Heavy neutrinos effects for oscillation of light neutrinos at short distances

V V Khruschov\textsuperscript{1,2} and S V Fomichev\textsuperscript{1,3}
\textsuperscript{1}NRC Kurchatov Institute, Academician Kurchatov Place 1, Moscow, 123182 Russia
\textsuperscript{2}Center for Gravitation and Fundamental Metrology, VNIIMS, Ozernaya Str. 46, Moscow, 119361 Russia
\textsuperscript{3}Moscow Institute of Physics and Technology (State University), Institutskii Lane 9, Dolgoprudnyi, Moscow Region, 141700 Russia
E-mail: khruschov\textsubscript{vv}@nrcki.ru; fomichev\textsubscript{sv}@nrcki.ru

Abstract. The transition and survival probabilities for the different light neutrinos are calculated and displayed with account of the contributions of heavy neutrinos. It is shown that in the case of the mixing matrix of a definite type the explanation of the neutrino anomalies at short distances is possible. A new parametrization and a certain form of the mixing matrix for light and heavy neutrinos are used with allowance for the possible violation of CP invariance.

The problem of new particles, which are additional to the Standard Model (SM) particles is amongst the most important problems of the particle physics. New particles are necessary for numerous models beyond the SM, and they include supersymmetric particles, new particles for Grand Unification Theories, new particles of phenomenological models, etc. As an example, let us point at sterile neutrinos (SNs) and dark matter particles (DMPs). There are many indications of their existence in cosmology, astrophysics and neutrino physics. For instance, a number of neutrino ground-based experiments at short distances point to the presence of neutrino- and antineutrino-flux anomalies (so-called LNSD, Reactor and Gallium anomalies) \cite{1–3}. If it is confirmed at a high confidence level, it will be beyond the Minimally Extended Standard Model (MESM). MESM is the SM with three active neutrinos having different masses. A possible explanation of short distance anomalies is SNs existence with masses about 1 eV. DMPs can be among new particles too \cite{4–6}. Characteristics of DMPs are still unknown, although their existence is most probably. Below we will call new fermionic and electrically neutral particles with masses more than active neutrinos masses as heavy neutrinos (HNs). The active neutrinos may be called as light neutrinos (LNs). HNs with masses less than half of the Z-boson mass are surely SNs. The most suitable for explanation of some cosmological and astrophysical data are SNs and DMPs with eV-keV-MeV-GeV masses \cite{5,7–9}. Intensive experimental and theoretical studies are being currently performed in order to solve the problem of SNs. It is expected that experimental data will make it possible to confirm or disprove the existence of the aforementioned anomalies in the near future \cite{1,10–13}.

Below we consider a phenomenological model to describe neutrino anomalies at short distances and other effects of HNs. This model includes three active neutrinos $\nu_a$ ($a = e, \mu, \tau$) and four HNs, which consist of a sterile neutrino $\nu_s$ and three extra HNs ($\xi, N$ and $S$). We consider this model in two options, which can be called as a low mass option and a high mass
option. Let us present three generations of known quarks and leptons and a new generation of four HNs in the form of a $4 \times 4$-matrix $C$. Here we regard only left chiral states of the $C$ particles. The multiplet $C_L$ represents the sixteen-dimensional representation of the new $SO(10)_L$ group [14]:

$$C_L = \begin{pmatrix}

(\nu_e)_L & (\nu_\mu)_L & (\nu_\tau)_L & (\nu_s)_L \\
(e^-)_L & (\mu^-)_L & (\tau^-)_L & (\xi)_L \\
(u)_L & (c)_L & (t)_L & (N)_L \\
(d')_L & (s')_L & (b')_L & (S)_L \\
\end{pmatrix},$$

(1)

where $(d')_L$, $(s')_L$ and $(b')_L$ are left chiral states of $d$, $s$ and $b$ quarks mixed by the Cabibbo-Kobayashi-Maskawa matrix. The new neutral particles are distributed among two doublets of $\chi$ and $X$ states, which differ considerably by their mass values: $\chi = \begin{pmatrix} \nu_s \\ \xi \end{pmatrix}$ and $X = \begin{pmatrix} N \\ S \end{pmatrix}$.

It is known that the mixing of neutrino states can be described in terms of the Pontecorvo–Maki–Nakagawa–Sakata matrix $U_{PMNS} \equiv U \equiv V \cdot P$ as $\psi_L^a = U_i^a \psi_L^i$, where $\psi_L^a$ are left-handed chiral fields with flavor index $a = e, \mu, \tau$ or mass index $i = 1, 2, 3$, respectively [15]. For three LNs, the matrix $V$ can be expressed in terms of standard parametrization [16] through mixing angles $\theta_{ij}$ and $CP$ phase $\delta \equiv \delta_{CP}$ with Majorana neutrinos, while $P = \text{diag}(1, e^{i\alpha}, e^{i\beta})$, with $\alpha \equiv \alpha_{CP}$ and $\beta \equiv \beta_{CP}$ the phases associated with $CP$ violation only for Majorana neutrinos. At present, there are experimental data for the neutrino mixing angles and the mass-squared differences $\Delta m^2_{23}$ and $\Delta m^2_{34}$ (where $\Delta m^2_{23} = m^2_2 - m^2_3$), which specify three-flavor neutrino oscillations in a vacuum. These data were obtained from a global analysis of the most recent high-precision measurements of neutrino oscillation parameters [17]. The $CP$ phases $\alpha_{CP}$ and $\beta_{CP}$ are still not known now. The absolute values of the neutrino masses can be ordered by two ways, namely, a) $m_1 < m_2 < m_3$ and b) $m_3 < m_1 < m_2$, that is, it may be either the normal ordering/hierarchy case [NH, case (a)] or inverted ordering/hierarchy case [IH, case (b)]. In the following, we restrict ourselves to the NH case only, by setting $\delta_{CP} = -\pi/2$.

At the same time indications exist that the neutrino fluxes for some processes have anomalies, which manifest themselves at short distances (more precisely, at distances $L$ such that the values of parameter $\Delta m^2 L/E$, where $E$ is the neutrino energy, are about unity). The experiments at such distances are referred to as short-baseline (SBL) experiments. Data on the anomalies concern both the appearance of electron neutrinos or antineutrinos in the fluxes of muon neutrinos or antineutrinos, respectively, and the disappearance of electron or muon neutrinos or antineutrinos. The anomalies observed to date in the neutrino fluxes data can be explained by existence of light SNs. The Universe also contains heavy DMPs, which can include HNs.

We will consider the mixing matrix for LNs and HNs in the form of a $7 \times 7$-matrix, which can be named as the generalized mixing matrix $U_{\text{mix}}$. We consider here only particular form of $U_{\text{mix}}$ and present $U_{\text{mix}}$ as $V \cdot P$, where diagonal matrix $P$ is diag$\{1, e^{i\phi_1}, \ldots, e^{i\phi_6}\}$ with Majorana $CP$-violating phases $\phi_i$, $i = 1, \ldots, 6$. We keep a succession for notations and denote fifteen Dirac $CP$ phases as $\delta_i$ and $\kappa_j$ and twenty one mixing angles as $\theta_i$ and $\eta_j$, with $\delta_1 \equiv \delta_{CP}$, $\theta_1 \equiv \theta_{12}$, $\theta_2 \equiv \theta_{23}$ and $\theta_3 \equiv \theta_{13}$. We choose an approximation when the mixing between two $X$ neutrinos, as well as their mixing with other neutral particles are suppressed. In this case we can reduce the $7 \times 7$ matrix $U_{\text{mix}}$ to $6 \times 6$ matrix $\tilde{U}$, which was considered in detail in Ref. [18] for the case of three active and three sterile neutrinos. We will use the indices 4, 5, 6 and 7 to distinguish among the extra mass states and then denote by $f$ the set of indices distinguishing the extra flavor states $\nu_s$, $\xi$ and $N$ among $h_f$ and by $i'$ the set of indices 4, 5 and 6 for mass states $h_{i'}$. The matrix $U_{\text{mix}}$ can then be expressed in terms of $3 \times 3$ matrices $R$, $T$, $V$ and $W$ as:

$$\begin{pmatrix}

\nu_a \\
\eta_f \\
S \end{pmatrix} = \begin{pmatrix}

R & T & 0 \\
V & W & 0 \\
0 & 0 & 1 \end{pmatrix} \begin{pmatrix}

\nu_i \\
\eta_{i'} \\
S \end{pmatrix}. $$

(2)
For matrix $\tilde{U}$ we will consider, taking into account additional physical assumptions, only some particular cases rather than the most general form. Firstly, the matrix $R$ will be represented in the form of $R = U + \Delta U$, where the matrix $\Delta U$, as well as the matrices $T$ and $V$ in Eq. (2) should be small as compared with $U$. In order to estimate quantitatively both the mixing between LNs and HNs and the HNs-induced corrections to LNs mixing, we assume that $\Delta U = -\epsilon U$ and $\epsilon = 1 - \kappa$. Then $R = \epsilon U$, where $U$ is well known unitary $3 \times 3$ matrix of LNs mixing. Taking into account the results of Ref. [18], the following forms for the matrices $a$ and $b$ can be used, namely

$$a = \begin{pmatrix} \cos \eta_2 & \sin \eta_2 & 0 \\ -\sin \eta_2 & \cos \eta_2 & 0 \\ 0 & 0 & e^{-i\kappa_2} \end{pmatrix},$$

$$b = \begin{pmatrix} \cos \eta_1 & \sin \eta_1 & 0 \\ -\sin \eta_1 & \cos \eta_1 & 0 \\ 0 & 0 & e^{-i\kappa_1} \end{pmatrix},$$

where $\kappa_1$ and $\kappa_2$ are new mixing phases and $\eta_1$ and $\eta_2$ are new mixing angles. In our calculations, we will use the following test values: $\kappa_1 = \kappa_2 = -\pi/2$, $\eta_1 = 5^\circ$, $\eta_2 = \pm 30^\circ$, and also assume that the small parameter $\epsilon$ satisfies the condition $\epsilon \lesssim 0.03$. The neutrino masses will be specified by means of the set \{m\} = \{m_1, m_2, m_7\} ordered normally. We will use estimations of LNs mass values from Refs. [9, 18] (in eV units) as $m_1 \approx 0.0016$, $m_2 \approx 0.0088$ and $m_3 \approx 0.0497$.

Let us consider two options for our model, which differ by mass values of HNs $h_4$, $h_5$, $h_6$ and $h_7$. In the framework of the first option we adopt the mass value of $h_4$ of the order of 1 eV and the mass value of $h_5$ of the order of 10 keV. Then it becomes possible to explain both the occurrence of SBL anomalies in neutrino data [3] and the detection of 3.55 keV line in $\gamma$-spectra of some astrophysical sources [19–21]. Next, we take the mass values of $h_6$ and $h_7$ of the order of 1 MeV and 1 GeV, respectively. In this case one can explain the cosmological origin of the baryonic matter in the Universe, as well as a number of the observations concerning the dark matter [5, 22]. In the framework of the second option we eliminate existence of most light HNs and choose the HNs masses to be higher [8, 23, 24]. So, it is convenient to introduce four test sets of mass values, two sets for $\chi_1$ and $\chi_2$ and two sets for $X_1$ and $X_2$, namely, \{m\}$_{LMX} = \{1$ eV, $10$ keV\}, \{m\}$_{HMX} = \{50$ keV, $10$ MeV\}, \{m\}$_{LMX} = \{1$ MeV, $1$ GeV\} and \{m\}$_{HMX} = \{500$ GeV, $2$ TeV\}. The low mass case with two sterile neutrinos, which are nearly degenerate with respect to their mass values has been studied in Ref. [18]. This case may be denoted as the low mass twins option (LMTO). Here we consider other two options for the absolute mass values of four HNs, namely, the low mass option (LMO) and the heavy mass option (HMO). Below they are presented in eV units for complete sets of seven LNs and HNs as \{m\}$_{LMO} = \{0.0016, 0.0088, 0.0497, 1, 1 \times 10^4, 1 \times 10^6, 1 \times 10^9\}$ and \{m\}$_{HMO} = \{0.0016, 0.0088, 0.0497, 5 \times 10^4, 1 \times 10^7, 5 \times 10^{11}, 2 \times 10^{12}\}$. The equations for the flavor amplitudes of neutrino propagation in a vacuum are well known (see, e.g., Ref. [18]). Moreover, one can obtain analytical expressions for transitions probabilities between neutrino flavors with the help of these equations [25], which can be used to control the accuracy of numerical results obtained on the basis of the equations for the probability amplitudes.

In the present study, we focus primarily on the possibility of describing the anomalies that were found in data from the LSND experiment on the oscillations of accelerator muon neutrinos and antineutrinos, which were tested afterwards and will be still tested in a number of future
accelerator experiments [26]. A typical ratio of the distance travelled by a neutrino before detection to the neutrino energy is either several meters per MeV or one meter per several MeV. Attempts of a simultaneous description of all data in these processes lead to difficulties. In particular, problems associated with different values of the excess of both the $\nu_e$ and $\bar{\nu}_e$ yields in the MiniBooNE experiment can be solved upon admitting $CP$ violation [27–29]. It should be noted that the Reactor and Gallium anomalies manifesting themselves as the disappearance of electron neutrinos and antineutrinos can be described within our model by appropriate choosing a value of $\epsilon$. The appearance probabilities for electron neutrinos and antineutrinos in accelerator beams of muon neutrinos and antineutrinos are shown in figures 1–2 for the LMO and HMO neutrino mass values, respectively, at the neutrino energy 20 MeV. Shown in the same figures for the sake of comparison are the dependences obtained for the probabilities for only three LNs, that is, in the absence of HNs contributions (at $\epsilon = 0$).

In figure 1, the results for $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ are shown for the mixing matrix in the form of the present paper and for the LMO mass values. In this case, there is distinctive difference between the left-hand and right-hand panels, so there is the difference between the appearance probabilities of electron neutrinos and antineutrinos in beams of muon neutrinos and antineutrinos, respectively. The main difference between the mixing matrix in the form of Ref. [18] and in the form of the present paper is in the introducing the new $CP$ violation with two phases $\kappa_1$ and $\kappa_2$. However, it is more important that there is a difference in the mass values of the HNs. For the LMO mass values used in the results of figure 1, only one mass ($m_4 = 1$ eV) is of the order of 1 eV, while other masses are much higher (e.g., $m_5 = 10$ keV). So, one light sterile neutrino with the mass of the order of 1 eV is sufficient for explanation of the possible

Figure 1. Appearance probabilities for electron neutrinos/antineutrinos from the beams of muon neutrinos/antineutrinos at various values of $\epsilon$ at $\eta_2 = \pi/6$ and for the LMO mass values.

Figure 2. The same as in figure 1 for the HMO mass values.
LNSD anomaly in neutrino data. In figure 2, the results for \(P(\nu_\mu \rightarrow \nu_e)\) and \(P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)\) are shown in the same form for the HMO mass values. In this case there are no distinctive features between the left-hand and right-hand panels, so there is no difference between the appearance probabilities of electron neutrinos and antineutrinos. The appearance probability of electron neutrino/antineutrino also strongly oscillates as a function of distance in both figures 1 and 2, with smooth envelopes which practically are the same for neutrino and antineutrino in figure 2. But the scale of the electron neutrino/antineutrino yields is the same as for the case of figure 1.

In conclusion, the properties of LNMs and HNMs have been examined in this paper on the basis of the phenomenological neutrino model. Specifically, this has been done by using two options of our model, namely, the LMO and the HMO. The properties of oscillations of LNMs and HNMs in a vacuum at test values of the model parameters have been calculated. All calculations have been performed for the case of normal hierarchy for the LNMs masses, taking into account possible CP violation in the lepton sector and setting the Dirac CP phase in the \(U_{\text{PMNS}}\) matrix for active neutrinos to \(-\pi/2\). The graphical dependences of the appearance probabilities for electron neutrinos/antineutrinos on the distance from the source of muon neutrinos/antineutrinos have been determined for neutrino energy 20 MeV. The results obtained allow to interpret experimental neutrino oscillation data permitting the existence of the LNSD anomaly at a neutrino energy of about 40 MeV and a distance of about 30 m from the source. The great advantage of our calculations lies in revealing of the asymmetry between the appearance probabilities for electron neutrinos and antineutrinos (see figure 1) due to another source of CP violation with respect to \(\delta_{\text{CP}}\). The model in question may also be used to describe some astrophysical data for the cases where heavy neutrinos are involved, as well as in predicting the results of new experiments relating to the sterile neutrino existence problem [1, 10–13].

References

1. Abazajian K N et al. Preprint hep-ph:1204.5379
2. Kopp J, Machado P A N, Maltoni M and Schwetz T 2013 J. High Energy Phys. JHEP05(2013)050
3. Gariazzo S, Giunti C, Laveder M and Lie Y F Preprint hep-ph:1703.00860v3
4. Vogelsberger M et al. 2014 Nature 509 177
5. Demianski M and Doroshkevich A G Preprint astro-ph.CO:1511.07989v6
6. Abazajian K N Preprint hep-ph:1705.01837v2
7. Undagoitia T M and Rauch L 2016 J. Phys. G 43 013001
8. Argüelles C R, Krut A, Rueda J A and Ruffini R Preprint astro-ph.GA:1606.07040v2
9. Yudin A V, Nadyozhin D K, Khruschov V V and Fomichev S V 2016 Astron. Lett. 42 800
10. Gavrin V N, Gorbachev V V, Veretennik E P and Cleveland B T Preprint nucl-ex:1006.2103v2
11. Bellini G et al. J. High Energy Phys. JHEP08(2013)038
12. Serebrov A P et al. 2015 Tech. Phys. 60 1863 (Preprint physics.ins-det:1501.04740)
13. Dentler M, Hernández-Cabezudo A, Kopp J, Maltoni M and Schwetz T Preprint hep-ph:1709.04294
14. Khruschov V V Preprint hep-ph:1609.01858
15. Bilenky S M and Pontekorvo B M 1977 Sov. Phys. Usp. 20 776
16. Patrignani C et al. [Particle Data Group] 2016 Chin. Phys. C 40 100001
17. Esteban I, Gonzalez-Garcia M C, Maltoni M, Martinez-Soler I and Schwetz T Preprint hep-ph:1611.01514v2
18. Khruschov V V, Fomichev S V and Titov O A 2016 Phys. At. Nucl. 79 708 (Preprint hep-ph:1612.06544v1)
19. Bulbul E et al. 2014 Astrophys. J. 789 13
20. Boyarsky A, Ruchayskiy O, Iakubovskyi D and Franse J 2014 Phys. Rev. Lett 113 251301
21. Horiuchi S et al. Preprint astro-ph.CO:1512.04548
22. Drewes M and Garbrecht B Preprint hep-ph:1502.00477
23. Vogelsberger M et al. Preprint astro-ph.CO:1512.05349v2
24. Bertuzzo E, Barros C J C and di Cortona G G Preprint hep-ph:1707.00725
25. Bilenky S M 2015 Phys. Part. Nucl. Lett. 12 453 (Preprint hep-ph:1502.06158)
26. Gariazzo S, Giunti C, Laveder M, Li Y F and Zavanin E M Preprint hep-ph:1507.08204
27. Maltoni M and Schwetz T 2007 Phys. Rev. D 76 093005
28. Palomares-Ruiz S, Pascoli S and Schwetz T 2005 J. High Energy Phys. JHEP09(2005)048
29. Karagiorgi G et al. 2007 Phys. Rev. D 75 013011 [Erratum: 2009 Phys. Rev. D 80 099902(E)].