NA48 results on neutral kaon rare decays and prospects for charged kaon physics*

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The NA48 collaboration has performed, with the data collected in the $\mathrm{Re}(\varepsilon'/\varepsilon)$ runs in 1997-99 and in special high intensity $\mathrm{K_S}$ runs, an extensive study of rare decays of $\mathrm{K_L}$ and $\mathrm{K_S}$ as well as hyperon studies. New measurements of the η mass and of the $\mathrm{K_S}$ lifetime have been published.

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1. Introduction

The main goal of the NA48 experiment has been the measurement of $\mathrm{Re}(\varepsilon'/\varepsilon)$ and it has been shown that direct CP violation in neutral kaon decays exists [1][2]. The data taken for this measurement has been used also for a series of studies of rare decays of $\mathrm{K_L}$, $\mathrm{K_S}$ and hyperons.

2. Data taking in 1997-2000

Starting from 1997 to 2000, NA48 has collected millions of $\mathrm{K_L}$, $\mathrm{K_S}$ decays for $\mathrm{Re}(\varepsilon'/\varepsilon)$ measurement. The available bandwidth in the data acquisition system allowed to configure the trigger such that it selected also specific rare decays, like $\mathrm{K_L} \to \pi^0\gamma\gamma$ or Ξ^0 decays.

During each year of run, special runs were also taken, in which a negative pion beam was transported in the path of $\mathrm{K_L}$ beam to a pair of 2 cm polyethylene targets, located inside the fiducial volume of $\mathrm{K_L}$,$\mathrm{K_S}$ decays. These pions generated π^0 and η, whose decays in two and six gammas were used to study the performances and the stability of the response of the liquid krypton calorimeter.

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3. Measurement of the K^0 and η masses

Using the η production from the special runs, it is possible to measure η mass in a way which is independent from the calorimeter energy scale. One can reconstruct the η vertex using the six photons with the relation

$$D_\eta = \frac{\sqrt{\sum E_i E_j d_{ij}}}{M_\eta}$$

and then can compute 3 vertices for each one of the 3 π^0 using

$$D_{vertex} = \frac{d_{12} \cdot \sqrt{E_1 E_2}}{M_{\pi^0}}$$

Equating the decay vertex with the average of the 3 pion vertices, one obtains the η mass as function of the π^0 mass and of the impact coordinates of the photon in the LKr. The measurement is in principle independent from the global energy scale. The high statistics available from $K_L \rightarrow 3\pi^0$ allows systematic checks to validate the η mass measurement. Systematic errors are due to:

- Non linearity in energy measurement: reduced using symmetric decays with $0.7 < (E_\gamma / {<}E_\gamma{>}) < 1.3$
- Non uniformity in the calorimeter response
- Energy leakage from one shower to another
- Non gaussian tails in the energy response mainly due to hadron photoproduction

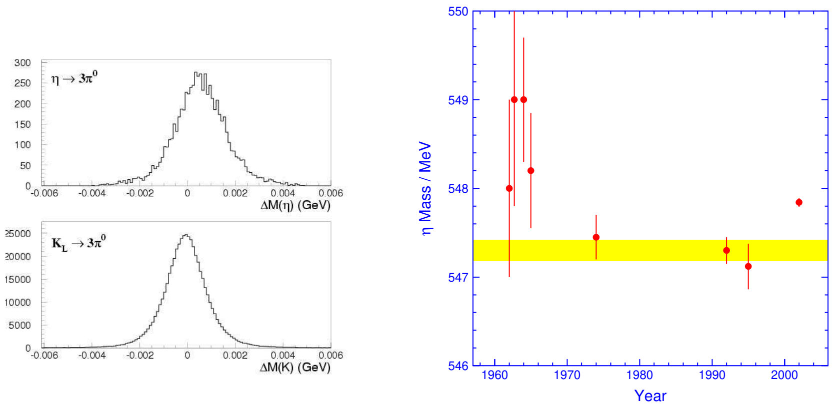

Fig. 1. *Mass distributions for η and K^0 and η mass measurement vs year*

The results are [3]:

- η mass : $547.843 \pm 0.030_{st} \pm 0.045_{sy}$ MeV/c^2
- K^0 mass : $497.625 \pm 0.001_{st} \pm 0.031_{sy}$ MeV/c^2

While the K^0 mass measurement is in agreement with the PDG value (showing no systematic effect in the measurement), the η mass is 4.2 σ off the PDG value with a smaller error.

4. Measurement of Ks lifetime

The K_S lifetime is presently known with a relative precision of about 0.1% dominated by the measurement from NA31 at CERN [4] and from E731 and E773 at Fermilab [5].

With the same data used for $\mathrm{Re}(\varepsilon'/\varepsilon)$ determination, the K_S lifetime has been measured using a method introduced by NA31 [4] which is essentially independent of the detector acceptance. The method consists in fitting the ratio $R = N_S/N_L$

$$R(E_K, z) = A(E_K)\frac{f_S(t_S)}{f_L(t_L)}$$

where E_K is the kaon energy, $A(E_K)$ is a normalisation function which depends on the relative beam intensities and $t_{S,L} = (z - z_{targS,L})/(m_K/p_K)$ are the proper lifetimes for kaon decays in the K_S or K_L beams. The functions $f(t)$ are given by

$$f_{S,L}(t) = e^{-t/\tau_S} + |\eta|^2 e^{-t/\tau_L} + 2D_{S,L}(E_K)|\eta|e^{-(t/\tau_S + t/\tau_L)/2} cos(\Delta_m t - \phi)$$

where τ_S and τ_L are the K_S and K_L mean lifetimes, $\Delta_m = m_L - m_S$ is the mass difference between the K_S and K_L states, $|\eta|$ and ϕ are the modulus and phase of the ratio $A(K_L \to \pi\pi)/A(K_S \to \pi\pi)$ of decay amplitudes, and the dilutions $D_{S,L}$ reflect the initial admixture of K^0 and $\bar{K}^0$ in each beam.

The ratio is fitted in 5 GeV energy bins and 0.1 τ_s lifetime bins. The available statistics for both K_S and K_L is of the order of 12 million events for the charged mode and 3 million events for the neutral one. Fits were performed separately for charged and neutral decays and for each year of run. Background from K_L decays has been subtracted as in $\mathrm{Re}(\varepsilon'/\varepsilon)$ analysis. The measured values for the K_S lifetime for each decay mode and for the two modes combined are [6]

$$\tau_S = (0.89592 \pm 0.00052_{st} \pm 0.00054_{sy}) \cdot 10^{-10}\ \mathrm{s} \qquad (\pi^+\pi^-)$$
$$\tau_S = (0.89626 \pm 0.00129_{st} \pm 0.00100_{sy}) \cdot 10^{-10}\ \mathrm{s} \qquad (\pi^0\pi^0)$$
$$\tau_S = (0.89598 \pm 0.00048_{st} \pm 0.00051_{sy}) \cdot 10^{-10}\ \mathrm{s} \qquad (\pi^+\pi^- + \pi^0\pi^0)$$

The combined result has a precision slightly better than the current PDG average and lies about 1.7 standard deviations above it.

5. Study of the decay $K_L \to \pi^0\gamma\gamma$

$K_L \to \pi^0\gamma\gamma$ decay is important because the decay rate prediction from $O(p^4)$ χPT is finite, but only 2-3 times smaller than the measured one [7]. Going to $O(p^6)$ and including vector meson exchange, the measured rate is reproduced and a tail at low $m_{\gamma\gamma}$ is predicted. The vector meson dominance contribution is parametrized by a_v, to be measured, and the low $m_{\gamma\gamma}$ tail determines the CPC amplitude to the decay $K_L \to \pi^0 e^+e^-$. Predictions from χPT are $BR(K_L \to \pi^0\gamma\gamma) = 1.5\ 10^{-6}$ and a_v = -0.7.

Data from 1998 and 1999 runs were selected using the same trigger as the $K_L \to \pi^0\pi^0$ mode, which has been used as normalization channel. In this way many systematic uncertainties cancel out.

The background from $K_L \to \pi^0\pi^0$ is rejected using invariant mass cuts: one pair of photons should be within 3 MeV from the pion mass, while the other should be outside the 110 MeV-160 MeV window. Transverse momentum of the lowest energy unpaired photon should be greater than 40 MeV/c.

The background from $K_L \to 3\pi^0$ with missing or overlapping photons is rejected on a basis of a variable (z_{max}) designed to estimate the true kaon position. This estimate applied to signal events produces an unphysical result with a distribution mainly populated in the region upstream of the final collimator. The condition $z_{max} <$ -5m rejects $\approx 99\%$ of the $3\pi^0$ background, keeping 46% of the signal.

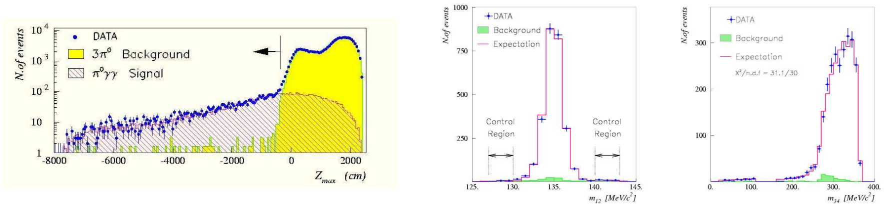

Fig. 2. *Background rejection, events in the signal region and* $m_{\gamma\gamma}$ *distribution*

$\approx$ 2500 events were found in the signal region (132 MeV $< M_{\pi^0} <$ 138 MeV) [8]. Fitting the $M_{\gamma\gamma}$ distribution, one obtains

$$a_v = -0.46 \pm 0.03_{st} \pm 0.03_{sy} \pm 0.02_{th}$$

Using the fitted a_v value, the branching ratio is

$$BR(K_L \to \pi^0\gamma\gamma) = (1.36 \pm 0.03_{st} \pm 0.03_{sy} \pm 0.03_{norm})\cdot 10^{-6}.$$

and the CP conserving part is

$$BR(K_L \to \pi^0 e^+e^-)_{CPC} = (4.7 \pm 2.2)\cdot\ 10^{-13}$$

6. Summary of other analyses

Many other channels were or are being studied by NA48. A lot of PhD theses have been written on these topics. Some of them have been presented and/or published:

- Indirect CP violation in $K_L \to \pi^+\pi^- e^+ e^-$ through the measurement of the asymmetry in the angle between the planes of $\pi^+\pi^-/e^+e^-$. It has been measured that A= $(13.9 \pm 2.7_{st} \pm 2.7_{sy})\%$

- First observation and preliminary branching ratio of $K_S \to \pi^+\pi^- e^+ e^-$ [9]: BR = $(4.5 \pm 0.7_{st} \pm 0.4_{sy}) \cdot 10^{-5}$. The asymmetry in the angle between π and e planes is consistent with zero.

- Upper limit to the branching ratio of $K_S \to \pi^0 e^+ e^-$ [10]: BR $< 1.4 \cdot 10^{-7}$

- Radiative decays and beta decay of the Ξ^0[11] [12]:
  - $M(\Xi^0)=(1314.82 \pm 0.06_{st} \pm 0.20_{sy})$ MeV/c^2
  - BR($\Xi^0 \to \Lambda\gamma$) = $(1.9 \pm 0.2) \cdot 10^{-3}$
  - BR($\Xi^0 \to \Sigma^0\gamma$) = $(3.7 \pm 0.5) \cdot 10^{-3}$
  - 60 events for the decay $\Xi^0 \to \Sigma^+ e^- \nu$

7. The NA48/1 High Intensity Ks proposal

The NA48 Collaboration has been approved [13] for a program of studies of rare K_S and hyperon decays using an high intensity K_S beam. The program includes:

- $K_S \to \pi^0 e^+ e^-$ and $K_S \to \pi^0 \mu^+ \mu^-$ to bound indirect CP violation in the corresponding K_L decay

- Search for CP violation in K_S decay, looking for $K_S \to 3\pi^0$ and $K_S \to \pi^0\pi^+\pi^-$

- Tests of chiral perturbation theory: $K_S \to \gamma\gamma$, $K_S \to \pi^0\gamma\gamma$,$K_S \to \pi^0\pi^0\gamma\gamma$

- Improve NA48 results on $\Xi^0 \to \Sigma^+ e^- \nu$, $\Xi^0 \to \Sigma^+ \mu^- \nu$, $\Xi^0 \to \Sigma^0\gamma$, $\Xi^0 \to \Lambda\gamma$

- Put an upper limit to the double beta decay $\Xi^0 \to p\pi^-$

At the end of 1999 run, a special high intensity run was taken for a total of 40 hours with an intensity of $6 \cdot 10^9$ protons per pulse (a factor 200 wrt the $\mathrm{K_S}$ intensity in $\mathrm{Re}(\varepsilon'/\varepsilon)$ runs), in order to demonstrate the feasibility of an high intensity run.

As in 2000 the spectrometer was being rebuild, a first phase of the high intensity program was started. After running for 40 days, 10^{10} $\mathrm{K_S}$ decays were collected. In the same year a run with only $\mathrm{K_L}$ (far target run) was taken.

8. Study of the decay $\mathrm{K_S} \to \gamma\gamma$

$\mathrm{K_S} \to \gamma\gamma$ is interesting because it is calculable in $\mathrm{O(p^4)}$ χPT with no counterterms and it is sensitive [14] [15] to loops. The theoretical prediction for the BR is $(2.1 \pm 0.2)\cdot 10^{-6}$. NA31 measured [16]

$$\mathrm{BR}(\mathrm{K_S} \to \gamma\gamma) = (2.4 \pm 0.9)\cdot 10^{-6}$$

With the data from the 1999 HIKs run with a dedicated trigger, NA48 has published [17] $\mathrm{BR}(\mathrm{K_S} \to \gamma\gamma) = (2.58 \pm 0.36_{st} \pm 0.22_{sy})\cdot 10^{-6}$.

A better measurement has been performed using data from the 2000 run. The normalisation channel is $\mathrm{K_S} \to \pi^0\pi^0$.

The $\mathrm{K_S} \to \pi^0\pi^0$ background is minimized using a 5 meter fiducial region after the $\mathrm{K_S}$ collimator. These decays with two lost γ have a maximum invariant mass of 458 MeV and the reconstructed vertex cannot be less than 9 meters. This number is reduced to 5 meters because of the effect of overlapping showers. Hadronic interactions in the collimator and accidental $\gamma\gamma$ pairs are eliminated with suitable cuts.

The background from $\mathrm{K_L} \to \gamma\gamma$ is instead irreducible and it amounts to 1.5 times the $\mathrm{K_S}$ channel. The subtraction of this background is done evaluating the $\mathrm{K_L}$ flux using $\mathrm{K_L} \to 3\pi^0$ and measuring $\Gamma(\mathrm{K_L} \to \gamma\gamma)/\Gamma(\mathrm{K_L} \to 3\pi^0)$ using the data from the far target run with $\mathrm{K_L}$ only. For this measurement the detector conditions are similar to the $\mathrm{K_S}$ data taking, so detector systematics cancel. The decay volume is the same as for $\mathrm{K_S} \to \gamma\gamma$ and the acceptance differences almost cancel. Nevertheless, after subtracting hadronic background and evaluating the systematic uncertainties due to acceptance and background subtraction, we obtain an independent measurement:

$$\Gamma(\mathrm{K_L} \to \gamma\gamma)/\Gamma(\mathrm{K_L} \to 3\pi^0) = (2.81 \pm 0.01_{st} \pm 0.02_{sy})\cdot 10^{-3}$$

The total number of $\mathrm{K}_{S,L} \to \gamma\gamma$ is 19916. The global systematic correction is -1.8 $\pm$ 1.4 %. Statistical errors on data and on the Montecarlo sample are respectively 2.0% and 0.6%.

The preliminary result is

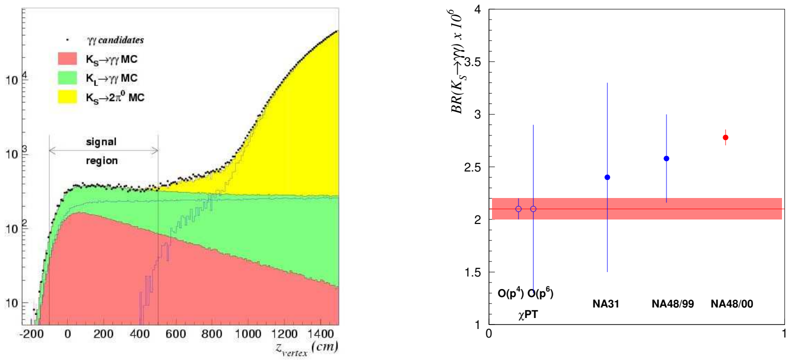

Fig. 3. *Background rejection, theoretical predictions and measured values*

$$\mathrm{BR}(\mathrm{K_S} \to \gamma\gamma) = (2.78 \pm 0.06_{st} \pm 0.02_{MCst} \pm 0.04_{sy}) \cdot 10^{-6}$$

This result is compatible with previous measurements, but it shows a 30% difference wrt to $\mathrm{O(p^4)}$ χPT predictions, indicating a possible large $\mathrm{O(p^6)}$ contribution.

9. Prospects for NA48/1 phase 2

During 2002 the NA48/1 proposal will be completed with the main goal to collect all the charged channels which couldn't be collected in 2000.

The main channel to be studied is $\mathrm{K_S} \to \pi^0 e^+ e^-$ with a Single Event Sensitivity of $2 \cdot 10^{-10}$. About 10 events are expected in the hypothesis that the parameter a_s is 1.

The beam has been upgraded with a magnetic field in the collimator to sweep out charged particles and with a Pt photon converter downstream of the $\mathrm{K_S}$ target. The detector will have a new readout for the DCH which will be able to remove overflow events present in the current readout and an improved readout scheme for the LKr calorimeter which will allow a factor 2 increase in the trigger rated and up to 1 GB/burst data handling.

10. The charged kaon proposal

The study of charged kaon decays, done with high statistics and systematic accuracy, can give new informations about direct CP violation, existence of $q\bar{q}$ condensate of the QCD vacuum, measurement of χPT parameters and detection of possible deviations from V-A theory. A proposal from NA48 has been approved for the year 2003 by the CERN SPSLC[18].

10.1. Direct CP violation in K$^{\pm}$ *decays*

The latest results from NA48 [1] [2] and KTEV [19] have clearly demonstrated direct CP violation in neutral kaon decays. The new world average is higher than the theoretical predictions, which can indicate disagreement with the SM or at least problems in the non-perturbative calculations of the decay matrix element. A measurement of direct CP violation in other processes could therefore be of great relevance. Direct CP violation could manifest itself in particular in an asymmetry of the slope of the Dalitz plot density of events as a function of the kinetic energy of the π^+ and π^- for $K^+ \to \pi^+\pi^+\pi^-$ and $K^- \to \pi^-\pi^-\pi^+$.

The matrix element for these decays could be parametrized as

$$\mid M(u,v) \mid^2 \propto 1 + g \cdot u + h \cdot u^2 + k \cdot v^2$$

where $u = (s_3 - s_0)/m_\pi^2, v = (s_1 - s_2)/m_\pi^2, s_0 = (s_1 + s_2 + s_3)/3, s_i = (P_K - P_i)^2$ and i=3 is the odd pion. The coefficients g, h, k should be equal for the two K charges if CP is conserved. Direct CP violation will show up with a value different from zero of the asymmetry

$$A_g = \frac{g^+ - g^-}{g^+ + g^-}$$

where g^+ and g^- are the above defined coefficients for K$^+$ and K$^-$ respectively.

Theoretical papers [20] [21] [22] [23] [24] predict values for A_g ranging from 10^{-5} to 10^{-4}. The only dedicated measurement, based on $1.6 \cdot 10^6$ events has given $A_g = (-7 \pm 5) \cdot 10^{-3}$ [25]. HyperCP at Fermilab [26] has $2 \cdot 10^8$ K$^-$ decays and twice as many for K$^+$, but it is not specifically studied for high systematic accuracy in K$^{\pm}$ decays.

The experiment will measure the ratio

$$R(u) = \frac{\int dv |M^+(u,v)|^2}{\int dv |M^-(u,v)|^2} \approx 1 + u \cdot (g^+ - g^-)$$

as a function of the variable u.

In order to reduce to the minimum the systematic effects which could simulate an A_g different from zero, we plan to take data using simultaneous overlapping K$^+$ and K$^-$ beams derived from the same target, alternating in sign the spectrometer field to equalize the acceptances in the presence of possible localised imperfections in the detector, binning data in reconstructed kaon momentum and averaging the ratios measured with different magnetic field polarities. Simulation shows that with a proper data analysis, systematics effects could be kept at a level less than few parts in 10^{-5}.

In one year of SPS operation we expect to collect $\approx 10^{10}$ $K^{\pm} \to \pi^{\pm}\pi^+\pi^-$ decays, giving a statistical accuracy of $\approx 10^{-4}$.

10.2. Study of $K^{\pm} \rightarrow \pi^{+}\pi^{-}e^{\pm}\nu$ *decays*

K_{e4} decays allows to verify the hypothesis that chiral symmetry is spontaneously broken by the formation of a strong $q\bar{q}$ condensate in the QCD vacuum. Up to now this hypothesis has no experimental confirmation. The dependence of the π mass on m_u and m_d is analyzed in χPT [27] and leads to the prediction that in the low energy $\pi\pi$ scattering the S-wave is particularly sensitive to the condensate. The interesting parameter in K_{e4} decay is the the S-wave scattering amplitude a_0^0.

The E865 experiment in Brookhaven has published [29] a value $a_0^0 = 0.228 \pm 0.012_{st} \pm 0.003_{sy}$. The NA48 proposal expects to collect more than 10^6 K_{e4} decays in one year, giving an accuracy of less than 0.01 on a_0^0.

10.3. Other decays

The latest measurement of the decay $K^{\pm} \rightarrow \pi^0 e^{\pm}\nu(\bar{\nu})$ gives significant values of the scalar and tensor form factors, indicating a deviation from V-A theory. To test this, the proposed experiment is expected to be at least 3 times more precise than [30].

10.4. The beams and the detector upgrade

To compare K^+ and K^- with the minimum systematic error, a design to transport simultaneously positive and negative beams has been conceived. The primary proton beam hits a target at 0 degrees. The central momentum and the momentum bite are selected symmetrically with a system of magnets and collimators (so called achromats) which then recombine the beams onto a common axis. The optimum momentum will be 60 $\pm$ 6 GeV/c. There will be $3.1 \cdot 10^6$ K^+ and $1.8 \cdot 10^6$ K^- per pulse, which, in one year of running, will give in a 50 m decay region $5.6 \cdot 10^9$ K^+ and $3.3 \cdot 10^9$ K^-. A K_L beam (simultaneous or alternated with the $K^{\pm}$ beams) will be used to monitor potential systematic effects.

The measurement of the K_{e4} decay is unambiguosly determined if the kaon momentum is measured. To do so, it is proposed to install tracking detectors (KABES) in three positions along the beams in the second achromat, to measure the position of the kaons to compute their momentum and direction. High rate capability is needed ($\approx 4 \cdot 10^7$ part/s) together with minimum material along the beam ($\leq 10^{-3} X_0$). It is planned to use a Micromegas like detector [31]. Simulations show that it is possible to get good time and momentum resolution.

Improvement in electron/pion rejection will be achieved with a neural network approach, which could give, together with the E/p cut, a global e/π rejection of $2.8 \cdot 10^{-4}$ with an electron identification efficiency of 94%.

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