial- and final-state mesons,\textsuperscript{7} \(I_{G}^{(P)}(q^2)\) a space-time part of the Lorentz-invariant transition form factor,\textsuperscript{4} \(v\) and \(v'\) the 4-velocities, \(q_{\mu}\) the momentum of emitted pseudoscalar mesons, and \(\langle \cdots \rangle\) means the trace taken over the spinor and flavor indices.

The matrix elements for the $\sigma$-emitted processes are given likewise by
\begin{equation}
T^{(\sigma)} = T_{ps}^{(\sigma)} + T_{pv}^{(\sigma)}
\tag{9a}
\end{equation}
with
\begin{equation}
T_{ps}^{(\sigma)} = g_{ps}\langle \overline{W}(v')(\phi_{\sigma})W(v)i\nu\gamma\rangle I_{G}^{(\sigma)}(q^2) + \text{c.c.}
\tag{9b}
\end{equation}
\begin{equation}
T_{pv}^{(\sigma)} = g_{pv}\langle \overline{W}(v')(-i\gamma_{\mu}q_{\mu}\phi_{\sigma})W(v)i\nu\gamma\rangle I_{G}^{(\sigma)}(q^2) + \text{c.c.}
\tag{9c}
\end{equation}

3.2 Evaluation of the coupling constants

The coupling constants \(g_{ps}\) and \(g_{pv}\) were evaluated by Maeda et al.\textsuperscript{11} They calculated the $D$-wave/$S$-wave amplitude ratio and width of $b_{1}(1235) \rightarrow \omega(782) + \pi$ decay and obtained the values \(g_{ps} = 2.07\ \text{GeV}\) and \(g_{pv} = 14.0\), using their experimental values \(D/S = 0.277 \ (\pm 0.027)\) and \(\Gamma[\omega\pi] \approx \Gamma_{\text{tot}} = 142 \ (\pm 9)\ \text{MeV}\textsuperscript{12}\) as input.

\textsuperscript{3}Here we take chiral $SU(2)_{L} \times SU(2)_{R}$ as imposed symmetry.

\textsuperscript{4}This is obtained from overlap integral of space-time wave functions for initial and final mesons. In the present analysis we simply take $I_{G}^{(P)} = I_{G}^{(\sigma)} = 1$, since initial and final mesons both belong to the ground-state ($L = 0$) multiplet in the $\tilde{U}(12)_{SF} \times O(3,1)_{L}$ -classification scheme.
We now calculate the decay width of $K^*(892) \rightarrow K + \pi$ to see the validity of the present decay model and obtain a reasonable value of $\Gamma[K\pi] = 58$ MeV, compared with the experimental value $\Gamma^{\text{tot}} = 50.8 \pm 0.9$ MeV. 12)

3.3 Strong decay widths of the $\kappa(800)$ and $\kappa'(1150)$

Since the $\kappa(800)$ and $\kappa'(1150)$ are generally mixtures of $\kappa(N)$ and $\kappa(E)$, we introduce the mixing angle $\theta$, which is the only free parameter in the present analysis, by

$$|\kappa(800)\rangle = \cos \theta \ |\kappa(E)\rangle + \sin \theta \ |\kappa(N)\rangle,$$

$$|\kappa'(1150)\rangle = -\sin \theta \ |\kappa(E)\rangle + \cos \theta \ |\kappa(N)\rangle.$$  \hspace{1cm} (10a)

(10b)

Here we take the mixing angle $\theta$ to be around $-65^\circ$ so that the $\kappa(800)$ has a width of several hundred MeV and the $\kappa'(1150)$ a rather narrow width, in conformity with their observed properties, $\Gamma[\kappa(800)] = 550 \pm 34$ MeV 12) and the BES II data mentioned above for the $\kappa'(1150)$.

Using the mixing angle $\theta = -65^\circ$, we evaluate the partial decay widths of the $\kappa(800)$ and $\kappa'(1150)$ for respective channels in the following.

3.3.1 Decay of the $\kappa(800)$

If we take a mass of the $\kappa(800)$ to be 800 MeV, we obtain $\Gamma[K\pi] = 354$ MeV for $\kappa(800) \rightarrow K + \pi$. This is consistent, though somewhat small, with the experimental value $\Gamma^{\text{tot}} \approx \Gamma[K\pi] = 550 \pm 34$ MeV.

3.3.2 Decays of the $\kappa'(1150)$

We take tentatively 1150 MeV for a mass of the missing state $\kappa'(1150)$ and then obtain

$$\Gamma[K\pi] = 18 \text{ MeV for } \kappa'(1150) \rightarrow K + \pi,$$

$$\Gamma[K\eta] = 2 \text{ MeV for } \kappa'(1150) \rightarrow K + \eta,$$

$$\Gamma[\kappa\sigma] = 30 \text{ MeV for } \kappa'(1150) \rightarrow \kappa(800) + \sigma(600),$$

where mass values of the $\kappa(800)$ and $\sigma(600)$ are taken tentatively to be 600 MeV and 350 MeV, respectively, and the singlet-octet mixing angle for the
pseudoscalar mesons $\eta$ and $\eta'$ to be $\theta_P = -11.5^\circ$. From these partial decay widths we could estimate the total width to be

$$\Gamma^{\text{tot}} \approx \Gamma[K\pi] + \Gamma[K\eta] + \Gamma[\kappa\sigma] = 50 \text{ MeV}. \quad (12)$$

It may be worthwhile to mention that the dominant decay mode of the $\kappa'(1150)$ is not $K\pi$ but $\kappa(800)\sigma(600)$ ($K\pi\pi\pi$), the $K\pi$ branching ratio is $\Gamma[K\pi]/\Gamma^{\text{tot}} \approx 0.36$, and therefore the $\kappa'(1150)$ is supposed not to be seen in the $K\pi$ scattering processes.\(^5\)

Here it goes without saying that the present treatment of the $\kappa(800)$ and $\sigma(600)$ as narrow resonances is quite a rough approximation and the evaluated decay width to $\kappa(800)\sigma(600)$ does not really make sense. In practice we should perform a dynamical calculation of the decay chain $\kappa'(1150) \rightarrow \kappa(800)\sigma(600) \rightarrow K\pi\pi\pi$, taking into account the effects of the broad $\kappa$ and $\sigma$ widths.

4 Concluding Remarks

We presented that there should exist an extra $\kappa'$ meson which has a mass around 1.1-1.2 GeV, a rather narrow width, and couples strongly to $\kappa(800)\sigma(600)$ ($K\pi\pi\pi$) but weakly to $K\pi$, based upon the $\tilde{U}(12)$-classification scheme and BES II data.

The strong coupling to $\kappa(800)\sigma(600)$ suggests that to observe the $\kappa'$ meson experimentally it might be favorable to study the $K\pi\pi\pi$ system, for example, in $J/\psi \rightarrow K^*(892)(K\pi\pi\pi)$ decay and $e^+e^- \rightarrow K^*(892)(K\pi\pi\pi)$ processes. However, if the main component of $\kappa'$ is $\kappa^{(E)}(0^{+-})$, as is in the present analysis (taking $\theta = -65^\circ$ in eq.10b), the $\kappa'$ production in these processes\(^6\) would be suppressed by charge-conjugation ($C$) invariance in the limit of $SU(3)_f$ symmetry.\(^{14}\) Rather, the $\chi_{0,1,2} \rightarrow K^*(892)(K\pi\pi\pi)$ decay processes would be more promising, since they are $C$-parity allowed decays in the $SU(3)_f$ limit.

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\(^5\)This is consistent with experimental data\(^{13}\) on the $S$-wave phase of the $K\pi$ scattering amplitude displaying no typical resonance-like behavior around the energy region 1.1-1.2 GeV.

\(^6\)The $J/\psi$ and virtual photon from $e^+e^-$ annihilation have negative $C$ parity. The $\kappa'(1150)$ production in the $J/\psi \rightarrow \bar{K}^*(892)^0K^+\pi^-$ decay process is doubly suppressed by $C$ invariance in the $SU(3)_f$ limit and its small $K\pi$ branching ratio. This suppression coincides with the experimental data of quite small production of the $\kappa'(1150)$ compared to the $\kappa(800)$, as is seen in fig.1.
In a future study it is necessary to calculate dynamically the decay $\kappa' \to \kappa(800)\sigma(600) \to K\pi\pi\pi$ in order to obtain a more realistic decay width and also to make the present decay model more effective by examining various strong decay processes.

References

1. I. Caprini et al., Phys. Rev. Lett. 96, 132001 (2006); Z.Y. Zhou et al., JHEP 02, 043 (2005); A. Dobado et al., Phys. Rev. D 56, 3057 (1997).

2. J.R. Peláez, Mod. Phys. Lett. A 19, 2879 (2004).

3. S. Descotes-Genon et al., Eur. Phys. J. C 48, 553 (2006); Z.Y. Zhou et al., Nucl. Phys. A 775, 212 (2006); H.Q. Zheng et al., Nucl. Phys. A 733, 235 (2004).

4. E.M. Aitala et al. [E791 Collaboration], Phys. Rev. Lett. 86, 770 (2001); E.M. Aitala et al. [E791 Collaboration], Phys. Rev. Lett. 89, 121801 (2002).

5. M. Ablikim et al. [BES Collaboration], Phys. Lett. B 598, 149 (2004).

6. M. Ablikim et al. [BES Collaboration], Phys. Lett. B 633, 681 (2006).

7. S. Ishida et al., Prog. Theor. Phys. 104, 785 (2000).

8. S. Ishida et al., Phys. Lett. B 539, 249 (2002).

9. K. Yamada, in: Proceedings of the Seminar on Perspectives for Studies of Chiral Particles at BES, (eds. W.G. Li et al., IHEP, Beijing, February 2006), 23 (KEK Proceedings 2006-8, November 2006).

10. C. McNeile et al. [UKQCD Collaboration], Phys. Rev. D 74, 014508 (2006).

11. T. Maeda et al., these proceedings.

12. W.-M. Yao et al. [Particle Data Group], J. Phys. G 33, 1 (2006) and 2007 partial update for edition 2008 (URL: http://pdg.lbl.gov).

13. D. Aston et al., Nucl. Phys. B296, 493 (1988).

14. H.E. Haber et al., Phys. Rev. D 32, 2961 (1985).