Studies of radiative ϕ meson decays with KLOE

The KLOE Collaboration*
Presented by P.Gauzzi[a†]

[a]Dipartimento di Fisica, Università degli Studi di Roma "La Sapienza" and INFN Sezione di Roma, P.le A.Moro 2, 00185 - Rome (Italy)

A sample of $\sim 5 \times 10^7 \phi$ mesons, produced at the ϕ-factory DAΦNE, has been used by the KLOE Collaboration to study the ϕ radiative decays. The decays $\phi \to \eta\pi^0\gamma$ and $\phi \to \pi^0\pi^0\gamma$ have been exploited to study the scalar mesons $a_0(980)$ and $f_0(980)$. Furthermore a new determination of the $\eta - \eta'$ mixing angle has been obtained from the measurement of the ratio of the decay rates of $\phi \to \eta'\gamma$ to $\phi \to \eta\gamma$.

1. Introduction

The Frascati ϕ-factory DAΦNE is an e^+e^- collider working at the peak of the $\phi(1020)$ resonance. The peak cross section is $\sigma_\phi \approx 3300$ nb. The KLOE experiment has collected an integrated luminosity of 25 pb^{-1}, corresponding to $7.5 \times 10^7\phi$, during the 2000 data taking, and 190 pb^{-1}, corresponding to $5.7 \times 10^8\phi$, during the 2001 one. The results reported in this paper have been obtained from the analysis of a sample of 16 pb^{-1} of good data collected during the year 2000. The analysis of the 2001 data is in progress. More details on the analyses presented here can be found in refs.[1].

2. $\phi \to$S$(0^{++})\gamma$ (S=f_0, a_0)

The nature of the scalar mesons ($J^{PC}=0^{++}$) $f_0(980)$ and $a_0(980)$ is not well established. They are not easily interpreted as ordinary $q\bar{q}$ mesons, belonging to the $^3P_0$ nonet, alternative hypotheses have been proposed: $q\bar{q}q\bar{q}$ states[2] or $K\bar{K}$ bound states[3]. According to the theory the branching ratios of $\phi \to f_0\gamma$ and $\phi \to a_0\gamma$, as well as the f_0 and a_0 mass shapes, are sensitive to structure of these particles[4].
Concerning the f_0, the decay $f_0 \to \pi^0\pi^0$ has been considered, by selecting events without charged tracks and with exactly five prompt photons in the detector. The same final state has been used to study the decay $\phi \to a_0\gamma$, with $a_0 \to \eta\pi^0$ and $\eta \to \gamma\gamma$. These two processes have been previously measured by the experiments SND and CMD-2 at VEPP-2M in Novosibirsk[5]. Another final state, consisting of two charged pions and five prompt photons, has been exploited to study the decay $\phi \to a_0\gamma$, corresponding to $a_0 \to \eta\pi^0$ and $\eta \to \pi^+\pi^-\pi^0$. This last decay chain has been observed by KLOE for the first time.
The processes that are expected to contribute to the five photon final state, besides the signals, are: (i) $\phi \to \sigma(500)\gamma$ with $\sigma \to \pi^0\pi^0$ ($\sigma(500)$ is

*The KLOE Collaboration: A. Aloisio, F. Ambrosino, A. Antonelli, M. Antonelli, C. Bacci, G. Bencivenni, S. Bertolucci, C. Bini, C. Bloise, V. Bocci, F. Bossi, P. Branchini, S. A. Bulychjov, R. Caloi, P. Campana, G. Capon, G. Carboni, M. Casarsa, V. Casavola, G. Cataldi, F. Ceradini, F. Cervelli, F. Cevenini, G. Chiefari, P. Ciambrone, S. Conetti, E. De Lucia, G. De Robertis, P. De Simone, G. De Zorzi, S. Dell'Agnello, A. Denig, A. Di Domenico, C. Di Donato, S. Di Falco, A. Doria, M. Dreucci, O. Erriquez, A. Farilla, G. Felici, A. Ferrari, M. L. Ferrer, G. Finocchiaro, C. Forti, A. Franceschi, P. Franzini, C. Gatti, P. Gauzzi, S. Giovannella, E. Gorini, F. Grancagnolo, E. Graziani, S. W. Han ,M. Incagli, L. Ingrosso, W. Kluge, C. Kuo, V. Kulikov, F. Lacava, G. Lanfranchi, J. Lee-Franzini, D. Leone, F. Lu, M.Martemianov, M. Matsyuk, W. Mei, L. Merola, R. Messi, S. Miscetti, M. Moulson, S. Müller, F. Murtas, M. Napolitano, A. Nedosekin, F. Nguyen, M. Palutan, E. Pasqualucci, L. Passalacqua, A. Passeri, V. Patera, E. Petrolo, L. Pontecorvo, M. Primavera, F. Ruggieri, P. Santangelo, E. Santovetti, G. Saracino, R. D. Schamberger, B. Sciascia, A. Sciubba, F. Scuri, I. Sfiligoi, T. Spadaro, E. Spiriti, G. L. Tong, L. Tortora, E. Valente, P. Valente, B. Valeriani, G. Venanzoni, S. Veneziano, A. Ventura, G. Xu, G. W. Yu
†E-mail: Paolo.Gauzzi@roma1.infn.it

the other scalar meson expected in the mass region below 1 GeV, recently observed at FNAL by the E791 Collaboration[6]), (ii) $\phi \to \rho^0\pi^0$ with $\rho \to \pi^0\gamma$, $\eta\gamma$, (iii) $e^+e^- \to \omega\pi^0$ with $\omega \to \pi^0\gamma$. Some contamination is expected from events with three ((iv) $\phi \to \eta\gamma$, $\eta \to \gamma\gamma$ and $\phi \to \pi^0\gamma$) and seven ((v) $\phi \to \eta\gamma$, $\eta \to \pi^0\pi^0\pi^0$) prompt photons, wrongly reconstructed as five photon ones. A kinematic fit is performed, by requiring the 4-momentum conservation for each prompt photon, to reject events from (iv) and (v), then the best photon pairing is searched for, in order to associate pairs of photons to π^0 and η, to discriminate between $\phi \to \pi^0\pi^0\gamma$ and $\phi \to \eta\pi^0\gamma$. The $\omega\pi^0$ background is reduced by rejecting events with $\pi^0\gamma$ invariant mass of compatible with the ω mass.

The final sample for $\phi \to \pi^0\pi^0\gamma$ consists of

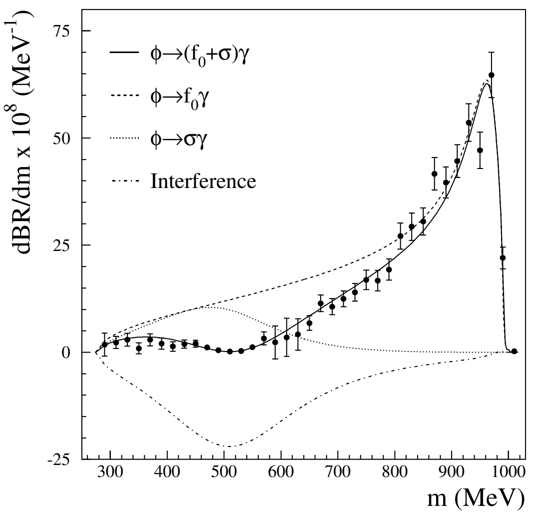

Figure 1. Differential decay rate for $\phi \to \pi^0\pi^0\gamma$; the solid line is the result of Fit B, individual contributions are also shown.

3102 events with a 20% contamination (evaluated by Monte Carlo (MC)). The total detection efficiency for the signal is 40%. By normalizing to the number of ϕ produced the following branching ratio can be obtained: $\mathrm{Br}(\phi \to \pi^0\pi^0\gamma) = (1.08 \pm 0.03 \pm 0.05) \times 10^{-4}$ in agreement with the Novosibirsk measurements[5], with much smaller

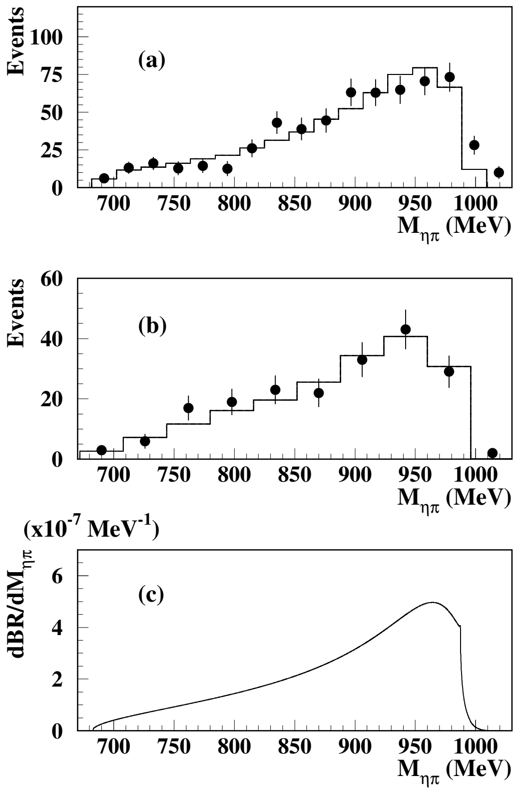

Figure 2. $\eta\pi^0$ invariant mass spectra: (a) five photon sample; (b) $\pi^+\pi^-$ plus five photon sample. (c) Theoretical curve obtained from the combined fit.

uncertainties.

In the case of $\phi \to \eta\pi^0\gamma$ 916 events have been selected with 30% contamination (MC), and 32% overall efficiency. By normalizing to the number of ϕ produced one can obtain $\mathrm{Br}(\phi \to \eta\pi^0\gamma) = (8.51 \pm 0.51 \pm 0.57) \times 10^{-5}$, also in agreement with the Novosibirsk measurements[5].

The final state corresponding to $\phi \to \eta\pi^0\gamma$, $\eta \to \pi^+\pi^-\pi^0$ decay consists of two charged tracks coming from the interaction point (IP) and five prompt photons; this signature is unique among the possible final states, so that the background comes from events with two tracks and three ($\phi \to \eta\gamma$, $\eta \to \pi^+\pi^-\pi^0$), four ($e^+e^- \to \omega\pi^0$, $\omega \to \pi^+\pi^-\pi^0$; $\phi \to K_L K_S$, $K_S \to \pi^0\pi^0$ and $K_L \to \pi l\nu$) or six ($\phi \to K_L K_S \to \pi^+\pi^-\pi^0\pi^0\pi^0$, with prompt K_L decay) prompt photons. The analysis scheme is similar to that of the five photon sample: 197 events have been selected with 4 ± 4 background events and with 19% efficiency. From this decay chain $\mathrm{Br}(\phi \to \eta\pi^0\gamma) = (7.96 \pm 0.60 \pm 0.47) \times 10^{-5}$ is extracted, in good agreement with the result of the five photon sample.

In order to disentangle the various contributions, the data have been fitted to theoretical mass spectra obtained from the following model: (a) the coupling of ϕ to $\mathrm{S}(0^{++})\gamma$ is assumed to occur through a charged kaon loop[4], (b) the scalar propagator with finite width corrections is used, (c) the $\phi \to \rho^0\pi^0$ parametrization is taken from VDM calculations[7].

Table 1
Fit results.

f_0	Fit A	Fit B
χ^2/ndf	109.5/34	43.2/33
M_{f_0} (MeV)	962 ± 4	973 ± 1
$g^2_{f_0KK}/(4\pi)$ (GeV^2)	1.29 ± 0.14	2.79 ± 0.12
$g^2_{f_0KK}/g^2_{f_0\pi\pi}$	3.22 ± 0.29	4.00 ± 0.14
$g_{\phi\sigma\gamma}$	-	0.060 ± 0.008
a_0		
χ^2/ndf	27.2/25	
$g^2_{a_0KK}/(4\pi)$ (GeV^2)	0.40 ± 0.04	
$g_{a_0\eta\pi}/g_{a_0KK}$	1.35 ± 0.09	
$\mathrm{Br}(\phi \to \rho^0\pi^0 \to \eta\pi^0\gamma)$	$(0.5 \pm 0.5) \times 10^{-5}$	

Concerning the $\pi^0\pi^0$ mass spectrum, after background subtraction, two different fits have been tried: without (Fit A) and with (Fti B) $\phi \to \sigma(500)\gamma$; the $\sigma(500)$ has been parametrized as a fixed width Breit-Wigner ($\mathrm{M}_\sigma = 478$ MeV, $\Gamma_\sigma = 324$ MeV[6]) and a point-like $\phi - \sigma\gamma$ coupling has been taken. The free parameters of the fits are: the f_0 mass, the squared coupling $g^2_{f_0KK}/(4\pi)$, the ratio $g^2_{f_0KK}/g^2_{f_0\pi\pi}$, the $\mathrm{Br}(\phi \to \rho^0\pi^0 \to \pi^0\pi^0\gamma)$ and $g_{\phi\sigma\gamma}$ (only for Fit B).

The parameter values are listed in tab.1, the $\phi \to \rho^0\pi^0$ contribution turns out to be negligible for both fits. Fit A gives a large χ^2, while Fit B shows a good agreement with the experimental data. In fig.1 the differential decay rate is plotted, together with the various contributions from Fit B; the decrease of the mass spectrum near 700 MeV is produced by a large negative interference between f_0 and σ.

Concerning $\phi \to \eta\pi^0\gamma$, a combined fit of the two mass spectra, after background subtraction, has been performed, by fixing their relative normalization to the ratio $\mathrm{Br}(\eta \to \gamma\gamma)/\mathrm{Br}(\eta \to \pi^+\pi^-\pi^0)$ from PDG. The free parameters are: the square coupling $g^2_{a_0KK}/(4\pi)$ (GeV^2), the ratio $g_{a_0\eta\pi}/g_{a_0KK}$ and $\mathrm{Br}(\phi \to \rho^0\pi^0 \to \eta\pi^0\gamma)$ (tab.1). The mass of the a_0 is not free, it has been fixed to the PDG value M_{a_0}=984.8 MeV. The results are shown in fig.2; by integrating the theoretical curve the a_0 contribution can be evaluated: $\mathrm{Br}(\phi \to a_0\gamma \to \eta\pi^0\gamma) = (7.4 \pm 0.7) \times 10^{-5}$.

In tab.2 the fit results are compared to the predictions of the $\mathrm{K}^+\mathrm{K}^-$ loop model for some possible structures of the scalar mesons. The f_0 parameters are well compatible with the $\mathrm{q\bar{q}q\bar{q}}$ model, while the a_0 ones disagree with that model.

3. $\phi \to \eta'\gamma/\phi \to \eta\gamma$

The mass eigenstates η and η' are related to the SU(3) octet-singlet states, η_8, η_1 through the psudoscalar mixing angle. Even in the case for two mixing angles wich appears in extended chiral perturbation theory, as well as from phenomenological analyses, it has been argued that the two mixing parameters in the quark flavour basis are equal apart from small terms which violate the OZI rule[8]. Is then possible to parametrize the mixing with only one angle φ_P, that can be extracted from the ratio R=$\mathrm{Br}(\phi \to \eta'\gamma)/\mathrm{Br}(\phi \to \eta\gamma)$[9].

Moreover the large $\mathrm{Br(B{\to}K\eta')}$ value observed[10], as opposed to theoretical predictions, raises also interest about the gluonium contents of the η'[11]. This gluonium contents can be tested with a precise measurement of $\mathrm{Br}(\phi \to \eta'\gamma)$.

The same final state, $\pi^+\pi^-$ and three prompt photons, has been choosen for both decays. This final state proceed through the chains: $\phi \to \eta\gamma$, $\eta \to \pi^+\pi^-\pi^0$, $\pi^0 \to \gamma\gamma$ (Br$\approx 3 \times 10^{-3}$) and $\phi \to \eta'\gamma$, $\eta' \to \eta\pi^+\pi^-$, $\eta \to \pi^0\pi^0$ (Br$\approx 2 \times 10^{-5}$). $\phi \to \eta\gamma$ decays are easily selected with small background; 50210 events have been counted with 37% efficiency. Since this decay chain is about 100 times more probable than the η' one, it is also the main source of background for $\phi \to \eta'\gamma$. After all background reduction, $120 \pm 12 \pm 5$, have been

Table 2
Comparison with K^+K^- loop predictions[4].

f_0 model	KLOE	$s\bar{s}(u\bar{u}+d\bar{d})/\sqrt{2}$	$(u\bar{u}+d\bar{d})/\sqrt{2}$	$s\bar{s}$
$g^2_{f_0KK}/(4\pi)$ (GeV^2)	2.79 ± 0.12	2.3	0.15	0.3
$gf_0\pi\pi/g^2_{f_0KK}$	0.50 ± 0.01	0.3 – 0.5	2	0.5
Br$(\phi \to \pi^0\pi^0\gamma)\times 10^4$	1.08 ± 0.07	~ 1	~ 0.15	~ 0.2
a_0 model		$s\bar{s}(u\bar{u}$-$d\bar{d})/\sqrt{2}$	$(u\bar{u}$-$d\bar{d})/\sqrt{2}$	
$g^2_{a_0KK}/(4\pi)$ (GeV^2)	0.40 ± 0.04	2.3	0.15	
$g_{a_0\eta\pi}/g_{a_0KK}$	1.35 ± 0.09	0.91	1.53	
Br$(\phi \to a_0\gamma)\times 10^4$	0.74 ± 0.07	~ 2	~ 0.2	

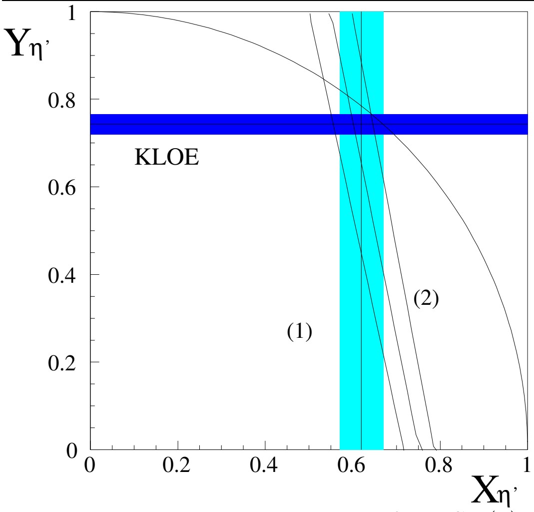

Figure 3. Bounds on $X_{\eta'}$ and $Y_{\eta'}$ from SU(3) calculations and experimental branching fractions.

selected with 23% overall efficiency.
Then $R = (4.70 \pm 0.47 \pm 0.31) \times 10^{-3}$ is obtained. From this ratio the mixing angle in the quark flavour basis can be extracted: $\varphi_P = (41.8^{+1.9}_{-1.6})^\circ$, that is equivalent to $\theta_P = (-12.9^{+1.9}_{-1.6})^\circ$ in the octet-siglet basis, in the picture with only one mixing angle. By using the current PDG value Br$(\phi \to \eta\gamma) = (1.297 \pm 0.003)\%$, follows Br$(\phi \to \eta'\gamma) = (6.10 \pm 0.61 \pm 0.43) \times 10^{-5}$, that is the most accurate determination up to now.
These values have been obtained neglecting any gluonium contents of η and η'. If one allows for gluonium:

$$|\eta\rangle = \quad X_\eta \left|u\bar{u} + d\bar{d}\right\rangle \sqrt{2} + Y_\eta \left|s\bar{s}\right\rangle + Z_\eta \left|glue\right\rangle$$
$$|\eta'\rangle = \quad X_{\eta'} \left|u\bar{u} + d\bar{d}\right\rangle \sqrt{2} + Y_{\eta'} \left|s\bar{s}\right\rangle + Z_{\eta'} \left|glue\right\rangle$$

A consistency check can be performed: if $Z_{\eta'} = 0$, then $|Y_{\eta'}| = \cos\varphi_P$; other constraints on $X_{\eta'}$ and $Y_{\eta'}$ can be obtained from (1) $\Gamma(\eta' \to \rho\gamma)/\Gamma(\omega \to \pi^0\gamma)$ and (2) $\Gamma(\eta' \to \gamma\gamma)/\Gamma(\pi^0 \to \gamma\gamma)$. Then in the $X_{\eta'}$, $Y_{\eta'}$ plane (fig.3) the overlap region of the three allowed bands is consistent within one standard deviation with no gluonium contents in the η', in fact: $X^2_{\eta'} + Y^2_{\eta'} = 0.94^{+0.06}_{-0.09}$.

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