A Precision Measurement of ϵ'/ϵ in CP-violating $K^0 \rightarrow \pi\pi$ Decays with the NA48 Experiment at the CERN SPS

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This article describes the NA48 experiment at CERN, in particular the layout of the simultaneous Kaon beams, the K_S -tagging, the magnetic spectrometer and the electromagnetic liquid krypton calorimeter. Some results from early runs, including rare decays, are presented.

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1. Introduction

The experiment aims for the measurement of the double ratio

$$R = \frac{\frac{\Gamma(K_L \rightarrow \pi^0 \pi^0)}{\Gamma(K_S \rightarrow \pi^0 \pi^0)}}{\frac{\Gamma(K_L \rightarrow \pi^+ \pi^-)}{\Gamma(K_S \rightarrow \pi^+ \pi^-)}} = 1 - 6Re(\epsilon'/\epsilon) \quad (1)$$

with a precision of $1 \cdot 10^{-3}$ [2]. This enhancement by a factor of four compared to earlier experiments [3,4] can only be achieved by an increase of the beam intensity and data acquisition rate by one order of magnitude and the simultaneous reduction of systematic uncertainties. The latter can be decreased substantially by concurrent recording of all four decay channels in the double ratio (1). This requires detectors for photons and charged particles, as well as simultaneous K_L and K_S beams with the facility to assign each observed decay to either one of the beams.

NA48 uses a two-target technique where a small fraction of primary protons, collected by a bent crystal, produces the K_S beam at the second target close to the decay region. K_S decays can be tagged by a time coincidence between a proton transported to the K_S target and a decay, observed in the downstream parts of the detector.

This detector, shown in fig. 1, consists of a magnetic spectrometer with two pairs of wirechambers in front and behind a dipole magnet, followed by a scintillator hodoscope, an electromagnetic liquid krypton calorimeter, an iron-scintillator hadron calorimeter and three planes of muon

counters. Seven rings of anticounters (scintillators preceded by 3.5 cm of steel) are installed along the decay region and the detector to veto decays $K_L \rightarrow 3\pi^0$ with photons escaping detection in the calorimeter. Only the last two of these rings are shown in fig. 1.

The requirements for beam intensity and trigger rates (up to 10 kHz) have led to the design of nearly deadtimeless readout electronics where all incoming data are kept for 200 μs in buffer memories. Data are extracted from these buffers and sent to a data merger only in case of a trigger decision, taken during this time.

2. Simultaneous K_L and K_S beams

The K_L beam is derived at 2.4 mrad from a Be-target which is hit by primary protons of 450 GeV energy, delivered from the SPS at an intensity of $\sim 1.5 \cdot 10^{12}$ protons per pulse. It is then defined by a set of three collimators over a length of 120 m before entering the decay region.

Protons passing through the target are subsequently used to produce the K_S component. To obtain similar rates of 2π decays for K_S and K_L in a fiducial volume of about three K_S decay lengths, the proton flux to the K_S target has to be reduced by a factor of $5 \cdot 10^4$. This is achieved by using the channeling effect in a $60 \times 18 \times 1.5$ mm³ Si-monocrystal, bent with 3 m radius of curvature [5]. While most protons traverse the crystal and are absorbed in a beam dump, a small fraction is deflected at 9.6 mrad. The reduction factor can be adjusted by rotating the crystal. The deflected

Figure 1: *The NA48 detector*

protons are then transported to the K_S target, located in front of the final K_L collimator and 72 mm above the K_L beam axis. The K_S beam is derived from this target at 4.2 mrad and collimated over a length of 6 m. An anticounter (preceded by a lead converter), immediately following the collimator, defines the beginning of the decay region. The knowledge of its position allows to fix the energy scale for neutral events, using the decay kinematics.

In order to produce similar illuminations, the two beams converge at the detector. Since the distance between the K_S target and the K_L beam axis is small, the beams are almost collinear, enclosing an angle of 0.6 mrad.

3. K_S Tagging

A set of scintillation counters (fig. 2), installed in the proton beam line between the bent crystal and the K_S target, detects protons for the K_S tagging [6]. Since the total rate of $\sim 3 \cdot 10^7$ protons per pulse would be prohibitive for a sin-

gle counter, the beam area ($3 \times 6 \text{ mm}^2$) is divided among several thin scintillating foils, each with a size of 4 mm along beam direction and 15 mm transverse to the beam. Their width, varying between 200 and 3000 μm , has been adapted to the beam profile in order to obtain an equal rate of $\sim 1 \text{ MHz}$ per counter. 24 foils, alternately arranged horizontally and vertically, are mounted on a precision carbon fiber support. To ensure good efficiency, adjacent scintillators overlap by 50 μm . The scintillation light is fed through air and lightguides into photomultipliers. Two 500-MHz flash ADCs per channel digitize the PM signals with 1 GHz effective sampling rate. A time resolution of 150 ps and double pulse separation down to 5 ns have been achieved with this setup.

4. The magnetic spectrometer

A spectrometer with two pairs of drift chambers on either side of a magnet is used to measure the momenta of charged particles. With a transverse momentum change of 267 MeV/c, produced

Figure 2: The K_S -tagging counters

in the magnet, momentum resolution is limited by multiple scattering to $\Delta p/p = 0.6\%$ for average momenta of 45 GeV/c. Each chamber contains four double-planes with staggered wires to resolve left-right ambiguities, thus providing redundancy in the reconstruction of spacepoints. The wire orientation in the double-planes is horizontal, vertical and under $\pm 45^\circ$ to the horizontal plane. Mounted on octagonal frames, the wires extend over a fiducial region of 2.4 m, except for the inner ones which are intercepted by the central beam pipe [7].

The chambers are read by TDCs which allow concurrent data taking and readout. Time is measured with respect to the experiment clock of 40 MHz. A delay chain with 16 elements, stabilized to the clock period by a phase locked loop, subdivides each clock cycle into bins of 25ns/16. In each plane, a fast reset logic sums up the number of hits recorded within 200 ns and clears the intermediate FIFOs in all TDC chips of this plane in case of a high instantaneous multiplicity. Incoming hits are stored with wire number and time of arrival in a buffer memory. From these data, the decay vertex and $\pi\pi$ invariant mass are reconstructed in a first trigger stage, using an array of lookup tables and fast processors. Rejection of

events with a mass incompatible with a K^0 decay allows to reduce K_L three-body background by a factor of 3.5 before the final level-2 trigger.

The drift chambers achieve a spatial resolution of 110 μm for track coordinates, resulting in a resolution of $\Delta m_K = 2.9 \text{ MeV}/c^2$ for the $\pi^+\pi^-$ invariant mass (fig. 3).

Figure 3: $\pi\pi$ invariant mass for charged decays, measured in a K_S beam

5. The liquid krypton calorimeter

The liquid krypton calorimeter combines the advantages of a liquid detection medium – radiation hardness, no signal amplification and therefore purely electronic calibration procedures, etc. – with the excellent energy resolution of a total absorption calorimeter. It consists of 13500 cells, arranged in an octagon, with the cells pointing towards the center of the fiducial decay region (fig. 4). The depth of 125 cm represents 25 radiation lengths.

The lateral width of an electromagnetic shower is characterized by the Moliere radius ($L_M = 4.7 \text{ cm}$ in liquid krypton). A resolution of 1 mm on the impact point can be achieved with a cell size of $2 \times 2 \text{ cm}^2$. The cells are formed by 1.8 cm wide and 40 μm thick CuBe-ribbons, stretched between the front and the end plate and

Figure 4: *Perspective view of the LKr calorimeter*

guided in a slight zigzag-structure by five intermediate vetronite spacer frames (fig. 5). Nonuniformities in the detector response are caused by the small 2 mm gap between adjacent vertical ribbons and by a signal loss due to the finite integration time of the readout electronics for shower impacts close to the anodes. Both effects are of the order 1 to 2% and can be corrected for.

The calorimeter is read by 10-bit flash-ADCs operated at 40 MHz. The required dynamic range from 3.5 MeV to 50 GeV is obtained by a gain-switching amplifier with four different gain ranges before the FADCs [8]. Gain switching is done “on the fly”, according to the actual pulseheight. It is however ensured that three consecutive samples around the pulse maximum are taken with the same gain factor.

The energy-, position- and space resolutions of this novel detector have been measured with a prototype [9]. Fig. 6 shows the $\pi\pi$ invariant mass of decays $K_S \rightarrow \pi^0\pi^0$, obtained with the final calorimeter in a testrun in 1996. Due to missing readout electronics, only the energy sums in groups of 2×8 channels were available. With

Figure 5: *Detail of cell structure and electrode guidance*

the complete readout, which is now installed, the mass resolution is expected to increase significantly.

6. Results from early runs

The following three results have been obtained among others from a first run in 1995 when all detector components, except for the liquid krypton calorimeter, were installed.

1.) The branching ratio of the rare decay $K_L \rightarrow \mu\mu\gamma$ was determined[10]. The result

$$\Gamma(K_L \rightarrow \mu\mu\gamma) = (3.9 \pm 0.7(stat)^{+0.6}_{-0.5}(sys)) \cdot 10^{-7}$$

is in agreement with earlier measurements.

2.) A new value for $|\eta_{\pm}|$ was derived from the branching ratio $\Gamma(K_L \rightarrow \pi^+\pi^-)/\Gamma(K_{e3})$ [11]. The accuracy of the obtained result

$$|\eta_{\pm}| = (2.25 \pm 0.019_{stat.} \pm 0.029_{sys.}) \cdot 10^{-3}$$

is comparable with the best measurements so far.

Figure 6: $\pi\pi$ invariant mass for neutral decays, measured in a K_S beam

3.) The radiative decay $K_L \rightarrow \pi\mu\nu\gamma$ was measured for the first time [12]. The branching ratio for a cut on $E_\gamma > 30$ MeV in the kaon restframe

$$\frac{\Gamma(K_{\mu 3\gamma})}{\Gamma(K_{\mu 3})} = (2.08 \pm 0.17_{stat.}^{+0.16}_{-0.21 syst.}) \cdot 10^{-3}$$

is in good agreement with theoretical predictions.

7. Conclusions and schedule

The complete detector is operational and working according to the expectations at the time of this report. Data taking has started in August and continues until middle of October. The analysis will start immediately after the run, a first result is expected for next year.

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Discussions

M. Jamin, Inst. Theor. Phys., Heidelberg
When will the designed accuracy of $\sim 2 \cdot 10^{-4}$ for ϵ'/ϵ be reached?

M. Bender

The designed accuracy requires 2-3 years with 120 effective days of data taking per year, starting from this year.

A.P. Contogouros, University of Athens

Near the end of your talk you gave a result on the branching ratio of $K_L \rightarrow \pi\mu\nu\gamma$ over $K_{\mu 3}$ and you said it agrees with some theoretical calculation. Which was the basis of that calculation and what is the significance of your agreement?

M. Bender

Calculations using chiral perturbation theory in next-to-leading-order have been performed some years ago [13]. They are compatible with earlier predictions from soft-photon theorems and current algebra [14]. The experimental result agrees with both predictions within one standard deviation.