KLOE RESULTS ON LIGHT MESON SPECTROSCOPY

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An important part of the program of the KLOE experiment has been dedicated to the study of the ϕ radiative decays into scalar ($f_0(980)$ and $a_0(980)$) and pseudoscalar (η and η') mesons.

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1. Introduction

The KLOE experiment has been carried out at the Frascati ϕ-factory DAΦNE; its data taking ended in March 2006 with a total integrated luminosity of 2.5 fb^{-1}, corresponding to $8 \times 10^9 \phi(1020)$ mesons produced. The decays $\phi(1020) \to PP\gamma$, where P means a pseudoscalar meson, are dominated by the exchange of a scalar meson S in the intermediate state ($\phi \to S\gamma$, and $S \to PP$), thus they are suitable processes to study the $f_0(980)$ and $a_0(980)$, and also to look for a possible signal of the $\sigma(600)$. It is still controversial whether the light scalars are ordinary $q\bar{q}$ mesons, compact $qq\bar{q}\bar{q}$ states, or bound states of a K and a $\bar{K}$ mesons. The measurement of the branching ratios of $\phi(1020) \to PP\gamma$ and of the parameters of the scalar resonances (masses and couplings) are sensitive to their internal structure. On the other hand large samples of η and η' mesons are produced, through

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the decays $\phi \to \eta(\eta')\gamma$, thus allowing for a precise determination of the $\eta - \eta'$ mixing angle, and of the slope parameters of the Dalitz plot of the $\eta \to 3\pi$ decay. Also a precise measurement of the η meson mass is presented.

2. Light scalar mesons

The branching ratios of $\phi \to f_0(980)\gamma \to \pi\pi\gamma$ and of $\phi \to a_0(980)\gamma \to \eta\pi^0\gamma$ have been measured and the parameters of the scalar resonances have been extracted from a fit of the Dalitz plot or of the invariant mass distribution of the two pseudoscalars. Two phenomenological models have been used: the Kaon Loop (KL) one, in which the ϕ is coupled to the scalar through a loop of charged kaons [1], and the No Structure (NS) one, that assumes a point-like coupling of the scalar to the ϕ [2].

A sample of 450 pb^{-1} of data has been used to study the $f_0(980)$ in the Dalitz plot of the process $e^+e^- \to \pi^0\pi^0\gamma$ [3] (Fig. 1). The two straight bands are due to the non resonant process $e^+e^- \to \omega\pi^0$, with $\omega \to \pi^0\gamma$, while the region of high $M_{\pi\pi}$ is dominated by the f_0. The results of the

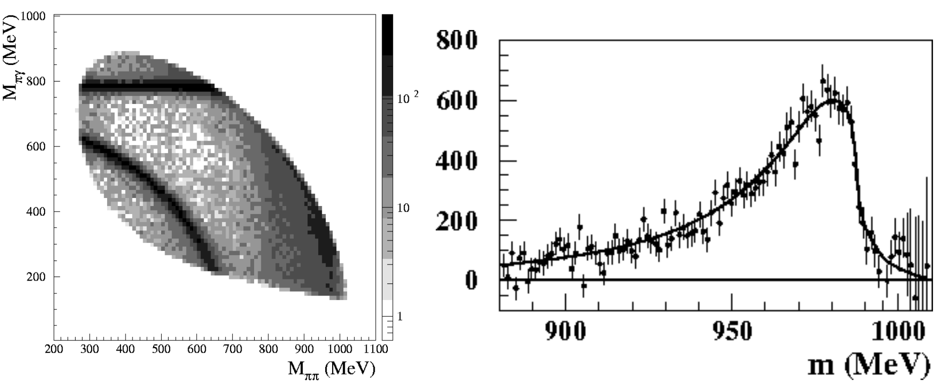

Fig. 1. Left: Dalitz plot of $e^+e^- \to \pi^0\pi^0\gamma$. Right: fit of $M_{\pi^+\pi^-}$.

fit to the Dalitz plot are shown in Table I ($R_{f_0} = g^2_{f_0 K^+K^-}/g^2_{f_0\pi^+\pi^-}$). In the KL case the fit function includes the contribution of the $\sigma(600)$ with fixed parameters ($M_\sigma = 462$ MeV, $\Gamma_\sigma = 286$ MeV, $g_{\sigma K^+K^-} = 0.5$ GeV, and $g_{\sigma\pi^+\pi^-} = 2.4$ GeV) [1]. The interfering vector background ($e^+e^- \to \omega\pi^0$ and $\phi \to \rho^0\pi^0$, with $\rho^0 \to \pi^0\gamma$) is also included in the fit. If the $\sigma(600)$ is excluded, the fit quality becomes very poor, $P(\chi^2) \sim 10^{-4}$. $g_{\phi f_0\gamma}$ is a free parameter of the NS model. Moreover, this model does not include explicitly the $sigma(600)$ contribution. The vector background has the same parametrization used for the KL. The branching ratio is obtained from the integral of the scalar contribution only: $\mathrm{Br}(\phi \to S\gamma \to \pi^0\pi^0\gamma) = \left(1.07^{+0.01}_{-0.03(\mathrm{fit})}\,{}^{+0.04}_{-0.02(\mathrm{syst})}\,{}^{+0.05}_{-0.06(\mathrm{mod})}\right) \times 10^{-4}$.

TABLE I

$f_0(980)$ parameters.

	Dalitz plot fit		$M_{\pi^+\pi^-}$ fit	
	KL model	NS model	KL model	NS model
M_{f_0} (MeV)	984.7	984.7	983.7	973–981
$g_{f_0K^+K^-}$ (GeV)	3.97	0.40	4.74	1.6–2.3
$g_{f_0\pi^+\pi^-}$ (GeV)	−1.82	1.31	−2.22	0.9–1.1
$g_{\phi f_0\gamma}$ (GeV^{-1})	—	2.61	—	1.2–2.0
R_{f_0}	4.8	0.09	4.6	2.6–4.4

The $f_0(980)$ has also been studied in $e^+e^- \to \pi^+\pi^-\gamma$ [3]; only a small fraction of $\pi^+\pi^-\gamma$ events originates from $\phi \to f_0\gamma$ with $f_0 \to \pi^+\pi^-$, the main contribution is given by events in which the photon is produced by either an initial state (ISR) or a final state (FSR) radiation. The ISR component is suppressed by requiring the polar angle of the photon $\vartheta_\gamma > 45°$. The $\pi^+\pi^-$ invariant mass distribution has been fit to the differential cross-section ($m = M_{\pi^+\pi^-}$): $\frac{d\sigma}{dm} = \frac{d\sigma_{\rm ISR}}{dm} + \frac{d\sigma_{\rm FSR}}{dm} + \frac{d\sigma_{\rho\pi}}{dm} + \frac{d\sigma_{\rm scalar}}{dm} \pm \frac{d\sigma_{\rm scalar\otimes FSR}}{dm}$. The scalar contribution is parametrized according to both KL and NS models, and the last term can be either added (constructive interference) or subtracted (destructive one). The fit results are shown in Fig. 1, and the f_0 parameters are listed in Table I. Destructive interference between f_0 and FSR is preferred. By integrating the scalar contribution, the following range for the branching ratio can be derived: ${\rm Br}(\phi \to f_0\gamma \to \pi^+\pi^-\gamma) = 2.1 \times 10^{-4} - 2.4 \times 10^{-4}$.

The $a_0(980)$ has been studied in $\phi \to \eta\pi^0\gamma$, by looking for the two final states corresponding to $\eta \to \gamma\gamma$ (39.31%) and $\eta \to \pi^+\pi^-\pi^0$ (22.73%). Concerning the first decay chain, 29061 events have been selected in the analyzed sample of 450 pb^{-1} with 38.5% efficiency; the irreducible background amounts to 55% of the final sample, and has been evaluated by Monte Carlo (MC) and checked on data control samples. After the background subtraction the following branching ratio is obtained [4]: ${\rm Br}(\phi \to \eta\pi^0\gamma) = (7.01 \pm 0.10_{\rm stat} \pm 0.20_{\rm syst}) \times 10^{-5}$. The second decay chain is characterized by very low background, since there are no other processes with the same final state as the signal. 4181 events are selected, with 19.4% efficiency, and 15% total background, corresponding to ${\rm Br}(\phi \to \eta\pi^0\gamma) = (7.12 \pm 0.13_{\rm stat} \pm 0.22_{\rm syst}) \times 10^{-5}$. By combining the two results, ${\rm Br}(\phi \to \eta\pi^0\gamma) = (7.06 \pm 0.22) \times 10^{-5}$ is obtained. A combined fit has been performed on the two $\eta\pi^0$ invariant mass distributions. Among the free parameters are also the branching ratio of the vector background and, as relative normalization, the ratio $R_\eta = {\rm Br}(\eta \to \gamma\gamma)/{\rm Br}(\eta \to \pi^+\pi^-\pi^0)$. In the NS fit also the $g_{\phi a_0\gamma}$ coupling is left free. The fit results are shown in Fig. 2 and in Table II.

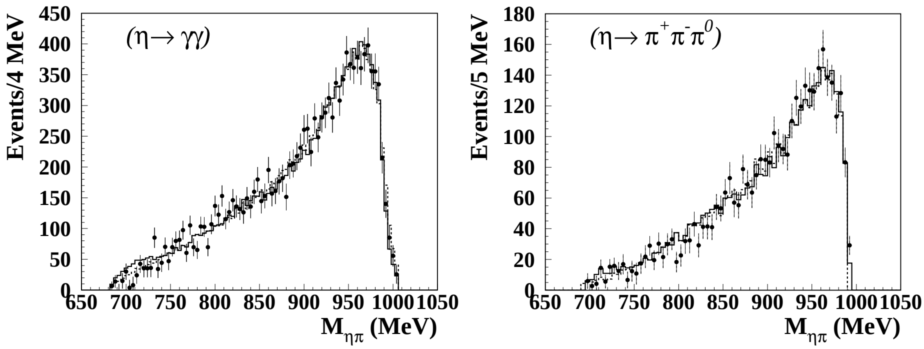

Fig. 2. $\eta\pi^0$ invariant mass distributions after background subtraction. Points — data; solid histogram — KL fit result, dashed — NS fit.

TABLE II

a_0 parameters from the combined fit of $M_{\eta\pi^0}$.

Fit parameters	KL model	NS model
M_{a_0} (MeV)	$982.5 \pm 1.3 \pm 2.7$	982.5 (fixed)
$g_{a_0K^+K^-}$ (GeV)	$2.15 \pm 0.05 \pm 0.17$	$2.01 \pm 0.07 \pm 0.28$
$g_{a_0\eta\pi^0}$ (GeV)	$2.82 \pm 0.04 \pm 0.12$	$2.46 \pm 0.08 \pm 0.11$
$g_{\phi a_0\gamma}$ (GeV^{-1})	$1.59 \pm 0.09 \pm 0.16$	$1.83 \pm 0.03 \pm 0.08$
$Br_{\rm vect} \times 10^6$	$0.92 \pm 0.40 \pm 0.15$	$0.1 \pm 4.0 \pm 0.1$
R_η	$1.70 \pm 0.04 \pm 0.05$	$1.70 \pm 0.04 \pm 0.01$
$R_{a_0} = (g_{a_0K^+K^-}/g_{a_0\eta\pi^0})^2$	$0.58 \pm 0.03 \pm 0.06$	$0.67 \pm 0.12 \pm 0.13$
$P(\chi^2)$	10.4%	30.9%

The decay $\phi \to K^0\bar{K}^0\gamma$ is dominated by the production of f_0/a_0 in the intermediate state. The K_SK_S channel with both $K_S \to \pi^+\pi^-$ has been chosen. In 2.18 fb^{-1} of data, 5 signal event have been found, with 3.2 background expected from MC, that corresponds to the limit: $\mathrm{Br}(\phi \to K^0\bar{K}^0\gamma) < 1.9 \times 10^{-8}$ @ 90% C.L. By using the couplings found in the $\phi \to \pi\pi\gamma$ and $\phi \to \eta\pi^0\gamma$ analyses, an expected range can be evaluated: $\mathrm{Br}(\phi \to K^0\bar{K}^0\gamma) = 4 \times 10^{-9} - 6.8 \times 10^{-8}$, compatible with the upper limit.

3. Pseudoscalar mesons

The $\eta - \eta'$ mixing angle φ_P in the quark flavour basis can be obtained from the measurement of the ratio $R = \mathrm{Br}(\phi \to \eta'\gamma)/\mathrm{Br}(\phi \to \eta\gamma)$. The decay chains $\eta' \to \eta\pi^+\pi^-$ with $\eta \to 3\pi^0$ and $\eta' \to \eta\pi^0\pi^0$ with $\eta \to \pi^+\pi^-\pi^0$

have been chosen. 3407± 75 $\phi \to \eta'\gamma$ and 16.7×10^6 $\phi \to \eta\gamma$ (with $\eta \to 3\pi^0$) events have been selected in a sample of 427 pb^{-1}, resulting in a ratio $R = (4.77\pm0.09\pm0.19)\times10^{-3}$ from which the mixing angle $\varphi_P = (41.4\pm0.3\pm0.9)^\circ$ is derived [5]. If one allows for some gluonium content, $|\eta' >= X_{\eta'}|q\bar{q} > +Y_{\eta'}|s\bar{s} > +Z_{\eta'}|G >$, where $X_{\eta'} = \cos\varphi_G \sin\varphi_P$, $Y_{\eta'} = \cos\varphi_G \cos\varphi_P$ and $Z_{\eta'} = \sin\varphi_G$. From a fit performed by using the measured R, together with other eight experimental constraints [6], a non negligible η' gluonium content has been found: $Z^2_{\eta'} = 0.12\pm0.04$ and $\varphi_P = (40.4\pm0.6)^\circ$ with $P(\chi^2) = 21\%$ (Fig. 3).

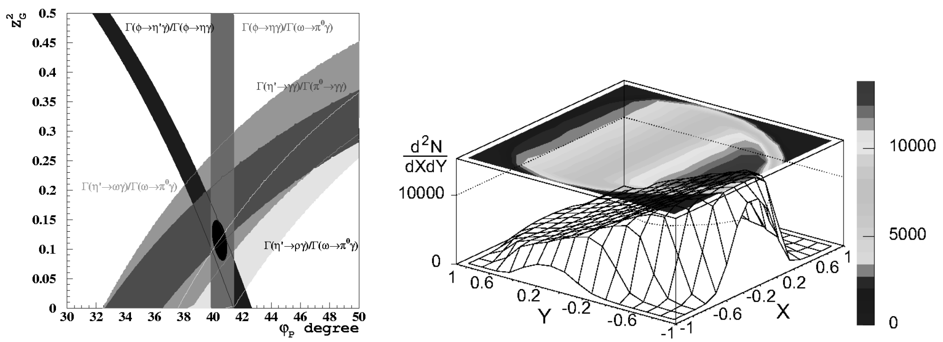

Fig. 3. Left: $Z^2_{\eta'}$ *versus* φ_P, the black ellipse is the fit result (68% C.L.). Right: Dalitz plot of $\eta \to \pi^+\pi^-\pi^0$.

TABLE III

Parameters of the $\eta \to \pi^+\pi^-\pi^0$ Dalitz plot.

a	b	c
$-1.090\pm 0.005\pm^{+0.008}_{-0.019}$	$0.124\pm 0.006\pm 0.010$	$0.002\pm 0.003\pm 0.001$
d	e	f
$0.057\pm 0.006\pm^{+0.007}_{-0.016}$	$-0.006\pm 0.007\pm^{+0.005}_{-0.003}$	$0.14\pm 0.01\pm 0.02$

The $\eta \to 3\pi$ decay is induced by strong interactions via the $u-d$ quark mass difference. Therefore, a high statistics study is a good test of Chiral Perturbation Theory [7]. The Dalitz plot of $\eta \to \pi^+\pi^-\pi^0$ (Fig. 3) contains 1.34×10^6 events selected from a sample of 450 pb^{-1}. It is usually parametrized as an expansion in powers of X and Y ($X = \sqrt{3}(E_+ - E_-)/Q$ and $Y = 3(E_0 - m_{\pi^0})/Q - 1$, where $Q = m_\eta - 2m_{\pi^\pm} - m_{\pi^0}$): $|A(X,Y)|^2 \propto 1+aY+bY^2+cX+dX^2+eXY+fY^3$. The coefficients have been determined with a fit (Table III). The fit quality is good, $P(\chi^2)$ =73% [8], c and e are compatible with zero, as expected since they violate charge conjugation, and a large cubic term in Y has been found. A bad quality fit ($P(\chi^2) \sim 10^{-6}$)

is obtained by imposing $f = 0$. The Dalitz plot of $\eta \to 3\pi^0$ is symmetric, the squared amplitude is described by only one slope parameter, $|A(Z)|^2 \propto 1 + 2\alpha Z$, where $Z = 2/3 \sum_{i=1}^{3}[(3E_i - m_\eta)/(m_\eta - 3_\pi)]^2$. 6.5×10^5 events have been selected, from which $\alpha = -0.0301 \pm 0.0035^{+0.0022}_{-0.0036}$ has been obtained, by using the KLOE value of the η mass. There is indeed an 8 σ discrepancy between the η mass measured by GEM, $m_\eta = 547.311 \pm 0.028 \pm 0.032$ MeV, and by NA48, $m_\eta = 547.822 \pm 0.005 \pm 0.069$ MeV; recently CLEO-c found $m_\eta = 547.785 \pm 0.017 \pm 0.057$. KLOE exploited the $\phi \to \eta\gamma$, $\eta \to \gamma\gamma$ decay chain to get a very precise measurement of the η mass, and checked the method with $\phi \to \pi^0\gamma$, $\pi^0 \to \gamma\gamma$. The region of the 3 γ Dalitz plot (Fig. 4) below the solid line has been selected, the projection shows the η and π^0 peaks. From a fit, $m_\eta = 547.874 \pm 0.007 \pm 0.029$ MeV has been obtained [9] improving the accuracy of NA48 and CLEO-c. $m_{\pi^0} = 134.906 \pm 0.012 \pm 0.049$ MeV in agreement with PDG.

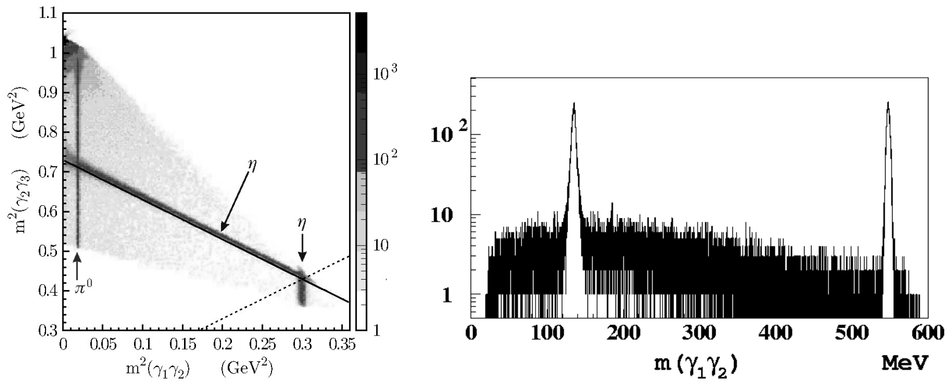

Fig. 4. Left: 3 γ Dalitz plot. Right: projection of the selected region.

4. Future prospects: KLOE-2

A proposal for the continuation of the KLOE physics program with an upgraded detector, KLOE-2, at an upgraded DAΦNE, has been presented [10], considering the physics potential with an integrated luminosity of about $50\,\mathrm{fb}^{-1}$ at the ϕ peak with the further possibility to increase the c.m. energy up to 2.5 GeV. Recently the DAΦNE interaction region has been modified, and a new scheme to increase the luminosity has been implemented. As a first step of the KLOE-2 project, in March 2010 a new data-taking will start, with the same KLOE detector with the minimal upgrade of the electron tagger for $\gamma\gamma$ physics [11].

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