Constraints on neutrino decay lifetime using MINOS charged and neutral current data

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Abstract

We investigate the status of a scenario involving oscillations and decay for charged and neutral current data from the MINOS experiment. We first present an analysis of charged current neutrino and anti-neutrino data in the framework of oscillation with decay and obtain a best fit for non-zero decay parameter $\tau_3$. The combined charged and neutral current data analysis results in the best fit for $|\Delta m^2_{23}| = 2.35 \times 10^{-3}$ eV$^2$, $\sin^2 2\theta_{23} = 0.60$ and zero decay parameter, which corresponds to the limit for standard oscillations. Our analysis reports a constraint at the 90\% confidence level for the neutrino decay lifetime $\tau_3/m_3 > 5.7 \times 10^{-12}$ s/eV. This is the best limit based only on accelerator produced neutrinos.

Keywords: neutrino, neutrino decay, neutrino oscillation

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1. Introduction

Recent results from reactor experiments, Double Chooz \textsuperscript{[1]}, Daya Bay \textsuperscript{[2]} and Reno \textsuperscript{[3]}, complete the picture that three active neutrinos oscillate with two known non-zero mass differences ($\Delta m^2_{21} \equiv m_2^2 - m_1^2$ and $\Delta m^2_{31} \equiv m_3^2 - m_1^2$), three mixing angles ($\theta_{12}$, $\theta_{23}$ and $\theta_{13}$) and an unknown CP phase ($\delta$) \textsuperscript{[4, 5]}. For a detailed description of neutrino oscillations see Ref. \textsuperscript{[6]}.

In this paper we discuss the large statistics of atmospheric neutrinos of the Super-Kamiokande \textsuperscript{[7]} and IceCube \textsuperscript{[8]} experiments show us that the deficit in the muon events can be understood as the result of oscillation $\nu_\mu \rightarrow \nu_e$. Other experiments also show a strong signal for $\nu_e$ disappearance. MINOS, for instance, fixed very precisely the scale of oscillations at the value $|\Delta m^2_{23}| = (2.41^{+0.06}_{-0.16}) \times 10^{-3}$ eV$^2$ and $\sin^2 2\theta_{23} = 0.950^{+0.035}_{-0.036}$ \textsuperscript{[9]}. The reactor experiments \textsuperscript{[1, 3]} show evidence for electron neutrino disappearance. For instance, the Daya Bay experiment show a signal for oscillations with a scale of $\Delta m^2_{ee} = (2.59^{+0.16}_{-0.20}) \times 10^{-3}$ eV$^2$ (the $\Delta m^2_{ee}$ parameter is the properly averaged quantity between $\Delta m^2_{32}$ and $\Delta m^2_{21}$ \textsuperscript{[10]}) and with amplitude of $\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$ \textsuperscript{[2]}. From solar neutrino experiments \textsuperscript{[5, 6]} and the reactor experiment KamLAND \textsuperscript{[11]} there is evidence for (anti-)electron neutrino disappearance. These two signals of oscillations can be explained by $\Delta m^2_{32} = (7.53 \pm 0.18) \times 10^{-5}$ eV$^2$ and the large mixing angle $\tan^2 \theta_{13} = 0.436^{+0.029}_{-0.025}$ \textsuperscript{[11]}, which are associated to 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 $\nu' \rightarrow 3\nu$ and $\nu' \rightarrow \nu\gamma$ are already too constrained and will not be discussed here (see Ref. \textsuperscript{[12]}). An interesting possibility is the scenario where the neutrino decays into another neutrino and a scalar (or Majoron): $\nu' \rightarrow \nu + X$ decays \textsuperscript{[13, 14]}. These non-radiative decays are from two types: (I) invisible decays, where neutrinos decay into non-observable final states \textsuperscript{[15–23]}, and (II) visible decays, where the final products contain active neutrinos \textsuperscript{[24–31]}.

We can parametrize the decay by the ratio of the lifetime parameter $\tau_3$ and the mass $m_3$ for each of the mass eigenstates $i = 1, 2, 3$. The role of invisible neutrino decay was investigated for the solar neutrino anomaly \textsuperscript{[15–32]} 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 $\tau_2$ and $m_2$ are respectively the lifetime and the highest mass eigenstate in a two generation scenario \textsuperscript{[15]}. In the visible decay scenario, we can search for $\nu_e \rightarrow \bar{\nu}_e$ conversion using a pure $\nu_e$ source such as the Sun \textsuperscript{[24]}. The null results from the solar $\nu_e$ appearance impose a constrain on the decay parameter: $\tau_2/m_2 > 6.7 \times 10^{-2}$ s/eV from the KamLAND experiment \textsuperscript{[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 \textsuperscript{[24, 25]} 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 \textsuperscript{[33]}. Other possibilities for neutrinos coming from a supernova include the neutrino decay catalyzed by a very dense media \textsuperscript{[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 $L \rightarrow \infty$, where all dependence on the lifetime parameter $\tau$, fades away. However, if we have a precise determination of the ratio of flavors of these neutrinos we can discriminate the case with and 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 $\tau_3/m_3$ decay parameter changes the $\nu_\mu \rightarrow \nu_\mu$ survival probability \[20\] \[21\]. The MINOS experiment made a search for the decaying neutrino and constrained the lifetime $\tau_3/m_3 > 2.1 \times 10^{-12}$ 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 show 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 $\nu_\mu$-decay 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) and on a combined charged and neutral current analysis (Section 5), comparing with previous limits.

### 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, $\nu_3 \rightarrow \nu_i + \phi$, 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

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

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

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

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

$$
P(\nu_\mu \rightarrow \nu_\mu) = \left[ \cos^2 \theta_{23} + \sin^2 \theta_{23} e^{-\frac{i\alpha_3 L}{E}} \right]^2 \quad (3)
$$

$$
- 4 \cos^2 \theta_{23} \sin^2 \theta_{23} e^{-\frac{i\alpha_3 L}{E}} \sin^2 \left( \frac{\Delta m_{32}^2 L}{4E} \right)
$$

where $L$ is the distance traveled by the neutrinos. You can notice that a non-zero decaying parameter $\alpha_3$ 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-\nu standard oscillation probability formula we have the symmetry $\cos^2 \theta_{23} \equiv \sin^2 \theta_{23}$, 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, $\Delta m_{32}^2 \rightarrow 0$, can also be tested. In this case the probability assumes the simple form

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

where now we have two free parameters, the mixing amplitude $\sin^2 \theta_{23}$ and the decay parameter $\alpha_3$. 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, $\sum_\beta P(\nu_\mu \rightarrow \nu_\beta)$, 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-\nu oscillations with decay scenario,

$$
P(\nu_\mu \rightarrow \nu_\tau) = \cos^2 \theta_{23} \sin^2 \theta_{23} \left[ 1 - e^{-\frac{i\alpha_3 L}{E}} \right]^2 + 4 \cos^2 \theta_{23} \sin^2 \theta_{23} e^{-\frac{i\alpha_3 L}{E}} \sin^2 \left( \frac{\Delta m_{32}^2 L}{4E} \right)
$$

which implies that

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

Thus, from the 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 \[22\] 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 NuMI target and the Far Detector is 735 km far from the target. 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 $Q_E$ enhanced beam with exposure of $10.71 \times 10^{20}$ protons on target (POT), with 23 points of non-equally divided bins
of energy up to 14 GeV; the second is the CC contained-vertex anti-neutrino disappearance data \[ \nu \bar{\nu} \] from the \( \nu_e \) enhanced beam with 3.36 \times 10^{20} \text{ POT}, using 12 points for energies up to 14 GeV as well; and the third is the neutral current data \[ N_i \] based on 7.07 \times 10^{20} \text{ POT}. The spectrum of NC events is described as a function of a reconstructed energy, \( E_{\text{reco}} \). We then use the information from a previous MINOS analysis \[ 23 \] to separate the NC data into two bins: (a) events with \( E_{\text{reco}} < 3.0 \) GeV and (b) events with \( 3.0 < E_{\text{reco}} < 20.0 \) GeV, which have median neutrino energies of 3.1 and 7.9 GeV, respectively.

For the \( \chi^2 \) calculation we use the following function

\[
\chi^2 = \sum_i \frac{(N_i^b - N_i^{\text{data}})^2}{\sigma_i^2}
\]

in bins of energy, where \( N_i^b = N_i^{\text{mod}} + \beta N_i^{\text{bg}} \) is the prediction for the theoretical model \( (N_i^{\text{mod}}) \) that we are using (e.g. oscillation plus decay scenario), based on the no-oscillation events \( (N_i^{\text{no-osc}}) \), and including the background contribution \( (N_i^{\text{bg}}) \) adjustable by a parameter \( \beta \). \( N_i^{\text{data}} \) is the data from one of the MINOS analyses and \( \sigma_i \) is the total error. The background events of the NC data set come from misidentified CC events. The numbers \( N_i^{\text{data}} \), \( N_i^{\text{bg}} \) and \( N_i^{\text{no-osc}} \) were read off from References \[ 9 \] and \[ 44 \].

The total error used for both neutrino and anti-neutrino CC data sets is given by

\[
\sigma_i = (\sigma_i^{\text{data}})^2 + (\sigma_i^{\text{stat}})^2 + (\sigma_i^{\text{syst}})^2
\]

where \( \sigma_i^{\text{data}} \) is the total error of the data, \( \sigma_i^{\text{stat}} \) and \( \sigma_i^{\text{syst}} \) are the statistical and systematic error of the prediction, respectively. We have \( \sigma_i^{\text{data}} = \sqrt{\sigma_i^2} = \sqrt{\ mockery error bar from the data, \( \sigma_i^{\text{stat}} = \sqrt{N_i^b} \) and \( \sigma_i^{\text{syst}} = 0.04 N_i^b \). For the NC data set we do not have the total error of the data events. We then calculate it summing in quadrature the statistical and systematic errors. The former is the square root of the number of data events, and the latter is an estimate based on the systematic error of the extracted expectation of events.

We scan the parameter region in the variables \( \tau_3/m_3, \sin^2 \theta_{23} \) and \( \Delta m^2_{32} \) and for the \( \beta \) parameter of our function \( \chi^2 = \chi^2(\tau_3/m_3, \sin^2 \theta_{23}, \Delta m^2_{32}, \beta) \). The \( \chi^2 \) is then marginalized over the nuisance \( \beta \) parameter to obtain the effective \( \chi^2_{\text{eff}} \) as a function of the other parameters

\[
\chi^2_{\text{eff}}(\tau_3/m_3, s_{23}^2, \Delta m^2_{32}) = \chi^2(\tau_3/m_3, s_{23}^2, \Delta m^2_{32}, \beta)|_{\beta=\text{min}}
\]

To have a guess about the range of the decay parameter we can probe, we will assume the argument of the exponential term in Eq. \[ 7 \] is of the order of unity, where we can get the most sensitivity. Using the MINOS distance and the energy range of \( E_{\nu} = (0.5, 10) \) GeV, we get \( \tau_3/m_3 \sim 10^{-13} - 10^{-11} \) s/eV.

4. Results of the Charged Current Analysis

To test the correctness of our \( \chi^2 \) analysis, we first consider the standard oscillation scenario, corresponding to the limit \( \alpha_3 \to 0 \) in Eq. \[ 1 \]. The results shown here are from neutrino and anti-neutrino charged current data obtained from Ref. \[ 9 \]. However, we also used our calculation on the neutrino charged current data from Ref. \[ 44 \]. For both data sets we obtain good concordance with the MINOS allowed region and best fit.

In Table \[ 1 \] we show the consistency between the best fit parameters obtained by our standard oscillation analysis (accelerator data only) and MINOS \[ 9 \] (which includes accelerator and atmospheric data). We obtain that the best fit of the oscillation parameters is for non-maximal mixing angle, \( \sin^2 2\theta_{23} = 0.92 \) and for \( |\Delta m^2_{32}| = 2.38 \times 10^{-3} \) eV\(^2\). The \( \chi^2 \) of the best fit point is 19.80 for 31 degrees of freedom, which corresponds to a G.O.F. (Goodness of Fit) of 94.0%. The \( \Delta \chi^2 \) for the no-oscillation hypothesis compared to the standard oscillation scenario,

\[
\Delta \chi^2 \equiv \chi^2_{\text{no-oscillation}} - \chi^2_{\text{standard-oscillation}}
\]

is equal to 304.9, which means that we can exclude the no-oscillation hypothesis with remarkable precision.

The allowed regions in the \( (\sin^2 2\theta_{23} - \Delta m^2_{32}) \) plane for neutrinos and anti-neutrinos under the standard oscillations model is shown in Fig. \[ 1 \]. The anti-neutrino data is compatible with the neutrino data but does not contribute significantly to improve the region of parameters in the combined CC analysis due to its small statistics compared to the neutrino one. Our results show that we are able to reproduce the allowed regions of square mass difference and mixing angle of the MINOS analyses.

Having confirmed the correctness of the analysis, we use it to test the oscillation with decay scenario. The procedure is the same as in the standard oscillation case, but now we have three free parameters, \( \Delta m^2_{32}, \sin^2 2\theta_{23} \) and \( \tau_3/m_3 \). For the combined (neutrino and anti-neutrino) CC analysis under the oscillation with decay framework we find a finite value for the best fit of
The e- also considered in our CC analysis resulting in a G.O.F. of 93.4%. The pure decay hypothesis is standard deviation level. The one-dimensional projection for the τ/3m3 (see Table 1),

\[ \tau_3/m_3 = 1.2 \times 10^{-11} \text{ s/eV}. \]  

(9)

The effect of a finite value of τ/3m3 results in a slightly lower value of Δm^2_{32} than the one obtained for standard oscillation. The χ^2 obtained is 19.28 for 30 degrees of freedom, which corresponds to a G.O.F. of 93.4%. The pure decay hypothesis is also considered in our CC analysis resulting in a χ^2 of 51.18 for 31 degrees of freedom, excluding this hypothesis at the 5.6 standard deviation level.

The projections of Δχ^2 for each parameter are obtained minimizing the function \( \chi^2 = \chi^2(\tau_3/m_3, \sin^2 \theta_{23}, \Delta m^2_{32}, \beta) \) accordingly to the parameters. We then use the function \( \Delta \chi^2 \equiv \chi^2 - \chi^2_{\text{min}} \), where \( \chi^2_{\text{min}} \) is the global minimum value for the oscillation with decay scenario. Next, we present the projections of Δχ^2 as a function of \( \tau_3/m_3, \Delta m^2_{32} \) and \( \sin^2 \theta_{23} \).

The one-dimensional projection for the \( \tau_3/m_3 \) parameter, shown in Fig. 2 (dashed curve), allows us to get a lower bound on \( \tau_3/m_3 \) or equivalently an upper bound on \( m_3 \). The allowed values for the neutrino decay lifetime is

\[ \tau_3/m_3 > 2.0 \times 10^{-12} \text{ s/eV} \]  

(10)

at the 90% C.L. (Table 1). We can compare the value we obtain for the oscillation with decay model to the one from MINOS [23], which used both charged and neutral current data in their analysis, but with lower statistics than the extracted data used here. We see that our combined CC result does not improve the MINOS lower limit which is τ/3m3 > 2.1 × 10^{-12} s/eV.

An interesting behavior appears in Fig. 3 (left), where we compare the allowed values for Δm^2_{32} with and without decay. When we include a finite value for the τ/3m3 parameter, smaller values of Δm^2_{32} are allowed for a certain confidence level. Then, under this scenario, we can explain the muon disappearance signal seen by MINOS as due partially to oscillation and partially to decay, since the limit Δm^2_{32} → 0 in Eq. 3 corresponds to the pure decay model.

The broken symmetry, \( \cos^2 \theta_{23} \leftrightarrow \sin^2 \theta_{23} \) mentioned after Eq. 3, is manifested in Fig. 3 (right), where the curve is broader for larger values of \( \sin^2 \theta_{23} \). This effect can be understood investigating the coefficient on the first term of Eq. 3. For \( \sin^2 \theta_{23} > \cos^2 \theta_{23} \) the decay term is more relevant, and for the opposite case the decay contribution is suppressed.

We also present two-dimensional projections of the allowed

| Model | χ^2/d.o.f. | Δm^2_{32} | sin^2 θ_{23} | sin^2 θ_{32} | τ3/m3 | τ3/m3^{90% C.L.} |
|-------|------------|-----------|---------------|---------------|--------|-----------------|
| No oscillation | CC analysis | 324.70/35 | 2.91 | 0.50 | 7.3 × 10^{-13} | > 2.1 × 10^{-12} |
| Standard oscillation | MINOS [23] | 76.4/40 | 0.96 | 0.60 | 1.4 × 10^{-12} | > 2.0 × 10^{-12} |
| | CC analysis | 51.18/31 | 0 | 1.00 | 7.4 × 10^{-13} | > 5.7 × 10^{-12} |
| Pure decay | MINOS [23] | 47.5/39 | 1.00 | 0.50 | ∞ | > 2.1 × 10^{-12} |
| | CC analysis | 19.28/30 | 0.93 | 0.63 | 1.2 × 10^{-11} | > 2.0 × 10^{-12} |
| | CC+NC analysis | 20.52/31 | 0.96 | 0.60 | ∞ | > 5.7 × 10^{-12} |

Figure 2: Projections of Δχ^2 as a function of τ/3m3 for the oscillation with decay model using the charged current analysis (dashed curve) and the combined charged and neutral current analysis (solid curve). The ranges of allowed parameter lie below the horizontal lines at 90%, 2σ and 3σ confidence levels.

Figure 3: Projections of Δχ^2 as a function of Δm^2_{32} (left) and sin^2 θ_{23} (right) for the standard oscillation (dashed curves) and oscillation with decay model for the CC only (dotted curves). The ranges of allowed parameter lie below the horizontal lines at 90%, 2σ and 3σ confidence levels.

Table 1: Comparison between our analyses (CC only and CC plus NC) and two analyses by the MINOS experiment [9, 23] for standard oscillation, pure decay, and oscillation with decay hypotheses. The values for the square mass difference |Δm^2_{32}| and the decay parameter τ3/m3 are in 10^{-3} eV^2 and s/eV, respectively.
three-dimensional region after normalization with respect to the undisplayed parameter. Figure 4 shows the 90% C.L. allowed region in the \((\tau_3/m_3 - \Delta m^2_{32})\) and \((\tau_3/m_3 - \sin^2 \theta_{23})\) planes for the oscillation with decay scenario and our best fit point (CC data only). We can observe that for smaller values of \(\tau_3/m_3\), when the effects of the decay are larger, the contours allow smaller values of \(\Delta m^2_{32}\) and higher values of \(\sin^2 \theta_{23}\) (the same behaviour shown in Fig. 3).

The 90% C.L. allowed regions for the oscillation parameters, \(\Delta m^2_{32}\) and \(\sin^2 \theta_{23}\), is presented in Fig. 5 both with and without decay. In agreement with the information shown in the discussion of Fig. 3 and Fig. 4 we can see that the decay allows a region of smaller values of \(\Delta m^2_{32}\) and larger values of \(\sin^2 \theta_{23}\) than the standard oscillation model.

The best fit points are also shown in Fig. 5 for both models (with and without decay). The standard oscillation analysis obviously shows two possible values of \(\theta_{23}\) due to the symmetry \(\cos^2 \theta_{23} \leftrightarrow \sin^2 \theta_{23}\). Since the oscillation with decay model does not manifest such a symmetry we find that the best fit point for this scenario is in the \(\theta_{23} > 45^\circ\) octant, with a value of \(\sin^2 \theta_{23} = 0.63\).

5. Results of the Combined Charged and Neutral Current Analysis

In this section we present the results obtained for the combined charged and neutral current data. We expect an effect on the neutrino lifetime due to the inclusion of the neutral current data in the analysis as described in Eq. 6. First, we calculate the ratio

\[
R_i = \frac{N^\text{data} - N^\text{bg}}{N^\text{th}},
\]

for each bin of reconstructed energy extracted from the NC data, where \(N^\text{data}\), \(N^\text{bg}\), and \(N^\text{th}\) are the number of data, background and expected events, respectively. The ratios we obtain are in good agreement with the ones from MINOS [23].

Under the oscillation with decay model the best fit point for the combined CC and NC analysis can be found in Table 1. The \(|\Delta m^2_{32}|\) and \(\sin^2 \theta_{23}\) values are consistent with the ones for standard oscillations. We obtain a neutrino lifetime \(\tau_3/m_3 \rightarrow \infty\), which corresponds to the case of no decay. If we compare this result to the best fit of the CC analysis, the decay effect becomes less relevant due to the inclusion of NC data, implying that the best fit value of \(|\Delta m^2_{32}|\) increases (from \(2.30 \times 10^{-3} \text{ eV}^2\) to \(2.35 \times 10^{-3} \text{ eV}^2\)).

The \(\chi^2\) of the best fit for the combined CC and NC analysis is 20.52 for 31 degrees of freedom resulting in a G.O.F. of 92.4%. The pure decay model is also used in our analysis, being excluded at the 8.8 standard deviation level. Our best fit value of \(\tau_3/m_3\) for the pure decay scenario is close to the one from MINOS [23].

The one-dimensional projection for the \(\tau_3/m_3\) parameter in the combined CC and NC analysis is shown in Fig. 2 (solid curve). We find a lower limit of

\[
\tau_3/m_3 > 5.7 \times 10^{-12} \text{ s/eV}
\]

at the 90% C.L., which improves the MINOS [23] limit by a factor of 2.7.

The two-dimensional projections in Fig. 4 show the effect of including the NC data into our analysis. The contours at the 90% C.L. become more symmetric when compared to the contours for CC data only (see also Fig. 5). For lower values of \(\tau_3/m_3\), when the effect of decay is stronger, both the higher values of \(\sin^2 \theta_{23}\) and the lower values of \(|\Delta m^2_{32}|\) are suppressed due to the inclusion of NC data.
We can understand the NC effect by observing that this data set does not suggest evidence for decay \((\tau_3/m_3 \rightarrow \infty)\), differently from the CC analysis where we find a finite value for \(\tau_3/m_3\). Thus, since the decay effect becomes less relevant, the symmetry between \(\cos^2 \theta_{23}\) and \(\sin^2 \theta_{23}\) manifests itself again, resulting in a contour of the oscillation with decay analysis under the combined CC and NC data close to the contour of the standard oscillation scenario.

The extracted MINOS spectrum data for CC neutrinos and anti-neutrinos are shown in Fig. 6. In both plots we also show the curves for the no-oscillation hypothesis, the best fit of standard oscillations, and the background from NC events. In addition, we also show the curves for the oscillation with decay scenario at the best fit for \(\Delta m^2_{32}\) and \(\sin^2 \theta_{23}\) and using the 90% C.L. value of the \(\tau_3/m_3\) parameter for the CC data only \((\tau_3/m_3 = 2.0 \times 10^{-12} \text{s/eV})\) and for the combined CC with NC data \((\tau_3/m_3 = 5.7 \times 10^{-12} \text{s/eV})\). The reason for using the 90% C.L. values of \(\tau_3/m_3\) is that the curves for the best fit parameters show no significant difference if compared to the standard oscillations curve. We can observe that the curve using the higher value of \(\tau_3/m_3\), which corresponds to smaller effect of decay, is closer to the one for standard oscillations. We also observe that the inclusion of the decay scenario into the oscillation model worsens the fit for both neutrino and anti-neutrino analyses.

6. Conclusions

The present scenario of standard neutrino oscillation observed by different experiments shows a strong case for non-zero neutrino masses and mixing. A direct consequence of non-zero neutrino masses is that the neutrino can decay, but usually with much longer lifetimes for decays like \(\nu' \rightarrow 3\nu\) or \(\nu' \rightarrow \nu + \gamma\). The only expectation to observe sizeable effects from neutrino decays is from \(\nu' \rightarrow \nu_i + \phi\), where the decay products are sterile states.

We use the more updated charged and neutral current data of the MINOS experiment for accelerator produced neutrinos and anti-neutrinos to study the impact of a non-zero decay parameter, \(\alpha_3 = m_3/\tau_3\), in the \(\nu_\mu \rightarrow \nu_\mu\) channel. Using the charged current data only we have found that the best fit scenario is for a finite \(\tau_3/m_3\) parameter, corresponding to a neutrino lifetime \(\tau_3/m_3 = 1.2 \times 10^{-11} \text{s/eV}\).

Based on the combined charged and neutral current analysis the best fit for the oscillation with decay model indicates a zero value for the \(\alpha_3\) parameter, that is equivalent to the standard oscillation model. Using the combined analysis we could improve the previous constraint on the allowed neutrino decay lifetime \(\tau_3/m_3 > 5.7 \times 10^{-12} \text{s/eV}\) at the 90% C.L., which is the best limit based only on accelerator produced neutrino data.

We have found that the 90% C.L. range for \(|\Delta m^2_{32}|\) is \((1.95 - 2.54) \times 10^{-3} \text{eV}^2\) and for the mixing angle is \(\sin^2 \theta_{23} = (0.32 - 0.75)\) in the oscillation with decay scenario. We could understand the effect of the non-zero decay parameter for the CC data analysis, implying smaller values of \(\Delta m^2_{32}\) and larger values of \(\sin^2 \theta_{23}\) than the ones in standard oscillation scenario. The inclusion of NC data, which is compatible to standard oscillations, constrains the decay parameter and makes the decay scenario more constrained than in the CC analysis only.

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