KLOE Results on Light Meson Properties

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The KLOE experiment operating at the ϕfactory DAϕNE has collected an integrated luminosity of about 2.5 fb^{-1} on the ϕ meson peak. We present recent results achieved from studying properties of light mesons using the full statistic.

1 KLOE at DAϕNE

The KLOE experiment [1] is placed at the Frascati ϕ-factory DAΦNE, an e^+e^- collider running at $\sqrt{s}\simeq$1020 MeV, corresponding to the ϕ meson mass. A ϕ-factory allow to access many of the light mesons via ϕ radiative decay and to study the inner structures of the mesons, in particular the s-quark content via the couplings with the $s\bar{s}$ state. KLOE has collected an integrated luminosity of 2.5 fb^{-1} at the ϕ peak, corresponding to $8 \times 10^9\phi$ decays, 10 pb^{-1} around the centre of mass energy and 250 pb^{-1} at $\sqrt{s} = 1$ GeV.
The KLOE detector consists of a large cylindrical drift chamber (3.75 m length and 4 m diameter), surrounded by a sampling calorimeter made of lead and scintillating fibers. The detector is inserted in a superconducting coil producing a uniform magnetic field of $\simeq$ 0.52T. Large angle tracks from the origin ($\theta > 45°$) are reconstructed with relative momentum resolution $\sigma_p/p = 0.4\%$. Photon energies and times are measured by the calorimeter with resolutions of $\sigma_E/E = 5.7\%/\sqrt{E(GeV)}$ and $\sigma_t = 57ps/\sqrt{E(GeV)} \oplus 100$ ps.

2 Scalar Mesons

The structure of the scalar mesons (S) with mass below 1 GeV is still an open question. The radiative decays $\phi \to PP'\gamma$ are dominated by the exchange of a S in the intermediate state. Branching ratio and mass spectra of decays are sensitive to the structure of intermediate S and they can clarify whether S are $q\bar{q}$ mesons, tetra-quark state, bound states of $K\bar{K}$ pair or a mix of these configurations. Many approaches have been used to parametrise the production of S in the ϕ radiative decays. We consider the Kaon Loop (KL) model [2] which assumes that the ϕ radiative decay proceeds through a virtual K^+K^- loop, while emitting a photon. Then the K^+K^- annihilate forming a S. The production amplitude of the S depends on the mass and couplings to $\pi\pi$ and KK. The fit parameters are the M$_S$ and the two couplings g$_{SPP'}$, g$_{SKK}$. An alternative parametrisation of the amplitude is the No Structure (NS) one [3]: a point-like coupling of the scalar to the ϕ meson is assumed; S is parametrised as a Breit-Wigner interfering with a polynomial background. Free parameters are the M$_S$ and the couplings g$_{\phi S\gamma}$, g$_{SPP'}$ and g$_{SKK}$. In the following we describe how we fit the data using the two approaches described above.

Parameter	Kaon Loop	No Structure
M_{a_0} (MeV)	$982.5 \pm 1.6 \pm 1.1$	982.5 (fixed)
$g_{a_0 KK}$ (GeV)	$2.15 \pm 0.06 \pm 0.06$	$2.01 \pm 0.07 \pm 0.28$
$g_{a_0 \eta\pi}$ (GeV)	$2.82 \pm 0.03 \pm 0.04$	$2.46 \pm 0.08 \pm 0.11$
$g_{\phi a_0 \gamma}$ (GeV^{-1})	$1.58 \pm 0.10 \pm 0.16$	$1.83 \pm 0.03 \pm 0.08$
BR($\phi \to \rho \to \eta\pi\gamma$)$\times 10^{-6}$	$0.92 \pm 0.40 \pm 0.15$	-0
BR($\eta \to \gamma\gamma$)/BR($\eta \to \pi\pi\pi$)	$1.70 \pm 0.04 \pm 0.03$	$1.70 \pm 0.03 \pm 0.01$
P(χ^2)	10.4%	30.9%

Table 1: Results from combined fit to $M_{\eta\pi}$ spectra

2.1 Searching for $a_0(980)$ in $e^+e^- \to \eta\pi^0\gamma$

Two independent analyses [4] using $\eta \to \gamma\gamma$ or $\eta \to \pi^+\pi^-\pi^0$ decays are performed from a sample of 450 pb^{-1}. In both analyses there is the requirement of five photons from the interaction point. The selection of also two tracks with balanced charge is required to select the charged final state. The fully neutral chain is characterised by high statistic and large background, while the charged one has small background but lower statistic. Since the interfering $\phi \to \rho\pi^0 \to \eta\pi^0\gamma$ background is small, it is possible to extract the branching ratio (BR) directly from event counting after the residual background subtraction and normalising to $\phi \to \eta\gamma$ decays with the same final state. The two samples lead to consistent branching ratio values, thus a combined fit of the two spectra, is performed to extract relevant parameters of the a_0 scalar meson. The couplings, fitted according to the KL [2] and the NS [3] models, point to a total width in the range [$80 \div 105$] MeV and to a size-able $s\bar{s}$ content of the $a_0(980)$, see Tab.1.

Recently a new model to describe S has been proposed by t'Hooft et al. [5]. They start from the point that tetra-quarks bound states naturally reproduce the $SU(3)$ nonet structure, with the correct mass ordering and then they add an instaton contribution to induce a mixing between tetra-quarks and diquarks states. The instaton contribution lead to a simple and satisfactory description of light states below 1 GeV and heavier scalar states around 1.5 GeV. The KLOE measurement concerning the f_0 scalar meson has been used as input parameter to evaluate the coefficient in the model and then to compare the effect on the a_0 meson. The results are intriguing [5].

2.2 $\phi \to K^0\bar{K}^0\gamma$

Using 2.18 fb^{-1} of the KLOE data, a search [6] for the decay $\phi \to K^0\bar{K}^0\gamma$ has been performed. This decay is expected to proceed mainly through $\phi \to [a_0(980) + f_0(980)]\gamma \to K^0\bar{K}^0\gamma$. In this decay the $K^0\bar{K}^0$ pair is produced with positive charge conjugation and a limited phase space due to the small mass difference between the ϕ and the production threshold of two neutral kaons (995 MeV). The signature of this decay is provided by the presence of either 2 K_S or 2 K_L and a low energy photon. We select only the K_SK_S component, looking for double $K_S \to \pi^+\pi^-$ decay vertex, because of the clean topology. The main background are the resonant $e^+e^- \to \phi\gamma \to K_SK_L\gamma$ and the continuum $e^+e^- \to \pi^+\pi^-\pi^+\pi^-\gamma$ processes.
After the selection cut we found 5 candidate events in data, whereas 3 events are expected from

Monte Carlo background samples. This leads to: BR($\phi \to K^0\bar{K}^0\gamma$) $< 1.9 \times 10^{-8}$ at the 90% C.L. Theory predictions for the BR spread over several orders of magnitude; several of them are ruled out by our result. Moreover the present upper limit is consistent with the BR($\phi \to K\bar{K}$) prediction computed with $a_0(980)$ [4], $f_0(980)$ [7] couplings measured by KLOE.

3 $\sigma(e^+e^- \to \omega\pi^0)$

We have studied the $e^+e^- \to \omega\pi^0$ cross section in the range $\sqrt{s} \sim 1000-1030$ MeV, on a sample of 600 pb^{-1}, searching for $\pi^+\pi^-\pi^0\pi^0$ and $\pi^0\pi^0\gamma$ final states. At low energy, below 1.4 GeV it is largely dominated by non resonant process. However around the ϕ mass a contribution from the OZI-G parity violating decay $\phi \to \omega\pi^0$ is expected. The strongly suppressed decay can be observed via interference with the non resonant processes, showing as a dip in the total cross section dependence from $\sqrt{s}$, see Fig.1.

The parametrisation for the cross section, that has been convoluted with the radiator function is the following:

$$\sigma(\sqrt{s}) = \sigma_0(\sqrt{s})|1 - Z\frac{M_\phi\Gamma_\phi}{D_\phi}|^2$$
$$\sigma_0(\sqrt{s}) = \sigma_0 + \sigma'(\sqrt{s} - M_\phi)$$

where the $\sigma_0(\sqrt{s})$ is the bare cross section for the non resonant process, Z is the interference parameter and M_ϕ, Γ_ϕ and D_ϕ are mass, width and inverse propagator of ϕ meson. By fitting the observed interference pattern around ϕ mass for both final states under study we extract the ratio $\Gamma(\omega \to \pi^0\gamma)/\Gamma(\omega \to \pi^+\pi^-\pi^0)$ and combining the result with rare branching fraction and imposing unitarity, we derive the branching fraction:

$$BR(\omega \to \pi^0\gamma) = (8.09 \pm 0.14)\% \quad (1)$$
$$BR(\omega \to \pi^+\pi^-\pi^0) = (90.24 \pm 0.19)\%$$

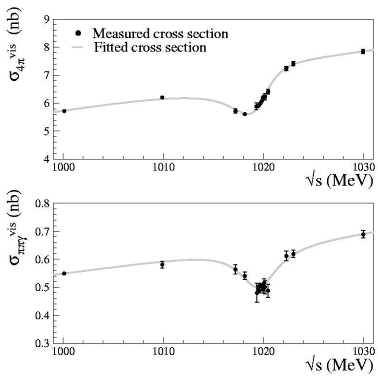

Figure 1: Measured cross section and fitted one. Up: $\pi^+\pi^-\pi^0\pi^0$ final state; down: $\pi^0\pi^0\gamma$ final state.

The interference parameter determined in the $\pi^+\pi^-\pi^0\pi^0$ analysis allow us to determine the branching ratio for the process $\phi \to \omega\pi^0$:

$$BR(\phi \to \omega\pi^0) = \frac{\sigma_0^{\omega\pi}|Z_{4\pi}|^2}{\sigma_\phi} = (5.63 \pm 0.70) \times 10^{-5} \quad (2)$$

and the error has been reduced by a factor two with respect to the best previous measurement by SND; the two values are in agreement.

4 $\gamma\gamma$ Fusion at KLOE: $\sigma(600) \to \pi\pi$

The question concerning the $\sigma/f_0(600)$ meson has been debated for a long time.

Evidences come from Dalitz Plot analysis of charged final states from E731, CLEO, Bes, but the values of mass and width are affected by large uncertainties. Indirect evidence comes also from the Dalitz Plot analysis of the $e^+e^- \to \pi^0\pi^0\gamma$ process by KLOE [8].

The preliminary analysis of 11 pb^{-1} at $\sqrt{s} = 1$ GeV, 5 % of the off-peak data sample, has been finalise to search for σ production in $\gamma\gamma$ interaction. An excess of events in the $\pi^0\pi^0$ final state has been observed, when the expected background from Monte Carlo are compared with data, see Fig.2.

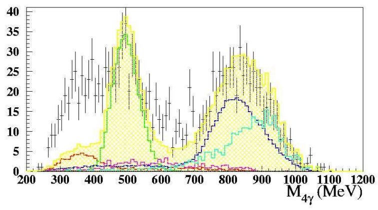

Figure 2: $M_{\gamma\gamma\gamma\gamma}$: data compared with Monte Carlo shows an excess of events compatible σ.

5 Pseudoscalar Mesons

The ϕ-factory DAϕNE can be considered also an η factory. The acquired luminosity of 2.5 fb^{-1} on peak correspond also to $\sim 10^8$ η meson, if we consider the radiative decay of the ϕ meson. The same can be for the η', on peak data furnish a sample of 5×10^5 η', again from radiative decay of the ϕ meson. In the following we describe part of the analysis performed at KLOE.

5.1 $\eta - \eta'$ mixing angle

We have measured the ratio $R_\phi = BR(\phi \to \eta'\gamma)/BR(\phi \to \eta\gamma)$ by looking for the radiative decays $\phi \to \eta'\gamma$ and $\phi \to \eta\gamma$ into the final states $\pi^+\pi^-7\gamma$ and 7γ, respectively, in a sample of $\simeq 1.4 \times 10^9\phi$ mesons. We obtained [9] $R_\phi = (4.77 \pm 0.09 \pm 0.19) \cdot 10^{-3}$, from which we derive BR$(\phi \to \eta'\gamma) = (6.20 \pm 0.11 \pm 0.25) \cdot 10^{-5}$.
The value of R_ϕ can be related to the $\eta - \eta'$ mixing angle in the flavor basis. Using the approach [10] and [11], where the SU(3) breaking is taken into account via constituent quark mass ratio $m_s/\bar{m}$, and the two parameters Z_{NS} and Z_S take into account the effect of the OZI-rule, which reduce the VP wave-function overlaps [12] we have:

$$R = \frac{BR(\phi \to \eta'\gamma)}{BR(\phi \to \eta\gamma)} = cot^2\varphi_P(1 - \frac{m_s}{\bar{m}}\frac{Z_{NS}}{Z_S}\frac{tan\varphi_V}{sin2\varphi_P})^2(\frac{p_{\eta'}}{p_\eta})^3 \qquad (3)$$

Equation 3 combined with our measurement produced the following result: $\varphi_P = (41.4 \pm 0.3_{stat} \pm 0.7_{sys} \pm 0.6_{th})^\circ$.
The η' meson is a good candidate to have a size-able gluonium content, so we can have $|\eta' >= X_{\eta'}|q\bar{q} > +Y_{\eta'}|s\bar{s} > +Z_{\eta'}|gluon >$, where the $Z_{\eta'}$ parameter takes in to account a possible mixing with gluonium. The normalisation implies $X^2_{\eta'} + Y^2_{\eta'} + Z^2_{\eta'} = 1$ with $X_{\eta'} = \cos\phi_G \sin\phi_P$, $Y_{\eta'} = \cos\phi_G \cos\phi_P$ and $Z_{\eta'} = \sin\phi_G$, where ϕ_G is the mixing angle for the gluonium contribution. Possible gluonium content of the η' meson corresponds to non-zero value for $Z^2_{\eta'}$. Introducing other constraints on $X_{\eta'}$ and $Y_{\eta'}$ [11, 12, 13], as: $\Gamma(\eta' \to \gamma\gamma)/\Gamma(\pi^0 \to \gamma\gamma)$; $\Gamma(\eta' \to \rho\gamma)/\Gamma(\omega \to \pi^0\gamma)$; $\Gamma(\eta' \to \omega\gamma)/\Gamma(\omega \to \pi^0\gamma)$, and allowing for gluonium, we built a χ^2, function of (ϕ_P, ϕ_G), to determine $Z^2_{\eta'}$ and ϕ_P. The solution in the hypothesis of no gluonium content, i.e. $Z^2_{\eta'} = 0$ yields $\phi_P = (41.5^{+0.6}_{-0.7})^\circ$; the χ^2 quality is bad, while allowing for gluonium the χ^2 quality is good, $P(\chi^2/N.d.f.) = 0.49$ and the results are $\phi_P = (39.7 \pm 0.7)^\circ$ with $Z^2_{\eta'} = 0.14 \pm 0.04$ showing a 3σ evidence for the η' gluonium content.
Moreover, combining R_ϕ with other constraints [14] and answering in this way to the objections

from [15], [16] to our paper [9], we find $Z^2_{\eta'} = 0.120 \pm 0.035$ and $\phi_P = (40.2 \pm 0.6)^\circ$ in agreement with the previous one.

5.2 $\eta \to \pi^+\pi^-e^+e^-$

The study of $\eta \to \pi^+\pi^-e^+e^-$ decay allows to probe the internal structure of the η meson [17] and could be used to compare the predictions based on Vector Meson Dominance (VMD) and Chiral Perturbation Theory (ChPT) [18]. Moreover, it would be possible to study CP violation not predicted by the Standard Model by measuring the angular asymmetry between the decay planes of the electrons and of the pions in the η rest frame.

The experimental scenario is rather poor to investigate the theoretical issue related to this process. Our $\eta \to \pi^+\pi^-e^+e^-$ analysis [18] is based on a sample of 1.7 fb$^-$1. The event selection is based on the requirement of one photon of $E > 250$ MeV energy, the recoil photon produced in the $\phi \to \eta\gamma$ decay, and four charged tracks coming from the interaction region. Mass assignment for each track is done using time of flight of the charged particles measured in the calorimeter. Background due to γ conversions on the beam pipe has been studied using off-peak data, where ϕ decays are negligible.
The contamination is evaluated by fitting the sidebands of the $M_{\pi\pi ee}$ data spectrum with background components after loose cuts on the kinematic fit χ^2 and on the sum of momenta of the charged particles. Signal events are computed after rejecting γ conversions, and from the fit the branching ratio is evaluated:

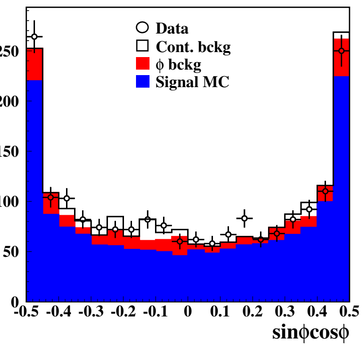

Figure 3: $sin\phi cos\phi$ in the signal region.

$$BR(\eta \to \pi^+\pi^-e^+e^-\gamma) = (26.8 \pm 0.9_{Stat.} \pm 0.7_{Syst.}) \times 10^{-5}. \quad (4)$$

The decay plane asymmetry is calculated starting from the momenta of the four particles and it is expressed as function of the angle ϕ between the pion and the electron planes in the η rest frame; it has been evaluated for the events in the signal region after background subtraction, see Fig. 3. The result is:

$$\mathcal{A}_\phi = (-0.6 \pm 2.5\ _{Stat.} \pm 1.8\ _{Syst.}) \times 10^{-2} \quad (5)$$

which is the first measurement of this parameter.

5.3 Search for Box Anomaly: $\eta/\eta' \to \pi^+\pi^-\gamma$

Significant contribution from chiral anomaly responsible for $\eta/\eta' \to \gamma\gamma$, which proceed through the triangle anomaly, is expected in $\eta/\eta' \to \pi^+\pi^-\gamma$, called box anomaly. The box anomaly is a higher term of WZW, describing the direct coupling of three pseudoscalar mesons with the photon (Fig. 4). The shapes of the Feynman diagrams representing the WZW gives the names for the anomaly.
The $\eta, \eta' \to \pi^+\pi^-\gamma$ decays provide a good tool to investigate the box anomaly, which describes

a non-resonant coupling. The invariant mass of the pions is a good observable to disentangle this contribution from other possible resonant ones, e.g. from the ρ-meson.

The kinematic range of the decays of η and η' are above the chiral limit where the WZW validity holds, for the η' even the ρ-mass is covered. The $\eta \to \pi^+\pi^-\gamma$ decay has been measured in 1970 by Gormely et al. (7250 events) [20] and in the 1973 by Layter et al. (18150 events) [21]. Theoretical papers trying to combine the two measurements found discrepancies in data treatment and problems in obtaining consistent results [22, 23]. Therefore new experimental results with larger statistics are needed to clarify the scenario. The KLOE data 2.5 fb^{-1}, corresponding to 5×10^6 $\eta \to \pi^+\pi^-\gamma$ decays. This statistics allows a detailed investigation of the di-pion invariant mass distribution. A selection procedure and background rejection criteria are in development.
The same framework can be applyed to the η' meson, taking into account that in this case also the ρ-mass is covered. Data related to the $\eta' \to \pi^+\pi^-\gamma$ decays are much more recent: in 1997 the analysis of 7392 events provided by Crystal Barrel gave a box anomaly evidence in the invariant mass of pions [24], while in 1998 the L3 Collaboration found that their data (2123 events) were well described by the resonant contribution [25].
The data already collected at KLOE, 2.5 fb^{-1}, provides 15×10^4 $\eta' \to \pi^+\pi^-\gamma$ decays. Accurate Monte Carlo simulation is under development.

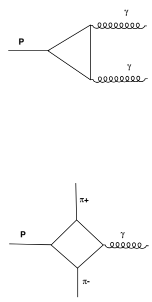

Figure 4: Diagrams for the triangle and box anomalies.

5.4 Conclusions and Outlooks

KLOE has been obtained several important results in hadronic physics, in this paper we descrive some of them. But this is not the end of the story, a new scheme to increase luminosity by a factor 5 is being implemented at DAϕNE, thanks to the *crab weist* and large crossing angle, to open new prospects for KLOE2. In the new data taking scheduled for KLOE, e^+e^- taggers for $\gamma\gamma$ physics will be inserted, to collect 5 fb^{-1}. Another upgrade will be performed in a second phase to insert the inner tracker and new small angle calorimeters. KLOE2 items will be focused on kaon physics and light hadrons, where in particular thanks to the e^+e^- taggers a dedicated data collection will allow us to investigate in a deepper way the $\gamma\gamma$ fusion processes.

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