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Results and prospects for $K \to \pi\nu\bar{\nu}$ at NA62 and KOTO

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Abstract. The $K \to \pi\nu\bar{\nu}$ ultra-rare decays are precisely computed in the Standard Model (SM) and are ideal probes for physics beyond the SM. The NA62 experiment at the CERN SPS is designed to measure the charged channel with a precision of 10%. The statistics collected in 2016 allows to reach the SM sensitivity. The KOTO experiment at J-PARC aims at reaching the SM sensitivity before performing a measurement with $\sim$ 100 signal events. The NA62 preliminary result for the charged channel is presented, together with the current experimental status of the neutral channel and their prospects for the coming years.

1 Introduction

Due to its strong suppression, the $K \to \pi\nu\bar{\nu}$ decay is a golden channel for precision tests of the Standard Model (SM) and search for physics Beyond the Standard Model (BSM). This decay is a flavour changing neutral current, forbidden at tree level, proceeding through box and electromagnetic penguin diagrams. It also benefits from an additional suppression from the CKM matrix element and a quadratic GIM mechanism.

This ultra-rare Kaon decay is also theoretically very clean. It is described mostly by a short-distance effective Hamiltonian receiving contributions from the top quark loop, with small contribution from the charm quark loop and long-distance corrections. The hadronic matrix element can be extracted from the well measured, isospin rotated $K^+ \to \pi^0 e^+ \nu$ decay. Overall the uncertainties on the CKM matrix elements are dominating the theoretical error budget [1]. The remaining relative uncertainties are about 3.6 % (1.5 %) for the charged (neutral) channel, and the continuous improvement on the precision of the CKM parameters therefore enables to further reduce the total uncertainties on the branching ratios. The latest numerical evaluation leads to:

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \cdot \left[\frac{|V_{cb}|}{40.7 \times 10^{-3}}\right]^{2.8} \left[\frac{\gamma}{73.2^\circ}\right]^{0.74} \quad (1)$$

$$= (8.4 \pm 1.0) \times 10^{-11} \quad (2)$$

$$\mathcal{B}(K^0 \to \pi^0\nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^{2} \left[\frac{|V_{cb}|}{40.7 \times 10^{-3}}\right]^{2} \left[\frac{\sin\gamma}{\sin 73.2^\circ}\right]^{0.74} \quad (3)$$

$$= (3.4 \pm 0.6) \times 10^{-11} \quad (4)$$

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In this context even small BSM effects could have a significant impact on the branching ratio. It is also interesting to exploit the correlations between the charged and the neutral channel as they vary significantly between different classes of models introducing BSM physics (Custodial Randall-Sundrum [2], MSSM analysis [3, 4], simplified Z,Z' models [5], littlest Higgs with T-parity [6], lepton flavour violation models [7]). The combination of the measurements for $K^+ \to \pi^+ \nu\bar{\nu}$ and $K^0 \to \pi^0 \nu\bar{\nu}$, but also with the their B physics counterparts ($B \to K\nu\bar{\nu}$), can lead to strong constraints on these models.

The experimental situation is very different from the theoretical one. For $K^+ \to \pi^+ \nu\bar{\nu}$, the only measurement is extracted from seven event candidates at the E787 and E949 experiments at BNL [8, 9]. For $K^0 \to \pi^0 \nu\bar{\nu}$ only an upper limit is available, where the strongest comes from the E391 experiment at KEK [10]. The measurements are:

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = \left(17.3^{+11.5}_{-10.5}\right) \times 10^{-11} \tag{5}$$

$$\mathcal{B}(K^0 \to \pi^0 \nu\bar{\nu}) < 2.6 \times 10^{-8} \text{ (90\% C.L.)} \tag{6}$$

The relative uncertainty on the charged measurement are of the order of 60 %, which does not allow to conclude on a possible discrepancy with the predictions. The neutral measurement is still an order of magnitude higher than the Grossman-Nir bounds [11], which limits the ratio of $\mathcal{B}(K^0 \to \pi^0 \nu\bar{\nu})/\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ based on CP violation considerations.

2 The NA62 experiment

The fixed target NA62 experiment at the CERN SPS aims at measuring $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ with a precision of 10% using an in-flight decay technique. In order to achieve this goal a total of 10^{13} kaon decays should be collected in a few years of data taking, with a maximum of 10% background contamination in the final signal sample. The primary 400 GeV/c proton beam impinges on a Beryllium target, producing secondary particles. The secondary beam optics selects, collimates and focuses particles with a momentum of 75 GeV/c to the 60 m long evacuated decay volume. The beam is composed of 70% pions, 23% protons and 6% kaons.

The signal consists of one incoming kaon track and one outgoing pion track, with no other activity in the detector. The main background to the signal comes from the kaon decay channels with highest branching ratio: principally $K^+ \to \mu^+\nu(\gamma)$ ($K_{\mu\nu(\gamma)}$) and $K^+ \to \pi^+\pi^0(\gamma)$ ($K_{\pi\pi(\gamma)}$). There are also contributions from upstream decays in the beam line and interactions between the beam particles and upstream detectors. The high background rejection required is provided by combining various techniques: kinematic suppression, high efficiency veto system, time resolution.

The full schematic of the detector can be seen in Fig. 1, and a detailed description of the experimental set-up can be found in [12]. A differential Cherenkov counter (KTAG) identifies kaons in the beam line with a time resolution of ~100 ps, which is matched to downstream activity to reject beam induced background. It is followed by the beam spectrometer (GTK) measuring the kaon momentum. Immediately following the decay volume, a straw spectrometer (STRAW) measures the downstream tracks momentum. A Ring Imaging Cherenkov detector (RICH) provides particle identification for $\pi^\pm, \mu^\pm, e^\pm$ in the momentum range 15 GeV/c–35 GeV/c. These measurements allow to build the squared missing mass variable $m^2_{\text{miss}} \equiv (p_K - p_\pi)^2$, where p_K and p_π are the 4-momenta of the beam and downstream tracks under the kaon and pion hypothesis, respectively. This variable is used to discriminate between the signal and background kinematics, allowing a 10^4 rejection factor. Finally a set of highly efficient veto for muons, photons and inelastic interaction provide an almost hermetic coverage reaching a 10^7 suppression factor.

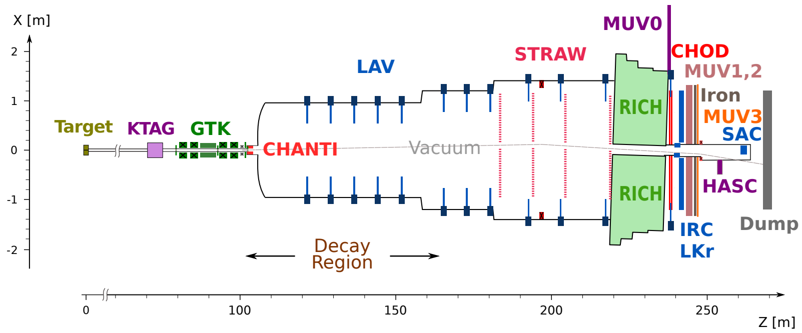

Figure 1. Schematic view of the NA62 experimental set-up

2.1 The $K^+ \to \pi^+\nu\bar{\nu}$ analysis

The events are reconstructed according to the signal signature described above: a single track topology is selected by spatially matching a reconstructed track in the STRAW with signals in the CHOD and RICH detectors. A K^+ identified in the KTAG detector and traced in the GTK is matched in time with the upstream track. The kaon decay vertex is built at the intersection of the two tracks and is required to be in a 50 m long region starting 10 m downstream of the last GTK station. The π^+ identification is performed using in combination the RICH and the calorimeters, providing a total muon rejection of 10^{-8} for a π^+ efficiency of 64 %, measured on independent samples of kinematically selected $K_{\pi\pi}$ and $K_{\mu\nu}$. The remaining background is principally $K_{\pi\pi}$ decays, which are further suppressed using the electromagnetic calorimeters (LKr, SAC, IRC, LAVs). Events with extra energy deposits in-time with the π^+ track are rejected, providing a π^0 suppression of 3×10^{-8}. The signal region defined in the m^2_{miss} variable is driven by its resolution (10^{-3} GeV$^2/c^4$) and is divided into two sub-regions (R1 and R2) below and above the $K_{\pi\pi}$ peak respectively. The 4-momenta used in the squared missing mass computation can be reconstructed using different methods: using STRAW or RICH for p_π, and using GTK or the nominal beam parameters for p_K. Imposing constraints on m^2_{miss} reconstructed using various combinations of these methods protects against mis-reconstruction of the momenta. A sample selected using calorimeters only is used to measure the kinematic suppression factors, which is 1×10^{-3} for $K_{\pi\pi}$ and 3×10^{-4} for $K_{\mu\nu}$. The expectations for the final background contamination are verified in control regions on the side of the signal regions R1 and R2 for $K_{\pi\pi(\gamma)}$ and $K_{\mu\nu}$, or estimated from MC for $K^+ \to \pi^+\pi^-e^+\nu$ (K_{e4}). The final acceptance for the signal, extracted from Monte-Carlo (MC) simulations, is 1 % (3 %) in R1 (R2), for a total acceptance of $A_{\pi\nu\bar{\nu}} = 4$ %.

The Single Event Sensitivity (SES) is defined as $SES = 1/\left(N_K \cdot A_{\pi\nu\bar{\nu}} \cdot \varepsilon_{\text{Trig}} \cdot \varepsilon_{\text{RV}}\right)$ where N_K, is the number of kaon decays, $\varepsilon_{\text{Trig}}$ is the $\pi\nu\bar{\nu}$ trigger efficiency and ε_{RV} is the signal efficiency resulting from the rejection of events due to accidental activity in the detector. The number of kaon decays $N_K = (1.21 \pm 0.02) \times 10^{11}$ is measured from a control-triggered sample of $K_{\pi\pi}$ selected using a $\pi\nu\bar{\nu}$-like selection on which the final γ, multiplicity and m^2_{miss} cuts are not applied. The trigger efficiency $\varepsilon_{\text{Trig}}$ is measured to be 88 % using control data. The random veto efficiency ε_{RV} depends on the beam intensity and is evaluated to 0.76 ± 0.04 from a sample of $K_{\mu\nu}$ candidates. The $SES = \left(3.15 \pm 0.01_{\text{stat}} \pm 0.24_{\text{syst}}\right) \times 10^{-10}$ for the data sample analysed is dominated by the systematic uncertainties, which are shown in Table 1.

Table 1. Summary of the systematic uncertainties for the SES computation.

Source	$\delta SES\,(10^{-10})$
Random Veto	±0.17
N_K	±0.05
Trigger efficiency	±0.04
Definition of $\pi^+\pi^0$	±0.10
Momentum spectrum	±0.01
Simulation of π^+ interactions	±0.09
Extra activity	±0.02
GTK Pileup simulation	±0.02
Total	±0.24

Table 2. Summary of the expected number of signal and background events in the signal regions R1 and R2 for the 2016 analysis.

Process	Expected events (R1+R2)
$K^+ \to \pi^+\nu\bar{\nu}$ (SM)	$0.267 \pm 0.001_{\text{stat}} \pm 0.020_{\text{syst}} \pm 0.032_{\text{ext}}$
Total Background	$0.15 \pm 0.09_{\text{stat}} \pm 0.01_{\text{syst}}$
$K^+ \to \pi^+\pi^0(\gamma)$ IB	$0.064 \pm 0.007_{\text{stat}} \pm 0.006_{\text{syst}}$
$K^+ \to \mu^+\nu(\gamma)$ IB	$0.020 \pm 0.003_{\text{stat}} \pm 0.003_{\text{syst}}$
$K^+ \to \pi^+\pi^-e^+\nu$	$0.018\ {}^{+0.024}_{-0.017}\big\vert_{\text{stat}} \pm 0.009_{\text{syst}}$
$K^+ \to \pi^+\pi^+\pi^-$	$0.002 \pm 0.001_{\text{stat}} \pm 0.002_{\text{syst}}$
Upstream background	$0.050\ {}^{+0.090}_{-0.030}\big\vert_{\text{stat}}$

2.2 NA62 result and prospect

After the full selection, one event is found in R2 after un-blinding the signal region. The summary of the expected signal and background events in the signal regions is shown in Table 2. From this, an upper limit on the branching fraction of $K^+ \to \pi^+\nu\bar{\nu}$ can be set using the CL$_s$ method: $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) < 10 \times 10^{-10}$ (90% C.L.). The result presented corresponds to the analysis of data taken in 2016, while approximately 20 times more data have been collected in 2017. Improvements on the signal acceptance, background reduction and reconstruction efficiency are also expected. With another year of data taking in conditions similar to 2017, a total of about 20 SM $K^+ \to \pi^+\nu\bar{\nu}$ events is expected.

3 The KOTO experiment

The KOTO experiment at J-PARC is complementary to NA62, both in its goal and in the technique used. The first phase of the experiment aims at observing a $K^0 \to \pi^0\nu\bar{\nu}$ signal, before increasing the sensitivity and moving to the second phase with a measurement of $\mathcal{B}(K^0 \to \pi^0\nu\bar{\nu})$ from about 100 events. A secondary K_L beam with 1.4 GeV/c peak energy is used by the experiment. The neutral kaons are allowed to decay in a 3 m long fiducial region evacuated at 5×10^{-7} bar.

The experimental signature consists only in detecting two photons with missing transverse momentum. The photon energy is measured by a Cesium Iodide calorimeter (CsI) located downstream of the decay volume. By assuming the two γ come from a neutral pion, the longitudinal vertex position Z_{vtx} and the π^0 missing transverse momentum P_t can be computed and define the signal region. The fiducial volume is further surrounded by veto systems to reject events with additional particles.

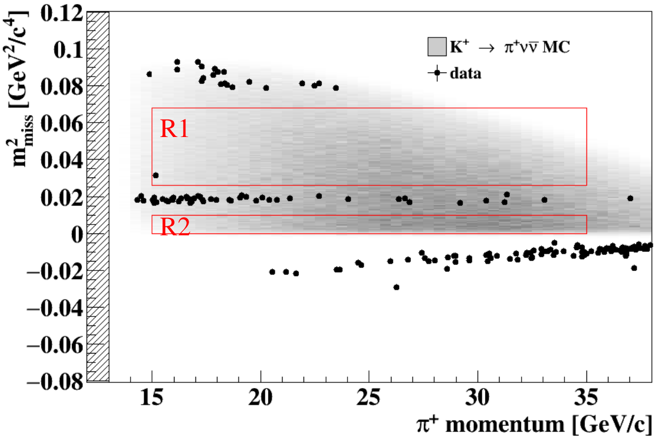

Figure 2. Distribution of the m^2_{miss} variable as a function of p_{π^+}. The dots are data events passing the $\pi\nu\bar{\nu}$ selection, except the cuts on m^2_{miss} and p_{π^+}. The grey area corresponds to the density of MC events. The red lines define the signal regions R1 and R2. One event is observed in R2.

3.1 KOTO results and prospects

The collaboration published results from the analysis of about 100 hours of run taken in 2013 [13]. The number of kaons collected is $N_K = 2.4 \times 10^{11}$, which corresponds to $SES = 1.3 \times 10^{-8}$. The upper limit set on the branching fraction is $\mathcal{B}(K^0 \to \pi^0\nu\bar{\nu}) < 5.1 \times 10^{-8}$ (90% C.L.) . The main background sources are $K_L \to \pi^+\pi^-\pi^0$ decays and halo neutrons interactions with the detector. Dedicated runs with an aluminium target have been performed to improve the discrimination between neutron and photon clusters in the CsI calorimeter. This resulted in a factor 5 improvement on the reduction of neutron induced background. Other improvements on the experimental system further reduce the impact of neutron interactions. Finally the installation of a new beam pipe charged veto allowed to reduce the acceptance loss by 40 %.

A preliminary result with 60 % more statistics and the improvements mentioned above indicate a $SES \sim 5.9 \times 10^{-9}$ with reduced background. The analysis of the full 2015-2016 dataset should bring the SES below 10^{-9}. Further upgrades of the detector and beam line are planned to bring the sensitivity down to the SM level.

4 Conclusions

The $K \to \pi\nu\bar{\nu}$ ultra-rare decays are excellent probes for new physics. Their branching ratios are both currently known to a very good precision in the SM, with uncertainties mostly arising from the precision on the CKM matrix elements. The analysis performed at the NA62 experiment reports one observed event with 0.27 expected SM signal event and 0.15 background events. This result validates the chosen decay-in-flight technique and allows to set a limit at 90 % C.L. of $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) < 10 \times 10^{-10}$. The KOTO experiment published a result which sets the limit $\mathcal{B}(K^0 \to \pi^0\nu\bar{\nu}) < 5.1 \times 10^{-8}$ at 90 % C.L. for the neutral channel. Both collaborations are continuing to improve their experimental set-up and to take data.

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