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# Sterile neutrino decay explanation of LSND and MiniBooNE anomalies

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We examine a recently proposed explanation of the liquid scintillator neutrino detector and MiniBooNE anomalies, given in terms of a sterile neutrino $N$ of the mass $40MeV \lesssim m_N \lesssim 80MeV$ mixed with $\nu_\mu$ at the strength $10^{-3} \lesssim |U_{\mu N}|^2 \lesssim 10^{-2}$ and which dominantly decays into a light neutrino and photon: $N \to \nu\gamma$. We check compatibility of this scenario with the existing experimental data on radiative $\tau$-lepton and $K$-meson decays. We find that neither of these data are able to totally rule out the above indicated region of $m_N - |U_{\mu N}|^2$. However, we show that the current experimental data on $K \to \mu\nu\gamma$ decay exclude a significant part of this region. We propose experimental cuts on this decay allowing to improve its sensitivity to the region in question. We also show that measurements of $K \to \mu\nu ee$ decay have good prospects for testing the decaying sterile neutrino scenario.

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Neutrino oscillation experiments have proven that neutrinos are massive, although very light particles, and that they exhibit flavor mixing. In order to give mass to neutrinos, most models introduce sterile (or right-handed) neutrinos, which generate the masses of the ordinary neutrinos via a seesaw mechanism or its modifications [1,2], This mechanism gives masses to the three light neutrinos, leaving open the possibility of having one or more additional heavy neutrinos $N$, which would be sterile with respect to electroweak gauge interactions. If this is the case, the sterile neutrinos $N$ in general will contain a certain admixture of the active flavors $\nu_{e,\mu,\tau}$, parametrized by the corresponding elements of a neutrino mixing matrix $U_{eN}$, $U_{\mu N}$, $U_{\tau N}$. Therefore, $N$ can participate in charged and neutral-current interactions of the standard model (SM), contributing to various processes. If a sterile neutrino with mass $m_N \lesssim 100$ MeV is produced in an intermediate state, it would typically decay into three leptons, but a radiative decay is also possible if a nonzero transition magnetic moment ($\mu_{\text{tr}}$) between the $N$ and $\nu$ mass states is introduced [3–6]. Usually the radiative decay of the sterile neutrino is assumed to be negligible compared to its decay into three leptons. However, it has been recently proposed that a sterile neutrino $N$ with a dominant radiative decay mode $N \to \nu\gamma$ and with mass $m_N$, mixing strength $U_{\mu N}$ and lifetime $\tau_N$ in the range [3,4]

$$\begin{aligned} 40\ \text{MeV} \lesssim m_N \lesssim 80\ \text{MeV}, \\ 10^{-3} \lesssim |U_{\mu N}|^2 \lesssim 10^{-2}, \\ \tau_N \lesssim 10^{-9}\ \text{s}, \end{aligned} \tag{1}$$

may be the source of the LSND evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations [7] and the anomalous event excess observed by MiniBooNE in $\nu_\mu$ and $\bar{\nu}_\mu$ beams [8]. This explanation is based on the fact that in these experiments, signals produced by single electrons or positrons are indistinguishable from signals produced by converted photons. Then, the excess events observed by LSND and MiniBooNE could originate from converted photons, and not from electrons. In the model proposed by the authors in Ref. [3,4], these converted photons arise from the radiative decay of a sterile neutrino $N$ in the range given by (1), which is produced by neutral-current interactions of the incoming $\nu_\mu$ or $\bar{\nu}_\mu$ with nuclei.

In order to search for this sterile neutrino in an independent way, a new muon decay experiment [5], direct searches through $K$-meson decays , and searches at neutrino telescopes [9] have already been proposed. It was also shown that the sterile neutrino parameters with the values in the range (1) are in some tension with the radiative muon capture [10]. However, this tension can be relaxed [5] and does not have an impact on the region (1). Other constraints relevant for the range (1) have been derived in [11] from the accelerator and Super-Kamiokande results. Discussions of other sterile neutrino decay explanations of the LSND anomaly can be found in Ref. [12]. Note that the results of our analysis presented below do not apply to the scenarios of Ref. [12].

Here we consider the restrictions on the sterile neutrino $N$ parameters that can be deduced from the existing experimental data on radiative $K$-meson and $\tau$-lepton decays. The purpose of this note is to check whether these restrictions are consistent or exclude some of the values in Eq. (1), necessary for the explanation of the MiniBooNE and LSND anomalies. Specifically, we analyze the contribution of the sterile neutrino $N$ to the following decays:

$$K^+ \to \mu^+\nu\gamma\ ,\ \tau^- \to \mu^-\nu\nu\gamma. \tag{2}$$

Here $\nu$ denotes the standard light neutrino or antineutrino, dominated by any of the neutrino flavors $\nu_e$, $\nu_\mu$, $\nu_\tau$. These decays receive their known SM contributions, which alone give good agreement with the experimental data. However, they also proceed according to the diagrams shown in Figs. 1(a) and 1(b), with the sterile neutrino $N$ as an intermediate particle. When $N$ is off

 

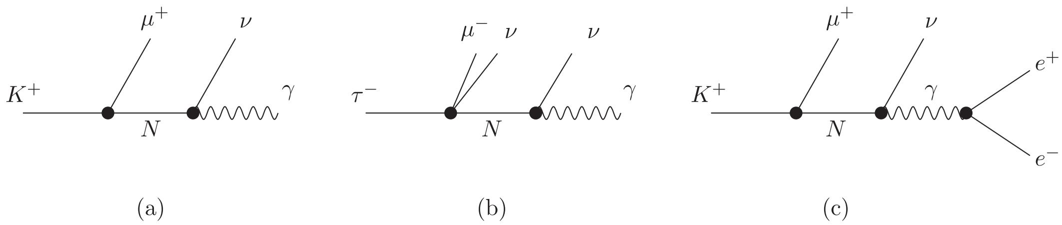


FIG. 1. Structure of the lowest order contribution of sterile neutrino N to the radiative decays of K-meson (a) and $\tau$-lepton (b) as well as to the leptonic decay of K-meson (c).

shell, the contribution of these diagrams is negligibly small [13,14] and far from experimental reach. On the other hand, there exist specific domains of sterile neutrino masses $m_N$ where $N$ comes close to its mass shell, leading to an enormous resonant enhancement [13,14] of the diagrams in Fig. 1. These domains, for the $K$ and $\tau$ decays in Eq. (2) are, respectively,

$$m_N < m_K - m_\mu, \qquad m_N < m_\tau - m_\mu, \tag{3}$$

where the light neutrino mass, $m_\nu$, has been neglected. The mass domains in Eq. (3) cover completely the sterile neutrino mass range of Eq. (1), proposed for the explanation of the LSND and the MiniBooNe anomalies. Therefore, if there is a neutrino $N$ with a mass which is appropriate to explain the anomalies, then the $K$ and $\tau$ radiative decays will necessarily have a contribution from this neutrino $N$ close to its mass shell. This means that an intermediate sterile neutrino is produced at the corresponding vertex on the left of the diagrams in Fig. 1, propagates as a free unstable particle, and then decays at the corresponding vertex on the right. Accordingly, the decay rate formulas for the reactions $K, \tau \to X\nu\gamma$ can be represented in the narrow width approximation ($\tau_N^{-1} \ll m_N$) as the product of two factors: the $K$ or $\tau$ decay rate into the sterile neutrino, $\Gamma(K \to \mu N)$ or $\Gamma(\tau \to \mu\nu N)$, times the branching ratio $\mathrm{Br}(N \to \nu\gamma)$. This approximation is clearly valid for $N$ with masses in the range of Eq. (1). The resulting decay rate formulas are then:

$$\Gamma(K^+ \to \mu^+\nu\gamma) \approx \Gamma(K^+ \to \mu^+ N)\mathrm{Br}(N \to \nu\gamma) \tag{4}$$

$$\Gamma(\tau^- \to \mu^-\nu\nu\gamma) \approx \{\Gamma(\tau^- \to \mu^-\nu_\tau N) + \Gamma(\tau^- \to \mu^-\bar{\nu}_\mu N)\}\mathrm{Br}(N \to \nu\gamma), \tag{5}$$

where the $K$ and $\tau$ decay rates into $N$ are [15]

$$\Gamma(K^+ \to \mu^+ N) = |U_{\mu N}|^2 \frac{G_F^2}{8\pi} f_K^2 |V_{us}|^2 m_K^3 \lambda^{1/2}(x_\mu^2, x_N^2, 1) \times (x_\mu^2 + x_N^2 - (x_\mu^2 - x_N^2)^2) \equiv |U_{\mu N}|^2 \Gamma_K^{(\mu N)}, \tag{6}$$

$$\Gamma(\tau^- \to \mu^-\nu_\tau N) = |U_{\mu N}|^2 \frac{G_F^2}{192\pi^3} m_\tau^5 I_1(z_N, z_\nu, z_\mu) \equiv |U_{\mu N}|^2 \Gamma_\tau^{(\mu\nu N)}, \tag{7}$$

$$\Gamma(\tau^- \to \mu^-\bar{\nu}_\mu N) = |U_{\tau N}|^2 \frac{G_F^2}{192\pi^3} m_\tau^5 I_1(z_N, z_\nu, z_\mu) \equiv |U_{\tau N}|^2 \Gamma_\tau^{(\mu\nu N)}. \tag{8}$$

Here $f_K = 159$ MeV and $V_{us} = 0.97377$. We denote $z_i = m_i/m_\tau$, $x_i = m_i/m_K$ with $m_i = m_N, m_\nu, m_\mu$, and we use the well-known phase space function $\lambda(a, b, c) = a^2 + b^2 + c^2 - 2ab - 2bc - 2ac$ and the kinematical function $I_1(x, y, z)$ is defined as

$$I_1(x, y, z) = 12 \int_{(x+y)^2}^{(1-z)^2} \frac{ds}{s}(s - x^2 - y^2)(1 + z^2 - s) \times \lambda^{1/2}(s, x^2, y^2)\lambda^{1/2}(1, s, z^2). \tag{9}$$

In the scenario under consideration the decay mode $N \to \nu\gamma$ is dominant, and therefore as a reasonable approximation,

$$\mathrm{Br}(N \to \nu\gamma) \approx 1. \tag{10}$$

A general issue to take into account in the radiative decays in question is that the intermediate neutrino $N$ propagates as a real particle and decays at a certain distance from the production point. If this distance is larger than the size of the detector, the neutrino $N$ escapes before decaying and the signature of $\tau \to \mu\nu\nu\gamma$ or $K \to \mu\nu\gamma$ cannot be recognized. Therefore, in order to calculate the rate of radiative $\tau$ or meson $K$ decays within the detector, one should multiply the theoretical rates (4) and (5) by the probability $P_N$ that the neutrino $N$ decays inside the detector. Roughly for a detector of length $L_D$, the probability $P_N$ takes the form [16]:

$$P_N \approx 1 - e^{-L_D/\tau_N} \tag{11}$$

However, for short enough lifetimes such as $\tau_N \lesssim 10^{-9}(s)$ in Eq. (1), and detectors of size $L_D \gtrsim 70$ cm, which is typical for this kind of experiments, we can use $P_N \approx 1$.

In Ref. [4] the author studied the consistency of a sterile neutrino with parameters in the range given in Eq. (1) with the data of several experiments, and found no constraints for this part of the parameter space. Here, with the same purpose, we examine the following experimental data [17]:

$$\mathrm{Br}\,(K^+ \to \mu^+ \nu\gamma) = (6.2 \pm 0.8) \times 10^{-3}, \tag{12}$$

$$\mathrm{Br}\,(\tau^- \to \mu^- \nu\nu\gamma) = (3.6 \pm 0.4) \times 10^{-3}. \tag{13}$$

These measured branching ratios agree with the SM prediction within the quoted experimental uncertainty, namely $\sigma = 0.8 \times 10^{-3}$ and $0.4 \times 10^{-3}$, respectively. Therefore, the additional contribution of a sterile neutrino to these processes should not exceed by much the respective experimental uncertainties. Using (4)–(10), we find the limits

$$|U_{\mu N}|^2 < \frac{n \cdot \sigma(K^+ \to \mu^+ \nu\gamma)}{\Gamma_K^{(\mu N)}/\Gamma_K}, \tag{14}$$

$$|U_{\mu N}|^2 < \frac{n \cdot \sigma(\tau^- \to \mu^- \nu\nu\gamma)}{\Gamma_\tau^{(\mu\nu N)}/\Gamma_\tau}, \tag{15}$$

where $\Gamma_K$ and $\Gamma_\tau$ are the total decay widths of K-meson and $\tau$-lepton, respectively. These limits are valid for a sterile neutrino in the range given in Eq. (1) and correspond to a significance of $1\sigma$ (68% CL) for $n = 1$ and $2\sigma$ (95% CL) for $n = 2$. The limits on $|U_{\mu N}|$ derived in this way are plotted in Figs. 2 and 3. As shown, the most stringent exclusion curves are those of Fig. 2, originating from the $K$ decay data (12). Clearly, these bounds are close, but still unable to definitely rule out the whole range of sterile neutrino parameters in Eq. (1) displayed in Figs. 2 and 3, as the gray zone. On the other hand, the experimental data on radiative $\tau$ decays (13), as seen from Fig. 3, lead to significantly weaker constraints.

Nevertheless, the following comment is in order. As we just saw, the experimental measurements of radiative $K$ decays are not yet in position to definitely exclude the sterile neutrino parameters of Eq. (1). However, if experimental cuts were incorporated to restrict the domain of the muon and photon energies, $E_\mu$ and $E_\gamma$, characteristic for this mechanism, more stringent bounds can be found. This is so because in the $K$ rest frame the muon is monoenergetic with a value of kinetic energy determined by the sterile neutrino mass

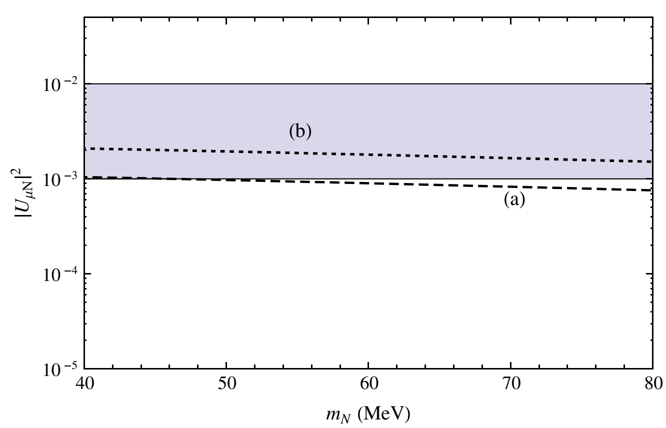


FIG. 2 (color online). The sterile neutrino mass $m_N$ and mixing $U_{\mu N}$ with $\nu_\mu$. In the gray region the explanation [3,4] of the LSND and MiniBooNE anomalies, in terms of a sterile neutrino decay, is possible. The experimental data on the radiative K-meson decay (12) exclude the regions above the curves (a) and (b) at $1\sigma$ (68% CL) and $2\sigma$ (95% CL) significance, respectively.

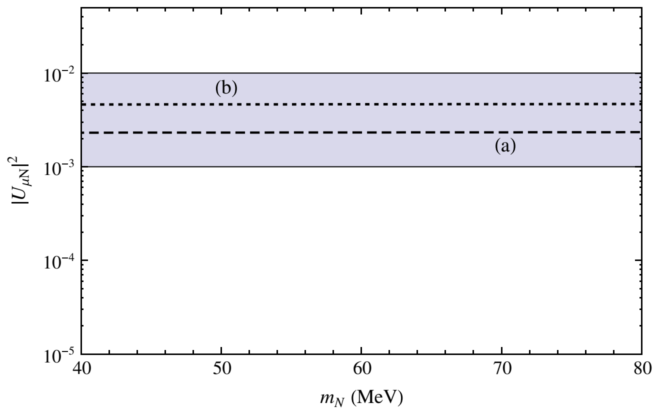


FIG. 3 (color online). The same as in Fig. 2, but for the experimental data on the radiative $\tau$-lepton decay (13).

$$E_{\mu(K)} = \frac{(m_K - m_\mu)^2 - m_N^2}{2m_K}. \tag{16}$$

For $m_N = (40\text{–}80)$ MeV as specified in Eq. (1), the muon energy $E_{\mu(K)}$ varies in a very narrow range $E_{\mu(K)} = (146\text{–}151)$ MeV. In turn, the photon energy in the $K$ rest frame ranges within the interval

$$\frac{1}{2}\left(E_N - \sqrt{E_N^2 - m_N^2}\right) \le E_\gamma \le \frac{1}{2}\left(E_N + \sqrt{E_N^2 - m_N^2}\right), \tag{17}$$

where $E_N$ is the sterile neutrino energy, also a fixed value,

$$E_N = \frac{m_K^2 - m_\mu^2 + m_N^2}{2m_K}. \tag{18}$$

For the required range of parameters of Eq. (1), the photon energy, unlike that of the muon, is within a rather broad range $E_\gamma = (6.8\text{–}235)$ MeV.

One last consistency check concerns the large value of the neutrino transition magnetic moment, required in the explanation of the LSND and MiniBooNE anomalies. If it exists, this hypothetical parameter must also appear in the process $K^+ \to \mu^+ \nu e^+ e^-$, via a contribution where the photon is virtual and decays into an $e^+e^-$ pair as shown in the diagram Fig. 1(c).

If the decay $K^+ \to \mu^+ \nu e^+ e^-$ is dominated by the amplitude where an intermediate sterile neutrino $N$ is on its mass shell, the decay rate factorizes as

$$\Gamma(K^+ \to \mu^+ \nu e^+ e^-)_N = \Gamma(K^+ \to \mu^+ N) \times \text{Br}(N \to \nu e^+ e^-) \quad (19)$$

This representation is valid for the sterile neutrino masses within the interval $m_K - m_\mu \le m_N \le 2m_e$. The first subprocess, $K^+ \to \mu^+ N$, can be easily estimated from $K_{\mu 2}$, except for a kinematic correction due to the neutrino mass $m_N$ and a factor $|U_{\mu N}|$ due to the $\nu_\mu$ admixture in $N$ (see Eq. (6)). The second subprocess is mediated by a photon, coupled to the neutrino transition current, which depends on two form factors, one of them being the magnetic moment

$$J^\mu_{(N\nu)} = \bar{\nu}\{F_1(q^2\gamma^\mu - \not{q}q^\mu) + i\mu_{\text{tr}}\sigma^{\mu\nu}q_\nu\}N. \quad (20)$$

For a real photon only $\mu_{tr}$ contributes. Specifically

$$\Gamma(N \to \nu\gamma) = \frac{\mu^2_{\text{tr}} m^3_N}{8\pi}. \quad (21)$$

Now, for a virtual photon both $F_1$ and $\mu_{tr}$ contribute, without interfering. Consequently, the expression for $\Gamma(N \to \nu e^+ e^-)$ has the lower bound:

$$\Gamma(N \to \nu e^+ e^-) > \frac{8\alpha_{\text{em}}}{3\pi}\left(\log\left(\frac{m_N}{2m_e}\right) - 2/3\right) \times \Gamma(N \to \nu\gamma) \sim 10^{-2}\Gamma(N \to \nu\gamma). \quad (22)$$

Since the experimental measurement [18]:

$$\text{Br}(K^+ \to \mu^+ \nu e^+ e^-) = (7.06 \pm 0.31) \times 10^{-8} \quad (23)$$

confirms its SM theoretical estimate, then the extra contribution due to the sterile neutrino (see Eq. (19)) should be at most of the size of the quoted error, thus imposing the bound

$$\text{Br}(K^+ \to \mu^+ \nu e^+ e^-)_N < 0.31 \times 10^{-8}. \quad (24)$$

Equations (19), (22), and (24) then impose the bound $\text{Br}(K^+ \to \mu^+ N) \times \text{Br}(N \to \nu\gamma) < 3. \times 10^{-7}$. Recalling Eq. (6), $Br(K^+ \to \mu^+ N) = |U_{\mu N}|^2 \Gamma_K^{(\mu N)}/\Gamma_K \gtrsim 0.6 \times |U_{\mu N}|^2$, we can draw the following bound:

$$|U_{\mu N}|^2 \times \text{Br}(N \to \nu\gamma) < 0.5 \times 10^{-6}. \quad (25)$$

This stringent bound, however, is not applicable for the sterile neutrino mass range (1) relevant for the explanation of the LSND and MiniBooNE anomalies since the experimental result (23), derived in Ref. [18], implies a cutoff

$$m_{ee} \ge 145 \text{ MeV} \quad (26)$$

on the invariant mass $m_{ee}$ of the $e^+e^-$ pair. On the other hand, the limit (25) shows that measurements of $K^+ \to \mu^+ \nu e^+ e^-$ could be a sensitive probe of the region (1) if this cutoff were be reduced below 40 MeV. The cutoff (26) was applied in the experimental measurements of Ref. [18] in order to suppress the background from the sequence of decays $K^+ \to \mu^+ \nu \pi^0$, $\pi^0 \to \gamma e^+ e^-$. Then improvement of the efficiency of veto system for the photons from $\pi^0$-decay and measurements of the kaon tracks for better control of the missing mass would probably able to achieve this goal.

*In conclusion*. We have shown that the existence of a sterile neutrino with mass and mixing in the range given in Eq. (1) is in tension with the existing experimental data on the radiative K-meson decay (12). Future measurements of its rate with better precision will probably be able to derive a more decisive conclusion on the studied question. A purely leptonic four-body K-decay (23) will be able to probe the region (1) required for the explanation of the LSND and MiniBooNE anomalies, if future measurements reduce the cutoff in the invariant mass of the $e^+e^-$ pair in the final state of this decay below 40 MeV.

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