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Rare ϕ decays

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Abstract. The Kloe experiment has collected an integrated luminosity $\sim 500pb^{-1}$ up to now, which means $\sim 1.65 \times 10^9$ ϕ decays. The huge amount of events allowed us to measure rare ϕ decays. We measured the radiative decays of the ϕ meson into π^0, η and $\eta'(958)$. These measurements are relevant to assess the mixing in the pseudoscalar nonet as well as to evaluate the gluon content in the $\eta'(958)$. Moreover also the radiative decays into $\pi^0\pi^0\gamma$ and $\eta\pi^0\gamma$ have been measured. These decays are dominated by the final states $f_0(980)$ and $a_0(980)$. The measurement of the branching ratios and of the $\pi^0\pi^0$ or $\eta\pi^0$ invariant mass spectrum helps to understand the controversial nature of the above scalar mesons.

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1 Introduction

The KLOE experiment operates at the Frascati ϕ-factory DAΦNE, which is an e^+e^- collider with $\sqrt{s} = 1020$ MeV and the peak cross section is $\sigma_\phi \approx 3.3\mu b$. KLOE started on April 1999, in 2000 collected an integrated luminosity of 25 pb^{-1}, 190 pb^{-1} during the 2001 and 300 pb^{-1} during the 2002.
The analysis of 2001 and 2002 data is in progress, while results from 2000 have been published [1,2,3].

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2 Pseudoscalar mesons

The mass eigenstates η, η' are related to the SU(3) octet-singlet states through the pseudoscalar mixing angle θ_P. Recent studies based on extended chiral perturbation theory and phenomenological analyses show the necessity to describe the mixing with two angles. In the quark flavour basis the two mixing parameters differ for small terms which violate the OZI rule [4], so it is still possible to describe the mixing with only one angle, φ_P. We will use the approch from Bramon [5] to extract the mixing angle from the ratio R = BR($\phi \to \eta'\gamma$)/BR($\phi \to \eta\gamma$).
A precise BR($\phi \to \eta'\gamma$) measurement can probe a possible η' gluon content. We measured R, studing $\phi \to \eta'\gamma$ and $\phi \to \eta\gamma$, both with $\pi^+\pi^-$ and three photons final state. The selection efficiency for $\phi \to \eta'\gamma$ is 23%, while the one for $\phi \to \eta\gamma$ is 37%; the $\phi \to \eta\gamma$ decay is the main background for the $\phi \to \eta'\gamma$. Other background comes from $\phi \to \pi^+\pi^-\pi^0$ and $\phi \to K_L K_S$. The events selected after all background rejection are $N_{\phi\to\eta'\gamma} = 120 \pm 12 \pm 5$ and $N_{\phi\to\eta\gamma} = 50210 \pm 220$, then R=$(4.70 \pm 0.47 \pm 0.31) \times 10^{-3}$ is obtained. Our R estimation with the PDG value for the branching ratio BR($\phi \to \eta\gamma$) = (1.297 ± 0.003)%, yields

$$BR(\phi \to \eta'\gamma) = (6.10 \pm 0.61 \pm 0.43) \times 10^{-5} \qquad (1)$$

From the ratio of the two branching ratios, we can extract our estimation for the mixing angle in the quark flavour basis:

$$\varphi_P = (41.8^{+1.9}_{-1.6})^\circ$$

This is true in the hypothesis of no gluonic content for the $\eta\prime$; if we allow it, we have

$$|\eta' >= X_{\eta'}|u\bar{u} + d\bar{d} > + Y_{\eta'}|s\bar{s} > + Z_{\eta'}|glue >$$

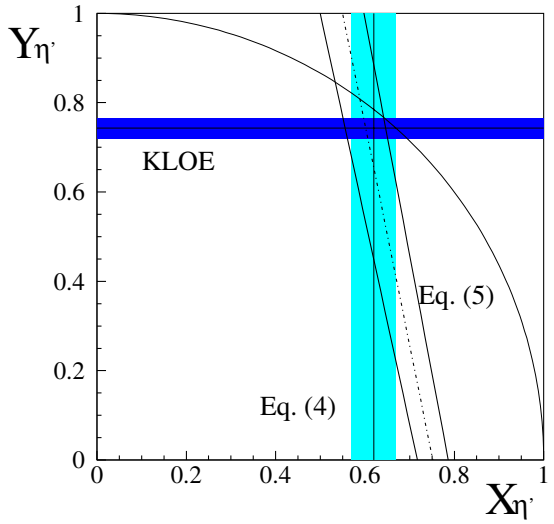

Fig. 1. Bounds on $X_{\eta'}$ and $Y_{\eta'}$: Equation (4) $\Gamma(\eta' \to \rho\gamma)/\Gamma(\omega \to \pi^0\gamma)$; Equation (5) $\Gamma(\eta' \to \gamma\gamma)/\Gamma(\pi^0 \to \gamma\gamma)$. The overlap region of the three allowed bands is consistent within one standard deviation with no gluonium contents in the η'

where $Z_{\eta'}$ allows for gluonium. We performed a consistency check of our measurement: if $Z_{\eta'} = 0$, measuring φ_P, we are measuring $|Y_{\eta'}| = cos\varphi_P$. Using constraints on $X_{\eta'}$ and $Y_{\eta'}$ from other decays, we find an overlap region of the three allowed bands in the $X_{\eta'}Y_{\eta'}$ plane (Fig. 1), which is consistent with a small value for $Z_{\eta'}$:

$$X^2_{\eta'} + Y^2_{\eta'} = 0.94^{+0.06}_{-0.09}$$

A first observation of $\phi \to \eta'\gamma$ with two tracks and seven photons final state has been performed by looking at the two decays:

1. $\phi \to \eta'\gamma$, $\eta' \to \eta\pi^+\pi^-$ and $\eta \to \pi^0\pi^0\pi^0$
2. $\phi \to \eta'\gamma$, $\eta' \to \eta\pi^0\pi^0$ and $\eta \to \pi^+\pi^-\pi^0$.

The analysis on the 2000 data gives the following result $\mathrm{BR}(\phi \to \eta'\gamma) = (7.05 \pm 0.50^{+0.53}_{-0.46}) \times 10^{-5}$ consistent with the published value (1).

3 Scalar mesons

The structure of the scalar mesons ($J^{PC} = 0^{++}$) $f_0(980)$ and $a_0(980)$ is not well understood. Several hypotheses have been proposed (tab.1): $q\bar{q}$ states, $q\bar{q}q\bar{q}$ states [6] and a $K\bar{K}$ bound state [7]. 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, can give information about the nature of these states [8].
KLOE has analysed the following processes:

1. $\phi \to f_0\gamma$, $f_0 \to \pi^0\pi^0$
2. $\phi \to a_0\gamma$, $a_0 \to \eta\pi^0$ and $\eta \to \gamma\gamma$
3. $\phi \to a_0\gamma$, $a_0 \to \eta\pi^0$ and $\eta \to \pi^+\pi^-\pi^0$
4. $\phi \to f_0\gamma$, $f_0 \to \pi^+\pi^-$

The first two decays are fully neutral final state: five prompt photons in the detector; these two processes have been previously measured by SND and CMD-2 at VEPP-2M in Novosibirsk [9]. The third decay, which has two charged pions and five prompt photons final state, has been observed by KLOE for the first time (2000 data).
The last decay has been studied analysing 340 pb^{-1} collected in 2001 and 2002 data taking.
The processes contributing to the five photon final state, besides the signals are:

1. $\phi \to \sigma(500)\gamma$, $\sigma \to \pi^0\pi^0$
2. $\phi \to \rho^0\pi^0$, $\rho \to \pi^0\gamma, \eta\gamma$
3. $e^+e^- \to \omega\pi^0$, $\omega \to \pi^0\gamma$

Table 1. Model prediction

Model	BR($\phi \to f_0\gamma$)	BR($\phi \to a_0\gamma$)
$q\bar{q}$	5×10^{-5}	2×10^{-5}
$q\bar{q}q\bar{q}$	3×10^{-4}	2×10^{-4}
$K\bar{K}$	10^{-5}	10^{-5}

A kinematic fit is performed, requiring the 4-momentum conservation, to reject events from decays with three and seven prompt photons, wrongly reconstructed as five photon ones. A discrimination between $\phi \to \pi^0\pi^0\gamma$ and $\phi \to \eta\pi^0\gamma$ is performed with a procedure of photon pairing, which associates pairs of photons to π^0 and η. Events with $\pi^0\gamma$ invariant mass compatible with the ω mass are recognised as $\omega\pi^0$ background and rejected. After all background subtraction the $\phi \to \pi^0\pi^0\gamma$ events selected are 3102 with a contamination at level of 20% as evaluated from Monte Carlo. The selection efficiency for the signal is 40% and by normalizing to the luminosity we find the following branching ratio:

$$BR(\phi \to \pi^0\pi^0\gamma) = (1.08 \pm 0.03 \pm 0.05) \times 10^{-4}$$

Concerning the decay $\phi \to \eta\pi^0\gamma$ with $\eta \to \gamma\gamma$ the selection efficiency is 32% and the contamination at level of 30%; the number of selected events is 916.
The branching ratio obtained is:

$$BR(\phi \to \eta\pi^0\gamma) = (8.51 \pm 0.51 \pm 0.57) \times 10^{-5}$$

both results are in agreement with the Novosibirsk measurements [9].
The decay $\phi \to \eta\pi^0$ with $\eta \to \pi^+\pi^-\pi^0$ produces in the detector two charged tracks coming from the interaction point and five prompt photons. No other decay has the same final state, but events with two tracks and three ($\phi \to \eta\gamma$, $\eta \to \pi^+\pi^-\pi^0$), four ($e^+e^- \to \omega\pi^0, \omega \to \pi^+\pi^-\pi^0$; $\phi \to K_LK_S, K_L \to \pi l\nu$ and $K_S \to \pi^0\pi^0$) or six ($\phi \to K_LK_S \to \pi^+\pi^-\pi^0\pi^0\pi^0$, with prompt K_L decay) prompt photons can mimic this final state.
The selection of this decay has been done with a strategy similar to the one used for fully neutral final state: 197 events have been selected with 4 ± 4 background events and with 19% efficiency. From this decay chain we find a branching ratio measurement in good agreement with the

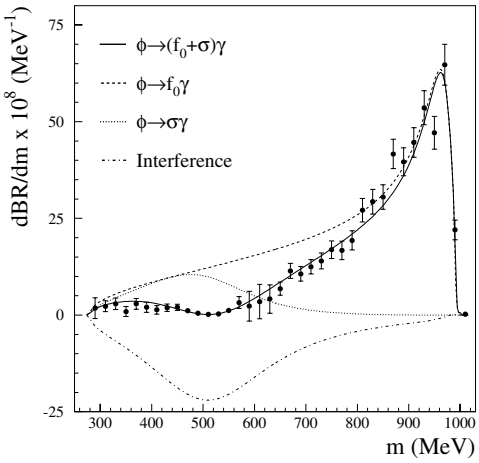

Fig. 2. Differential decay rate for $\phi \to \pi^0\pi^0\gamma$; the solid line is the result of the fit, single contributions are also shown

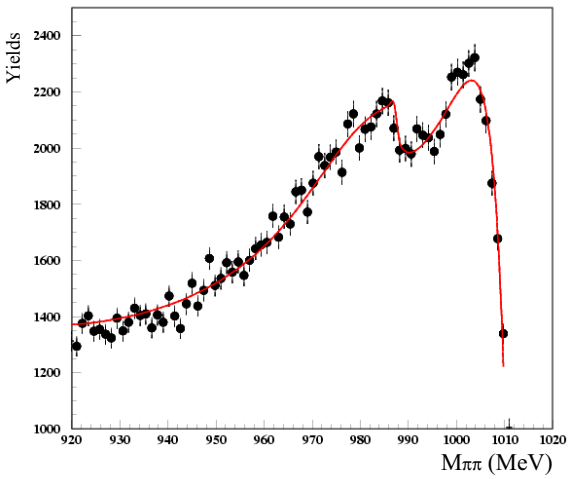

Fig. 3. $\pi^+\pi^-$ invariant mass spectrum

result of the five photon sample:

$$BR(\phi \to \eta\pi^0\gamma) = (7.96 \pm 0.60 \pm 0.47) \times 10^{-5}$$

The structure of f_0 a_0 states can be investigated by comparing the $M_{\pi\pi}$ and $M_{\eta\pi}$ spectra to the theoretical models. We tried to fit our data with the kaon-loop model used for the CMD-2/SND data: (a) the coupling of ϕ to $S(0^{++})\gamma$ is assumed to occur through a charged kaon loop [8], (b) the scalar propagator with finite width corrections is used, (c) the $\phi \to \rho^0\pi^0$ parametrization is taken from VDM calculations [11]. We fit the $\pi^0\pi^0$ mass spectrum, after background subtraction. The fit indicates a negligible $\rho^0\pi^0$ contribution and a large $f_0 - \sigma$ destructive interference [1] at $M_{\pi\pi} < 700\ MeV$. The free parameters of the fit are the f_0 mass, the coupling $g^2_{f_0KK}/(4\pi)$, the ratio $g^2_{f_0KK}/g^2_{f_0\pi\pi}$, the $BR(\phi \to \rho^0\pi^0 \to \pi^0\pi^0\gamma))$. The results of the fit are compatible with the four quarks hypothesis. In Fig 2 the differential decay rate is plotted, together with the various contributions. A similar study has been applied to the $\phi \to \eta\pi^0\gamma$ decay. A combined fit of the two mass spectra, one from the fully neutral decay, another from the charged and neutral final state, after background subtraction, has been performed. We fix the relative normalization to the ratio BR($\eta \to \gamma\gamma$)/BR($\eta \to \pi^+\pi^-\pi^0$) from the PDG. In this case the free parameters are the coupling $g^2_{a_0KK}/(4\pi)$ (GeV^2), the ratio $g_{a_0\eta\pi}/g_{a_0KK}$ and the BR($\phi \to \rho^0\pi^0 \to \eta\pi^0\gamma$). The fit results indicate again a negligible $\rho^0\pi^0$ contribution, but appear not to be compatible with the four quark model. The integration of the a_0 contribution on the theoretical curve gives:

$$BR(\phi \to a_0\gamma \to \eta\pi^0\gamma) = (7.4 \pm 0.7) \times 10^{-5}$$

The study of the decay $\phi \to f_0\gamma$, $f_0 \to \pi^+\pi^-$ has been performed on a sample of 2001 and 2002 data.We fitted the $M_{\pi\pi}$ spectrum with the f_0 signal plus the contributions from initial state and final state radiation, allowing interference of the f_0 with final state radiation. The best results come up for destructive interference as shown in Fig. 3 where the f_0 structure is visible around 980 MeV.

[1] The σ meson has been parametrized as a fixed width Breit-Wigner, with $M_\sigma = 478$ MeV and $\Gamma_\sigma = 324$ MeV [10], and a point-like $\phi - \sigma\gamma$ coupling has been used.

4 Conclusions

Using year 2000 data we published our first papers on ϕ-radiative decays about the $\eta - \eta'$ mixing and the scalar mesons. We have observed for the first time the $\phi \to \eta'\gamma$ decay with two tracks and seven photon final state and the $\phi \to a_0\gamma$ decay with $a_0 \to \eta\pi^0$ and $\eta \to \pi^+\pi^-\pi^0$. A new and more complete study of the nature of the f_0 and a_0 mesons is in progress with the full statistics collected up to now.

References

1. A. Aloisio et al., *Measurement of $\Gamma(\phi \to \eta'\gamma)/\Gamma(\phi \to \eta\gamma)$ and the pseudoscalar mixing angle*, Phys. Lett. B **541** (2002), 45
2. A. Aloisio et al., *Study of the Decay $\phi \to \pi^0\pi^0\gamma$ with the KLOE detector*, Phys. Lett. B **537** (2002), 21
3. A. Aloisio et al., *Study of the Decay $\phi \to \eta\pi^0\gamma$ with the KLOE detector*, Phys. Lett. B **536** (2002), 209
4. H. Luetwyler, Nucl. Phys. Proc. Suppl. **64** (1998) 223; R. Escribano, J.M. Frére, Phys. Lett. B **459** (1999), 288
5. A. Bramon et al., Eur. Phys. J. C **7** (1999) 271;
6. R.L. Jaffe, Phys. Rev. D **15** (1977) 267
7. J. Weinstein, N. Isgur, Phys. Rev. Lett. **48** (1982) 659
8. N.N. Achasov, V.I. Ivanchenko, Nucl. Phys. B **315** (1989) 465
9. M.N. Achasov et al., Phys. Lett. B **485** (2000) 349; Phys. Lett. B **479** (2000) 53; R.R. Akhmetsshin et al., Phys. Lett. B **462** (1999) 380
10. E.M. Aitala et al., Phys. Rev. Lett. **86** (2001) 770
11. N.N. Achasov, V.V. Gubin, Phys. Rev. D **63** (2001)