ε'/ε Measurement by NA48 at CERN

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The NA48 experiment at CERN has performed a new accurate measurement of direct CP violation in the K^0 system. Technique and results are briefly summarized.

1. Introduction

Although the breakdown of CP symmetry and time-reversal symmetry in the neutral kaon system is mainly manifested in the mixing of the two CP eigenstates [1], parametrised by $|\varepsilon| = (2.271 \pm 0.017) \cdot 10^{-3}$, in the context of the Standard Model *direct* CP violation in the decay amplitudes $K_L \to 2\pi$, parametrised by ε', is also predicted. The flavour structure and accidental cancellations result in a large suppression of direct CP violation, computations of ε'/ε in the SM (see e.g. [2]) mostly falling in the range $(0 \div 10) \cdot 10^{-4}$.

The relevance of the measurement of a non-zero value for ε' lies in the experimental proof of CP violation being a general phenomenon of nature through weak interactions, while indirect CP violation could be described by a "superweak" interaction [3], resulting in observable effects mostly limited to the neutral kaon system.

The two previous ε'/ε experiments were only marginally consistent: NA31 at CERN [4] measured $(23.0 \pm 6.5) \cdot 10^{-4}$, showing evidence of direct CP violation, while E731 at FNAL [5] measured $(7.4 \pm 5.9) \cdot 10^{-4}$, consistent with no effect. Recent results from Fermilab experiment E832 (KTeV) [6]: $(28.0 \pm 4.1) \cdot 10^{-4}$ and NA48 at CERN [7]: $(18.5 \pm 7.3) \cdot 10^{-4}$, based on part of the collected statistics, support the presence of direct CP violation.

The NA48 collaboration at CERN has recently obtained a new measurement [Lai et al.] of $\mathrm{Re}(\varepsilon'/\varepsilon)$, based on the analysis of the sample collected so far (in 1998 and 1999), which is briefly summarized here.

2. The experiment

The measured quantity is the double ratio of decay widths

$$R \equiv \frac{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)}{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)} \simeq 1 - 6\,\mathrm{Re}(\varepsilon'/\varepsilon)$$

For what concerns the statistical precision, the limiting mode is the CP violating decay $K_L \to \pi^0\pi^0$, 3.3 million of which have been collected by NA48 in 1998–1999.

The double ratio measurement exploits the cancellation of several effects, thus allowing a good control of systematic uncertainties. The general philosophy of the NA48 experiment is to maximize these cancellations in order to minimize the magnitude of the corrections which have to be applied to the measured double ratio.

The absolute knowledge of kaon fluxes, detection and triggering efficiencies, dead-times, and effects due to accidental activity in the detectors are not required, and only differential effects between K_L and K_S or $\pi^+\pi^-$ and $\pi^0\pi^0$ decay modes are relevant.

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K_L and K_S decays are provided by two quasi-collinear neutral beams, produced by protons hitting two targets at different distances from the detector (see Figure 2). The K_L and K_S decay momentum spectra are made similar by the choice of proton targeting angles, and residual differences are irrelevant for the analysis which is performed in small bins of kaon energy.

The background is due almost exclusively by other kaon decay modes, and is only present for the K_L, generating a potential bias if not subtracted. To keep the level of background subtraction very low, high performance detectors are used.

The unavoidable difference in longitudinal decay position spectra of the two beams, due to the different lifetime of K_S and K_L, leads to asymmetric differences between charged and neutral modes due to the different dependence of detector acceptance on the longitudinal decay position for the two modes. This would lead to a very large acceptance correction to the measured double ratio, which would require relying on very accurate modeling and simulations of the apparatus. This issue is addressed in NA48 by collecting K_L and K_S decays only in the region where both are present, and by weighting the K_L events with a function of their proper time of decay. In such a way, at the loss of some statistical power ($\approx$ 35%), the longitudinal decay position distributions are made equal for 2π decays originating from either beam, achieving a good cancellation of acceptance differences, and thus avoiding large corrections.

The K_L beam is produced by $1.1 \cdot 10^{12}$ 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.

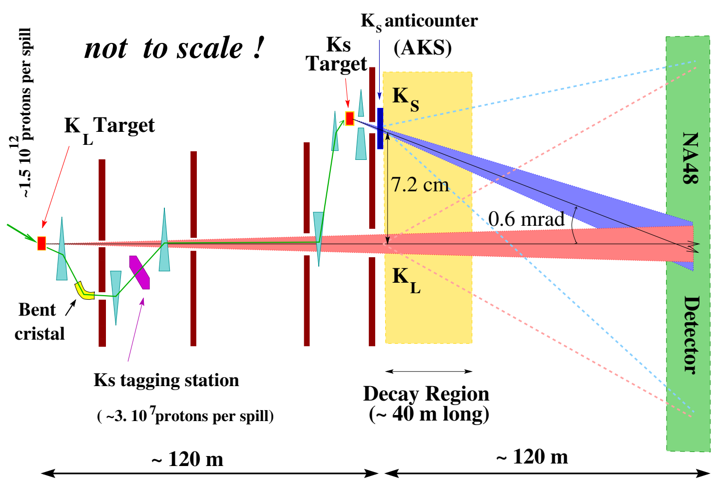

Figure 1: Schematic drawing of the NA48 beam setup.

A small fraction of the non-interacting protons ($3 \cdot 10^7$ 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 [8]. 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 nature 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. Large fluxes of neutrons and photons are present in both beams, but they always stay within an evacuated beam pipe crossing all detectors and are therefore not an issue.

3. Detector and performance

$K_{L,S} \to \pi^0\pi^0$ decays are detected in a fine-grained quasi-homogeneous liquid krypton calorimeter, working as an ionization chamber with no gain and longitudinal tower structure [9]. By exploiting projective geometry, the calorimeter allows to measure angles between photons independently of their initial conversion depth.

The initial current induced by the ionization drift on copper ribbon electrodes in the ≈ 13000 2×2 cm^2 cells is read and continuously flash-digitized at 40 MHz, allowing for a fast response and an intrinsic time resolution ≈ 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, resulting in a π^0 mass resolution below 1 MeV/c^2.

The main detector for $K_{L,S} \to \pi^+\pi^-$ decays is a magnetic spectrometer, consisting of four large drift chambers and a dipole magnet providing a 265 MeV/c transverse momentum kick. Each chamber 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), resulting in a K^0 mass resolution of 2.5 MeV/c^2. Event time for $\pi^+\pi^-$ decays is measured by a scintillator hodoscope. Other detectors are used for background suppression.

4. Data analysis

The double ratio R is measured in the proper lifetime interval (0,3.5 τ_S) and kaon energy interval (70–170 GeV). R is insensitive in first order to all sources of biases which are common to the two beams or to the two $\pi\pi$ charge 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.

Mistagging of the K_S or K_L nature of events can give a bias only if this is different for the two decay modes. For charged mode decays, the decay vertex vertical position resolution is good enough to identify the beam to which a decaying K belongs without ambiguities; this independent tagging information is used to measure and study the time-based mistagging probabilities.

The presence of an accidental proton in the secondary proton beam line (30 MHz rate), close in time to a K_L decay, leads to the mistagging of the decay as a K_S: this happens for $(10.649 \pm 0.008)\%$ of the K_L events but leads to no first-order bias on R, being *a priori* the same for charged and neutral decays. A very small effect is induced by the rate dependence of the charged trigger inefficiency, and is corrected for.

A related potential bias is due to proton tagging inefficiencies or time reconstruction tails, resulting in a K_S event being mistagged as K_L. Redundant time information shows that most of the effect is due to inefficiencies of the tagger detector itself (decay mode symmetric); the charged-neutral asymmetric component of this effect is measured in several independent ways to be negligible.

Trigger efficiencies were measured by using data continuously collected with less restrictive independent trigger conditions; for the charged mode (eff. $\approx 97.2\%$) a small correction due to K_S-K_L differences is applied, while for the neutral mode (eff. $\approx 99.9\%$) no difference is measured.

To reconstruct $\pi^0\pi^0$ events, the longitudinal vertex position is computed from the measured energies and positions of the four clusters in the calorimeter, assuming K^0 decay kinematics; this leaves 2 constraints available (the two π^0 masses) to suppress the background, the residual level of which is measured to be $< 0.1\%$. Being the longitudinal decay position directly linked to the absolute energy scale, the latter is fixed by matching the reconstructed position of a veto counter edge located at the beginning of the fiducial decay region. This scale factor is is known and stable to better than $5 \cdot 10^{-4}$, and is cross-checked by using events produced at a well-known longitudinal position during special runs.

The background in the charged mode due to K_L semi-leptonic decays is reduced by an E/p cut and by using the muon veto counters; further cuts on the reconstructed $\pi^+\pi^-$ invariant mass and on a rescaled K transverse momentum, result in a background below 0.2%.

Due to the use of simultaneous beams, R is largely insensitive to accidental effects caused by the high-rate environment, and moreover the two beams' intensities are measured to be highly correlated in time. Accidental effects are studied mainly by software overlaying randomly triggered events (proportional to beam intensities) to normal events; no effect due to K_S-K_L differences is measured. Losses of $\pi^+\pi^-$ events due to trigger dead-time or missing drift chambers' data in case of high hit multiplicity are continuously monitored and recorded on an event-by-event basis, allowing for symmetric $\pi^0\pi^0$ rejection to avoid any biases.

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.

Other small effects due to e.g. the scattering of K_L on collimators, energy scale non-linearities, etc. are measured and corrected for (Table I).

Table I Corrections to R and their systematic uncertainties.

	Correction	Uncertainty (10^{-4})
Mistagging probability	+8.3	± 3.4
Tagging inefficiency	0	± 3.0
Charged trigger eff.	-3.6	± 5.2
Neutral background	-5.9	± 2.0
Charged background	+16.9	± 3.0
Beam scattering	-9.6	± 2.0
Accidental activity	0	± 4.4
Energy scale/linearity	0	± 5.8
Charged vertex scale	+2.0	± 2.8
Veto counter ineff.	+1.1	± 0.4
Acceptance	+26.7	± 5.7
Total	+35.9	± 12.6

5. Result and conclusions

The result from the analysis of 1998 and 1999 data after all corrections is

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (15.0 \pm 1.7 \pm 2.1) \cdot 10^{-4}$$

where the first error is statistical and the second is systematic (although a part of it is statistical in nature). Combining with the published 1997 data ($0.5 \cdot 10^6 K_L \to \pi^0\pi^0$ decays) one obtains

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

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

The world average (after rescaling the errors as required by the PDG [10]) is now $\mathrm{Re}(\varepsilon'/\varepsilon) = (17.3 \pm 2.4) \cdot 10^{-4}$, with $\chi^2 = 5.65/4$ *d.o.f.* (see Figure 2).

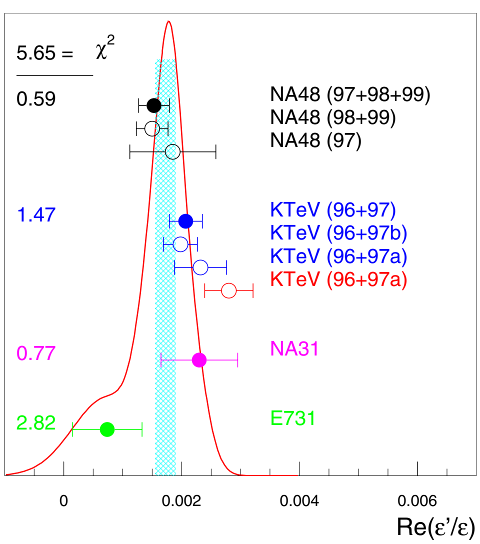

Figure 2: Compilation of $\Re(\varepsilon'/\varepsilon)$ results

This measurement adds a key element to our knowledge of nature, and represents a constraint for any present or future theoretical model of particle physics.

The running of NA48 in 2000 and 2001 has been devoted to further systematic studies, while an upgrade program to study rare K_S decays and direct CP violation in $K^{\pm}$ decays has been approved by CERN for 2002–2003.

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