The MiniBooNE anomaly, the decay $D_s^+ \rightarrow \mu^+ \nu_{\mu}$ and heavy sterile neutrino

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I. INTRODUCTION

The MiniBooNE collaboration, which studies the interactions of neutrinos from the $\pi^+$ decays in flight at FNAL, has observed an excess of low energy electron-like events in the energy distribution of charge-current quasi-elastic electron neutrino events [1]. This anomaly has been recently further confirmed with larger statistics [2]. As the collaboration has not yet clarified the origin of the excess, several models involving new physics were considered to explain the discrepancy, see e.g. [2] and references therein.

It is well known, that the neutrino weak flavor eigenstates ($\nu_e$, $\nu_\mu$, $\nu_\tau$, ...) need not coincide with the mass eigenstates ($\nu_1$, $\nu_2$, $\nu_3$, $\nu_4$...), but would, in general, be related through a unitary transformation. Such a generalized mixing:

$$\nu_l = \sum_i |U_{li}|^2 \nu_i; \quad l = e, \mu, \tau, ..., \quad i = 1, 2, 3, 4, ... \quad (1)$$

results in neutrino oscillations when the mass differences are small, and in decays of heavy neutrinos when the mass differences are large. In the recent work [3] it has been shown that the MiniBooNE excess could be explained by the production of a sterile neutrinos, $\nu_h$, of the mass around $\approx 500$ MeV, which, being created by mixing in $\nu_\mu$ neutral-current interactions, decay (dominantly) into photons and light neutrinos in the MiniBooNE detector target. Such kind of $\nu_h$ could arise in many interesting extensions of the Standard Model (SM), such as GUTs, Superstring inspired models, Left-Right Symmetric models, and others. It can decay radiatively into $\nu_\gamma$, if e.g. there is a non-zero transition magnetic moment ($\mu_\nu$) between the $\nu_h$ and active neutrino $\nu$ [4]. The required mixing strength

$$|U_{\nu_h}|^2 \simeq (1 - 4) \times 10^{-3} \quad (2)$$

was found to be consistent with existing experimental

FIG. 1: The shaded area is the experimentally allowed region of the mixing strength $|U_{\nu_h}|^2$ calculated for $\mu_\nu = 10^{-3} \mu_B$ in the model of Ref. [3]. The rectangular area represents the region in parameter space favorable for the suggested in Ref. [3] explanation of the MiniBooNE anomaly.
data for $\mu_{tr} \simeq (1 - 6) \times 10^{-9} \mu_B$ (here $\mu_B$ is the Bohr magneton) [3]. For illustration, experimentally allowed region of the mixing strength $|U_{\mu h}|^2$ in the $\nu_h$ mass range around 500 MeV is shown in Fig. 1 for $\mu_{tr} = 10^{-9} \mu_B$ together with the parameter region favorable for the explanation of the MiniBooNE anomaly. It worth to mention that the model [3] is also consistent with the absence of a significant low-energy excess in MiniBooNe antineutrino data [5].

In this letter we put forward an idea that sterile-active neutrino mixing in the allowed range shown in Fig. 1 could be tested by searching for the admixtures of $\nu_h$ in the decay $D_s^+ \rightarrow \mu^+ \nu_h$. In addition we point out that the present discrepancy of about 3$\sigma$ between the measured and predicted decay rate of $D_s^+ \rightarrow \mu^+ \nu_\mu$ could be explained by the unrecognized contribution from the decay $D_s^+ \rightarrow \mu^+ \nu_h$.

II. THE DECAY $D_s^+ \rightarrow \mu^+ \nu_\mu$ AND HEAVY NEUTRINO

If the $\nu_h$ exists, it could be a component of $\nu_\mu$, and as follows from Eq. (1), would be produced by any source of $\nu_\mu$ according to the mixing $|U_{\mu h}|^2$ and kinematic constraints. In particular, $\nu_h$ could be produced in any leptonic and semileptonic decays of sufficiently heavy mesons and baryons. For the interesting mass range $m_{\nu_h} \approx 400 - 600$ MeV the most promising process is the leptonic decay $D_s^+ \rightarrow \mu^+ \nu_\mu$.

In the SM, $D_s$ meson decays leptonically via annihilation of the $c$ and $\pi$ quarks through a virtual $W^+$. The decay rate of this process is given by

$$\Gamma(D_s^+ \rightarrow l^+ \nu) = \frac{G_F^2 f_{D_s^+}^2 m_{D_s^+}^2}{8\pi} \left(1 - \frac{m_l^2}{M_{D_s^+}^2}\right)|V_{cs}|^2,$$

where the $M_{D_s^+}$ is the $D_s^+$ meson mass, $m_l$ is the mass of the charged lepton, $f_{D_s^+}$ is the decay constant, $G_F$ is the Fermi constant, and $V_{cs}$ is a Cabibbo-Kobayashi-Maskawa matrix element which value equals 0.97334 [6]. The decay rate (3) is suppressed by the lepton mass squared, since the very leptonic decay is due to chirality-flip.

The mixing between the sterile neutrino and muon neutrino results in the decay $D_s^+ \rightarrow \mu^+ \nu_h$, as illustrated in Fig. 2. For the interesting mass interval $m_{\nu_h} \approx 400 - 600$ MeV the chirality-flip is mostly due to sterile neutrino mass which results in

$$\Gamma(D_s^+ \rightarrow \mu^+ \nu_h) \approx \Gamma(D_s^+ \rightarrow \mu^+ \nu_\mu)|U_{\mu h}|^2 \left(\frac{m_{\nu_h}}{m_\mu}\right)^2.$$ (4)

Using Eq. (2) and taking into account the most precise determination of the $D_s^+ \rightarrow \mu^+ \nu_\mu$ branching ratio $\text{Br}(D_s^+ \rightarrow \mu^+ \nu_\mu) = (0.565 \pm 0.045 \pm 0.017)$% [7], we find that the branching fraction of $D_s^+ \rightarrow \mu^+ \nu_h$ is in the experimentally accessible range:

$$\text{Br}(D_s^+ \rightarrow \mu^+ \nu_h) \approx (1.2 - 5.5) \times 10^{-4} \left(\frac{m_{\nu_h}}{500 \text{ MeV}}\right)^2.$$ (5)

III. DIRECT EXPERIMENTAL SEARCH FOR THE DECAY $D_s^+ \rightarrow \mu^+ \nu_h$

Consider now, as an example, the CLEO-c experiment, where the search for the decay $D_s^+ \rightarrow \mu^+ \nu_h$ could be performed. In this experiment several of the most precise measurements of properties of $D_s^+$ mesons have been performed by using the CLEO-c detector at CESR [8]. Recently, the CLEO collaboration studying the process $e^+e^- \rightarrow D_s^+ D_s^{*+}, D_s^- D_s^{*-}$ has reported on measurements of the decay constant $f_{D_s^+}$ of $D_s$ mesons to a precision of a few % [7, 9], see also [10].

The detector is well equipped to identify and measure the momenta/energy and directions of charged particles and photons. The experiment was performed at a centre-of-mass energy of 4170 MeV, where the cross section of a charmed meson pair production is relatively large. This allowed to fully reconstruct the $D_s^+$ as a 'tag' and study the leptonic decay properties of the other through the decay chains

$$e^+e^- \rightarrow D_s^+ D_s^{*+} \rightarrow D_s^- \gamma D_s^+ \rightarrow D_s^- \gamma \mu^+ \nu,$$

$$e^+e^- \rightarrow D_s^+ D_s^{*-} \rightarrow \gamma D_s^- D_s^+ \rightarrow \gamma D_s^- \mu^+ \nu.$$ (6)

The decays $D_s^+ \rightarrow \mu^+ \nu_\mu$ were identified by selecting the events with a single missing massless neutrino, for which the missing mass-squared, $MM^2$, evaluated by taking into account the reconstructed $\mu^+$, $D_s^-$ and $\gamma$ should peak at zero. The $MM^2$ is calculated as

$$MM^2 = (E_{CM} - E_{\mu} - E_{\gamma} - E_{D_s^+})^2 - (p_{CM} - p_{\mu} - p_{\gamma} - p_{D_s^+})^2,$$ (7)

where $E_{CM}$ and $p_{CM}$ are the centre-of-mass energy and 3-momentum, $E_{D_s^+}$ and $p_{D_s^+}$ are the energy and 3-momentum of the fully reconstructed $D_s^+$ tag, $E_{\mu}$ and $p_{\mu}$ are the energy and 3-momentum of the photon and $E_{\gamma}$ and $p_{\gamma}$ are the energy and 3-momentum of the muon [7].

Similarly to this approach, the basic idea of probing the model under discussion is to search for a peak corresponding to the value $m_{\nu_h}^2$ in the $MM^2$ distribution. It should be calculated taking into account measured properties of observed $\mu$, $D_s^+$ and photon from the decay.
chains:

\[ e^+e^- \rightarrow D_s^- D_s^{*-} \rightarrow D_s^- \gamma D_s^{*+} \rightarrow D_s^- \gamma \mu^+ \nu_h \rightarrow \]
\[ D_s^- \gamma \mu^+ \gamma_h \nu \]  
\[ e^+e^- \rightarrow D_s^{*-} D_s^+ \rightarrow \gamma D_s^- D_s^{*-} \rightarrow \gamma D_s^- \mu^+ \nu_h \rightarrow \gamma D_s^- \mu^+ \gamma_h \nu \]  

(8)

where \( \gamma_h \) denotes a photon from the dominant decay mode \( \nu_h \rightarrow \gamma \nu \) of sterile neutrino. In the largest part of the \( (|U_{\mu h}|^2, \mu_{tr}) \) parameter space favored by MiniBooNE, the \( \nu_h \) is expected to be a short-lived particle with the lifetime less than \( 10^{-9} \) s [3]. Then, its decay length is significantly less than the radius of the CLEO detector (95 cm), and most of the \( \nu_h \rightarrow \gamma \nu \) decays would occur inside the CLEO-c detector fiducial volume in the vicinity of the primary vertex.

The experimental signature of the decay \( \nu_h \rightarrow \gamma \nu \) is a peak in the mass range 0.16 - 0.36 GeV\(^2\) of the distribution of (7). Using Eqs.(2),(4) and the total number of (235.5±13.8) \( \mu^+\nu_\mu \) events observed by CLEO-c with 600 pb\(^{-1}\) [7], \((5-22) \times (\frac{m_{\nu\nu}}{200 \text{MeV}})^2 \) events are expected to be found at the peak. To obtain the correct \( MM^2 \) value, the photon from the decay \( \nu_h \rightarrow \gamma \nu \) should not be used in calculations of Eq. (7). For the energy greater than threshold, \( E_{\gamma_h} > 300 \) MeV, the \( \gamma_h \) could be identified as an extra photon in the event candidate for the decay chains (6).

Finally, note that a search for the decay mode \( \nu_h \rightarrow \mu \pi \) is also of a special interest. Although this decay is subdominant, for the mixing as large as in Eq. (2) its branching fraction could be of the order of few \( \% \) [3], and a few events could be observed in the CLEO-c experiment for the 600 pb\(^{-1}\) of data. The experimental signature of the event \( \nu_h \rightarrow \mu \pi \) would be two charged tracks originated from a common vertex displaced from the primary vertex. Since there is no neutrino in the final state, it is possible to reconstruct the invariant mass of the heavy sterile neutrino, that would manifest itself as a peak in the range 0.16-0.36 GeV\(^2\) of the invariant mass squared. An observation of a few \( \mu \pi \) events with the same invariant mass would provide an excellent cross-check of the model.

IV. THE \( D_s^+ \rightarrow \mu^+ \nu_\mu, \tau^+ \nu_\tau \) DECAYS PUZZLE

Interestingly, the above discussions might be relevant to the discrepancy of about 3\( \sigma \) between the measured and predicted rates of \( D_s^+ \rightarrow \mu^+ \nu_\mu \), see e.g. Refs. [7, 9] and discussion therein. Presently, in spite of the substantial theoretical and experimental efforts, the decay rates of \( D_s^+ \rightarrow \mu^+ \nu_\mu \) measured by the CLEO-c [7], Belle [11], and BABAR [12] experiments are found to be slightly higher than the predicted one, most accurately calculated in the framework of lattice QCD [13]. Taking into account the most precise results on the \( D_s^+ \rightarrow \mu^+ \nu_\mu \) decay rate from these experiments one arrives at

\[ \frac{\Gamma^{exp}(D_s^+ \rightarrow \mu^+ \nu_\mu) - \Gamma^{th}(D_s^+ \rightarrow \mu^+ \nu_\mu)}{\Gamma^{exp}(D_s^+ \rightarrow \mu^+ \nu_\mu)} = 0.166 \pm 0.060 \]  

(9)

where \( \Gamma^{exp}(D_s^+ \rightarrow \mu^+ \nu_\mu) \) and \( \Gamma^{th}(D_s^+ \rightarrow \mu^+ \nu_\mu) \) are the average measured and predicted values for the \( D_s^+ \rightarrow \mu^+ \nu_\mu \) decay rate, respectively, with the statistical and systematical uncertainties combined in quadrature. Thus, the ratio of Eq. (9) differs from zero by about 2.8\( \sigma \) standard deviations.

Various models of new physics giving additional contribution to the rate of \( D_s^+ \rightarrow \mu^+ \nu_\mu \) have been investigated in order to resolve the discrepancy, see e.g. [14, 15]. We propose here that the reason of why the experimental rate of \( D_s^+ \rightarrow \mu^+ \nu_\mu \) is higher than the theoretical expectations may be due the contribution from the decay \( D_s^+ \rightarrow \mu^+ \nu_h \).

Consider again, as an example, search for \( D_s^+ \rightarrow \mu^+ \nu_\mu \) events in the CLEO experiment [7]. If the \( \gamma_h \) from the decay chain (8) is used, the calculated \( MM^2 \) should peak at zero regardless of whether or not the \( \gamma_h \) is produced in the direct \( D_s^+ \) decay. This is valid under assumption that the \( \nu \) from the \( \nu_h \rightarrow \nu \gamma \) decay is light. Thus, the events (8) may be accepted and contribute to the number of the \( D_s^+ \rightarrow \mu^+ \nu_\mu \) signal events. Using Eqs. (3,4,9) one finds that in order to explain the discrepancy the branching fraction of decay mode to sterile neutrinos of masses \( m_{\nu_h} \approx 400 - 600 \) MeV should be within the range

\[ Br(D_s^+ \rightarrow \mu^+ \nu_h) = \frac{(9.85 \pm 4.16) \times 10^{-4}}{k} \]  

(10)

where factor \( k = \frac{P(D_s^+ \rightarrow \mu^+ \nu_h)}{P(D_s^+ \rightarrow \mu^+ \nu_\mu)} \) is the ratio of the overall probabilities for the events (8) and (6) to pass selection criteria in the analysis of \( D_s^+ \rightarrow \mu^+ \nu_\mu \) events in [7]. In this search, for the selection of \( D_s^+ \rightarrow \mu^+ \nu_\mu \) candidates it was required that there should be no additional photon, not associated with the tag, detected in the ECAL with energy greater than 300 MeV (photon veto) [7]. The fraction of \( \gamma_h \) from (8) that would pass this veto cut is roughly estimated to be \( k \approx 40\% \). This results in

\[ Br(D_s^+ \rightarrow \mu^+ \nu_h) = (24.6 \pm 10.4) \times 10^{-4} \]  

(11)

The corresponding mixing strength is (c.f. (5) and (2))

\[ |U_{\mu h}|^2 = (25.2 \pm 10.7) \times 10^{-3} \left( \frac{500 \text{ MeV}}{m_{\nu_h}} \right)^2 \]  

(12)

The explanation of the MiniBooNE anomaly implies somewhat smaller contribution to the decay \( D_s^+ \rightarrow \mu^+ \nu_\mu \). However, the regions for the obtained mixing strength of Eq. (12) and branching fraction of Eq. (11) overlap at the level of less than 2\( \sigma \) with the ranges of Eqs. (2) and (5), respectively, required to explain the MiniBooNE anomaly, see also Fig. 1. This enhances motivation for a sensitive search of the decay \( D_s^+ \rightarrow \mu^+ \nu_h \).
In close analogy with the case of $D_s^+$, the mixing (2) can also be probed with study of the leptonic decay rates of the $D^+$-meson. In particular, our model implies the quite similar to (4) contribution to the total muonic decay rate of $D^+ \to \mu^+ \nu$. However, the achieved accuracy in measurement of this decay rate [6] is worse than that for the $D_s$-meson, hence the suggested new contribution is unrecognizable yet.

It should be mentioned that the best precision in measurements of the decay rate of $D_s^+ \to \tau^+ \nu_\tau$ has also been achieved at CLEO [9], and the result is consistent with theoretical predictions. However, from other measurements at CLEO [7], based on study of another decay mode of outgoing $\tau$-lepton, 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 comparable to Eq. (9). Thus, one may speculate that this discrepancy is due to existence of an additional sterile neutrino coupled to the tau neutrino. Similar to above consideration we found that the mixing strength required to explain $D_s^+ \to \tau^+ \nu_\tau$ discrepancy should be

$$|U_{\tau h}|^2 = 0.16 \pm 0.09$$

for the mass range much below 190 MeV, where phase space suppression is negligible. Note, that this result is consistent with direct experimental limits [16, 17].

It is worth noting that heavy sterile neutrino of mass about 500 MeV and mixing to muon neutrino as strong as (2), (12) can be searched in other decays of charmed hadrons, beauty hadrons and $\tau$-leptons. Pure leptonic modes are more promising, since heavy neutrino contribution is enhanced with respect to that of the SM by a squared mass ratio of sterile neutrinos and charged lepton. This is not the case for other decay modes which branching ratios are roughly the same as corresponding decay to active muon neutrino multiplied by $|U_{\tau h}|^2$, and somewhat suppressed due to reduced phase space volume. By making use of general formulae for meson and $\tau$-lepton decays to sterile neutrinos presented in Ref. [18] and similar formulae for baryons [19] one can obtain more accurate estimates.

V. SUMMARY

To summarize, we show that the recently suggested explanation [3] of the MiniBooNE anomaly [1, 2] can be probed by studying leptonic decays of charmed mesons. This study can be undertaken with already collected data. We speculate that the present $2.8 \sigma$ discrepancy between the measured and predicted rate of $D_s^+ \to \mu^+ \nu_\mu$ can be a hint at the presence of heavy sterile neutrino suggested in Ref.[3].

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