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Sterile neutrino decay as a common origin for LSND/MiniBooNE and T2K excess events

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I point out that the excess of electronlike neutrino events recently observed by the T2K Collaboration may have a common origin with the similar excess events previously reported by the LSND and MiniBooNE experiments, and interpreted as a signal from the radiative decays of a sterile neutrino ν_h with the mass around 50 MeV produced in ν_μ neutral current (NC) interactions. In this work, I assumed that the ν_h can also be produced in ν_τNC reactions.

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Over the past 10 years, there has been a puzzle of the 3.8σ event excess observed by the LSND Collaboration [1]. This excess, originally interpreted as a signal from $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations, was not confirmed by further measurements from the similar KARMEN experiment [2]. The MiniBooNE experiment, designed to examine the LSND effect, also found no evidence for $\nu_\mu \to \nu_e$ oscillations. However, an anomalous excess of low-energy electronlike (e-like) events in quasi-elastic neutrino events has been observed [3]. New MiniBooNE results from a search for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations also show an excess of events, which has a small probability to be identified as the background-only events [4]. The data are found to be consistent with $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations in the 0.1 eV^2 range and with the evidence for antineutrino oscillations from the LSND.

In the recent work of Ref. [5] (see also Refs. [6–8]), it has been shown that puzzling LSND, KARMEN, and MiniBooNE results all could be explained in a consistent way by assuming the existence of heavy sterile neutrinos (ν_h). The ν_h is created in ν_μ neutral-current interactions and decays subsequently into a photon and a lighter neutrino ν in the LSND and MiniBooNE detectors, but it cannot be produced in the KARMEN experiment due to the high energy threshold. The ν_h could be Dirac or Majorana type, and it could be produced, e.g., through the $\nu_\mu - \nu_h$ mixing. The ν_h could decay *dominantly* into $\gamma\nu$ pair if, for example, there is a large enough transition magnetic moment between the ν_h and ν mass states. This kind of ν_h may be present in many interesting extensions of the standard model; see, e.g. Ref. [9]. Assuming the ν_h is produced through mixing with ν_μ, the combined analysis of the LSND and MiniBooNE excess events suggests that the ν_h mass, mixing strength, and lifetime are, respectively, in the range

$$40 \lesssim m_h \lesssim 80\ \mathrm{MeV}, \qquad 10^{-3} \lesssim |U_{\mu h}|^2 \lesssim 10^{-2}, \qquad 10^{-11} \lesssim \tau_h \lesssim 10^{-9}\ \mathrm{s}. \tag{1}$$

A detailed discussion of consistency of these values with the constraints from previous searches for heavy neutrinos [10], as well as of the interpretation of the ν_h decay in terms of transition magnetic moment, is presented in Refs. [5,8]. Briefly, the mixing of Eq. (1) is not constrained by the limits from the most sensitive experiments searched for extra peaks in two-body π, K decays [10], because the ν_h mass range of Eq. (1) is outside the kinematical limits for $\pi_{\mu 2}$ decays and not accessible to $K_{\mu 2}$ experiments due to experimental resolutions. The parameter space of Eq. (1) cannot be ruled out by the results of high-energy neutrino experiments such as NuTeV or CHARM, as they searched for ν_hs of higher masses ($m_h \gtrsim 200$ MeV) decaying into muonic final states ($\mu\pi\nu$, $\mu\mu\nu$, $\mu e\nu, \ldots$) [10], which are not allowed in this case. The best limits on $|U_{\mu h}|^2$ derived for the mass range Eq. (1) from the search for $\nu_h \to e^+e^-\nu$ decays in the PS191 experiment [11], as well as the LEP bounds [12], are found to be compatible with Eq. (1), assuming the dominance of the ν_h decay. New limits on mixing $|U_{\mu h}|^2$ obtained by using the recent results on precision measurements of the muon Michel parameters by the TWIST experiment [13] are also found to be consistent with Eq. (1). Finally, the most stringent bounds on $|U_{\mu h}|^2$ coming from the primordial nucleosynthesis and SN1987A considerations, as well as the limits from the atmospheric neutrino experiments, are also evaded due to the short ν_h lifetime.

Very recently, the T2K Collaboration, which studied ν_μ neutrino-neutrino interactions in a long baseline experiment at the Japan Proton Accelerator Research Complex (J-PARC), has reported on observation of an excess of electronlike events in charge-current quasi-elastic (CCQE) neutrino events over the expected standard neutrino interaction events [14]. A confirmation of the T2K excess and clarification of its origin have great importance for neutrino physics. Although the most popular mechanism for this excess is $\nu_\mu \to \nu_e$ neutrino oscillations with nonzero value of the neutrino mixing angle Θ_{13}, one can still reasonably ask whether neutrino oscillations are the only explanation for the T2K result (see, e.g, Ref. [15]. In this work, I study a possible manifestation of the presence of ν_hs in the J-PARC neutrino beam and show that the excess of e-like events observed by T2K could be interpreted as a signal from the production and radiative decay of a ν_h, previously suggested for the explanation of the origin of similar excess events observed by the LSND and MiniBooNE experiments.

In the T2K experiment, specifically designed to search for $\nu_\mu \to \nu_e$ oscillations and for measurements at the first $\nu_\mu - \nu_\tau$ oscillation maximum (corresponding to the atmospheric neutrino parameters $\sin^2 2\Theta_{23} = 1$ and $\Delta m^2_{23} = 2.4 \times 10^{-3}$ eV^2), the neutrino flux at the far detector location is dominated by ν_τs. Therefore, we will assume in the following that the ν_h also can be produced in ν_τNC interactions, e.g. through mixing with the ν_τ neutrino [16]. Taking into account that the corresponding mixing strength $|U_{\tau h}|^2$ is purely constrained by existing experimental data makes this assumption more interesting. For example, the bounds from the NOMAD experiment $|U_{\tau h}|^2 \lesssim (4-1) \times 10^{-2}$ for the ν_h masses from 40 to 80 MeV were obtained from the search for the $\nu_h \to \nu_\tau e^+ e^-$ decay under the assumption that this decay is the principal decay mode of the ν_h. These limits can be significantly relaxed assuming the dominance of the $\nu_h \to \gamma\nu$ decay. Direct searches for radiative decays of an excited neutrino $\nu^* \to \nu\gamma$ produced in $Z \to \nu^*\nu$ decays have also been performed at LEP [10]. For the best limit $\mathrm{Br}(Z \to \nu^*\nu)\mathrm{Br}(\nu^* \to \nu\gamma) < 2.7 \times 10^{-5}$ from ALEPH [12], taking into account $\frac{\mathrm{Br}(Z\to\nu\nu_h)}{\mathrm{Br}(Z\to\nu\nu)} \simeq |U_{\tau h}|^2$, we find [5]

$$|U_{\tau h}|^2 \times \frac{m_{\nu_h}[\mathrm{MeV}]}{\tau_{\nu_h}[\mathrm{s}]} < 4.8 \times 10^9. \qquad (2)$$

For the mass and mixing range of Eq. (1), it results in $\tau_{\nu_h} \gtrsim 10^{-11}$ s.

In addition, there is also a hint from the measurements of the $D_s^+ \to \tau^+\nu_\tau$ decay rate at CLEO [17,18]. It has been observed that for some decay modes of outgoing τ -leptons, the obtained decay rate of $D_s^+ \to \tau^+\nu_\tau$ is significantly higher than the predicted one, so that combined branching ratio deviates from the theoretical prediction at the level of $\simeq 10\%$. One may speculate that this inconsistency is due to the existence of a sterile neutrino mixed into the tau neutrino. This would result in an additional contribution to the $D_s^+ \to \tau^+\nu_\tau$ decay rate from the decay $D_s^+ \to \tau^+\nu_h$. It has been found that for the mass range below 190 MeV, the mixing strength required to explain $D_s^+ \to \tau^+\nu_\tau$ discrepancy should be $|U_{\tau h}|^2 = 0.16 \pm 0.09$ [7], which for the mass and lifetime range of Eq. (1) is consistent with Eq. (2) within the large error.

The T2K experiment is described in detail in Ref. [19]. It uses an almost pure off-axis ν_μ beam originated from the π^+ and K decays in flight, which are generated by 30 GeV protons from the J-PARC Main Ring accelerator. The detector consists of a near detector complex, used to measure precisely the ν_μ flux and to predict the standard neutrino interaction rate in the far detector, which is the Super-Kamiokande (SK) water Cherenkov detector located at a distance of 295 km from the proton target. The SK detector is a cylindrical tank, about 40 m in diameter and 40 m high, filled with $\simeq 50$ kt of purified water [20]. The detector has a fiducial volume (FV) of 22.5 kton within its cylindrical inner detector (ID) and a 2 m-wide outer detector (OD) served as a veto against cosmic rays and neutrino interactions in the surrounding rock. The Cherenkov light rings generated by muon, electron, and converted photon tracks are used for the reconstruction of events. The T2K search for e-like events from $\nu_\mu \to \nu_e$ neutrino oscillations uses the data sample collected during the years 2010–2011 [14]. The strategy of the analysis is to identify the ν_eCCQE candidate events by reconstructing in the FV isolated single e-like rings that are accompanied by no other activity in the outer detector. The measured rate of the e-like events is then compared to the one expected from known reactions.

An excess of $\Delta N = 4.5$ electronlike events (6 events observed and 1.5 ± 0.3 expected) has been observed in the data accumulated with 1.43×10^{20} protons on target (pot). For the following discussion several distinctive features of the excess events are of importance [14]: (a) the excess is observed for single e-like tracks, originating either from an electron, or from a photon converted into a e^+e^- pair with a typical opening angle $\simeq m_e/E_{e^+e^-} < 1$ degree (for $E_{e^+e^-} > 100$ MeV), which is too small to be resolved into two separate Cherenkov rings in the SK detector (here, m_e, $E_{e^+e^-}$ are the electron mass and the e^+e^- pair energy); (b) the reconstructed neutrino energy is in the range $200 < E_\nu^{\mathrm{QE}} < 1000$ MeV. The variable E_ν^{QE} is calculated under the assumption that the observed electron track originates from a ν_eCCQE interaction; (c) the visible energy E_{vis} is required to be $E_{\mathrm{vis}} \gtrsim 100$ MeV; (d) the angular distribution of the excess events with respect to the incident neutrino direction is wide and consistent with the shape expected from ν_eCCQE interactions; (e) there is no additional significant activity in the OD detector.

To satisfy the criteria (a)–(e), I propose that the excess events originate from the production and subsequent radiative decay of a heavy neutrino ν_h in the FV of the SK detector. The heavy neutrinos are assumed to be produced in the neutral-current quasi-elastic (NCQE) interactions $\nu_{\mu(\tau)} + N \to \nu_h + N$ of muon or tau neutrinos in the SK FV, the ID region outside FV, the OD region, or the surrounding rock. In the later case, if ν_h is a relatively long-lived particle, the flux of ν_hs would penetrate the rock shielding without significant attenuation and would be observed in SK through their $\nu_h \to \gamma\nu$ decays with the subsequent conversion $\gamma \to e^+e^-$ of the decay photons in the SK water target. Similar to $\nu_\mu \to \nu_e$ neutrino oscillations, the occurrence of $\nu_h \to \gamma\nu$ decays would appear as an excess of single e-like events from decay photon conversion in the SK detector, above those expected from standard neutrino interactions. To make a quantitative estimate, we performed simplified simulations of the ν_h production and decay processes in the SK discussed previously.

The flux of the produced ν_hs can be calculated by using the following equation for the ν_h production cross-section:

$$\sigma(\nu_{\mu(\tau)}N \to \nu_h N) = \sigma(\nu_{\mu(\tau)}N \to \nu_{\mu(\tau)}N)|U_{\mu(\tau)h}|^2 f, \quad (3)$$

where $\sigma(\nu_{\mu(\tau)} + N \to \nu_{\mu(\tau)} + N)$ is the cross-section for $\nu_{\mu(\tau)}$NCQE interactions and f is the phase space factor calculated for this two-body reaction, which takes into account dependence on the ν_h mass. The energy spectra of the produced ν_hs, whose momenta pointing to the SK fiducial volume as well as the angular distribution of the ν_hs, were calculated for different ν_h masses by taking into account the ν_μ, ν_τ energy distributions at the far detector [14]. In these simulations we used a parametrized ν_μ energy spectrum obtained at far detector from the reconstructed ν_μCCQE events [14]. The ν_τ energy distribution at the far detector position was calculated from the primary ν_μ spectrum within the standard two-neutrino oscillations scheme for the atmospheric parameters quoted previously. The total number of NC events in the FV of the SK detector was used for normalization.

Once the ν_h flux was known, the next step was to calculate the e^+e^- spectrum based on the $\nu_h \to \gamma\nu$ decay rate. For a given flux Φ_{ν_h}, the expected number of signal events from $\nu_h \to \gamma\nu$ decays occurring within the fiducial length L of the SK detector with the FV entrance point located at a distance L' from the ν_h production vertex is given by

$$n_{\nu_h} = \sum_{\nu_\mu,\nu_\tau} \int A\left(\frac{d\Phi_{\nu_h}}{dE_{\nu_h}}\right)_{\nu_\mu(\nu_\tau)} \exp\left(-\frac{L' m_{\nu_h}}{p_{\nu_h}\tau_h}\right) \times \left[1 - \exp\left(-\frac{L m_{\nu_h}}{p_{\nu_h}\tau_h}\right)\right]\frac{\Gamma_{\gamma\nu}}{\Gamma_{\rm tot}} \varepsilon_\gamma \varepsilon_{e^+e^-} dE_{\nu_h} dV, \quad (4)$$

where p_{ν_h} is the ν_h momentum and τ_h is its lifetime at the rest frame, $\Gamma_{e^+e^-}$, $\Gamma_{\rm tot}$ are the partial and total mass dependent ν_h-decay widths, respectively, ε is the e^+e^- pair reconstruction efficiency, and the integral is taken over the FV, ID region outside FV, OD and the surrounding rock volume. It is assumed that the total rate $\Gamma_{\rm tot}$ of the ν_h decays is dominated by the radiative decay $\nu_h \to \gamma\nu$, i.e. the branching fraction $\mathrm{BR}(\nu_h \to \gamma\nu) = \frac{\Gamma(\nu_h \to \gamma\nu)}{\Gamma_{\rm tot}} \simeq 1$ [5]. The acceptance A of the SK detector was calculated by tracing the produced ν_hs to the detector FV, taking momentum and angular distributions into account. The energy of the photon from the ν_h decay depends on the initial neutrino energy and on the center-of-mass angle Θ between the photon momentum and the ν_h momentum direction. Therefore, the photon laboratory energy spectrum depends on the c.m. angular distribution, which is generally given by $dN/d\cos\Theta \simeq 1 + a \cdot \cos\Theta$, where asymmetry coefficient a is in the range $-1 < a < 1$ for Dirac, and $a = 0$ for Majorana neutrinos [21]. The reconstruction efficiency of the photon converted in the fiducial volume of the SK detector was taken to be $\simeq 70\%$ from the T2K simulations of the ν_e CCQE events [14]. An example of the calculated number of the ν_h decays in the SK FV is shown in Fig. 1 as a function of the thickness of the rock surrounding the detector for the ν_h mass of 50 MeV and several τ_h values. It is seen that if the ν_h is a relatively short-lived particle, i.e $\frac{L m_{\nu_h}}{p_{\nu_h}\tau_h} < 1$, the number of the signal events is quickly saturated and does not depend on the rock thickness. Neutrino interactions, with little hadronic activity in the final state, occuring in the OD or SK support structure, as well as in the part of the ID outside FV, can also yield an isolated e-track from the ν_h decay in the FV. The attenuation of the ν_h–flux due to ν_h interactions in the rock with the average density 3.2 g/cm^3 was found to be negligible.

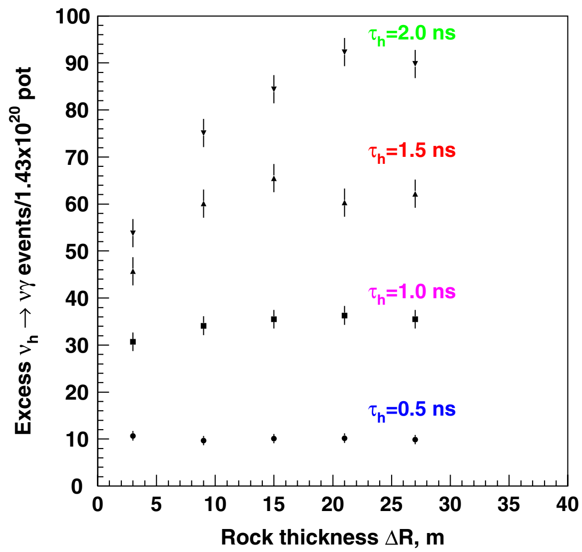

FIG. 1 (color online). The number of ν_h decays from the ν_hs produced in the rock as a function of rock thickness calculated for ν_μ and ν_τ energy spectra at the far detector, assuming $|U_{\mu h}|^2 = 1$ and $|U_{\tau h}|^2 = 1$, for different τ_h values shown in the plot, $a = 0$, and 1.43×10^{20} pot. The fraction of $\nu_h \to \gamma\nu$ decays from ν_μNC reactions is $\lesssim 15\%$, while the rest is due to ν_τNC interactions.

In Fig. 2, an example of distributions of the kinematic variable $E_\nu^{\rm QE}$ for the excess ν_h decays events in the SK detector reconstructed as ν_eCCQE events plus neutrino background predicted in Ref. [14] are shown for $E_{\rm vis} >$ 100 MeV, $m_{\nu_h} = 50$ MeV, $\tau_{\nu_h} = 10^{-9}$ s, and different values of a. These distributions are calculated for the dominant production of ν_hs by ν_τ's assuming that the e^+e^- pair from the converted photon is misreconstructed as a single track from the ν_eCCQE reaction. The distributions are then normalized to six events, which corresponds with $|U_{\tau h}|^2 \simeq 0.025$, to compare them with the T2K data. Simulations are in reasonable agreement with the experimental distributions. For instance, for the distributions shown in Fig. 2, the χ^2 test of their consistency with T2K data yields *p–values* of 0.79, 0.87, and 0.92 for $a = -1$, 0, and $+1$, respectively. In these calculations

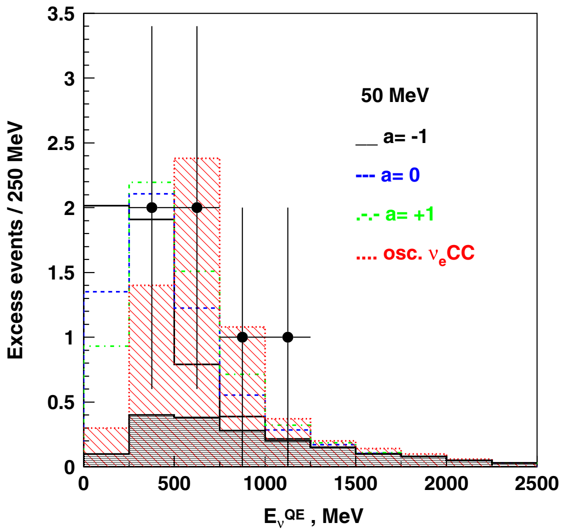

FIG. 2 (color online). Distributions of the excess events reconstructed as ν_eCCQE events in the SK detector as a function of variable $E_\nu^{\rm QE}$ for $E_{\rm vis} > 100$ MeV from the experimental data sample (dots), and from a combination of the $\nu_h \to \gamma\nu$ decay of ν_hs produced in ν_τNC plus expected neutrino background (bottom shaded histogram, from Ref. [14]), calculated for $a = -1$ (solid line), $a = 0$ (dashed line), and $a = +1$ (dashed-dotted line) cases shown in the plot, the ν_h mass of 50 MeV, and the ν_h lifetime $\tau_{\nu_h} = 10^{-9}$ s. Error bars include only statistical errors. The distributions are normalized to six events, which corresponds with $|U_{\tau h}|^2 \simeq 0.025$. A distribution of neutrino background plus $\nu_\mu \to \nu_e$ neutrino oscillations at $\sin^2 2\Theta_{13} = 0.1$ (dotted histogram, from Ref. [14]) is also shown for comparison.

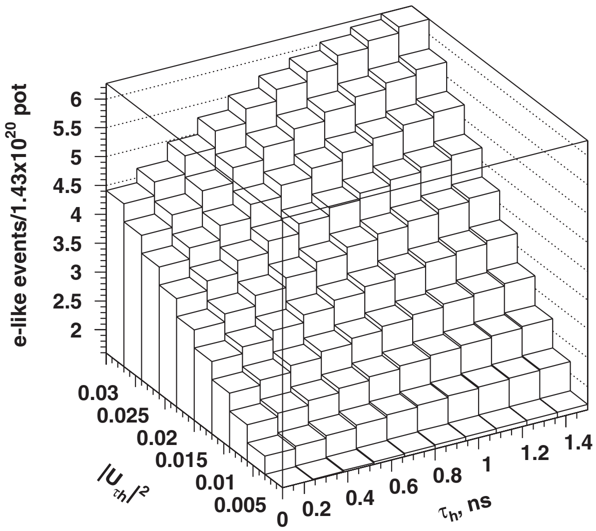

FIG. 3. Number of expected e-like events from ν_h decays plus neutrino background in the SK FV for 1.43×10^{20} pot as a function of the mixing strength $|U_{\tau h}|^2$ and the ν_h lifetime τ_h from the region of Eq. (1) calculated for $m_h = 50$ MeV and $a = 0$.

only statistical errors for both experimental, as reported in Ref. [14], and simulated spectra are included. The test is based on the method of comparison of experimental and simulated histograms recently proposed in Ref. [22], which can be applied to analyzing data samples containing small numbers of events per bin. The simulated excess events, shown in Fig. 2, are mainly distributed in the region $200 \lesssim E_\nu^{\rm QE} \lesssim 1,200$ MeV. The simulations showed that the shape of the $E_\nu^{\rm QE}$ distributions is sensitive to the choice of the ν_h mass, τ_{ν_h}, and, in particular, the a–parameter values: The smaller the a, the softer the spectrum. The distribution of cosine of the opening angle between the e-like ring and neutrino beam direction is found to be consistent with ν_eCCQE events. Taking into account the estimated number of 71 events expected to be observed in the FV from the ordinary NC interactions [14], the total number of ν_h events inside the fiducial volume of the SK detector is given by $n_{\nu_h} \simeq n_\mu |U_{\mu h}|^2 + n_\tau |U_{\tau h}|^2$, where coefficients n_μ, n_τ vary in the range $n_\mu \simeq 12$–30 and $n_\tau \simeq 70$–160, depending on τ_h. As $|U_{\mu h}|^2 < |U_{\tau h}|^2$ by a factor of a few, mainly ν_τNC interactions in the FV and in the rock contribute to the total number of excess events. The number of excess events from interactions in the FV is, roughly, $\propto |U_{\tau h}|^2$, while the number of events from the rock is $\propto |U_{\tau h}|^2 \tau_h$. In Fig. 3, an example of distribution for the expected number of signal plus neutrino background events is shown in more detail in the $(\tau_h; |U_{\tau h}|^2)$ parameter space. For the larger mixing, the number of ν_h events increases, while for smaller lifetime values it decreases due to the more rapid decays of ν_hs, and mostly NC interactions in the FV contribute in this case. The fraction of excess events expected to be seen in the OD depends on the ν_h lifetime and typically is $\lesssim 20\%$ ($\lesssim 1$ event), which is consistent with observations [14]. It is also interesting to compare the spatial distributions of the excess events, which in the case of ν_h decays, is a combination of the uniform distribution from the NC interactions in the FV and a distribution from NC interactions outside the FV. The later is the ν_h lifetime dependent: For shorter τ_h the excess events are expected to be distributed presumably near the edge of the FV. One interesting feature of the spatial distribution of events in SK is that they are all in the first half of the detector. To reproduce this feature, one could try to use the ν_h lifetime shorter than $\tau_h \lesssim 0.5$ ns, so that ν_hs produced in the rock decay mainly in the first part of the SK. For shorter lifetimes, as one can see from Fig. 1, the number of events from the rock decreases, and mixing values $|U_{\tau h}|^2 \gtrsim 0.03$ are required to keep the signal in the range of 4–5 events. Note that the increase of $|U_{\tau h}|^2$ results also in increase of the relative fraction of events produced in NC interactions in the FV (typically, about 40% for the long τ_hs), which are distributed uniformly over the FV.

The probability $P(n_{\nu_h} > 5)$ to observe more than 5 events in the T2K experiment calculated as a function of mixings $|U_{\mu h}|^2$ and $|U_{\tau h}|^2$ is shown in Fig. 4. It was obtained by using the approach of Ref. [23] and taking into account the uncertainties in the background estimate [14]. For example,

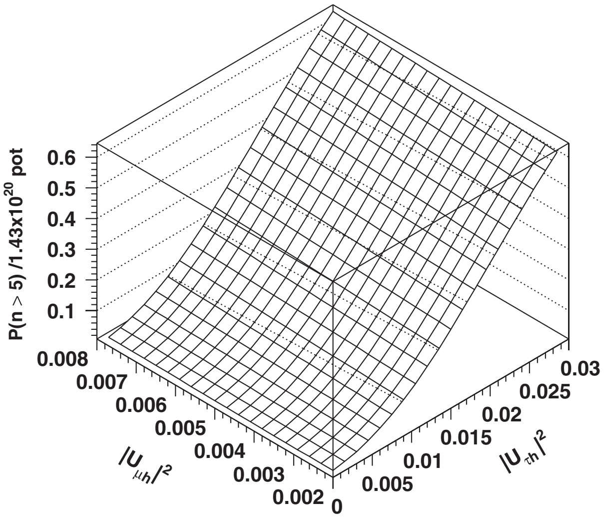

FIG. 4. The probability of observing more than 5 events in the T2K experiment as a function of $|U_{\mu h}|^2$ and $|U_{\tau h}|^2$ for $\tau_h = 10^{-9}$ s.

for $P(n_{\nu_h} > 5) > 0.25$, using Eq. (2) to constrain the τ_h, the most suitable values of the parameters are

$$40 \lesssim m_h \lesssim 80\,\mathrm{MeV}, \qquad 10^{-3} \lesssim |U_{\mu h}|^2 \lesssim 10^{-2}, \\ 10^{-2} \lesssim |U_{\tau h}|^2 \lesssim 3\times 10^{-2}, \qquad 10^{-10} \lesssim \tau_h \lesssim 10^{-9}\,\mathrm{s}. \tag{5}$$

In summary, in this work I study a possible manifestation of the presence of heavy neutrinos in the J-PARC neutrino beam and show that, assuming the ν_h mixing into the ν_τ, the T2K excess events could originate from the same mechanism as those observed by the LSND and MiniBooNE experiments, namely, from the production and radiative decay of a sterile neutrino with properties of Eq. (5). This interpretation is found to be compatible with all the constraints (a)–(e). The distribution of the excess events in kinematic variable E_ν^{QE} is found to be consistent with of the shapes of distributions obtained within this interpretation. My analysis may be improved by more accurate and detailed simulations of the T2K experiment, which are beyond the scope of this work. A definite conclusion on the presence of ν_h events can be drawn when the T2K statistics are sub stantially increased. Finally, note that several ideas on searching for ν_h in μ decays [8], with existing neutrino data [24], in radiative K decays [25,26], and with neutrino telescopes [27] have been recently proposed.

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