Measurements of CP violation parameters at the NA48 experiment at CERN

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Abstract
Recent precise measurements of CP violation parameters in kaon decays at the NA48 experiment: indirect CPV parameter $|\eta_{+-}|$, and charge asymmetries in $K^\pm \to 3\pi$ decays, are presented.

Key words: CP violation, kaon decays

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1. Introduction

The CERN programme in experimental kaon physics of the last decade has been carried out by the NA48 series of experiments. NA48 has accomplished several physics subprogrammes based on data taken with $K_L$, $K_S$, $K^\pm$ and neutral hyperon beams in 1997–2004. The principal components of the experimental setup (modified and upgraded in the course of operation) are a beam line followed by a vacuum decay volume, a magnetic spectrometer consisting of four drift chambers, a trigger scintillator hodoscope, a liquid krypton electromagnetic calorimeter, a hadron calorimeter, and a muon detector [1].

The present paper reports a number recent precise measurements of CP violation (CPV) parameters: 1) the indirect CPV parameter $|\eta_{+-}|$ with $K_L \to \pi^+\pi^-$ decays; 2) the direct CP violating charge asymmetries of Dalitz plot slopes $A_g$ in $K^\pm \to 3\pi^\pm$ and $K^\pm \to \pi^\pm\pi^0\pi^0$ decays.

2. Measurement of the indirect CP violation parameter $|\eta_{+-}|$

The interest in a precise measurement of the indirect CPV parameter $|\eta_{+-}| = A(K_L \to \pi^+\pi^-)/A(K_S \to \pi^+\pi^-)$ stems, in particular, from the fact that its recent measurements by KTeV and KLOE experiments published in 2004 and 2006, respectively, differ by $\sim 5\%$, or more than four standard deviations, from the previous world average.
The NA48 measurement of $|\eta_{+-}|$ \cite{2} is based on a data set taken during two days of dedicated running in 1999. The directly measured quantity is the ratio of the decay rates $R = \Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_L \to \pi^0\pi^0)$; these decays are characterized by similar signatures involving two reconstructed tracks of charged particles. Then $|\eta_{+-}|$ is computed as

$$|\eta_{+-}| = \sqrt{\frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)} \cdot \frac{\text{BR}(K_L \to \pi^0\pi^0)}{\text{BR}(K_S \to \pi^0\pi^0)} \cdot \frac{\tau_{KL}}{\tau_{KS}}}.$$  \hspace{1cm} (1)

In this approach the $K_L$ and $K_S$ lifetimes $\tau_{KL}$ and $\tau_{KS}$, and the branching fractions $\text{BR}(K_L \to \pi^0\pi^0)$ and $\text{BR}(K_S \to \pi^0\pi^0)$ are external inputs taken from the best single measurements.

The data sample contains about $80 \times 10^6$ 2-track triggers. Event selection is similar for the $K_L \to \pi^+\pi^-$ and $K_L \to \pi^0\pi^0$ modes. A crucial difference is electron vs pion identification based on the ratio of particle energy deposition in the EM calorimeter to its momentum measured by the spectrometer (expected to be close to 1 for electrons). Particle identification efficiencies were directly measured and corrected for.

Samples of $47 \times 10^3 K_L \to \pi^+\pi^-$ and $5.0 \times 10^6 K_L \to \pi^0\pi^0$ candidates were selected, with about 0.5% background contamination in each. Acceptance corrections and background subtraction were performed by Monte Carlo simulation. Trigger efficiencies were measured directly with the data and corrected for. The most relevant systematic uncertainties come from precision of simulation of kaon momentum spectrum, precision of radiative corrections, and precision of trigger efficiency measurement. The final result is

$$\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_L \to \pi^0\pi^0) = (4.835 \pm 0.022_{\text{stat.}} \pm 0.016_{\text{syst.}}) \times 10^{-3}. \hspace{1cm} (2)$$

This leads, subtracting the $K_L \to \pi^+\pi^-\gamma$ direct emission contribution, but retaining the inner bremsstrahlung contribution, to

$$\text{BR}(K_L \to \pi^+\pi^-) = (1.941 \pm 0.019) \times 10^{-3}. \hspace{1cm} (3)$$

Finally, the CP violation parameter is computed according to (1) to be

$$|\eta_{+-}| = (2.223 \pm 0.012) \times 10^{-3}. \hspace{1cm} (4)$$

The result is in agreement with the recent KLOE and KTeV measurements, while it contradicts the 2004 PDG average. The latter disagreement is understood to be due to the improved treatment of the radiative corrections in the recent analyses.

3. Measurement of the direct CPV parameter $A_g$ in $K^{\pm} \to 3\pi$ decays

$K^{\pm} \to \pi^{\pm}\pi^{\pm}\pi^{-}$ and $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ decays are among the most promising processes in kaon physics to search for CPV phenomena. The decay density is parameterized (up to radiative and $\pi\pi$ rescattering effects studied separately \cite{37}) by a polynomial expansion

$$d^2\Gamma/dudv \sim 1 + gu + hu^2 + kv^2,$$

where $g, h, k$ are the so-called linear and quadratic Dalitz plot slope parameters ($|h|, |k| \ll |g|$), and the two Lorentz invariant kinematic variables $u$ and $v$ are defined as

$$u = \frac{s_3 - s_0}{m_\pi^2}, \quad v = \frac{s_2 - s_1}{m_\pi^2}, \quad s_i = (P_K - P_i)^2, \quad i = 1, 2, 3; \quad s_0 = \frac{s_1 + s_2 + s_3}{3}. \hspace{1cm} (6)$$
Here \( m_\pi \) is the charged pion mass, \( P_K \) and \( P_\pi \) are the kaon and pion four-momenta, the indices \( i = 1, 2 \) correspond to the two pions of the same electrical charge, and the index \( i = 3 \) to the pion of different charge. A non-zero difference \( \Delta g \) between the slope parameters \( g^+ \) and \( g^- \) describing the decays of \( K^+ \) and \( K^- \), respectively, is a manifestation of direct CP violation expressed by the corresponding slope asymmetry

\[
A_g = (g^+ - g^-)/(g^+ + g^-) \approx \Delta g/(2g).
\]

The above slope asymmetry is expected to be strongly enhanced with respect to the asymmetry of integrated decay rates. A recent full next-to-leading order ChPT computation \[3\] predicts \( A_g \) to be of the order of \( 10^{-5} \) within the SM. Calculations involving processes beyond the SM \[4,5\] allow a wider range of \( A_g \), including substantial enhancements up to a few \( 10^{-4} \).

A measurement of the quantity \( A_g \) was performed with a record data sample collected in 2003–04 with simultaneous \( K^+ \) and \( K^- \) beams \[8\]. The measurement method is based on the study of ratios of \( u \) spectra of \( K^+ \) and \( K^- \) decays, and exploits cancellations of major systematic effects due to the simultaneous collection of \( K^+ \) and \( K^- \) decays, and regular inversions of magnetic fields in the beam line and the spectrometric magnet, which allows achieving \( \sim 10^{-4} \) precision. The event samples are practically background-free, and contain \( 3.11 \times 10^9 \) \( K^\pm \to \pi^\pm \pi^\mp \pi^- \) candidates, and \( 9.13 \times 10^7 \) \( K^\pm \to \pi^\pm \pi^0 \pi^0 \) candidates (the \( K^+/K^- \) flux ratio, on which however the results do not depend, is 1.8).

The CP violating charge asymmetries of the linear slope parameter of the Dalitz plot of the \( K^\pm \to \pi^\pm \pi^\mp \pi^- \) and \( K^\pm \to \pi^\pm \pi^0 \pi^0 \) decays were measured to be

\[
A_g^e = (-1.5 \pm 1.5_{\text{stat.}} \pm 1.6_{\text{syst.}}) \times 10^{-4} = (-1.5 \pm 2.2) \times 10^{-4},
A_g^n = (1.8 \pm 1.7_{\text{stat.}} \pm 0.6_{\text{syst.}}) \times 10^{-4} = (1.8 \pm 1.8) \times 10^{-4}.
\]

The archived precision is more than an order of magnitude better that those of the previous measurements. The results do not show evidences for large enhancements due to non-SM physics, and can be used to constrain certain SM extensions predicting enhanced CPV effects.

4. Summary

A number of recent measurements of CPV parameters in kaon decays by the NA48 collaboration at CERN are presented. The achieved precisions are similar to or better than the best previous ones.

References

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