Search for Heavy Neutral Leptons in T2K Experiment
Поиск Тяжёлых Нейтральных Лептонов в Эксперименте T2K

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В данной работе рассматривается поиск распадов тяжёлых нейтрино (N) с массами $m_N < 493\,\mathrm{MeV}/c^2$. Тяжёлые нейтрино могут рождаться в распадах: $K^{\pm}, \pi^{\pm} \to l^{\pm} N$, где $(l = e, \mu)$. Были рассмотрены следующие моды распада тяжёлых нейтрино: $N \to l_{\alpha}^{\pm}\pi^{\mp}$, $N \to l_{\alpha}^{+} l_{\beta}^{-} \nu(\overline{\nu})$, где $(\alpha, \beta = e, \mu)$. Поиск сигнальных событий выполняется во время-проекционных камерах ближнего детектора ND280 ускорительного нейтринного эксперимента T2K. Использование дополнительной статистики, новый метод восстановления траекторий во время-проекционных камерах и обновлённая модель Монте-Карло позволяют повысить чувствительность предыдущего анализа 2019 года и расширить его в область малых масс. Приведены предварительные эффективности отбора сигнальных событий, статистические и систематические неопределённости, ожидаемое число фоновых событий и ожидаемая чувствительность эксперимента.

The paper reports on search for heavy neutrinos (N) decays with masses $m_N < 493\,\mathrm{MeV}/c^2$. Heavy neutrinos can be produced in decays: $K^{\pm}, \pi^{\pm} \to l^{\pm} N$, where $(l = e, \mu)$. Considered heavy neutrino decay modes are the following: $N \to l_{\alpha}^{\pm}\pi^{\mp}$, $N \to l_{\alpha}^{+} l_{\beta}^{-} \nu(\overline{\nu})$, where $(\alpha, \beta = e, \mu)$. Search for signal events is performed in Time Projection Chambers (TPCs) of ND280 detector of T2K experiment. Inclusion of more statistics, a new tracking method in TPCs and an updated Monte-Carlo model aid in an increase of the sensitivity of the earlier analysis of 2019 and additionally helps to extend the studies into the lower mass region. Preliminary signal selection efficiencies, statistical and systematic uncertainties, expected number of background events and expected experiment sensitivity are presented.

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Introduction

Non-zero neutrino mass is not explained in the Standard Model (SM). To address the problem is the so-called Neutrino Minimal Standard Model (νMSM) extension [1]. νMSM is based on the type I see-saw mechanism with 3 right-handed Majorana neutrinos N_I ($I = \{1, 2, 3\}$, $M_1 \sim$ keV, $M_{2,3} \sim$

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MeV–GeV), which further will be called as heavy neutrinos or heavy neutral leptons (HNLs). Active neutrino flavor eigenstates can be written as a combination of mass eigenstates:

$$\nu_\alpha = \sum_{i=1}^{3} V_{\alpha i}^{\mathrm{PMNS}} \nu_i + \sum_{I=1}^{3} \Theta_{\alpha I} N_I, \ (\alpha = e, \mu, \tau;\ i, I = 1, 2, 3), \qquad (1)$$

where $V_{\alpha i}^{\mathrm{PMNS}}$ – Pontecorvo-Maki-Nakagawa-Sakata matrix, $\Theta_{\alpha I}$ – matrix which connects active and heavy neutrinos. We assume $M_2 \sim M_3 \equiv M_N$. Therefore, experiment is sensitive to $|U_\alpha|^2 = \sum_{I=2,3} |\Theta_{\alpha I}|^2$.

It is possible to probe heavy neutrinos in neutrino experiments. The approach is to search for HNL decays in a detector and to study kinematics of daughter particles. The search for HNLs was carried by the T2K neutrino experiment back in 2019 which resulted in setting yet competitive limits on the mixing parameters. [2]. Motivation for the new HNL search is the following:

1. Probe HNL mass region $m_N < 140\,\mathrm{MeV}/c^2$ using $\pi^\pm \to l^\pm N$ decays ($l = e, \mu$). In 2019 only $K^\pm \to l^\pm N$ decays in mass range $140 < M_N < 493\,\mathrm{MeV}/c^2$ were studied.

2. Include positive and negative-charged pions and kaons in both ν- and $\bar{\nu}$-dominant beam running modes to increase statistics.

3. Larger statistics: in the analysis we use total exposure of 12.34×10^{21} protons-on-target (POT) in ν-mode and 8.61×10^{21} POT in $\bar{\nu}$-mode compared to the same POT in ν-mode and 6.29×10^{21} POT in $\bar{\nu}$-mode in year 2019. We use updated NEUT [3] Monte-Carlo model and new tracking method in Time-Projection Chambers for better sensitivity.

Experimental setup and analysis strategy

T2K (Tokai-to-Kamioka, Japan) is a long-base accelerator neutrino oscillation experiment [4]. By changing polarity of the current of the focusing horns the experiment can study ν_μ or $\overline{\nu}_\mu$-enhanced beam. The search of HNLs is carried out by means of ND280. ND280 includes π^0 detector (P0D), Electromagnetic Calorimeter (ECal), 3 gaseous-argon Time Projection Chambers (TPCs), 2 Fine-Grained Detectors (FGDs) all inside UA1 0.2 T magnet additionally equipped to form the Side Muon Range Detector (SMRD). An example of a simulated HNL decay in ND280 is shown in Fig. 1.

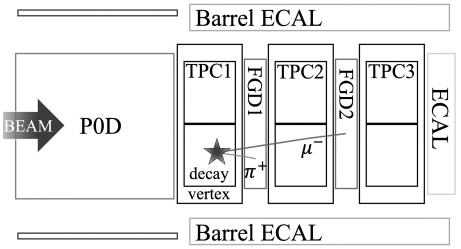


Fig. 1. Simulation of HNL decay $N \to \mu^- \pi^+$ in detector ND280

The search for HNLs is carried out in TPC gas volume to reduce backgrounds from active neutrino interactions. HNL flux simulation starts from active neutrino flux which is modified to account for a different kinematics as in [5]. The signal topology is a pair of oppositely charged tracks originating from the same point inside the TPC fiducial volume. The selection is based on vetoing, particle identification and kinematics-based criteria and is further split in the following branches: $\mu^{\pm}\pi^{\mp}$, $e^{-}\pi^{+}$, $e^{+}\pi^{-}$, $\mu^{-}\mu^{+}$, $e^{-}e^{+}$.

Signal systematic uncertainties and selection efficiency

We account for systematic uncertainties' related to ND280 detector and meson flux. For the flux a 20 % (10 %) total normalization uncertainty for $K^{\pm}$ ($\pi^{\pm}$) is a applied which is based on NA61/SHINE data [6]. The ND280-related uncertainties are due to tracking and modelling of the detector and were estimated to be < 6.5 % across all production and decay modes.

Selection efficiencies as a function of HNL mass are presented in Fig. 2. Solid lines correspond to the current analysis, dashed lines – to T2K analysis conducted in 2019 [2]. Relative errors were calculated using statistical and systematical (only detector-related) uncertainties.

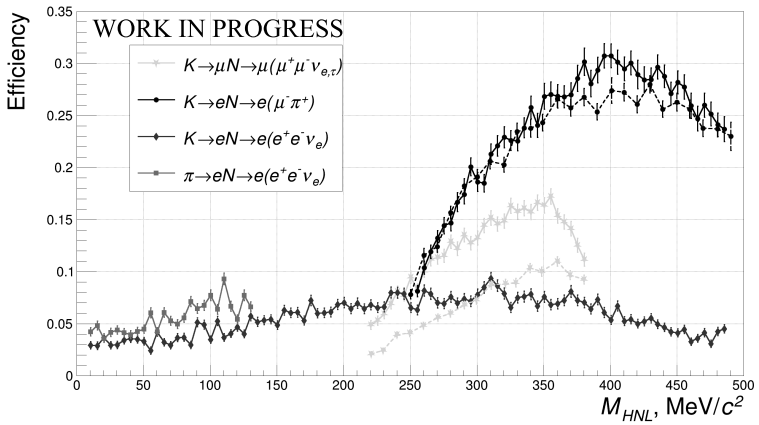


Fig. 2. Signal selection efficiencies for different HNL production and decay modes. Solid lines correspond to current analysis, dashed lines – to T2K analysis [2]

Background estimation and experiment sensitivity

Background was studied with NEUT Monte-Carlo [3]. Rescaled to data POT expected numbers of events for each selection channel are presented in the Table 1. Dominant contribution for $\mu\pi$ and $\mu\mu$ channels is neutrino-induced coherent pion production on argon nuclei in TPC gas: $\nu_{\mu} + \mathrm{Ar} \to \mu^{-} + \pi^{+} + \mathrm{Ar}$.

To estimate the sensitivity for $|U_{\alpha}|^2$ we consider each HNL production and decay mode independently and the results are obtained with a Bayesian method using log-normal prior probabilities and scaled to data POT. Expected sensitivity (90% confidence limits) is presented in Figs. 3-4. On

Table 1. Monte-Carlo background with the total error rescaled to data POT

Analysis channel	Background (ν-mode)	Background ($\overline{\nu}$-mode)
$\mu^{\pm}\pi^{\mp}$	1.05 ± 0.40	0.36 ± 0.21
$e^{-}\pi^{+}$	0.05 ± 0.05	0 ± 0
$e^{+}\pi^{-}$	0.12 ± 0.13	0 ± 0
$\mu^{+}\mu^{-}$	0.93 ± 0.35	0.36 ± 0.21
$e^{+}e^{-}$	0.12 ± 0.12	0 ± 0

the left (right) side of Fig. 3 we can see limits on $|U_e|^2$ ($|U_\mu|^2$) from $K \to eN$, $N \to e\pi$ ($K \to \mu N$, $N \to \mu\pi$) mode. Expected sensitivity is compared to results from: T2K [2], PS191 [7], NA62 [8], E949 [9]. We expect improvements for $|U_e|^2$ limits in mass range $415 < m_N < 493\,\mathrm{MeV}/c^2$ and for $|U_\mu|^2$ limits in $340 < m_N < 388\,\mathrm{MeV}/c^2$. In Fig. 4 we present expected $|U_e|^2$ sensitivity from $\pi \to eN$, $N \to e^{-}e^{+}\nu_e$ mode. It is compared to PIENU [10] and PS191 [7]. We expect improvements in mass range $125 < m_N < 135\,\mathrm{MeV}/c^2$.

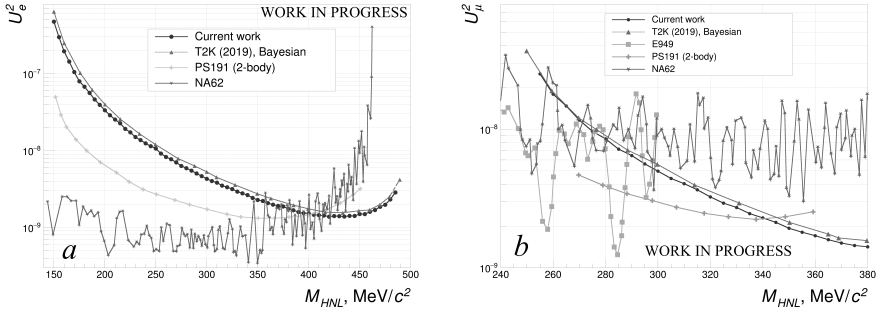


Fig. 3. *(a)* Expected limits on $|U_e|^2$ from $K \to eN$, $N \to e\pi$ mode, 90% CL. *(b)* Expected limits on $|U_\mu|^2$ from $K \to \mu N$, $N \to \mu\pi$ mode, 90% CL.

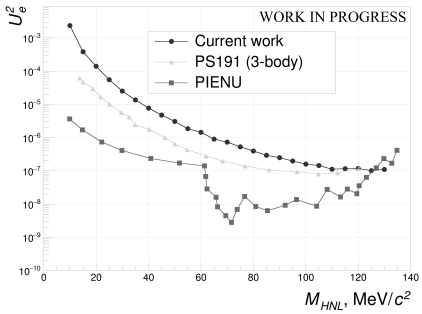


Fig. 4. Expected limits on $|U_e|^2$ from $\pi \to eN$, $N \to e^{-}e^{+}\nu_e$ mode, 90% CL.

Conclusion

An updated search for HNLs is performed with the T2K ND280 detector. Selection of 2 oppositely charged tracks in TPC gas allows one to isolate HNL decays from active neutrino interactions. For the considered T2K dataset we expect less than one background event across all analysis channels. Improvements are expected for $|U_e|^2$ limits in mass ranges $415 < m_N < 493\,\mathrm{MeV}/c^2$ and $125 < m_N < 135\,\mathrm{MeV}/c^2$, for $|U_\mu|^2$ limits in mass range $340 < m_N < 388\,\mathrm{MeV}/c^2$.

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Conflict of interest

The author declares that he has no conflicts of interest.

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