RESULTS ON RARE KAON DECAYS FROM THE NA48 EXPERIMENT

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The NA48 experiment, designed to measure with great accuracy the direct CP violation in $K_{L,S} \to \pi\pi$ decays, is also exploiting the high intensity of its beams to detect a wide range of neutral kaon and hyperon decays. The most recent results, as well as the future experimental program on rare decays, are presented.

1 Rare decays in NA48

The NA48 experiment has been conceived for the high–precision measurement of the direct CP violation parameter $\mathrm{Re}(\varepsilon'/\varepsilon)$ and is presently running at the CERN SPS. The high intensity of its primary neutral beam, about 3×10^{10} K_L decays in the fiducial region per year, allows the study of rare K_L and neutral hyperon decays with competitive sensitivity. Concurrently, about 7×10^7 K_S decays occur in the same fiducial region from a less intense secondary beam, in order to have similar rates of two–pion decays from K_L and K_S . At the end of 1999 the experiment was operated for two days with the K_S beam only, at about 200 times its nominal intensity. During this high–intensity K_S (HIKS) run about 2.3×10^8 K_S decays were produced, allowing for a substantial increase of the experiment's sensitivity to rare K_S decay modes.

A detailed description of the experimental apparatus, based on a large magnetic spectrometer and on a cold homogeneous calorimeter, can be found elsewhere [1]. A large number of rare decay modes can be looked for, thanks to the high capability of trigger and data acquisition systems, and to the excellent resolution of detectors. The decay channels presently under study are listed in table 1. Some of them are useful to improve the understanding of CP violation in kaon decays. A relatively large effect of indirect CP violation is observed in the $K_L \to \pi^+\pi^-e^+e^-$ mode, and constraints can be put on the very rare $K_L \to \pi^0 e^+e^-$ decay, that is expected to manifest direct CP violation. The other strong motivation for these studies is the understanding of low–energy hadron dynamics, by probing non–perturbative effective theories such as Chiral Perturbation Theory (χPT).

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Decay	B.R. (order)	Main motivations
$K_L \to \pi^+\pi^- e^+e^-$	10^{-7}	indirect CPV
$K_L \to \pi^0\gamma\gamma$	10^{-6}	test of χPT at $\mathcal{O}(p^6)$, constraints on $\Gamma(K_L \to \pi^0 e^+e^-)$
$K_L \to e^+e^-e^+e^-$	10^{-8}	test of χPT for $K_L \to \gamma^*\gamma^*$ vertex
$K_L \to \mu^+\mu^-e^+e^-$	10^{-9}	test of χPT for $K_L \to \gamma^*\gamma^*$ vertex
$K_L \to e^+e^-\gamma\gamma$	10^{-6}	main background to $K_L \to \pi^0 e^+e^-$
$K_S \to \pi^+\pi^- e^+e^-$	10^{-5}	check of $K_L \to \pi^+\pi^- e^+e^-$ analysis
$K_S \to \pi^0 e^+e^-$	$< 10^{-7}$	constraints on $\Gamma(K_L \to \pi^0 e^+e^-)$
$K_S \to \gamma\gamma$	10^{-6}	clean χPT prediction
$K_S \to \pi^0\pi^0\pi^0$	$< 10^{-5}$	indirect CPV, test of CPT
$\Xi^0 \to \Lambda^0\gamma$	10^{-3}	test of SU(3) symmetries
$\Xi^0 \to \Sigma^0\gamma$	10^{-3}	test of SU(3) symmetries
$\Xi^0 \to \Sigma^+ e^-\bar{\nu}_e$	10^{-4}	test of SU(3) symmetries
$\Xi^0 \to p\pi^-$	$< 10^{-6}$	$\Delta S = 2$ transition

Table 1: A non-exhaustive list of rare decay modes under investigation in NA48.

2 Recent Results

2.1 $K_{L,S} \to \pi^+\pi^- e^+e^-$

The K_L decay can be described in terms of two components: the CP–violating $K_L \to \pi^+\pi^-$ transition with inner Bremsstrahlung, and the direct emission process, that conserves CP. The interference of the two terms gives rise to a CP–violating asymmetry in the distribution of the angle ϕ between the normals to the $\pi^+\pi^-$ and e^+e^- planes in the kaon rest frame $A(\phi) \equiv (N_{\cos\phi\sin\phi>0} - N_{\cos\phi\sin\phi<0})/(N_{\cos\phi\sin\phi>0} + N_{\cos\phi\sin\phi<0})$, predicted [2] to be as large as 14%, as first confirmed by the KTeV experiment [3].

More than 1300 candidates for the K_L decay have been selected from the 1998 and 1999 data. The background contamination, dominated by $K_L \to \pi^+\pi^-\pi^0$ with π^0 Dalitz decay, is suppressed to less than 3 % through kinematical cuts. An acceptance correction obtained through Monte Carlo simulation must be applied. An evident CP–violating asymmetry in the $\cos(\phi)\sin(\phi)$ distribution can be observed in figure 1, where the $M_{\pi\pi ee}$ invariant mass distribution of the candidate events is also shown. Preliminary results are:

$$\mathrm{BR}(K_L \to \pi^+\pi^- e^+e^-) = (3.1 \pm 0.1 \pm 0.2) \times 10^{-7}$$
$$A^L(\phi) = (13.9 \pm 2.7 \pm 2.0)\%$$

From the 1998 ε'/ε data sample, 56 candidates for $K_S \to \pi^+\pi^- e^+e^-$ were also selected, constituting the first observation of this decay [4]. After the inclusion of 1999 data, notably of the HIKS run, the number of candidates raised to 921, leading to the preliminary results:

$$\mathrm{BR}(K_S \to \pi^+\pi^- e^+e^-) = (4.3 \pm 0.2 \pm 0.3) \times 10^{-5}$$
$$A^S(\phi) = (-0.2 \pm 3.4 \pm 1.4)\%$$

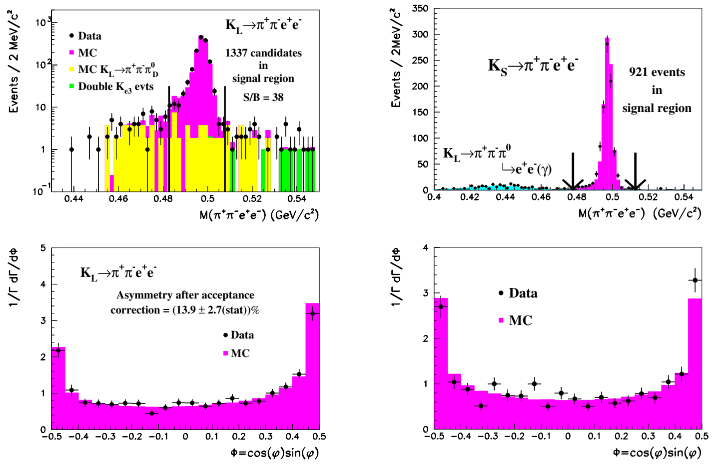

Figure 1: The distributions for $\pi\pi ee$ invariant mass and asymmetry are shown on the left for $\mathrm{K_L} \to \pi^+\pi^-e^+e^-$ candidates, on the right for $\mathrm{K_S} \to \pi^+\pi^-e^+e^-$ candidates.

As expected, no asymmetry is observed in this case, since the $\mathrm{K_S}$ mode is largely dominated by the inner Bremsstrahlung process.

2.2 $\mathrm{K_S} \to \pi^0 e^+e^-$

The main motivation to look for this decay is its bound with the analogous $\mathrm{K_L}$ mode, whose branching ratio receives a contribution of order $\mathcal{O}(10^{-12})$ from direct CP violation, cleanly predicted in terms of $Im(\lambda_t) = Im(V_{td}V_{ts}^*)$. However, also the CP conserving process $\mathrm{K_L} \to \pi^0\gamma^*\gamma^*$ gives a contribution (that can be constrained by measuring the $\mathrm{K_L} \to \pi^0\gamma\gamma$ mode) and the CP violating amplitude is partly due to indirect CP violation:

$$\frac{\mathrm{BR}(\mathrm{K_L} \to \pi^0 e^+e^-)_{CPV}}{10^{-12}} = \left[15.3\ a_S^2 - 6.8\frac{Im(\lambda_t)}{10^{-4}}\ a_S + 2.8\left(\frac{Im(\lambda_t)}{10^{-4}}\right)^2\right] \quad (1)$$

where a_S, naively predicted to be of order $\mathcal{O}(1)$, can be obtained from the $\mathrm{K_S}$ branching ratio [5]

$$BR(\mathrm{K_S} \to \pi^0 e^+e^-) = 5.2\ a_S^2 \times 10^{-9} \quad (2)$$

A search for this decay was performed using the data collected in the HIKS run. The most dangerous background comes from the copious $\mathrm{K_S} \to \pi^0\pi^0$

decays with a π^0 Dalitz decay and an undetected photon. This is suppressed by requiring an e^+e^- invariant mass well above the π^0 mass. A cut at 165 MeV/c^2 reduces the expected background to 0.3 events, while retaining half of the simulated signal. No events survive the cuts, leading to the result [6]
$\mathrm{BR}(\mathrm{K_S} \to \pi^0 e^+ e^-) < 1.4 \times 10^{-7}$ (90% C.L.)
that improves by an order of magnitude the previous limit set by NA31.

2.3 $\mathrm{K_S} \to \gamma\gamma$

The branching ratio for this decay, that is dominated by one–loop diagrams, can be predicted within χPT to be [7] $(2.3\pm0.2)\times10^{-6}$, while experimentally only 35 events have been reported so far by NA31 [8], leading to BR=$(2.4\pm0.9)\times10^{-6}$.

A dedicated trigger for this mode was set up during the HIKS run. The candidate events were selected in the first five meters after the anticounter defining the beginning of the fiducial region. In fact, for the most severe background, namely $\mathrm{K_S} \to \pi^0\pi^0$ with two undetected photons, the reconstructed vertex position is displaced forward by 9 meters at least. The longitudinal vertex distribution was fitted to disentangle the $\mathrm{K_L}$ and $\mathrm{K_S}$ components, using the known value of the $\mathrm{K_L}$ branching ratio [9], and 149 ± 21 $\mathrm{K_S} \to \gamma\gamma$ events were obtained, leading to [10]:
$\mathrm{BR}(\mathrm{K_S} \to \gamma\gamma) = (2.58 \pm 0.36 \text{ (stat.)} \pm 0.22 \text{ (syst.)}) \times 10^{-6}$
in good agreement with the χPT prediction.

2.4 $\mathrm{K_L} \to 3\pi^0$ *Dalitz Plot*

The huge amount of common semileptonic and three-pion $\mathrm{K_L}$ decays can be used to improve the knowledge of the matrix element parameters. In the case of $\mathrm{K_L} \to 3\pi^0$, the Dalitz plot distribution must depend quadratically from the kinematical variable $R \equiv \sqrt{u^2 + v^2/3}$, where u and v are the usual Dalitz variables. The quadratic parameter h is predicted from χPT calculations of order $\mathcal{O}(p^4)$ to be [11] $(-12 \pm 4) \times 10^{-3}$. A sample of 14.6×10^6 events with negligible background was selected from the 1998 data. The distribution of the R^2 variable is compared with a Montecarlo simulation generated with $h = 0$. The ratio shows the expected linear behavior, and a fit gives the result [12]
$h = (-6.1 \pm 0.9 \text{ (stat.)} \pm 0.5 \text{ (syst.)}) \times 10^{-3}$
in fair agreement with the theoretical prediction and the previous measurement by E731 [13] ($(-3.3 \pm 1.3) \times 10^{-3}$).

3 Future plans for rare decays

A two–years extension of the NA48 experimental program beyond the ε'/ε measurement has been recently approved. The whole 2002 data–taking will be devoted to $\mathrm{K_S}$ physics, by running in the $\mathrm{K_S}$ high–intensity configuration after minor modifications of the beam layout. About 3×10^{10} $\mathrm{K_S}$ decays are foreseen. One of the most relevant expected results is the measurement of $\eta_{000} \equiv \frac{A(\mathrm{K_S}\to\pi^0\pi^0\pi^0)}{A(\mathrm{K_L}\to\pi^0\pi^0\pi^0)}$, describing the indirect CP violation in $3\pi^0$ decays, with 1 % accuracy, an order of magnitude better than the present limit. A more accurate bound on η_{000} can significantly improve the test of CPT in the neutral kaon sector through the Bell–Steinberger relation. The other main physics goals are the search for $\mathrm{K_S} \to \pi^0 e^+ e^-$ with a single event sensitivity of about 6×10^{-10}, the possible first observation of more rare decays such as $\mathrm{K_S} \to \pi^0\gamma\gamma$ and $\mathrm{K_S} \to \pi^0\pi^0\gamma\gamma$, and precision measurements of the Ξ^0 physics.

During 2003, the experiment will run with two simultaneous K^+ and K^- beams, with two main physics goals: the search for direct CP violation in $K^\pm \to \pi^+\pi^-\pi^\pm$, and the high–precision study of the low–energy $\pi\pi$ scattering amplitudes through the measurement of K_{e4} decays, in order to extract the size of the $q\bar{q}$ vacuum condensate predicted by QCD.

4 Conclusions

NA48 is producing many interesting results in kaon physics other than the $\mathrm{Re}(\varepsilon'/\varepsilon)$ measurement. During the ε'/ε data–taking competitive results on rare $\mathrm{K_L}$ and hyperon decays could be obtained. The successful data–taking with a high–intensity $\mathrm{K_S}$ beam performed in 1999 and 2000 proved the capability of the experiment to measure many $\mathrm{K_S}$ decay modes with unprecedented sensitivity. Relevant results are expected from the continuation of the experimental program in the two next years.

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