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Searches for heavy neutral lepton production and lepton flavor violation in kaon decays at the NA62 experiment

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Search for heavy neutral lepton (HNL) production and lepton flavor and number violation (LFV/LNV) in charged kaon decays using the data collected by Kaon experiment NA62 at CERN are reported. Upper limits are established on the elements of the extended neutrino mixing matrix for heavy neutral lepton mass in the range 130-450 MeV, improving on the results from previous HNL production search. The progress and prospects in different LNV/LFV analysis on data sets from 2015-2018 are reviewed.

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1. Introduction

The recently published results by the experiments NA62 on Heavy Neutral Leptons [1] together with the further expected progress are presented.

Neutrinos in Standard Model (SM) are due to the absence of right-handed states strictly massless. However, neutrino oscillations imply a non-zero masses of neutrinos and suggest an inclusion of massive "sterile" neutrinos, also called Heavy Neutral Leptons (HNLs), which mix with the ordinary light "active" neutrinos. A possible extension of SM is Neutrino Minimal SM (νMSM) [2], which postulates three right-handed neutrinos N_i, with masses $m_1 \sim 10$ keV/c^2 and $m_{2,3} \sim 1$ GeV/c^2. N_1 can be considered as a Warm Dark Matter candidate, and $N_{2,3}$ can introduce extra CP violating phases to account for the Baryon Asymmetry of the Universe and produce SM masses via see-saw mechanism. Hence the (νMSM) can explain simultaneously ν oscillations and smallness of ν masses, offer cosmic Dark Matter candidate and explain leptogenesis due to Majorana mass term.

If $m_N < m_{\mathrm{K}^+}$, heavy neutrinos can be observed in Kaon decays via production in [3, 4]:

$$\Gamma(\mathrm{K}^+ \to \ell^+ \mathrm{N}) = \Gamma(\mathrm{K}^+ \to \ell^+ \nu) \cdot \rho_\ell(m_N) \cdot |U_{\ell 4}|^2, \tag{1.1}$$

where $\rho_\ell(m_N)$ is a kinematic factor. Evidence of HNL in $\mathrm{K}^+ \to l^+\mathrm{N}$ with undecayed N would appear as peaks in the $\mathrm{K}^+ \to l^+\nu$ m^2_{miss} distribution, with $m^2_{miss} = (P_K - P_\ell)^2$ where P_K and P_ℓ are the kaon and lepton 4-momenta, respectively.

Search for Majorana neutrinos in lepton number violating $\mathrm{K}^+ \to \pi^-\mu^+\mu^+$ decay was performed by NA48/2 collaboration and the limit was set to [5]:

$$\mathrm{BR}(K^\pm \to \pi^\mp\mu^\pm\mu^\pm) < 8.6 \times 10^{-11} \quad @ \quad 90\% \text{ CL}.$$

νMSM with real scalar field (inflaton X) and scale invariant couplings can explain universe homogeneity and isotropy on large scales, and structures on smaller scales [6]. Search for resonances (N, X, etc.) in the opposite-sign muons sample can be sensitive for such a models. HNL peak search in $\mathrm{K}^+ \to \mu^+(\pi^+\mu^-)$ and inflatons peak search in $\mathrm{K}^+ \to \pi^+(\mu^-\mu^+)$ were performed by NA48/2 experiment on data set from 2003/2004 [5].

2. Experimental Apparatus and Data Taking conditions

The protons from CERN SPS accelerator impinge the beryllium target producing a secondary kaon beam at nominal momentum of 75 GeV/c and 1% momentum spread (rms) transmitting 750 MHz particles to the NA62 experiment, about 6% of which are kaons. The beam is accompanied by a muon halo at the nominal rate of 3 MHz in the detector acceptance.

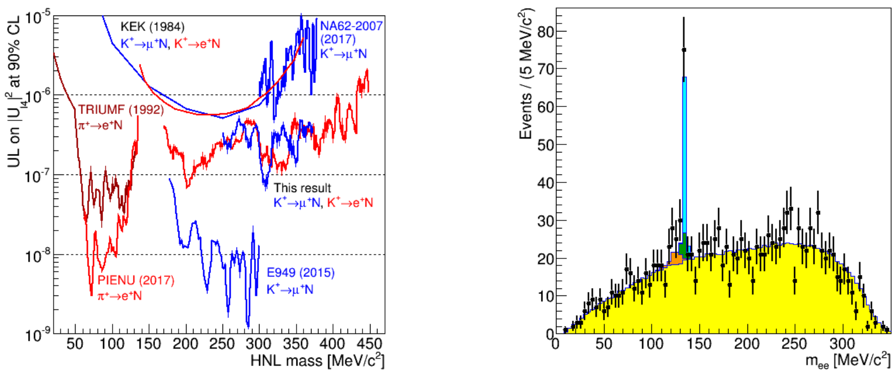
The first upstream detector is the Differential Cerenkov counter (KTAG) used to identify K^+ in the beam followed by the silicon pixel beam spectrometer GTK (under commissioning in 2015). The GTK is followed by the Charged Anti-counter detector, used to suppress products of deep inelastic scattering in the GTK. After that, the beam line opens into the 110 m long vacuum tank with fiducial volume in first 60 m, where about 13% of the K^+ entering the experiment decay. It contains a fully enclosed four tracking stations of the magnetic spectrometer. Along the vacuum tube twelve ring-shaped Large Angle Vetoes (LAV) are located with increasing diameter with distance from the target, which together with electromagnetic Liquid Krypton calorimeter (LKr), Inner Ring Calorimeter and Small Angle Calorimeter provide hermetic acceptance for photons emitted in K^+ decays for θ up to 50 mrad. Downstream to vacuum tube, before the LKr, is a ring-imagining Cherenkov counter (RICH) for particle identification and two plastic scintillator charged hodoscopes (CHOD). For further particle identification two hadronic calorimeters and muon veto detector (MUV1,2,3) follow the LKr. The full detector description can be found in Ref. [7].

3. Search for HNLs in Kaon decays

Reported results are based on 2015 data sample recorded during the 5 day period at about 1% of nominal intensity.

The data analysis strategy for $K^+ \to \mu^+ N$ and $K^+ \to e^+ N$ is based on one single charged track common up to the particle identification in the LKr, MUV1-3, RICH, and definition of start of the fiducial volume (FV), to suppress beam halo originating from the upstream decays of $K^+ \to \mu^+ \nu$. The background is estimated on the data-driven basis, qualitatively understood by the MC simulation.

Mass scans with 1 MeV/c^2 step size and $\pm 1\sigma_{m_\ell}$ window was performed, where σ_{m_ℓ} was evaluated with the MC simulations. The total number of kaon decays in the fiducial region, N_K, is $N_{K^e} = (3.00 \pm 0.11) \times 10^8$, $N_{K^\mu} = (1.06 \pm 0.02) \times 10^8$ for positron and muon mode respectively. In each HNL mass hypothesis Rolke-Lopez method [8] is used to find a 90% confidence intervals on the number of reconstructed $K^+ \to \ell^+ N$ assuming Poissonian process in the presence of the Gaussian backgrounds. The upper limits at 90% CL compared with other HNL production experiments in π^+ [9, 10] and K^+ [11, 12] decays are presented in Figure 1a. The result improves the muon mode in $300 \leq m_N \leq 373$ MeV/c^2 mass range and positron mode in the full mass range.



(a) (b)

Figure 1: (a) Upper limits on $|U_{\ell_4}|^2$ at 90% CL obtained for each assumed HNL mass compared to other experimental results. (b) Reconstructed m_{ee} distribution of $K^+ \to \pi^+ e^+ e^-$ candidates with $488\text{MeV}/c^2 < m_{\pi ee} < 500\text{MeV}/c^2$: data and MC estimates of contributing processes.

4. Lepton number and flavor violating processes

Several searches for LFV/LNV in 3-track decays are ongoing, reaching sensitivities down to 10^{-11}.

World's largest $K^+ \to \pi^+\mu^+\mu^-$ sample with expected $\sim$ 20k candidates in total promises a competitive measurement and possibility to search for new scalar $K^+ \to \pi^+ S$,$S^+ \to \mu^+\mu^-$ with single event sensitivity (SES) $\sim 10^{-10}$ for lifetimes up to $O(1\text{ns})$. Search for LNV and Majorana neutrinos in $K^+ \to \pi^-\mu^+\mu^+$ is background-free, reaching SES $\sim 10^{-10}$.

Background-free but not world's largest $K^+ \to \pi^+e^+e^-$ sample (1.1k events) is used for search for LNV process $K^+ \to \pi^-e^+e^+$ with expected SES $\sim 10^{-10}$. First observation of $K^+ \to \pi^+e^+e^-$ decay in the mass range $m_{ee} < 140$ MeV/c^2 thanks to background suppression from the decay chain: $K^+ \to \pi^+\pi^0$, $\pi^0_{Dalitz} \to \gamma e^+e^-$, with an excellent resolution is demonstrated in Figure 1b. Great resolution gives us an opportunity to search for $K^+ \to \pi^+ X$, $X^+ \to e^+e^-$, $10 < m_X < 100$ MeV/c^2 with SES at the level of 10^{-9} for lifetime $\ll 1$ ns.

Searches for LNV $K^+ \to \pi^-\mu^+e^+$ and LFV $K^+ \to \pi^+\mu^\pm e^\mp$ decays on the data set corresponding to 2.3×10^{11} kaon decays are also ongoing. Expected sensitivities are about 10^{-11} for all cases, once 2016-2018 data will be analyzed.

5. Conclusions

Upper limits on the HNL mixing parameters $|U_{\ell_4}|^2$ at 90% CL were established in the ranges 170-448 MeV/c^2 and 250-373 MeV/c^2, for positron and muon modes respectively, at the level between 10^{-7} and 10^{-6}. Major improvement is foreseen with the new data taken in years 2016-2018. Studies on LNV/LFV processes are ongoing and will improve over the world limits.

Acknowledgments and Appendices

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