

Study of invisible neutrino decay and oscillation in the presence of matter with a 50 kton magnetised iron detector

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The sensitivity to the invisible decay of the mass eigenstate ν_3 in the presence of Earth matter effects is studied. Only the charged current interactions of atmospheric ν_μ and $\bar{\nu}_\mu$ for 500 kTon year exposure of a future magnetised iron detector at INO are analysed. The analysis with observed muon energy in the range would give a constraint of $\tau_3/m_3 > 1.51 \times 10^{-10}$ s/eV at 90% CL with this exposure. Here τ_3 is the lifetime and m_3 is the mass of ν_3 , when it is the heaviest. The effect of decay on the precision measurement of $\sin^2 \theta_{23}$ and $|\Delta m_{32}^2|$ and neutrino mass hierarchy are also studied. Since the presence of decay affects the oscillation amplitude rather than its phase, it is seen that the precision on $\sin^2 \theta_{23}$ worsens whereas that on $|\Delta m_{32}^2|$ is not much affected. Sensitivity to hierarchy also worsens slightly in the presence of the invisible decay of ν_3 .

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1. Introduction

Flavour oscillations of neutrinos have been established from the observation of neutrino oscillations at various energies and baselines by different experiments over the world. Currently, the major open questions in neutrino oscillation physics are neutrino mass hierarchy, octant of the mixing angle θ_{23} and the value of the CP phase δ_{CP} . The Iron Calorimeter (ICAL) detector [1, 2] at the proposed India-based Neutrino Observatory (INO) is an atmospheric neutrino experiment aiming to study the 2–3 oscillation parameters by probing the Earth matter effects on the propagation of atmospheric neutrinos. The main goal of ICAL is to determine neutrino mass hierarchy and to perform precision measurements on $\sin^2 \theta_{23}$ and $|\Delta m^2_{32}|$. New physics phenomena are expected to change the oscillation probabilities and will affect the number of observed events. Hence oscillation experiments can be used to study the sensitivity to the new physics parameter itself. The presence of the new physics parameter will also affect the determination of the standard oscillation parameters and thus creating new degeneracies. Here we investigate one such phenomenon namely the invisible decay of the mass eigen state ν_3 while its travel from its production point to the detector. For this simulation study we have used charged current ν_μ and $\bar{\nu}_\mu$ events obtained with 500 kTon year exposure of INO ICAL to atmospheric neutrinos whose oscillation probabilities in matter are modified by the invisible decay model we consider. Here the mass eigen state ν_3 is considered to decay invisibly via $\nu_3 \rightarrow \nu_s + J$, where J is a pseudo-scalar and ν_s is a sterile neutrino; and oscillations in the presence of full 3-flavour matter. Since ν_s does not mix with the three active neutrinos, the mixing matrix U in vacuum will be:

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta} & c_{23}c_{13} \end{pmatrix}, \quad (1.1)$$

where $c_{ij} = \cos \theta_{ij}$, $s_{ij} = \sin \theta_{ij}$; θ_{ij} are the mixing angles and δ is the CP violating phase.

Three-flavour evolution equation in the presence of Earth matter, with invisible decay is:

$$i \frac{d\tilde{\nu}}{dt} = \frac{1}{2E} [UM^2U^\dagger + \mathbb{A}_{CC}] \tilde{\nu}, \quad (1.2)$$

$$\mathbb{M}^2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 - i\alpha_3 \end{pmatrix}, \quad \text{and} \quad \mathbb{A}_{CC} = \begin{pmatrix} A_{cc} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad (1.3)$$

where E is the neutrino energy, $\alpha_3 = m_3/\tau_3$ is the decay constant in units of eV^2 , m_3 is the mass of ν_3 and τ_3 its rest frame life time. The conversion factor used to make α_3 to have the units of eV^2 is $1 \text{ eV/s} = 6.58 \times 10^{-16} \text{ eV}^2$. Matter potential is

$$A_{cc} = 2\sqrt{2}G_F n_e E = 7.63 \times 10^{-5} \text{ eV}^2 \rho(\text{gm/cc}) E(\text{GeV}), \quad (1.4)$$

where, G_F is the Fermi constant and n_e is the electron number density in matter and ρ is the matter density. For anti-neutrinos, the sign of A_{cc} and the phase δ in Eq. (1.2) will be reversed.

1.1 Why use an atmospheric neutrino experiment to probe α_3 ?

Since the decay term appears in the oscillation probabilities in the form $\exp(-\alpha L/E)$, no decay corresponds to $\alpha = 0$. The effect of α for various values of L/E are shown in Fig. 1; here $\exp(-\alpha L/E)$ vs L/E is plotted for $\alpha = 10^{-3}, 10^{-4}, 10^{-5}$ and 10^{-6} eV². The values of α to which a given experiment spanning a specified L/E range is sensitive to, can be understood from here. The red (blue) shaded region in Fig. 1 indicates the L/E range covered by the narrow band NO ν A neutrino beam with $L = 810$ km and $E = 1-3$ GeV (atmospheric neutrinos at a baseline $L = 9700$ km and $E = 0.5-25$ GeV). It can be seen from the figure that NO ν A's sensitivity is limited to larger values of α ; i.e 10^{-3} and 10^{-4} eV² for which the exponential terms shows substantial departure from the no decay value of $\exp(-\alpha L/E) = 1$. Since atmospheric neutrino oscillation experiments span an L/E range of $\sim [0.6, 25484]$ (km/GeV), they will be sensitive to a wider range of α from $\sim 10^{-6} - 10^{-3}$ eV². Larger L/E values will be sensitive to smaller values of α and vice versa. Since INO ICAL is an atmospheric neutrino detector and has good exposure, it is well suited to probe a phenomenon like invisible neutrino decay. As seen from Fig. 1 ICAL could be sensitive to even α of the order of 10^{-6} eV². The sensitivity to low α values come from low energies, while the higher energies will help in ruling out the larger values of α .

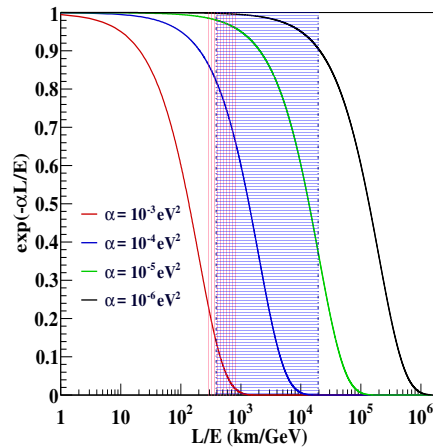


Figure 1: The value of $\exp(-\alpha L/E)$ as a function of L/E for different values of α - from left to right - $1 \times 10^{-3}, 1 \times 10^{-4}, 1 \times 10^{-5}$ and 1×10^{-6} eV² respectively. The red shaded region denotes the L/E range accessible with NO ν A narrow band neutrino beam ($E = 1-3$ GeV), the dashed blue shaded region indicates the range for $L = 9700$ km, when E is in the range $0.5-25$ GeV.

2. Three flavour neutrino oscillation probabilities with α_3

The three flavour oscillation probabilities in Earth matter, for a baseline of 9700 km in the presence of invisible decay are shown in Fig. 2. The values of parameters used to generate the oscillation probabilities are : $\delta_{CP} = 0^\circ$; $\theta_{12} = 34.08^\circ$; $\theta_{23} = 39^\circ, 45^\circ, 51^\circ$; $\theta_{13} = 8.5^\circ$; $\Delta m_{21}^2 = 7.6 \times 10^{-5}$ (eV²); $|\Delta m_{32}^2| = 2.4 \times 10^{-3}$ (eV²); $\alpha_3 = 0, 10^{-4}, 10^{-3}$ (eV²).

Several things can be understood from the figure. For a given value of θ_{23} , $\alpha_3 = 0$ corresponds to the no decay case. The effect of decay is to reduce the oscillation probabilities at maxima

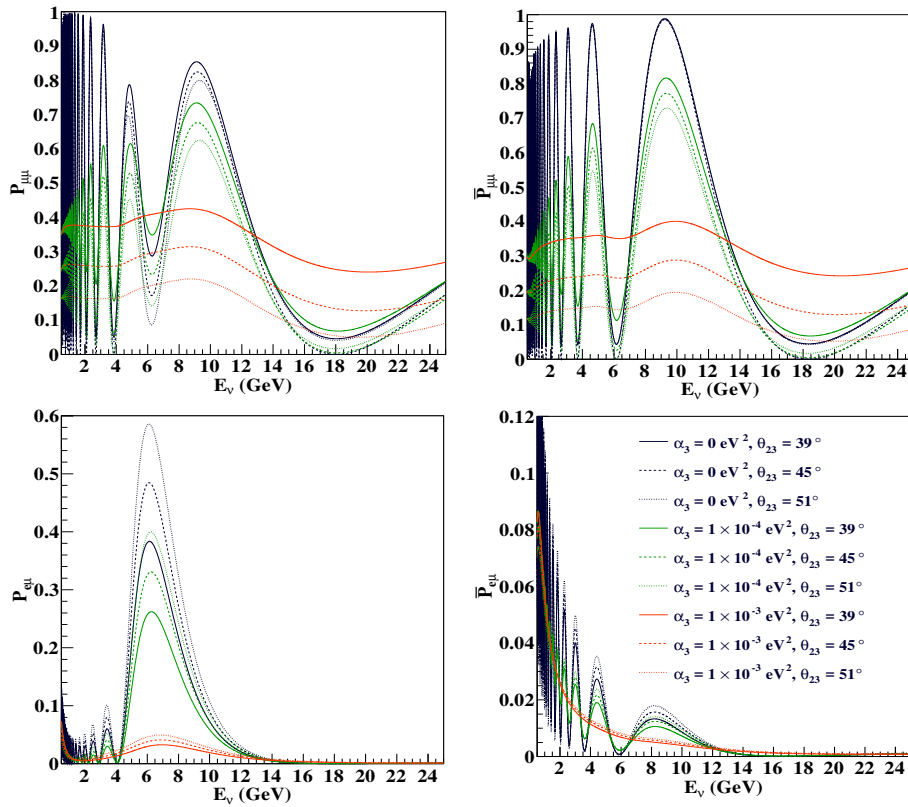


Figure 2: From left to right $P_{\mu\mu}^{matt}$, $\bar{P}_{\mu\mu}^{matt}$, $P_{e\mu}^{matt}$ and $P_{\mu\mu}^{matt}$ for $L = 9700$ km and with different θ_{23} and α_3 . NH is taken as the true hierarchy.

and elevate at minima, thus causing a damping effect. When α_3 is very large say $1 \times 10^{-3} \text{ eV}^2$, oscillations are completely washed out. The larger the value of α_3 , the more the dampening will be. Also the effect is more at lower energies. Since the relative change in $\bar{P}_{\mu\mu}$ ($P_{e\mu}$) due to decay is more than that in $P_{\mu\mu}$ ($\bar{P}_{e\mu}$), the contribution to the α_3 sensitivity χ^2 will be more from $\bar{\nu}_\mu$ (ν_μ). But $P_{\mu\mu}$ and $\bar{P}_{\mu\mu}$ being the dominant channels at ICAL, the major contribution to α_3 sensitivity will come from $\bar{\nu}_\mu$ events in the present study.

Since the effect of α_3 is to alter the amplitude of the oscillations, it will affect the measurement of θ_{23} which also alters the oscillation amplitudes. This creates a degeneracy between α_3 and θ_{23} , i.e., θ_{23} in the first octant combined with a larger (smaller) value of α_3 can give a probability similar to that with θ_{23} in second octant + a smaller (larger) value of α_3 for $P_{\mu\mu}$ and $\bar{P}_{\mu\mu}$ ($P_{e\mu}$ and $\bar{P}_{e\mu}$). This combined effect affects the sensitivity(discovery potential) to(of) α_3 and the precision measurement on θ_{23} .

3. Sensitivity to α_3

Sensitivity studies to α_3 are done with ν_μ and $\bar{\nu}_\mu$ charged current events obtained with 500 kTon years exposure of INO ICAL. The details of the numerical simulations and χ^2 analysis can be found in [3, 4]. Analyses with fixed parameters as well as marginalisation in the 3σ ranges of these parameters were performed. Since there is no real data, the “data” events are simulated with

a true set of parameters and then fitted with theory events by varying the parameter values. For the sensitivity study of α_3 , “data” was simulated with $\alpha_3 = 0$ and is fitted with theory with different non-zero values of α_3 . The number of oscillated events for different $\alpha_3 = 0, 1 \times 10^{-5}, 1 \times 10^{-4} \text{ eV}^2$, in different bins of E_μ^{obs} are shown in Fig.3.

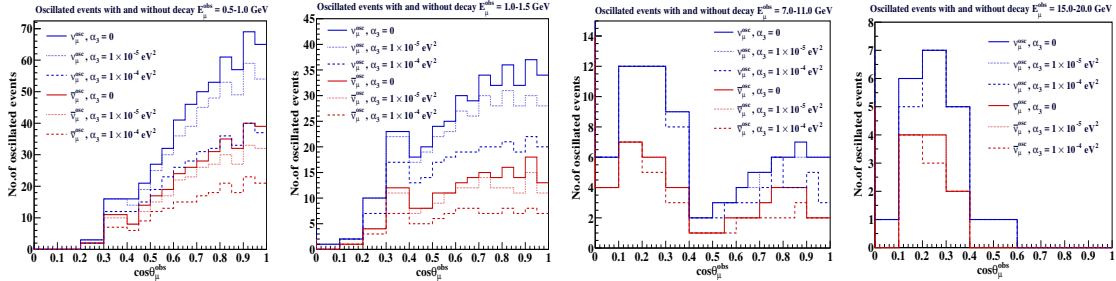


Figure 3: Oscillated ν_μ and $\bar{\nu}_\mu$ events for each E_μ^{obs} bin as a function of $\cos \theta_\mu^{obs}$ for $\alpha_3 = 0, 1 \times 10^{-5}$ and $1 \times 10^{-4} \text{ eV}^2$. Only up-coming events (oscillated) are shown here.

The sensitivity of 500 kTon year exposure of ICAL with NH (IH) as the true hierarchy is shown in Fig. 4. Previous analyses [5, 6] had obtained a bound of $\alpha_3 < 2.35 \times 10^{-4} \text{ eV}^2$ ($\tau_3/m_3 > 2.8 \times 10^{-12} \text{ s/eV}$) at 90% C.L, with charged current and neutral current events. For true NH, ICAL analysis with charged current ν_μ and $\bar{\nu}_\mu$ events only give bounds of $\alpha_3 < 2.73 \times 10^{-6} \text{ eV}^2$ ($\tau_3/m_3 > 2.39 \times 10^{-10} \text{ s/eV}$) at 90% CL with all parameters fixed. With marginalisation over θ_{13}, θ_{23} and $|\Delta m_{32}^2|$ the limit at 90% CL is $\alpha_3 < 4.36 \times 10^{-6} \text{ eV}^2$ ($\tau_3/m_3 > 1.51 \times 10^{-10} \text{ s/eV}$) for true NH. This is *two orders of magnitude tighter* than the bounds given by the previous MINOS and T2K analyses [5, 6]. The results for true IH are similar, with 90% CL limits of $\alpha_3 < 2.78 \times 10^{-6} \text{ eV}^2$ ($\tau_3/m_3 > 2.42 \times 10^{-10} \text{ s/eV}$) for fixed parameters and $\alpha_3 < 5.82 \times 10^{-6} \text{ eV}^2$ ($\tau_3/m_3 > 1.14 \times 10^{-10} \text{ s/eV}$) with marginalisation.

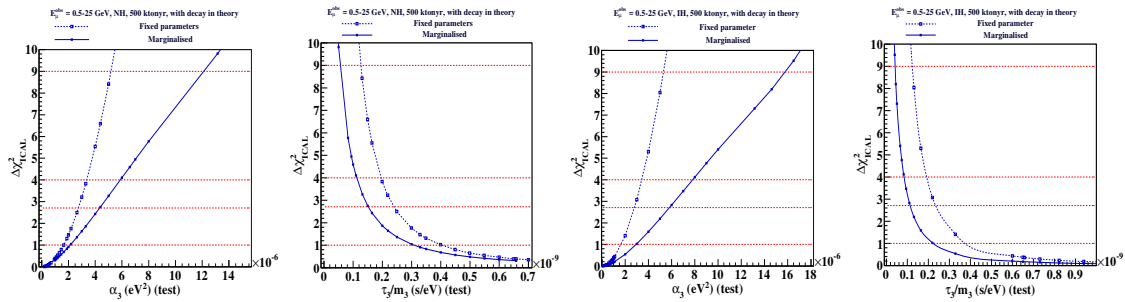


Figure 4: Expected sensitivity of ICAL to neutrino decay with true NH (first and second from the left) and true IH (third and fourth from the left). The expected χ^2 is shown as a function of α_3 (test) eV^2 (panels 1 and 3) and τ_3/m_3 (test) (s/eV) (panels 2 and 4) with 500 kton-yr exposure of ICAL.

4. Precision measurement of $\sin^2 \theta_{23}$ and $|\Delta m_{32}^2|$ in the presence of decay

The effect of the presence of invisible decay on the precision measurement of $\sin^2 \theta_{23}$ and $|\Delta m_{32}^2|$ is also studied. Since decay affects the amplitude of oscillations, it is expected that the

precision measurement on θ_{23} will be affected. For these analyses, both “data” and theory are simulated with decay. The value of α_3 is taken as $1 \times 10^{-5} \text{ eV}^2$ in “data” and kept at this value in theory for fixed parameter analysis and varied in the range $[0 - 2.35 \times 10^{-4}] \text{ eV}^2$ for marginalised analysis. The comparison with no decay case is also made. The results are shown in Fig. 5.

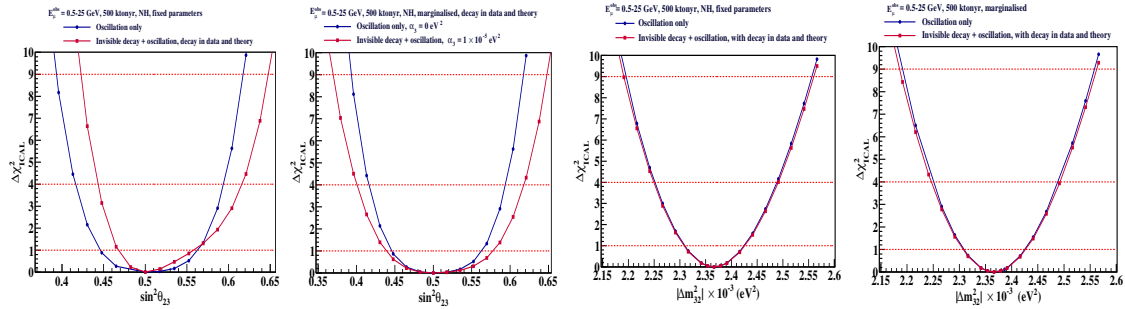


Figure 5: From left to right : Precision on $\sin^2 \theta_{23}$ (left-set) and $|\Delta m_{32}^2|$ (right-set) in the presence and absence of invisible decay for fixed parameters and with marginalisation. The value of decay parameter α_3 in “data” is taken to be $1 \times 10^{-5} \text{ eV}^2$.

For the fixed parameter case eventhough the relative 1σ precision on $\sin^2 \theta_{23}$ with $\alpha_3 = 0$ and $1 \times 10^{-5} \text{ eV}^2$ are similar, 8.9% for the former and 8.6% for the latter, the parameter space shifts to the higher $\sin^2 \theta_{23}$ side in the with decay case. This can be understood from Fig. 6.

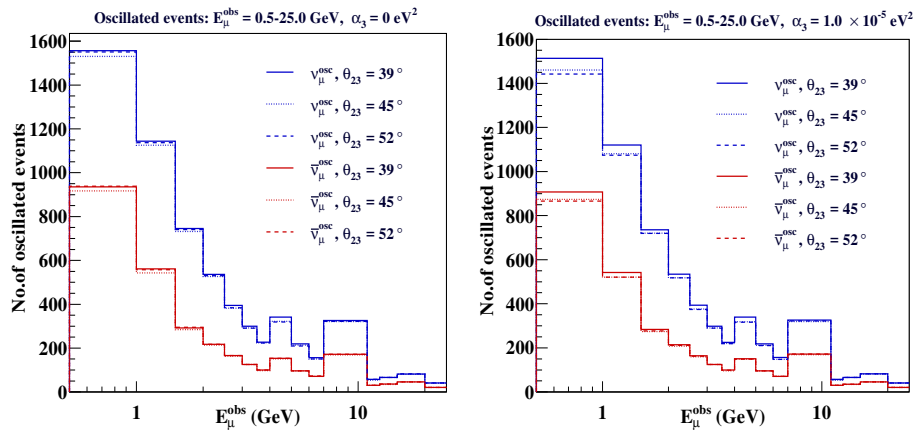


Figure 6: Oscillated ν_μ events as a function of E_μ for (left) $\alpha_3 = 0 \text{ eV}^2$ and (right) $\alpha_3 = 1 \times 10^{-5} \text{ eV}^2$ for $\theta_{23} = 39, 45$ and 52° .

When there is decay, the difference between the events with θ_{23} in the first octant and those with $\theta_{23} = 45^\circ$ is more than that with θ_{23} in the second octant and those with $\theta_{23} = 45^\circ$. This causes the parameter space to shift towards the higher θ_{23} side. When marginalisation is done, the precision without and with decay are 8.9% and 10.9% respectively. Here α_3 can be varied in theory to match the theory events with the “data” generated with true $\theta_{23} = 45^\circ$.

The precision on $|\Delta m_{32}^2|$ remains the same both in the absence and presence of invisible decay. For fixed parameters the relative 1σ on $|\Delta m_{32}^2|$ is 2.5% whereas with marginalisation it is 2.6%.

5. Conclusions

The sensitivity to invisible neutrino decay with 500 kTon year exposure of ICAL is studied. The analysis with only charged current ν_μ and $\bar{\nu}_\mu$ events give a bound of $\alpha_3 < 2.73 \times 10^{-6} \text{ eV}^2$ ($\alpha_3 < 4.36 \times 10^{-6} \text{ eV}^2$) at 90% CL for fixed parameters (marginalised case), assuming true NH. This is two orders of magnitude tighter than the bounds on α_3 given by the previous analyses with charged and neutral current events. This means that if we include the analysis of neutral current events also, ICAL should be able to put an even better bound on α_3 . The effect of the presence of decay on the precision of $\sin^2 \theta_{23}$ and $|\Delta m_{32}^2|$ was also studied; it was found that the precision on $\sin^2 \theta_{23}$ worsens in the presence of invisible decay since it is related to the amplitude of oscillations which the decay also affects.

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