Search for heavy neutrino in kaon decays

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Abstract

Heavy neutrinos exist in many New Physics (NP) models. They can be effectively searched for in kaon decays. In this paper, we concentrate on the following decay modes: $K \to \mu\nu_h$ and $K \to \mu\nu_h, \nu_h \to \nu\gamma$. Limits on the mixing matrix element $|U_{\mu h}|^2$ from different experiments are presented.

1 Introduction

Heavy neutrinos naturally arise in many NP models. They can contribute to Dark Matter (DM), Baryon asymmetry of the Universe (BAU) and anomalies observed by neutrino experiments (see the talk by D. Gorbunov at this conference). The detection of the heavy neutrinos is based on the assumption that they have mixing with Standard Model (SM) neutrino flavor eigenstates (either produced in neutral currents or in charged currents). Various scenarios are considered in talks by D. Gorbunov, E. Nougaev, A. Radionov and D. Tlisov.

New types of neutrino can be effectively searched for in pion and kaon decays (this idea was proposed in [1]). The simplest way to do it is to study two-body decays $\pi \to \mu\nu$ and $K \to \mu\nu$ and look for a peak in the muon energy distribution ($E_\mu = (M^2 + m_\mu^2 - m_h^2)/2M$) below the main one from $\pi \to \mu\nu_\mu$ ($\pi_{\mu 2}$) and $K \to \mu\nu_\mu$ ($K_{\mu 2}$). These decays allow to search for ν_h with masses up to ~300 MeV/c^2. Neutrinos with such masses could exist in many models (e.g. in νMSM [2]) and are not completely excluded by the existing experimental data [3].

Another possibility to search for heavy neutrino in kaon decays is to measure $K \to \mu\nu_h(\nu_h \to \nu\gamma)$ decay chain. The radiatively decaying ν_h can be used for an alternative interpretation of the latest results of short-baseline neutrino experiments [4]. For more than ten years there is no clear understanding of an event excess observed by LSND [5] and MiniBooNE [6, 7] experiments and their contradiction with KARMEN [8] results. Oscillation interpretations of the event excess require additional sterile neutrino(s) with $\Delta m^2 \sim 1\text{eV}^2/c^4$ (see [9] for review). The main idea (proposed for the first time in [10]) of the alternative interpretation is that in the experiments mentioned above signals from electrons and photons are indistinguishable. One could introduce heavy sterile neutrino ν_h as a component of ν_μ flavor eigenstate with a corresponding mixing matrix element $U_{\mu h}$ which is produced in ν_μ neutral current (NC) interactions and decays radiatively into a photon and a light neutrino ν. The decay channel $\nu_h \to \nu\gamma$ is dominant if there is a large enough magnetic transition moment μ_{tr} (it requires substantial new physics because in a minimally extended SM μ_{tr} is not large enough, see [11]). In this case the event excess in LSND and MiniBooNE experiments comes from photons and not from electrons. In KARMEN experiment, ν_h's with $m > 40$ MeV/c^2 cannot be produced within the detector because of a kinematic threshold effect.

Sterile neutrino ν_h could be either of a Dirac or Majorana type. In the latter case a photon angular distribution in ν_h rest frame is isotropic while for the Dirac case there is an anisotropy depending on ν_h mass: $\frac{dN}{dcos\theta^\star} \sim (1 + \frac{m_\mu^2 - m_h^2}{m_\mu^2 + m_h^2} cos\theta^\star)$.

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The combined analysis of LSND, KARMEN and MiniBooNE data results in the following properties of ν_h (regardless of the neutrino type):

- $40\text{MeV/c}^2 \lesssim m_h \lesssim 80\text{MeV/c}^2$;
- $10^{-11}s \lesssim \tau_h \lesssim 10^{-9}\text{s}$;
- $10^{-3} \lesssim |U_{\mu h}|^2 \lesssim 10^{-2}$.

It was mentioned that ν_h could be considered as a component of ν_μ. This leads to a very important consequence that ν_h is also produced in charged current (CC) interactions and can be effectively searched for in kaon decays.

2 Search for ν_h in $K \to \mu\nu_h$ decay

Best limits for 2-body kaon decays come from KEK E104 experiment [12]: $|U_{\mu h}|^2 < 10^{-4}$ for $70\text{MeV/c}^2 \leq m_h \leq 300\text{MeV/c}^2$. The experimental setup is shown in Fig. 1. High intensity

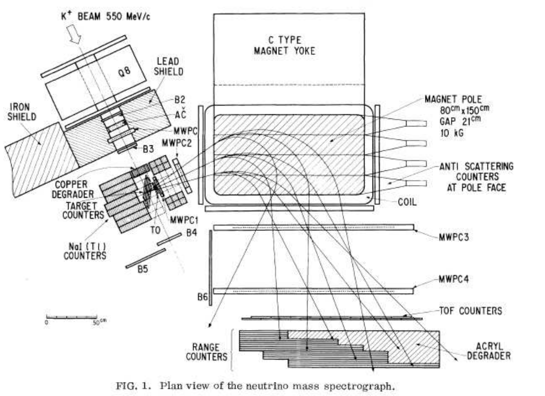

Figure 1: E104 setup.

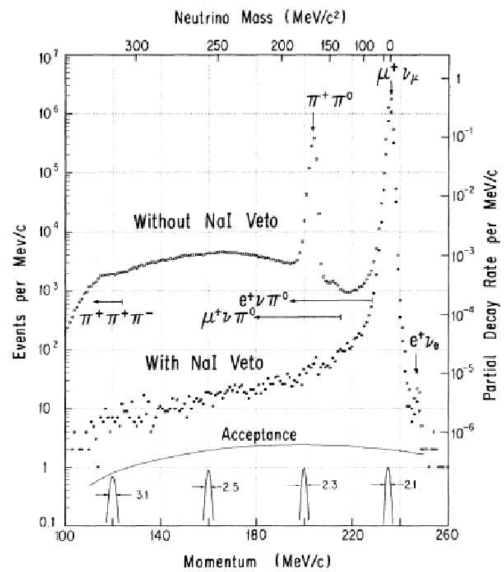

Figure 2: Muon momentum in E104 experiment.

dc-separated beam contained $\sim 20\%$ of kaons. The muon momentum was measured with good precision (FWHM $\sim 1\%$). To suppress backgrounds from kaon decays with photons in the final state, veto counters (NaI) were used. E104 experiment studied decays of stopped kaons.

Fig. 2 illustrates the distribution over muon momentum P_μ. Two main backgrounds come from $K \to \mu\nu_\mu\pi^0$ and $K \to \mu\nu_\mu\gamma$ decays with missing gamma(s). To obtain upper limits for the mixing matrix element $|U_{\mu h}|^2$, χ^2 square test for an extra peak in P_μ was performed. The results are shown in Fig.3. Also in this Figure are shown the limits from the pion decay $\pi_{\mu 2}$ [13] obtained for $5\text{MeV/c}^2 \leq m_h \leq 30\text{MeV/c}^2$. $K_{\mu 2}$ decay is not sensitive to low m_h masses because of resolution effects and strong background from $K \to \mu\nu_\mu\gamma(K_{\mu 2\gamma})$ decay. The region $30\text{MeV/c}^2 < m_h < 70\text{MeV/c}^2$ is not constrained at all. All results were obtained for relatively long-living ν_h that escape the setup (the photon veto was applied).

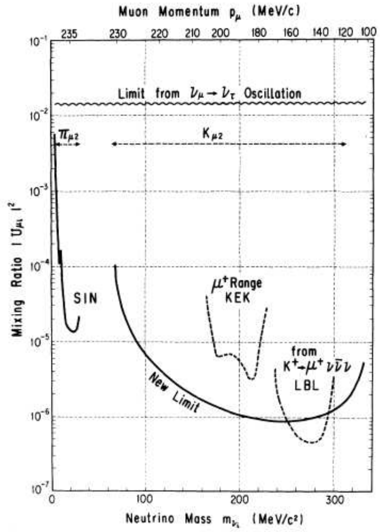

Figure 3: Upper limits on $|U_{\mu h}|^2$.

3 Search for ν_h in $K \to \mu\nu_h$, $\nu_h \to \nu\gamma$ decay chain

In this case the background from $K_{\mu2}$ and $K_{\mu2\gamma}$ is small and one can search for ν_h in a low mass region. One should stress here that only the case of radiatively decayed neutrinos is considered.

The search for heavy neutrino in $K^- \to \mu^-\nu_h(\nu_h \to \nu\gamma)$ with the properties described in [4] and in the following parameter range: $30\mathrm{MeV/c}^2 \le m_h \le 80\mathrm{MeV/c}^2$, $10^{-11}s \le \tau_h \le 10^{-9}$s has been recently done by ISTRA+ collaboration [14].

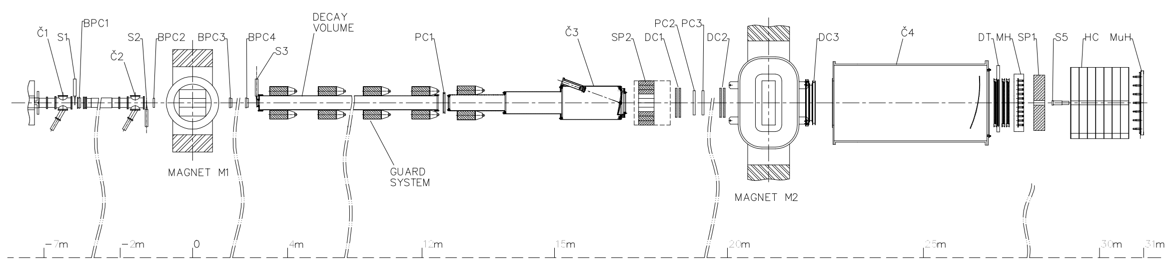

Figure 4: Elevation view of the ISTRA+ detector.

The experiment was performed at the IHEP 70 GeV proton synchrotron U-70. The experimental setup ISTRA+ (Fig. 4) was described in details in [15]. The setup was located in the negative unseparated secondary beam. The beam momentum in the measurements was $\sim$ 26 GeV/c with $\Delta p/p \sim 1.5\%$. The fraction of K^- in the beam was $\sim 3\%$. The ISTRA+ studied kaon decays in flight.

For signal and backgrounds studies, the standard Dalitz-plot was used ($x = 2 \cdot E_\gamma/m_K, y = 2 \cdot E_\mu/m_K$). The main background came from 3 decay modes: $K^- \to \mu^-\bar{\nu}_\mu\gamma(K_{\mu2\gamma})$, $K^- \to \mu^-\bar{\nu}_\mu\pi^0(K_{\mu3})$ with one gamma lost from $\pi^0 \to \gamma\gamma$ and $K^- \to \pi^-\pi^0(K_{\pi2})$ with one gamma lost and π misidentified as μ. Dalitz-plot distributions for the signal, $K_{\mu2\gamma}$, $K_{\mu3}$ and $K_{\pi2}$ are shown in Figs. 5 – 8. For the analysis the following region was selected: $0.2 < x < 0.55$ (49MeV $< E_\gamma <$ 136MeV). Selected x-stripes are shown in Fig. 5 (details of the event selection can be found in [16]). Dalitz-plot for the data with selected x-stripes is shown in Fig. 9.

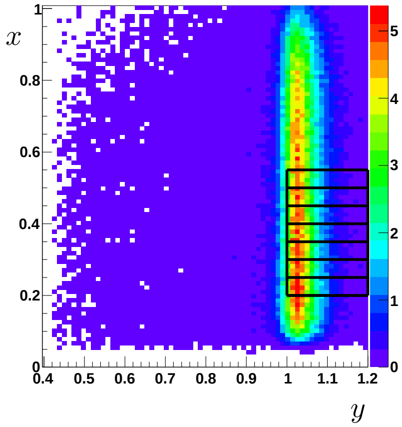

Figure 5: Dalitz-plot density for the signal (m_h=60MeV/c^2, $\tau_h = 10^{-10}s$).

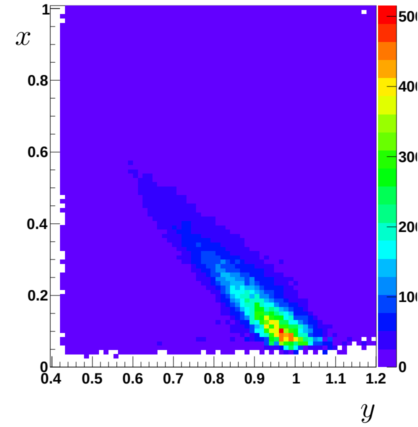

Figure 6: Dalitz-plot density for the $K_{\mu 2\gamma}(IB)$ background.

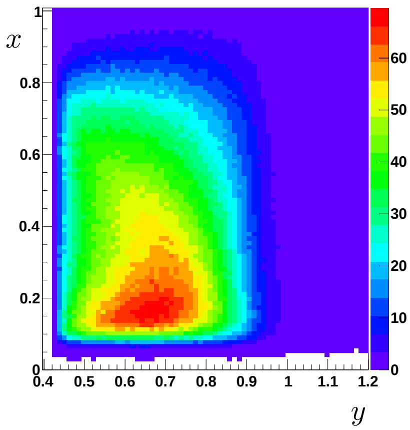

Figure 7: Dalitz-plot density for the $K_{\mu 3}$ background.

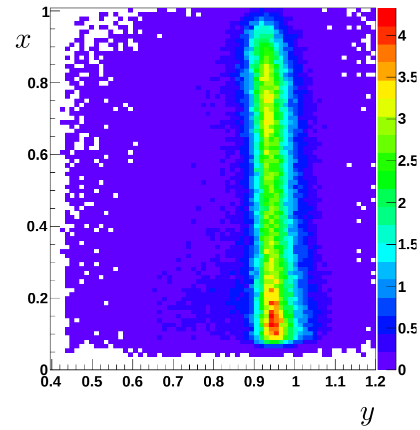

Figure 8: Dalitz-plot density for the $K_{\pi 2}$ background.

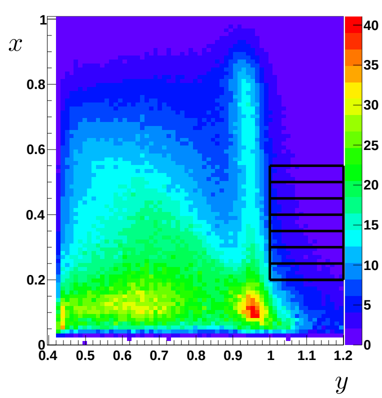

Figure 9: Dalitz-plot density for the data.

Obtained upper limits for different lifetimes as a function of m_h are shown in Figs. 10, 11. The limits are calculated for the following values of m_h: 30, 40, 50, 60, 70 and 80 MeV/c^2.

The curve in the figures is the interpolation between these values. The upper limits could be compared with the region predicted in [4] (shown with a blue stripe). Exact numbers are

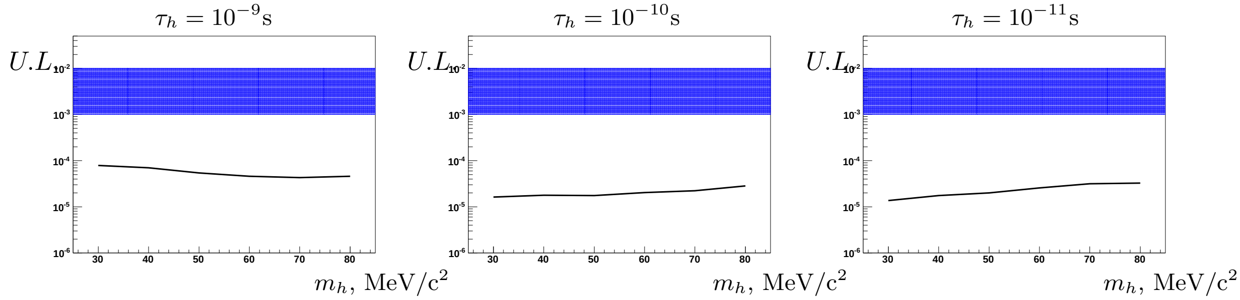

Figure 10: Upper limit for $|U_{\mu h}|^2$ vs m_h (Dirac case). Black line – obtained upper limits, blue stripe – prediction from [4].

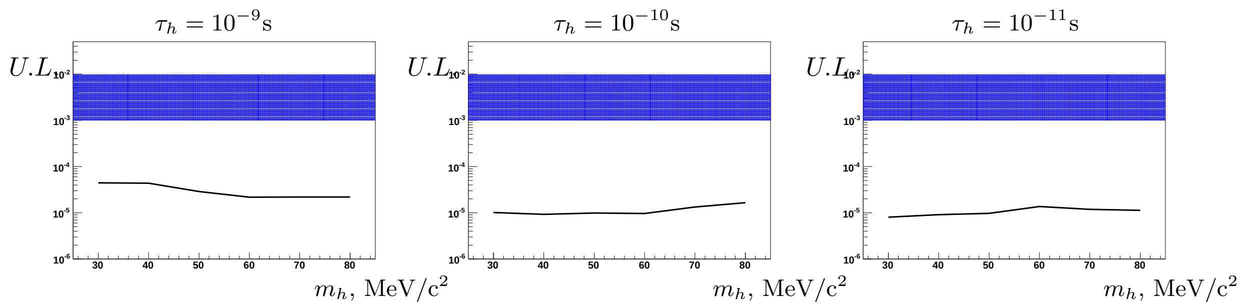

Figure 11: Upper limit for $|U_{\mu h}|^2$ vs m_h (Majorana case). Black line – obtained upper limits, blue stripe – prediction from [4].

collected in Tables 1 and 2.

m_h, MeV/c^2	$U.L.$, $\tau_h = 10^{-9}$s	$U.L.$, $\tau_h = 10^{-10}$s	$U.L.$, $\tau_h = 10^{-11}$s
30	7.9	1.6	1.4
40	7.0	1.8	1.8
50	5.4	1.8	2.0
60	4.6	2.0	2.6
70	4.3	2.2	3.2
80	4.6	2.8	3.3

Table 1: Upper limits for ν_h of the Dirac type. $U.L.$'s are in 10^{-5} units.

m_h, MeV/c^2	$U.L.$, $\tau_h = 10^{-9}$s	$U.L.$, $\tau_h = 10^{-10}$s	$U.L.$, $\tau_h = 10^{-11}$s
30	4.5	1.0	0.8
40	4.4	0.9	0.9
50	2.9	1.0	1.0
60	2.2	1.0	1.4
70	2.2	1.3	1.2
80	2.2	1.7	1.1

Table 2: Upper limits for ν_h of the Majorana type. $U.L.$'s are in 10^{-5} units.

4 Conclusions

Two ways of searching for heavy neutrinos in kaon decays have been considered. The existing limits on $|U_{\mu h}|^2$ from $K \to \mu\nu_h$ vary from 10^{-4} to 10^{-6} for $70\text{MeV/c}^2 < m_h < 300\text{MeV/c}^2$.

The upper limits on the mixing matrix element for radiatively decaying ν_h ($K \to \mu\nu_h, \nu_h \to \nu\gamma$) are $\sim 10^{-4} \div 10^{-5}$ for $30\text{MeV/c}^2 \leq m_h \leq 80\text{MeV/c}^2$ and $10^{-11}\text{s} \leq \tau_h \leq 10^{-9}\text{s}$. The obtained values close the allowed region for $|U_{\mu h}|^2$ suitable for LSND/KARMEN/MiniBooNE anomaly explanation proposed in [4].

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