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## Two or Four: A Hint from Scalar Mesons in Radiative $\phi$ Decays ? \*)

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In this write-up, we summarize our recent analysis of radiative decays involving light scalar mesons. Our analysis using the vector meson dominance model at tree level indicates that it may be difficult to distinguish  $qq\bar{q}\bar{q}$  picture and  $q\bar{q}$  picture for the light scalar nonet. Our result on the process of  $\phi \rightarrow \pi^0\eta\gamma$  shows that the derivative-type  $f_0K\bar{K}$  interaction reproduces experimental data below 950 GeV well, but gives a poor fit above 950 GeV, i.e., in the energy region around the mass of  $a_0(980)$ , but that the discrepancy can be compensated by the effect of the  $K$  loop.

### §1. Introduction

According to recent theoretical and experimental analyses, there is a strong possibility that nine light scalar mesons exist below 1 GeV, and they form a scalar nonet.<sup>1)</sup>  $\sigma(600)$  and  $\kappa(900)$  together with the well-established  $f_0(980)$  and  $a_0(980)$ . As is shown in Ref. 2), the mass hierarchy of the light scalar nonet can be explained qualitatively when the members of the nonet have a  $qq\bar{q}\bar{q}$  quark structure. The 4-quark scalar mesons have the same quantum numbers as the ordinary scalar mesons made from the quark and anti-quark (2-quark picture). The patterns of the interactions of the scalar mesons to other mesons made from  $q\bar{q}$ , on the other hand, depend on the quark structure of the scalar mesons. The analysis of the interactions of the scalar mesons will shed some light on the quark structure of the scalar nonet. In Refs. 2), 3), several hadronic processes related to the scalar mesons are studied, which shows that the scalar nonet takes dominantly the  $qq\bar{q}\bar{q}$  structure.

For getting more information on the structure of the low-lying scalar mesons, we studied the radiative decays involving scalar mesons in Refs. 4) and 5). In this write-up we summarize the main results of the analyses.

### §2. Scalar Nonet Field

In Ref. 2), the scalar meson nonet is embedded into the  $3 \times 3$  matrix field  $N$  as

$$N = \begin{pmatrix} (N_T + a_0^0)/\sqrt{2} & a_0^+ & \kappa^+ \\ a_0^- & (N_T - a_0^0)/\sqrt{2} & \kappa^0 \\ \kappa^- & \bar{\kappa}^0 & N_S \end{pmatrix}, \quad (2.1)$$

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\*) Talk given by M. Harada at Yukawa International Seminar (YKIS) 2006 “New Frontiers in QCD –Exotic Hadrons and Hadronic Matter–”.

where  $N_T$  and  $N_S$  represent the ‘‘ideally mixed’’ fields. The physical  $\sigma(600)$  and  $f_0(980)$  fields are expressed by the linear combinations of these  $N_T$  and  $N_S$  as

$$\begin{pmatrix} \sigma \\ f_0 \end{pmatrix} = \begin{pmatrix} \cos \theta_S & -\sin \theta_S \\ \sin \theta_S & \cos \theta_S \end{pmatrix} \begin{pmatrix} N_S \\ N_T \end{pmatrix}, \quad (2.2)$$

where  $\theta_S$  is the scalar mixing angle. The scalar mixing angle  $\theta_S$  can parameterize the quark contents of the scalar nonet field: The case with  $\theta_S = \pm 90^\circ$  is a natural assignment of the scalar meson nonet based on the  $q\bar{q}$  picture, while the case with  $\theta_S = 0^\circ$  or  $180^\circ$  is a natural assignment based on the  $qq\bar{q}\bar{q}$  picture (see, e.g., Ref. 2) for details). Then, the present treatment of nonet field with the scalar mixing angle can express both pictures for quark contents.

By fitting to the masses of the scalar nonet members, the value of  $\theta_S$  was found<sup>2)</sup> to be either  $\theta_S \simeq -20^\circ$  (corresponding to the case where the scalar nonet is dominantly made from  $qq\bar{q}\bar{q}$ ) or  $\theta_S \simeq -90^\circ$  (corresponding to the case where the scalar nonet is from  $q\bar{q}$ ). Some preference for the  $\theta_S = -20^\circ$  case for obtaining the best value of the coupling constant  $\gamma_{f\pi\pi}$ , was expressed in section IV of Ref. 2).

### §3. Radiative Decays Involving Light Scalar Mesons

In Ref. 4), the trilinear scalar-vector-vector terms were included into the effective Lagrangian as

$$\begin{aligned} \mathcal{L}_{SVV} = & \beta_A \epsilon_{abc} \epsilon^{a'b'c'} [F_{\mu\nu}(\rho)]_{a'}^a [F_{\mu\nu}(\rho)]_{b'}^b N_c^c + \beta_B \text{tr}[N] \text{tr}[F_{\mu\nu}(\rho)F_{\mu\nu}(\rho)] \\ & + \beta_C \text{tr}[NF_{\mu\nu}(\rho)] \text{tr}[F_{\mu\nu}(\rho)] + \beta_D \text{tr}[N] \text{tr}[F_{\mu\nu}(\rho)] \text{tr}[F_{\mu\nu}(\rho)], \quad (3.1) \end{aligned}$$

where  $N$  is the scalar nonet field defined in Eq. (2.1).  $F_{\mu\nu}(\rho)$  is the field strength of the vector meson fields defined as  $F_{\mu\nu}(\rho) = \partial_\mu \rho_\nu - \partial_\nu \rho_\mu - i\tilde{g}[\rho_\mu, \rho_\nu]$ , with  $\tilde{g} \simeq 4.04$ <sup>6)</sup> being the coupling constant. In Ref. 4), the vector meson dominance is assumed to be satisfied in the radiative decays involving the scalar mesons. Then, the above Lagrangian (3.1) determines all the relevant interactions. Actually, the  $\beta_D$  term will not contribute so there are only three relevant parameters  $\beta_A$ ,  $\beta_B$  and  $\beta_C$ .

We determined the values of  $\beta_A$  and  $\beta_C$  from the experimental values of  $\Gamma(a_0 \rightarrow \gamma\gamma)$  and  $\Gamma(\phi \rightarrow a_0\gamma)$ , independently of the scalar mixing angle  $\theta_S$ . The value of  $\beta_B$ , on the other hand, depends on  $\theta_S$  and there are two possible solutions for each  $\theta_S$ . We determined the value for  $\theta_S = -20^\circ$  as well as for  $\theta_S = -90^\circ$ , and then made several predictions on radiative decays such as  $\Gamma(\phi \rightarrow f_0\gamma)$  and  $\Gamma(\sigma \rightarrow \gamma\gamma)$ . We found<sup>4)</sup> that the predictions for two cases of the scalar mixing angle are very close to each other (see Table I). This result indicates that it may be difficult to distinguish two pictures just from radiative decays. Of course, other radiative decays should be studied to get more information on the structure of the scalar mesons.

We should note that our prediction on the  $\phi \rightarrow f_0\gamma$  is too small when compared with experiment.<sup>1),7)</sup> A preliminary investigation including the effect of mixing between a light non- $q\bar{q}$  scalar nonet  $N$  and a heavier  $q\bar{q}$ -type nonet  $N'$  described through a mixing Lagrangian  $\mathcal{L}_{\text{mix}} = \gamma \text{Tr}(NN')$  introduced to explain the properties of the  $I = 1$  and  $I = 1/2$  scalar meson in Ref. 8) showed that the width is still too

$\theta_S$	$-20^\circ$		$-90^\circ$	
$\beta_A$	$0.72 \pm 0.12$	$0.72 \pm 0.12$	$0.72 \pm 0.12$	$0.72 \pm 0.12$
$\beta_B$	$0.61 \pm 0.10$	$-0.62 \pm 0.10$	$-0.12 \pm 0.13$	$1.1 \pm 0.1$
$\beta_C$	$7.7 \pm 0.52$	$7.7 \pm 0.52$	$7.7 \pm 0.52$	$7.7 \pm 0.52$
$\Gamma(\sigma \rightarrow \gamma\gamma)$	$0.024 \pm 0.023$	$0.38 \pm 0.09$	$0.023 \pm 0.024$	$0.37 \pm 0.10$
$\Gamma(\phi \rightarrow \sigma\gamma)$	$137 \pm 19$	$33 \pm 9$	$140 \pm 22$	$35 \pm 11$
$\Gamma(\omega \rightarrow \sigma\gamma)$	$16 \pm 3$	$33 \pm 4$	$17 \pm 4$	$33 \pm 5$
$\Gamma(\rho \rightarrow \sigma\gamma)$	$0.23 \pm 0.47$	$17 \pm 4$	$0.20 \pm 0.43$	$17 \pm 4$
$\Gamma(f_0 \rightarrow \omega\gamma)$	$126 \pm 20$	$88 \pm 17$	$125 \pm 19$	$86 \pm 16$
$\Gamma(f_0 \rightarrow \rho\gamma)$	$19 \pm 5$	$3.3 \pm 2.0$	$18 \pm 8$	$3.4 \pm 3.2$
$\Gamma(a_0 \rightarrow \omega\gamma)$	$641 \pm 87$	$641 \pm 87$	$641 \pm 87$	$641 \pm 87$
$\Gamma(a_0 \rightarrow \rho\gamma)$	$3.0 \pm 1.0$	$3.0 \pm 1.0$	$3.0 \pm 1.0$	$3.0 \pm 1.0$

Table I. Fitted values of  $\beta_A$ ,  $\beta_B$  and  $\beta_C$  together with the predicted values of the decay widths of  $V \rightarrow S + \gamma$  and  $S \rightarrow V + \gamma$  for  $\theta_S = -20^\circ$  and  $\theta_S = -90^\circ$ . Units of  $\beta_A$ ,  $\beta_B$  and  $\beta_C$  are  $\text{GeV}^{-1}$  and those of the decay widths are keV.

small. Actually, the mixing between the scalar mesons, especially for  $I = 0$  states are more complicated than just  $\mathcal{L}_{\text{mix}}$  (see, e.g., Ref. 9)). An analysis in Ref. 10) shows that the inclusion of the mixing of  $f_0(980)$  to heavier  $f_0$ 's improves the prediction but not enough for explaining experiment.

We should include the correction from the  $K$ -loop, which gives an important contribution in the models with non-derivative type  $f_0 K \bar{K}$  interaction.<sup>11)</sup> Our model includes the derivative-type  $f_0 K \bar{K}$  interaction, so that it is not so clear that the same mechanism appears in the present model. In Ref. 5) we studied the  $K$ -loop correction to the effective  $\phi$ - $a_0$ - $\gamma$  interaction, and studied the process of  $\phi \rightarrow \pi^0 \eta \gamma$ .

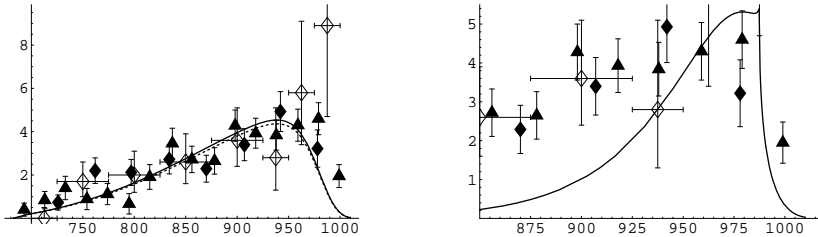


Fig. 1.  $dB(\phi \rightarrow \pi^0 \eta \gamma)/dq \times 10^7$  (in units of  $\text{MeV}^{-1}$ ) as a function in the  $\pi^0$ - $\eta$  invariant mass  $q = m_{\pi^0 \eta}$  (in MeV). Left panel shows the best fitted curve with only the tree level contribution included, while right panel shows the one with only  $K$ -loop contribution. Experimental data indicated by white diamonds ( $\diamond$ ) are from the SND collaboration<sup>7)</sup> and those by filled triangles and filled diamonds are shown in Ref. 12) extracted from the KLOE collaboration.<sup>7)</sup>

In the left panel of Fig. 1, we show the best fitted curve for  $dB(\phi \rightarrow \pi^0 \eta \gamma)/dq$  using the derivative-type  $f_0 K \bar{K}$  interaction together with experimental data.<sup>7),12)</sup> This shows that our model with the derivative interaction well reproduces experimental data. On the other hand, as seen in Fig.5 of Ref. 5), if one were to use a tree model with nonderivative SPP-type couplings, the resonant peaks were seen to get completely washed out. This would appear to be an advantage for the derivative coupling, which is dictated by chiral symmetry in the present framework. Nevertheless, since even with derivative coupling the spectrum shape is not very well fitted

in the energy region above 950 MeV, there must be another mechanism at work.

In the right panel of Fig. 1, we show the contribution from the  $K$ -loop. This shows that, for  $q$  below the resonance region, the  $K$ -loop contribution in the present model falls off rapidly, as one might reasonably expect with derivative coupling, and lies lower than the data points. In the energy region around the mass of  $a_0(980)$ , on the other hand, the  $K$ -loop gives an important contribution. A next step is to combine the tree and one-loop contributions as well as the effect of mixing between a  $qq\bar{q}\bar{q}$ -type scalar nonet and a  $q\bar{q}$ -type nonet.<sup>13)</sup> Determination of the mixing between two types of scalar nonets is expected to give an important clue to understand the vacuum structure of underlying QCD.<sup>14)</sup>

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