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Detecting K Mesons Leptonic Decays with KLOE

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Abstract. The KLOE detector is presently under construction at DAΦNE , the Frascati $\phi - factory$, with the aim of studying $\mathcal{CP}$ violation in the $\mathrm{K^o\bar{K}^o}$ system. We discuss the measurements of the slope of the scalar form factor λ_o for the K's, which will be done at the DAΦNE start up time when the expected luminosity will be $\mathcal{L}_o = 10^{32}$ $\mathrm{cm^{-2}s^{-1}}$. At the design luminosity $\mathcal{L}_o = 10^{33}$ $\mathrm{cm^{-2}s^{-1}}$ about 4.2×10^{10} kaons will be produced per year: this will be a unique opportunity to collect enough K_{l4} decays which provides the only means for the determination of the $\pi\pi$ phase shifts.

ϕ PRODUCTION AT DAΦNE

The Frascati $\phi - factory$ DAΦNE (Double Annular $\phi - factory$ for Nice Experiments) [1] is an e^+e^- collider optimized for operation at a center of mass energy equal to the ϕ mass.

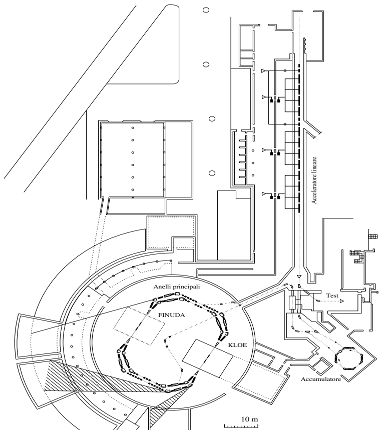

FIGURE 1. The DAΦNE machine complex.

TABLE 1. The DAΦNE machine parameters.

E_{beam}(MeV)	510
energy spread (MeV)	0.4
$\mathcal{L}_o(\mathrm{cm^{-2}s^{-1}})$	$10^{32} \rightarrow 10^{33}$
σ_x(cm)	2.1×10^{-1}
σ_y(cm)	2.1×10^{-3}
σ_z(cm)	3.
particles/bunches	8.9×10^{10}
N bunches	$30 \rightarrow 120$
time between collisions	$10.8 \rightarrow 2.7$ ns
crossing half angle	10 to 15 mrad
commissioning date	end of 1997

TABLE 2. ϕ decays (M_ϕ = 1019.41 MeV, Γ_ϕ = 4.41 MeV, $\Gamma_{ee} = 1.37$ KeV, $J^{PC} = 1^{--}$)

Mode	Br(%)	β_K	$\beta\gamma c\tau_K$(cm)	p_{lab}(MeV/c)	# per year
K^+K^-	49.5	0.249	95.4	127	2.5 $\times 10^{10}$
K_S K_L	34.4	0.216	343.8 (K_L) 0.59 (K_S)	110	1.7 $\times 10^{10}$
$\rho\pi$	12.9	-	-	182	6 $\times 10^9$
$\pi^+\pi^-\pi^o$	1.9	-	-	462	1 $\times 10^9$
$\eta\gamma$	1.28	-	-	362	6 $\times 10^8$
other	$\sim$ 1.	-	-	-	5 $\times 10^8$

The machine complex of DAΦNE is shown in Fig. 1. The initial luminosity is expected to be 10^{32}cm^{-2}s^{-1}. In one or two years the luminosity will reach 10^{33}cm^{-2}s^{-1}. The DAΦNE machine parameters are listed in Table 1. At the target luminosity of DAΦNE, given that the cross section for $e^+e^- \rightarrow \phi$ at the ϕ resonance peak is $\simeq$ 5μb , about 5000 ϕ's will be produced per second. The vector meson ϕ decays into other mesons with the Br's given in Table 2 together with other relevant kinematic quantities, as well as the number of particles produced per year. One note therefore that DAΦNE is indeed a kaon-factory, and because the ϕ decays at rest the kaons are produced in pairs collinear and monocromatic, the observation of one kaon guarantees the existence of the other with determined direction and identity, i.e. K's can be tagged, and an absolute normalization of the K_S , K_L fluxes is available.

THE KLOE DETECTOR

The main physics motivation of the KLOE experiment is the measurement of the $\mathcal{CP}$ violation parameters to an accuracy of $\mathcal{O}(10^{-4})$. This will be done with the classical method of the double ratio and also by kaon interferometry experiments [2]. Concerning the $\mathcal{CP}$ studies, the main tasks of the KLOE detector are the control of the efficiencies for the decays of interest, and the rejection of the background from the copious K_L decays to states other than $\pi\pi$. The main components of the KLOE detector are the drift chamber [3] and the electromagnetic calorimeter (EmC) [4], both embedded in a

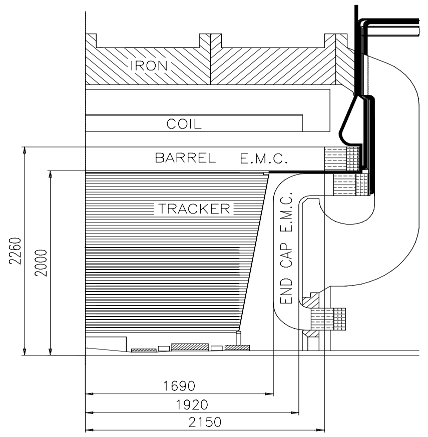

FIGURE 2. Cross section along the beam axis of 1/4 of the KLOE detector.

magnetic field of 0.6 T, generated by a superconducting solenoid (see Fig. 2). Because of the decay length of K_L's, to maximize the fiducial volume for the charged decay detection, the chosen radius of the drift chamber is 2 m. The K_L decay vertices are uniformly distributed in the tracking volume, and to obtain high and uniform track and vertex reconstruction efficiency the wires are in an all-stereo configuration in order to have an uniform filling of the chamber with square cells (2×2 cm^2 for the first 12 layers, and 3×3 cm^2 for the 46 outer layers). The expected resolution of the single position measurements is $\sigma_{r,\phi} \leq 200$ μm; this will give us the possibility to measure the vertices with a resolution at least of 500 μm in(r, ϕ), and of 2 mm in z. A very good momentum resolution is required, $\sigma_{p_\perp}/p_\perp \simeq 0.5\%$, and because of the low momenta of the particles ($50 \geq p \geq 300$ MeV/c), a helium based gas mixture has been chosen to minimize the multiple scattering ($90\% He - 10\% iC_4H_{10}$). Also, the KLOE chamber needs all its walls to be very thin in order for them to be transparent to γ's from π^o decays to be detected in the calorimeter; the whole mechanical structure is made of carbon fiber.
The main tasks of the KLOE EmC are the measurements of the neutral vertices with a resolution of $\simeq 1$ cm, and the rejection of the background due to the $3\pi^o$ mode. To reach this purposes the EmC has to provide good energy resolution, excellent timing performance, resolution on the γ apices measurement of $\simeq 1$ cm, high efficiency for the detection of low energy γ (down to 20 MeV) and hermetic coverage. The KLOE EmC is a very fine sampling lead (0.5 mm thick) scintillating fiber(1 mm) calorimeter with photomultipliers read-out, covering $\sim 98\%$ of the solid angle. The barrel is a cylinder of 4 m inner diameter and 4.3 m length, and is made of 24 modules 23 cm thick, with fibers running parallel to the beam line. The end-caps are made of 32 **C** shaped modules of variable length with fibers running perpendicular to the beam line. Test done with prototypes and with the final barrel modules gave the following results for the relevant parameters: $\sigma_E/E \simeq 4.7\%/\sqrt{E(GeV)}$, and $\sigma_t \simeq 55$ ps$/\sqrt{E(GeV)}$.

K_{l3} DECAYS

A convenient parametrization of the K_{l3} matrix element of the hadronic current is in term of the form factors $f_+(t)$ and $f_o(t)$ [5], where t is the square of the 4-momentum transfer to the leptons. Analyses of K_{l3} data frequently assume a linear dependence $f_{+,o}(t) = f_{+,o}(0)(1 + \lambda_{+,o}\frac{t}{m_\pi^2})$. The measurement of the Dalitz plot distribution, $\rho(E_\pi, E_l)$, of K_{l3} data allows to determine the form factors in the range $m_l^2 \leq t \leq (M_K - m_\pi)^2$.

Tables 3 and 4 show respectively the measured average values [1] and the

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1) Note that the form factor f_o cannot be determined from the K_{e3} mode because its contribution to the decay probability is suppressed by the factor $(m_e/M_K)^2 \simeq 10^{-6}$.

TABLE 3. $\lambda_{+,o}$ determined with the Dalitz plot analysis of the $K_{\mu 3}$ and K_{e3} data.

	$K^o_{\mu 3}$	$K^{\pm}_{\mu 3}$	K^o_{e3}	$K^{\pm}_{e3}$
λ_+ [6]	0.034 ± 0.005	0.032 ± 0.008	0.0300 ± 0.0016	0.0285 ± 0.0043
λ_0 [7]	the $K_{\mu 3}$ data analysis done by Chounet et al. favors a negative slope for $f(t)$		-	-
λ_0 [6]	0.025 ± 0.006	0.004 ± 0.007	-	-

TABLE 4. Theoretical predictions for $\lambda_{+,o}$.

	Fubini-Furlan	Callan-Treiman	χ_{PT} theory
λ_+	-	-	0.031
λ_0	-0.025 ± 0.013	0.017 ± 0.013	0.017

theoretical predictions of the parameters λ_+ and λ_o.
The average values of λ_+ measured with the neutral and the charged $K_{\mu 3}$ decays agree, are fairly consistent with the results from the analysis of the K_{e3} data, and agree with the chiral theory (χ_{PT}) prediction. The situation is completely different for the λ_o parameter; the experimental results gives different indications that favor different theoretical predictions. Nowadays, the χ_{PT} predictions for λ_o are generally accepted as being correct, however new, precise measurements will help to determine this still unknown parameter.

The number of collected $K_L \to \pi^{\pm}\mu^{\mp}\nu_\mu$ events used to calculate the average value of the λ_o parameter shown in Table 3 is $\simeq 4. \times 10^6$ [6]. The increase in statistic obtainable in the first year of running at DAΦNE is $\simeq \times 14$:

$$N(K^o_{\mu 3}) = \underbrace{5 \times 10^9}_{N\phi} \times \underbrace{.334}_{Br(\phi \to K_S K_L)} \times \underbrace{.27}_{Br(K^o_{\mu 3})} \times \underbrace{(e^{-40/350} - e^{-170/350})}_{a_{FV}} \times \underbrace{.44}_{\epsilon_V} \simeq 5.6 \times 10^7$$

where a_{FV} is the K_L acceptance, and ϵ_V is the 0^{th}-order vertex reconstruction efficiency.

The first step to reconstruct one $K^o_{\mu 3}$ event is the measurement of the $\pi\mu$ vertex coordinates from which the K_L direction can be determined (the expected resolution on the K_L momentum is $\sigma(P_K) \simeq 3$ MeV). Then, the momentum and the energy of the $\pi\mu$ pair in the kaon rest frame can be evaluated. Without any particle identification applied there are two possible pairs of energy values ($E_{\pi 1} = \sqrt{p_1^2 + m_\pi^2}\,; E_{\mu 1} = \sqrt{p_2^2 + m_\mu^2};\;\; E_{\pi 2} = \sqrt{p_2^2 + m_\pi^2}\,; E_{\mu 2} = \sqrt{p_1^2 + m_\mu^2}$) and the probability density function f, that is, the Dalitz function $\rho(E_\pi, E_l)$ normalised to the whole space phase, becomes

$$f_{sim}(E_\pi, E_\mu; \lambda_+, \lambda_0) = \frac{1}{2}[f(E_{\pi 1}, E_{\mu 1}; \lambda_+, \lambda_0) + f(E_{\pi 2}, E_{\mu 2}; \lambda_+, \lambda_0)]$$

To have a chance that f_{sim} will describe correctly the Dalitz plot distribution, the measured number of $K^o_{\mu 3}$ decays in each bin of the (E_π, E_μ) plane has to be weighted with ϵ_V. This will be controlled at KLOE at

TABLE 5. Predicted $\sigma(\lambda_o)$ from $K^o_{\mu 3}$.

	$\sigma(\lambda_0)$
KLOE	$0.96/\sqrt{N1} = 1.2 \times 10^{-4}$
	$0.96/\sqrt{N2} = 6.4 \times 10^{-5}$
Donaldson [8]	$4. \times 10^{-3}$

TABLE 6. Predicted $\sigma(\lambda_o)$ from $K^{\pm}_{\mu 3}$.

	$\sigma(\lambda_0)$
KLOE	$0.73/\sqrt{N1} = 1.5 \times 10^{-4}$
	$0.73/\sqrt{N2} = 7.3 \times 10^{-5}$
Merlan [9]	1.5×10^{-2}

the level of $\Delta\epsilon/\epsilon \simeq 10^{-3} \div 10^{-4}$ using, for example, the very copious K_L (K_S)$\rightarrow \pi^+\pi^-\pi_o$ ($\pi^+\pi^-$) events ($\simeq 9.5 \times 10^7$ in 1 year of running). Then, there will be some contamination due to the $K_L \rightarrow \pi^+\pi^-$events ($Br(K_{\mu 3})/Br(K_L \rightarrow \pi^+\pi^-) \simeq 133$) that will be easily removed through kinematic cuts.
The "a priori" error estimates on λ_o have been calculated and are shown in Table 5 for two samples of $K^o_{\mu 3}$ events; the first sample (N_1) corresponds to the DAΦNE initial luminosity, while the second one (N_2) corresponds to a later luminosity of $5 \times 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

The number of collected $K^{\pm} \rightarrow \pi^o\mu^{\pm}\nu_{\mu}$ events used to evaluate the λ_o avarage value shown in Table 3 is $\simeq 10^5$ [6]. The increase in statistic obtainable in the first year of running at DAΦNE is a factor of $\simeq 250$:

$$N(K^+_{\mu 3}) = \underbrace{5 \times 10^9}_{N\phi} \times \underbrace{.495}_{Br(\phi \rightarrow K^+K^-)} \times \underbrace{.032}_{Br(K^+_{\mu 3})} \times \underbrace{.71}_{\epsilon_{\pi^o}} \times \underbrace{.44}_{\epsilon_V} \simeq 2.5 \times 10^7$$

The steps to reconstruct one charged $K_{\mu 3}$ event are the measurement of the $K\mu$ vertex coordinates, and of the energies and apices of the photons from the π^o. The main background is due to $K^{\pm} \rightarrow \pi^{\pm}\pi^o$: $Br(K^{\pm} \rightarrow \pi^{\pm}\pi^o)/Br(K^{\pm} \rightarrow \pi^o\mu^{\pm}\nu) \simeq 6.7$. To identify and to reject this background, some constrained kinematic fit techniques will be applied, and taking advantage of the good timing performance of the KLOE EmC, the $\pi\mu$ discrimination can be accomplished using TOF measurements. The Table 6 shows the evaluated accuracies on the λ_o parameter for two samples of $K^{\pm}_{\mu 3}$ events corresponding to the initial (N_1) and to a later (N_2) DAΦNE luminosity. The "a priori" evaluation of $\sigma(\lambda_o)$ in the $K^{\pm}_{\mu 3}$ case considers a perfect subtraction of the $K^{\pm} \rightarrow \pi^{\pm}\pi^o$ background.

K_{l4} DECAYS

The K_{l4} decays have a partial rate decay of the form

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

where s_π, s_l, θ_π, θ_l and ϕ are a set of kinematic variables necessary to describe the K_{l4}, defined in ref. [5]. The quantity J_5 can be written as an expansion of simple functions of ϕ and θ_l multiplying nine intensities

TABLE 7. K_{l4} statistic in 1 year of running at $\mathcal{L}_o = 5 \times 10^{32}$ cm^{-2}s^{-1}.

channel	Br	# events(PDG)	DAΦNE	impr.
1) $K^{\pm} \rightarrow \pi^+\pi^- e^{\pm}\nu_e$	3.9×10^{-5}	3×10^4	3×10^5	10
2) $K^{\pm} \rightarrow \pi^+\pi^- \mu^{\pm}\nu_{\mu}$	10^{-6}	7	8.4×10^3	1.2×10^3
3) $K^{\pm} \rightarrow \pi^o\pi^o e^{\pm}\nu_e$	2.1×10^{-5}	< 50	2×10^5	$> 4 \times 10^3$
4) $K_L \rightarrow \pi^o\pi^{\pm} e^{\mp}\nu_e$	5.2×10^{-5}	729	5×10^4	68

$I_i(s_\pi, s_l, \theta_\pi, F, G, H, R)$. The explicit dependences may be found in ref [5]. The form factors F, G, H, and R can be written in a partial wave expansion in the variable θ_π. The partial wave amplitudes f_l, g_l, r_l, and h_l depend on s_π and s_l, and their phases coincide with the phase shifts δ_l^I in elastic $\pi^+\pi^-$scattering. Introducing the partial wave expansions of the form factors in the $I_i (i = 1, ..., 9)$, one can get the expression of the intensity distribution J_5 in terms of the $\pi^+\pi^-$ phase shifts, which allows their determination as a function of s_π in a global analysis, together with the form factors f_s, f_p, etc. The decay $K^+ \rightarrow \pi^+\pi^- e^+\nu_e$ has been already used by L. Rosselet et al. to determine the δ_l^I and the related isoscalar S-wave scattering length a_o^o [10]: $a_o^o = 0.26 \pm 0.05$. This result must be compared with the $SU(2)_R \times SU(2)_L$ prediction: $a_o^o = 0.20 \pm 0.01$. Low energy $\pi^+\pi^-$ scattering is one of the few places where chiral symmetry allows a precise prediction within the framework of QCD. The standard picture of the vacuum structure in QCD [11] would have to be revised, should the central value $a_o^o = 0.26$ be confirmed with a substantially smaller error.

The Table 7 shows the number of K_{l4} events collected until now for each observed channel [6], and the number of K_{l4} events that will be produced at DAΦNE in 1 year of running at the luminosity of 5×10^{32} cm^{-2}s^{-1}.

The reconstruction of the channels 1 and 2 requires the measurement of the 4-prong $K^{\pm}\pi^+\pi^- l^{\pm}$ vertex coordinates. The main background for these channels is due to the $K^{\pm} \rightarrow \pi^+\pi^-\pi^{\pm}$ events (Br $\simeq$ 5.59%). The identification of the channel 3 requires the reconstruction of the $K^{\pm}e^{\pm}$ vertex, and of $2+2$ e.m. clusters in the EmC not associated at any charged tracks, and then the γ's pairing into π^o's. The main background for this channel is due to the $K^{\pm} \rightarrow \pi^o\pi^o\pi^{\pm}$ events (Br $\simeq$ 1.73%). Finally, the identification of the channel 4 requires the reconstruction of the $\pi^{\pm}e^{\mp}$ vertex, from which the $\mathrm{K_L}$ flight direction can be determined, and of 2 e.m. clusters in the EmC not associated at any charged tracks, and then the γ's pairing into π^o's. The background related to this channel is due to $K_L \rightarrow \pi^+\pi^-\pi^o$ events (Br $\simeq$ 12.33%). A part from channel 2, the backgrounds will be easily removed thanks to the big difference on mass between pions and electrons.

The experimental accuracies of the parameters describing the $K^{\pm} \rightarrow \pi^+\pi^- e^{\pm}\nu_e$ decay has been evaluated using the maximum likelihood method [12]. In particular, concerning the $\pi^+\pi^-$ phase shifts, the error on the isoscalar S-wave scattering length has been estimated using the parametrization introduced by J.L.Basdevant et al. [13]. For 30000 K_{e4} events the estimated error is $\delta a_o^o = 0.029$ to be compared with 0.05 in ref. [10]. This estimate at the "Rosselet statistics" is purely statistical, but apply to a "perfect" detector, i.e., one which covers the whole phase space with unity efficiency everywhere. This is close to being true for KLOE which is a hermetic detector, operating at DAΦNE producing self-tagging $K^{\pm}$ pairs, with high reconstruction efficiency of neutral and charged low energy particles that will be controlled at the level of $\simeq 10^{-3} \div 10^{-4}$. So, in one year of running at the luminosity of 5×10^{32} cm^{-2}s^{-1}, a factor of 5 improvement in the error on the $\pi^+\pi^-$ scattering length is expected: $\delta a_o^o = 0.01$.

CONCLUSIONS

The capabilities of the KLOE detector and the over constrained kinematic of the ϕ's decays at DAΦNE, will make possible in the first year of running (10^{32}cm^{-2}s^{-1}) to measure the scalar form factor λ_o in the $K^o_{\mu 3}$ decays with an error $\simeq 30$ times smaller than the error reached in previous experiments. When $\mathcal{L}_o = 5 \times 10^{32}$cm^{-2}s^{-1} will be reached we expect, that the $\pi^+\pi^-$ scattering length a_o^o should be measurable to an accuracy of about 0.01, sufficient to determine if the existing discrepancy between present measurements and predictions is statistically significant.

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