Direct CP Violation in Charged Kaon Decays by the NA48/2 Experiment at CERN

G. Collazuol, on behalf of the NA48/2 Collaboration
Scuola Normale Superiore, Piazza dei Cavalieri 7, 56126 Pisa Italy
E-mail: gianmaria.collazuol@pi.infn.it

The NA48/2 experiment at CERN is performing high precision studies of charged kaon decays, using an upgraded NA48 setup and a novel design for simultaneous unseparated $K^{\pm}$ beams. The main goal is to search for direct CP violation in decays to three pions with a sensitivity at a level of 10^{-4} on the asymmetry $A_g = (g_+ - g_-)/(g_+ + g_-)$ where g is the linear slope parameter in the Dalitz plot. The experimental procedure and the main systematic effects are discussed, based on the preliminary analysis of a fraction (less than 50%) of the data recorded. The statistical errors on the $K^{\pm} \to \pi^+\pi^-\pi^{\pm}$ and $K^{\pm} \to \pi^0\pi^0\pi^{\pm}$ asymmetries are 2.7×10^{-4} and 5×10^{-4}, respectively. The large amount of charged kaon decays collected allow also precision measurements of several rare decay processes.

1. Introduction

The study of direct CP violation (CPV) in kaon decays with high precision and in different channels provides a powerful tool for over-constraining the CKM matrix and searching for new physics.

NA48 contributed to this program by establishing the existence of and precisely measuring the direct CPV in the neutral kaon system [1]. In the K^0 system the following decay width asymmetry is measured:

$$\frac{\Gamma(K^0 \to \pi^+\pi^-) - \Gamma(\overline{K^0} \to \pi^+\pi^-)}{\Gamma(K^0 \to \pi^+\pi^-) + \Gamma(\overline{K^0} \to \pi^+\pi^-)} = \\ = (4.8 \pm 0.7) \times 10^{-6}$$

The origin of the decay amplitude imbalance: $|A(K^0 \to (2\pi))| \neq |A(\overline{K^0} \to \overline{(2\pi)})|$ is explained by the interference of two amplitudes with $\Delta I = 1/2$ and $\Delta I = 3/2$ which differ in both weak and strong phases.

Direct CP violation in $K^{\pm}$ is expected to induce different decay amplitudes: $|A(K^+ \to (3\pi)^+)| \neq |A(K^- \to (3\pi)^-)|$. The three-body decay has a low Q value, which allows for the following parametrization in terms of the two Dalitz variables $u = (s_3 - s_0)/m_\pi^2$ (odd pion coordinate) and $v = (s_1 - s_2)/m_\pi^2$ (even pion coordinate): $|A(K \to (3\pi))| = a + b \times u + \mathcal{O}(u^2, v^2)$, where a and b are two $\Delta I = 1/2$ interfering amplitudes. If a and b have different weak and strong phases, the transitions to the two charge conjugate states $(3\pi)^{\pm}$ are not equally affected by the interference, resulting in different distributions of final state momentum for K^+ and K^- decays. If the matrix element is parametrized as $|M(u,v)|^2 \propto 1 + g \times u + \mathcal{O}(u^2, v^2)$, the asymmetry

$$A_g = \frac{g^+ - g^-}{g^+ + g^-} \neq 0$$

of the slope parameter g would be a signal of direct CP violation.

Theoretical predictions based on the Standard Model cover the range $\sim 10^{-6} - 10^{-3}$ for A_g [9,10], relative to the "charged 3π channel" $K^{\pm} \to \pi^+\pi^-\pi^{\pm}$. The asymmetry $A_{g'}$ for the "neutral 3π channel" $K^{\pm} \to \pi^0\pi^0\pi^{\pm}$, which is dominated by NLO counterterms in the chiral perturbation theory (χPT), is expected to be of the same order of magnitude of A_g, due to the suppression of the $\Delta I = 3/2$ transition observed in ϵ'/ϵ. Values of A_g above the level of 5×10^{-5} would imply physics beyond the standard model [3] and would strengthen the still open question about non-standard contributions to ϵ'/ϵ.

In the past no slope asymmetries were found at a level of 10^{-3}. The BNL experiment [6] studied A_g with a total of 3×10^6 decays and measured a slope asymmetry $A_g = (-7\pm5)\times10^{-3}$ and a total decay rate asymmetry $\Delta\Gamma/2\Gamma = (5 \pm 7) \times 10^{-4}$. Recently HyperCP [5] at FNAL measured $A_g = (2.2 \pm 1.5 \pm 3.7) \times 10^{-3}$.

An experiment [7] at the CERN-PS measured a slope asymmetry at a level of $A_{g'} = (0.2\pm1.2)\times 10^{-2}$ and $\Delta\Gamma/2\Gamma = (4\pm3)\times10^{-4}$ in the "neutral channel". Recently experiment ISTRA+ [8] at TNF-IHEP found $A_{g'} = (0.2 \pm 1.9) \times 10^{-3}$.

The aim of NA48/2 is to measure A_g and $A_{g'}$ with an accuracy of 10^{-4} (statistically dominated).

2. Experimental method and set up

NA48/2 uses simultaneous K^+ and K^- beams overlapping in space with a narrow momentum band.

The experimental method consists in detecting the asymmetries by considering slopes of ratios of normalized u distributions of K^+ and K^- : $R(u) = C \times (N^+(u)/N^-(u))$, where $N^+(u)$ and $N^-(u)$ are the u spectra of $K^+ \to \pi^+\pi^+\pi^-$ and $K^- \to \pi^-\pi^-\pi^+$ decays respectively, and C provides the normalization of $R(0) = 1$.

If the acceptances for K^+ and K^- are properly equalized, for instance by frequently alternating the polarities of the relevant magnets along the particle paths during data taking, then the ratio of the u distributions of K^+ and K^- would be independent of acceptances. A linear slope in the ratio:

$$R(u) = \frac{1 + g^+u + \mathcal{O}(u^2)}{1 + g^-u + \mathcal{O}(u^2)} = \\ = 1 + (g^+ - g^-) \times u$$

would then be a signal of direct CP violation.

2.1. Simultaneous, coaxial, focused $K^\pm$ beams

The novel design of the K12 beam line (Fig. 1) allows the transport simultaneously of positive and negative particles. A 400 GeV/c primary proton beam with an intensity of 7×10^{11} protons per spill impinge the Be target located $\sim$ 200 m upstream from the central detector. The particles of opposite charge produced at 0^o are split, selected in a narrow momentum band ($p_K = 60 \pm 2.5$ GeV/c) and recombined by passing through an achromatic dipole magnet system. A quadruplet of quadrupoles focuses the beams so that they overlap with an accuracy of better than 1 mm at the beginning of the central detector. A second "achromat" houses a collimator to absorb neutrons, and two stations of Micromegas type TPC detector (KAon-BEam-Spectrometer). In combination with a third chamber, located downstream, the KABES chambers provide tagging and momentum measurement of individual kaons. The particle rate at the KABES position is $\sim$ 40 MHz. The final collimator, placed $\sim$ 100 m downstream of the target, is followed by a decay volume of $\sim$ 115 m length.

2.2. The NA48/2 central detector

The NA48 central detector described elsewhere [2] was used with new drift chamber readout capable of withstanding high rates without introducing deadtime. The spectrometer magnet was operated to give a p_T = 120 MeV/c kick, and the resolution in momentum (GeV/c) was $\sigma_p/p = 0.5\% + 0.015\%p$. The Liquid Krypton calorimeter, which has been very stable across years of running, provides an energy resolution of $\sigma_E/E = 3.2\%/\sqrt{E} + 9\%/E + 0.42\%$ where E is in GeV.

Kaon masses from three-pion decay are reconstructed with very good resolution (1.7 MeV for $K^\pm \to \pi^+\pi^-\pi^\pm$ decays and 1.2 MeV for $K^\pm \to \pi^0\pi^0\pi^\pm$ decays), allow for precise calibration and monitoring of the spectrometer performance.

2.3. Trigger

The trigger is based on a low level (L1) fast pre-selection (hodoscope multiplicity) and a high level (L2) selection (on-line processing of the information from calorimeter and drift chambers). From an input rate of 1 MHz, an output rate of 10 kHz triggers the read-out with negligible dead time.

The full on-line kinematics reconstruction at L2 and the narrow range of beam momenta allow for triggering on both three-track events and (two or) one-track events (with some π^o or photons in the LKr calorimeter) with adequate missing mass in

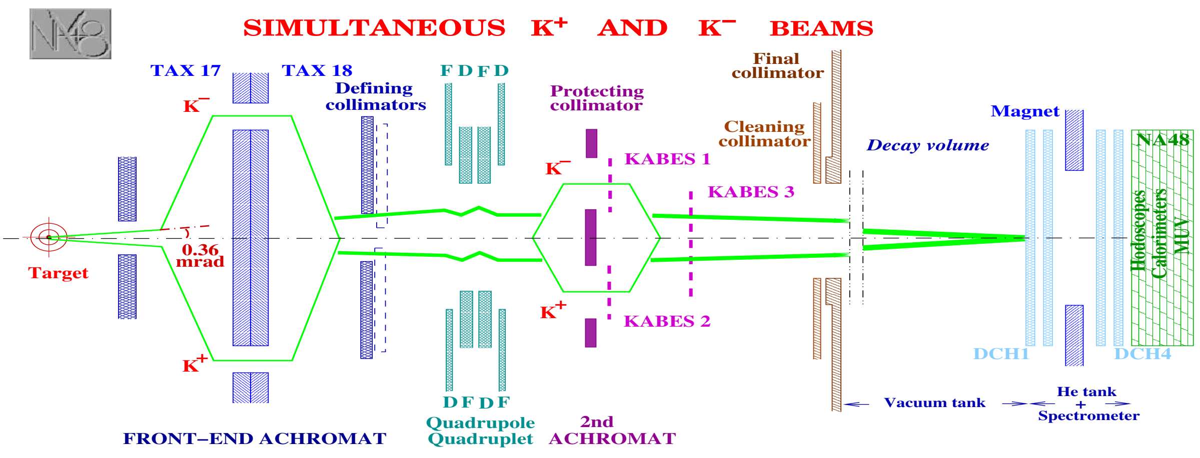

Figure 1. Schematic vertical section of the simultaneous K^+ and K^- beam line (not to scale).

order to reject the main background from $\pi^{\pm}\pi^{o}$.

2.4. Data Taking

Data were taken in the years 2003 and 2004 for a total of more than 100 days of effective running, providing more than 2 billion $K^{\pm} \to \pi^+\pi^-\pi^{\pm}$ and more than 100 million $K^{\pm} \to \pi^0\pi^0\pi^{\pm}$. In the following we report the analysis of the last 28 days of data taken in 2003, for which stable running conditions were reached.

3. Evaluation of the direct CP violation asymmetry in the "charged mode"

The absence of background in the $K^{\pm} \to \pi^+\pi^-\pi^{\pm}$ channel allows very simple online and off-line selection. Only information from the spectrometer and the hodoscope are used, while calorimeters and the muon veto will be used eventually to cross-check systematics uncertainties.

The analysis is arranged so that for K^+ and K^- decays the rate-dependent inefficiencies and the accidental effects are the same. Special care is devoted to equalize the geometrical acceptance, as will be clarified by the following description of the experimental procedure.

(1) In the search for the CP-violating asymmetry A_g only the slopes of ratios of normalized u-distributions are considered. In particular, the main observables for the asymmetry measurement are defined by comparing normalized u distributions of K^+ with $B^{\uparrow}$ and K^- with $B^{\downarrow}$. They illuminate the detector in almost the same way (in particular downstream of the spectrometer magnet) and the resulting asymmetry (A_R) is independent of acceptance:

$$R_R = \frac{N(u, K^+, B^{\uparrow})}{N(u, K^-, B^{\downarrow})} = \\ = \frac{1 + g_+ u}{1 + g_- u} \sim 1 + 2g \times A_R \times u$$

The analogous ratio (R_L) of u spectra of K^+ with $B^{\downarrow}$ and K^- with $B^{\uparrow}$ provides an independent measurement of the asymmetry (A_L). A deviation from zero in the average of these linear slopes $A = 0.5 \times (A_R + A_L)$, which is the measurement of A_g, would be a signal of CP-violation, as long as both the detector set-up and the beams are either *stable in time*[1] or *right-left symmetric.*

(2) In order to compensate for left-right asymmetries, the polarity of the relevant magnets along the beam line and the detector are periodically inverted during data taking.

[1] As will be clarified in (2), events K^+ with $B^{\uparrow}$ and K^- with $B^{\downarrow}$ are not collected simultaneously, which is the main origin of possible time instabilities

i) Every day the spectrometer magnetic field sign (B) is reversed ($B^{\downarrow}$ / $B^{\uparrow}$), in order to cope with the difference in detector illumination by K^+ and K^- decay products for a given sign of B.

ii) Every week the achromat magnetic field sign (A) is reversed ($A^{\uparrow}$ / $A^{\downarrow}$) in order to cope with the difference in the flight path of K^+ and K^- .

Obviously A_L and A_R require measurements with opposite sign B ($B^{\downarrow}$ or $B^{\uparrow}$), which are taken at different times. In 2003 the spectrometer field was reversed every $\sim$ 24 hours. In 2004 the field was reversed every few hours, in order to further reduce the effects of time instabilities (see below).

Some magnetic fields along the beam lines cannot be reversed (residual earth and stray magnetic fields[2]). They were accurately measured and taken into account in the reconstruction programs. The systematic uncertainty on A_g expected from these effects is estimated to be less than 10^{-5}.

(3) Concerning the variations in time of the detector response, two effects are found to be important:

i) Time instabilities of detector geometry mainly due to variations of the transverse alignment of the chambers, which were measured to drift by small amounts (below 70 μm);

ii) Time instabilities of the spectrometer magnetic field, whose value cannot be reproduced after sign reversal to better than 10^{-3}.

The right-left accuracy of the relative transverse DCH alignment is obtained by properly adjusting the transverse position of the chambers or equivalently, by imposing that K^+ and K^- three-pion decays have the same reconstructed invariant mass averaged over periods of $\sim$ 1 hour. The sensitivity of m_K is $\sim 150\,\mathrm{keV}/c^2$ for 100 mm displacement along the horizontal direction.

Finally the absolute momentum scale is tuned so that the reconstructed invariant mass of $K^{\pm} \to \pi^+\pi^-\pi^{\pm}$ decays equals, when averaged over data samples of $\sim$ 1 hour, the PDG value for the kaon mass[3]: $M_{K^+} = M_{K^-} = M_{K^{\pm}{}_{PDG}}$.

(4) Concerning variation in time of the two beam geometries, the most important effects are related to beam movements in short term (beam spill) and long term (hours) and to the imperfect overlap and coaxiality of the two beams.

Owing to the presence of the beam pipe pions at impact radius below 11 cm are lost, thus some radial cut is needed. In order to avoid systematics induced by a selection centered on the nominal beam axis, the real beam geometries are considered so that events are rejected if any pion intersects the volume of a cylinder of appropriate radius and with axis centered on the momentum-weighted barycenter (CoG) of the measured positive (negative) kaon beam. Thus the radial acceptance selection follows the movement of each beam.

In summary, the adopted experimental procedure ensures the highest immunity to even minor perturbations, and after the described kinematics reconstruction and selection 720 (400) million K^+ (K^-) are used to estimate the final asymmetry. This is shown in Fig. 2 as a function of time (i.e. for pair two consecutive days). An offset is applied to make the analysis blind.

Beside the above-mentioned main systematics, other sources of error are being investigated.

i) Residual acceptance affects (after symmetrizations) as well as resolution and non-linearity effects are studied by Monte Carlo;

ii) The trigger inefficiency is preliminarly estimated to affect the asymmetry at a level below 10^{-4};

iii) Accidental particles might affect the asymmetry only if asymmetrically correlated in space with K^+ and K^- ;

iv) The effects of π interactions with the detector material are investigated from other decay channels;

[2]The transverse momentum kick due to those fields is $\sim 10^{-4}$ relative to the spectrometer momentum kick.

[3]The sensitivity of m_K to a 10^{-3} change of the magnetic field induces a change in mass of about $20\,\mathrm{keV}/c^2$.

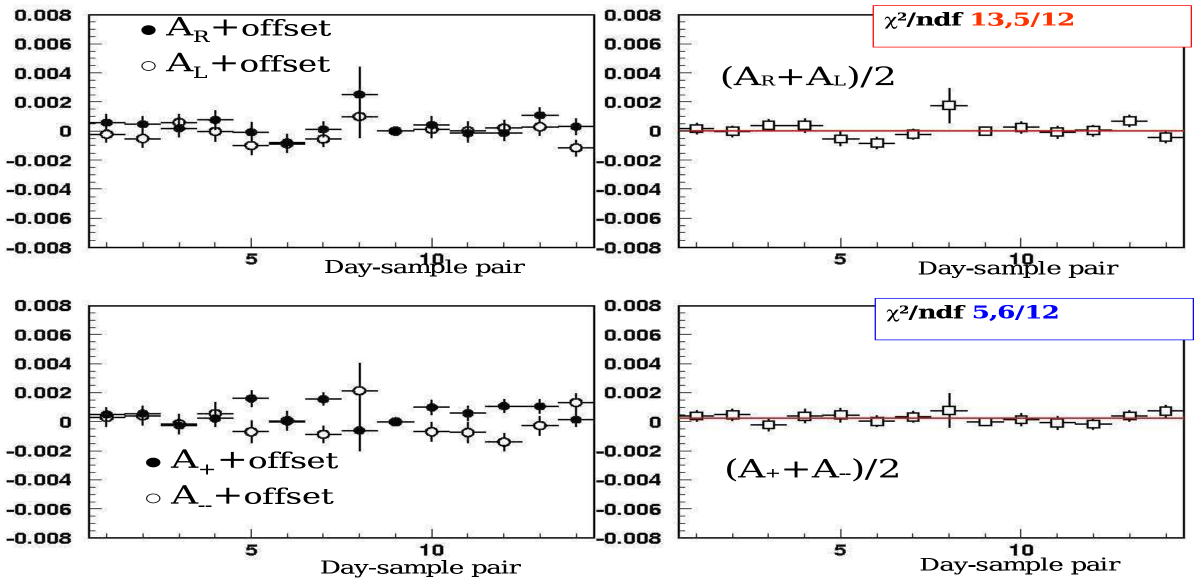

Figure 2. The measured asymmetries (above) A_R , A_L and their average are shown as a function of the 14 day-pairs. An offset is applied because the analysis is still blind. There is no evidence of dependence on time. The "fake asymmetries" A_+ and A_- are also shown (below) as a function of time.

v) The reconstruction efficiency, residual background and pion decay are studied both from other decay channels and Monte Carlo simulations.

In order to cross-check the effects from various systematics some "fake asymmetries" are studied, which should be zero from first principles, but can differ from zero due to detector/beam effects. For instance the slope asymmetries extracted from the ratios $\frac{N(u,K^+,B^\uparrow)}{N(u,K^+,B^\downarrow)}$ and $\frac{N(u,K^-,B^\uparrow)}{N(u,K^-,B^\downarrow)}$ (Fig. 2) are good indicators of the degree of left-right symmetry of the setup after the above-mentioned analysis procedure.

In addition an interesting control sample is provided by three-pion events where only two pions are detected in the spectrometer. Due to the measurement of the kaon kinematics provided by KABES, the two-pion events with completely measured kinematics give a useful handle to cross-check the systematics from reconstruction efficiency, pion interactions, pion decay and effects of accidental particles overlapping.

4. Study of the "neutral mode" $K^\pm \to \pi^0\pi^0\pi^\pm$ decay

The interest in the decay $K^\pm \to \pi^0\pi^0\pi^\pm$ has various reasons. First, although being statistically disfavored with respect to $K^\pm \to \pi^+\pi^-\pi^\pm$ it is more sensitive to the CP violating linear slope differences, and the expected uncertainty is also at the level of 10^{-4}.

A second reason is that this decay allows precision studies of π-π scattering lengths. The charge-exchange process $\pi^+\pi^- \to \pi^o\pi^o$ following a $K^\pm \to \pi^+\pi^-\pi^\pm$ decay gives non negligible under threshold and interferes destructively [4] with the direct emission $K^\pm \to \pi^0\pi^0\pi^\pm$. A high statistics and low systematics analysis of the shape of the $K^\pm \to \pi^0\pi^0\pi^\pm$ events as a function of the Dalitz variable u will then provide a precise (1%) measurement of the difference of scattering lengths a_0 and a_2.

It is important to underline that a precise ($\sim 1\%$) measurement of the π-π scattering-length parameter a_0 will also be obtained from the analysis of more than 10^6 K_{e4} decays collected in the years 2003 and 2004. The analysis of this channel has completely different systematics with respect to that discussed above, so that the two studies are complementary.

Eventually, as a byproduct of the $K^{\pm} \to \pi^0\pi^0\pi^{\pm}$ Dalitz plot analysis, and due to the excellent resolution on $m_{\pi^o\pi^o}$ ($\sim 350\,\mathrm{keV}/c^2$) of the LKr calorimeter in the Dalitz plot region of $m_{\pi^o\pi^o} = 2m_{\pi^{\pm}}$, the signal from the formation of the pionium atoms can be extracted and its branching ratio precisely measured.

At present, the analysis of $K^{\pm} \to \pi^0\pi^0\pi^{\pm}$ is less advanced than that of the "charged" mode. The event selection is based only on the spectrometer and LKr calorimeter information. KABES provides useful information on kaon kinematics. It is important to note that also this channel is background free.

The event sample analyzed so far comes from the 28-day data taking discussed above. From these data after the kinematics reconstruction and selection 23 (13) million K^+ (K^-) are used to estimate the charge asymmetry. The resulting statistical error on $A_{g'}$ is $\sim 5 \times 10^{-4}$. The final sample (including 2003 and 2004 data taking) to be used for measuring the asymmetry and the strong interaction parameters in the Dalitz plot will include more than 100 million $K^{\pm} \to \pi^0\pi^0\pi^{\pm}$ events.

Different sources of systematics with respect to the "charged" mode are expected. For instance the role of inner radial acceptance selection is less critical than it is in the $K^{\pm} \to \pi^+\pi^-\pi^{\pm}$ case.

The u variable can be reconstructed using either the information from the LKr calorimeter detection of the $\pi^o\pi^o$ pair independent of the spectrometer resolution, or using the spectrometer (charged π) and KABES information (kaon), independently of the calorimeter resolution. The former method provides very good resolution (especially at small $m_{\pi^o\pi^o}$ invariant mass), while the latter allows systematic studies of resolution and reconstruction effects (especially at high $m_{\pi^o\pi^o}$ masses).

5. Conclusions

The largest samples ever of $K^{\pm} \to \pi^+\pi^-\pi^{\pm}$ (more than 2×10^9 events), $K^{\pm} \to \pi^0\pi^0\pi^{\pm}$ (more than 10^8 events), including many rare decays were recently collected by NA48/2 and are being analyzed.

In the main channel $K^{\pm} \to \pi^+\pi^-\pi^{\pm}$, important sources of systematics in the study of the charge asymmetry are well identified and studied in detail. So far the uncertainty on the asymmetry ($< 3 \times 10^{-4}$) measured on a data sub-sample (less than half of the total) is still statistically dominated.

The $K^{\pm} \to \pi^0\pi^0\pi^{\pm}$ channel is very interesting, not only to measure the charged asymmetry, but also to determine with precision ($\sim 1\%$) important parameters of the pion strong interaction at low energy. Those results will be complemented by the study of the K_{e4} channel.

In addition the following kaon rare decays: $K^{\pm} \to \pi^{\pm}\pi^0\gamma$, $K^{\pm} \to \pi^{\pm}\gamma\gamma$ and $K^{\pm} \to \pi^{\pm}l^+l^-$ will provide further tests of NLO predictions of χPT.

REFERENCES

1. A. Lai *et al.*, Eur. Phys. J. C **22**, 231 (2001).
2. V. Fanti *et al.*, Phys. Lett. B **465**, 335 (1999)
3. S. Weinberg, Phys. Rev. Lett. **37**, 657 (1976).
4. N. Cabibbo, Phys. Rev. Lett. **93**, 121801 (2004).
5. Choong W-S., PhD Thesis LBNL-47014, Berkeley, 2000.
6. W. T. Ford *et al.*, Phys. Rev. Lett. **25**, 1370 (1970).
7. K. M. Smith *et al.*, Nucl. Phys. B **60**, 411 (1973) and Nucl. Phys. B **91**, 45 (1975).
8. Akopdzhanov *et al.*, hep-ex/04060008 (2004).
9. G. D'Ambrosio and G. Isidori, Int. Journ. of Mod. Phys. A **13**, (1998).
10. G. D'Ambrosio, G. Isidori and G. Martinelli, hep-ph/9911522 (1999).