Chiral Approach to $\phi$ radiative decays

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Abstract. Rare decays of the $\phi$ vector meson, to $\pi\pi\gamma$ and $\pi\eta\gamma$, have been measured in the last few years. We give some background about why these decays are of interest in that they may provide some insights about the puzzling light scalar mesons. We then present our approach to studying strong and radiative decays involving light scalar mesons more generally, pointing out that it has the advantage of potentially relating many radiative decays at tree-level. Finally we discuss the rare radiative $\phi$ decays and comparison with recent experimental data in more detail.

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INTRODUCTION

Motivation for studying rare radiative $\phi$ decays

In the late 1980s it was realized that certain rare radiative decays of the $\phi$ vector meson, to two pseudoscalar mesons and a photon, could possibly shed some light on the scalar mesons $a_0(980)$ and $f_0(980)$. The main interest was in studying CP violation in the kaon system at $\phi$ factories such as Daphne at Frascati, but it was realized that the process $\phi \to K\bar{K}\gamma$ would be one of the backgrounds to the main decay $\phi \to K\bar{K}$. Initial calculations of this background gave branching ratios varying between about $10^{-6}$ and $10^{-4}$ [1]. In these calculations the radiative decays occur primarily through charged kaon loops like the ones shown in Fig. 2. The kaons in the loop couple to a scalar meson ($S$) which in turn couples to two pseudoscalar mesons (say $P$ and $P'$) in the final state. Therefore estimates for the branching ratio for $\phi \to PP'\gamma$ depend on the $SPP'$ and $SK\bar{K}$ couplings, meaning that measuring such radiative $\phi$ decays can potentially give information about the scalar mesons involved. Two sets of experiments (see [2] and references therein) have recently reported measurements of the decays $\phi \to \pi\pi\gamma$ and $\phi \to \pi\eta\gamma$ and many authors have studied these decays from a theoretical perspective (see [3] for references).

Light scalar mesons in pseudoscalar meson scattering and decays

The light scalar mesons are an old puzzle from the point of view of quark model spectroscopy. For example, their masses are much lower than one would expect for p-wave quark-antiquark states. Also, assuming that $f_0(600)$ or $\sigma$, $K_0^*(800)$ or $\kappa$, $a_0(980)$
and $f_0(980)$ form an SU(3) nonet, it is surprising that the I=0 state $a_0(980)$, which would contain no strange quarks if it is a conventional meson, is heavier than the strange state. Some possibilities are that these scalar mesons are multiquark states, meson-meson molecules or dynamically generated states, possibly mixing with conventional and glueball states having the same quantum numbers (see also talks at this conference by B. Hiller, H. Leutwyler, J. Pelaez, N.A. Tornqvist and H. Zheng).

In our approach (see [4] and references therein for more detail) a nonet of scalar mesons is added in a chiral invariant way to the lowest order nonlinear chiral Lagrangian for pseudoscalar mesons, giving the following trilinear interaction:

$$L_{SPP} = A \epsilon_{ij} N_{ij} \partial_{ij} P_{ij} + B \text{Tr} [N \partial_{ij} P_{ij} + D \text{Tr} [N \partial_{ij} P_{ij}] .$$

Here $N$ is the putative nonet of scalar mesons and $P$ is the usual pseudoscalar multiplet. We found that including the light scalar mesons in this way gave a good fit to $\pi\pi$ and $\pi K$ scattering data, up to energies beyond the $f_0(980)$ and the $K_0(1430)$ regions respectively, as well as $\eta' \to \eta\pi\pi$ decay data. In addition to neatly explaining the mass ordering and general pattern of decays of the scalar states below 1 GeV, a multiquark interpretation for these states is also suggested by the value of the scalar meson octet-singlet mixing angle, which was a parameter fixed by our fits. Our best fit was about $-20^\circ$ which, in our mixing convention, would be close to ideal mixing for a “dual” diquark-antidiquark nonet.

### RADIATIVE DECAYS INVOLVING LIGHT SCALAR MESONS

A phenomenologically successful non-linear chiral Lagrangian treatment of both pseudoscalar and vector mesons is given in [5] (which is equivalent at tree level to that based on Hidden Local Symmetry [6]). It turns out that in this chiral invariant formulation, vector meson dominance emerges naturally in the sense that the direct photon coupling to two pseudoscalar mesons vanishes in the limit where the KSRF relation holds. In [7] we extended our framework to also include chiral invariant interactions of the vector and scalar mesons. An attractive feature of this approach is that many processes, amongst them the radiative decays of the $\phi$, are related. The hope is that using most of the scalar parameters as fixed from fits to scattering and strong decays, we get many predictions. We only introduce four new parameters, which appear as coupling constants in a new effective Scalar-Vector-Vector interaction given by:

$$L_{SVV} = \beta_{A} \epsilon_{abc} \epsilon^{d'c'} \left [ F_{\mu d}(\rho) \right ]^{b}_{a} \left [ F_{\mu c}(\rho) \right ]^{b}_{D} + \beta_{B} \text{Tr} [N \partial_{ij} F_{\mu c}(\rho)] + \beta_{D} \text{Tr} [N \partial_{ij} F_{\mu c}(\rho)] .$$

Here $\rho$ is the vector meson multiplet and $F_{\mu c}(\rho) = \partial_{\mu} \rho_{c} - \partial_{c} \rho_{\mu} - i g [\rho_{\mu}, \rho_{c}]$ (see [5] for more detail). Using this effective interaction the radiative decays occur at tree-level as shown in Fig. 1 for the example of $\phi \to \pi \eta \gamma$. In [7] we fit to the experimental values for the total widths $\Gamma (a_0 \to \gamma \gamma)$, $\Gamma (f_0 \to \gamma \gamma)$ and $\Gamma (\phi \to a_0 \gamma)$ and predicted nine other branching ratios, including those for $\phi \to f_0 \gamma$ and $\sigma \to \gamma \gamma$. Assuming that $\phi \to \pi \eta \gamma$
and $\phi \to \pi \pi \gamma$ are dominated by $\phi \to a_0 \gamma$ and $\phi \to f_0 \gamma$ respectively, our prediction for $\Gamma(f_0 \to \gamma \gamma)$ was too small when compared with [2].

We considered [8] the effect of changing the scalar isoscalar mixing angle from the small angle $\sim -20^\circ$ (suggestive of a multiquark interpretation for the scalar mesons), found in our scattering fits, to a large angle $\sim -90^\circ$ which is consistent with the scalar meson masses and would be natural for conventional $q\bar{q}$ mesons. We found that the predictions for these two scenarios did not differ significantly in our tree-level model.

We also did a preliminary investigation of the effect of mixing between a light, probably non-$q\bar{q}$, scalar nonet $N$ and a heavier $q\bar{q}$-type nonet $N'$ described by a mixing Lagrangian $\mathcal{L}_{\text{mix}} = \gamma \text{Tr}(NN')$. We take the mixing parameter $\gamma = 0.33\text{GeV}^4$ from a fit to the properties of the $I = 1$ and $I = \frac{1}{2}$ scalar mesons in [9]. Considering only the simplest OZI-type couplings for each nonet, given by

$$\mathcal{L} = \alpha \epsilon_{abc} \epsilon^{a'b'c'} \left[ F_{\mu\nu}(\rho) \right]_{ab}^a \left[ F_{\mu\nu}(\rho) \right]_{b'b'}^{b'b'} N_{c'}^c + \beta \text{Tr} \left[ N' F_{\mu\nu}(\rho) F_{\mu\nu}(\rho) \right],$$

and fitting to the measured two-photon widths of $a_0$ and $f_0$ we found predictions for the widths for $\phi \to a_0 \gamma$ and $\phi \to f_0 \gamma$ which were still too small. In fact mixing between scalar mesons is likely to be more complicated than just $\mathcal{L}_{\text{mix}}$, especially for the $I = 0$ states (see for example [10]), and we could of course include more general interactions of both scalar nonets with the vector mesons than Eq. (3).

In [3] we used our simple model to study the radiative $\phi$ decay spectra in detail. For example in Fig. 1 we show our best fits for the partial branching fraction for $\phi \to \pi \eta \gamma$. We see that the fit is quite good, except towards the higher end of the spectrum, where there is also a larger spread in the central values obtained by the different experimental groups. We note that in our non-linear chiral Lagrangian approach there is derivative coupling between the scalar and pseudoscalar mesons. The resultant extra momentum factor in the decay width counteracts falling phase space towards the end of the spectrum and we found that this gives a substantially better fit than a model where the scalar and pseudoscalar mesons couple non-derivatively. We also calculated the contribution of the
charged kaon loop diagrams in our model. In Fig 2, we show our prediction for the kaon loop contribution to the $\phi \rightarrow \pi \eta \gamma$ partial branching ratio in the $a_0(980)$ resonance region towards the high end of the spectrum. A next step is to combine the tree and one-loop contributions, also including known non-resonant background contributions.

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