PRECISION MEASUREMENTS OF RADIATIVE CHARGED KAON DECAYS AT NA48/2*

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This paper presents results obtained by the NA48/2 experiment at CERN SPS. Data samples of 1.24×10^5 $K^\pm \to \pi^\pm\pi^0\gamma$, 7146 $K^\pm \to \pi^\pm e^+e^-$, 1164 $K^\pm \to \pi^\pm\gamma\gamma$ and 120 $K^\pm \to \pi^\pm e^+e^-\gamma$ decays (this last one observed for the first time) have been collected with small background, allowing precise measurements of branching fractions and other characteristics of these rare kaon decays.

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1. Introduction

Radiative nonleptonic kaon decays are a source of information on the structure of the weak interactions at low energies and provide crucial tests of Chiral Perturbation Theory (ChPT). This paper reviews recent results on $K^\pm \to \pi^\pm\pi^0\gamma$, $K^\pm \to \pi^\pm e^+e^-$, $K^\pm \to \pi^\pm\gamma\gamma$ and $K^\pm \to \pi^\pm e^+e^-\gamma$ decays, obtained by the NA48/2 experiment at the CERN SPS.

The $K^\pm \to \pi^\pm\pi^0\gamma$ decay is known to proceed mainly through Inner Bremsstrahlung (IB), with a small but interesting component due to Direct Emission (DE). The IB contribution has been known [1] for a long time, while up to now the DE contribution has only been measured [2–5] in a limited kinematic range in order to avoid large background contaminations.

The flavor-changing neutral current process $K^\pm \to \pi^\pm e^+e^-$, arising at one-loop level in the Standard Model and highly suppressed by the GIM mechanism [6], has been described by the ChPT [7]: two models [8,9] provide

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parametrizations for the shape of the dilepton invariant mass spectrum and the decay rate. The $K^+ \to \pi^+ e^+ e^-$ decay has been first observed at CERN PS [10] and later studied at BNL [11, 12] with higher statistics.

The $K^\pm \to \pi^\pm \gamma\gamma$ and $K^\pm \to \pi^\pm e^+ e^- \gamma$ decays are induced at one-loop level in the ChPT [13]. The decay rates and spectra have been computed at leading and next-to-leading order [14, 15], and strongly depend on a single theoretically unknown parameter $\hat{c}$. Only one observation of the $K^+ \to \pi^+ \gamma\gamma$ decay has been reported [16] while the $K^- \to \pi^- \gamma\gamma$ and $K^\pm \to \pi^\pm e^+ e^- \gamma$ decays were never observed.

2. The NA48/2 experiment

The NA48/2 experiment took data in 2003 and 2004 using two simultaneous beams of (60 ± 3) GeV/c oppositely charged kaons, produced by 400 GeV/c protons from CERN SPS impinging on a beryllium target.

The charged particle reconstruction is provided by a magnetic spectrometer, consisting of a dipole magnet and four drift chambers, with a spatial resolution of 100 μm and a momentum resolution $\Delta p/p = (1.0 \oplus 0.044p$ [GeV/c])%.

The energy and position of photons and electrons are precisely measured by a liquid kripton electromagnetic calorimeter, consisting of a $27X_0$ almost homogeneous ionization chamber with high-granularity tower read-out: its energy resolution is $\Delta E/E = 3.2\%/\sqrt{E[\mathrm{GeV}]} \oplus 9\%/E[\mathrm{GeV}] \oplus 0.42\%$ and its spatial resolution about 1.5 mm.

A scintillator hodoscope for fast triggering and precise time measurement, an iron-scintillator hadron calorimeter and veto counters for muons and photons complete the experimental apparatus, a detailed description of which can be found in [17].

3. $K^\pm \to \pi^\pm \pi^0 \gamma$

The $K^\pm \to \pi^\pm \pi^0 \gamma$ decay amplitude is the sum of two terms: the dominant one arises from the inner bremsstrahlung (IB) associated to the decay $K^\pm \to \pi^\pm \pi^0$ in which the photon is emitted from the outgoing charged pion, the other is due to direct emission (DE) in which the photon is radiated in the intermediate states of the decay. The DE term contains a magnetic amplitude which can be evaluated using ChPT and an electric amplitude for which there is no definite theoretical prediction. The latter can be determined by measuring its interference (INT) with the purely electric IB.

In order to kinematically separate (on a statistical basis) IB, DE and INT components in the differential decay width we use the Lorentz invariant variable W, defined as $W^2 = (P_K^* \cdot P_\gamma^*)(P_\pi^* \cdot P_\gamma^*)/(m_K m_\pi)^2$, where P_x^* is the

4-momentum of the particle $x = K^\pm, \pi^\pm, \gamma$. The differential decay width depends on both W and the charged pion kinetic energy T^*_π in the kaon rest frame. Integrating on T^*_π we obtain an expression that splits the different contributions into terms with different powers of W:

$$\frac{d\Gamma^\pm}{dW} \simeq \frac{d\Gamma^\pm_{\mathrm{IB}}}{dW}\left[1+2\frac{m_\pi^2}{m_K^2}W^2|E|\cos((\delta_1-\delta_0)\pm\phi)+\frac{m_\pi^4}{m_K^4}W^4\left(|E|^2+|M|^2\right)\right], \quad (1)$$

where $d\Gamma^\pm_{\mathrm{IB}}/dW$ is calculable [18] from $\Gamma(K^\pm \to \pi^\pm\pi^0)$ thanks to the Low theorem, $|E|$ and $|M|$ describe electric and magnetic DE transitions, $(\delta_1-\delta_0)$ is the difference between p- and s-wave $\pi^\pm\pi^0$ phase shifts, ϕ is an unknown phase responsible for CP violation and the three terms in the sum represent IB, INT and DE contributions, respectively. A recent theoretical work by Cappiello and D'Ambrosio [18] suggest the presence of a form factor in the DE term, not yet included in the present analysis, that would modify Eq. (1).

Measurements of the DE component have been performed up to now [2–5] ignoring the INT term, in the kinematical region 55 MeV $< T^*_\pi <$ 90 MeV, which is less affected by $K^\pm \to \pi^\pm\pi^0(\pi^0)$ background.

In order to improve the sensitivity to DE and INT components, events have been selected in a wider kinematic region (defined by $T^*_\pi <$ 80 MeV and $E_\gamma >$ 5 GeV), containing a large fraction of DE and INT spectra. An almost background-free data sample of 1.24×10^5 $K^\pm \to \pi^\pm\pi^0\gamma$ candidate events has been selected from data taken in 2003.

The measured W distribution has been fitted to the sum of Monte Carlo simulated W spectra for IB, DE and INT, obtaining the following preliminary values for the fractions of DE and INT, normalized to IB:

$$\mathrm{Frac(DE)} \equiv \Gamma(\mathrm{DE})/\Gamma(\mathrm{IB}) = (3.35 \pm 0.35_{\mathrm{stat.}} \pm 0.25_{\mathrm{syst.}}) \times 10^{-2}, \quad (2)$$
$$\mathrm{Frac(INT)} \equiv \Gamma(\mathrm{INT})/\Gamma(\mathrm{IB}) = (-2.67 \pm 0.81_{\mathrm{stat.}} \pm 0.73_{\mathrm{syst.}}) \times 10^{-2}. \quad (3)$$

This is the first measurement of a non vanishing interference term in the $K^\pm \to \pi^\pm\pi^0\gamma$ decay. The DE and INT contributions are very much correlated ($\rho = -0.92$). A substantial reduction in both statistical and systematic errors is foreseen using the full 2003–2004 data set.

4. $K^\pm \to \pi^\pm e^+e^-$

The $K^\pm \to \pi^\pm e^+e^-$ ($K^\pm_{\pi ee}$) decay proceeds through suppressed FCNC, with an internal conversion of a virtual photon in an e^+e^- pair. Its differential decay rate can be written [8] as $d\Gamma/dz = \alpha^2 M_K P(z)\,|W(z)|^2$, where α is the fine-structure constant, M_K the mass of the charged kaon, $P(z)$ is a phase space factor (described in Eq. (2.3) of Ref. [8]), $W(z)$ is a Lorentz-invariant form factor completely specifying the dynamics of the decay, $z = M_{ee}^2/M_K^2$ and M_{ee} is the e^+e^- invariant mass.

Three different parametrizations of $W(z)$ have been considered in this analysis: a linear function $W(z) = G_{\rm F} M_K^2 f_0(1 + \delta\, z)$ with free parameters f_0 and δ, and two models [8, 9] based on ChPT.

The selected data sample contains 7146 candidates, with a residual background of 0.6%. The more abundant $K^\pm \to \pi^\pm \pi^0_D$ decay is used as normalization channel. Background is evaluated from the data, using "wrong-sign" ($\pi^\mp e^\pm e^\pm$) and unphysical "$Q = 3$" ($\pi^\pm e^\pm e^\pm$) events.

The model-independent BR in the interval $z > 0.08$ (corresponding to the low-background region $M_{ee} > 140$ MeV$/c^2$) is measured to be:

$$\mathrm{BR}(K^\pm_{\pi ee},\, z > 0.08) = (2.26 \pm 0.03_{\rm stat.} \pm 0.03_{\rm syst.} \pm 0.06_{\rm ext.}) \times 10^{-7}\,, \quad (4)$$

where the third error arises from the uncertainties in the BR of the normalization channel [19]. The three models mentioned above have been used to extrapolate the measured z distribution into the region $0 < z < 0.08$ and calculate the full (model-dependent) BR. All of them provide reasonably good fits to the data. Results are then combined, introducing an additional uncertainty due to the model dependence:

$$\mathrm{BR}(K^\pm_{\pi ee}) = (3.08 \pm 0.04_{\rm stat.} \pm 0.04_{\rm syst.} \pm 0.08_{\rm ext.} \pm 0.07_{\rm model}) \times 10^{-7}\,. \quad (5)$$

These results are in good agreement with previous measurements which, however, have been performed only on K^+ decays.

We have the opportunity to compare, for the first time, the πee decays of K^+ and K^- and measure the CP-violating asymmetry

$$\Delta(K^\pm_{\pi ee}) = \frac{\mathrm{BR}^+ - \mathrm{BR}^-}{\mathrm{BR}^+ + \mathrm{BR}^-} = (-2.1 \pm 1.5_{\rm stat.} \pm 0.3_{\rm syst.}) \times 10^{-2}\,. \qquad (6)$$

The measured asymmetry is consistent with CP conservation, although far from the sensitivity required to check expectations by Standard Model ($\sim 10^{-5}$) and SUSY ($\lesssim 10^{-3}$). A paper describing this analysis [20] has been recently submitted for publication.

5. $K^\pm \to \pi^\pm\gamma\gamma$

The $K^\pm \to \pi^\pm\gamma\gamma$ decay is entirely due to loop diagrams: the leading order contribution is at order $O(p^4)$ in ChPT and contains an undetermined constant $\hat{c}$ of order 1 [14], influencing both the predicted BR [13] and the two-photon invariant mass ($M_{\gamma\gamma}$) spectrum. The only existing measurement [16] of this decay, based on 31 $K^+ \to \pi^+\gamma\gamma$ events, obtains a BR of $(1.10\pm0.32)\times 10^{-6}$ and a parameter value $\hat{c} = 1.8 \pm 0.6$.

The $K^{\pm} \to \pi^{\pm}\gamma\gamma$ decay rate is measured using as normalization channel the $K^{\pm} \to \pi^{\pm}\pi^{0}$ decay. These channels have identical particle composition of the final states, and the event selection of the signal and normalization data samples only differ in the cut on the $\gamma\gamma$ invariant mass. About 40% of the total NA48/2 data set has been analyzed, and 1164 $K^{\pm} \to \pi^{\pm}\gamma\gamma$ decay candidates are found, with a 3.3% background contamination (estimated by Monte Carlo) from $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ events. The reconstructed spectrum of $\gamma\gamma$ invariant mass in the accessible kinematic region $M_{\gamma\gamma} > 0.2$ GeV$/c^2$ is shown in Fig. 1, along with a Monte Carlo expectation assuming ChPT $O(p^6)$ distribution [14] with a realistic parameter $\hat{c} = 2$. A cusp-like enhancement of the decay rate at the $\pi\pi$ mass threshold $m_{\gamma\gamma} \approx 280\,\mathrm{MeV}/c^2$ is predicted by ChPT, independently of the value of the $\hat{c}$ parameter. The observed spectrum provides the first clear evidence for this effect.

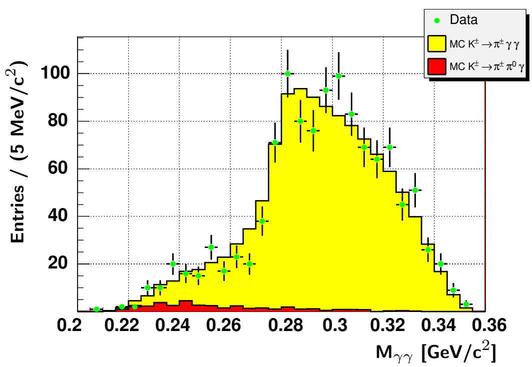

Fig. 1. Two-photon invariant mass spectrum in $K^{\pm} \to \pi^{\pm}\gamma\gamma$ events.

As a first step of the analysis, the branching fraction of the decay is measured assuming the ChPT $O(p^6)$ shape of the $M_{\gamma\gamma}$ spectrum, with a fixed parameter $\hat{c} = 2$. We obtain the following preliminary result:

$$\mathrm{BR}(K^{\pm} \to \pi^{\pm}\gamma\gamma) = (1.07 \pm 0.04_{\mathrm{stat.}} \pm 0.08_{\mathrm{syst.}}) \times 10^{-6}\,, \tag{7}$$

in agreement with the ChPT computation with $\hat{c} = 2$.

In order to determine the value of the $\hat{c}$ parameter, a combined fit of the decay rate and the shape of the $M_{\gamma\gamma}$ distribution is in progress.

6. $K^{\pm} \to \pi^{\pm}e^{+}e^{-}\gamma$

The $K^{\pm} \to \pi^{\pm}e^{+}e^{-}\gamma$ decay kinematics is very similar to that of the $K^{\pm} \to \pi^{\pm}\gamma\gamma$ decay, with one of the photons internally converting into an $e^{+}e^{-}$ pair. Model dependent theoretical estimates based on ChPT [15] predict a BR in the range $(0.9\text{–}1.6)\times 10^{-8}$.

The $K^{\pm} \to \pi^{\pm}e^{+}e^{-}\gamma$ decay rate is measured relatively to the $K^{\pm} \to \pi^{\pm}\pi^{0}_{D}$ channel, having the same particle composition in the final state.

From the analysis of the full NA48/2 data sample 120 $K^{\pm} \to \pi^{\pm}e^{+}e^{-}\gamma$ decay candidates are found in the selected kinematic region ($\pi^{\pm}e^{+}e^{-}\gamma$ invariant mass within 480 and 505 MeV$/c^2$, and $M_{ee\gamma} > 260\,\mathrm{MeV}/c^2$), with a Monte Carlo evaluated background of 6.1%. The distribution of the $e^{+}e^{-}\gamma$ invariant mass ($M_{ee\gamma}$) is shown in Fig. 2, along with a Monte Carlo evaluation for background contributions.

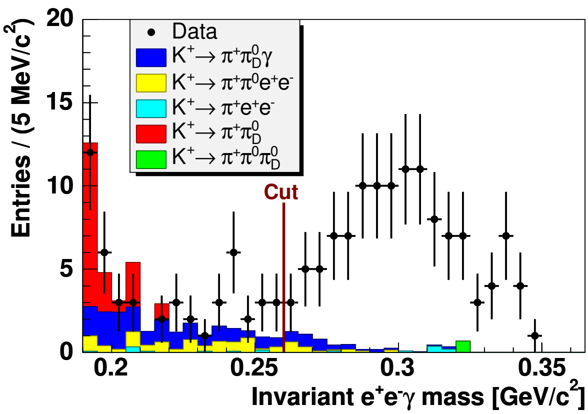

Fig. 2. $e^{+}e^{-}\gamma$ invariant mass spectrum in $K^{\pm} \to \pi^{\pm}e^{+}e^{-}\gamma$ events.

This measurement represents the first observation of the rare decay $K^{\pm} \to \pi^{\pm}e^{+}e^{-}\gamma$. More details on the analysis can be found in [21]. The branching fraction in the selected kinematic range is measured to be:

$$\mathrm{BR}\left(M_{ee\gamma} > 0.26\ \mathrm{GeV}/c^2\right) = (1.19 \pm 0.12_{\mathrm{stat.}} \pm 0.04_{\mathrm{syst.}}) \times 10^{-8}\,. \qquad (8)$$

In order to extract the $\hat{c}$ parameter, the measured $M_{\gamma\gamma}$ distribution has been fitted to the absolute prediction of Ref. [15] in the range $M_{\gamma\gamma} > 0.26$ GeV$/c^2$, obtaining $\hat{c} = 0.90 \pm 0.45$, where the error is dominated by the statistics. This result is in agreement within about 1.2 standard deviations with the value of 1.8 ± 0.6 previously measured in $K^{+} \to \pi^{+}\gamma\gamma$ [16]. Using our measured $\hat{c}$ value and Ref. [15] to compute the branching fraction in the region $M_{\gamma\gamma} < 0.26$ GeV$/c^2$, we obtain for the total branching fraction

$$\mathrm{BR}\left(K^{\pm} \to \pi^{\pm}e^{+}e^{-}\gamma\right) = (1.29 \pm 0.13 \pm 0.03_{\hat{c}}) \times 10^{-8}\,, \qquad (9)$$

where the first error is the overall experimental one (statistical and systematic) and the second reflects the uncertainty on $\hat{c}$.

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