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K meson semileptonic decays at KLOE: measuring form factors and phase shifts.

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Abstract

The excellent performances of the KLOE [1] detector and the overcostrained kinematics of the ϕ decays of DaΦne (which started its operation during this spring) will give the opportunity to measure the Kaon form factors and the $\pi\pi$ scattering phase shifts differences with very good accuracy and to solve the discrepancies between existing data and the Chiral Perturbation Theory (CHPT) predictions.

Form factors will be measured through the study of the $K_{\mu 3}$ decays. We expect to measure the slope of the form factors λ_0 and λ_+ down to a precision better than an order of magnitude with respect to the existing measurements, already in three months of data taking at one tenth of design luminosity. Some very preliminary details of the analysis will be given.

The $\pi\pi$ scattering phase shifts differences will be measured through the detection of K_{e4} decays. A preliminary study of the KLOE ca-

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pabilities in this analysis indicates that we can improve the present accuracies by a factor ranging from 2 to 5.

1 Introduction

The main goal of the KLOE experiment [1] at the Frascati ϕ-factory (DAΦNE) is the investigation of the CP violation parameters in the K system, both by measuring $Re(\varepsilon'/\varepsilon)$ with an accuracy of the order of 10^{-4} and by Kaon interferometry [2].

DAΦNE is a double-ring e^+e^- working at the ϕ resonance peak energy with a designed instantaneous luminosity of $L_0 = 5 \times 10^{32}$ cm^{-2} s^{-1}. Given the production cross-section of $4.4\mu b$, 2200 ϕ per second will be produced. A sample of 5×10^{10} ϕ will be collected in two years of data taking.

Given the decay of the ϕ meson in neutral or charged Kaons, DAΦNE will also be a "Kaon" factory, producing 5×10^{10} charged K and 1.7×10^{10} $K_S K_L$ pairs. In the first three months of data taking at one tenth of the designed luminosity we can measure the form factors of K_{l3} decay in both $K^\pm$ and K^0_L, improving the present precision, at least, of one order of magnitude.

With the full data taking we will collect about 2×10^6 $K^\pm \rightarrow \pi^+\pi^-e^\pm\nu_e$ which will give the possibility to improve the knowledge of the $\pi\pi$ scattering phase shifts differences and then solve the discrepancies between existing data and the Chiral Perturbation Theory (CHPT) predictions.

2 The KLOE detector

The KLOE detector [3] consists of, in order of increasing radius, a cylindrical drift chamber (DC) and an hermetic electromagnetic calorimeter (EmC) made of lead and scintillating fibers, both embedded in a 0.6 T magnetic field provided by a solenoidal superconducting coil.

Due to the large K_L decay path, the isotropic angular distribution of the charged products of K_L decays and the momentum range of the particles detectable at KLOE, the chamber must assure high and uniform tracking efficiency in the active volume, accurate determination of the decay vertices, good momentum resolution and high transparency. The tracking detector [4] is a large cylindrical drift chamber ($\sim$ 2 m radius, $\sim$ 3.3 m length), in which $\sim$ 12600 single sense wire, square cells are arranged in 58 circular and coaxial stereo layers. The chosen gas mixture is 90%-10% He-iC_4H_{10}, allowing for good resolution ($\sigma_{\rho\phi} \sim 200\mu m$, and $\sigma_z \sim 2mm$), good efficiency, low multiple scattering and stable operating conditions. The drift chamber transverse momentum resolution is $\sigma_{p_\perp}/p_\perp \simeq 0.5\%$.

The main task of the electromagnetic calorimeter is the measurement of the neutral vertices with a resolution of $\sim 1cm$. The calorimeter has to provide good impact point determination, good energy resolution end efficiency down to low energy γ, excellent timing performances and hermetic coverage. The KLOE EmC [5] is a very fine sampling lead-scintillating fiber calorimeter with photomultipliers read-out, covering ~98% of the solid angle. The barrel is a cylinder of 4 m inner diameter and 4.3 m length with fibers running parallel to the beam line, while the end-caps are made of C-shaped modules of variable length with fibers running perpendicular to the beam line. The EmC measured energy and time resolutions are $\sigma_E/E \simeq 4.7\%/\sqrt{E(GeV)}$ and $\sigma_t \simeq 55$ ps$/\sqrt{E(GeV)}$ respectively, with high efficiency for the detection of low energy γ as low as 20 MeV.

3 Form factors in K_{l3} semileptonic decays

Kaon semileptonic decays $K^\pm \to \pi^0 l^\pm \nu$ and $K_L^0 \to \pi^\pm l^\mp \nu$ can be described, in the Cabibbo Theory picture, by a local vector current-current coupling

$$\mathcal{M}_{if} = \frac{G_F}{\sqrt{2}} \sin\theta_C \langle l\nu | l^\mu | 0 \rangle \langle \pi | S_\mu^+ | K \rangle \tag{1}$$

where G_F is the Fermi constant and θ_C is the Cabibbo angle.

The matrix elements of the hadronic current are generally parametrized in terms of the form factors $f_+(t)$ and $f_0(t)$ [6] where $t = q^2$ is the square of the 4-momentum transfer to the leptons. A linear dependence is frequently assumed for these form factors $f_{+,0}(t) = f_{+,0}(0)(1 + \frac{\lambda_{+,0}}{m_\pi^2} t)$, and, then, four parameters are involved: $f_+(0)$, $f_0(0)$, λ_+ and λ_0. The measurement of the Dalitz plot distribution, $\rho(\lambda_+, \lambda_0; E_\pi, E_l)$ of K_{l3} data allows us to determine the form factors in the allowed phase space range.

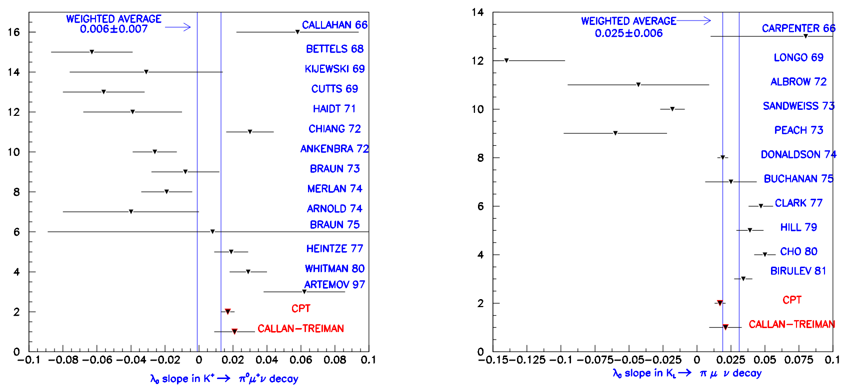

Figure 1: *Measured values (black triangles) for the parameter λ_0 in $K^\pm$ (left) and K_L (right) $\pi\mu\nu$ decay. The world weighted average and Theoretical prediction (white squares) from Chiral Perturbation Theory (χ_{PT}) and Callan Treiman relation are also reported.*

While data and theory (χ_{PT}) agree fairly well for λ_+, the situation on parameter λ_0, which can be measured only in $K_{\mu 3}$ decays, is not yet well understood. The experimental results and theoretical predictions on λ_0 are shown in fig. 1 for $K^0_{\mu 3}$ and $K^\pm_{\mu 3}$.

New measurement of these parameters will then help to check the Chiral Perturbation Theory (χ_{PT}) predictions which is, so far, one of the best theory for the description of low energy processes.

3.1 $K^0_L \to \pi\mu\nu$ decays

At a ϕ factory like DAΦNE the neutral Kaons are produced in pairs and this allows for very clean K_L tagging using the $K_S \to \pi^+\pi^-$ decay. The reconstruction of this decay will allow to determine the K_L direction of flight and its momentum with good resolution ([8]: $\sigma_{P_{x,y}} \sim 1.2$ MeV/c, $\sigma_{P_z} \sim 1.7$ MeV/c). The expected energy resolutions of the pion and the muon in the K_L reference frame are, respectively, 0.7 MeV and 0.6 MeV.

Without any particle identification a simmetrized density function should be built: the effect will be a slight increase (20%) of the expected precision in the determination of the λ_+ and λ_0 parameters. A small contamination

	KLOE	Donaldson[9]
$N(K^0_{\mu 3})$	3×10^6	1.5×10^6
$\sigma(\lambda_0)$	5×10^{-4}	4×10^{-3}

	KLOE	Merlan[10]
$N(K^\pm_{\mu 3})$	10^6	6527
$\sigma(\lambda_0)$	7×10^{-4}	1.5×10^{-2}

Table 1: *Expected number of fully reconstructed $K_{\mu 3}$ events and a priori estimated error on the λ_0 parameter for a sample of 5×10^8 ϕ. Statistics and error of the most precise measurements obtained up to now is shown for comparison.*

in this channel is represented by the CP violating $K_L \to \pi^+\pi^-$ decay which can be easily removed through kinematic cuts.

In the first three months of data taking at one tenth of the DAΦNE design luminosity, about 3×10^7 $K^0_{\mu 3}$ decays will be produced. Given the $K_S \to \pi^+ \pi^-$ decay reconstruction efficiency $\epsilon^{id}_{K_S} = 0.68$, the geometrical acceptance of the K_L in the fiducial volume $\epsilon_{FV} = 0.28$ and the "zeroth order" vertex reconstruction efficiency $\epsilon^{rec}_{K_L} = 0.50$, the expected number of collected $K^0_{\mu 3}$ decays will be $\sim 3 \times 10^6$ giving "a priori" estimated errors on the λ_+ and λ_0 parameters shown in table 1

3.2 $K^\pm \to \pi^0 \mu^\pm \nu$ decays

The selection of charged Kaons starts with the requirement of a charged track coming from the interaction point and with the appropriate momentum ($\sim$ $127 MeV$). A charged vertex is then made with the identified Kaon and the muon and the clusters in the EmC are added if they belongs to a neutral pion. The momentum resolution for $K^\pm$ is 1.3 MeV/c and the resulting energies resolution of the neutral pion and the muon are respectively 15 MeV and 1 MeV.

The main background to this channel is represented by $K^\pm \to \pi^\pm \pi^0$ decay, which has a branching ratio $\sim$ 7 times larger than the signal. It can be reduced using a constrained fit procedure and π/μ discrimination using TOF measurements. In table 1 are shown the expected number of events and the "a priori" estimate of the error on λ_0 evaluated taking into account only the statistics and resolution contributions.

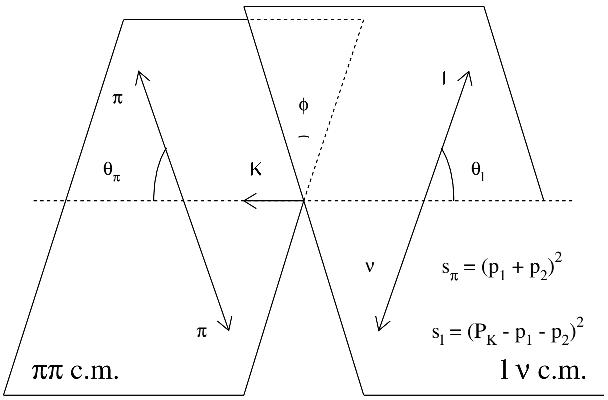

Figure 2: *Kinematic variables used in K_{l4} decay: squared of the invariant mass s_π of the dipion system and of the dilepton system s_l, and angles θ_π, θ_l and ϕ built in three different reference system, the K rest frame, and the dipion and dilepton center of mass systems.*

4 K_{l4} semileptonic decays

The full kinematic of the K_{l4} decay requires 5 variables [11] depicted in figure 2. The K_{l4} partial decay rate can be written as

$$d^5\Gamma = G_F^2 |V_{us}|^2 N(s_\pi, s_l) J_5(s_\pi, s_l, \theta_\pi, \theta_l, \phi) ds_\pi ds_l d(\cos\theta_\pi) d(\cos\theta_l) d\phi \qquad (2)$$

where $N(s_\pi, s_l)$ is a kinematical factor, $J_5(s_\pi, s_l, \theta_\pi, \theta_l, \phi)$ is an expression of simple functions of θ_l and ϕ multiplying nine quantities $I_i(s_\pi, s_l, \theta_\pi, F, G, H, R)$ [6] where F, G, R, and H are the form factors. These last quantities can be described as a partial wave expansion in the variable θ_π, and the partial wave amplitudes (f_l, g_l, h_l, r_l) depend on variables s_π and s_l while their phases are identified with the phase shifts δ_l^I in elastic $\pi^+\pi^-$ scattering.

The introduction of the partial wave expansion of the form factors in the nine I_i intensities, allows the quantity J_5 to be expressed in terms of the phase shifts. This permits their determination (as function of s_π) in a global analysis, together with the partial wave amplitudes (which can be parametrized as function of $t = q^2$).

Furthermore, by using the Roy equation analysis [12], one can extract the isoscalar S-wave scattering length a_0^0 [13], which can be compared with $SU(2)_L \times SU(2)_R$ predictions $a_0^0 = 0.20 \pm 0.01$ [14]. The central value of the best experimental measurement $a_0^0 = 0.26 \pm 0.05$ [13] has uncertainties which do not permit to confirm the χ_{PT} predictions, so a new measurement with higher statistics and better experimental error is necessary to solve this discrepancy.

Two complementary methods will be exploited at KLOE: the Pais-Treiman method [15] which is model independent and the Maximum Likelihood Method [16] which requires some approximations and assumptions.

The Pais Treiman method requires us to integrate $(\frac{d\Gamma^2}{dcos\theta_l d\phi})$ over s_l and $cos\theta_\pi$ in each s_π bin, and to fit it to the event distribution in the $\theta_l \times \phi$ plane, using the intensity distribution functions $\langle I_i \rangle$ as free parameters. The phase-shift difference $(\delta_o^o - \delta_1^1)$ for each s_π bin is given by

$$tan(\delta_o^o - \delta_1^1) = \frac{1}{2}\frac{\langle I_7 \rangle}{\langle I_4 \rangle}$$

$$tan(\delta_o^o - \delta_1^1) = 2\frac{\langle I_8 \rangle}{\langle I_5 \rangle}$$

The Maximum Likelihood Method (MLM) implies a detailed amplitude analysis of the $K_{e4}^{\pm}$ decays to be performed with respect to all the five kinematic variables. This method is more complicated, but it yields the absolute best possible determination of any given set of parameters. This method gives an "a priori" estimate (obtained with a perfect detector) of the error on the isoscalar S-wave scattering length, $\Delta a_0^0 = 0.029$ at the Rosselet statistic (30k events) (to be compared with $\Delta a_0^0 = 0.05$ of reference [13]).

In table 2 are shown the number of K_{l4} decays collected up to now from previuos experiments for each channel [7] and the expected number of events produced at KLOE in two years of running at full luminosity.

This statistical improvements on the number of events will allow KLOE to understand the dependence of the form factors on s_l and s_π, which was

channel	Br	# events(PDG)	DAΦNE
$K^\pm \to \pi^+\pi^- e^\pm \nu_e$	3.9×10^{-5}	3×10^4	1.9×10^6
$K^\pm \to \pi^+\pi^- \mu^\pm \nu_\mu$	10^{-6}	7	4.8×10^4
$K^\pm \to \pi^o\pi^o e^\pm \nu_e$	2.1×10^{-5}	< 50	1×10^6
$K_L \to \pi^o\pi^\pm e^\mp \nu_e$	5.2×10^{-5}	729	1×10^5

Table 2: *Expected number of events in KLOE for each of the K_{l4} channels, compared with the events collected until now from previous experiments*

not possible in previous experiments and will also permit to do independent checks on the form factors that are related, because of the Bose symmetry and the $\Delta I = 1/2$ rule, by the relations:

$$(F, G, R, H)_{oo} = -(F^+, G^-, R^+, H^-)_{+-}$$

$$(F, G, R, H)_{o-} = \sqrt{2}(F^-, G^+, R^-, H^+)_{+-}.$$

Taking into account, for example, only the decay $K^\pm \to \pi^+\pi^- e^\pm \nu_e$ the analysis will be based on the reconstruction of the 4 charged tracks vertex and the reduction of the background due to the $K^\pm \to \pi^+\pi^-\pi^\pm$ decay, whose branching ratio is $\simeq 5.59\%$. A constrained vertex fit will allow easily the reduction of this backgound due to the big mass difference between electrons and pions. The main difficulty in reconstructing this kind of events is due to the low momenta of the particles involved, especially for electrons which will often spiralize in the KLOE magnetic field. A detailed study on the optimization of tracking program for this channel is in progress, together with the reconstruction of 4-tracks vertices (all algorithm have being optimized for CP violationg decays). An example of reconstructed Montecarlo K_{e4} event is shown in fig. 3.

5 Conclusions

The capabilities of the KLOE detector will allow to measure the scalar form factor λ_o in the neutral $K_{\mu 3}$ decays with an error $\simeq 10$ times smaller than the error reached in previous experiments and similar result will be reached also with the charged $K_{\mu 3}$ decays. KLOE will also be able to measure the $\pi^+\pi^-$ scattering length a_0^0 to a very good accuracy, sufficient to determine if

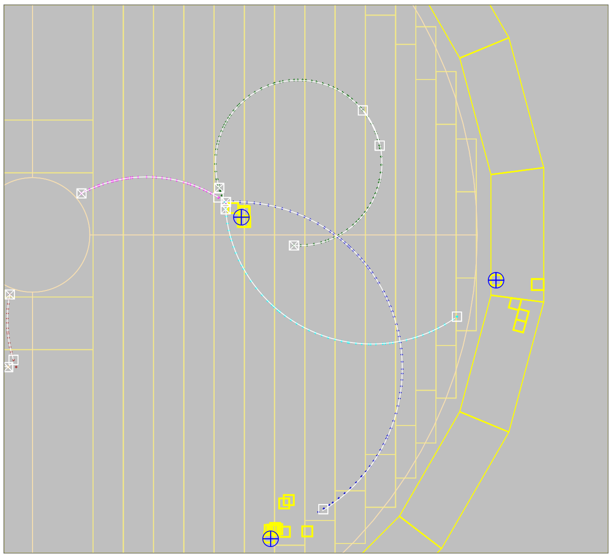

Figure 3: *A reconstructed K_{e4} events in the KLOE Detector.*

the existing discrepancies between present measurements and chiral perturbation theory predictions are statistically significant.

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