LATEST RESULTS FROM KAON EXPERIMENTS AT CERN*

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on behalf of the NA62 and NA48/2 collaborations

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Received 7 February 2023, accepted 24 August 2023, published online 27 October 2023

The NA48/2 and NA62 experiments at CERN were designed to measure kaon decays from a high-intensity fixed-target setup that took data between 2003–04 and 2016–18, respectively. The first observation of the $K^\pm \to \pi^0\pi^0\mu^\pm\nu$ decay based on the 2003–04 data sample is reported. Several preliminary results using the 2016–18 data set are presented. The result from the $K^+ \to \pi^+\nu\bar{\nu}$ analysis of the 2018 data sample is presented, as well as the combination with the previous 2016 and 2017 results. An analysis of the $K^+ \to \pi^0 e^+\nu\gamma$ decay is presented, improving the previous measurement of the relative branching ratio with respect to the $K^+ \to \pi^0 e^+\nu$ decay and the T-asymmetry in three kinematic regions. An updated measurement of the $K^+ \to \pi^+\mu^+\mu^-$ form-factor is presented. The Chiral Perturbation Theory parameter $\hat{c}$ is measured using the $K^+ \to \pi^+\gamma\gamma$ decay.

DOI:10.5506/APhysPolBSupp.16.8-A14

1. Introduction

The NA48/2 and NA62 experiments stem from a long history of fixed-target kaon experiments at the CERN SPS. In both experiments, a 400 GeV/c proton beam is extracted from the SPS 3.5 s long spills. The proton beam impinges on a beryllium target and a secondary hadron beam contaning 6% kaons is formed and delivered to the experiment. The NA48/2 experiment collected data in 2003–04 simultaneously from K^+ and K^- beams selected to have a mean momentum $P_K \approx 60$ GeV/c. The beam particle momentum is measured by a kaon beam spectrometer (KABES). The momenta of the $K^\pm$ decay products are measured with a magnetic spectrometer equipped with 4 drift chambers (DCH), one pair located at each side of a dipole magnet, located inside a vessel filled with helium. The spectrometer

* Presented at *Excited QCD 2022*, Sicily, Italy, 23–29 October, 2022.

was followed by a scintillator hodoscope (NA48-CHOD), a liquid krypton (LKr) calorimeter, a hadronic calorimeter, and a muon veto system. The experimental setup is described in detail in [1].

The NA62 experiment has been operating since 2016 and is dedicated to the measurement of the $K^+ \to \pi^+\nu\bar{\nu}$ branching fraction. The K^+ beam has a mean momentum $P_K \approx 75$ GeV/c. The beam particle rate is 750 MHz. The kaons in the beam are tagged by the KTAG and the beam momentum is measured by the GTK spectrometer. The momenta of the charged decay products are measured with a magnetic spectrometer equipped with 4 STRAW chambers, a pair on each side of a dipole magnet, located inside a vacuum vessel. The spectrometer is followed by a Ring Imaging Cherenkov (RICH) detector, two scintillator hodoscopes (NA48-CHOD and CHOD), a hadronic calorimeter (LKr), and a muon veto system. A hermetic photon veto system formed by the LAV, LKr, IRC, and SAC detectors surrounds the fiducial volume. The experimental setup is described in detail in [2].

2. First observation of the $K^\pm \to \pi^0\pi^0\mu^\pm\nu$ decay

The four-body semi-leptonic $K \to \pi\pi\ell\nu$ decay has four configurations ($K^\pm_{e4}$, K^{00}_{e4}, $K^\pm_{\mu4}$, $K^{00}_{\mu4}$), with $\ell = e, \mu$, and with the pions either both charged or both neutral. While the $K^\pm_{e4}$ and K^{00}_{e4} decays have already been well measured [3, 4], only 7 candidates have been observed for the $K^\pm_{\mu4}$ decay, and the $K^{00}_{\mu4}$ decay has never been observed. The decay amplitudes are parameterized by four form factors (F, G, R, H)[1]. They are functions of the dipion and the dilepton invariant masses squared (S_π, S_ℓ). The parametrization of $F(S_\pi, S_\ell)$ that is well measured from K^{00}_{e4} can be used in $K^{00}_{\mu4}$ thanks to lepton universality. The form factor $R(S_\pi, S_\ell)$ is predicted by the Chiral Perturbation Theory (ChPT) [5] but has not previously been measured.

The $K^{00}_{\mu4}$ decay is measured at NA48/2 and is normalised to the $K^\pm \to \pi^\pm\pi^0\pi^0$ ($K_{3\pi}$) decay. Both decays are selected by requiring 4 isolated photons consistent with two π^0 matching in time and space a KABES beam track and a DCH track. A total of 72.99×10^6 $K_{3\pi}$ events are selected by setting requirements on the invariant mass and transverse momentum of the reconstructed $\pi^\pm\pi^0\pi^0$ system. In addition to further requirements on the kinematic variables, the analysis is restricted to the phase space $S_\ell > 0.03$ GeV$^2/c^4$ to further reject background. The analysis yields 2437 candidates in the signal region, with an estimated $354 \pm 33_{\mathrm{stat}} \pm 62_{\mathrm{syst}}$ background events from a sideband fit. The branching ratio (BR) is measured as

[1] However, in the case of $K_{\mu4}$, only F and R contribute to the amplitude.

$$\begin{aligned}&\mathrm{BR}\left(K^{\pm}\to\pi^0\pi^0\mu^{\pm}\nu; S_\ell>0.03\ \mathrm{GeV}^2/c^4\right)\\&=\left(0.650\pm0.019_{\mathrm{stat}}\pm0.024_{\mathrm{syst}}\right)\times10^{-6}\,,\end{aligned}\tag{1}$$

which is consistent with a contribution of the R form factor as computed at 1-loop ChPT. A model-dependent extrapolation to the full phase space is possible.

3. $K^+\to\pi^+\nu\bar{\nu}$

The flavour is changing neutral current decay $K^+\to\pi^+\nu\bar{\nu}$ proceeding through box and electroweak penguin diagrams. This process is extremely rare thanks to a quadratic GIM mechanism and strong suppression from the CKM matrix elements. It is also extremely clean theoretically, with the error budget being dominated by the experimental uncertainties in the CKM matrix element. The SM predicts $\mathrm{BR}(K^+\to\pi^+\nu\bar{\nu})=(0.84\pm0.10)\times10^{-10}$ [6]. The previous measurement of the BR is from the E787 and E949 experiments at BNL [7, 8], with a value of $(1.73^{+1.15}_{-1.05})\times10^{-10}$.

The experimental signature of a $K^+\to\pi^+\nu\bar{\nu}$ event is an incoming K^+ and an outgoing π^+, with missing energy in the final state. The squared missing mass is defined as $m^2_{\mathrm{miss}}=(P_K-P_\pi)^2$, with P_K being the 4-momentum of the K^+ and P_π — the 4-momentum of the downstream track in the charged pion mass hypothesis. This variable is used to select the signal, background, and control regions. The event selection relies on time and space association of signals from the downstream and upstream detectors to select a single track topology, powerful particle identification, and rejection of events with additional activity in the veto detectors.

The result presented here is based on the analysis of the data collected in the full Run 1 [9]. The 2018 dataset is divided into two sub-samples (S1 and S2) corresponding to before and after the installation of a collimator aiming at reducing upstream background. The S2 sample is subdivided into six categories, defined by 5 GeV$/c$ wide momentum bins, and the selection is optimized separately for each category.

A total of $7.03^{+1.05}_{-0.82}$ background events are expected in the signal region, for $10.01\pm0.42_{\mathrm{syst}}\pm1.19_{\mathrm{ext}}$ expected signal events. Upon unblinding, 20 events are observed. The BR is extracted by performing a maximum likelihood fit using the signal and background expectations and the number of observed events in nine categories. The resulting measurement is

$$\mathrm{BR}\left(K^+\to\pi^+\nu\bar{\nu}\right)=\left(1.06^{+0.40}_{-0.34}\Big|_{\mathrm{stat}}\pm0.09\Big|_{\mathrm{syst}}\right)\times10^{-10}\,.\tag{2}$$

The result is compatible with the SM prediction within one standard deviation and corresponds to a significance of 3.4σ of observation of this process and is the most precise measurement so far.

4. $K^+ \to \pi^0 e^+ \nu\gamma$

The $K^+ \to \pi^0 e^+ \nu\gamma$ ($K_{e3\gamma}$) decay is a radiative decay that can be described in ChPT. The final-state photon can be produced either by direct emission (DE) or inner Brehmsstrahlung (IB), interfering together in the decay amplitude. The IB component is divergent both as the photon energy in the kaon rest frame $E_\gamma \to 0$, and as the angle between the positron and the photon in the kaon rest frame $\theta_{e,\gamma} \to 0$. To avoid divergence, three kinematic regions are defined and the relative fractional BR with respect to the $K^+ \to \pi^0 e^+ \nu$ (K_{e3}) decay is measured. The definition of the regions, as well as the predicted and experimental values of the relative fractions R_j, are shown in Table 1.

Table 1. R_j definitions in terms of E_γ and $\theta_{e,\gamma}$ in the kaon rest frame, and respective expectations from the $\mathcal{O}(p^6)$ ChPT calculations [10] and results of the measurements performed by the ISTRA+ experiment.

	E_γ [MeV]	$\theta_{e,\gamma}$	$\mathcal{O}\left(p^6\right)$ ChPT	ISTRA+
$R_1 \times 10^2$	$E_\gamma > 10$	$\theta_{e,\gamma} > 10°$	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$
$R_2 \times 10^2$	$E_\gamma > 30$	$\theta_{e,\gamma} > 20°$	0.640 ± 0.008	$0.63 \pm 0.02 \pm 0.03$
$R_3 \times 10^2$	$E_\gamma > 10$	$0.6 < \cos\theta_{e,\gamma} < 0.9$	0.559 ± 0.006	$0.47 \pm 0.02 \pm 0.03$

Possible T-violation effects in this decay can be studied using the T-odd observable ξ and the corresponding asymmetry A_ξ

$$\xi = \frac{\vec{p}_\gamma \cdot \vec{p}_e \times \vec{p}_\pi}{m_K^3}\,; \qquad A_\xi = \frac{N_+ - N_-}{N_+ + N_-}\,, \tag{3}$$

where N_+ (N_-) is the number of events with a positive (negative) value of ξ. The predictions of these observables are $|A_\xi| < 10^{-4}$ in the SM and beyond. The only experimental measurement from the ISTRA+ experiment [11] is $A_\xi(R_3) = 0.015 \pm 0.021$ [11].

The values of R_j and A_ξ were measured at NA62 using data collected in 2017–18. The event selection is based on the time and space association of an initial K^+ candidate with an e^+ track and two γ clusters in the final state, where the two γ are compatible with a π^0 decay. A third in-time, isolated, γ cluster is required in the LKr for the radiative photon. Events with additional activity in the detector are rejected to suppress K^+ decays with two π^0. The selection results in 66.4×10^6 K_{e3} normalization events. The number of signal events in each kinematic region, as well as the corresponding R_j and A_ξ measurements, are shown in Table 2. These results are the most precise measurements of R_j and $A_\xi(R_3)$, and are the first measurements of $A_\xi(R_1)$ and $A_\xi(R_2)$.

Table 2. Preliminary results from NA62 of the measurements of R_j and A_ξ for the three kinematic regions of the $K_{e3\gamma}$ decay. The uncertainties are statistical and systematic.

	N_{cand}	$R_j \times 10^2$	A_ξ
R_1	1.3×10^5	$1.684 \pm 0.005 \pm 0.010$	$0.001 \pm 0.003 \pm 0.002$
R_2	0.5×10^5	$0.559 \pm 0.003 \pm 0.005$	$-0.003 \pm 0.004 \pm 0.003$
R_3	0.4×10^5	$0.523 \pm 0.003 \pm 0.003$	$-0.009 \pm 0.005 \pm 0.004$

5. $K^+ \to \pi^+\mu^+\mu^-$

The $K^+ \to \pi^+\mu^+\mu^-$ ($K_{\pi\mu\mu}$) decay is a flavour-changing neutral current mediated by a virtual photon exchange. The decay amplitude contains a form factor $W(z)$ with $z = M_{\mu\mu}^2/M_K^2$, where $M_{\mu\mu}^2$ is the dimuon invariant mass squared and M_K^2 is the kaon mass squared. The form factor can be parameterized by a_+ and b_+ in ChPT [12]. These parameters are predicted in the SM to be identical for $K^+ \to \pi^+\mu^+\mu^-$ and $K^+ \to \pi^+e^+e^-$ decays, and any difference is indicative of the Lepton Flavour Universality (LFU) violation.

The $K_{\pi\mu\mu}$ decay is measured at the NA62 experiment using data collected in 2017–18, with the measurement normalised to the $K_{3\pi}$ decay. The event selection yields 2.8×10^4 signal events, for only 8 expected background events. The best value of (a_+, b_+) is extracted from a fit of simulated MC events to the z spectrum of the data. The fit prefers a solution with negative values: $a_+ = -0.592 \pm 0.015$, $b_+ = -0.699 \pm 0.058$. The model-independent measurement of the branching fraction is $\text{BR}(K_{\pi\mu\mu}) = (9.27 \pm 0.11) \times 10^{-8}$. These results are the most precise determination of (a_+, b_+) and the branching ratio, and are compatible with the earlier measurement as well as LFU.

6. $K^+ \to \pi^+\gamma\gamma$

The $K^+ \to \pi^+\gamma\gamma$ ($K_{\pi\gamma\gamma}$) decay is a radiative non-leptonic decay which is well described in ChPT [13]. The decay is described by two kinematical variables

$$z = \frac{(q_1 + q_2)^2}{M_K^2} = \left(\frac{M_{\gamma\gamma}}{M_K}\right)^2 ; \qquad y = \frac{p(q_1 - q_2)}{M_K^2} , \tag{4}$$

where p and $q_{1,2}$ are the 4-momenta of the kaon and the two photons respectively, $M_{\gamma\gamma}$ is the diphoton invariant mass, and m_K is the kaon mass. The decay rate and z spectrum are determined by a single unknown ChPT parameter $\hat{c}$.

The $K_{\pi\gamma\gamma}$ decay is measured at the NA62 experiment using data collected in 2016–18, and using normalisation from the $K^+ \to \pi^+\pi^0$ decay, which has the same final state. The main source of background comes from $K^+ \to \pi^+\pi^0\gamma$ and $K^+ \to \pi^+\pi^0\pi^0$ with merged clusters in the LKr. This background is modelled from a control region with the enhanced contribution from merged clusters. Events with a single track and three clusters are selected, and it is assumed that one of the clusters is merged. The cluster is tagged as merged if the kinematical configuration in this assumption is compatible with a $K^+ \to \pi^+\pi^0\pi^0$ event. To further reduce background from $K^+ \to \pi^+\pi^0\gamma$ which is dominant at low z values, the measurement is performed in the region of $z > 0.25$. A total of 4039 events are selected in the data, for $393 \pm 9_{\rm stat} \pm 18_{\rm syst}$ expected background events. A fit of the z spectrum is performed to extract the best value of $\hat{c}$, which is found to be $\hat{c} = 1.713 \pm 0.075_{\rm stat} \pm 0.037_{\rm syst}$. This value corresponds to a branching ratio of $\mathrm{BR}(K_{\pi\gamma\gamma}) = 9.73 \pm 0.17_{\rm stat} \pm 0.08_{\rm syst}$. This result represents a factor three improvement on the previous result.

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