New muon decay experiment to search for heavy sterile neutrino

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It has been recently shown that puzzling excess events observed by the LSND and MiniBooNE neutrino experiments could be interpreted as a signal from the radiative decay of a heavy sterile neutrino (ν_h) of the mass from 40 to 80 MeV with a muonic mixing strength $|U_{\mu h}|^2 \simeq 10^{-3} - 10^{-2}$. If such ν_h exists its admixture in the ordinary muon decay would result in the decay chain $\mu \to e\nu_e\nu_h \to e\nu_e\gamma\nu$. We proposed a new experiment for a sensitive search for this process in muon decay at rest allowing to definitively confirm or exclude the existence of the ν_h. To our knowledge, no experiment has specifically searched for the signature of radiative decay of massive neutrinos from muon decays as proposed in this work. The search is complementary to the current experimental efforts to clarify the origin of the LSND and MiniBooNE anomalies. Bounds on $|U_{\mu h}|^2$ from precision measurements with muons are discussed.

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Over the past 10 years there is a puzzle of the 3.8 σ event excess observed by the LSND collaboration [1]. This excess originally interpreted as a signal from $\overline{\nu}_\mu \to \overline{\nu}_e$ 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 electron-like events in quasi-elastic neutrino events over the expected standard neutrino interactions has been observed [3]. Recently, MiniBooNE has reported new results from a search for $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations [4]. An excess of events was observed which has a small probability to be identified as the background-only events. The data are found to be consistent with $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations in the 0.1 eV^2 range and with the evidence for antineutrino oscillations from the LSND.

In the recent work [5] (see also [6, 7]) it has been shown that these puzzling results could all be explained in a consistent way by assuming the existence of a heavy sterile neutrinos (ν_h), which are created in ν_μ neutral-current interactions and decay subsequently into a photon and a lighter neutrino ν. The ν_h's could be Dirac or Majorana type. They 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. Such kind of heavy neutrinos may be present in many interesting extensions of the standard model; see e.g. [8]. 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

$$40 \lesssim m_h \lesssim 80 \text{ MeV}, \; 10^{-3} \lesssim |U_{\mu h}|^2 \lesssim 10^{-2}, \\ 10^{-11} \lesssim \tau_h \lesssim 10^{-9} \; s. \quad (1)$$

A detailed discussion of consistency of these values with the constraints from previous searches for heavy neutrinos [9] is presented in [5]. Briefly, it has been shown, that taking into account the dominance of the radiative decay $\nu_h \to \gamma\nu$, most of the allowed $(m_h; |U_{\mu h}|^2)$ parameter space of (1) is not constrained by the limits from the most sensitive K decay [10], neutrino beam-dump [11] and LEP [12] experiments. An interpretation of the $\nu_h \to \gamma\nu$ decay in terms of transition magnetic moment is also found to be in agreement with the existing data. Finally, new limits on mixing $|U_{\mu h}|^2$ obtained by using the recent results on precision measurements of the Michel parameter by the TWIST experiment [13] are also found to be consistent with (1).

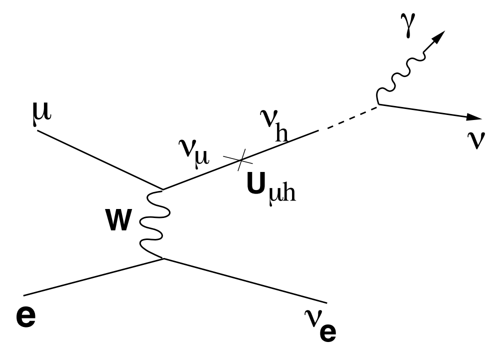

FIG. 1: Schematic illustration of the production and subsequent radiative decay of heavy neutrino in the ordinary muon decay.

If the ν_h is indeed a component of ν_μ's, it would be produced by any source of ν_μ according to the proper mixing and phase space and helicity factors [14, 15]. In particular, the ν_h could be produced in charge-current weak interactions of muons. For example, for the mass range of (1) the nonzero mixing $|U_{\mu h}|^2$ would result in the decay $\mu \to e\nu_e\nu_h$. The muon, which is normally decays into an $e\nu_e$ pair and a ν_μ, might instead decay to an $e\nu_e$ pair and a heavy neutrino ν_h which decays subsequently into $\gamma\nu$, as schematically illustrated in Fig.1. In this Letter we propose an experiment to search for the muon decay chain $\mu \to e\nu_e\nu_h \to e\nu_e\gamma\nu$ with the sensitivity in $|U_{\mu h}|^2$ much higher than the corresponding values from (1). To our knowledge, no experiment has specifically

cally searched for the clear signature of radiative decay of massive neutrinos from muon decays as proposed in this work. Note that for the mixing and mass regions of (1), the inclusion of the heavy neutrino effect results in the $\mu \to e\nu_e\nu_h$ decay rate which can be well approximated by [15, 16]

$$\Gamma(\mu \to e\nu_e\nu_h) \approx \frac{G_F^2|U_{\mu h}|^2}{192\pi^3 m_\mu^3}\Big[m_\mu^8 - m_h^8 + 8m_h^6 m_\mu^2 - -8m_h^2 m_\mu^6 + 24m_h^4 m_\mu^4 Log(\frac{m_\mu}{m_h})\Big] \quad (2)$$

and in the corresponding branching fraction

$$B(\mu \to e\nu_e\nu_h) \simeq 10^{-5} - 10^{-3}, \quad (3)$$

which is in the experimentally accessible range. More detailed calculations of the $\mu \to e\nu_e\nu_h$ decay rate including arbitrary ν_h weak couplings can be found in [17].

Let us examine first, for completeness of the analysis of constraints reported in [5], the recent precision measurements results obtained with muons. Very recently, the MuLan collaboration has reported on measurements of the mean lifetime τ_μ of positive muons to a precision of 0.6 ppm [18]. Using the new world average, $\tau_\mu = 2.1969803(22)\,\mu$s and the relation between the muon lifetime and the Fermi constant G_F $\tau_\mu^{-1} = \frac{G_F^2 m_\mu^5}{192\pi^3}(1+\Delta)$, where Δ is the sum of phase space, QED and hadronic corrections, results in new determination of the Fermi constant $G_F^\mu = 1.1663788(7) \times 10^{-5}$ GeV^{-2} to a precision of 0.6 ppm [18]. The mixing of the ν_h into ν_μ would decrease the determined value of G_F^μ. To estimate the allowed contribution from the $\mu \to e\nu_e\nu_h$ decay, one could compare the experimentally measured muon decay rate to a predicted one, by using G'_F extracted from another measurements which are not directly affected by the contribution from heavy neutrino. One possible way is to use the pure leptonic decay of the tau $\Gamma(\tau \to e\nu_e\nu_\tau)$, which provide corresponding Fermi constant $G_F^{\tau e} = 1.1668(28) \times 10^{-5}$ GeV^{-2} [9]. Comparing it with MuLan values for G_F one finds $\Delta G_F = G_F^{\tau e} - G_F^\mu < 5 \times 10^{-3}\ GeV^{-2}$ (90%$C.L.$). Taking into account (2) leads to the bound $|U_{\mu h}|^2 < 8 \times 10^{-3}$, which is consistent with (1). One can also use a number of indirect prescriptions for extracting of precise values of G_F [19]. For example, one can define $G'_F = \frac{4\pi\alpha}{\sqrt{2}m_Z^2 sin^2 2\Theta_W(m_Z)(1-\Delta r)}$ where Θ_W, m_Z and Δr are the Weinberg angle, the mass of the Z gauge bosons extracted from the precision measurements at LEP, and a factor for radiative corrections, respectively. Using the values of Θ_W, m_Z and Δr reported in [19], one can obtain $G'_F = 1.1672(\pm 0.0008)\begin{pmatrix} +0.0018 \\ -0.0007 \end{pmatrix} \times 10^{-5}\ GeV^{-2}$. Comparing it with G_F^μ and adding statistical and systematic errors in quadrature, one finds at 90% CL, $\Delta G_F = G'_F - G_F^\mu < 4.1 \times 10^{-3}\ GeV^{-2}$ (90%$C.L.$), which leads to the bound $|U_{\mu h}|^2 < 7 \times 10^{-3}$, which is also consistent with (1).

As the final states of the decay $\mu \to e\nu_e\nu_h \to e\nu_e\gamma\nu$ and the radiative muon decay $\mu \to e\nu_e\nu_\mu\gamma$ are identical, the decay rate of the former can be constrained from the precise measurements of the branching fraction $B(\mu \to e\nu_e\nu_\mu\gamma)$. The most precise measurements of the radiative muon decay are reported by the PIBETA Collaboration [20]. The measured branching fraction $B_{exp}(\mu \to e\nu_e\nu_\mu\gamma) = (4.4 \pm 0.1) \times 10^{-3}$ is in a good agreement with predicted value $B_{SM}(\mu \to e\nu_e\nu_\mu\gamma) = 4.3 \times 10^{-3}$ for the photon energy $E_\gamma > 15$ MeV, and the $e-\gamma$ opening angle $\Theta_{e\gamma} > 45^o$. Thus, the contribution from the decay $\mu \to e\nu_e\nu_h$ is allowed to be at the level $|B_{exp}(\mu \to e\nu_e\nu_\mu\gamma) - B_{SM}(\mu \to e\nu_e\nu_\mu\gamma)| \simeq (1.0 \pm 1.0) \times 10^{-4}$, which, taking into account the efficiency for the above selection criteria, results for the ν_h mass range (1) in 2σ limit $B(\mu \to e\nu_e\nu_h) \lesssim (2.6 - 4.1) \times 10^{-4}$, which is consistent with (3).

The decay chain $\mu \to e\nu_e\nu_h \to e\nu_e\gamma\nu$ could also contribute to the background for the lepton flavor violating decay $\mu \to e\gamma$ whose branching fraction is constrained to $B_{exp}(\mu \to e\gamma) < 1.2 \times 10^{-11}$ by the MEGA collaboration [21]; see also [22]. In this experiment, to avoid background from the radiative $\mu \to e\nu_e\nu_\mu\gamma$ decay, only back-to-back $e\gamma$ pairs were selected for analysis. The energy of the electron was required to be around the end point of $E_e = 52.8$ MeV within the energy resolution of 0.23 MeV [21]. Because of the maximal allowed electron energy in the decay $\mu \to e\nu_e\nu_h \to e\nu_e\gamma\nu$ is $E_e^{max} = (m_\mu^2 - m_{\nu_h}^2)/2m_\mu < 44$ MeV, this potential background decay mode was rejected by the above selection criteria.

Recent bounds on $|U_{\mu h}|^2$ have been also obtained from the measurements of the radiative muon capture (RMC) on hydrogen [23] (see also [24]). The new limits seem are in tension with $|U_{\mu h}|^2$ values from (1), although their exclusion strength is a factor of few. For ν_h masses from 40 to 70 MeV the limits are, respectively, from $|U_{\mu h}|^2 \lesssim 7 \cdot 10^{-4}$ to $|U_{\mu h}|^2 \lesssim 5 \cdot 10^{-4}$ (Fig. 4, $a = 1$ in [23]), and the corresponding 2σ lower bounds of the allowed LSND-MiniBooNE parameter region (Fig. 24, $a = -1$ in [5]) are in the range from $|U_{\mu h}|^2 \gtrsim 2 \cdot 10^{-3}$ to $|U_{\mu h}|^2 \gtrsim 3 \cdot 10^{-3}$ (In Ref.[23] the definition of sign of the asymmetry parameter a of the photon angular distribution in the rest frame is opposite to the one in [5]). However, the more conservative 3 σ LSND-MiniBooNE lower bounds for the same mass range are calculated to be, respectively, from $|U_{\mu h}|^2 \gtrsim 4 \cdot 10^{-4}$ to $|U_{\mu h}|^2 \gtrsim 5 \cdot 10^{-4}$, and the tension is not apparent. Furthermore, regardless of the level of the exclusion strength, there is also a direct way to evade RMC limit by shifting the photon energy spectrum from the $\nu_h \to \gamma\nu$ decay towards the lower energy region below 60 MeV by allowing the neutrino ν to be massive enough, as suggested in [23].

In order to either confirm or definitively disprove the heavy neutrino interpretation of the LSND-MiniBooNE excess events, we propose a new experiment to search for the $\mu \to e\nu_e\nu_h \to e\nu_e\gamma\nu$ decay chain from the muon decays at rest with a sensitivity in $|U_{\mu h}|^2$ several orders

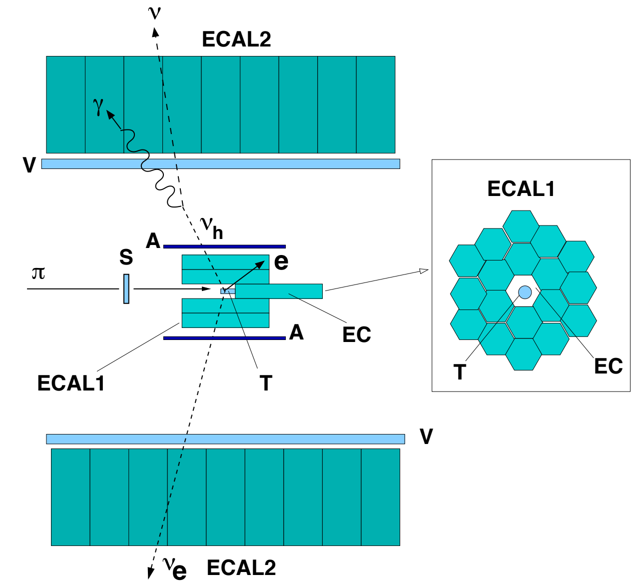

FIG. 2: Schematic illustration of the proposed experimental setup to search for the decay $\mu^+ \to e^+\nu_e\nu_h \to e\nu_e\gamma\nu$. Shown are the beam defining scintillator counter S, the active target T surrounded by the electromagnetic calorimeters ECAL1 and ECAL2, and the ECAL1 endcap counter EC used as a light guide for the light produced in the target. Electrons and photons from the ordinary muon decay $\mu^+ \to e^+\nu_e\nu_\mu(\gamma)$ are absorbed in the ECAL1+ lead absorber A used as a shield for the ECAL2. The ν_h produced through the mixing with the muon neutrino penetrates the ECAL1 and decays in flight in the free space between the ECAL1 and ECAL2 into a light neutrino and photon, which is detected by the ECAL2. The insert shows front view of the ECAL1 assembly.

of magnitude higher than the $|U_{\mu h}|^2$ values of (1). The main components of the detector are schematically shown in Fig.2. Beam of positive pions is stopped in an active target (T) instrumented with energy deposition and time readout. The source of muons is the $\pi \to \mu + \nu$ decay at rest in T. To reject background from the radiative muon decay $\mu \to e\nu_e\nu_\mu\gamma$, the target T is surrounded by an assembly consisting of an electromagnetic calorimeter ECAL1 and lead absorber A, where all the electrons and photons from muon decays in T are absorbed. The ECAL1 is surrounded by another bigger ECAL2 to detect photons from the $\nu_h \to \gamma\nu$ decays in flight. It is assumed that the ν_h produced via the mixing in the $\mu \to e\nu_e\nu_h$ decay is a weakly interacting particle which penetrates the (ECAL1+A) assembly without significant attenuation and subsequently decays in the free space between the calorimeters, as shown in Fig.2.

The experimental signature of the decay chain $\mu \to e\nu_e\nu_h \to e\nu_e\gamma\nu$ is two signals of energy deposition in each calorimeter, which are separated in time by a small interval $\Delta t \simeq 1$ ns corresponding to the ν_h time-of-flight. The readout of the energy deposition in the ECAL2 is triggered by a tag signal of the $e(\gamma)$ appearance, which is defined by a coincidence of a signal from a stopped pion, a delayed signal from the stopped decay muon and a delayed signal from the ECAL1. The muon signal should correspond to the 4.2 MeV energy deposition in the target from the muon kinetic energy. The light signals produced in T could be readout through the ECAL1 endcap crystal (EC) which acts as a light guide as shown in Fig.2. The T signals could be distinguished from the EC signals due to their significantly different decay times by using the technique described in detail in Ref.[25].

To estimate the sensitivity of the proposed experiment a feasibility study based on simplified Monte Carlo simulations, similar to the one described in [26], has been performed. The beam of positive pions is stopped in the central part of the cylindrical target in a volume of $\lesssim 1$ cm^3. The active target T is a plastic scintillator with a diameter of 5-10 mm and a height of 10 mm. According to simulations the 4.2 MeV muon came to rest passing about 1 mm in T. The ECAL1, is an array of 18 BGO counters, as schematically shown in Fig.2, each of 52 mm in diameter and 220 mm long, which were previously used in the PSI experiment on precise measurements of the π_{e2} decay rate [27] and then in the positronium experiment [25]. The ECAL2 is an array of the same counters. The significance of the ν_h discovery in the proposed experiment scales as $S = 2(\sqrt{n_s + n_b} - \sqrt{n_b})$, where n_s, n_b are the number of detected signal and background events [28]. The number of events expected from $\mu \to e\nu_e\nu_h \to e\nu_e\gamma\nu$ decay chain is calculated as

$$n_s \simeq n_\mu B(\mu \to e\nu_e\nu_h)B(\nu_h \to \gamma\nu)P_{\nu_h\to\gamma\nu}f_\gamma\epsilon_\gamma t, \quad (4)$$

where n_μ is the muon stop rate in the target, $B(\nu_h \to \gamma\nu) \simeq 1$ [5], $P_{\nu_h\to\gamma\nu} \simeq exp(-l/c\gamma\tau_h)$ is the probability for the ν_h to decay in flight in free space , where l is an effective (ECAL1+A) thickness and $\gamma \simeq 1$ is the gamma-factor of the ν_h, $f_\gamma \gtrsim 0.8$ is the fraction of events with the energy deposition in the ECAL2 $E_\gamma > 10$ MeV, $\epsilon_\gamma \simeq 0.1$ is the average γ detection efficiency, and t is the running time. Simulations show that the energy spectrum of decay photons, is well above $\simeq 10$ MeV for the ν_h masses of (1) and wide range of the ν masses. To estimate n_b, the following background sources are considered: (i) the radiative muon decay $\mu \to e\nu_e\nu_\mu\gamma$ which has the branching fraction $B(\mu \to e\nu_e\nu_\mu\gamma) \simeq 10^{-2}$ for $E_\gamma \gtrsim 10$ MeV [9]. To suppress this background the effective thickness of the (ECAL1+A)-assembly is selected to be about 12 $X_0(\simeq 10$ cm) resulting in less than about 10^{-8} decay photons per ordinary μ-decay penetrating the shield; (ii) bremsstrahlung of decay electrons in the ECAL1 results in the leak of low energy photons to the ECAL2. The energy cut $E_\gamma \gtrsim 10$ MeV is sufficient to reject this background; (iii) accidental γ's from π, μ radiative decays in flight can be rejected by a passive shield and by the requirement to have only one particle entering setup during the measurements of a particular event; (iv) the scattering of γ's from the $\mu \to e\nu_e\nu_\mu\gamma$ decays in the S counter and accidental coinsidences from cosmic rays can be removed by an active shield and can be neglected. Finally, we found that the expected background rate is dominated by (i). Assuming $S \gtrsim 3$ and the muon stop rate $n_\mu \simeq 10^4\ \mu/s$ one could expect the sensitivity in the $\mu \to e\nu_e\nu_h$ decay branching ratio as small as $B(\mu \to e\nu_e\nu_h) \lesssim 10^{-9}$ for the beam exposure $\simeq 1$ month. If no signal events are observed, the limit on the mixing strength:

$$|U_{\mu h}|^2 \lesssim 10^{-8} e^{0.3/\tau_h[ns]} \Big[1 - \frac{m_h}{m_\mu}\Big]^{-7/2} \qquad (5)$$

could be set as a function of the ν_h mass and lifetime. Using (5), one can see that for the mass range of (1) and lifetime values in the range $5 \cdot 10^{-11} \lesssim \tau_h \lesssim 10^{-9}$ s the limits on the mixing strength are $|U_{\mu h}|^2 \lesssim 10^{-7} - 10^{-4}$ and hence, the $|U_{\mu h}|^2$ values of (1) would be firmly excluded. The choice of the (ECAL1+A)-assembly thickness compromises the rejection factor of γ's from the $\mu \to e\nu_e\nu_\mu\gamma$ decay and the sensitivity in $|U_{\mu h}|^2$. For the lifetimes as short as $\tau_h \lesssim 5 \cdot 10^{-11}$ s the vast majority of ν_h's decays in the vicinity of the target and the limit is less restrictive. To improve sensitivity, one could replace the ECAL1 with thin plastic scintillator counters to detect decay electrons and A with an absorber made of a higher-Z material, e.g. tungsten, such that the overall thickness is reduced to a few cm.

In summary, we show that recently proposed explanation of the puzzling results from the LSND, KARMEN and MiniBooNE experiments in terms of the radiative decay of 40-80 MeV sterile neutrino, could be uniquely probed by the proposed new experiment on direct search for the muon decay chain $\mu \to e\nu_e\nu_h \to e\nu_e\gamma\nu$ with the sensitivity in branching fraction $B(\mu \to e\nu_e\nu_h)$ as small as a few parts in 10^9. The quoted sensitivity could be obtained with the proposed setup optimized for several its properties during a month of data taking. Two different designs could be implemented to cover the range of the lifetime values $10^{-11} - 10^{-9}$. To our knowledge, no experiment has specifically searched for the signature of radiative decay of massive neutrinos from muon decays as proposed in this work. The performed Monte Carlo simulations give an illustrative correct order of magnitude for the sensitivity of the proposed experiment and may be strengthened by more accurate and detailed Monte Carlo simulations of the concrete experimental setup. The proposed search is complementary to the current experimental efforts to clarify the origin of the neutrino anomalies observed by the LSND and MiniBooNE experiments. This enhance motivation for the proposed experiment to be performed in the near future.

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