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Rare and Radiative Kaon Decays from the NA48/2 Experiment

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Results on rare charged kaon decays obtained by the NA48/2 experiment at the CERN/SPS are presented. The analysis of more than one million $K^{\pm} \rightarrow \pi^{+}\pi^{-}e^{\pm}\nu$ (K_{e4}) decays allowed to obtain very precise measurements of the decay form factors and $\pi\pi$ scattering lengths a_0^0 and a_0^2. This last result is in excellent agreement with predictions of Chiral Perturbation Theory (ChPT). In the decay $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$, both direct photon emission (DE) and interference (INT) with the inner bremsstrahlung (IB) amplitudes were measured with an improved precision, the INT term beeing observed for the first time. In addition the CP violating asymmetry between K^{+} and K^{-} decays was estimated. The branching fraction of the decay $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$, based on more than 1000 events, is also presented.

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1. Introduction

Chiral Perturbation Theory (ChPT), based on an effective Lagrangian [1], is a powerful tool to study low energy QCD. In the hadronic sector, calculations at LO, NLO and NNLO have now converged towards very precise predictions of the underlying constants of the theory, the S-wave $\pi\pi$ scattering lengths in the isospin 0 and 2 states, denoted a_0^0 and a_0^2, respectively. The study of K_{e4} decays is of particular interest due to the clean final state $\pi\pi$-interaction excluding any other hadron. Radiative kaon decays offer also a unique possibility to test predictions of the theory for very rare decay modes vanishing at first order.

The NA48/2 experiment was designed to search for direct CP violating asymmetries in $K^\pm$ decays [2] and to study rare kaon decays. It recorded several billions triggers over the 2003 – 2004 years. Two simultaneous K^+ and K^- beams were produced by 400 GeV primary protons from the CERN/SPS impinging on a Be target and selected in the momentum range (60 ± 3) GeV/c by two "achromats". The flux ratio of the K^+ and K^- beams was $R \simeq 1.8$. The NA48/2 detector is described in full detail elsewhere [3]. Its main components are: a magnetic spectrometer achieving a charged particle momentum resolution of $\sigma(p)/p = (1.02 \oplus 0.044p)\%$ (p in GeV/c); a two plane scintillator hodoscope used for trigger purposes, with a time resolution of $\sim$ 150 ps; a liquid-krypton calorimeter (LKr) with transverse segmentation into 13248 projective cells (2 cm x 2 cm each) and 27 radiation length thickness, measuring electron and photon energies with a resolution of $\sigma(E)/E = (3.2/\sqrt{E} \oplus 9.0/E \oplus 0.42)\%$ (E in GeV) and a space resolution for transverse position of isolated showers $\sigma_x = \sigma_y = (0.42/\sqrt{E} \oplus 0.06)$ cm.

2. The K_{e4} decay analysis

A total of 1 130 703 K_{e4} candidates (726 367 K^+ and 404 336 K^-) were selected from $\sim 2.5 \cdot 10^{10}$ triggers recorded in 2003 – 2004 using criteria described in [4].

There are two main background sources: $K^\pm \to \pi^+\pi^-\pi^\pm$ decays with subsequent $\pi \to e\nu$ decay or a pion mis-identified as an electron; and $K^\pm \to \pi^\pm\pi^0_D(\pi^0)$ decays with a subsequent Dalitz decay $\pi^0_D \to e^+e^-\gamma$ with one electron mis-identified as a pion and photon(s) undetected. The background contamination to the signal is estimated from "wrong sign" (WS) events ($\pi^\pm\pi^\pm e^\mp\nu$) and quoted (twice the observed numbers of WS events) at the low relative level of $\sim 0.6\%$.

Five Cabibbo-Maksymowicz variables [5] describe the K_{e4} decay: the squared invariant masses of the dipion ($S_\pi = M^2_{\pi\pi}$) and dilepton ($S_e = M^2_{e\nu}$); the angles θ_π and θ_e of π^+ and e^+ with respect to the dipion and dilepton directions (in the K rest frame) in the $\pi\pi$ and $e\nu$ planes, respectively; the angle ϕ between the dipion and dilepton rest frames. The decay matrix element is described in terms of the above five kinematic variables and of four hadronic complex form factors which can be developed in a partial wave expansion with respect to the $\cos\theta_\pi$ variable, introducing three (F,G,R) axial-vector and one (H) vector complex form factors. Within the current experimental precision, K_{e4} decay is well described by S- and P-wave terms and depends only on four real form factors F_s, F_p, G_p, H_p and a single phase shift $\delta = \delta_s - \delta_p$ to be extracted from the data distributions in the five-dimensional space.

Distributing data events over a grid of 15 000 equi-populated boxes, a combined fit of form factors and phase shift δ was performed in the five-dimensional space to obtain model-independent

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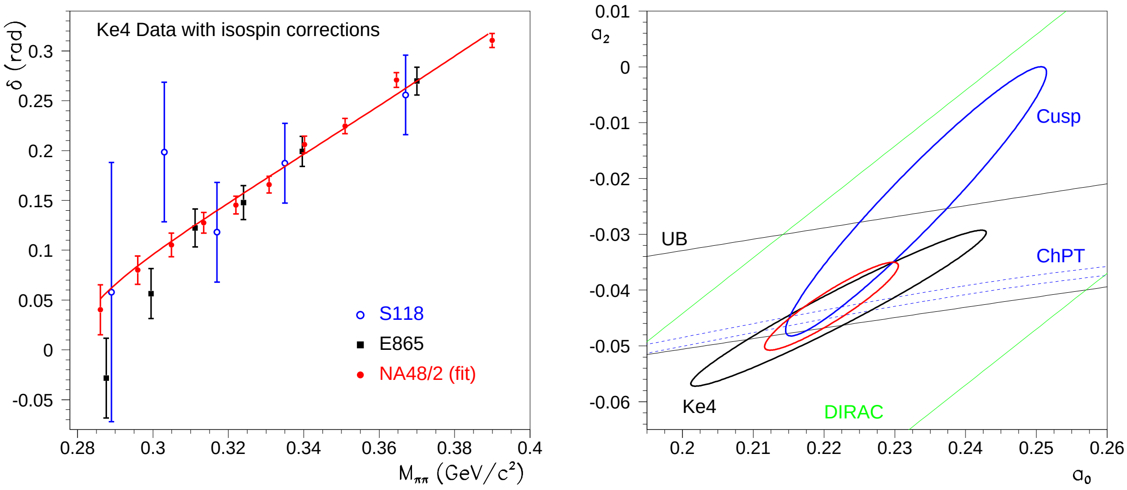

Figure 1: *Left*: phase shift (δ) measurements corrected for isospin symmetry breaking for all K_{e4} available results [6, 7] (the line corresponds to the two-parameter fit of the NA48/2 data alone); *Right*: K_{e4} and cusp [10] results from the two-parameter fits (68% CL ellipses), the smallest contour corresponds to the combination of both NA48/2 results; the dashed lines to the ChPT constraint band, the solid lines to the Universal Band (UB) [9], the other lines correspond to the DIRAC result band [11].

results as a function of $M_{\pi\pi}$. Figure 1-left shows the measured phase shift variation together with the earlier measurements of the S118 (Geneva-Saclay) and BNL E865 experiments [6, 7]. Isospin symmetry breaking effects ($m_{\pi^+} \neq m_{\pi^0}$, $m_d \neq m_u$) neglected in previous studies, are now considered [8] and induce a coherent shift of all phase values of 12 to 15 mrad in the considered range.

Numerical solutions of the Roy equations [9], which relate scattering lengths (a_0^0, a_0^2) and $\pi\pi$ phases, are used to extract the corresponding values from the phase shift measurements. A two-parameter fit where both a_0^0 and a_0^2 are free parameters gives:

$$a_0^0 = \ 0.2220 \pm 0.0128_{stat} \pm 0.0050_{syst} \pm 0.0037_{th},$$
$$a_0^2 = -0.0432 \pm 0.0086_{stat} \pm 0.0034_{syst} \pm 0.0028_{th}.$$

The theoretical error is dominated by the experimental precision of the inputs to the Roy equations (for a_0^2) and the neglected higher order terms when introducing the mass effects (for a_0^0).

The resulting 68% CL ellipse is presented in Fig.1-right (K_{e4}) together with the result of another NA48/2 $\pi\pi$ scattering lengths measurement from the fit of the $\pi^0\pi^0$ invariant mass distribution of $K^\pm \to \pi^\pm\pi^0\pi^0$ decays (cusp effect) [10]. The combined result of K_{e4} and cusp analyses is also shown on the figure as the smallest ellipse. All results strongly confirm the precise predictions of ChPT [12]: $a_0^0 = 0.220 \pm 0.005$. $a_0^2 = -0.0444 \pm 0.010$. Taking into account an additional ChPT constraint between a_0^2 and a_0^0 [12], the one-parameter fit result is $a_0^0 = 0.2206 \pm 0.0049_{stat} \pm 0.0018_{syst} \pm 0.0064_{th}$, corresponding to $a_0^2 = -0.0442 \pm 0.0008_{ChPT}$.

Full details of the form factors measurement can be found in a forthcoming publication [13].

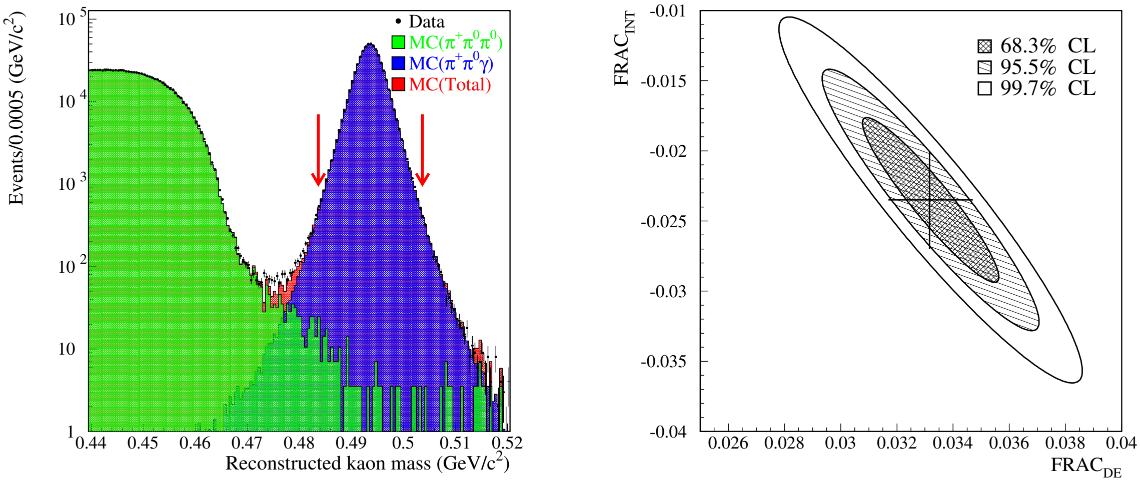

Figure 2: *Left*: Reconstructed invariant mass of the $\pi^{\pm}\pi^0\gamma$ system for data and simulated signal and background; *Right*: Measured DE and INT terms with several CL contours and a -0.93 correlation coefficient. The error bars correspond to 1σ statistical uncertainties.

3. Study of $K^{\pm} \to \pi^{\pm}\pi^0\gamma$ decay

The total amplitude of the $K^{\pm} \to \pi^{\pm}\pi^0\gamma$ decay is the sum of two terms: inner bremsstrahlung (IB) and direct emission (DE). The IB component can be predicted from QED corrections to $K^{\pm} \to \pi^{\pm}\pi^0$ decay with a photon emitted from the charged pion. For the DE contribution, the photon is emitted at the weak vertex. This can occur through both electric (E) and magnetic (M) dipole transitions. The M part consists of two amplitudes, one being reducible and the other expected to be small. No definite prediction exists for the E part. The E transition can interfere with the IB component giving rise to an interference term (INT), which can have CP violating contributions. In ChPT calculations, DE arises only at $O(p^4)$ and cannot be evaluated in a model independent way. Therefore an experimental measurement of both DE and INT terms allows to disentangle the E and M contributions. The $K^{\pm} \to \pi^{\pm}\pi^0\gamma$ decay properties can be described in terms of the variables T^*_{π}, the $\pi^{\pm}$ kinetic energy in the kaon rest frame, and $W^2 = (P_K \cdot P_{\gamma})(P_{\pi} \cdot P_{\gamma})/(m_K m_{\pi})^2$, where P_K, P_{π}, P_{γ} are the $K^{\pm}$, $\pi^{\pm}$ and γ four-momenta, respectively.

The excellent performances of the LKr calorimeter allow a strong rejection of the background component and the extension of the kinematic region to $0 < T^*_{\pi} < 80$ MeV. The mass distribution of the 600k $K^{\pm} \to \pi^{\pm}\pi^0\gamma$ selected decays with a background level below 10^{-4} is shown in Fig.2-left. An extended maximum-likelihood fit of the W distribution in the range [0.2,0.9] was performed using simulated distributions of the IB, DE and INT contributions and gave the following results:

$$\mathrm{Frac(DE)}_{0<T^*_{\pi}<80\ \mathrm{MeV}} = BR_{DE}/BR_{IB} = (3.32 \pm 0.15_{stat} \pm 0.14_{syst}) \cdot 10^{-2},$$
$$\mathrm{Frac(INT)}_{0<T^*_{\pi}<80\ \mathrm{MeV}} = BR_{INT}/BR_{IB} = (-2.35 \pm 0.35_{stat} \pm 0.39_{syst}) \cdot 10^{-2}.$$

This is the first observation of an interference term (INT) in the $K^{\pm} \to \pi^{\pm}\pi^0\gamma$ decay. The correlation in the (DE,INT) plane is shown in Fig.2-right.

In addition, possible direct CP violation in the decay rate asymmetry of K^+ and K^- was investigated. The asymmetry can be expressed in terms of the total number of events as $A_N = (N^+ - RN^-)/(N^+ + RN^-)$, where N^+ and N^- are the numbers of K^+ and K^- decays, respectively, and R is the ratio of the numbers of K^+ and K^- in the beam. Using the full statistics of more than one million decays, a value $A_N = (0.0 \pm 1.2) \cdot 10^{-3}$ has been obtained. The measured asymmetry of the W spectra gives another result for CP violation in the INT term: $A_W = (-0.6 \pm 1.0) \cdot 10^{-3}$, in good agreement with the A_N value. The detailed analysis has been reported in [14].

4. The $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$ decay

This decay is of high interest in ChPT as tree-level contributions $O(p^2)$ vanish, thus providing sensitivity to $O(p^4)$ and $O(p^6)$. At $O(p^4)$, only two $\Delta I = 1/2$ invariant amplitudes contribute, $A(z,\hat{c})$ and $C(z)$, where $z = m^2_{\gamma\gamma}/m^2_K$ and $m_{\gamma\gamma}$ is the 2γ's invariant mass. The only parameter $\hat{c}$ fixes the branching ratio and the $m_{\gamma\gamma}$ spectrum shape. The C term accounts for $\sim 10\%$ of the total amplitude and can be calculated. A sample of 1 164 fully reconstructed candidates was selected with 3.3% background, mainly from $K^{\pm} \rightarrow \pi^{\pm}\pi^0\gamma$ decays. The reconstructed $m_{\gamma\gamma}$ spectrum above 0.2 GeV/c^2 exhibits the expected cusp at $2m_{\pi^+}$. The model dependent branching ratio, using a ChPT $O(p^6)$ simulation and $\hat{c} = 2$ to compute detector acceptance, is obtained:

$$BR(K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma) = (1.07 \pm 0.04_{stat} \pm 0.08_{syst}) \cdot 10^{-6}.$$

It is compatible with the less precise measurement of the E787 experiment based on 31 events [15].

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