Physics Letters B 740 (2015) 345–352

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Constraints on neutrino decay lifetime using long-baseline charged and neutral current data

R.A. Gomes [a,b,*], A.L.G. Gomes [a], O.L.G. Peres [c,d]

[a] Instituto de Física, Universidade Federal de Goiás, 74001-970, Goiânia, GO, Brazil
[b] Argonne National Laboratory, 60439, Argonne, IL, USA
[c] Instituto de Física Gleb Wataghin, Universidade Estadual de Campinas, 13083-859, Campinas, SP, Brazil
[d] Abdus Salam International Centre for Theoretical Physics, ICTP, I-34010, Trieste, Italy

ARTICLE INFO

Article history:
Received 2 October 2014
Received in revised form 4 December 2014
Accepted 5 December 2014
Available online 12 December 2014
Editor: A. Ringwald

Keywords:
Neutrino
Neutrino decay
Neutrino oscillation

ABSTRACT

We investigate the status of a scenario involving oscillations and decay for charged and neutral current data from the MINOS and T2K experiments. We first present an analysis of charged current neutrino and anti-neutrino data from MINOS in the framework of oscillation with decay and obtain a best fit for non-zero decay parameter α_3. The MINOS charged and neutral current data analysis results in the best fit for $|\Delta m^2_{32}| = 2.34 \times 10^{-3}$ eV^2, $\sin^2\theta_{23} = 0.60$ and zero decay parameter, which corresponds to the limit for standard oscillations. Our combined MINOS and T2K analysis reports a constraint at the 90% confidence level for the neutrino decay lifetime $\tau_3/m_3 > 2.8 \times 10^{-12}$ s/eV. This is the best limit based only on accelerator produced neutrinos.

1. Introduction

Recent results from reactor experiments, Double Chooz [1], Daya Bay [2] and Reno [3], complete the picture that three active neutrinos oscillate with two known non-zero mass differences ($\Delta m^2_{21} \equiv m^2_2 - m^2_1$ and $\Delta m^2_{31} \equiv m^2_3 - m^2_1$), three mixing angles ($\theta_{12}$, θ_{23} and θ_{13}) and an unknown CP phase (δ) [4,5]. For a detailed description of neutrino oscillations, see Ref. [6].

In this picture the large statistics of atmospheric neutrinos of the Super-Kamiokande [7] and IceCube [8] experiments show us that the deficit in the muon events can be understood as the result of oscillation $\nu_\mu \to \nu_\tau$. Other experiments also show a strong signal for ν_μ disappearance. MINOS, for instance, fixed very precisely the scale of oscillations at the value $|\Delta m^2_{32}| = (2.41^{+0.09}_{-0.10}) \times 10^{-3}$ eV^2 and $\sin^2 2\theta_{23} = 0.950^{+0.035}_{-0.036}$ [9]. The reactor experiments [1–3] show evidence for electron neutrino disappearance. For instance, the Daya Bay experiment shows a signal for oscillations with a scale of $\Delta m^2_{ee} = (2.59^{+0.19}_{-0.20}) \times 10^{-3}$ eV^2 (the Δm^2_{ee} parameter is the properly averaged quantity between Δm^2_{32} and Δm^2_{31} [10]) and with amplitude of $\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$ [2]. From solar neutrino experiments [6] and the reactor experiment KamLAND [11] there is evidence for (anti-)electron neutrino disappearance. These two signals of oscillations can be explained by $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV^2 and the large mixing angle $\tan^2\theta_{12} = 0.436^{+0.029}_{-0.025}$ [11], which are associated with what is called the Large Mixing Angle (LMA) solution for the solar neutrino anomaly.

Now that it is established that neutrinos are massive, this also implies that they could decay. The idea of neutrino decay is as old as the idea of neutrino masses and mixing. The decays of the neutrino in the Standard Model, $\nu' \to 3\nu$ and $\nu' \to \nu\gamma$, are already too constrained and will not be discussed here (see Ref. [12]). An interesting possibility is the scenario where the neutrino decays into another neutrino and a scalar (or Majoron): $\nu' \to \nu + \phi$ decays, where ϕ can be a scalar or pseudo-scalar massless boson [13,14]. These non-radiative decays are from two types: (I) *invisible decays*, where neutrinos decay into non-observable final states [15–23]; and (II) *visible decays*, where the final products contain active neutrinos [24–31].

We can parametrize the decay by the ratio of the lifetime parameter τ_i and the mass m_i for each of the mass eigenstates $i = 1, 2, 3$. The role of invisible neutrino decay was investigated for the solar neutrino anomaly [15,32,33] and showed no evidence for the dominance of the decay scenario. From these we can constrain values of the decay parameter, $\tau_2/m_2 > 8.7 \times 10^{-5}$ s/eV at 90% C.L., where τ_2 and m_2 are respectively the lifetime and the highest mass eigenstate in a two-generation scenario [15].

* Corresponding author.
E-mail address: ragomes@if.ufg.br (R.A. Gomes).

http://dx.doi.org/10.1016/j.physletb.2014.12.014

In the visible decay scenario, we can search for $\nu_e \to \bar{\nu}_e$ conversion using a pure ν_e source such as the Sun [24]. The null results from the solar $\bar{\nu}_e$ appearance impose a constraint on the decay parameter: $\tau_2/m_2 > 6.7 \times 10^{-2}$ s/eV from the KamLAND experiment [27].

Neutrinos produced in supernovas are interesting to investigate for the presence of decays due to the large distance traveled by the neutrino. From the observation of electron neutrinos from SN1987A [34,35] we should have a lower limit in neutrino lifetime. Otherwise we could not see any signal. For larger values of the mixing angle, such as the current LMA solution for the solar neutrino anomaly, no constraint is possible [36]. Other possibilities for neutrinos coming from a supernova include the neutrino decay catalyzed by a very dense media [25,29] where the matter effects can increase the decay rate of neutrinos. The diffuse supernova neutrinos (neutrinos coming from all past supernova explosions) [17] can provide very robust sensitivity in the range of $\tau/m < 10^{10}$ s/eV [18,19].

Astrophysical neutrino sources megaparsec away can generate all neutrino flavors. Due to the long distance from the sources we are in the limit $L \to \infty$, where all dependence on the lifetime parameter τ_i fades away. However, if we have a precise determination of the ratio of flavors of these neutrinos, we can discriminate the case with or without decay [37–40].

Concerning the accelerator and atmospheric neutrinos we can test the decay scenario of the third generation of neutrino mass eigenstates investigating how the τ_3/m_3 decay parameter changes the $\nu_\mu \to \nu_\mu$ survival probability [20,21]. The MINOS experiment made a search for the decaying neutrino and constrained the lifetime to $\tau_3/m_3 > 2.1 \times 10^{-12}$ s/eV at 90% C.L., using both neutral and charged current events [23]. The combined analysis of Super-Kamiokande atmospheric neutrinos with K2K and MINOS accelerator neutrinos shows a 90% C.L. lower bound value of $\tau_3/m_3 > 2.9 \times 10^{-10}$ s/eV [21].

This article is organized as follows. In Section 2 we discuss our neutrino decay scenario. Next, we introduce the χ^2 analysis developed for the neutrino charged and neutral current data of the MINOS experiment in Section 3. We then present our bounds for the neutrino lifetime based on a charged current analysis (Section 4.1) and on a combined charged and neutral current analysis (Section 4.2) using MINOS data. In Section 4.3 we discuss the sensitivity of the T2K experiment for the neutrino decay scenario and present the constraints on neutrino lifetime for analyses using T2K data only and the combined MINOS and T2K data. Section 5 presents a discussion on the relation of this scenario under Majoron models.

2. Decay model for neutrinos

We are going to introduce the neutrino evolution equation in which the neutrino can decay. This is made by putting an imaginary part related to the neutrino lifetime, which is the ratio $\alpha_3 \equiv m_3/\tau_3$, in the evolution equation. We are going to assume the decay of the heaviest state, $\nu_3 \to \nu_s + \phi$, where both final products are invisible. The two-generation system is considered, which is adequate to describe the muon neutrino and anti-neutrino data from MINOS. The evolution equation is

$$i\frac{d}{dx}\tilde{\nu} = U\left[\frac{\Delta m^2_{32}}{2E}\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} - i\frac{\alpha_3}{2E}\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}\right]U^\dagger\tilde{\nu} \tag{1}$$

where the state $\tilde{\nu} \equiv \binom{\nu_\mu}{\nu_\tau}$, and E is the neutrino energy. U is the usual rotation matrix,

$$U = \begin{pmatrix} c_{23} & s_{23} \\ -s_{23} & c_{23} \end{pmatrix}, \tag{2}$$

where $c_{23} \equiv \cos\theta_{23}$ and $s_{23} \equiv \sin\theta_{23}$. The same evolution equation applies for anti-neutrinos as well.

From Eq. (1) we obtain the muon neutrino survival probability as

$$P(\nu_\mu \to \nu_\mu) = \left[\cos^2\theta_{23} + \sin^2\theta_{23} e^{-\frac{\alpha_3 L}{2E}}\right]^2 - 4\cos^2\theta_{23}\sin^2\theta_{23} e^{-\frac{\alpha_3 L}{2E}} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right) \tag{3}$$

where L is the distance traveled by the neutrinos. We can notice that a non-zero decaying parameter α_3 changes only the amplitudes: the *constant* amplitude (first term of the equation above), and the oscillation amplitude (second term). Both amplitudes are damped but the oscillation phase does not change. In the two-ν standard oscillation probability formula we have the symmetry $\cos^2\theta_{23} \leftrightarrow \sin^2\theta_{23}$, but in Eq. (3) the symmetry is broken, and then we should scan the parameter space of the variable $\sin^2\theta_{23}$ in the range $(0, 1)$. This broken symmetry will appear in our plots later.

The limiting case where the oscillations are induced only by decay, $\Delta m^2_{32} \to 0$, can also be tested. In this case the probability assumes the simple form

$$P(\nu_\mu \to \nu_\mu) = \left[\cos^2\theta_{23} + \sin^2\theta_{23} e^{-\frac{\alpha_3 L}{2E}}\right]^2 \tag{4}$$

where now we have two free parameters, the mixing amplitude $\sin^2\theta_{23}$ and the decay parameter α_3. Even at this limit we also have an asymmetry between $\sin^2\theta_{23}$ and $\cos^2\theta_{23}$.

In the standard neutrino oscillation scenario, the sum of the probabilities over the active states is equal to unity. Then the spectrum of neutral current (NC) events is not effected by active oscillation, which means that the expected number of NC events is the same with or without oscillations. But in the extended scenario involving sterile neutrinos the sum of probabilities, $\sum_\beta P(\nu_\mu \to \nu_\beta)$, where $\beta = \mu, \tau$, obviously does not sum up to 1. This is discussed in the general context of non-unitary neutrino evolution in Ref. [41].

We can compute the conversion probability for the two-ν oscillations with decay scenario,

$$P(\nu_\mu \to \nu_\tau) = \cos^2\theta_{23}\sin^2\theta_{23}\left[1 - e^{-\frac{\alpha_3 L}{2E}}\right]^2 + 4\cos^2\theta_{23}\sin^2\theta_{23} e^{-\frac{\alpha_3 L}{2E}} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right), \tag{5}$$

which implies that

$$\sum_{\beta=\mu,\tau} P(\nu_\mu \to \nu_\beta) = \cos^2\theta_{23} + \sin^2\theta_{23} e^{-\frac{\alpha_3 L}{E}}. \tag{6}$$

Thus, from Eq. (6) we observe that there will be an effect on the neutral current interaction events under the oscillations with decay model.

3. Analysis of MINOS charged and neutral current data

We have performed a combined analysis using the published data of charged and neutral current MINOS analyses. MINOS is a long-baseline neutrino experiment [42] using two detectors and exposed to a neutrino beam produced at Fermilab. The NuMI beam line is a two-horn-focused neutrino beam that can be configured to produce muon neutrinos or anti-neutrinos. The Near Detector is located at Fermilab, around 1 km from the NuMI target and the Far Detector is 735 km far from the target.

The first data set used in our analysis comprises the charged current (CC) contained-vertex neutrino disappearance data [9] using the ν_μ enhanced beam with exposure of 10.71×10^{20} protons on target (POT), with 23 points of non-equally divided bins