Overview of K physics results from NA48

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Besides its main goal of measuring direct CP violation, the NA48 experiment at CERN has performed several accurate measurements of rare K^0 decays, and has an ongoing experimental program in this field. Some results and prospects are briefly summarized.

1. Introduction

The NA48 experiment at CERN was designed to measure direct CP violation in the neutral kaon system. Besides its main goal, the availability of an intense neutral beam and a high-performance detector allow other physics studies to be carried out, mainly concerning rare K^0 and hyperon decays.

The collaboration has recently obtained a new measurement [1] of $\mathrm{Re}(\varepsilon'/\varepsilon)$, based on the analysis of all the data collected so far, while several results on rare K^0 decays have been published and are under study.

2. The experiment and detector

During ε'/ε data-taking, the K_L beam is produced by 1.1×10^{12} protons per SPS spill (2.4 s) of 450 GeV/c momentum impinging on a beryllium target located 126 m upstream of the beginning of the fiducial decay region, while a small fraction of the non-interacting protons (3×10^7 per pulse) is deflected towards a second target, located 6 m upstream of the beginning of the fiducial region, by exploiting *channeling* on a single bent crystal [2]. On its way to this K_S production target, the proton beam crosses an array of thin scintillator counters which measures the time of passage of individual protons with 120 ps resolution, and is used to *tag* the K_L or K_S origin of a decay by comparing the event and proton times. The two neutral beams are separated by 7 cm only in the transverse direction at the beginning of the decay region (120 m from the detector), and they converge towards the centre of the detector at a 0.6 mrad angle.

EM interacting particles are detected in a fine-grained quasi-homogeneous liquid krypton calorimeter, working as an ionization chamber with no gain and longitudinal tower structure [3]. The initial current induced by the ionization drift on copper ribbon electrodes in the $\approx$ 13000 2×2 cm^2 cells is read and continuously flash-digitized at 40 MHz, allowing for a fast response, high-rate capability and good intrinsic time resolution, $\approx$260 ps for photon energies above 20 GeV, with no significant tails. The energy resolution is measured to be $\sigma(E)/E = 3.2\%/\sqrt{E(\mathrm{GeV})} \oplus 90\,\mathrm{MeV}/E \oplus 0.42\%$ and the spatial resolution better than 1.3 mm above 20 GeV.

Charged particles are detected in a magnetic spectrometer, consisting of four large drift chambers and a dipole magnet providing a 265 MeV/c transverse momentum kick. Each chamber [4] has four double planes of staggered wires with $\simeq$ 99.5% efficiency. The momentum resolution is measured to be $\sigma(p)/p = 0.5\% \oplus 0.009\% \cdot p$ (GeV/c). Other detectors used for triggering and background suppression include a plastic scintillator hodoscope, a hadron calorimeter, a set of muon counters and annular veto scintillator counters.

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3. $\Re(\varepsilon'/\varepsilon)$ measurement

Direct CP violation[1] is is measured by the double ratio R of K_L/K_S partial decay widths to $\pi^0\pi^0$ and $\pi^+\pi^-$ final states, which is insensitive in first order to all sources of biases which are common to the two beams or to the two decay modes, being biased only by the small effects affecting just one of the four decay modes, or by the differential component of beam- or detector-related effects.

An asymmetric correction is the one due to backgrounds in K_L modes, due to $K_L \to 3\pi^0$ and $K_{e3}, K_{\mu 3}$ decays; these are reduced to $< 1\times10^{-3}$ and $< 2\times10^{-3}$ respectively by cuts, before being subtracted.

The small asymmetric component of the K_S or K_L mistagging errors is measured through independent tagging methods and corrected for. Trigger efficiencies are continuously monitored and measured to be rather high; only for the $\pi^+\pi^-$ mode (eff. $\approx 97.2\%$) a small correction due to K_S-K_L differences is required, while for the neutral mode (eff. $\approx 99.9\%$) no difference is measurable.

Due to the use of simultaneous beams, R is largely insensitive to accidental effects caused by the high-rate environment, which are measured to be negligible by software data overlay of randomly-triggered events.

As mentioned above, K_S-K_L acceptance differences are minimized by the K_L lifetime weighting approach; small residual differences due to beams' acollinearity and divergence are modeled by two independent Monte Carlo simulations of the apparatus.

Among other small corrections and uncertainties due to e.g. the scattering of K_L on collimators, the control of the detector geometry, an important one is due to the knowledge, stability and linearity of the calorimeter absolute energy scale - directly linked to the longitudinal vertex position for $\pi^0\pi^0$ decays - which is measured by matching the reconstructed positions of well-known detector edges to their nominal values.

The double ratio is measured in the proper lifetime interval (0,3.5 τ_S) and kaon energy interval (70-170 GeV), and the result from the analysis of 1998 and 1999 data (3.3 million $K_L \to \pi^0\pi^0$ decays) after all corrections is $\mathrm{Re}(\varepsilon'/\varepsilon) = (15.0\pm1.7\pm2.1)\times10^{-4}$, where the first error is statistical and the second is systematic (although a part of it is statistical in nature). Combining this result with the published 1997 result [5], one obtains

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (15.3 \pm 2.6) \times 10^{-4}$$

This result by itself confirms the existence of direct CP violation with a significance of 5.9 standard deviations.

4. Rare K^0 decays

During the standard ε'/ε data-taking period (1997-1999), the beam fluxes were $\sim 2 \times 10^7 K_L$ and $\sim 3 \times 10^2 K_S$ per 2.4 s SPS spill, corresponding to $3.2 \times 10^{10} K_L$ and $6.5 \times 10^7 K_S$ decays per year (assuming 10% acceptance).

During this period, rare K_L decays were measured as a byproduct, including $K_L \to e^+e^-\gamma$ [6]:

$$BR(K_L \to e^+e^-\gamma) = (1.06 \pm 0.05) \times 10^{-5}$$

with 6864 events. Other channels which have been studied are $K_L \to e^+e^-\mu^+\mu^-$ ($\sim$ 20 events), $K_L \to \pi^0\gamma\gamma$ ($\sim$ 1400 events, preliminary BR = $(1.36 \pm 0.05) \times 10^{-6}$), $K_L \to \pi^+\pi^-e^+e^-$ ($\sim$ 1400 events, preliminary BR = $(3.1 \pm 0.2) \times 10^{-7}$). Results on $K_L \to e^+e^-e^+e^-$, $K_L \to e^+e^-\gamma\gamma$ and the $K_L \to 3\pi^0$ Dalitz plot slope [7] have also been obtained.

During a two-day test in 1999, the proton beam was steered on the K_S target, resulting in a K_S intensity a factor $\sim$ 200 higher, with no K_L beam. Among the results obtained from this data is the measurement of the $K_S \to \gamma\gamma$ branching ratio, which is an important test of chiral perturbation theory, being calculable to 10% without short-distance corrections. Based on 450 $\gamma\gamma$ events, out of which the K_L component is subtracted, NA48 measured [8]:

$$BR(K_S \to \gamma\gamma) = (2.58 \pm 0.36 \pm 0.22) \times 10^{-4}$$

[1] See the relative talk in the E5 working group.

with $149 \pm 21 K_S$ events; 50% of the uncertainty is due to the knowledge of $\mathrm{BR}(K_L \to \gamma\gamma)$.

The 1999 test-run data also allowed the measurement of the decay plane asymmetry in $K_S \to \pi^+\pi^-e^+e^-$ (detected for the first time in 1998 data [9]), which is found consistent with 0 with ~ 900 events, thus providing a cross-check on the measured CP-violating asymmetry in K_L (preliminary value $(13.9 \pm 2.7 \pm 2.0)\%$).

A search for $K_S \to \pi^0 e^+e^-$ allowed to lower the limit [10] on this branching ratio, expected to be $O(10^{-9})$, which provides a key information to extract the indirect CP-violating contribution to $K_L \to \pi^0 e^+e^-$:

$$\mathrm{BR}(K_S \to \pi^0 e^+ e^-) < 1.4 \times 10^{-7}$$

The same data also provided interesting preliminary results on neutral hyperon decays accessible to NA48, such as $\Xi^0 \to \Lambda\gamma$, $\Xi^0 \to \Sigma\gamma$ and $\Xi^0 \to \Sigma^+ e^- \nu$.

A second 40-day high-intensity run in 2000, unfortunately with no magnetic spectrometer available, allowed the collection of $\sim 10^{10} K_S$ decays, which are being analyzed.

5. Prospects and conclusions

Two additional experimental programs have been approved by CERN for NA48: a high-sensitivity K_S and hyperon rare decays search and a search for direct CP violation in $K^\pm$ decays.

The first program [11] will exploit the increase of K_S beam intensity by a factor ≈ 400 with respect to standard running, with $\sim 1 \times 10^{10}$ proton per pulse, while keeping the rates on detectors within a factor 1.5. The SPS will run with a better duty cycle 5.2/16.8, and an additional magnet after the target will improve the sweeping of charged particles. The single event sensitivity for rare K_S decays should reach $\sim 3 \times 10^{-10}$ (for 10% acceptance).

One of the main goals of the program is the search for $K_S \to \pi^0 e^+e^-$ decay, whose BR is estimated to be $BR = 5.2 \times 10^{-9}|a_s|^2$ with $a_s \sim O(1)$ in chiral perturbation theory, although with no degree of confidence. NA48/2 expects ~ 7 events in 1 year at $a_s = 1$ (5% acceptance), with small backgrounds mainly from $K_{L,S} \to e^+e^-\gamma\gamma$ and $K_S \to \pi^0\pi^0_{\mathrm{Dalitz}}$.

The $K_S \to \gamma\gamma$ decay should be measured with high accuracy, with ~ 24000 events in 1 year, and more than ~ 100 $K_S \to \pi^0\gamma\gamma$ events, with 30% K_L background, should be collected in the same period.

Collecting 1.5×10^6 $3\pi^0$ events per K_S lifetime, the search for $K_S \to 3\pi^0$ decays will allow to put a bound at $\sim 1\%$ on the CP-violating parameter η_{000} in 1 year. The perspectives for hyperon rare decay measurements are summarized elsewhere[2].

The second experimental project [12] approved for running in 2003 will use new simultaneous collinear K^+ and K^- beams, with 60 GeV/c $\pm$ 15% momentum, magnetically selected by a set of two identical achromats. Around $2 \times 10^6 K^+$ and $1 \times 10^6 K^-$ per SPS cycle will be available.

The $K^\pm \to 3\pi$ decay matrix elements can be parameterized in terms of the u, v variables, u being proportional to the kinetic energy of the odd pion in the CM: $|M|^2 \propto 1 + gu + hu^2 + kv^2$. By measuring the slopes $g^\pm$ of the Dalitz plot distributions for $\pi^\pm\pi^+\pi^-$ or $\pi^\pm\pi^0\pi^0$ decays, for the two beams and the two orientations of the spectrometer magnetic field, a double ratio can be formed in which most of the systematic effects cancel, thus allowing a precise measurement of the direct CP-violating asymmetry $A_g \equiv (g^+ - g^-)/(g^+ + g^-)$. With more than $2 \times 10^9 K^\pm$ decays in 1 year, the asymmetry can be measured to better than 2×10^{-4} accuracy. The Standard Model predictions for A_g are mostly very small $(10^{-6} - 10^{-4})$, thus allowing sensitivity to new physics; some super-symmetric models predict $A_g \sim 10^{-4}$ [13].

With the same setup, CP violation can also be investigated in $K^\pm \to \pi^\pm\pi^0\gamma$ decays. Moreover, the experiment will study $K^\pm \to \pi^+\pi^-e^+\nu(\overline{\nu})$ (K_{e4}) decays, important to obtain information on the size of the quark condensate from the measurement of the $\pi^+\pi^-$ elastic scattering length a_0^0. With $10^6 K_{e4}$ events in 1 year, a statistical accuracy of ~ 0.007 on a_0^0 can be achieved.

Possible upgrades of the detectors include the installation of a beam spectrometer to obtain an independent measurement of the $K^\pm$ momentum, allowing an increase in effective acceptance for

[2] See the relative talk in the E5 working group.

3π decays and the avoidance of ambiguities in K_{e4} decays, and of a transition radiation detector to improve electron identification for the K_{e4} measurement.

In conclusion, besides the new important measurement of direct CP violation, a great wealth of results on rare K^0 decays is being obtained, with two programs well under way for further improvements in K_S and hyperon decays and $K^{\pm}$ direct CP violation.

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