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RARE $K_{\rm S}$ DECAYS WITH NA48*

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Recent results obtained by the NA48 Collaboration on rare $K_{\rm S}$ decays and future prospects are presented.

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1. Introduction

The NA48 experiment at CERN has been designed to measure the direct CP violation parameter $\mathrm{Re}(\varepsilon'/\varepsilon)$ with a precision of 2×10^{-4}. However, given the high resolution of the NA48 detectors and the quality of the $K_{\rm S}$ and $K_{\rm L}$ beams, it is possible to investigate rare decays in the neutral kaon sector. In particular, the use of an intense proton beam at the $K_{\rm S}$ target station allows NA48 to search for very rare $K_{\rm S}$ decays, such as $K_{\rm S}\to\pi^0e^+e^-$ or $K_{\rm S}\to\pi^0\pi^0\pi^0$. In the following sections I will review recent results on $K_{\rm S}$ decays obtained by NA48 and describe the potential for further investigation in the $K_{\rm S}$ sector in the near future.

A detailed description of the experimental layout can be found in [1].

2. The intense $K_{\rm S}$ beam in 1999

During the 1999 run, a short period of two days was devoted to the investigation of rare $K_{\rm S}$ decays and neutral hyperons. The intensity of the proton beam at the $K_{\rm S}$ target station was increased by a factor of about 200 (6×10^9 protons per SPS pulse of 2.5 s every 14.4 s). The photon veto detector used in normal ε'/ε running to define the beginning of the fiducial region for $K_{\rm S}\to\pi^0\pi^0$ decays was partially removed from the $K_{\rm S}$ beam

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and the $K_{\rm L}$ beam switched off. In these conditions, the instantaneous rates in the NA48 detectors were slightly above the ones in the standard ε'/ε configuration.

2.1. $K_{\rm S} \to \gamma\gamma$

The measurement of the branching ratio of the decay $K_{\rm S} \to \gamma\gamma$ is a critical test of Chiral Perturbation models. Within this framework the one-loop contributions are finite and predict unambiguously the branching ratio. Its precise measurement can therefore provide insight on contributions from high-order loop corrections.

Due to a very large background from $K_{\rm S} \to \pi^0\pi^0$ decays, the study of $K_{\rm S} \to \gamma\gamma$ can be carried out in a very restricted region close to the end of the final beam collimator. The maximum invariant mass for a $\gamma\gamma$ pair originating from $K_{\rm S} \to \pi^0\pi^0$ decays is 458 MeV/c^2; this produces an apparent neutral vertex shift of about 9 m downstream the beam line, leaving the beginning of the fiducial region populated mainly by $K_{\rm L,S} \to \gamma\gamma$.

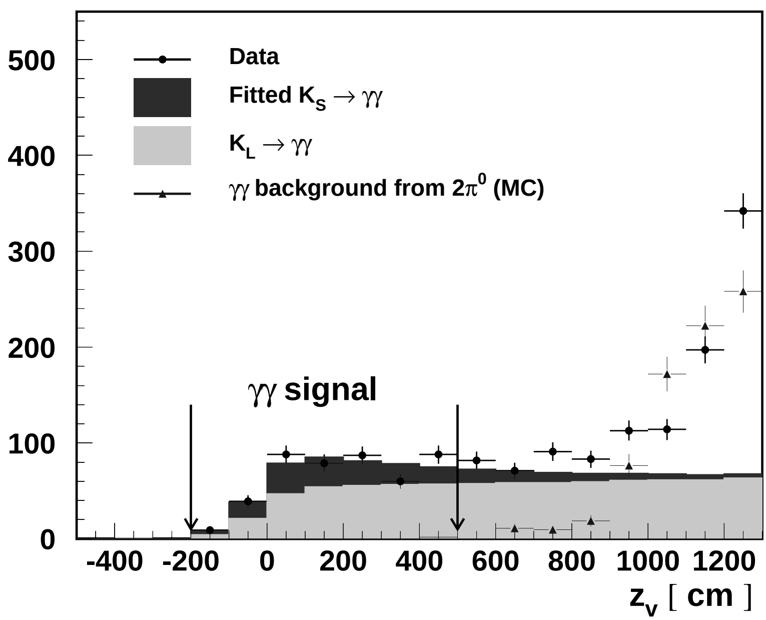

Fig. 1. Z-vertex distribution for fitted $K_{\rm S} \to \gamma\gamma$ events (black area) and $K_{\rm L} \to \gamma\gamma$ component (grey area). The dots show the data and the arrows show the fitted region.

Using data collected during the two-day long test run in 1999, 450 $K \to \gamma\gamma$ events with energy between 60 and 170 GeV/c^2 and reconstructed Z-vertex between -2 and 5 m were identified. A background of 2 ± 2 events from $K_S \to \pi^0\pi^0$ decays and 11 ± 8 events from $\Lambda \to n\pi^0$ was then subtracted. Using the existing branching ratio for $K_L \to \gamma\gamma$ and a binned Maximum Likelihood method, 149 ± 21 events were identified as $K_S \to \gamma\gamma$. The result which the NA48 Collaboration published in [2], using $K_S \to \pi^0\pi^0$ as normalization sample, is

$$\mathrm{BR}(K_S \to \gamma\gamma) = (2.58 \pm 0.36_{\mathrm{stat}} \pm 0.22_{\mathrm{syst}}) \times 10^{-6}\,.$$

2.2. Search for $K_S \to \pi^0 e^+e^-$

Decays of K_L mesons into $\pi^0 l\bar{l}$ are of considerable interest due to their sensitivity to direct CP violation [3]. However, in $\pi^0 e^+e^-$ decays both CP conserving and indirect CP violating amplitudes also contribute. The CP conserving contribution to this decay process can be obtained by measuring the low $m_{\gamma\gamma}$ component of the decay $K_L \to \pi^0\gamma\gamma$. The contribution to the branching ratio $\mathrm{BR}(K_L \to \pi^0 e^+e^-)$ is $\approx 4 \times 10^{-12}$ [4]. The direct and indirect CP violating (CPV) contributions interfere, and their contribution to the branching ratio can be written as [5]:

$$\mathrm{BR}(K_L \to \pi^0 e^+e^-)_{CPV} \times 10^{12} \simeq\; 15.3\, a_S^2 - 6.8\, a_S \frac{\mathrm{Im}(\lambda_t)}{10^{-4}} + 2.8 \left(\frac{\mathrm{Im}(\lambda_t)}{10^{-4}}\right)^2,$$

where $\lambda_t = V_{\mathrm{ts}}^* V_{\mathrm{td}}$ is the relevant combination of CKM matrix elements which describe the short distance CP violation. The parameter a_S describes the strength of the indirect CP violating component in the $K_L \to \pi^0 e^+e^-$ decay, and is related to $\mathrm{BR}(K_L \to \pi^0 e^+e^-)$ *via* the relation [5]:

$$\mathrm{BR}(K_L \to \pi^0 e^+e^-) \;=\; 5.2 \,\times\, 10^{-9}\, a_S^2\,.$$

According to dimensional analysis in chiral perturbation theory, $a_S \sim \mathcal{O}(1)$. The NA31 experiment obtained the upper bound

$$\mathrm{BR}(K_S \to \pi^0 e^+e^-) < 1.1 \times 10^{-6}$$

at 90% confidence level [6]. A more precise measurement of this mode is clearly important to place a bound on the indirect CP violating term in the K_L decay.

During the test run at high intensity, NA48 has improved the limit on $\mathrm{BR}(K_S \to \pi^0 e^+e^-)$ by almost a factor of 10.

The most important background source is $K_S \to \pi^0\pi^0$ decays with the subsequent Dalitz decay of either π^0. The most effective rejection can be done requiring the invariant mass of the electron pair above the m_{π^0} kinematic limit, in order to take into account possible resolution effects or interactions in the detector material.

Fig. 2 shows the m_{ee} distribution for background, data and simulated signal events. The observed m_{ee} distribution is very well accounted for by the $K_S \to \pi^0\pi^0_D$ simulation; above the value $m_{ee} = 165$ MeV/c^2, which defines the signal region, no candidate is observed. Contaminations from $K_S \to \pi^0\pi^0_D$ or $K_S \to \pi_D\pi_D$ are estimated to be less than 0.03 events for each channel. Using fully reconstructed $K_S \to \pi^0\pi^0_D$ as normalization, a preliminary upper limit on the branching ratio for $K_S \to \pi^0 e^+e^-$ can be set

$$\mathrm{BR}(K_S \to \pi^0 e^+e^-) < 1.6 \times 10^{-7}$$

at 90% CL.

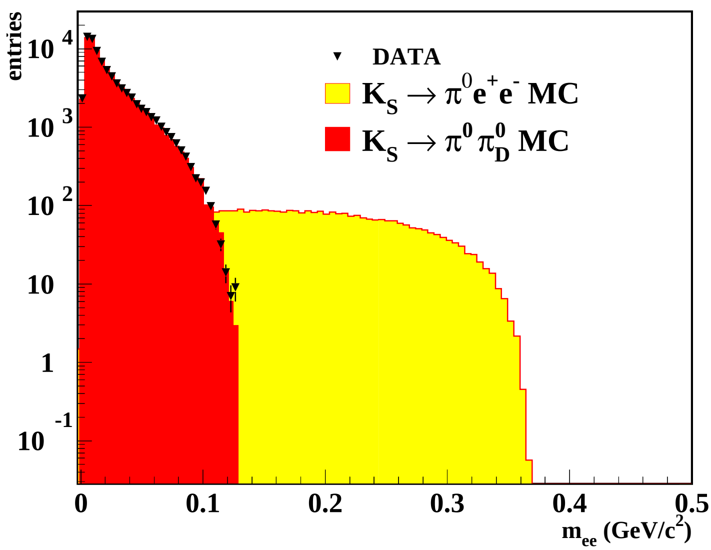

Fig. 2. Invariant mass distribution of the electron–positron pair for data (triangles), $K_S \to \pi^0\pi^0_D$ simulation (black area) and $K_S \to \pi^0e^+e^-$ simulation (grey area, arbitrary normalization).

3. The intense K_S beam in 2000

At the end of 1999 a beam-pipe implosion seriously damaged the four drift chambers that are part of the NA48 spectrometer. As a consequence only neutral kaon decays could be recorded during the 2000 run. The chambers were removed from the beam line and a continuous vacuum established between the K_S target and the beginning of the main detector. About 40 days were devoted to a high intensity run aimed at the investigation of purely neutral modes of rare K_S decays. The proton intensity on the target was increased to 9×10^{-9} per SPS pulse of 3.2 s every 14.4 s. The momentum of the proton beam was reduced to 400 GeV/c and the kaon production angle decreased to 3 mrad to compensate the beam momentum loss.

3.1. $K_S \to \pi^0\pi^0\pi^0$

A very interesting decay to search for at high intensity is $K_S \to \pi^0\pi^0\pi^0$. As the $3\pi^0$ state is pure $CP = -1$, the observation of $K_S \to \pi^0\pi^0\pi^0$ is a clear signature of CP violation. This effect is parametrized by

$$\eta_{000} = \frac{A(K_S \to \pi^0\pi^0\pi^0)}{A(K_L \to \pi^0\pi^0\pi^0)}\,.$$

So far, the best measurement of η_{000} has been reported by the CPLEAR Collaboration [7]: Re(η_{000})=0.18 ± 0.15 and Im(η_{000})=0.15 ± 0.20, corresponding to a branching ratio of $\mathrm{BR}(K_S \to \pi^0\pi^0\pi^0) < 1.9\times10^{-5}$ at 90% CL. The SND experiment has later lowered the limit on the branching ratio to 1.4×10^{-5} at 90% CL [8].

A precise measurement of η_{000} is also fundamental for CPT tests. Assuming unitarity, it is possible to measure the CPT parameters Re(ε) and Im(δ) through the Bell–Steinberger relations which relates K_S and K_L amplitudes in the final states:

$$\mathrm{Re}(\varepsilon) - i\mathrm{Im}(\delta) = \frac{1}{2\left(i\Delta m + \frac{1}{2}\gamma\right)} \times \sum A_{f_L} A^*_{f_S}\,,$$

where $\Delta m = m_L - m_S$, $\gamma = \Gamma_L + \Gamma_S$ and $A_{f_{L,S}}$ are the decay amplitudes to a final state.

The best measurements of Re(ε) and Im(δ) come from CPLEAR [9]: $\mathrm{Im}(\delta)=(2.4\pm5.0)\times10^{-5}$ and $\mathrm{Re}(\varepsilon)=(164.9\pm2.5)\times10^{-5}$. As the uncertainty on these parameters is dominated by the one on η_{000}, a better limit on η_{000} would also improve CPT tests.

NA48 can extract η_{000} by measuring the $K_S - K_L$ interference term in the $K \to 3\pi^0$ decay probability as a function of proper decay time:

$$I_{3\pi^0} \propto \mathrm{e}^{-t/\tau_L} + |\eta_{000}|^2 \mathrm{e}^{-t/\tau_S} + 2D|\eta_{000}|\mathrm{e}^{-t/2(1/\tau_S+1/\tau_L)}\cos(\Delta m t + \phi_{000})\,,$$

where D is the $K^0\overline{K}^0$ dilution at production (about 0.3 for NA48). The oscillation is superimposed to a very large and flat $K_L \to \pi^0\pi^0\pi^0$ component and is mostly contained in a few K_S lifetimes from the target. This loss of sensitivity can however be partly compensated by the very good proper time resolution ($\sim 0.1\ c\tau_{\rm S}$) provided by the combination of high energy beams and high resolution calorimetry.

In order to improve the present limit on η_{000}, high statistics samples of $K \to \pi^0\pi^0\pi^0$ must be collected within a few lifetimes from the target. In addition, excellent knowledge of detector acceptance is required.

In the data taken in 2000, the estimated number of fully reconstructed events in the 90–140 GeV/c^2 range is about $1 \times 10^6/c\tau_{\rm S}$. A preliminary analysis of this data indicates that a limit of about 3% on Re(ε) and Im(δ) could be reached.

4. Prospects for 2002

The CERN Research Board has approved the proposal to run NA48 in 2002 with a slightly modified beam-line to study rare $K_{\rm S}$ decays and neutral hyperons [10]. The changes will consist in the exploitation of a longer SPS duty cycle (5.2 s of spill length every 16.8 s), the insertion of a sweeping magnet at the end of the $K_{\rm S}$ collimator in order to reject photon conversion, and an upgraded readout for drift chambers and electromagnetic calorimeter. This should allow the proton flux on target to be increased to 1×10^{10} protons per pulse, corresponding to about 3×10^{10} $K_{\rm S}$ decays per year in the fiducial volume of the experiment. Assuming an overall acceptance of 5%, the single event sensitivity for $K_{\rm S} \to \pi^0 e^+ e^-$ would be 6×10^{-10}. The expected signal for this decay channel, assuming a branching ratio of 5×10^{-9}, is 7 events/year. The main background, coming from $K_{\rm S} \to \pi^0\pi^0_{\rm D}$, is kept under control (less than 0.3 events/year) by the m_{ee} cut described in Sec. 2.2; other background coming from $K_{\rm S,L} \to e^+e^-\gamma\gamma$ and $K_{\rm S} \to \pi_{\rm D}\pi_{\rm D}$ should be negligible. For what concerns the decay $K_{\rm S} \to \pi^0\pi^0\pi^0$, the experiment should be able to put a bound on η_{000} of about 1%, therefore further improving CPT tests.

Several other $K_{\rm S}$ decays that can be investigated by NA48 are presented in Table I.

TABLE I

Rare $K_{\rm S}$ decay modes. The number of estimated event is calculated considering 3×10^{10} events/year in the NA48 fiducial volume.

Decay mode	BR (exp)	BR (th)	Events/year
$K_{\rm S} \to \gamma\gamma$	$(2.58 \pm 0.42) \times 10^{-6}$	2.25×10^{-6}	24000
$K_{\rm S} \to \pi^0\gamma\gamma$		3.8×10^{-8}	114
$K_{\rm S} \to \pi^0\pi^0\gamma\gamma$		5.6×10^{-9}	7
$K_{\rm S} \to \pi^0\pi^0\pi^0$	$< 1.4 \times 10^{-5}$	2.5×10^{-9}	3

5. Conclusions

The investigation of rare K_S decays by NA48 is providing interesting results for the understanding of Chiral Perturbation Theory and CP violation in the neutral kaon sector. The results obtained in the last two years clearly demonstrate the capability of NA48 to reach high sensitivities in the study of such decays. The run in 2002 will allow NA48 to present very competitive results on this interesting subject.

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