Measurement of ϵ'/ϵ with NA48

G. Unal[a] *

[a]Laboratoire de l'Accélérateur linéaire
IN2P3-CNRS et Université Paris-Sud,
B.P.34, 91898 Orsay Cedex, France

The NA48 experiment at CERN has performed a measurement of direct CP violation in the neutral kaon system, based on data collected in 1997 and 1998. The preliminary result for the parameter Re(ϵ'/ϵ) is $(14.0\pm4.3)\times10^{-4}$

1. Introduction

CP violation has been discovered in the neutral kaon system in 1964 [1]. The main component of the effect [2] occurs in the mixing between K_0 and $\overline{K_0}$ eigenstates. The physical states K_S and K_L deviate from pure CP = $\pm$ 1 eigenstates, with the mixing described by the parameter ϵ. On the other hand, direct CP violation can also occur in the decay of neutral kaons into a two pion final state, which has CP = + 1. This is coming from the interference of the amplitudes corresponding to different final state isospin [3], and is described by the parameter ϵ'. The quantity which can be measured experimentally is the double ratio of the decay widths :

$$\begin{aligned} R &= \frac{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)}{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)} \\ &\approx 1 - 6 \times Re(\epsilon'/\epsilon) \end{aligned}$$

In the Standard Model, CP violation arises from the existence of three generations of quarks and from the resulting complex phase in the CKM matrix [4]. Direct CP violation is predicted by the Standard Model, with typical computations for ϵ'/ϵ ranging from ≈ 0 to 20×10^{-4} [5].

Previous measurements of ϵ'/ϵ were reported by NA31 [6] $(23.0\pm6.5)\times10^{-4}$ which indicated a value different from 0 and E731 [7] $(7.4\pm5.9)\times10^{-4}$. More recently, KTeV [8] published a result based on part of their data collected $(28.0\pm4.1)\ \times10^{-4}$, and NA48 [9] published a result based on the data taken in 1997 $(18.5\pm7.3)\times10^{-4}$. These recent results showed the existence of direct CP violation in the neutral kaon system.

We report here on the preliminary result from NA48 based on data collected in 1998. The method used to measure the double ratio is outlined. The beam and detector setups are briefly described. Some highlights of the analysis are given and the result is presented. The analysis follows quite closely the one performed on the 97 data, and therefore more details on the analysis method can be found in [9].

2. NA48 method

The measurement of the double ratio R proceeds by counting the number of events in each of the four decay modes. To achieve the aimed accuracy of $\approx 2\times10^{-4}$ on ϵ'/ϵ, a large statistic of events is needed ($\approx 4\times10^6$ $K_L \to \pi^0\pi^0$, which is the limiting mode). To minimise systematic effects, the NA48 experiment is designed in such a way that most of the effects contribute symmetrically to different components of the ratio and therefore cancels out in the computation of R :

Data are collected simultaneously in the four decay modes, cancelling the absolute fluxes and minimising the sensitivity of the measurement to accidental activity and variations of the detection efficiency.

The K_L and K_S decays are provided by two

*on behalf of the NA48 Collaboration (Cagliari, Cambridge, CERN, Dubna, Edinburgh, Ferrara, Firenze, Mainz, Orsay, Perugia, Pisa, Saclay, Siegen, Torino, Warsaw, Wien) nearly collinear beams, with similar momentum spectra and converging in the centre of the main detector. To minimise the difference in acceptance due to the large difference in average decay lengths, only K_L decays occurring in the region also populated by K_S are used. The K_L events used in the double ratio are furthermore weighted as a function of the proper lifetime in order to equalise the decay vertex distribution of K_L and K_S events. With this procedure, the acceptance correction disappears at first order from the double ratio, thus minimising the systematic uncertainty from Monte-Carlo modelling of the experiment.

High resolution detectors (a quasi homogeneous Liquid Krypton calorimeter and a magnetic spectrometer) are used to select the two pion decays, thus minimising the residual backgrounds.

3. Beam and detector

3.1. The kaon beams

The neutral beams are derived from 450 GeV/c protons extracted from the CERN SPS. Because of the different mean decay lengths of K_L and K_S (respectively 3400 m and 5.9 m at the average momentum of 110 GeV/c), two different production targets are used, located 126 m and 6 m upstream of the beginning of the decay region. For each SPS pulse (2.4 s every 14.4 s), $\approx 1.5\times 10^{12}$ protons hit the K_L production target. Three stages of collimation are used to define the K_L beam, at a production angle of 2.4 mrad. Part of the non-interacting protons impinge on a bent silicon mono-crystal. A small fraction undergoes channelling and produces a proton beam of $\approx 3\times 10^7$ protons per pulse transported to the K_S production target, where a second neutral beam is derived, at a production angle of 4.2 mrad. The K_S beam enters the fiducial decay region 6.8 cm above the K_L beam. The beams converge with an angle of 0.6 mrad and the axes of the two beams cross at the position of the electromagnetic calorimeter. To distinguish K_L and K_S decays, the protons directed to the K_S target are detected by an array of scintillation counters which comprise the tagging detector. The time of each proton is recorded and is compared with the time of the decay as measured in the main detector. The presence (absence) of a proton in coincidence with the event defines the event as K_S (K_L). The K_S beam traverses an anti-counter (AKS), formed by a set of scintillation counters following a 3 mm thick iridium crystal. This detector provides an accurate definition of the beginning of the decay region where it is located by vetoing K_S decays occurring upstream. The decay region is contained in an evacuated 90 m long tank, with a 0.003 radiation lengths thick polyimide (Kevlar) window at the end. The neutral beam continues in a 16 cm diameter tube going through the detector elements to the beam dump.

3.2. Main detector

Charged pion decays are measured by a magnetic spectrometer comprised of four drift chambers and a dipole magnet giving a momentum kick of 265 MeV/c^2. The momentum resolution is $\sigma_p/p = 0.5\% \oplus 0.009\% \times p$ (p in GeV/c). Two plastic scintillator hodoscope planes are located after the spectrometer. They are used to determine the event time of the charged events for the tagging procedure.

A quasi-homogeneous liquid krypton electromagnetic calorimeter with a projective tower readout is used to measure the photons from $\pi^0\pi^0$ events. The electrode structure consists of copper/beryllium ribbons extending between the front and the back of the detector with a ± 48 mrad accordion geometry. The 13212 readout cells have each a cross-section of $\approx 2\times 2$ cm^2. The initial current induced on the electrodes by the drift of the ionization is measured using pulse shapers with 80 ns FWHM and digitised with 40 MHz FADCs. The energy resolution is $\sigma(E) = 0.032/\sqrt{E} \oplus 0.1/E \oplus 0.005$, where E is in GeV. The spatial resolution is better than 1mm above 25 GeV. This detector is also used to measure the time of the photons for the tagging procedure.

Located after the electromagnetic calorimeter are a iron-scintillator hadron calorimeter, followed by a muon counter consisting of three planes of scintillators sandwiched between 80 cm thick iron walls.

3.3. Trigger

The electromagnetic calorimeter is used to trigger on $\pi^0\pi^0$ events. At the trigger level, the calorimeter data are reduced to x and y projections which are used to reconstruct the total energy as well as to estimate the decay position of the event.

A two level trigger is used for $\pi^+\pi^-$ decays. At first level, the hodoscope is placed in coincidence with a total energy condition defined using both calorimeters. The second level trigger uses information from the drift chambers to perform a fast event reconstruction.

Auxiliary triggers are used to check the performances of the main triggers and to extract various control samples. The total trigger rate in 1998 was about 18000 triggers per SPS pulse, corresponding to $\approx$ 250 Mbytes of data per pulse.

4. Data Analysis

4.1. Data Sample

The 1997 data measurement was based on a sample containing 0.49×10^6 $K_L \to \pi^0\pi^0$ decays. Several improvements were done for the 1998 data taking. The statistic accumulated in 1998 corresponds to 1.14×10^6 $K_L \to \pi^0\pi^0$ decays. This data sample is used for the preliminary result reported here.

4.2. Event Selection and Background Subtraction

To select $\pi^+\pi^-$ decays, and reject in the K_L mode the background from the much more abundant K_L semileptonic decays, events in which there is a track consistent with being either an electron or a muon are rejected. To identify electrons, the ratio E/p of the energy deposited in the electromagnetic calorimeter to the track momentum is computed. Both tracks must satisfy $E/p < 0.8$. Tracks are identified as muons if hits are found in time in the muon counters near the extrapolated track impact point. For good $\pi^+\pi^-$ events, the invariant mass $m_{\pi\pi}$ should be equal to the kaon mass. The invariant mass resolution is typically 2.5 MeV/c^2. An energy dependent cut of $\pm\, 3\sigma$ is applied. A further reduction of the background is obtained using a cut based on the kaon transverse momentum ${p'_t}^{\,2}$. The cut applied is ${p'_t}^2 < 2\times10^{-4}$ (GeV/c)^2. A cut is also made on a variable $\mathcal{A}$ related to the decay orientation in the kaon rest frame $\mathcal{A} = \frac{|p_1-p_2|}{p_1+p_2}$ (where p_1 and p_2 are the track momenta). This cut removes events with tracks near the beam hole and also entirely removes Λ decays in the K_S beam. To estimate the residual semileptonic background in the K_L candidates, a fit is performed in a wide ($m_{\pi\pi}$,${p'_t}^2$) plane using $\pi^+\pi^-$ (from K_S decays) and K_{e3} and $K_{\mu 3}$ components. The resulting background in the signal region is estimated to $(19 \pm 3) \times 10^{-4}$. Figure 1 shows the result of this fit in the ${p'_t}^2$ distribution.

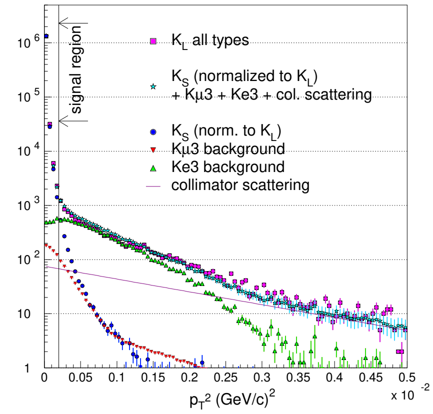

Figure 1. Distribution of ${p_t'}^2$ for K_L candidates fulfilling the $\pi^+\pi^-$ invariant mass cut.

To select $\pi^0\pi^0$ events, four photons are detected in the calorimeter. The longitudinal decay vertex position relative to the calorimeter D is reconstructed from the measured energies E_i and positions x_i,y_i of the four photons, assuming that

[2] defined as the component of the kaon momentum orthogonal to the line joining the production target and the point where the kaon trajectory crosses the first drift chamber. With this definition, the resolution is the same for K_S and K_L events

their invariant mass is the kaon mass (M_K) :

$$D = \sqrt{\Sigma_{i>j} E_i E_j [(x_i - x_j)^2 + (y_i - y_j)^2]} / M_K$$

The invariant masses m_1 and m_2 of the two photon pairs are computed using D and compared to the nominal π^0 mass (M_{π^0}). For this, a χ^2 variable is computed as follows:

$$\chi^2 = \left(\frac{\frac{m_1+m_2}{2} - M_{\pi^0}}{\sigma_+} \right)^2 + \left(\frac{\frac{m_1-m_2}{2}}{\sigma_-} \right)^2$$

The pairing selection is done to minimise this χ^2. To select $\pi^0\pi^0$ candidates, the best pairing is required to have $\chi^2 < 13.5$. This requirement rejects the $K_L \to \pi^0\pi^0\pi^0$ background with two undetected photons. The residual background is estimated by extrapolating the number of events in the χ^2 control region to the signal region, as illustrated in figure 2. Using this method, the background to the weighted K_L sample is found to be $(6.6 \pm 2.0) \times 10^{-4}$.

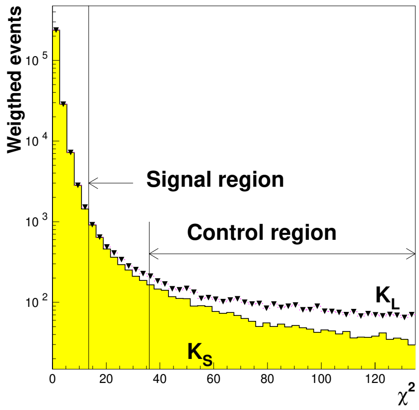

Figure 2. Distribution of χ^2 for weighted K_L candidates (black triangles) compared to the shape for pure $2\pi^0$ events derived from K_S candidates

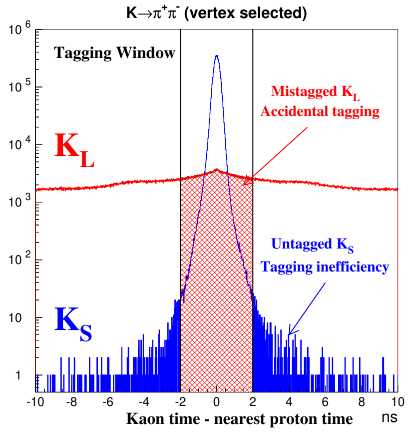

Figure 3. Distribution of the minimum difference between tagger and event times for $\pi^+\pi^-$ decays, for vertex-selected K_S and K_L events

4.3. K_S and K_L Identification

The event is tagged by classifying it as K_S if there is a proton within a $\pm$ 2 ns coincidence window centred on the event time, otherwise the event is classified as K_L. The resolution of the coincidence is $\approx$ 200 ps for $\pi^+\pi^-$ events and $\approx$ 250 ps for $\pi^0\pi^0$ events. Inefficiencies in reconstructing the proton or the event time can cause a coincidence to be lost and to misidentify a K_S event as a K_L ("tagging inefficiency"). Accidental coincidence between a proton traversing the tagger and a K_L event may cause the event to be wrongly counted as K_S ("accidental tagging"). In the charged mode, these probabilities can be easily measured by using the vertical position of the reconstructed decay vertex to cleanly separate K_L and K_S events independently of the tagging system. The tagging inefficiency for $\pi^+\pi^-$ events is measured to be $(1.97\pm0.05)\times10^{-4}$, while the accidental tagging probability is $(11.05\pm0.01)\%$. This is illustrated in Figure 3

Bias on R could come from different misidentification probabilities for $\pi^+\pi^-$ and $\pi^0\pi^0$ events. To check the difference of tagging inefficiencies, neutral events containing photon conversions are used to estimate the difference in time reconstruction efficiency between $\pi^+\pi^-$ and $\pi^0\pi^0$ decays. No difference is found at the level of 0.5×10^{-4} and the resulting systematic error on the double ratio is $\pm\ 3\times10^{-4}$. At first order, the accidental tagging (which comes from random coincidences in the tagger) should be the same. To estimate residual effects, the difference in accidental proton rates between $\pi^+\pi^-$ and $\pi^0\pi^0$ K_L events is measured by looking at times which are offset from the actual event. To extrapolate between these "side-bands" and the coincidence at the event time, $\pi^+\pi^-$ (selected with the vertex position) and $\pi^0\pi^0\pi^0$ (for which there are only K_L) events are used. The difference in accidental tagging is found to be $(0.3\pm4.2)\times10^{-4}$, where the error is limited by the $\pi^0\pi^0\pi^0$ statistic available at the time of this preliminary analysis. This corresponds to a correction to R of $(0.6\pm8.4)\times10^{-4}$.

4.4. Energy and distance scales

The fiducial decay region is defined in proper time, expressed in K_S lifetime units, and covers the interval 0 to 3.5. In the neutral mode, the decay vertex position reconstruction relies on the measured photon energies and positions with the calorimeter. To set the overall energy scale, $K_S\to\pi^0\pi^0$ events are used. The energy scale is adjusted such that the sharp rise in the reconstructed decay vertex position created by the AKS veto use is at the known geometrical position of the AKS. The accuracy of the energy scale setting is estimated to $\pm3\times10^{-4}$. The calorimeter non linearity is mainly studied using K_{e3} decays, in which the reconstructed electron energy in the calorimeter can be compared to the momentum measured by the spectrometer. Residual non linearities are at the level of 0.2% in the energy range 5 to 100 GeV, and correspond to an uncertainty on R of $\pm5\times10^{-4}$. Other systematic effects, such that uncertainties in the transverse size of the calorimeter, residual non uniformities and effects of non gaussian tails in the energy response have also been studied. An overall cross-check is performed using special runs with a π^- beam striking a thin target near the AKS counter and producing π^0 and η ($\to\gamma\gamma$, $3\pi^0$) with known decay position. Overall, for this preliminary result, the total systematic error coming from the reconstruction of neutral events is estimated to be $\pm10.2\times10^{-4}$ on R. Systematic uncertainties in the measurement of the $\pi^+\pi^-$ vertex position are estimated to contribute to a $\pm2\times10^{-4}$ error on R.

4.5. Acceptance correction

The K_S and K_L acceptances are made very similar by using the technique of weighting the K_L events according to their proper decay time so that the effective longitudinal vertex distribution of K_L events is made equal to the K_S distribution. The residual acceptance differences are studied with a full simulation of the beams and detector. The overall correction to apply to the double ratio is found to be $(31\pm6.4(\mathrm{MC\ stat})\pm6.0(\mathrm{syst}))\times10^{-4}$, where the main sources of systematic error are due to uncertainties in the positions and divergences of the beams.

4.6. Summary of systematic errors and result

Other corrections and errors not discussed above include the measurement of the trigger efficiencies. This is done using events taken with less selective triggers. The $\pi^0\pi^0$ trigger efficiency is found to be $\approx$ 99.9%, and differences between K_L and K_S are negligible. The average $\pi^+\pi^-$ trigger efficiency is $\approx$97.2%. The difference of this efficiency between weighted K_L events and K_S events is $(-1.4\pm11.5)\times10^{-4}$, consistent with zero within the statistic of the control sample.

The possible effect of event losses caused by beam related activity ("accidental losses") has also been studied. This effect is minimised by the simultaneous data taking of K_L and K_S events and by applying offline to both $\pi^+\pi^-$ and $\pi^0\pi^0$ events the dominant dead time conditions which are recorded and are coming from the $\pi^+\pi^-$ trigger ($\approx$ 4%) and from the read-out of the drift chambers ($\approx$ 25%). To estimate the residual effects, various methods are used, including overlaying signal events with "random" events representing the typical beam activity. The uncertainty on R is conservatively estimated to $\pm12.2\times10{-}4$.

Finally, in the K_L beam, a small fraction of events comes from K_S decays originating from scattering and regeneration on the collimators. Since these events are removed from the $\pi^+\pi^-$ sample by the transverse momentum cut, but kept in the neutral sample, a correction on R of (-9.9±3.0)$\times 10^{-4}$ should be applied.

All the corrections and uncertainties on the double ratio are summarised in table 1. It should be noted that all corrections on R are smaller than few per mills, in accordance with the design of the experiment.

Table 1
Corrections and uncertainties to R ($\times$ 10^4)

$\pi^+\pi^-$ trigger efficiency	-1.4	±11.5
Accidental tagging	+0.6	±8.5
Tagging efficiency	-	±3.0
Energy scale and linearity	-	±10.2
Charged vertex	+2.0	±2.0
Acceptance	+31.1	±8.7
$\pi^0\pi^0$ background	-6.6	±2.0
$\pi^+\pi^-$ background	+19.0	±3.0
Beam scaterring	-9.9	±3.0
Accidental losses	+2.0	±12.2
Total	+36.8	±23.8

The total event statistic used in the measurement of R from 98 data is (after background and mistagging corrections) : 1.14×10^6 $K_L \to \pi^0\pi^0$, 1.80×10^6 $K_S \to \pi^0\pi^0$, 4.87×10^6 $K_L \to \pi^+\pi^-$ and 7.46×10^6 $K_S \to \pi^+\pi^-$.

In order to be insensitive to the difference in the beam momentum spectra, the range used in kaon energy ($70 < E < 170$ GeV) is divided in 20 bins. R is computed in each bin and the various corrections are applied separately bin per bin. The average value for the double ratio is $R = 0.9927 \pm 0.0017 \pm 0.0024$, where the first error is statistical and the second is systematic. Part of the systematic error is actually limited by the statistic of the control samples used. The corresponding preliminary result for the CP violating parameter is :

$$Re(\epsilon'/\epsilon) \quad = \quad (12.2 \pm 2.9 \pm 4.0) \times 10^{-4}$$

5. Prospects and conclusion

Combining with the published NA48 result from the 97 data, and taking into account the small correlation in the systematic errors, the preliminary NA48 result is :

$$Re(\epsilon'/\epsilon) \quad = \quad (14.0 \pm 4.3) \times 10^{-4}$$

The analysis of 1998 data is continuing and some systematics are expected to be reduced (accidental tagging, acceptance correction, accidental activity, energy scale). The analysis of 1999 sample whose statistic is twice larger is also in progress.

The implosion of the beam pipe by the end 1999 badly damaged the four drift chambers. The run of 2000 (without the spectrometer) is therefore used to perform systematic checks related to the neutral mode. In the meantime, the repair of the drift chambers is underway, and NA48 will be ready for data taking in 2001 with the full detector working.

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