CP violation results on Kaons by the NA48 experiment

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Recent results on CP violation on kaons by the CERN NA48 experiment will be discussed. A preliminary measurement of the charge asymmetry in $K_L \to \pi^{\pm} e^{\mp} \nu$ has been made: $\delta_L^e = (3.317 \pm 0.070_{stat} \pm 0.072_{syst}) \times 10^{-3}$. A search for $K_S \to 3\pi^0$ decays has been performed with a preliminary estimation of the real and imaginary part of the η_{000} parameter: $Re(\eta_{000}) = (-2.6 \pm 1.0_{stat} \pm 0.5_{syst}) \times 10^{-2}$ and $Im(\eta_{000}) = (-3.4 \pm 1.0_{stat} \pm 1.1_{syst}) \times 10^{-2}$. The angular asymmetry in $K_L \to \pi^+ \pi^- e^+ e^-$ has been measured to be $A_\phi^L = (14.2 \pm 3.0_{stat} \pm 1.9_{syst})\%$, while no asymmetry has been observed in $K_S \to \pi^+ \pi^- e^+ e^-$: $A_\phi^S = (0.5 \pm 4.0_{stat} \pm 1.6_{syst})\%$. Finally, the direct CP violation in $K_{S,L} \to 2\pi$ has been clearly settled, with $Re(\epsilon'/\epsilon) = (14.7 \pm 2.2) \times 10^{-4}$.

1. INTRODUCTION

Neutral Kaons were the place where CP violation was discovered for the first time. NA48 is an experiment dedicated to the precise study of CP violation in the neutral Kaon system: its beam setup is made of two neutral beams [1], one dominated by K_L decays, the other by K_S decays.
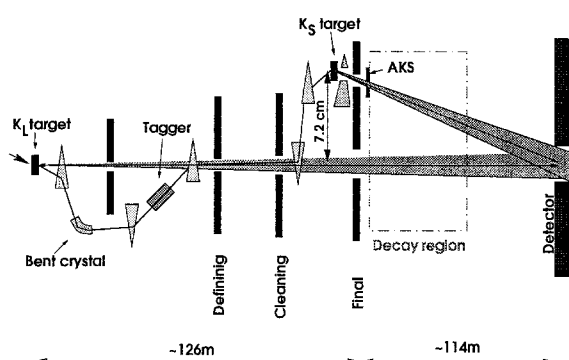
1.1. The beam setup

Figure 1. The NA48 beam setup.

A primary proton beam from the CERN Su-

per Proton Syncroton impinges, with a nominal flux of 1.5×10^{12} particles per spill, on a beryllium target ("far target") 40 cm long and 2 mm wide; after a magnet sweeping sector and several stages of collimation, a neutral beam is formed. The exit face of the last collimator is located 126 m downstream of the target, at the entrance of the fiducial kaon decay region.

The primary protons which have not interacted in the target are deflected towards a bent silicon crystal: a small fraction of these protons is channeled by the crystal and form a secondary proton beam which is transported towards a second beryllium target ("near target"); after only 6 m of magnet sweeping and collimation another neutral beam is formed.

The two neutral beams can be present at the same time ("simultaneous beam runs") or one per time ("far target run" or "near target run") if only K_L or K_S decays have to be studied.

The secondary proton beam is usually at much lower intensity (about 3×10^7 particles per spill) with respect to the primary one. In some special runs ("High Intensity K_S runs") the primary proton beam is sent directly to the second target, removing the first target and by-passing the silicon crystal; the proton beam is attenuated and collimated to the desired intensity far upstream of the second target.

*on behalf of the NA48 collaboration
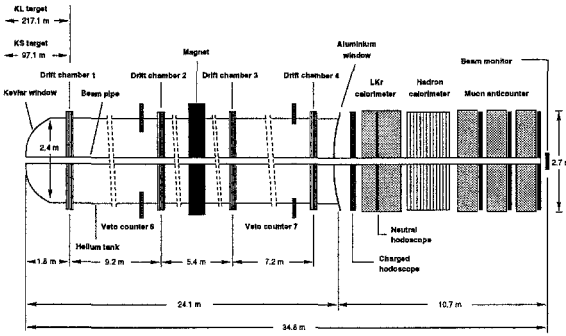
1.2. The Detectors

Figure 2. The NA48 detectors.

The detectors are located downstream of the kaon decay volume which lies inside a large, 90 m long, vacuum tank terminated by a 0.3% radiation lenghts thick Kevlar window; starting at the center of the Kevlar window, a 16 cm diameter vacuum beam pipe traverses all the detectors to let the neutral beam pass through vacuum.

Charged particles are detected using a high resolution magnetic spectrometer which consists of a dipole magnet with a horizontal transverse momentum kick of 265 MeV/c and a set of four drift chambers, two of them located upstream of the magnet and two downstream. The magnetic spectrometer is contained inside a tank filled with helium in order to reduce multiple scattering. The momentum resolution is:

$$\frac{\sigma_p}{p}(\%) = 0.48 \oplus 0.009\,p \text{ (p in GeV/c)} \qquad (1)$$

A quasi-homogeneous liquid krypton (LKr) calorimeter is located downstream of the spectrometer. This detector has a 127 cm long projective tower structure which is made of copper-beryllium ribbons extending between the front and the back of the calorimeter with a ±48 mrad accordion geometry. The 13212 readout cells each have a cross-section of 2×2 cm². The energy resolution is:

$$\frac{\sigma_E}{E}(\%) = \frac{3.2}{\sqrt{E}} \oplus \frac{9.0}{E} \oplus 0.42 \text{ (E in GeV)} \qquad (2)$$

Two planes of scintillators, segmented in horizontal and vertical slabs, form the charged hodoscope, located in between the magnetic spectrometer and the LKr calorimeter; it is used for triggering and measuring the time of charged particles.

Behind the LKr electromagnetic calorimeter, a 6.7 nuclear interaction lenght thick hadronic calorimeter is located, followed by a set of three planes of muon veto counters.

1.3. Data samples

Section 2 is based on data collected with the "simultaneous beams" setup in the year 1999.

Section 3 is based on data collected in the year 2000 with a 40 days long "near target high intensity run" and a 40 days long "far target run". The magnetic spectrometer was not present in these two runs.

Section 4 is based on data collected with the "simultaneous beams" setup in the year 1998 and 1999 and with the "near target" setup in a 2 days long high intensity run in 1999.

Section 5 is based on data collected with the "simultaneous beams" setup in the year 1997, 1998, 1999 and 2001.

2. CHARGE ASYMMETRY IN $K_L \rightarrow \pi^\pm e^\mp \nu$

The charge asymmetry in K_{e3} decays is defined as

$$\delta_L^e \equiv \frac{\Gamma(K_L \rightarrow \pi^- e^+ \nu_e) - \Gamma(K_L \rightarrow \pi^+ e^- \bar{\nu}_e)}{\Gamma(K_L \rightarrow \pi^- e^+ \nu_e) + \Gamma(K_L \rightarrow \pi^+ e^- \bar{\nu}_e)} \qquad (3)$$

If CPT symmetry holds, this observable is equal to $2\mathrm{Re}(\epsilon)$.

During the 2001 run about 2×10^8 K_{e3} decays have been collected, along with $\pi\pi$ samples for $\mathrm{Re}(\epsilon\prime/\epsilon)$ measurement. The systematic effects due to detector asymmetry are reduced by regular changes of the spectrometer magnet polarity. The backgrounds could be reduced to a negligible level by selection cuts. The main source of systematic uncertainties arises from charge dependent interactions of $\pi^\pm$ in the electromagnetic calorimeter which are reflected in asymmetric trigger and particle identification efficiency (Table 1).

Table 1: Systematic corrections to δ_L^e

	in 10^{-5}
Trigger	$+26.2 \pm 6.0$
Punch trough	-1.4 ± 3.5
Pion ID	-17.1 ± 2.4
Acceptance	± 0.5
Background	± 0.5

The corrections are calculated using various control samples involving charged pions, like $K_S \to \pi^+\pi^-$ and $K_L \to \pi^+\pi^-\pi^0$.
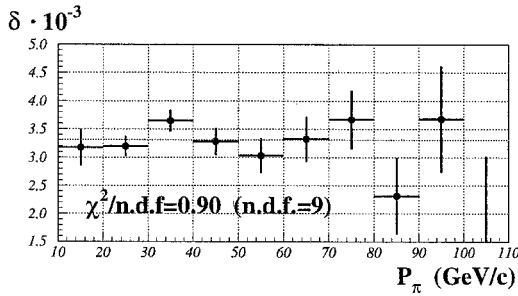
Figure 3. δ_L^e as a function of pion momentum.

The charge asymmetry in K_{e3} decays, after all the corrections, is shown in Fig.3 in bins of pion momentum.

The preliminary result is

$$\delta_L^e = (3.317 \pm 0.070_{stat} \pm 0.072_{syst}) \times 10^{-3} \quad (4)$$

which is in good agreement with previous measurements [2].

3. SEARCH FOR $K_S \to 3\pi^0$

The CP violating parameter η_{000} is defined as

$$\eta_{000} \equiv \frac{A(K_S \to \pi^0\pi^0\pi^0)}{A(K_L \to \pi^0\pi^0\pi^0)} \quad (5)$$

If CPT symmetry is conserved, the real part of η_{000} is given by CP violation in mixing and is equal to $Re(\epsilon)$ while the imaginary part can be sensitive to direct CP violation.

The data for this measurement has been collected during the last period of 2000 data taking in special conditions with high intensity near target beam and without the spectrometer. Almost 6.5×10^6 $K^0 \to \pi^0\pi^0\pi^0$ events have been collected. This data is normalized to pure $K_L \to \pi^0\pi^0\pi^0$ sample from far-target beam run (about 155×10^6 events) immediately preceding the near-target run in practically the same detector conditions, which lead to cancellation of the acceptance in the first order. The result is obtained from a fit to a function

$$f(E,t) = \frac{I_{3\pi^0}^{near}}{I_{3\pi^0}^{far}} = A(E)[1 + |\eta_{000}|^2 e^{t/\tau_L - t/\tau_S}$$

$$+ 2D(E)e^{t/2\tau_L - t/2\tau_S}(Re(\eta_{000})\cos(\Delta mt)$$

$$- Im(\eta_{000})\sin(\Delta mt))] \quad (6)$$

in kaon energy E and proper time t bins. The $D(E)$ denotes $K^0 - \bar{K}^0$ production asymmetry (dilution) at the target and is fixed to the values measured by NA31 [3].
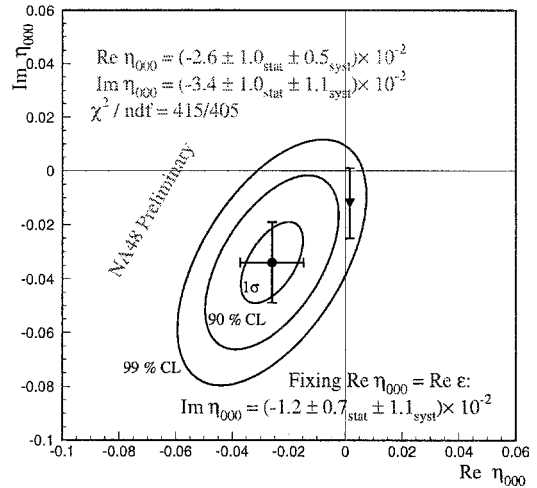
Figure 4. Preliminary result of the η_{000} fit.

The fit results in (Fig.4)

$$Re(\eta_{000}) = (-2.6 \pm 1.0_{stat} \pm 0.5_{syst}) \times 10^{-2} \quad (7)$$

$$Im(\eta_{000}) = (-3.4 \pm 1.0_{stat} \pm 1.1_{syst}) \times 10^{-2} \quad (8)$$

The systematic uncertainties are summarised in Table 2.

Table 2: uncertainties in η_{000}

	in 10^{-2}	
	$Re(\eta_{000})$	$Im(\eta_{000})$
Accidentals	±0.1	±0.6
Energy scale	±0.1	±0.1
$K^0 - \bar{K}^0$ dilution	±0.3	±0.4
Acceptance	±0.3	±0.8
Binning	±0.1	±0.2
Total	±0.5	±1.1

The uncertainty of this preliminary measurement is ten times smaller than the best previously published result by CPLEAR [4].

Assuming CPT conservation and fixing the real part of η_{000} to $Re(\epsilon) = 1.6 \times 10^{-3}$, the imaginary part of η_{000} can be constrained with better precision to

$$Im(\eta_{000}) = (-1.2 \pm 0.7_{stat} \pm 1.1_{syst}) \times 10^{-2} \quad (9)$$

This corresponds to $BR(K_S \to \pi^0\pi^0\pi^0) < 3.0 \times 10^{-7}$ at 90% CL. This result improves by two orders of magnitude the best limit obtained by the SND collaboration [5].

4. ANGULAR ASYMMETRY IN $K_L \to \pi^+\pi^-e^+e^-$

The $K_L \to \pi^+\pi^-e^+e^-$ decay is dominated by the CP-violating inner bremsstrahlung (IB) term and by the CP-conserving direct M1 emission (DE) graph. The interference between the IB (CP=+1) and the DE (CP=−1) amplitudes produces a CP-violating circular polarization of the γ^*. If ϕ is the angle between the e^+e^- and $\pi^+\pi^-$ planes, the following asymmetry can be measured:

$$A_\phi^L = \frac{N_{\sin\phi\cos\phi>0} - N_{\sin\phi\cos\phi<0}}{N_{\sin\phi\cos\phi>0} + N_{\sin\phi\cos\phi<0}} \quad (10)$$

The prediction by the Heiliger and Sehgal[6] model is $A_\phi \approx 14\%$.
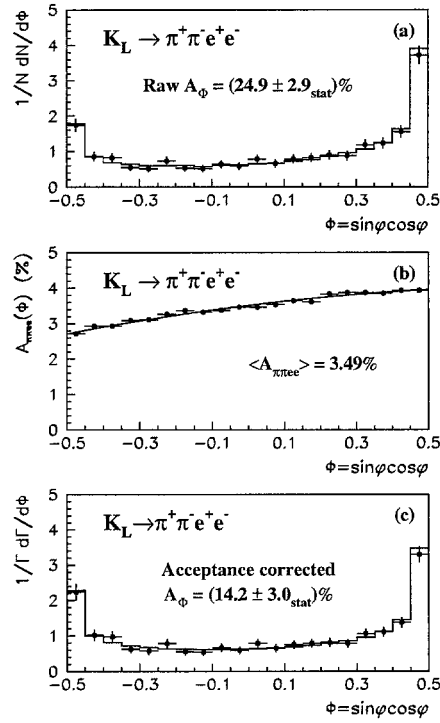

Figure 5. Distribution of $K_L \to \pi^+\pi^-e^+e^-$ events in the angular variable $\sin\phi\cos\phi$ before(a) and after(c) acceptance corrections. The histograms are Monte Carlo predictions. Acceptance as a function of $\sin\phi\cos\phi$ (b); the solid line is a polynomial fit to the Monte Carlo calculation.

1162 $K_L \to \pi^+\pi^-e^+e^-$ candidates have been selected in data collected in 1998 and 1999. The angular asymmetry before any acceptance correction is $(24.9 \pm 2.9_{stat})\%$. The measured A_ϕ^L, obtained in a model-dependent way by taking into account the acceptance correction is[7]:

$$A_\phi^L = (14.2 \pm 3.0_{stat} \pm 1.9_{syst})\% \quad (11)$$

and it is a clear signature of indirect CP violation.

The $K_S \to \pi^+\pi^-e^+e^-$ decay is dominated by the CP-conserving inner bremsstrahlung (IB) term only and no angular asymmetry is expected:
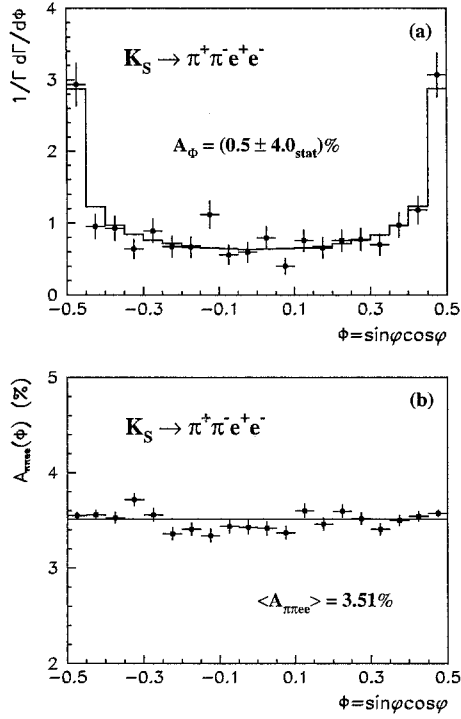
Figure 6. Distribution of events(a) and acceptance(b) for $K_S \to \pi^+\pi^-e^+e^-$ decays as a function of $\sin\phi\cos\phi$. The histogram in (a) is the Monte Carlo prediction. The solid line in (b) represents the average value of the acceptance.

it is an important cross-check of the K_L analysis. Since no interference term is present in the amplitude of this decay mode, the acceptance correction is uniform over the entire $\sin\phi\cos\phi$ domain. Based on the data collected in 1999 the asymmetry is[7]:

$$A_\phi^S = (0.5 \pm 4.0_{stat} \pm 1.6_{syst})\% \qquad (12)$$

which is compatible with a null asymmetry and gives confidence that A_ϕ^L is not generated by detector effects.

5. DIRECT CP VIOLATION IN $K_{S,L} \to 2\pi$

The double ratio of decay widths of K_S and K_L into 2 pions is given by:

$$R = \frac{\frac{\Gamma(K_L \to \pi^0\pi^0)}{\Gamma(K_S \to \pi^0\pi^0)}}{\frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)}} = 1 - 6Re\left(\frac{\epsilon\prime}{\epsilon}\right) \qquad (13)$$

If the four modes are taken in the same decay region and simultaneously, R reduces to the double ratio of the number of decays. The data have been collected in the years 1997, 1998, 1999 and 2001. The main aim of the 2001 run was not only to add more statistics to the already published $Re(\epsilon\prime/\epsilon)$ result [8] but also to perform additional systematic checks. This was possible due to several changes in the experimental conditions (Table 3).

Table 3: Change in conditions of 2001 run

	98-99	2001
proton energy	450 GeV	400 GeV
SPS cycle time	14.4 s	16.8 s
spill lenght	2.4 s	5.2 s
effective s.l.	1.7 s	3.6 s
duty cycle	0.17	0.31
K_L beam intensity (ppp)	1.5×10^{12}	2.4×10^{12}
K_S beam intensity (ppp)	3×10^7	5×10^7

Besides rebuilt drift chambers and change in the beam energy, a significant increase of the duty cycle allowed to collect 29% of the total statistics with reduced instantaneous beam intensity. The fact that the result is fully compatible with the one obtained from 1997-1999 period confirms the robustness of the $Re(\epsilon\prime/\epsilon)$ measurement with respect to the accidental beam activity.

The result from 2001 data only is [9]

$$Re(\epsilon\prime/\epsilon) = (13.7 \pm 3.1) \times 10^{-4} \qquad (14)$$

the result from 97-98-99 data is [8]

$$Re(\epsilon\prime/\epsilon) = (15.3 \pm 2.6) \times 10^{-4} \qquad (15)$$

and the combined result is

$$Re(\epsilon\prime/\epsilon) = (14.7 \pm 2.2) \times 10^{-4} \qquad (16)$$
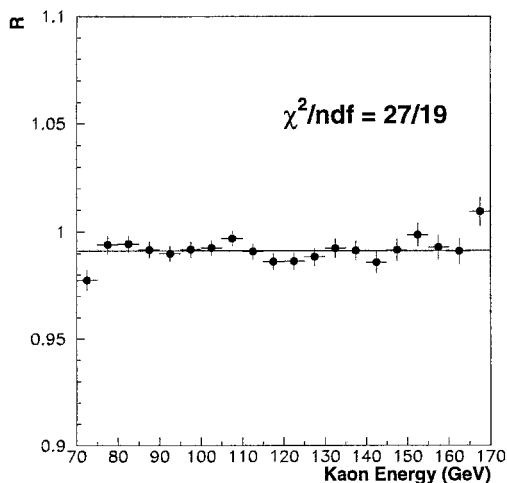
Figure 7. The Double Ratio versus kaon energy.

This final result reaches the design accuracy and leads to a world average of $(16.6 \pm 1.6) \times 10^{-4}$.

6. CONCLUSIONS

The NA48 experiment provided several measurement of CP violation effects in the neutral kaon system. In the year 2003 a search for CP violation in the charged kaons sector will be performed.

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