Investigating Possible Neutrino Decay in Long Baseline Experiment Using ICAL as Far end Detector

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We investigate the effects of possible decay of neutrinos from a neutrino factory in a long baseline experiment. We consider the neutrinos from a factory at CERN and the detector to be the 50 kTon iron calorimeter (ICAL) detector proposed for India-based Neutrino Observatory (INO). We found considerable depletion of muon yield at INO for certain value of decay parameters.

High energy neutrino beams are now playing a very crucial role to determine the yet unknown features of neutrino physics. Apart from determination of neutrino mass hierarchy and determination of $\theta_{13}$ based on neutrino oscillation theory, another possibility could be to search neutrino decay over long baselines. The neutrino decay scenario has been discussed earlier in Ref. [1, 2, 3, 4]. The neutrino decay scenario has also been discussed in connection to atmospheric and solar neutrinos in Refs. [5, 6, 7, 8, 9, 10, 11, 12]. Decay of Supernova neutrinos has also been addressed by several authors [13, 14, 15, 16, 17]. The possible neutrino decay for cosmic ultra high energy neutrinos are also studied [18] and also neutrino decay is addressed in the context of recently proposed unparticle in [19, 20, 21]. Furthermore, MiniBooNE collaboration [22] searching for $\nu_\mu \rightarrow \nu_e$ oscillation recently reported null result within the energy range $475 < E_\nu < 1250$ MeV and hence disfavours two neutrino oscillation theory, however, excess of $\nu_e$ events has been observed within the energy interval $300 < E_\nu < 475$ MeV. Attempts have been made to explain such result either through the inclusion of two sterile neutrinos [23] or through neutrino decaying into unparticles, [21].

In the present work, we explore the possibility to observe neutrino decay for neutrinos from neutrino factory through longbaseline neutrino experiment assuming a
beam from muon storage ring at CERN to India-based Neutrino observatory (INO) covering the distance of around 7152 Km. The detector at INO site is a magnetized Iron Calorimetre (ICAL) \cite{24} which has an unique ability to distinguish charge of the particle passing through it. The mass of the proposed is around 50 kTon An exposure time of five years will be enough to collect large number of events. Assuming such mass and exposure time, in the present work we studied the

Neutrino beams are generated from the decay of muons, $\mu^\pm \rightarrow e^\pm + \nu_e(\bar{\nu}_e) + \nu_\mu(\bar{\nu}_\mu)$ from the straight section of the muon storage ring \cite{25, 26}. For unpolarized muon beam, the flux distributions of $\bar{\nu}_e$ and $\nu_\mu$ are given by

\begin{equation}
\left( \frac{d^3N}{dt dA dE_{\nu}} \right)^{\nu_\mu}_{\text{lab}} = \frac{4g_{\text{lab}} J^2}{\pi L^2 E_{\nu_\mu}^3} \frac{E_{\nu_\mu}^2}{E_\mu^3} \left( 3 - 4 \frac{E_{\nu_\mu}}{E_\mu} \right) \tag{1}
\end{equation}

\begin{equation}
\left( \frac{d^3N}{dt dA dE_{\nu}} \right)^{\bar{\nu}_e}_{\text{lab}} = \frac{28g_{\text{lab}} J^2}{\pi L^2 E_{\nu_\mu}^4} E_{\bar{\nu}_e}^2 (E_\mu - 2E_{\bar{\nu}_e}) \tag{2}
\end{equation}

where $g_{\text{lab}}$ is the number of muons produced, $J$ is the Jacobian factor arising due to transformation from rest frame to lab frame and is given by

\begin{equation}
J = \frac{1}{\gamma (1 - \beta \cos \theta)} \tag{3}
\end{equation}

$E_\mu$ be the muon energy and $E_{\nu_\mu}$ and $E_{\bar{\nu}_e}$ are energies of produced corresponding neutrinos, $\gamma$ is the boost factor and $\beta = p_\mu / E_\mu$ and $\theta$ is the off axis angle which we set zero. For our analysis, we set all those parameters as $g_{\text{lab}} = 0.35 \times 10^{20}$ considering 35% efficiency of the produced muon number with energy $E_\mu = 20$ GeV. The parameter $L$ is the length traversed by the neutrino from the source to the detector through earth. In the present work, we take $L = 7152$Km which is the distance between the source at CERN to the detector at INO site at PUSHEP (11°5'N, 76°6'E). The distribution of flux for both $\nu_\mu$ and $\bar{\nu}_e$ are shown in Fig. 1 and Fig. 2 respectively. $E_{\nu_\mu}$ varies from 0-15 GeV $E_{\bar{\nu}_e}$ varies from 0-10 GeV and we observe for both the cases a large number of muons hitting the detector.

Next, we consider the path of neutrino traversing through the earth from CERN to the proposed INO site at PUSHEP considering earth matter density profile and assuming three flavor neutrino oscillation without CP violating phase. The CERN-INO baseline length of 7152 Km is very close to the “magic baseline” that produces null CP violation effect.
We consider $\nu_e \rightarrow \nu_\mu$ as well as $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ mode including three flavor oscillation. The cross-sections due to interaction of $\nu$ with the ICAL (Iron Calorimeter) detector proposed at INO site are mainly arising through quasi-elastic (QE) and Deep inelastic scattering (DIS). At low energy we have considered QE mode ($E_\nu \simeq 1\text{GeV}$), and for $E_\nu > 1\text{GeV}$ dominant contribution will come from DIS. We have also included resolution function of the detector obtained from exact simulation of the ICAL detector which correlate the energy of the incident neutrino on the detector to the produced muons inside the detector [24].

In the present decay scenario, we consider that the neutrino states $|\nu_2\rangle$ and $|\nu_3\rangle$ are unstable and they decay into the stable state of $|\nu_1\rangle$. The exponential decay term for the $i$th neutrino state is given by $\exp(-4\pi L/\lambda_{d_i})$ where $L$ is the baseline length in kilometers and 

$$\lambda_{d_i} = 2.5 \text{km} \frac{E}{\text{GeV}} \frac{\text{eV}^2}{\alpha_i}$$

(4)

where $\alpha_i = m_i/\tau$, $m_i$ being the mass of the neutrino mass eigenstate $|\nu_i\rangle$ and $\tau$ being the decay lifetime.

The purpose of this work is to investigate whether the effect of any possible decay of neutrinos can be detected by an iron calorimeter detector such as INO. For this purpose we have chosen the long baseline neutrinos from a future neutrino factory at CERN.

We have considered the oscillation of such neutrinos with decay. The neutrino flavour and mass eigenstates are connected by the MNS mixing matrix as $|\nu_a\rangle = U_{ai}|\nu_i\rangle$, where $U_{ai}$ are the $3 \times 3$ MNS mixing matrix of the flavour and mass eigenstates of neutrinos. Here, $a \equiv e, \mu, \tau$ (the flavour indices) and $i = 1, 2, 3$, the mass indices. In order to incorporate the effect of any possible decay of the mass eigenstates $|\nu_2\rangle$ and $|\nu_3\rangle$, we fold the matrix elements $U_{ai}$ with exponential decay terms such that $U_{ai} \rightarrow U_{ai} \exp(-4\pi L/\lambda_{d_i})$ for $i = 2, 3$.

The matter effect induced due to the passage of neutrinos through earth matter for traversing the CERN-INO baseline is also taken into account. We have taken an average matter density of 4.14 gm/cc for the purpose. This average density for the particular baseline considered is calculated using PREM [27] earth matter profile.

We have made a three flavour calculation and the oscillation parameters used in the calculations are

$$\Delta m_{32}^2 = |m_3^2 - m_2^2| = 2.21 \times 10^{-3}\text{eV}^2, \quad \Delta m_{21}^2 = |m_2^2 - m_1^2| = 8.1 \times 10^{-5}\text{eV}^2$$
for two mass square differences and

$$\theta_{23} = 45^\circ, \ \theta_{12} = 33.21^\circ, \ \theta_{13} = 9^\circ.$$  

for three mixing angles.

We calculate the variation of total muon yield at INO with the decay constant $\alpha$ for such a decay scenario. In two cases; a) variation with $\alpha_2$ for different fixed values of $\alpha_3$ and b) variation with $\alpha_3$ values for different fixed values of $\alpha_2$. The results are shown in Figs 3 and 4 respectively. From Fig. 3, one sees that decay effect due to $\alpha_2$ is most effective in the region $0.0001 \lesssim \alpha_2 \lesssim 0.001$. From Fig. 3, it is also seen that the total muon yield depletes to even less than half as $\alpha_3$ varies from $10^{-6}$ eV$^2$ to $10^{-2}$ eV$^2$. With $\alpha_3 = m_3/\tau$ eV$^2$ and $m_2 \sim \sqrt{\Delta m_{32}^2} \sim 0.05$ eV, the lifetime $\tau$ can be estimated as $\sim 10^{-14}$ sec. for $\alpha_3 = 10^{-2}$ eV$^2$ and $\sim 10^{-10}$ sec. for $\alpha_3 = 10^{-6}$ eV$^2$. This is consistent with the limits given as in Ref. [6]. Fig. 4 shows similar plots for variation of total muon yield with $\alpha_3$ for three different fixed values of $\alpha_2$. From Figs 2 and 3 it is seen that the decay effect is more sensitive to $\alpha_3$ than $\alpha_2$. Some of the muon yield values are tabulated below for reference.

| $\alpha_2$ (eV$^2$) | $\alpha_3$ (eV$^2$) | Total Muon yield |
|---------------------|---------------------|------------------|
| $10^{-6}$           | $10^{-6}$           | 525326           |
| $10^{-6}$           | $10^{-2}$           | 227087           |
| $10^{-2}$           | $10^{-6}$           | 425453           |

**Table 1.** Muon yield at INO from a neutrino factory beam at CERN for different values of neutrino decay parameters $\alpha_2$ and $\alpha_3$. There can be more than 50% depletion in muon yield at INO due to neutrino decay.

From the range of values of $\alpha_2$ and $\alpha_3$ that produces significant decay effects as demonstrated in this calculation, we make an attempt to verify whether the sum of the masses $m_1 + m_2 + m_3$ for three neutrinos is within the cosmological limit. In doing this we take the range of decay parameter $\alpha$ as $10^{-6} \leq \alpha_{2,3} \leq 10^{-2}$. We have

$$R = \frac{\alpha_2}{\alpha_1} = \frac{m_2/\tau}{m_3/\tau} = \frac{m_2}{m_3}$$  \hspace{1cm} (5)

$$m_3 = \sqrt{\frac{\Delta m_{32}^2}{1 - R^2}}$$  \hspace{1cm} (6)

$$m_2 = \sqrt{m_3^2 - \Delta m_{32}^2}$$  \hspace{1cm} (7)
\[ m_1 = \sqrt{m_2^2 - \Delta m_{21}^2} \]  \hspace{1cm} (8)
\[ M = m_1 + m_2 + m_3 \]  \hspace{1cm} (9)

Eqs. (5 - 9) is evaluated for normal hierarchy only. Using Eqs. (5 - 9) we compute M and found that within the ranges of \( \alpha \) considered above M is always less than the cosmological bound of 0.7 eV.

In summary, we have investigated possible decay of light neutrinos in a long baseline experiment for a neutrino beam from CERN neutrino factory to ICAL detector proposed for INO covering a baseline length of 7152 Km. A unique facility of ICAL detector, the charge identification, has opened up the possibility of such study. A significant depletion of neutrino flux caused by the neutrino decay can be observed in the form of depleted muon signal at INO for a reasonable choice of decay parameters \( \alpha_2, \alpha_3 \) and other neutrino oscillation parameter inputs from atmospheric and solar neutrino experiments.

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Figure Captions

Fig 1. The $\nu_\mu$ flux from a neutrino factory vs different $\nu_\mu$ energies ($E_{\nu_\mu}$) for initial muon energy $E_\mu = 50$ GeV. See text for details.

Fig. 2 The $\bar{\nu}_e$ flux from a neutrino factory vs different $\bar{\nu}_e$ energies ($E_{\bar{\nu}_e}$) for initial muon energy $E_\mu = 50$ GeV. See text for details.

Fig. 3 The variation of total muon yield at INO with decay parameter $\alpha_2$ for three different fixed values of decay parameter $\alpha_3$.

Fig. 4 The variation of total muon yield at INO with decay parameter $\alpha_3$ for three different fixed values of decay parameter $\alpha_2$. 