Recent results of the NA48/2 experiment

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NA48/2 collected the world largest sample of $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ decays. Direct Emission (DE) and Interference (INT) fractions with respect to the internal bremsstrahlung (IB) have been measured in the range $0 < T_\pi^* < 80$ MeV:

$$\begin{aligned} \text{Frac}_{\text{DE}}(0 < T_\pi^* < 80 \text{ MeV}) &= (3.32 \pm 0.15_{\text{sta}} \pm 0.14_{\text{sys}}) \times 10^{-2} \\ \text{Frac}_{\text{INT}}(0 < T_\pi^* < 80 \text{ MeV}) &= -(2.35 \pm 0.35_{\text{sta}} \pm 0.39_{\text{sys}}) \times 10^{-2} \end{aligned}$$

where T_π^* is the kinetic energy of the charged pion in the kaon rest frame.

A sample of 7253 $K^\pm \rightarrow \pi^\pm e^+ e^-$ decay candidates has been collected by the NA48/2 experiment. The branching ratio in the full kinematic range was measured to be $BR = (3.11 \pm 0.12) \cdot 10^{-7}$. For both decays CP violating asymmetry has been studied.

Introduction

The NA48/2 experiment at CERN SPS has collected the world largest amount of charged kaon decays. During two runs in 2003 and 2004, about $18 \cdot 10^9$ events were recorded. The main goal of NA48/2 was the search for direct CP violation in $K^\pm$ decays into three pions¹. However, given the high statistics achieved, many tests of Chiral Perturbation Theory (ChPT) were also possible in rare Kaon decays. In the following sections, recent tests of ChPT performed by the NA48/2 collaboration using $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ and $K^\pm \rightarrow \pi^\pm e^+ e^-$ decays will be presented.

1 Study of $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ decay

The total amplitude of the $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ decay is the sum of two terms: the inner bremsstrahlung associated with the $K^\pm \rightarrow \pi^\pm \pi^0$ decay with a photon emitted from the outgoing charged pion and the direct emission in which the photon is emitted at the weak vertex. Using the Low theorem the branching ratio of the IB component can be predicted from that of the $K^\pm \rightarrow \pi^\pm \pi^0$ channel, using QED corrections^{2,3}.

The DE term has been extensively studied in the framework of Chiral Perturbation Theory (ChPT)^{4,5,6}. Direct photon emission can occur through both electric and magnetic dipole transitions. The electric dipole transition can interfere with the IB amplitude giving rise to an interference term, which can have CP violating contributions. The magnetic part at order $O(p^4)$ in ChPT is the sum of two anomalous amplitudes: one reducible, that can be calculated using the Wess-Zumino-Witten functional, and one direct amplitude, whose size is not model independent but is expected to be small. There is no definite prediction from ChPT for the electric transition amplitude, which depends on undetermined constants.

The properties of the $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ decay can be conveniently described using the T_π^* , W variables, where T_π^* is the kinetic energy of the charged pion in the kaon rest frame and W is

Figure 1: a) Kaon mass distribution for $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ candidates b) Contour plot in the DE INT plane.

Lorentz invariant variable given by^{2,3}:

$$W^2 = \frac{(P_K \cdot P_\gamma)(P_\pi \cdot P_\gamma)}{(m_K m_\pi)^2} \quad (1)$$

P_K, P_π, P_γ are the 4 momenta of the kaon, the charged pion and the radiative gamma. Using these variables, the differential rate for the $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ process can be written as^{2,3,6}:

$$\frac{\partial^2 \Gamma^\pm}{\partial T_\pi^* \partial W} = \frac{\partial^2 \Gamma_{IB}^\pm}{\partial T_\pi^* \partial W} \left[1 + 2 \cos(\pm \phi + \delta_1^I - \delta_0^I) m_\pi^2 m_K^2 (|X_E|) W^2 + m_\pi^4 m_K^4 (|X_E|^2 + |X_M|^2) W^4 \right], \quad (2)$$

where $\frac{\partial^2 \Gamma_{IB}^\pm}{\partial T_\pi^* \partial W}$ is the differential rate for the IB component, ϕ is the CP violating phase, δ_L^I are the strong π - π re-scattering phases for a final state of momentum L and isospin I , and X_E, X_M are normalized electric and magnetic amplitudes respectively.

In the NA48/2 analysis the main background (BG) sources are $K^\pm \rightarrow \pi^\pm \pi^0$ and $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$. The first decay needs an accidental photon or an hadronic extra cluster to mimic the signal final state, while the second a lost or two fused γ . The rejection of $K^\pm \rightarrow \pi^\pm \pi^0$ relies on the $T_\pi^* < 80$ MeV cut. To suppress $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ BG the very good kaon mass resolution, (2.2 MeV) and the identification of fused gamma events by kinematical constraints have been used. In fig. 1 the data kaon mass spectrum is compared with the sum of signal plus BG MC. To correctly reconstruct the W value is very important to distinguish the radiative γ from the two coming from the π^0 decay. Using a set of cuts a misidentification probability, computed using MC simulation, lower than the permille for all the components has been achieved. At the end of the selection $\sim 600K$ $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ candidates have been identified with a BG contamination $< 1\%$ with respect to the DE component.

The extraction of DE and INT fractions relies on their different W distribution. An algorithm based on extended maximum likelihood assigns weights to MC W distributions of the three components to reproduce data. The fit has been performed in the region $0.2 < W < 0.9$. The following values for the DE and INT fractions have been obtained:

$$\text{Frac(DE)}_{T_\pi^* < 80 \text{ MeV}} = (3.32 \pm 0.15_{sta} \pm 0.14_{sys}) \times 10^{-2} \quad (3)$$

$$\text{Frac(INT)}_{T_\pi^* < 80 \text{ MeV}} = -(2.35 \pm 0.35_{sta} \pm 0.39_{sys}) \times 10^{-2} \quad (4)$$

with a χ^2 of the residuals with respect to zero of 14.3/13 d.o.f. This is the first measurement of non vanishing interference term in the $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ decay. The contour plot in Fig. 1 shows

the very high correlation (-0.93) of the two contributions. In order to compare the NA48 result with those from previous experiments, the ML fit has been redone setting the INT term to zero. The χ^2 of the residuals, 51/13 d.o.f., demonstrates that the data distribution cannot be properly described without an INT term.

To investigate CP violation in $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ with maximum statistical accuracy, the whole W spectrum has been considered. Candidates were separated depending on the reconstructed kaon charge, leading to a sample with 695×10^3 K^+ and 386×10^3 K^- . The simplest CP violation observable, the difference in the decay rates of K^+ and K^- , can be expressed in term of number of events as:

$$A_N = (N_+ - RN_-)/(N_+ + RN_-) \quad (1)$$

where N_+ , N_- are the number of K^+ , K^- decays to $\pi^\pm \pi^0 \gamma$, and R is the ratio of the number of K^+ to K^- in the beam, computed from another channel for which no CP violation is expected. The NA48/2 data has shown no CP violation asymmetry in the Dalitz plot for $K^\pm \rightarrow \pi^\pm \pi^0$ decays at the level of 10^{-4} ¹. The large number of $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ decays collected, allows the measurement of R with an accuracy of $\delta R/R \sim 2 \times 10^{-4}$. The ratio R has been computed in bins of kaon momentum and the asymmetry A_N calculated to be:

$$A_N = (0.0 \pm 1.0_{sta} \pm 0.6_{sys}) \times 10^{-3} \quad (2)$$

From the above value a limit for the rate asymmetry of $|A_N| < 1.5 \times 10^{-3}$ at 90% CL can be deduced. Another interesting observable of CP violation can be obtained by fitting the asymmetry distribution as function of the variable W . Using Equation 2, the following dependence of the asymmetry (A_W) is predicted:

$$\frac{dA_W}{dW} = \frac{eW^2}{1 + aW^2 + bW^4} \quad (3)$$

The parameters a and b are related to the fractions of DE and INT, while e is left free in the fit. Using the value of e obtained from the fit A_W is computed to be: $A_W = (-0.6 \pm 1.0) \times 10^{-3}$. The value of both A_N and A_W are consistent with no charge asymmetry.

2 The $K^\pm \rightarrow \pi^\pm e^+ e^-$ decay rate and form factor

The flavour-changing neutral current process $K^\pm \rightarrow \pi^\pm e^+ e^-$, induced at one-loop level in the Standard Model and highly suppressed by the GIM mechanism, is of particular interest. The decay is supposed to proceed through one photon exchange, resulting in a spectrum of the $z = (M_{ee}/M_K)^2$ kinematic variable sensitive to the form factor $W(z)$. In ChPT several models predicting the form factor characterizing the dilepton invariant mass spectrum, and thus the decay rate, have been proposed^{7,8}. The following parameterizations of the form factor $W(z)$ are considered in the analysis:

1. Linear: $W(z) = G_F M_K^2 f_0 (1 + \delta z)$
with free normalization and slope (f_0, δ).
2. Next-to-leading order ChPT: $W(z) = G_F M_K^2 f_0 (a_+ + b_+ z) + W^{\pi\pi}(z)$
with free parameters (a_+, b_+), and an explicitly calculated pion loop term $W^{\pi\pi}(z)$ ⁷.
3. The Dubna⁸ version of ChPT involving meson form factors: $W(z) \equiv W(M_a, M_\rho, z)$
with resonance masses (M_a, M_ρ) treated as free parameters.

After Moriond conference we discovered the existence of a 4th model for the $K^\pm \rightarrow \pi^\pm e^+ e^-$ form factor⁹. The result of the fit to all the four models can be found in reference¹⁰.

In NA48/2 analysis the $K^\pm \rightarrow \pi^\pm e^+ e^-$ rate is measured relatively to the abundant $K^\pm \rightarrow \pi^\pm \pi^0$. The final states of the signal and normalization channels contain identical sets of charged particles. Thus particle identification efficiencies, representing a significant source of systematic

Figure 2: a) Reconstructed $\pi^\pm e^+ e^-$ invariant mass: data (dots) and MC simulation (filled area)
b) Computed $d\Gamma_{ee}/dz$ and fit results according to the three considered models.

uncertainties, cancel in the first order. At the end of the selection on whole 2003 2004 data sample 7253 candidates $K^\pm \rightarrow \pi^\pm e^+ e^-$ are found in the signal region with 1.0% background contamination (see Fig.2).

The result of fits to the distribution of rate vs z , using the three different parametrization are shown in Fig.2. All the fits are of reasonable quality, however the linear form-factor model leads to the smallest χ^2 . Values of all form factor parameters can be found in reference¹⁰. Unfortunately the data sample is insufficient to distinguish between the models considered. The branching ratio in the full kinematic range, which is computed as the average between the two extremes corresponding to the models (1) and (3), and includes an uncertainty due to extrapolation into the inaccessible region $z < 0.08$, is:

$$BR_{MI} = (3.11 \pm 0.04_{sta} \pm 0.05_{sys} \pm 0.08_{ext} \pm 0.07_{mod}) \cdot 10^{-7} = (3.11 \pm 0.12) \cdot 10^{-7} \quad (8)$$

Finally, a first measurement of the direct CP violating asymmetry of K^+ and K^- decay rates in the full kinematic range was obtained by performing BR measurements separately for K^+ and K^- and neglecting the correlated uncertainties: $\Delta(K_{\pi ee}^\pm) = (BR^+ - BR^-)/(BR^+ + BR^-) = -2.2 \pm 1.5_{sta} \pm 0.6_{sys} \%$. A conservative limit for the charge asymmetry of $|\Delta(K^\pm \rightarrow \pi^\pm e^+ e^-)| < 1.1 \cdot 10^{-2}$ at 90% CL can be deduced. The result is consistent with no CP violation.

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