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# The $K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-}$ decay: first observation and study with the NA48/2 experiment at CERN

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The NA48/2 experiment collected data in 2003 and 2004 with the main purpose to study direct CP violation in charged kaons decaying into three pions. Thanks to the huge statistics collected, other studies are also possible. This paper reports the first observation of the $K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-}$ decay from an exposure of $1.7 \times 10^{11}$ charged kaon decays. The Branching Ratio has been determined to be $\mathrm{BR}(K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-}) = (4.24 \pm 0.14) \times 10^{-6}$, using a sample of 4919 candidates with 4.9% background contamination. Studies of the kinematic space and of several P- and CP-violating asymmetries are also reported.

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PoS(EPS-HEP2019)237

## 1. Introduction and theoretical framework

The study of kaons has always been an important source for the investigation of the flavour sector of fundamental interactions and for the understanding of the symmetries of nature. Complementary to the high energy frontier, the flavour sector can probe the high energy scale exploiting the precision frontier. In addition, processes that are suppressed in the Standard Model (SM) are very sensitive to New Physics (NP), therefore the study of rare kaon decays can provide a deeper insight in fundamental physics. In particular, radiative kaon decays can probe models describing low-energy quantum chromodynamics (QCD), such as the chiral perturbation theory (ChPT), an effective field theory valid below a scale $\mathscr{O}(1\ \text{GeV})$.

The radiative decay $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{+}e^{-}$ is of special interest, since it has never been observed so far. It proceeds through virtual photon exchange followed by internal conversion into an electron-positron pair: $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma^{*} \rightarrow \pi^{\pm}\pi^{0}e^{+}e^{-}$. Two different mechanisms can produce the virtual photon: the Inner Bremsstrahlung (IB) where the $\gamma$ is emitted by one of the charged mesons in the initial or final state, and the Direct Emission (DE) where the $\gamma$ is radiated off at the weak vertex. The differential decay rate consists of three terms: the dominant long-distance IB contribution, the DE component (with electric (E) and magnetic (M) parts), and their interference, that includes different contributions (IB-E, IB-M and E-M). The theoretical papers that investigate radiative kaon decays [1, 2, 3, 4] predict the BR of IB, DE and INT components of the decay, also on the basis of previous results from NA48/2 [5].

## 2. The NA48/2 experiment

The main purpose of the NA48/2 experiment was to search for direct CP violation in charged kaon decays into three pions [6]. A measurement of the charge asymmetry, using simultaneous $K^{+}$ and $K^{-}$ beams and samples of fully reconstructed $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$ and $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$ decays, from data collected in 2003-2004, allowed a result of an unprecedented precision. At the same time, the large collected statistics can be exploited to perform other decay studies, such as $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{+}e^{-}$.

Two simultaneous $K^{+}$ and $K^{-}$ beams were produced by 400 GeV/c protons extracted from the CERN SPS and impinging on a beryllium target, with a central momentum of 60 GeV/c and a momentum dispersion of $\pm$ 3.8%. Both beams travelled, with similar paths, along the decay volume, inside a 114 m long vacuum tank. The main components of the detector were: a magnetic spectrometer, used to measure the charged decay products, composed of four drift chambers (DCH1-DCH4) and a dipole magnet, providing a momentum kick p = 20 MeV/c, with a momentum resolution of $\sigma(p)/p = (1.02 \pm 0.044p)\%$; a Liquid Krypton electromagnetic calorimeter (LKr), an almost homogeneous 7 m$^3$ ionization chamber, 27 $X_0$ deep, used to measure the position and energy of electrons and photons, with energy resolution of $\sigma(E)/E = (3.2 + 0.9E + 0.42)\%$. In addition, a scintillator hodoscope (HOD), consisting of two planes of plastic scintillators, each segmented into 64 counters arranged in four quadrants, with a time resolution of $\sim$150 ps, was used for trigger purposes; a muon veto system, essential to distinguish muons from pions, was placed as last detector of the apparatus. A complete description of the NA48 beam and detector can be found in [7].

## 3. Event selection and analysis

The signal events were collected concurrently with the events of the normalization channel $K^{\pm} \to \pi^{\pm}\pi^0$, which is very abundant and exhibits a similar experimental signature. The $\pi^0$ is identified through the $\pi^0 \to \gamma\gamma$ decay for the signal and through the Dalitz decay $\pi^0 \to e^+e^-\gamma$ for the normalization. Candidate events are reconstructed, both for signal and normalization channels, from three tracks: two same sign tracks and one opposite sign track are required to form a vertex with a total charge $q = \pm 1$. The tracks are required to be in time, within 5 ns, with the average HOD time associated to the tracks. The track momenta are required to be in the range (2–60) GeV/c and track-to-track distances at DCH1 to be larger than 2 cm to suppress photon conversions to $e^+e^-$ pairs in the upstream material. Events with all three tracks hitting the same HOD quadrant were rejected for trigger efficiency. Clusters in the LKr with a minimum energy of 2 GeV and without associated tracks, in time within 5 ns with the vertex time, were identified as photon candidates. The reconstructed $\pi^0$ and $K^{\pm}$ masses are required to be within $\pm$ 15 MeV/c$^2$ and $\pm$ 45 MeV/c$^2$, respectively, from the PDG value [8]. In addition, in order to take into account the correlation between the reconstructed $\pi^0$ and $K$ masses, a kinematical constrain is applied, $|\mathrm{m}_{\pi^0} - 0.42 \cdot \mathrm{m_K} + 72.3| < 6\ \mathrm{MeV/c^2}$, allowing particle identification without using the LKr. The signal is affected by two main sources of background: $K^{\pm} \to \pi^{\pm}\pi^0\pi^0_D$ with one photon lost (or merged) and $K^{\pm} \to \pi^0\pi^0_D$ with one extra accidental photon. In order to suppress the $K^{\pm} \to \pi^{\pm}\pi^0\pi^0_D$ decay, the squared mass of the $\pi^+\pi^0$ system is required to be greater than 0.12 $(\mathrm{GeV/c^2})^2$, exploiting the larger phase space available in the signal mode. In order to reject the $K^{\pm} \to \pi^0\pi^0_D$ background, each of the two possible $m_{ee\gamma}$ is required to be more than 7 MeV/c$^2$ apart from the nominal $\pi^0$ mass. The main background to the normalization decay is due to $K^{\pm} \to \mu^{\pm}\nu\pi^0_D$ and $K^{\pm} \to e^{\pm}\nu\pi^0_D$ events, when the pion mass is wrongly assigned to the lepton candidate.

## 4. Branching Ratio measurement

The $K^{\pm} \to \pi^{\pm}\pi^0 e^+e^-$ decay rate is measured relative to the normalization decay $K^{\pm} \to \pi^{\pm}\pi^0$. This method does not rely on the absolute kaon flux measurement. The ratio of partial rates (and branching ratios) is obtained as:

$$\frac{BR(K^{\pm} \to \pi^{\pm}\pi^0 e^+e^-)}{BR(K^{\pm} \to \pi^{\pm}\pi^0)} = \frac{N_s - N_{bs}}{N_n - N_{bn}} \cdot \frac{A_n \times \varepsilon_n}{A_s \times \varepsilon_s} \cdot \frac{\Gamma(\pi^0_D)}{\Gamma(\pi^0_{\gamma\gamma})}$$

where $N_s$, $N_n$ are the numbers of signal and normalization candidates; $N_{bs}$ and $N_{bn}$ are the numbers of background events in the signal and normalization samples; $A_s$ and $\varepsilon_s$ are the acceptance and the trigger efficiency for the signal sample; $A_n$ and $\varepsilon_n$ are those for the normalization sample. The branching ratio of the normalization mode is $BR(K^{\pm} \to \pi^{\pm}\pi^0) = (20.67 \pm 0.08)\%$ and the ratio of the $\pi^0$ partial rates is $\Gamma(\pi^0_D)/\Gamma(\pi^0_{\gamma\gamma}) = (1.188 \pm 0.035)\%$ [8]. Acceptances are obtained from a detailed Monte Carlo simulation based on GEANT3 [9] and efficiencies of the triggers are measured from down-scaled control samples, recorded concurrently with the three-track trigger. At the end of the event selection and background evaluation, samples of 4919 signal candidates and $16.3 \times 10^6$ normalization candidates have been selected from a subset of a $1.7 \times 10^{11}$ kaon decay exposure in 2003–2004. The background contamination estimated from simulation is $(4.9 \pm 0.4)\%$

in the signal mode and about 0.11% int he normalization mode. Reconstructed $e^+e^-$ invariant mass distributions for the normalization and signal candidates are shown in Fig. 1.

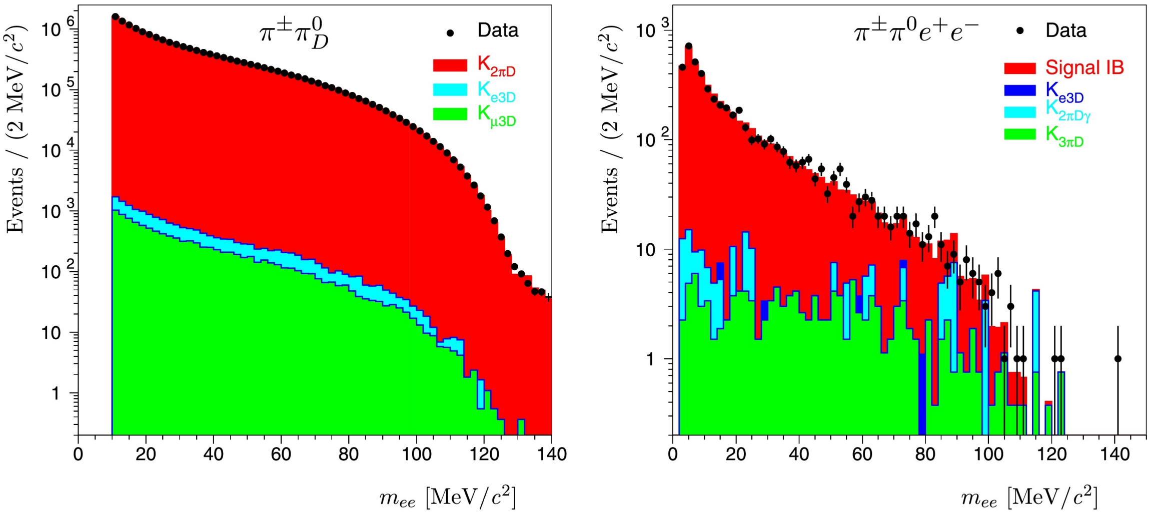


**Figure 1:** Reconstructed $e^+e^-$ mass distribution for the normalization (left) and the signal (right) candidates with the lower cuts of 10 and 3 MeV/c$^2$, respectively. Simulated background and normalization (signal) contributions are also displayed.

The final result obtained for the branching ratio is:

$$BR(K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-}) = (4.237 \pm 0.063_{stat} \pm 0.033_{syst} \pm 0.126_{ext}) \times 10^{-6}$$

where the systematic error includes uncertainties related to acceptances, trigger efficiencies and radiative corrections. The external error accounts for the normalization mode branching ratio uncertainty. The obtained result is in good agreement with theoretical predictions [2, 4].

## 5. Kinematic space studies

The contribution of the DE magnetic term (M) to the total decay rate, expected to be around 1%, cannot be quantified within the collected statistics. However, in the articles [2, 4], the authors pointed out that the contributions of IB, M, and IB-E terms have different distributions in the Dalitz plot $(T^*_\pi, E^*_\gamma)$ for different ranges of $q^2$, where $(T^*_\pi,\ E^*_\gamma,\ q^2)$ are the charged pion kinetic energy and the virtual photon energy in the kaon rest frame, and the $e^+e^-$ mass squared, respectively. A detailed study of the kinematic space has been performed: 3d-boxes in the kinematic space $(q^2, T^*_\pi, E^*_\gamma)$ are used to determine the relative fraction of each component. The data 3d-space is split first into N1 slices along $q^2$, then into N2 slices along $T^*_\pi$ and, finally, into N3 $E^*_\gamma$ slices. In this way, $N1 \times N2 \times N3$ exclusive boxes of variable size, but equal population, are formed.

The fractions (M)/IB and (IB-E)/IB reproducing the data are obtained minimizing a $\chi^2$ estimator:

$$\chi^2 = \sum_{i=1}^{N1\times N2\times N3} (N_i - M_i)^2/(\delta N_i^2 + \delta M_i^2)$$

where $N_i$ ($\delta N_i$) is the data population (error) and $M_i$ ($\delta M_i$) is the expected population (error) in box $i$. The expected number of events in box $i$ is computed as (N is a global scale factor)

$$M_i = N \times (N_i^{IB} + a \cdot N_i^M + b \cdot N_i^{IB-E}) + N_i^{Bkg}$$

At the end of minimization, the obtained values of $a$ and $b$ can be related to the relative contributions (M)/IB and (IB-E)/IB. The obtained value, (M)/IB = $0.0114 \pm 0.0043_{stat}$, is consistent with the predicted value from [2], $0.0141 \pm 0.0014_{ext}$, obtained using the experimental measurement of $N_M^{(0)}$. The (IB-E)/IB value of $-0.0014 \pm 0.0036_{stat}$ shows that there is no sensitivity to this contribution within the current data statistics and agrees with the value from [4], $-0.0039 \pm 0.0028_{ext}$, obtained using experimental inputs to $N_E^{(0,1,2)}$ values. The external errors on the predicted values arise from the uncertainties of the measurements used as input in the evaluations.

## 6. Asymmetry investigations

The measurements of asymmetries between $K^+$ and $K^-$ partial rates can give information on the electroweak phases involved in the decay. These phases change sign under charge conjugation (unlike the strong one involved in the pion system final state), therefore switching from $K^+$ to $K^-$ possible asymmetries can be extracted. The simplest CP-violating asymmetry is the charge asymmetry between $K^+$ and $K^-$ partial rates integrated over the whole phase space:

$$A_{CP} = \frac{\Gamma(K^+ \to \pi^+\pi^0 e^+e^-) - \Gamma(K^- \to \pi^-\pi^0 e^+e^-)}{\Gamma(K^+ \to \pi^+\pi^0 e^+e^-) + \Gamma(K^- \to \pi^-\pi^0 e^+e^-)}$$

The value of $A_{CP}$ can be related to the IB-E interference term and is proportional to a possible CP-violating phase appearing in the form factors. $A_{CP}$ can be extracted from the statistically independent measurements of $K^+$ and $K^-$ Branching Ratios:

$$BR(K^+ \to \pi^+\pi^0 e^+e^-) = (4.151 \pm 0.078_{stat}) \times 10^{-6}$$
$$BR(K^- \to \pi^-\pi^0 e^+e^-) = (4.394 \pm 0.108_{stat}) \times 10^{-6}$$

The value obtained, $A_{CP} = -0.0284 \pm 0.0155$ (the error is statistical only, since the systematic and external errors cancel in the ratio) is consistent with zero and can be translated to a single-sided limit:

$$|A_{CP}| < 4.82 \times 10^{-2} \text{ at 90\% CL.}$$

Other angular/charge asymmetries (as defined in [2]), can be extracted defining an angular variable $\phi$ and choosing particular integration regions for combining the branching ratios measured in the $\phi$ variable space. In this way, two additional asymmetries have been evaluated: $A_{CP}^{\phi^*}$, that selects CP violation in $\gamma$-mediated $K^{\pm} \to \pi^{\pm}\pi^0 e^+e^-$ decays, and $A_{CP}^{\tilde{\phi}}$, that gives access to CP violation in direct short-distance operators to the $K^{\pm} \to \pi^{\pm}\pi^0 e^+e^-$ decay. Both measured asymmetries are consistent with zero and single-sided limits can be set:

$$A_{CP}^{\phi^*} = 0.0119 \pm 0.0150_{stat} \implies |A_{CP}^{\phi^*}| < 3.11 \times 10^{-2} (90\% CL)$$
$$A_{CP}^{\tilde{\phi}} = 0.0058 \pm 0.0150_{stat} \implies |A_{CP}^{\tilde{\phi}}| < 2.50 \times 10^{-2} (90\% CL)$$

The long distance P-violating asymmetry $A_P^{(L)}$ also has been found to be consistent with zero.

## 7. Conclusions

The NA48/2 experiment, analyzing data collected in 200-2004, performed a search for the $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{+}e^{-}$ decay, never observed before. From a total of $1.7 \times 10^{11}$ kaon decays, a sample of 4919 decay candidates, with 4,9% background, has been extracted.

The branching ratio has been measured relative to the $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}$ mode, followed by a Dalitz decay $\pi^0 \rightarrow e^+e^-\gamma$. The result

$$BR(K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{+}e^{-}) = (4.237 \pm 0.063_{stat} \pm 0.033_{syst} \pm 0.126_{ext}) \times 10^{-6}$$

is in agreement with predictions from ChPT.

A study of the kinematic space of the decay has been performed to extract information on the fraction of magnetic (M) and interference (IB-E) contributions with respect to inner bremsstrahlung (IB). The results of the relative contribution (M)/IB and (IB-E)/IB are found to be consistent with theoretical expectations. In addition, several CP-violating asymmetries and a long-distance P-violating asymmetry have also been evaluated and found to be consistent with zero, allowing to set upper limits. If larger data statistics would become available in future (for example at the NA62 experiment, if running after LS2 will be appoved), more detailed studies of the kinematic space will allow for an improved evaluation of the DE term contribution. A complete description of the analysis procedures and extraction of the results can be found in [10].

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PoS(EPS-HEP2019)237