

Invisible neutrino decays at the MOMENT experiment

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We investigate invisible decays of the third neutrino mass eigenstate in future accelerator neutrino experiments using muon-decay beams such as MuOn-decay MEDium baseline NeuTrino beam experiment (MOMENT). MOMENT has outstanding potential to measure the deficit or excess in the spectra caused by neutrino decays, especially in muon neutrino/antineutrino disappearance channels. Such an experiment will improve the constraints of the neutrino lifetime. Compared with exclusion limits in the current accelerator neutrino experiments T2K and NOvA under the stable neutrino assumption, we expect that MOMENT gives the better bound. The non-decay scenario is expected to be excluded by MOMENT at a confidence level of more than 3σ , if the best fit results in T2K and NOvA are confirmed. We further find that reducing systematic uncertainties is more important than the running time. Finally, we find some impact of neutrino invisible decays on the precision measurement of other oscillation parameters.

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1. Introduction

The framework of three-generation neutrino oscillation has been well established through solar, atmospheric, accelerator and reactor neutrino experiments [1, 2, 3, 4]. In this paradigm, neutrino oscillations are dominated by two mass-squared splittings (*i.e.*, Δm_{31}^2 , Δm_{21}^2) and three mixing angles (*i.e.* θ_{12} , θ_{13} , θ_{23}) [5]. Up to now, most of the oscillation parameters have been measured well [6], except the Dirac CP phase δ and the neutrino mass ordering (normal mass hierarchy: $\Delta m_{31}^2 > 0$; inverted mass hierarchy: $\Delta m_{31}^2 < 0$). The current precision measurement in the quark sector reaches the sub-percent level and serves as a tool to probe new physics. Following the same strategy, it is natural to expect near future neutrino oscillation experiments such as JUNO [7], T2HK [8], DUNE [9] and MOMENT [10] to search for new physics beyond three-generation neutrino oscillations including sterile neutrinos [11, 12, 13], non-standard neutrino interactions [14, 15, 16, 17] and neutrino decays [18, 19, 20, 21].

Neutrino decays are classified into invisible and visible scenarios. In the visible decay scenario, decay products can be detected by the detector, like $\nu_j \rightarrow \bar{\nu}_i(\nu_i) + J$ have been put forward, where J denotes a Majoron. If the final states of neutrino decays are unobservable to the detector, those decays are called invisible decays [21]. Given that neutrinos are Dirac particles, the coupling gives rise to neutrino decay products: $\nu_i \rightarrow \bar{\nu}_{jR} + \chi$, where χ is a light iso-singlet scalar and ν_{iR} is a right-handed fermion [19, 23]. Majorana neutrinos lead to decay products [24, 25], $\nu_j \rightarrow \nu_4 + J$. The ν_2 decay in the invisible channel has been constrained well from solar neutrino oscillation data, which gives the bound $\tau_2/m_2 > 7.2 \times 10^{-4}$ s/eV at 90% C.L. [26]. Recently a combined analysis of NOvA and T2K data pointed to a result of $\tau_3/m_3 > 1.5 \times 10^{-12}$ s/eV along with the constraints by an individual experiment: $\tau_3/m_3 \geq 7 \times 10^{-13}$ s/eV in NOvA and $\tau_3/m_3 \geq 1.41 \times 10^{-12}$ s/eV in T2K [27].

Compared with the superbeam experiment by pion decays, MOMENT will offer clean neutrino sources from muon decays to probe new physics with a baseline detector using Gd-doped water cherenkov technology, which have been demonstrated to have excellent properties to study new physics. In this work [28], we focus on invisible neutrino decays and demonstrate how the eigenstate ν_3 decay would affect precision measurements of standard neutrino mixing parameters.

2. Simulation of neutrino invisible decays at MOMENT

We assume that the neutrino decay products are sterile neutrinos and the mass ordering is given by $m_3 > m_2 > m_1 > m_4$ as the following decay process: $\nu_3 \rightarrow \nu_4 + J$. The connection between flavour eigenstates and mass eigenstates can be given as:

$$\begin{pmatrix} \nu_\alpha \\ \nu_s \end{pmatrix} = \begin{pmatrix} U & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_4 \end{pmatrix} \quad (2.1)$$

The Hamiltonian of neutrino propagation in matter can be written as:

$$H = U \left\{ \frac{1}{2E} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} - i \frac{m_3}{2E\tau_3} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \right\} U^\dagger + \begin{pmatrix} 2\sqrt{2}G_F N_e E & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad (2.2)$$

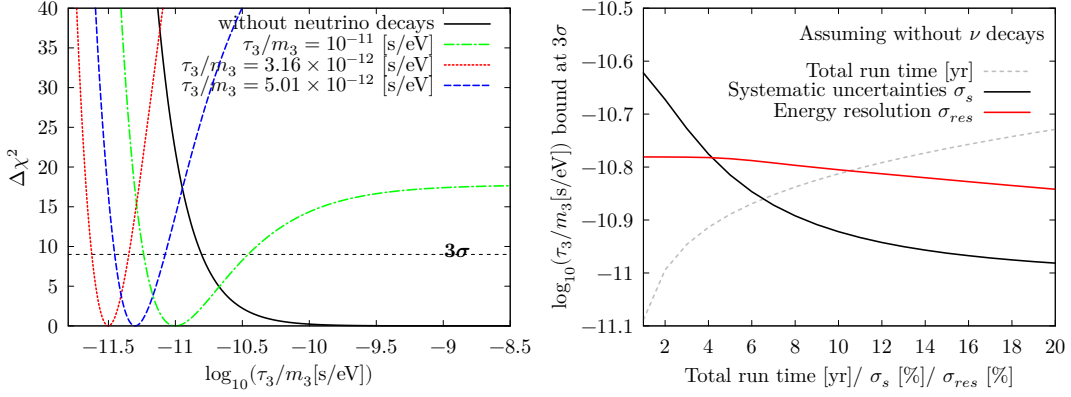


Figure 1: The left panel shows $\Delta\chi^2 = \chi^2 - \chi_{\min}^2$ as a function of the test value of τ_3/m_3 . The input (true) value of τ_3/m_3 is assumed to be stable (black solid), 10^{-11} (green dashed-dotted), 5.01×10^{-12} (blue short-dashed) and 3.16×10^{-12} s/eV (red dotted) at MOMENT. The right panel presents constraints at 3σ on τ_3/m_3 for the stable-neutrino case against the total running time (the short-dashed grey curve), the size of systematic uncertainty σ_s (black), and the energy resolution σ_{res} (red). We run experiments from 1 to 20 years, while σ_s and σ_{res} vary in the range [1%, 20%] [28].

where U is the PMNS mixing matrix [29, 30], G_F is the Fermi coupling constant, N_e is the electron density, E is the neutrino energy and τ_3 is the lifetime of ν_3 . Obviously, probabilities in neutrino and antineutrino modes remain invariant after a replacement of $\delta \rightarrow -\delta$ and $N_e \rightarrow -N_e$, *i.e.* $P_{\nu_\alpha \rightarrow \nu_\beta}(E, L; \delta, N_e) = P_{\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta}(E, L; -\delta, -N_e)$. Numerical oscillation probabilities were done by diagonalizing the Hamiltonian matrix [31]. The simulation details for MOMENT were given in Ref. [17, 13] with eight oscillation channels: $\nu_e \rightarrow \nu_e$, $\nu_e \rightarrow \nu_\mu$, $\nu_\mu \rightarrow \nu_e$, $\nu_\mu \rightarrow \nu_\mu$ and their CP-conjugate partners. The major backgrounds are mostly from the atmospheric neutrinos, neutral current backgrounds and charge mis-identifications. They can be largely suppressed by the beam direction and proper modelling of background spectra within the beam-off period. Our simulation was carried out with the help of GLOBES [32, 33]. The central values and their uncertainties for the standard oscillation parameters were taken from the NuFit4.0 [6].

When we switch on neutrino decays with $\tau_3/m_3 = 10^{-12}$ s/eV, a clear difference between the cases with and without invisible neutrino decays could be easily observed in simulations. Invisible decays washed out the extreme of neutrino oscillations, where the differences in ν_μ and $\bar{\nu}_\mu$ disappearance channels were more significant than the other channels. This could affect the precision measurement of neutrino mixing parameters such as θ_{23} and Δm_{31}^2 which are mostly involved in these channels. In other words, the other channels could help with a clarification of this bias induced by neutrino decays.

In Fig. 1, we show the constraint on τ_3/m_3 for four different true values. As the true value of τ_3/m_3 gets smaller, the constraint becomes tighter. It is obvious that the larger neutrino decays take place, the tighter constraint we can obtain. The appearance of the upper bound at 3σ is significant, which did not show up in the current measurements by T2K and NOvA. We note that the behaviour of $\Delta\chi^2$ looks symmetric for $\tau_3/m_3 = 3.16 \times 10^{-12}$ [s/eV], but does not for the larger value of τ_3/m_3 . It is because in that case, $\Delta\chi^2$ is approaching to ~ 120 when neutrino is stable. The range of $\Delta\chi^2$ shown in Fig. 1 is near the bottom. We find an important result by comparing

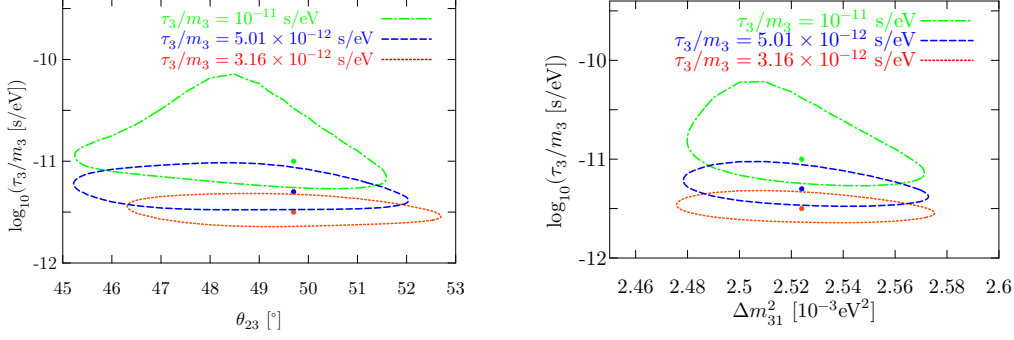


Figure 2: The exclusion contour at 3σ on the planes any two of $\log_{10}(\tau_3/m_3)$ [s/eV] and θ_{23} (left) and Δm_{31}^2 (right). We show for different true values: $\tau_3/m_3 = 10^{-11}$ (dashed-dotted green), 5.01×10^{-12} (short-dashed blue) and 3.16×10^{-12} (dotted red) s/eV [28].

the impact of the total running time and energy resolution σ_s . We can see improving $\sigma_s = 1\%$ can improve better ($\log_{10}(\tau_3/m_3)$ [s/eV]) = -10.6) than that by doubling the total running time ($\log_{10}(\tau_3/m_3)$ [s/eV]) = -10.7).

Thanks to the precision measurement of τ_3/m_3 , we can obtain a closed contour in Fig. 2 instead of a wide band as what we saw in the combined fitting result of T2K and NOvA in Ref. [27]. On average, the precision at 3σ in θ_{23} is almost $3 - 3.5^\circ$ at MOMENT. We also observe some impact from the true value of τ_3/m_3 on the θ_{23} measurement. The uncertainty of Δm_{31}^2 at 3σ C.L. is about $0.05 \times 10^{-3} \text{eV}^2$. The impact on θ_{23} is more pronounced than the mass squared difference here.

3. Summary

Neutrino decays lead to suppression and damping effects in the framework of three-generation neutrino oscillations, and could be measured in the precisely reconstructed spectra at the MOMENT experiment. The ν_μ and $\bar{\nu}_\mu$ disappearance channels are more important than other channels while focusing on the maximum or minimum is a good strategy to scrutinize these effects caused by neutrino decays. We have simulated the MOMENT experiment and found outstanding potential to constrain the τ_3/m_3 parameter. Given the best-fit values hinted by T2K and NOvA [27], we have found that MOMENT would improve the precision measurement of invisible neutrino decays. If the current best fit discovered in [27] is confirmed, the standard non-decay scenario can be excluded at a confidence level of more than 3σ . The projections of $\theta_{23} - \log_{10}(\tau_3/m_3)$ and $\Delta m_{31}^2 - \log_{10}(\tau_3/m_3)$ have demonstrated little correlations between θ_{23} and Δm_{31}^2 at 3σ confidence level.

We have further investigated the impact of statistical and systematic uncertainties by varying the total running time, changing the size of the normalisation uncertainty σ_s and energy resolution respectively. By increasing the total running time or reducing the systematic uncertainties, we will improve the sensitivity in invisible neutrino decays. Reducing systematic uncertainties is more important than increasing the total running time in the MOMENT experiment. Neither is it important to improve energy resolution in the detector.

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