Interpretation of the XENON1T excess in the model with decaying sterile neutrinos

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The phenomenological model with three active and three sterile neutrinos is used for interpretation of the observed XENON1T excess of electronic recoil events in the 1 – 7 keV energy region. Assuming two sterile neutrinos with appropriate mass values decay while the third sterile neutrino is stable it is possible to explain the observed energy spectrum of electronic recoil events. Moreover using this approach three peaks in the 1 – 7 keV energy region are predicted. Dark bosons have to mix to only a small extent with photons which can emit the energy in this region. The possible existence of the three massive sterile neutrinos may have perceptible influence on some phenomena in neutrino physics, astrophysics and cosmology.

Keywords: Excess of electronic recoil events; XENON1T anomaly; Dark bosons; Decaying sterile neutrinos

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1. Introduction

Recently the XENON1T experiment data concerning electronic recoil events in the energy region between 1 and 210 keV have been reported[1] The excess of electronic recoil events in the energy region between 1 and 7 keV has been observed by means of the data. At the moment there is an increasing list of papers related to explanation for the excess (e.g.[2],[3]). In the present paper we suggest an interpretation of the observed effect in the framework of the neutrino model with three active and three sterile neutrinos[6] with decaying two sterile neutrinos.

It is known that oscillations of solar, atmospheric, reactor and accelerator active neutrinos can be attributed to mixing of three mass states of neutrinos that is effected by way of the Pontecorvo–Maki–Nakagawa–Sakata matrix $U_{PMNS} \equiv U = VP$, so that $\psi^L_a = \sum_i U_{ai} \psi^L_i$, where $\psi^L_{a,i}$ are left chiral fields with flavor $a$ or mass $m_i$, $a = \{e, \mu, \tau\}$ and $i = \{1, 2, 3\}$. The matrix $V$ is expressed in the standard parametrization[7] for three active neutrinos via the mixing angles $\theta_{ij}$ and the CP-phase, namely, the phase $\delta \equiv \delta_{CP}$ associated with CP violation in the lepton sector

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for Dirac or Majorana neutrinos, and $P = \text{diag}\{1, e^{i\alpha}, e^{i\beta}\}$, where $\alpha \equiv \alpha_{\text{CP}}$ and $\beta \equiv \beta_{\text{CP}}$ are phases associated with CP violation only for Majorana neutrinos.

With the help of high-precision experimental data, the values of the mixing angles $\theta_{ij}$ and the differences of the neutrino masses in square $\Delta m^2_{21}$ and $\Delta m^2_{31}$ were found [7, 8] (where $\Delta m^2_{ij} = m_i^2 - m_j^2$), but only absolute value of $\Delta m^2_{31}$ is known, therefore, the absolute values of the neutrino masses can be ordered by two ways, namely, as $m_1 < m_2 < m_3$ or $m_3 < m_1 < m_2$ which are called as normal neutrino mass ordering (NO) and as inverse neutrino mass ordering (IO), respectively. Including nonzero neutrino masses results in the Modified Standard Model (MSM) instead of the Standard Model (SM). If we take into account the results of the T2K experiment [9] and the restrictions on the sum of the neutrino masses from cosmological observations [10], then the NO-case of the neutrino mass spectrum turns out to be preferable (see also [8]). Now the estimation of the value of CP-phase $\delta_{\text{CP}}$ [8] and the possibility of realization of the IO-case [11] has been obtained. Nevertheless we restrict ourselves to the NO-case only, assuming $\delta_{\text{CP}} = 1.2\pi$.

At the same time, there are indications to anomalies of neutrino fluxes for some processes that can not be explained with using oscillation parameters only for three active neutrinos. These anomalies include the LSND (or accelerator) anomaly [12–15], the reactor antineutrino anomaly [15, 21], and the gallium (or calibration) anomaly [22–24]. The anomalies manifest themselves at short distances (more precisely, at distances $L$ such that the numerical value of the parameter $\Delta m^2 L / E$, where $E$ is the neutrino energy, is of the order of unity). In the LSND anomaly, an excess of the electron antineutrinos in beams of muon antineutrinos in comparison with the expected value according to the MSM is observed. Similar results were observed in the MiniBooNE experiments for electron neutrinos and antineutrinos [14–15]. Deficit of reactor electron antineutrinos at short distances is called as the reactor antineutrino anomaly, while the deficit of electron neutrinos from a radioactive source observed at calibration of detectors for the SAGE and GALLEX experiments is commonly called as the gallium anomaly. In other words, data on the neutrino anomalies refer to both the appearance of the electron neutrinos or antineutrinos excess in beams of muon neutrinos or antineutrinos, respectively, and to the deficit of electron neutrinos or antineutrinos. These three types of the shot-baseline (SBL) neutrino anomalies, for which there are indications at present, are attributed to the presence of one or two new neutrinos that do not interact directly with the gauge bosons of the MSM, that is sterile neutrinos. The characteristic mass scale of sterile neutrino used for explanation of the SBL anomalies is about 1 eV.

In principle, the number of additional neutrinos can be arbitrary (see, for example, Refs. [25–27]). Phenomenological models with sterile neutrinos are usually denoted as $(3+N)$ models, or, in detail, as $(k+3+n+m)$ models, where $k$ is a number of new neutrinos with masses less than masses of active neutrinos, and $n$ and $m$ are numbers of new neutrinos with masses higher and considerably higher, respectively, than masses of the active neutrinos.
In Section 2, the main concepts of the (3+3) model (to be exact, the (3+1+2) model) are given, which based on the results reported in Ref. 6. In Section 3, we present a short description of data relevant to the electronic recoil events excess in the XENON1T experiment and their interpretation in the context of the (3+1+2) model. In the final Section 4 it is noticed that the results of the present paper can help to explain the available XENON1T experimental data, as well as to interpret both data of SBL experiments on the search of sterile neutrinos and some astrophysical and cosmological data.

2. Basic concepts of the phenomenological (3+1+2) model

The (0+3+N) or (0+3+m+n) phenomenological neutrino models can be used to describe the SBL anomalies, as well as some astrophysical data, where \( N = m + n \) is the number of additional neutrinos. It is desirable that the number of new neutrinos would be minimal, so the most common are the (3+1) and (3+2) models \(^{31} \) ((3+1) is used instead of (0+3+1) for short). However, if we apply the principle of extended symmetry of weak interactions, then, for example, for the left-right symmetry it is necessary to consider (3+3) models\(^{28–30} \). So, below we use the (3+1+2) model to account for effects of light and heavy sterile neutrinos. This model includes three active neutrinos \( \nu_a \) (\( a = e, \mu, \tau \)) and three new neutrinos: a sterile neutrino \( \nu_s \), a hidden neutrino \( \nu_h \) and a dark neutrino \( \nu_d \). Thus six neutrino flavour states and six neutrino mass states are present in the (3+1+2) model. Hence below we consider the 6×6 mixing matrix, which can be called as the generalized mixing matrix \( U_{\text{mix}} \), or the generalized Pontecorvo–Maki–Nakagawa–Sakata matrix \( \tilde{U}_{\text{PMNS}} \equiv U_{\text{mix}} \). This matrix can be represented as the matrix product \( VP \), where \( P \) is a diagonal matrix with Majorana CP-phases \( \phi_i \), \( i = 1, \ldots, 5 \), namely, \( P = \text{diag}\{1, e^{i\phi_1}, \ldots, e^{i\phi_5}\} \). We deal only with a particular type of matrix \( V \). Keeping continuity of the notations, we denote Dirac CP-phases as \( \delta_i \) and \( \kappa_j \), and mixing angles as \( \theta_i \) and \( \eta_j \), with \( \delta_1 \equiv \delta_{\text{CP}}, \ \theta_1 \equiv \theta_{12}, \ \theta_2 \equiv \theta_{23} \) and \( \theta_3 \equiv \theta_{13} \).

For the compactness of the formulas, we introduce the symbols \( h_s \) and \( h_{i'} \) for generalized left flavor fields and generalized left mass fields, respectively. As \( s \) we will use a set of indices that allocate \( \nu_s \), \( \nu_h \) and \( \nu_d \) fields among \( h_s \), and as \( i' \) we will use a set of indices 4, 5 and 6. The common 6×6 mixing matrix \( U_{\text{mix}} \) can then be expressed through 3×3 matrices \( R \), \( T \), \( V \) and \( W \) as follows

\[
\begin{pmatrix}
\nu_a \\
h_s
\end{pmatrix} =
U_{\text{mix}}
\begin{pmatrix}
\nu_i \\
h_{i'}
\end{pmatrix} =
\begin{pmatrix}
R & T \\
V & W
\end{pmatrix}
\begin{pmatrix}
\nu_i \\
h_{i'}
\end{pmatrix}.
\]

(1)

We represent the matrix \( R \) in the form of \( R = \varepsilon U_{\text{PMNS}} \), where \( \varepsilon = 1 - \epsilon \) and \( \epsilon \) is a small value, while the matrix \( T \) in equation (1) should also be small as compared with the known unitary 3×3 mixing matrix of active neutrinos \( U_{\text{PMNS}} \) \( (U_{\text{PMNS}}U_{\text{PMNS}}^\dagger = I) \). Thus, when choosing the appropriate normalization, the active neutrinos mix, as it should be in the MSM, according to Pontecorvo–Maki–Nakagawa–Sakata matrix \( U_{\text{PMNS}} \). Below we use the notation \( U_{\text{PMNS}} \equiv U \).
On the current stage of the study, it is quite reasonable to restrict us to the minimal number of mixing matrix parameters that is able to explain the available (still rather dispersive) experimental data pertaining to the SBL anomalies. The transition to full matrix with all parameters can be done in further, when quite reliable experimental results will be obtained. So, we will consider only some particular cases, but not the most common form for the matrix $U_{\text{mix}}$. Bearing in mind that, in accordance with data available due to astrophysical and laboratory measurements, the mixing between active and new neutrinos is small, we choose the matrix $T$ as

$$T = \sqrt{1 - \kappa^2} a,$$

where $a$ is an arbitrary unitary $3 \times 3$ matrix, that is, $aa^+ = I$. The matrix $U_{\text{mix}}$ can now be written in the form of

$$U_{\text{mix}} = \left( \begin{array}{c|c} R & T V W \end{array} \right) \equiv \frac{\kappa}{\sqrt{1 - \kappa^2}} \left( \begin{array}{c|c} U_{\text{mix}} & \sqrt{1 - \kappa^2} a \\ \hline \kappa & c \end{array} \right),$$

(2)

where $b$ is also an arbitrary unitary $3 \times 3$ matrix ($bb^+ = I$), and $c = -ba$. With these conditions, the matrix $U_{\text{mix}}$ will be unitary ($U_{\text{mix}}U_{\text{mix}}^+ = I$). In particular, we will use the following matrices $a$ and $b$:

$$a = \begin{pmatrix} \cos \eta_2 & \sin \eta_2 & 0 \\ -\sin \eta_2 & \cos \eta_2 & 0 \\ 0 & 0 & e^{-i\kappa_2} \end{pmatrix}, \quad b = -\begin{pmatrix} \cos \eta_1 & \sin \eta_1 & 0 \\ -\sin \eta_1 & \cos \eta_1 & 0 \\ 0 & 0 & e^{-i\kappa_1} \end{pmatrix},$$

(3)

where $\kappa_1$ and $\kappa_2$ are mixing phases between active and sterile neutrinos, whereas $\eta_1$ and $\eta_2$ are mixing angles between them. The matrix $a$ in the form of equation (3) was proposed in Ref. [30]. In order to make our calculations more specific, we will use the following sample values for new mixing parameters:

$$\kappa_1 = \kappa_2 = -\pi/2, \quad \eta_1 = 5^\circ, \quad \eta_2 = \pm 30^\circ,$$

(4)

and assume that the small parameter $\epsilon$ satisfies at least the condition $\epsilon \lesssim 0.03$.

The neutrino masses will be given by a normally ordered set of values $\{m\} = \{m_1, m_1', m_2, m_3\}$. For active neutrinos we will use the neutrino mass estimations, which were proposed in Refs. [29,30,32] for NO-case (in units of eV) and which do not contradict to the known experimental data up to now.

$$m_1 \approx 0.0016, \quad m_2 \approx 0.0088, \quad m_3 \approx 0.0497.$$

The values of the mixing angles $\theta_{ij}$ of active neutrinos that determine the Pontecorvo–Maki–Nakagawa–Sakata mixing matrix will be taken from relations $\sin^2 \theta_{12} \approx 0.318$, $\sin^2 \theta_{23} \approx 0.566$ and $\sin^2 \theta_{13} \approx 0.222$, which are obtained from the processing of experimental data for NO and given in Ref. [8]

In Ref. [6] the version of the Light Mass Option (LMO1 version) of the $(3+1+2)$ model has been considered for $m_4$, $m_5$, and $m_6$ mass values:

$$\{m\}_{\text{LMO1}} = \{1.1, 1.5 \times 10^3, 7.5 \times 10^3\}.$$  

(6)

In order to reproduce in every detail the electrons energy spectrum observed in the XENON1T experiment in what follows we choose a comparatively higher mass $m_5$, than the corresponding mass value given in Ref. [6] (see (6)). The $m_4$ and practically
m_6\) mass values are unchanged, furthermore the \(m_4\) value meets currently available constraints. Thus, below we will use the following \(m_4\), \(m_5\), and \(m_6\) mass values for sterile mass states:

\[
\{m\}_{\text{LMO}} = \{1.1, 3.4 \times 10^3, 7.6 \times 10^3\}. \tag{7}
\]

With the LMO set of the mass values above it remains possible to explain the appearance of anomalies at short distances in neutrino data\(^{33,34}\). Note that sterile neutrinos with masses from 1 keV to 10 keV are also used for interpretation of some astrophysical data\(^{35}\), so this adds considerable support for our choice of the \(m_5\) mass value as 3.4 keV and the \(m_6\) mass value as 7.6 keV.

3. Data relevant to the electronic recoil events excess in the XENON1T experiment and their interpretation in the context of the \((3+1+2)\) model

Recently the XENON1T experiment data have been reported on the observation of the excess of electronic recoil events in the energy region between 1 and 7 keV\(^1\). The XENON1T experiment operated underground at the INFN Laboratori Nazionali del Gran Sasso. This experiment, employing a liquid-xenon time projection chamber with a 2.0-tonne active target, was primarily designed to detect Weakly Interacting Massive Particle (WIMP) dark matter. A particle interaction within the detector produces both prompt scintillation and delayed electroluminescence signals. These light signals are detected by arrays of photomultiplier tubes on the top and bottom of the active volume, and are used to determine the deposited energy and interaction position of an event. The ratio between delayed electroluminescence signals and prompt scintillation signals is used to distinguish electronic recoils, produced by, e.g., gamma rays or beta electrons, from nuclear recoils, produced by, e.g., neutrons or WIMPs, allowing for a degree of particle identification.

In what follows we focus on the possibility of describing, in the framework of the \((3+1+2)\) model considered above, the excess of electronic recoil events observed in the XENON1T experiment. We suggest that this excess can be naturally attributed to interaction of electrons with dark bosons arose for the most part in decay processes of hidden and dark neutrinos. Note that these processes can scarcely produce photons as well. A plausible mechanism for photon appearance can be a kinetic mixing to only a small extent between a photon and a dark boson\(^{37}\). So dark bosons and photons with energies about 3.4 keV, 4.2 keV and 7.6 keV can be emitted in transitions among mass component parts of dark, hidden and sterile neutrinos assuming that the sterile neutrino, which is mainly the \(m_4\) mass state, is stable. Thus using this approach we predict three peaks in the 1–7 keV energy region of electronic recoil events at energies about 3.4 keV, 4.2 keV and 7.6 keV. This prediction can be tested as in the XENON1T experiment when a high-statistics data set will be available as in future experiments of this kind. Note that the used above the LMO variant of the \((3+1+2)\) neutrino model with the decaying heavy neutrinos and the...
light stable sterile neutrino still remain operable for description of the SBL neutrino anomalies (see, e.g., \[6, 38–40\]).

4. Discussion and conclusions

In this paper, we use the phenomenological (3+1+2) neutrino model with three active and three sterile neutrinos for description of the excess of electronic recoil events in the 1 – 7 keV energy region found in the data of the XENON1T experiment.\[1\] This excess can be naturally attributed to interaction of electrons with dark bosons and photons emitted in decays of the sterile neutrino mass states with the masses \(m_5 = 3.4\) keV and \(m_6 = 7.6\) keV while the sterile neutrino mass state with the mass \(m_4 = 1.1\) eV is stable. In the context of this approach three peaks in the 1 – 7 keV energy region of electronic recoil events at energies about 3.4 keV, 4.2 keV and 7.6 keV are predicted. These predictions will be tested as in the XENON1T experiment as in future experiments, such as the upcoming PandaX-4T\[41] and XENONnT experiments.

The possible existence of the three massive sterile neutrinos may have a perceptible influence on some phenomena in neutrino physics, astrophysics and cosmology. By way of illustration we refer to the possibility to interpret the SBL anomalies data in the framework of the (3+1+2) model with sterile neutrinos.\[6\] Moreover the incorporation of two decaying sterile neutrinos with 3.4 keV and 7.6 keV masses allows us to predict amplification or appearance of the lines at 3.4 keV, 4.2 keV and 7.6 keV in the gamma spectra of some astrophysical sources. The presence of stable sterile neutrino mass state with the mass 1.1 eV will make an impact on a value of the important cosmological parameter \(\Delta N_{\text{eff}}\), besides it is possible this can matter for the resolution of the issue concerning the \(H_0\) tension.\[33, 34\]

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