Scalar meson exchange in $\Phi \to P^0 P^0 \gamma$ decays *

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The scalar meson exchange in $\Phi \to P^0 P^0 \gamma$ decays is discussed in a chiral invariant framework where the scalar meson poles are incorporated explicitly. $\phi \to \pi^0 \pi^0 \gamma$ and $\phi \to \pi^0 \eta \gamma$ are in agreement with recent experimental data and can be used to extract valuable information on the properties of the light scalar meson resonances ($S = \sigma, a_0, f_0$). In addition, their study complements other analyses based on central production, $D$ and $J/\psi$ decays, etc. Particularly interesting are the $\phi$ radiative decays, namely $\phi \to \pi^0 \pi^0 \gamma$, $\phi \to \pi^0 \eta \gamma$ and $\phi \to K^0 \bar{K}^0 \gamma$, which, as we will see, can provide us with valuable information on the scalar mixing angle.

In Sec. 2 the most recent experimental data on the $\phi \to P^0 P^0 \gamma$ decays is presented. Sec. 3 is a short review of the approaches used in the literature to study these processes emphasizing the different treatments of the scalar contribution. $\phi \to \pi^0 \pi^0 \gamma$, $\phi \to \pi^0 \eta \gamma$ and $\phi \to K^0 \bar{K}^0 \gamma$ are discussed in Secs. 4, 5 and 6 respectively. The ratio $\phi \to f_0 \gamma/a_0 \gamma$ is discussed in Sec. 7. Concluding remarks are presented in Sec. 8.

1. INTRODUCTION

The radiative decays of light vector mesons ($V = \rho, \omega, \phi$) into a pair of neutral pseudoscalars ($P = \pi^0, K^0, \eta$), $V \to P^0 P^0 \gamma$, are an excellent laboratory for investigating the nature and extracting the properties of the light scalar meson resonances ($S = \sigma, a_0, f_0$). In addition, their study complements other analyses based on central production, $D$ and $J/\psi$ decays, etc. Particularly interesting are the $\phi$ radiative decays, namely $\phi \to \pi^0 \pi^0 \gamma$, $\phi \to \pi^0 \eta \gamma$ and $\phi \to K^0 \bar{K}^0 \gamma$, which, as we will see, can provide us with valuable information on the scalar mixing angle.

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2. EXPERIMENTAL DATA

For $\phi \to \pi^0 \pi^0 \gamma$, the first measurements of this decay have been reported by the SND and CMD-2 Collaborations. For the branching ratio they obtain $B(\phi \to \pi^0 \pi^0 \gamma) = (1.221 \pm 0.098 \pm 0.061) \times 10^{-4}$ [4] and $(1.08 \pm 0.17 \pm 0.09) \times 10^{-4}$ [2]. More recently, the KLOE Collaboration has measured $B(\phi \to \pi^0 \pi^0 \gamma) = (1.09 \pm 0.03 \pm 0.05) \times 10^{-4}$ [3]. In all the cases, the spectrum is clearly peaked at $m_{\pi \pi} \approx 970$ MeV, as expected from an important $f_0(980)$ contribution.

For $\phi \to \pi^0 \eta \gamma$, the branching ratios measured by the SND, CMD-2 and KLOE Collaborations are $B(\phi \to \pi^0 \eta \gamma) = (8.8 \pm 1.4 \pm 0.9) \times 10^{-5}$ [4], $(9.0 \pm 2.4 \pm 1.0) \times 10^{-5}$ [2], and $B(\phi \to \pi^0 \eta \gamma) = (8.51 \pm 0.51 \pm 0.57) \times 10^{-5}$ ($\eta \to \gamma \gamma$) and $(7.96 \pm 0.60 \pm 0.40) \times 10^{-5}$ ($\eta \to \pi^+ \pi^- \pi^0$) [5]. Again, in all these cases, the observed mass spectrum shows a significant enhancement at large $\pi^0 \eta$ invariant mass that is interpreted as a manifestation of the dominant contribution of the $a_0(980) \gamma$ intermediate state.

For $\phi \to K^0 \bar{K}^0 \gamma$, no experimental data is yet available.

For the ratio $\phi \to f_0 \gamma/a_0 \gamma$, the experimental value measured by the KLOE Collaboration is $R(\phi \to f_0 \gamma/a_0 \gamma) = 6.1 \pm 0.6$ [5].

3. THEORETICAL FRAMEWORK

A first attempt to explain the $V \to P^0 P^0 \gamma$ decays was done in Ref. 9 using the vector me-
son dominance (VMD) model. In this framework, the $V \to P^0 P^0 \gamma$ decays proceed through the decay chain $V \to VP^0 \to P^0 P^0 \gamma$. The intermediate vectors exchanged are $V = V' = \rho$ for $\phi \to \pi^0 \gamma$, $V = \rho$ and $V' = \omega$ for $\phi \to \pi^0 \eta \gamma$, and $V = K^{*0}$ and $V' = K^{*0}$ for $\phi \to K^0 K^{*0}$. The calculated branching ratios $B_{\phi \to \pi^0 \gamma} = 1.2 \times 10^{-5}$, $B_{\phi \to \pi^0 \eta \gamma} = 5.4 \times 10^{-6}$, and $B_{\phi \to K^0 K^{*0} \gamma} = 2.7 \times 10^{-12}$ are found (for the first two processes) to be substantially smaller than the experimental results.

Later on, the $V \to P^0 P^0 \gamma$ decays were studied in a Chiral Perturbation Theory (ChPT) context enlarged to include on-shell vector mesons.\[7\] In this formalism, $B_{\phi \to \pi^0 \gamma} = 5.1 \times 10^{-5}$, $B_{\phi \to \pi^0 \eta \gamma} = 3.0 \times 10^{-5}$, and $B_{\phi \to K^{*0} \gamma} = 7.6 \times 10^{-9}$. Taking into account both chiral and VMD contributions, one finally obtains $B_{\phi \to \pi^0 \gamma} = 6.1 \times 10^{-5}$ and $B_{\phi \to \pi^0 \eta \gamma} = 3.6 \times 10^{-5}$, which are still below the experimental results, and $B_{\phi \to K^{*0} \gamma} = 7.6 \times 10^{-9}$.

Additional contributions are thus certainly required and the most natural candidates are the contributions coming from the exchange of scalar resonances. A first model including the scalar resonances explicitly is the no structure model, where the $V \to P^0 P^0 \gamma$ decays proceed through the decay chain $V \to \pi^0 \gamma \to P^0 P^0 \gamma$ and the coupling $V S \gamma$ is considered as pointlike. This model is ruled out by experimental data on $\phi \to \pi^0 \gamma$ decays.\[1\] A second model is the kaon loop model,\[5\] where the initial vector decays into a pair of charged kaons that, after the emission of a photon, rescatter into a pair of neutral pseudoscalars through the exchange of scalar resonances.

The previous two models include the scalar resonances ad hoc, and the pseudoscalar rescattering amplitudes are not chiral invariant. This problem is solved in the next two models which are based not only on the kaon loop model but also on chiral symmetry. The first one is a chiral unitary approach (Uχ) where the scalar resonances are generated dynamically by unitarizing the one-loop pseudoscalar amplitudes. In this approach, $B_{\phi \to \pi^0 \gamma} = 8 \times 10^{-5}$, $B_{\phi \to \pi^0 \eta \gamma} = 8.7 \times 10^{-5}$, and $B_{\phi \to K^0 K^{*0} \gamma} = 5 \times 10^{-8}$ are found (for the first two processes) to be substantially smaller than the experimental results.

In the next four sections, we discuss the scalar contributions to the $\phi \to \pi^0 \pi^0 \gamma$, $\phi \to \eta \gamma$, and $\phi \to K^0 K^{*0} \gamma$ decays, and the ratio $\phi \to f_0(500)/a_0(980)$, in the framework of the $L\sigma$M.

4. $\phi \to \pi^0 \pi^0 \gamma$

The scalar contribution to this process is driven by the decay chain $\phi \to K^+ K^- (\gamma) \to \pi^0 \pi^0 \gamma$. The contribution from pion loops is known to be negligible due to the Zweig rule. The amplitude for $\phi(q^*, \epsilon^*) \to \pi^0 (p) \pi^0 (p') \gamma (\gamma, \epsilon)$ is given by\[11\]

$$\mathcal{A} = \frac{e g_s}{2\pi^2m_{K^+}} \{a\} L(m^2_{\pi^0 \pi^0}) \times \mathcal{A}_{L\sigma M}^{K^+ K^- \to \pi^0 \pi^0} \ ,$$

where $\{a\} = (\epsilon^* \cdot \epsilon) (q^* \cdot q) - (\epsilon^* \cdot q) (\epsilon^* \cdot q^*)$, $m^2_{\pi^0 \pi^0} \equiv s$ is the dipion invariant mass and $L(m^2_{\pi^0 \pi^0})$ is a loop integral function. The $\phi K K$ coupling constant $g_s$ takes the value $|g_s| \approx 4.5$ to agree with $\Gamma_{\phi \to K^+ K^-} = 2.10$ MeV.\[12\] The $K^+ K^- \to \pi^0 \pi^0$ amplitude in Eq. (1) is calculated using the $L\sigma$M and turns out to be

$$\mathcal{A}_{L\sigma M}^{K^+ K^- \to \pi^0 \pi^0} = \frac{m^2_{\pi^0 \pi^0}}{2\pi f_{K^+} f_{K^-}} \left[ \left( \frac{m^2_{\pi^0 \pi^0}}{2D_{\pi^0}(s)} \right) c_{\phi S}(c_{\phi S} - \sqrt{2} s_{\phi S}) + \frac{m^2_{\pi^0 \pi^0}}{2D_{\pi^0}(s)} s_{\phi S}(s_{\phi S} + \sqrt{2} c_{\phi S}) \right] \ ,$$

where $D_{\pi^0}(s)$ are the $S = \sigma, f_0$ propagators, $\phi_S$ is the scalar mixing angle in the quark-flavour basis and $(c_{\phi S}, s_{\phi S}) \equiv (\cos \phi_S, \sin \phi_S)$. A Breit-Wigner propagator is used for the $\sigma$, while for the $f_0$ a complete one-loop propagator taking into account finite width corrections is preferable.\[8\]

It is worth mentioning that the amplitude\[11\] is the result of adding a resonant amplitude containing the scalar poles in the $s$-channel —the $\sigma$ and $f_0$ poles in Eq. (2)— and a non-resonant one including all other contributions. This latter is
obtained from the subtraction
\[ A_{\phi \rightarrow \pi^0\pi^0\gamma}^{\text{non-res.}} = A_{\phi \rightarrow \pi^0\pi^0\gamma}^{\text{chiral-loop}} - \lim_{m_\sigma,f_0 \to \infty} A_{\phi \rightarrow \pi^0\pi^0\gamma}^{\text{res.}} \propto \frac{m_\sigma^2-s/2}{2f_\sigma f_K}, \tag{3} \]
where \( A_{\phi \rightarrow \pi^0\pi^0\gamma}^{\text{chiral-loop}} \) is the corresponding chiral-loop amplitude, \( A_{\phi \rightarrow \pi^0\pi^0\gamma}^{\text{res.}} \) is the aforementioned resonant contribution. In this way, \( A_{\phi \rightarrow \pi^0\pi^0\gamma}^{\text{non-res.}} \) encodes the effects of all resonances in the \( t- \) and \( u- \) channel —and also of higher spin resonances in the \( s- \) channel—in the limit \( m_K \to \infty \).

Notice also that for \( m_S \to \infty \) (\( S = \sigma, f_0 \)), the amplitude \( \mathbf{1} \) reduces to the chiral-loop prediction and is thus expected to account for the lowest part of the \( \pi\pi \) spectrum. In addition, the presence of the scalar propagators in Eq. \( \mathbf{2} \) should be able to reproduce the effects of the \( f_0 \) (and the \( \sigma \)) pole(s) at higher \( \pi\pi \) invariant mass values. This complementarity between ChPT and the LoM makes the whole analysis quite reliable.

The final results for \( A(\phi \rightarrow \pi^0\pi^0\gamma) \) are then the sum of the LoM contribution in Eq. \( \mathbf{1} \) plus the VMD contribution that can be found in Ref. \[11\]. The \( \pi^0\pi^0 \) invariant mass distribution, with the separate contributions from the LoM, VMD and their interference, as well as the total result, are shown in Fig. \( \mathbf{1} \). We use \( m_{\sigma} = 478 \) MeV \[14\], \( \Gamma_{\sigma} = 256 \) MeV, as required by the LoM, \( m_{f_0} = 985 \) MeV and \( \phi_S = -9^\circ \) \[11\]. Notice that the contribution of the \( \sigma \) to this process is suppressed since \( g_{\sigma KK} \propto (m_{\sigma}^2 - m_K^2) \approx 0 \) for \( m_{\sigma} \gtrsim m_K \); by contrast, the chiral loop prediction shows no suppression in the region \( m_{\pi\pi} \approx 500 \) MeV, see Fig. \( \mathbf{1} \).

Integrating the \( \pi^0\pi^0 \) invariant mass distribution over the whole physical region one finally obtains \( B(\phi \rightarrow \pi^0\pi^0\gamma) = 1.16 \times 10^{-4} \). The shape of the \( \pi\pi \) mass spectrum and the branching ratio are in agreement with the experimental results. However, both predictions are very sensitive to the values of the \( f_0 \) mass and the scalar mixing angle (this latter because of \( g_{f_0\pi\pi} \propto \sin \phi_S \)). Consequently, the \( \phi \rightarrow \pi^0\pi^0\gamma \) decay could be used to extract valuable information on these parameters.

5. \( \phi \rightarrow \pi^0\eta\gamma \)

The scalar contribution to the \( \phi \rightarrow \pi^0\eta\gamma \) decay is identical to that of \( \phi \rightarrow \pi^0\pi^0\gamma \) with the replacement of \( A_{K^+K^- \rightarrow \pi^0\pi^0\gamma}^{M} \) by \( A_{K^+K^- \rightarrow \pi^0\eta}^{M} \) in
Eq. (2). This latter amplitude is written as

\[ A_{K^+K^-\rightarrow\pi^0\eta}^\sigma = \frac{m^2_{K^-}-s/2}{2f\kappa} - \frac{s-m^2_{K^-}}{2f\kappa} \left( c\phi_P - \sqrt{2}s\phi_P \right) \]

where \( \phi_P \) is the pseudoscalar mixing angle and \( D_{a_0(s)} \) the complete one-loop \( \phi_0 \) propagator [5].

The separate contributions to the \( \pi^0\eta \) invariant mass distribution, and the total result, are shown in Fig. 2. The chiral loop prediction is also included for comparison. We use \( m_{a_0} = 984.7 \) MeV [12] and \( \phi_P = 41.8^\circ \) [15]. Integrating the \( \pi^0\eta \) invariant mass spectrum one obtains \( B(\phi \rightarrow \pi^0\eta\gamma) = 8.3 \times 10^{-5} \). The \( \pi^0\eta \) mass spectrum and the branching ratio are in fair agreement with experimental results and with previous phenomenological estimates [10,17].

6. \( \phi \rightarrow K^0\bar{K}^0\gamma \)

This process is interesting to study since it could pose a background problem for testing CP violation at DAΦNE. The analysis of CP-violating decays in \( \phi \rightarrow K^0\bar{K}^0 \) has been proposed as a way to measure the ratio \( e'/e \) [18], but because this means looking for a very small effect, a \( B(\phi \rightarrow K^0\bar{K}^0\gamma) \gtrsim 10^{-6} \) will limit the precision of such a measurement.

The scalar contribution to the \( \phi \rightarrow K^0\bar{K}^0\gamma \) decay is again identical to that of \( \phi \rightarrow \pi^0\pi^0\gamma \) (since it is driven by the same charged kaon loop) with the replacement of \( A_{K^+K^-\rightarrow\pi^0\eta}^\sigma \) by \( A_{K^+K^-\rightarrow\eta\gamma}^\sigma \) in Eq. (2). This latter amplitude is written as

\[ A_{K^+K^-\rightarrow\eta\gamma}^\sigma = \frac{m_{K^-}^2-s/2}{2f\kappa} - \frac{s-m_{K^-}^2}{2f\kappa} \left( c\phi_P - \sqrt{2}s\phi_P \right) \left( 1 + \frac{m_{K^+}^2-m_{K^-}^2}{m_{K^+}^2-m_{K^-}^2} \times \frac{D_{a_0(s)}}{D_{a_0(s)}} \right) \]

where the contributions of the \( a_0, f_0 \) and \( \sigma \) mesons are explicitly shown. The \( \sigma \) contribution to this process is negligible not only because of the \( \sigma KK \) coupling suppression if \( m_\sigma \ll m_K \) but also for kinematical reasons. The contributions of the \( a_0, f_0 \) are of the same order but with opposite sign \( g_{a_0,K^+K^-} = g_{f_0,K^+K^-} \) and \( -g_{a_0,K^+K^-} = g_{f_0,K^+K^-} \) due to isospin invariance.

7. \( \phi \rightarrow f_0\gamma/a_0\gamma \)

In the kaon loop model, these two processes are driven by the decay chain \( \phi \rightarrow K^+K^- (\gamma) \rightarrow f_0\gamma \) and \( a_0\gamma \). The amplitudes are given by

\[ A = \frac{e g_{a_0}}{2\pi^2 m^2_{K^+}} \left\{ a \right\} L(m_{f_0(a_0)^2}) \times g_{f_0(a_0)K^+K^-} \]

where the scalar coupling constants are fixed within the LσM to

\[ g_{f_0K^+K^-} = \frac{m_{K^-}^2-m_{K^+}^2}{2f\kappa} (s\phi_S + \sqrt{2}c\phi_S) \]

\[ g_{a_0K^+K^-} = \frac{m_{K^-}^2-m_{a_0}^2}{2f\kappa} \]

The \( K^0\bar{K}^0 \) invariant mass distribution is shown in Fig. 3. The chiral loop prediction is also included. Integrating the \( K^0\bar{K}^0 \) invariant mass spectrum one obtains \( B(\phi \rightarrow K^0\bar{K}^0\gamma) = 6 \times 10^{-8} \). This value is in agreement with previous phenomenological estimates [10,14] (see also Ref. 19 for a review of earlier predictions). Notice that the branching ratio obtained here is one order of magnitude larger than the chiral-loop prediction [21]. However, it is still one order of magnitude smaller than the limit, \( \mathcal{O}(10^{-6}) \), in order to pose a background problem for testing CP-violating decays at DAΦNE.
The ratio of the two branching ratios is thus
\[
\frac{R_{\phi \to f_0 \gamma/a_0 \gamma}^{\text{L}\sigma\text{M}}}{R_{\phi \to \eta \gamma}^{\text{L}\sigma\text{M}}(\phi^{0})} = \frac{|L(m_{a_0}^2)|^2}{|L(m_{f_0}^2)|^2} \frac{(1-m_{a_0}^2/m_{f_0}^2)^3}{(1-m_{a_0}^2/m_{f_0}^2)} \times \frac{g_{a_0 K^0 K^-}}{g_{f_0 K^0 K^-}} \approx (s\phi_S + \sqrt{2}c\phi_S)^2,
\]
where the approximation is valid for \( m_{f_0} \approx m_{a_0} \).

\[\phi_S = -9^\circ,\]

one gets \( R_{\phi \to f_0 \gamma/a_0 \gamma}^{\text{L}\sigma\text{M}} \approx 1.5 \) which should be compared to the experimental value \( R_{\phi \to \eta \gamma}^{\text{LOE}}(\phi^{0}) = 6.1 \pm 0.6 \) [3]. However, this value is obtained from a large destructive interference between the \( f_0 \gamma \) and \( \sigma \gamma \) contributions to \( \phi \to \pi^0 \pi^0 \gamma \), in disagreement with other experiments [4]. Conversely, the measurement of the ratio could be used to get some insight into the value of the scalar mixing angle.

8. CONCLUSIONS

- The radiative decays \( \phi \to \pi^0 \pi^0 \gamma, \phi \to \pi^0 \eta \gamma \) and \( \phi \to K^0 \bar{K}^0 \gamma \) have been shown to be very useful to extract relevant information on the properties of the \( f_0(980), a_0(980) \) and \( \sigma(500) \) scalar resonances.

- The complementary between ChPT and the L\( \sigma \text{M} \) is used to parametrize the needed scalar amplitudes. This guarantees the appropriate behaviour at low dimeson invariant masses but also allows to include the effects of the scalar meson poles.

- The L\( \sigma \text{M} \) predictions for the invariant mass spectra and their respective branching ratios of the \( \phi \to \pi^0 \pi^0 \gamma \) and \( \phi \to \pi^0 \eta \gamma \) decays are compatible with experimental data.

- The prediction for \( \phi \to \pi^0 \pi^0 \gamma \) is dominated by \( f_0(980) \) exchange and is strongly dependent on the values of \( m_{f_0} \) and \( \phi_S \). For the preferred values \( m_{f_0} = 985 \text{ MeV} \) and \( \phi_S = -9^\circ \), one obtains \( B(\phi \to \pi^0 \pi^0 \gamma) = 1.16 \times 10^{-4} \). The suppression of the \( \sigma \) contribution to this process is explained in terms of the smallness of the \( \sigma K K \) coupling for \( m_{\sigma} \approx m_{K} \). The process \( \phi \to \pi^0 \eta \gamma \) is dominated by \( a_0(980) \) exchange. For the values \( m_{a_0} = 984.8 \text{ MeV} \) and \( \phi_P = 41.8^\circ \), one obtains \( B(\phi \to \pi^0 \eta \gamma) = 8.3 \times 10^{-5} \).

- The decay \( \phi \to K^0 \bar{K}^0 \gamma \) is confirmed not to pose a background problem for testing \( CP \) violation at Da\( \text{Phi} \)ne. The ratio \( \phi \to f_0 \gamma/a_0 \gamma \) may be used to obtain valuable information on the scalar mixing angle and on the nature of the \( f_0(980) \) and \( a_0(980) \) scalar states.

Acknowledgements

I would like to express my gratitude to the Photon 2003 Organizing Committee (and in particular to G. Pancheri and A. Mantella) for the opportunity of presenting this contribution, and for the pleasant and interesting conference we have enjoyed.

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