# The impact of neutrino decay on medium-baseline reactor neutrino oscillation experiments

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## Abstract

In this work we use the fact that JUNO has the best opportunity to put the most stringent constraint on $\nu_3$ lifetime over other experiments which utilize artficial neutrinos source. If there is a neutrino decay into invisible states, we find, by studying the $\chi^2$ function that $\nu_3$ decay lifetime can be constrained to $\tau_3/m_3 \geq 7.5\,(5.5) \times 10^{-11}\, s/\mathrm{eV}$ at 95% (99%) C.L by JUNO by 100kt.years of exposure. We also discuss the effect of $\nu_3$ decay on the determination of neutrino mass ordering as well as the precision of oscillation parameters to be measured by JUNO.


## INTRODUCTION

Nowadays there are bounds on the lifetime of $\nu_2$ and $\nu_1$ [1–6], however the state of the art of neutrino decay shows us there is not a strong constraint on $\nu_3$ decay by using either astrophysical or supernova neutrinos. In order to constraint the lifetime of $\nu_3$, perhaps, the best method is to use the neutrino oscillation phenomenon because is possible to research by choosing a specific flavor oscillation or energy scale where this quantum phenomenon is most sensitive to $\nu_3$ [7, 8]. We assume a $\nu_3$ decay into invisible final states and in order to constraint the lifetime neutrino decay, we analyze the deformation of the expected event distribution curves which data will be collected, in the future, through medium baseline neutrino reactor as JUNO [9] and RENO-50 [10]. We argue that JUNO could get the best bound on $\nu_3$ because it is the unique artificial neutrino source which can measure the atmospheric-scale neutrino oscillation at the baseline around the solar-scale oscillation *a detailed picture can be found in Ref* [11], this means a severer bound on lifetime by a factor of $\Delta m^2_{13}/\Delta m^2_{12} \approx 30$. Also in this work we study the possibility of a confuse measure of the mass ordering as well as lost of sensitivity to constraint the mixing parameters by JUNO due to the $\nu_3$ decay effect.

## THE OSCILLATION PROBABILITY

The neutrino decay effect changes the survival probability oscillation which now can be written as:

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - c_{13}^4 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) - \\ s_{13}^4\left(1 - e^{-\Gamma_3 L}\right) - \frac{1}{2}\sin^2 2\theta_{13}\left[1 - \cos\left(\frac{\Delta m^2_{\mathrm{atm}} L}{2E}\right) e^{-\frac{\Gamma_3 L}{2}}\right], \tag{1}$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$, *for derivation see appendix A in* [11]. As we can see in eq (1) there is an attenuation on the oscillation amplitude due to the term $e^{-\frac{\Gamma_3 L}{2}}$ which affect the atmospheric scale. Also there is a decrease of the probability introduced by the factor $(1 - e^{-\Gamma_3 L})$.

As the oscillation probability is directly related to the expected events distribution, therefore there are effects through $\nu_3$ decay that must be disscused. The first impact is that neutrino decay smooth out the small waves which are related to the atmospheric-scale, however, this effect could be mimic by a reduction on $\theta_{13}$. Fortunately, this misunderstand is avoid with a precision measurement of $\theta_{13}$ by short baseline reactor neutrino experiments [12]. The reduction of the oscillation amplitude also can be due to a low energy resolution of the experiment, however, 3% of energy resolution will be reached by JUNO and RENO-50 [13]. We also want to study how much the $\nu_3$ decay could confuse the determination of the mass ordering by JUNO and how much the sensitivity to the mixing parameters is affected by $\nu_3$ decay. We are going to answer these two important questions at the end of this work.

## ANALYSIS METHOD

In this work we need to built the $\chi^2$ fuction as $\chi^2 = \chi^2_{\text{stat}} + \chi^2_{\text{param}} + \chi^2_{\text{sys}}$ [14, 15], each term is defined as:

$$\chi^2_{\text{stat}} \equiv \int_0^{E_{\text{vis}}^{\text{max}}} dE_{\text{vis}} \left( \frac{\dfrac{dN^{\text{obs}}}{dE_{\text{vis}}} - \displaystyle\sum_{i=\text{reac, U, Th}} (1+\xi_i) \frac{dN_i^{\text{fit}}}{dE_{\text{vis}}}}{\sqrt{\dfrac{dN^{\text{obs}}}{dE_{\text{vis}}}}} \right)^2 , \tag{2}$$

where $dN^{\text{obs}}/dE_{\text{vis}}$ is the event distribution of the signal that we have simulated and denoted as: “observed”, $\xi_i$ is the parameter that normalizes the flux of the reactor neutrinos. The second term is defined as: $\chi^2_{\text{param}} \equiv \sum_{i=1}^{4} \left( \frac{\bar{x}_i - x_i^{\text{fit}}}{\sigma(x_i)} \right)^2$, where $\bar{x}_i$ represents the inputs and $x_i^{\text{fit}}$ are the fitted values, each index denote the mixing parameters where $x_1 \equiv \sin^2\theta_{12}$, $x_2 \equiv \Delta m^2_{21}$, $x_3 \equiv \sin^2\theta_{13}$, $x_4 \equiv \Delta m^2_{31}$. For the values of $\sigma(x_i)$ we have used the current uncertainty in [16]. The third term is defined as: $\chi^2_{\text{sys}} \equiv \left(\frac{\xi^{\text{fit}}_{\text{reac}}}{\sigma_{\xi_{\text{reac}}}}\right)^2 + \left(\frac{\xi^{\text{fit}}_{\text{U}}}{\sigma_{\xi_{\text{U}}}}\right)^2 + \left(\frac{\xi^{\text{fit}}_{\text{Th}}}{\sigma_{\xi_{\text{Th}}}}\right)^2 + \left(\frac{\eta^{\text{fit}}}{\sigma_\eta}\right)^2$ where $\sigma_{\xi_{\text{reac}}} = 3\%$ for reactor neutrinos following [17], and the other uncertainties are $\sigma_{\xi_{\text{U}}} = \sigma_{\xi_{\text{Th}}} = 20\%$ for geoneutrinos [15]. We also include the uncertainty of the energy resolution by using a pull term with $\sigma_{\xi_\eta} = 10\%$. With respect to the energy resolution we have used the stochastic term $\sigma_E/E = 0.03(1+\eta)/\sqrt{E/\text{MeV}}$. The bound on the decay timelife by

JUNO is shown in the FIG 1, we can see that after 5 (15) years of data taking the constraint is $\tau_3/m_3 \geq 5.5\,(8.5) \times 10^{-11}\,\text{s/eV}$ at 99% C.L.

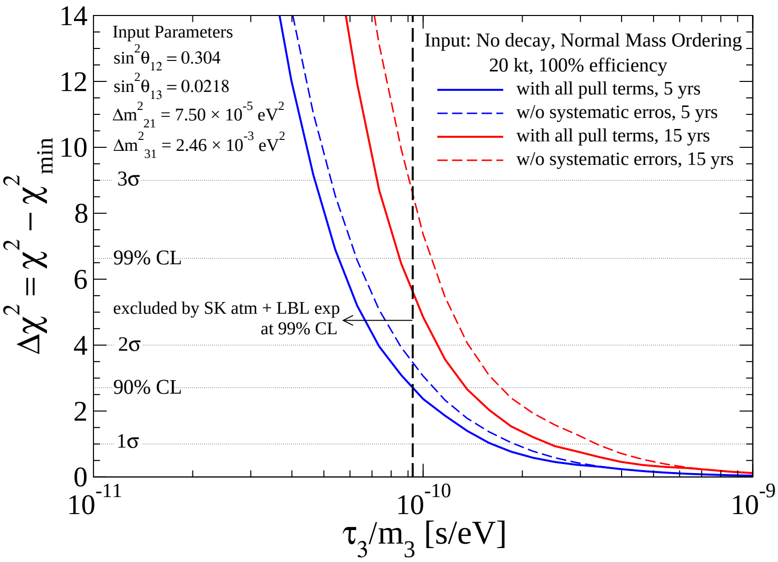


FIG. 1. $\Delta\chi^2 \equiv \chi^2 - \chi^2_{\rm min}$ is shown by the red (blue) curves for 5 (15) years of data taking, as a function of the fitted value of $\tau_3/m_3$ calculated for the JUNO detector placed at $L = 52.5$ km from a reactor with 35.8 GW thermal power, assuming 5 years of exposure and 100% detection efficiency. We have taken that the true (input) value of $\tau_3/m_3$ is infinite (stable $\nu_3$). The solid curves correspond to the results obtained by using our full $\chi^2$ whereas the dashed ones correspond to the case without assuming systematic errors. The contributions from the reactors at Daya Bay and Huizhou as well as those from geoneutrinos are taken into account. The bound comes from the SK atmospheric neutrinos plus long-baseline oscillation experiment obtained is indicated by the vertical black dashed line.

## SUMMARY AND REMARKS

- We found that the bound on the decay lifetime of the massive neutrino state $\nu_3$ is $\tau_3/m_3 \geq 7.5\,(5.5) \times 10^{-11}\,\text{s/eV}$ at 95% (99%) C.L can be obtained by JUNO with 5 years of exposure at 100% efficiency. *See figure* 1,

- After 15 years running, the expected bound we found is $\tau_3/m_3 \geq 11\,(8.5) \times 10^{-11}\,\text{s/eV}$. *See figure* 1,

- After 15 years running JUNO the bound on the decay can be constrained to the level of the current atmospheric neutrinos experiment. *See* [7],

- There is an impact of the decay on the mass ordering determination by a reduction of $\Delta\chi^2$ in five units, but only in the case where the decay is allowed in both the input and the fit. *For details see* [11],
- Regarding to the impact of the decay on the determination of the oscillation parameters by JUNO, we found there is a small effect of the decay. However for $\Delta m^2_{31}$ when the decay effect is allowed in both the input and the fit the uncertainty of $\Delta m^2_{31}$ would be 30% larger. *For details see* [11].

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