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Results from the KLOE collaboration: study of the eta/ eta' mesons.

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The KLOE experiment has successfully completed its data taking in March 2006 with a total integrated luminosity of about 2.5 pb^{-1}. We report the results on the pseudoscalars η/η' mesons, such as the η meson mass measurement, the dynamics of $\eta \to 3\pi$, the $\eta - \eta'$ mixing angle, and the measurement of the rare Branching Ratio for the $\eta \to \pi^+\pi^-e^+e^-$ decay.

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The KLOE experiment [1] runs at the Frascati ϕ-factory DAΦNE, a high luminosity e^+e^- collider working at $\sqrt{s} \simeq$1020 MeV, corresponding to the ϕ meson mass.
The KLOE detector consists of a large cylindrical drift chamber, surrounded by a sampling lead-scintillating fiber electromagnetic calorimeter. Both detectors operate inside a uniform magnetic field of $\simeq$ 0.5T provided by a superconducting coil.
In the whole data taking $(2001-2006)$ KLOE has collected an integrated luminosity of 2.7 fb^{-1}: 2.5 fb^{-1} at the ϕ peak (corresponding to about $6\times10^9\phi$ decays) and 0.2 fb^{-1} around the center of mass energy, $\sqrt{s} = 1$ GeV, out of the ϕ-resonance region. In the following the results obtained by KLOE concerning the ϕ radiative decays into pseudoscalar mesons and the η mass measurements are presented and discussed.

1. η mass measurement

We present precise measurements of the η mass using the processes $\phi \to \eta\gamma, \eta \to \gamma\gamma$.
The decay chain $\phi \to \eta\gamma$, for ϕ- meson at rest, is a source of monochromatic η- mesons of $\simeq$ 362.8 MeV momentum, recoiling against a photon of equal momentum. Detection of such a photon signals the presence of the η- meson. Photons from $\eta \to \gamma\gamma$ have a flat spectrum in the range $147 < E_\gamma < 510$ MeV in the laboratory reference frame. The accuracy of the kinematic reconstruction of the event is due to the precise measurement of the photon emission angles. Together with the stability of the continuously calibrated detector and the very large sample of η- mesons collected we have obtained the most accurate measurement of the η- mass [2]:

$$m_\eta = (547.874 \pm 0.007_{stat} \pm 0.029_{syst}) MeV. \tag{1.1}$$

The η- mass value is not much sensitive to the calorimeter energy calibration and the systematic errors considered for this measurement are due to the detector response and alignment, event selection cuts, kinematic fit and beam energy calibration.
The KLOE measurement together with the CLEO-c collaboration one [3], seems to resolve the obvious inconsistency of the previously available high precision η mass measurements by NA48 [4] and GEM [5] in favor of the higher η mass from NA48 [6].

2. $\eta \to 3\pi$ dynamics

The decay of isoscalar η into three pions occurs, besides a negligible electromagnetic contribution of second order [7], through isospin violation, as a consequence it is sensitive to the up-down quark mass difference. Using 17 millions η mesons produced in $2001-2002$ data taking, the dynamics of both $\eta \to \pi^+\pi^-\pi^0$ and $\eta \to \pi^0\pi^0\pi^0$ final states has been studied through a Dalitz plot analysis. The background is at level of few per mill for both channels.
For the $\eta \to 3\pi^0$ decay the Dalitz plot distribution is described by a single quadratic slope parameter α: $|A_{\eta\to3\pi^0}(z)|^2 \sim 1+2\alpha z$. Here $z = \rho/\rho_{max}$ is the square ratio of the distance of a point from the Dalitz plot center (ρ) to the maximum kinematically allowed distance (ρ_{max}).
Photons are paired to π^0's after kinematically constraining the total 4-momentum, thus improving the energy resolution. A further improvement of the resolution is obtained with a second fit with η and π^0 masses constraints. To estimate α an unbinned likelihood function is built by convoluting

the event density with the resolution function and correcting for the probability of wrong pairing in π^0's. Using a sample with 92% purity on pairing and fitting in the region $0 < z < 0.7$ we obtain the preliminary [8] result:

$$\alpha = -0.027 \pm 0.004(stat)^{+0.004}_{-0.006}(syst), \tag{2.1}$$

consistent with the present world data and with current chiral perturbation theory calculations within the unitary approach [9].
For the $\eta \to \pi^+\pi^-\pi^0$ final state, we have used the Dalitz variables $X \propto T_{\pi^+} - T_{\pi^-}$ and $Y = (3T_{\pi^0}/Q - 1)$, where T is the kinetic energy of the pion and $Q = m_\eta - 2m_{\pi^-} - m_{\pi^0}$. The efficiency as function of Dalitz plot variables, is almost flat all over the kinematically allowed region and its mean value is about 33%. Following the conventional notation, the decay amplitude is parametrized as:

$$|A(X,Y)|^2 = 1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 \tag{2.2}$$

and the fit results [10] are reported in Table 1.

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

Table 1: Results for the slope parameter of Dalitz -plot.

As expected from C-invariance in $\eta \to \pi^+\pi^-\pi^0$ decay, the odd powers of X are consistent with zero and can be removed from the fit without affecting the determination of the remaining parameters. We clearly observe a non zero quadratic slope in X, and we reach for the first time sensitivity to a cubic term of the expansion; all the cubic terms other than f turn out to be zero in our fit. The χ^2 probability of fit is 73 %. The systematics errors take into account the efficiency evaluation, the resolution effects and the background contamination.
While the polynomial fit of the Dalitz plot density gives valuable information on the matrix element, some integrated asymmetries are very sensitive in assessing the possible contributions to C violation in amplitudes with fixed ΔI. In Table 2 the results for the left-right, quadrants, sextant asymmetries (for a definition see ref. [11]) are reported. We have also fitted the Dalitz plot with

Left-Right	$(+0.09 \pm 0.10\ ^{+0.09}_{-0.14}) \times 10^{-2}$
Quadrant	$(-0.05 \pm 0.10\ ^{+0.03}_{-0.05}) \times 10^{-2}$
Sextant	$(+0.08 \pm 0.10\ ^{+0.08}_{-0.13}) \times 10^{-2}$

Table 2: Results for the Dalitz -plot asymmetries.

a different parametrization [10] which takes into account the final state π-π rescattering; in this framework it is possible to relate the $\pi^+\pi^-\pi^0$ slopes to that for $\eta \to 3\pi^0$. We obtained a prediction for the $\eta \to 3\pi^0$ slope, $\alpha = -0.038 \pm 0.003(stat)^{+0.012}_{-0.008}(syst)$, which is consistent with the PDG average and KLOE preliminary measurements, cfr eq. 2.1.

3. $\eta - \eta'$ 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 [12] $R_\phi = (4.77 \pm 0.09 \pm 0.19) \cdot 10^{-3}$, from which we derive $\mathrm{BR}(\phi \to \eta' \gamma) = (6.20 \pm 0.11 \pm 0.25) \cdot 10^{-5}$.
The value of R_ϕ can be related to the $\eta - \eta'$ mixing angle in the flavor basis. Using the approach [13] and [14] , where the SU(3) breaking is taken into account via constituent quark mass ratio $m_s/\overline{m}$, and the two parameters C_{NS} and C_S take into account the effect of the OZI-rule, which reduce the VP wave-function overlaps [15]:

$$R = \frac{BR(\phi \to \eta' \gamma)}{BR(\phi \to \eta \gamma)} = cot^2 \varphi_P (1 - \frac{m_s}{\overline{m}} \frac{C_{NS}}{C_S} \frac{tan \varphi_V}{sin 2\varphi_P})^2 (\frac{p_{\eta'}}{p_\eta})^3 \tag{3.1}$$

From eq. 3.1, assuming no gluonium content in the η' we obtained 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 sizeable gluonium content, 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 normalization 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 $Y_{\eta'}$ [14, 15, 16], 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 minimized the 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 [19] and answering in this way to the objections from [17], [18] to our paper [12], 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.

4. Branching ratio $\eta \to \pi^+\pi^-e^+e^-$

The study of $\eta \to \pi^+\pi^-e^+e^-$ decay allows to probe the internal structure of the η meson [20] and could be used to compare the predictions based on Vector Meson Dominance (VMD) and Chiral Perturbation Theory (ChPT) [21]. 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 preliminary measurement presented here is based on 600 pb^{-1}, and is the first observation of such a process. The number of selected signal events ($N_{events} = 733 \pm 62$) has been determined using the MC signal and background shapes, we obtained:

$$BR(\eta \to \pi^+\pi^-e^+e^-) = (24 \pm 2_{stat} \pm 4_{syst}) \times 10^{-5}. \tag{4.1}$$

The selection efficiency of our signal, ε, is evaluated by MC to be $\varepsilon = 0.1175(5)$.

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