SEARCH FOR DIRECT CP-VIOLATION IN $K^\pm \to 3\pi$ DECAYS BY NA48/2

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A high precision search for direct CP-violation in $K^\pm \to 3\pi$ decays was performed by the NA48/2 experiment at CERN SPS. The asymmetry in the Dalitz plot linear slopes $A_g = (g^+ - g^-)/(g^+ + g^-)$ is measured to be $A_g^c = (-1.3 \pm 2.3) \times 10^{-4}$ by studying 3.1×10^9 $K^\pm \to \pi^\pm\pi^+\pi^-$ decays and $A_g^n = (2.1 \pm 1.9) \times 10^{-4}$ by studying 91×10^6 $K^\pm \to \pi^\pm\pi^0\pi^0$ decays. The unique double-beam system, the design of the detectors and the method of analysis provide good control of the instrumental charge asymmetries and allow to keep the precision of the result limited by statistics, reaching accuracy one order of magnitude better than in previous experiments.

Keywords: CP-violation, Kaon physics.

1. Introduction

More than 40 years after its discovery in the mixing of neutral kaons, the full understanding of CP violation is far from being reached. Two recent breakthroughs spread light over this puzzling phenomenon: In the late 90s the experiments NA48 and KTeV confirmed the earlier indication from NA31 experiment for direct CP-violation in K^0 system. Secondly, in the beginning of this century the CP-violating processes were found in B mesons field by the experiments Belle and Babar. In order to explore possible non-Standard Model (SM) enhancements to heavy-quark loops which are at the core of direct CP-violating processes, various systems must be studied. In kaons, besides the ε'/ε parameter in $K^0 \to \pi\pi$ decays, promising complementary observables are the rates of GIM-suppressed rare kaon decays proceeding through neutral currents, and an asymmetry between K^+ and K^- decays to three pions.

The $K \to 3\pi$ matrix element can be parameterized by a polynomial expansion in two Lorentz-invariant variables u and v:

$$|M(u,v)|^2 \propto 1 + gu + hu^2 + kv^2 + \ldots, \quad (1)$$

where $|h|, |k| \ll |g|$ are the slope parameters, and

$$u = \frac{s_3 - s_0}{m_\pi^2}; \quad v = \frac{s_1 - s_2}{m_\pi^2}; \quad (2)$$

where m_π is the charged pion mass, $s_i = (p_K - p_i)^2$, $s_0 = \sum s_i/3$ $(i = 1;2;3)$, p_K and p_i are kaon and i-th pion 4-momenta, respectively. The index $i = 3$ corresponds to the odd pion[a]. The parameter of direct CP violation is usually defined as:

$$A_g = \frac{g^+ - g^-}{g^+ + g^-}; \quad (3)$$

where g^+ is the linear coefficient in (1) for K^+ and g^- – for K^-. A deviation of A_g from zero is a clear indication for direct CP violation. Several experiments[1] have searched for such asymmetries both in $K^\pm \to \pi^\pm\pi^+\pi^-$ and $K^\pm \to \pi^\pm\pi^0\pi^0$ decay modes, and obtained consistent with zero result with a precision at the level of 10^{-3}. SM predictions for A_g vary from a few 10^{-6} to a few 10^{-5}[2], however some theoretical calculations involving processes beyond the SM[3] predict substantial enhancements of the asymmetry, which could be observed in the present experiment.

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[a] The other two pions have the same charge.

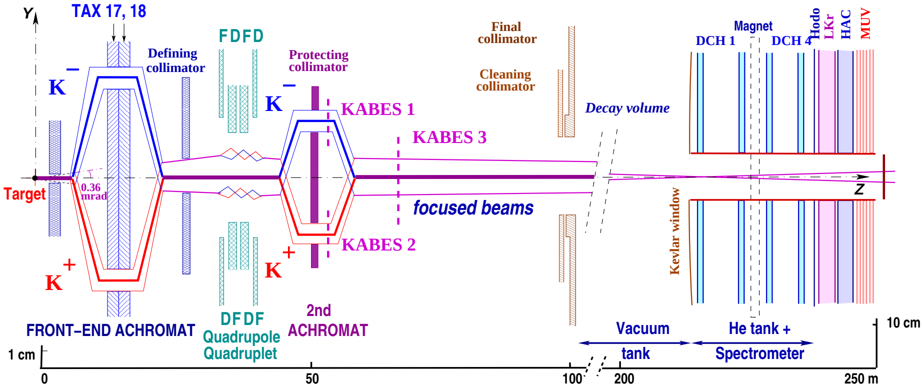

Fig. 1. Schematic lateral view of the NA48/2 experiment. Region 1 (from target to decay volume): beam line (TAX17,18: motorized beam dump/collimators used to select the momentum of the K^+ and K^- beams; DFDF: focusing quadrupoles; KABES1–3: beam spectrometer stations). Region 2: decay volume and detector (DCH1–4: drift chambers; Hodo: hodoscope; LKr: electromagnetic calorimeter; HAC: hadron calorimeter; MUV: muon veto). The vertical scales for the two regions are different.

2. Description of the Experiment

The NA48/2 experiment at the CERN SPS was designed to search for direct CP-violation in the decays of charged kaons to three pions, and collected data in 2003 and 2004. In order to reach a high accuracy in the measurement of the charge asymmetry parameter A_g, the highest possible level of charge symmetry between K^+ and K^- was a crucial requirement in the choice of beam, experimental apparatus, strategy of data taking and analysis.

A novel beam line (Fig. 1) with two simultaneous charged beams of opposite charges was designed and built in the high intensity hall (ECN3) at the CERN SPS. The charged particle beams were produced by 400 GeV protons with high intensity from the SPS impinging on a beryllium target. Charged particles with momentum (60 ± 3) GeV/c were selected symmetrically by an achromatic magnet system ('achromat') which separates vertically the two beams and recombines them again on the same axis. Frequent inversion of the magnetic field polarities in all the beam line elements provides a high level of intrinsic cancellation of the possible systematic effects in the beam line. The K^+/K^- flux ratio is about 1.8.

The entire reconstruction of $K^\pm \to \pi^\pm\pi^+\pi^-$ decays and the determination of the kaon charge in $K^\pm \to \pi^\pm\pi^0\pi^0$ decays rely on a magnetic spectrometer. Two drift chambers are located upstream and two downstream of a dipole magnet which deflects charged particles horizontally with a transverse momentum kick of 120 MeV/c. The magnetic field was reversed frequently in order to cancel possible left-right asymmetries in the detector system. The momentum resolution of the magnetic spectrometer is $\sigma(p)/p = 1.0\% \oplus 0.044\%\, p$ (p in GeV/c). The acceptance of the spectrometer is defined mainly by an evacuated beam tube passing through its centre, with a diameter of ~ 16 cm, in which the surviving beam particles as well as the muons from $\pi \to \mu\nu$ decays travel.

The reconstruction of $K^\pm \to \pi^\pm\pi^0\pi^0$ decays is based mainly on the use of liquid krypton calorimeter (LKr), which measures the energies of the four photons from π^0 decays. The LKr has an energy resolution $\sigma(E)/E = 0.032/\sqrt{E} \oplus 0.09/E \oplus 0.0042$ (E in GeV) and spatial resolution for a single electromagnetic shower $\sigma_x = \sigma_y = 0.42/\sqrt{E} \oplus 0.06$ cm for the transverse coordinates x and y. The use of a priori charge symmetric detector helps to keep the result in K ! ^{0} ^{0} mode practically unbiased.

A hodoscope is used for precise time measurement of the charged particles and as a component in the trigger system for both decay modes. Detailed description of the detector components can be found elsewhere[4].

3. Asymmetry measurement method

The asymmetry measurement is based on the comparison of the u spectra for K^{+} and K decays, $N^{+}(u)$ and $N(u)$, respectively. The ratio of the u spectra $N^{+}(u)/N(u)$ is proportional to

$$\frac{N^{+}(u)}{N(u)} / \frac{1+(g+ g)u+hu^{2}}{1+gu+hu^{2}}; \quad (4)$$

where g and h are the actual of the Dalitz-slope parameters[5]. The possible presence of a direct CP violating difference between the linear slopes of K^{+} and K, $g = g^{+}$ g, can be extracted from a fit to this ratio. The measured asymmetry is then given by $A_{g} = g/2g$.

In order to minimize the effect of beam and detector asymmetries, we use the ratio $R_{4}(u)$, defined as a product of four $N^{+}(u)/N(u)$ ratios:

$$R_{4}(u) = R_{US} \quad R_{J} \quad R_{S} \quad R_{J} =$$

$$= R \quad 1+\frac{g \quad u}{1+gu+hu^{2}} \quad ^{4} : (5)$$

The first subscript U (D) denotes a configuration of the beam magnet polarities which corresponds to the positive beam traversing the upper (lower) path in the achromats. The second subscript S denotes the spectrometer magnet polarities (opposite for the events in the numerator and in the denominator of each ratio) deflecting the kaon to negative x (towards the Saleve mountain, given the topographical situation of the experiment in relation to the mountains surrounding CERN) and J corresponds to the deflection of the pions in the opposite direction (towards the Jura mountain chain). The spectra $N^{+}(u)$ and $N(u)$ for each of the four individual ratios in (5) are obtained from successive runs taken with the same beam magnet polarities and with the deflected in the same direction by the spectrometer magnet. The parameter g and the normalization R are extracted from a fit to the measured quadruple ratio $R_{4}(u)$ using the function in eq. (5)[b]. The measured slope difference g is insensitive to the normalization parameter R, which reflects the ratio of K^{+} and K fluxes.

The quadruple ratio method complements the procedure of magnet polarity reversal. It allows a three-fold cancellation of systematic biases: 1) beam line biases cancel between K^{+} and K samples in which the beams follow the same path; 2) the effect of local non-uniformities of the detector cancel between K^{+} and K samples in which charged pions illuminate the same parts of the detectors; 3) as a consequence of using simultaneous K^{+} and K beams, global, time dependent, instrumental charge asymmetries cancel between K^{+} and K samples.

A reduction of possible systematic biases due to the presence of stray permanent magnetic fields (Earth field, vacuum tank magnetization) is achieved by the radial cuts around the average beam position, which make the geometrical acceptance to charged pions azimuthally symmetric. The only residual sensitivity to instrumental charge asymmetries is associated with time variations of any acceptance asymmetries occurring on a time scale shorter than the magnetic field alternation period, which are studied carefully by a number of monitors recorded throughout data taking.

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[b] Due to smallness of the parameters g ad h in K ! $^{+}$ mode, a fit with a function $R_{4}(u) = R(1+ g u)^{4}$ is sufficient.

4. Result and conclusions

The whole 2003 and 2004 data-set contains several[c] samples with all possible combinations of magnetic field polarities in the beam optics and in the magnetic spectrometer, needed to construct the quadruple ratio (5) and self-sufficient for g measurement. The raw asymmetry is extracted for each of them separately, and the final result then is obtained as their weighted average. In total, $3.1 \quad 10^{9}$ $K \to {}^{+}$ and $91 \quad 10^{6}$ $K \to {}^{0\,0}$ decays were selected for the analysis. The result in terms of linear slope difference g with only the statistical error quoted is $g^{c} = (0.7 \quad 0.7) \quad 10^{4}$ for $K \to {}^{+}$ and $g^{n} = (2.7 \quad 2.0) \quad 10^{4}$ for $K \to {}^{0\,0}$ decay mode. These results are free of systematic biases in the first approximation due to the implemented method of cancellation of various apparatus imperfections. However, the checks of possible systematic contributions have been done, and corresponding uncertainties were obtained [6]. The preliminary results for the whole 2003 and 2004 data-set are:

$$A_g^{c} = (\quad 1.3 \quad 1.5_{stat.} \quad 0.9_{trig.} \quad 1.4_{syst.}) \quad 10^{4} \qquad (6)$$

$$A_g^{n} = (2.1 \quad 1.6_{stat.} \quad 1.0_{syst.} \quad 0.2_{ext.}) \quad 10^{4} \qquad (7)$$

correspondingly for $K \to {}^{+}$ and $K \to {}^{0\,0}$ decay modes[d]. The reason for a similar precision of the results given in (6) and (7), despite a factor of 30 in the collected statistics, is the fact that the population density of the Dalitz plot is more favourable in the $K \to {}^{0\,0}$ mode and $|g({}^{0\,0})| \quad 3 \quad |g({}^{+})|$. The results are one order of magnitude more precise than previous measurements and are consistent with the predictions of the SM.

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[c] 9 for $K \to {}^{+}$ and 7 for $K \to {}^{0\,0}$ decay mode.

[d] The trigger error 0.9 in (6) is an upper limit for eventual charge asymmetric response of the trigger system for $K \to {}^{+}$ decays and it is limited by the statistics in the control sample used for this estimation; for $K \to {}^{0\,0}$ decays this error is included in the total systematic error. The external uncertainty 0.2 in (7) arises from the experimental precision on g and h [5].