

Review of the NA48 CP violation measurements with neutral and charged kaons

Patrizia Cenci¹

INFN Perugia

Via A. Pascoli, 06123 Perugia, Italy

E-mail: patrizia.cenci@pg.infn.it

The main results on the CP violation measurements with neutral and charged kaons from the NA48 experiment at the CERN SPS are reviewed in this paper. The direct CP violating parameter $\text{Re}(\epsilon'/\epsilon)$ has been measured by NA48 from the decay rates of neutral kaons into pion pairs. The final result, based on data collected in 1997, 1998, 1999 and 2001, clearly established the existence of direct CP violation. NA48 also measured the CP violation parameter $|\eta_{+-}|$, defined as the amplitude ratio of CP violating to CP conserving neutral kaon decays into two charged pions: $|\eta_{+-}| = A(K_L \rightarrow \pi^+\pi^-)/A(K_S \rightarrow \pi^+\pi^-)$. The CP violating decay $K_S \rightarrow \pi^0\pi^0\pi^0$ has been studied by the NA48/1 experiment, using data collected in 2000 and 2002 with a K_S beam at high intensity. Only direct CP violation occurs in charged kaon decays, since mixing is not allowed. NA48/2 has measured the Dalitz plot asymmetry of $K^\pm \rightarrow 3\pi^\pm$ decays from data collected in 2003 and 2004, posing a new limit on the asymmetry in the decay matrix slope parameters. Based on the same data sample, the result on the search for direct CP violation in the decay rate asymmetry in $K^\pm \rightarrow \pi^0\pi^\pm\gamma$ processes is also presented.

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¹ Speaker, on behalf of the NA48, NA48/1 and NA48/2 Collaborations.

1. Introduction

CP violation was discovered in $K_L^0 \rightarrow \pi\pi$ decays in 1964 [1]. The same mode provided the evidence for direct CP violation [2-4]. All three types of CP violation are observed in neutral kaons. The phenomenon of neutral kaon mixing accounts for the indirect CP violation measured with the parameter $\text{Re}(\varepsilon)$, where ε represents the asymmetric mixing of the CP eigenstates into the mass eigenstates. Direct CP violation is due to an asymmetry in the amplitude of K^0 decays into two pions, with different isospin values. This effect is quantified by the parameter $\text{Re}(\varepsilon')$. A non-zero value of ε' arises naturally in the Standard Model (SM) from the complex phase of the CKM matrix. The violation of CP symmetry takes also place in the interference between decays with and without mixing, represented in terms of the parameters $\text{Im}(\varepsilon)$ and $\text{Im}(\varepsilon')$. Only direct CP violation effects occur in the charged kaon sector, since mixing is not allowed.

Over the past 10 years, the NA48 experiment at CERN SPS has carried out an extensive physics programme devoted to the study of CP violation. The main results on CP violation measurements with neutral and charged kaons from NA48, NA48/1 and NA48/2 are presented.

2. CP Violation in Neutral Kaons

NA48 was a fixed target experiment at the CERN SPS aiming at the measurement of direct CP violation in the neutral kaon sector. The NA48 detector and its performances are described in [5]. Simultaneous K_L and K_S beams, produced by the same primary 450 GeV/c proton beam, have been exploited. Given the different decay lengths of K_L and K_S mesons, two production targets were used, located 126 m (“far-target”) and 6 m (“near-target”) upstream of the decay region. A bent silicon crystal was deflecting the protons non interacting in the far-target by channelling, thus defining an attenuated proton beam impinging on the K_S target. In order to distinguish K_S and K_L decays, the protons directed to the K_S target were tagged by an array of thin scintillator counters. Fig. 1 shows a scheme of the NA48 beam and detector.

Direct CP violation was established in 1999 with the first results of the precision experiments E832 (KTeV) [3] at FNAL and NA48 [4]. The observable was the double ratio:

$$R = \frac{\Gamma(K_L \rightarrow \pi^0 \pi^0) \cdot \Gamma(K_S \rightarrow \pi^+ \pi^-)}{\Gamma(K_S \rightarrow \pi^0 \pi^0) \cdot \Gamma(K_L \rightarrow \pi^+ \pi^-)} = \left| \frac{\eta_{00}}{\eta_{+-}} \right|^2 \cong 1 - 6 \text{Re}(\varepsilon'/\varepsilon)$$

In order to cancel systematic effects at first order in R , the measurement is accomplished by counting events under the following conditions: the K_L and K_S beams are produced concurrently and the four $\pi\pi$ decay modes, coincident in space, are measured simultaneously. The two experiments exploit similar detector concepts, with high performance calorimetry for the $\pi^0\pi^0$ measurement – a liquid Krypton ionization chamber for NA48 and pure CsI crystals for KTeV – and high quality magnetic spectrometers for the $\pi^+\pi^-$ detection. The final result from NA48 [6], based on data taken in the years 1997 to 2001, is: $\text{Re}(\varepsilon'/\varepsilon) = (14.7 \pm 2.2) \times 10^{-4}$.

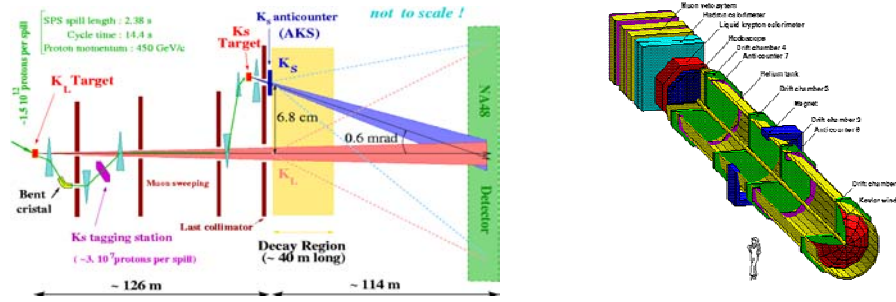


Figure 1: the layout of the NA48 neutral beams (left); the NA48 detector (right).

The amplitude ratio of CP violating to CP conserving decays of the neutral kaons into two charged pions is related to the CP violation parameters: $|\eta_{+-}| = A(K_L \rightarrow \pi^+ \pi^-) / A(K_S \rightarrow \pi^+ \pi^-) \approx \epsilon + \epsilon'$.

In order to compute the branching ratio of the decay $K_L \rightarrow \pi^+ \pi^-$, needed to calculate $|\eta_{+-}|$, the decay rates ratio $R = \Gamma(K_L \rightarrow \pi^+ \pi^-) / \Gamma(K_L \rightarrow \pi e \nu)$ has been measured in NA48. The final result is $|\eta_{+-}| = (2.223 \pm 0.012) \times 10^{-3}$ [7]. This value is in agreement with the measurements done by KTeV [8] and by KLOE [9], while contradicts the 2004 PDG value [10].

The NA48/1 experiment was aiming at the measurement of K_S rare decays with a near-target modified with respect to the NA48 one and an intense K_S beam [5]. It took data in 2000 and 2002. NA48/1 has measured the branching fraction of the CP violating process $K_S \rightarrow 3\pi^0$ and the amplitude ratio $|\eta_{000}| = A(K_S \rightarrow 3\pi^0) / A(K_L \rightarrow 3\pi^0)$ [11]. An indirect method was exploited, based on the measurement of K_S - K_L interference effects close to the K_S production target, achieving an accuracy comparable to the more precise direct measurement done by KLOE [12].

3. CP Violation in Charged Kaons

Direct CP violation is expected to induce different amplitudes for K^+ and K^- decays into the same three-pion final states. A non-zero value of the asymmetry of the decay matrix slope parameter g , i.e. $A_g = [g(K^+) - g(K^-)] / [g(K^+) + g(K^-)]$, would indicate direct CP violation effects. In those modes, the slope asymmetry A_g is expected to be strongly enhanced with respect to the asymmetry of integrated decay rates. The SM predictions for A_g are of the order of 10^{-5} [13] or even smaller, while calculations involving processes beyond the SM [14,15] do not exclude enhancements up to few 10^{-4} . NA48/2 accomplished an extensive study of direct CP violation effects in K^\pm decays into three pions, using a modified NA48 experimental setup and a new design of simultaneous, narrow band, non separated K^+ / K^- beams [16]. The experiment aimed to measure the slope asymmetry A_g in $K^\pm \rightarrow 3\pi^\pm$ and $K^\pm \rightarrow \pi^\pm \pi^0 \pi$ events with a sensitivity of $O(10^{-4})$, one order of magnitude better than the best available measurements.

The simultaneous data taking with K^+ / K^- beams of similar momentum spectra, associated to the regular reversal of the polarity of the magnets along the beam line and of the spectrometer magnetic field, allow the cancellation of most of the systematic effects due to asymmetries in the setup. Possible local effects on the acceptances due to the electric charge are equalized. Several data samples were collected in all possible combinations of polarities of both the beam line and the spectrometer magnets. This procedure allows to accomplish further cancellation of systematic biases due to differences in the beam line geometry, in the rates and in the detector.

The method is independent on the K^+/K^- flux ratio and on the size of the samples collected under the different conditions. The result is only sensitive to asymmetries in the experimental conditions with time variation scales smaller than those of the magnetic field inversions and it is free of systematic biases. In addition, no Monte Carlo corrections to the acceptance are required.

Based on $3.1 \times 10^9 K^\pm \rightarrow 3\pi^\pm$ decays and $9.1 \times 10^7 K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ decays, collected in 2003-04, the final results of the measurements of the charged A_g^c and neutral A_g^n asymmetries are [17]:

$$A_g^c = (-1.5 \pm 1.5_{stat.} \pm 0.9_{trig.} \pm 1.3_{syst.}) \times 10^{-4} = (-1.5 \pm 2.2) \times 10^{-4}$$

$$A_g^n = (1.8 \pm 1.7_{stat.} \pm 1.7_{syst.}) \times 10^{-4} = (1.8 \pm 1.8) \times 10^{-4}$$

The accuracy achieved by NA48/2 is one order of magnitude better than the previous measurements. The results are compatible with the SM and do not show evidence of direct CP violation, giving constrains to SM extensions which predict enhancements of the asymmetries.

The interference component of the $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ processes has been measured by NA48/2 for the first time [18]. No evidence of direct CP violation has been found in the measurement of the $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ decay rate asymmetry $A_N = [\Gamma(K^+) - \Gamma(K^-)] / [\Gamma(K^+) + \Gamma(K^-)]$. Based on a sample of 1.08×10^6 events, a new limit has been set by NA48/2: $A_N < 1.5 \times 10^{-3}$ (90% C.L.).

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