Recent results from KLOE at DAΦNE

The KLOE collaboration[1]
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Abstract. The KLOE experiment at DAΦNE collected about 450 pb^{-1} of data in 2001–2002. Much of this data set has been analyzed and has yielded definitive results on K_S and radiative ϕ decays, as well as studies concerning a wide range of topics in kaon and hadronic physics.

KLOE is a large, general-purpose detector with optimizations for the study of discrete symmetries in the neutral kaon system. The experiment is permanently installed at DAΦNE, the Frascati ϕ factory, an e^+e^- machine with $W \approx m_\phi \approx 1.02$ GeV. The DAΦNE design luminosity is $5.3 \cdot 10^{32}$ cm^{-2} s^{-1}. ϕ's are produced with a cross section of ~ 3.2 μb, and decay into K^+K^- and K_SK_L pairs with branching ratios (BR's) of $\sim 49\%$ and $\sim 34\%$. These pairs are produced in a pure $J^{PC} = 1^{--}$ quantum state, so observation of a K_S in an event signals the presence of a K_L and vice versa. With an appropriate tagging technique, highly pure and nearly monochromatic K_S, K_L, K^+, or K^- beams can be obtained.

The KLOE detector consists essentially of a large drift chamber surrounded by an electromagnetic calorimeter. The drift chamber [1] is 4 m in diameter and 3.3 m in length, which results in a fiducial volume for K_L decays that extends to about half of a decay length. The momentum resolution for tracks with $p \gtrsim 100$ MeV and $\theta > 45°$ is $\sigma_p/p \leq 0.4\%$. The lead/scintillating-fiber calorimeter [2] consists of a barrel and two endcaps and covers 98% of the solid angle. The energy resolution is $\sigma_E/E = 5.7\%/\sqrt{E(\text{GeV})}$. The intrinsic timing resolution is $\sigma_t = 54$ ps$/\sqrt{E(\text{GeV})} \oplus 50$ ps, which allows photon vertices from π^0 decays to be reconstructed with a resolution of ~ 1.5 cm. A superconducting coil surrounding the calorimeter barrel provides a 0.52 T

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magnetic field.

During 2002 data taking, the maximum luminosity sustained by DAΦNE was $7.5 \cdot 10^{31}$ cm^{-2}s^{-1}. Although this is lower than the design value, the performance of the machine during 2002 was much improved with respect to previous years, and the KLOE experiment was able to collect as much as 4.5 pb^{-1} per day. The combined KLOE 2001–2002 data set amounts to about 450 pb^{-1}, or 1.4 billion ϕ decays.

A series of recent upgrades to the machine, including an overhaul of the interaction region inside the KLOE detector, is expected to bring the design luminosity to within reach. Data taking with KLOE is scheduled to restart during the fall of 2003.

Kaon physics with KLOE. The tagging of K_L and K_S decays is fundamental to all KLOE studies of the K_SK_L system. The $K_S \to \pi^+\pi^-$ decay provides an efficient tag for K_L decays. K_S's can be tagged by identifying a K_L interaction in the calorimeter. Since the neutral kaons from ϕ decays have $\beta = 0.22$ at KLOE, the signature of such an interaction, or "K_L crash," is a late, high-energy cluster that is not associated to any track in the drift chamber. In either case, reconstruction of one kaon establishes the trajectory of the other with an angular resolution of $\sim 1^\circ$ and a momentum resolution of ~ 2 MeV.

Using the K_L crash to tag K_S decays, KLOE has measured the ratio of the partial widths for the dominant K_S decay modes: $\Gamma(K_S \to \pi^+\pi^-(\gamma))/\Gamma(K_S \to \pi^0\pi^0) = 2.236 \pm 0.003 \pm 0.015$ [3]. This value was obtained using just 17 pb^{-1} of data from the 2000 run. In addition to providing the first part of the double ratio for $\mathrm{Re}\,(\varepsilon'/\varepsilon)$, the measurement of this value allows determination of $\chi_0 - \chi_2$, the difference in $\pi\pi$ phase shifts in $K \to \pi\pi$ transitions with $I = 0$ and 2. As argued in [4], the extraction of the $K \to \pi\pi$ amplitudes from the measured widths must take into account the effective cutoff for the detection of final state photons from $K_S \to \pi^+\pi^-\gamma$ decays. Due to the tagging technique used at KLOE, the detection efficiency for such decays is good out to high values of the photon energy, which allows a fully inclusive measurement to be made. By the evaluation of [4], the previously existing data give $\chi_0 - \chi_2 = (56 \pm 8)^\circ$, which is in somewhat poor agreement with the estimates of the difference in strong $\pi\pi$ phase shifts, $\delta_0 - \delta_2$, from chiral perturbation theory, $(45 \pm 6)^\circ$ [5], and from the phenomenological analysis of $\pi\pi$ scattering data, $(45 \pm 6)^\circ$ [6].[2] The KLOE measurement gives $\chi_0 - \chi_2 = (48 \pm 3)^\circ$, which considerably improves the agreement with the predictions from phenomenology.

KLOE has also measured the BR's for the K_{e3} decays of the K_S. The π and e assignments are made using time-of-flight measurements, so the BR's to final states of each lepton charge are measured independently. Based on 170 pb^{-1} of 2001 data, KLOE obtains the preliminary values for the BR's to $\pi^-e^+\nu$, $(3.46 \pm 0.09 \pm 0.06) \cdot 10^{-4}$, and to $\pi^+e^-\overline{\nu}$, $(3.33 \pm 0.08 \pm 0.05) \cdot 10^{-4}$. A nonzero value for $A_S - A_L$, the difference in the semileptonic charge asymmetries for the K_S and K_L, would signal CPT violation, either in the K_S-K_L mixing or in direct transitions that also violate the $\Delta S = \Delta Q$ rule. While A_L has recently been measured with precision [7], these preliminary KLOE results give the first-ever measurement of A_S: $(19 \pm 17 \pm 6) \cdot 10^{-3}$. When the semileptonic final states

[2] The difference between $\chi_0 - \chi_2$ and $\delta_0 - \delta_2$ is that the former quantity includes an additional phase shift difference from isospin-breaking electromagnetic effects, estimated to be about 3° [4].

are not distinguished by charge, KLOE obtains $(6.81 \pm 0.12 \pm 0.10) \cdot 10^{-4}$ for the BR. With respect to the previous KLOE measurement [8], this represents a tenfold increase in statistics accompanied by a reduction of the systematic error by a third. The difference between the partial widths for the K_{e3} decays of the K_S and K_L can be related to Re x_+, the parameter which quantifies violations of the $\Delta S = \Delta Q$ rule in CPT-conserving transitions. The preliminary KLOE measurement of the charge-undifferentiated K_{e3} branching ratio of the K_S gives Re $x_+ = (3.3 \pm 5.2 \pm 3.5) \cdot 10^{-3}$, which is comparable in significance to the CPLEAR result [9]. KLOE has an additional 280 pb^{-1} of data under analysis, and forthcoming KLOE measurements of the K_L lifetime and K_{e3} BR will allow further improvements on the value of Re x_+.

Using the $K_S \to \pi^+\pi^-$ decay to tag K_L decays, KLOE has recently completed a measurement of $\Gamma(K_L \to \gamma\gamma)/\Gamma(K_L \to 3\pi^0)$. The BR for the decay $K_L \to \gamma\gamma$ provides interesting tests of chiral perturbation theory; additionally, this decay dominates the long-distance contribution to $K_L \to \mu^+\mu^-$ [10]. For the ratio of BR's, KLOE obtains $(2.793 \pm 0.022 \pm 0.024) \cdot 10^{-3}$ from 362 pb^{-1} of 2001–2002 data [11]. This value is comparable in significance to that from NA48 [12]. The normalization sample of $K_L \to 3\pi^0$ decays (which is downscaled by a factor of ten) provides a value for the K_L lifetime that is comparable in statistical significance to the world-average value.

KLOE is currently studying the BR's of the various K_L decays to charged particles. As a proof of principle, an analysis of the tagged K_L vertices in 78 pb^{-1} of 2002 data has been performed, and gives values for the K_L BR's to $\pi^+\pi^-\pi^0$, $\pi\mu\nu$, and $\pi e\nu$ that are consistent with, and which have statistical significance comparable to, the world-average values. When a similar, dedicated analysis of $\mathrm{BR}(K_L \to \pi^+\pi^-)$ is performed (on 429 pb^{-1} of 2001–2002 data), the value $(2.04 \pm 0.04) \cdot 10^{-3}$ is obtained. The systematic errors on the above values have not been fully evaluated yet, but are thought to be at the 1–2% level.

In the longer term, KLOE intends to measure $\mathrm{Re}\,(\varepsilon'/\varepsilon)$ via the double ratio:

$$1 - 6\,\mathrm{Re}\,(\varepsilon'/\varepsilon) = \frac{K_L \to \pi^0\pi^0}{K_L \to \pi^+\pi^-} \cdot \frac{K_S \to \pi^+\pi^-}{K_S \to \pi^0\pi^0}.$$

The manner in which this expression is written calls attention to the fact that at KLOE, cancellations of experimental systematics are sought principally in the ratios of the BR's for the charged and neutral decay modes. KLOE prospects for the measurement of $\mathrm{Re}\,(\varepsilon'/\varepsilon)$ can be summarized as follows. The current KLOE measurement of the ratio of $K_S \to \pi\pi$ BR's has a negligible statistical error and a systematic error of 0.7%. This error is expected to be reduced to the 0.1% level when the 2001–2002 data are analyzed, both because of changes to the tagging algorithm already implemented, and because the errors on the various corrections are determined by the statistics of the control samples used to obtain them. The statistical errors on the $K_L \to \pi\pi$ BR measurements obtained using the entire 2001–2002 data set are currently at the 1.5% level; systematic errors are at about the same level and work is in progress to significantly reduce them. A measurement of the ratio of the $K_L \to \pi\pi$ BR's with an overall error at the level of a few per mil will require at least a factor of ten more data.

KLOE is also undertaking a comprehensive program for the study of the decays of the charged kaons. The most advanced analysis concerns the BR and Dalitz plot for the

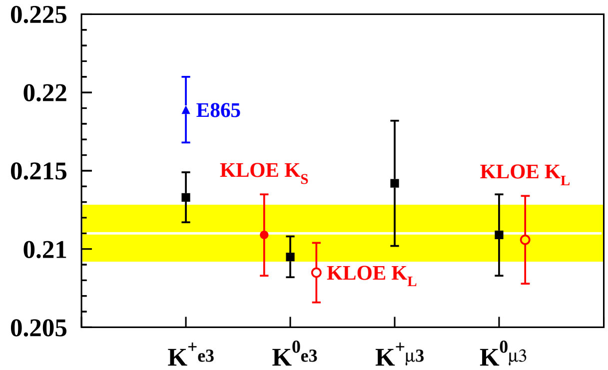

FIGURE 1. Current status of $|V_{us}| f_+^{K^0\pi^-}(0)$. Evaluations of $|V_{us}| f_+^{K^0\pi^-}(0)$ from the published world data on $K_{\ell 3}$ decays are shown as the squares [15]. The average over the K_{e3}^+ and K_{e3}^0 modes (with its error) is shown as the horizontal band. The value obtained [15] from the recent measurement of the K_{e3}^+ BR by BNL-E865 [16] is shown as the triangle. The values from the preliminary KLOE measurements of the $K_{\ell 3}$ decays of the K_S and K_L are shown as the solid and open circles.

decay $K^\pm \to \pi^\pm \pi^0 \pi^0$. Charge asymmetries in the rates and Dalitz plot slopes for this decay would signal direct *CP* violation (see *e.g.* [13]). Based on 188 pb^{-1} of 2001–2002 data, the KLOE value for the BR is $(1.781 \pm 0.013 \pm 0.016)\%$ [14].

The measurement of the CKM matrix element $|V_{us}|$ represents a point of convergence for KLOE studies of charged and neutral kaon decays. Fig. 1 summarizes values for the quantity $|V_{us}| f_+^{K^0\pi^-}(0)$ obtained from measurements of the $K_{\ell 3}$ BR's and kaon lifetimes. The errors on these values are completely dominated by the experimental inputs. The four essentially independent evaluations of $|V_{us}| f_+^{K^0\pi^-}(0)$ from published world data are in agreement. The recent measurement of the K_{e3}^+ BR by BNL-E865, on the other hand, gives a discrepant value. This is intriguing, because the value for $|V_{us}|$ obtained from the E865 measurement agrees with current determinations of $|V_{ud}|$ given the first-row unitarity constraint on the CKM matrix elements. Preliminary KLOE results, on the other hand, decisively weigh in on the side of the existing value for $|V_{us}|$. A KLOE measurement of the K_{e3}^+ BR would offer direct comparison with the E865 result, and is forthcoming. In the longer term, KLOE should be able to measure all four $K_{\ell 3}$ BR's to much better than 1%, and to significantly improve the determinations of the lifetimes of the K_L and $K^\pm$, as well as the form factor slopes λ_+ and λ_-.

Hadronic physics with KLOE. KLOE has recently completed an analysis of the decay $\phi \to \pi^+\pi^-\pi^0$, which proceeds mainly through $\rho\pi$ intermediate states [17]. A fit to the Dalitz plot containing 2 million events from 17 pb^{-1} of 2000 data gives values for the masses and widths of the ρ^+, ρ^-, and ρ^0. When the fit is performed such that all three ρ charge states are described by the same mass and width, KLOE obtains $m_\rho = 775.8 \pm 0.5 \pm 0.3$ MeV (in agreement with other recent e^+e^- measurements; see [18]) and $\Gamma_\rho = 143.9 \pm 1.3 \pm 1.1$ MeV (confirming the result of [19]). When this constraint is relaxed, no significant differences are observed between the masses of the charged and neutral ρ's, or between the masses of the ρ^+ and ρ^-.

The ratio of BR's for the decays $\phi \to \eta'\gamma$ and $\phi \to \eta\gamma$ provides information on the

η-η' mixing angle and on the gluonium content of the η' [20, 21]. KLOE has measured this ratio using 17 pb^{-1} of 2000 data and obtained a value for the pseudoscalar mixing angle in the flavor basis, $\varphi_P = (41.8\,^{+1.9}_{-1.6})^\circ$, as well as a limit on the gg content of the η' [22]. An extension of the analysis based on the 2001-2002 data set is in progress.

KLOE has also analyzed the ϕ decays to $\pi^0\pi^0\gamma$ and $\eta\pi^0\gamma$, where the dominant contributions involve production and decay of the scalar mesons f_0 and a_0, respectively. Fits based on a kaon-loop model to the $\pi\pi$ and $\eta\pi$ invariant-mass spectra obtained from 17 pb^{-1} of 2000 data have been used to obtain values of the coupling constants g_{f_0KK} and g_{a_0KK}. The value obtained for g_{f_0KK} is compatible with predictions that assume a $q\bar{q}q\bar{q}$ model for the f_0 structure, while that obtained for g_{a_0KK} is in poor agreement with these predictions [23, 24]. The factor-of-ten increase in statistics from the 2001–2002 data has allowed KLOE to undertake a model-independent analysis of these decays featuring a complete study of the contributions to the Dalitz plots.

Finally, KLOE is concluding a determination of $\sigma(e^+e^- \to \pi^+\pi^-)$ as a function of s_π, the squared CM energy of the $\pi\pi$ system, for $0.3 < s_\pi < 1$ GeV^2. DAΦNE operates exclusively at $W \approx m_\phi$, so the actual measurement is the cross section for the process $e^+e^- \to \pi^+\pi^-\gamma$, where the photon is radiated from the initial state (ISR). The PHOKHARA generator [25] is then used to relate $\sigma(e^+e^- \to \pi^+\pi^-\gamma)$ to $\sigma(e^+e^- \to \pi^+\pi^-)$. Complications from processes with final-state radiation (FSR) are avoided by restricting the current study to events with low-angle photons ($\theta < 15^\circ$); in this kinematic region ISR events completely dominate the sample. Detection of the photon is unnecessary; s_π and the photon angle are reconstructed in the drift chamber. The preliminary KLOE data presented in Fig. 2 provide valuable comparison to the energy-scan data from CMD-2 [19] with respect to the determination of the hadronic contribution to the anomalous magnetic moment of the muon, $a_\mu^{\rm had}$. Evaluations of $a_\mu^{\rm had}$ based on e^+e^--annihilation and τ-decay data differ by -3.0σ and -0.9σ from consistency with the a_μ measurement from BNL-E821 [26]; at present, the CMD-2 results dominate the value of $a_\mu^{\rm had}$ from e^+e^- data [27]. The KLOE data in Fig. 2 give $a_\mu^{\rm had}(0.37 < s_\pi < 0.93\ {\rm GeV}^2) = 374.1 \cdot 10^{-10}$, with a negligible statistical error and a 1.6% systematic error including all experimental and theoretical sources except for the lack of ISR+FSR events in the simulation (these are already included in a new version of PHOKHARA). In this same interval for s_π, the CMD-2 data give $a_\mu^{\rm had} = (368.1 \pm 2.6 \pm 2.2) \cdot 10^{-10}$. The discrepancy between the KLOE and CMD-2 results is concentrated below the ρ peak; the values of $a_\mu^{\rm had}$ from the two experiments agree for the interval $0.6 < s_\pi < 0.97$ GeV^2, where the $\pi^+\pi^-$ spectral functions for e^+e^- and τ data disagree by 10–15% [28].

Conclusions. KLOE is currently analyzing a unique data set consisting of 500 pb^{-1} of ϕ decays. Extensions of previous KLOE results on K_S and radiative ϕ decays are nearly ready, and important new measurements such as those of $|V_{us}|$ and $\sigma(e^+e^- \to \text{hadrons})$ are forthcoming. In 2003–2004 running, KLOE expects to collect a few fb^{-1} of data, which will allow the broad physics reach of the experiment to be further extended.

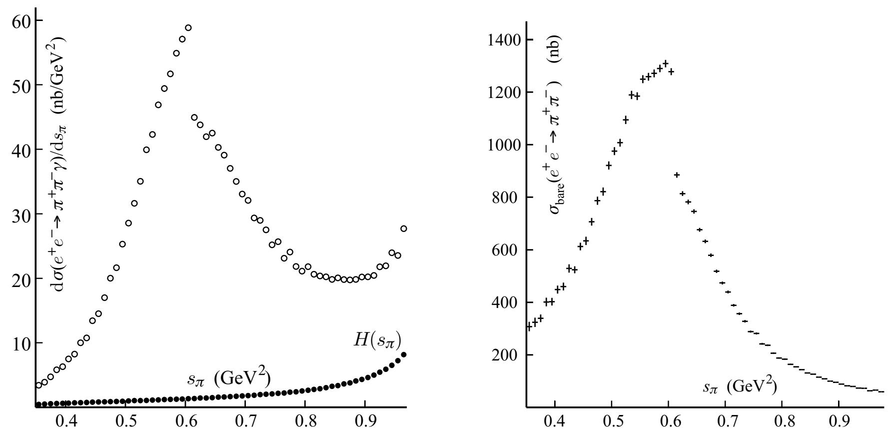

FIGURE 2. Left: Open markers show preliminary KLOE measurements of $d\sigma(e^+e^-\to\pi^+\pi^-\gamma)/ds_\pi$ from 1.5 million events (140 pb^{-1}) of 2001 data; solid markers show the radiation function used to extract $\sigma(e^+e^-\to\pi^+\pi^-)$. Right: KLOE determination of the bare cross section for the process $e^+e^-\to\pi^+\pi^-$.

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