Status of Oscillation plus Decay of
Atmospheric and Long-Baseline Neutrinos

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Abstract

We study the interplay of neutrino oscillation and invisible decay in atmospheric and long-baseline neutrinos experiments. We perform a global analysis of the full atmospheric data from Super-Kamiokande together with long-baseline K2K and MINOS in these scenarios. We find that the admixture of $\nu_\mu \rightarrow \nu_\tau$ oscillations with parameters $\Delta m^2_{32} = 2.6 \times 10^{-3} \text{ eV}^2$ and $\theta_{23} \sim 34^\circ$ plus decay of the heavy neutrino, $\nu_3$, with lifetime of the order $\tau_3/m_3 \sim 2.6 \times 10^{-12} \text{ s/eV}$ provides a reasonable fit to atmospheric neutrinos, although this solution becomes more disfavored (dropping to the 99% CL) once long-baseline data are included. Other than this local minimum, the analysis shows no evidence in favor of a non-vanishing neutrino decay width and an lower bound on the decay lifetime $\tau_3/m_3 \geq 9.3 \times 10^{-11} \text{ s/eV}$ is set at 99% CL. In the framework of Majoron models, this constraint can be translated into a bound on the Majoron coupling to $\nu_3$ and an unmixed very light sterile state, $|g_{s3}| \leq 8.6 \times 10^{-3} \text{ (2.2 eV/m}_3)$. 

Key words: neutrino oscillations, neutrino decay, Majoron models

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Neutrino oscillations have entered an era in which the observations from underground experiments obtained with neutrino beams provided to us by Nature
– either from the Sun or from the interactions of cosmic rays in the upper atmosphere – are confirmed and refined by experiments using terrestrial beams from accelerators and nuclear reactors [1].

In particular, with its high statistics data [2] Super-Kamiokande (SK) established beyond doubt that the observed deficit in the \( \mu \)-like atmospheric events is due to \( \nu_\mu \to \nu_\tau \) oscillations, a result also supported by other atmospheric experiments such as MACRO [3] and Soudan-2 [4]. This was further confirmed in terrestrial experiments, first by the KEK to Kamioka long-baseline (LBL) neutrino oscillation experiment (K2K) [5], and currently by the Fermilab to Soudan LBL experiment, MINOS [6]

Mass-induced neutrino oscillations are not the only possible mechanism for \( \nu_\mu \to \nu_\tau \) flavor transitions. They can also be generated by a variety of non-standard neutrino interactions or properties [1]. Prior to the highest-statistics SK data, some of these scenarios could provide a good description – alternative to \( \Delta m^2 \)-induced oscillations – of the atmospheric neutrino phenomenology. In particular, it was early noticed [7] that a scenario of very fast \( \nu_j \to \nu_i \) oscillations plus invisible neutrino decay \( \nu_j \to \nu_i X \) could describe the \( L/E \) dependence (where \( L \) is neutrino flight length and \( E \) its energy) and the up-down asymmetry of the contained events in SK if \( \sin^2 \theta_{ij} \sim 0.87 \) and \( m_j/\tau_i \sim 1 \text{ GeV}/D_E \) (where \( D_E \) is the diameter of the Earth). However, with more precise data, it was shown that the description of the global contained event sample in this scenario was worse than in the case of oscillations. Furthermore for lifetimes favored by the contained event data very little \( \nu_\mu \) conversion is expected for upgoing stopping muons in contradiction with observation. Based on these facts this mechanism was subsequently ruled out in its simpler form [8, 9].

The possibility of atmospheric neutrino decay was revisited in Ref. [10], where the interplay of oscillations and decay where discussed under the assumption that oscillations where suppressed for atmospheric neutrinos, \( \Delta m^2_{ij} < 10^{-4} \text{ eV}^2 \), so that only the mixing plus decay effects were relevant. It was found that a good fit to the contained and upgoing muon atmospheric data at that time could be obtained for \( \tau_i/m_i = 63 \text{ km/GeV} \) and \( \sin^2 \theta_{ij} = 0.30 \). Again, this scenario became disfavored as the statistics accumulated by SK increased. In particular, in Ref. [11] the SK collaboration presented a study of the \( \nu_\mu \) disappearance probability as a function of \( L/E \), finding evidence for a dip in the \( L/E \) distribution – in agreement with the sinusoidal flavor transition probability predicted by mass-induced oscillations. From this they concluded that the mixing plus decay scenario of Ref. [10] provided a worse fit (by about 3.4\( \sigma \)) than the standard oscillation hypothesis to the observed event distribution.

At present, besides the strong bounds from atmospheric data, the observation
of the $\nu_\mu$ energy spectrum both at K2K and MINOS further constrains any $\nu_\mu$ flavor transition mechanism which does not lead to the correct oscillatory behavior. However, this does not exclude that neutrino decay could play a role, even if sub-dominant, in the atmospheric and LBL neutrino phenomenology, and in principle affect our determination of the neutrino parameters. Conversely, if this is not the case, from a joint analysis of oscillations and decay in atmospheric and LBL experiments one can derive a robust bound on the neutrino decay lifetime of the relevant states. In this paper we address these questions by performing a global analysis of the atmospheric and LBL data with $\nu_\mu \rightarrow \nu_\tau$ transitions driven by neutrino masses and mixing and allowing for neutrino decay.

For the sake of concreteness we focus on scenarios with normal mass ordering of the neutrino states, $m_3 \geq m_2 \geq m_1$, in which the heaviest neutrino ($\nu_3$ by convention) decays invisibly. Since $\nu_1$ and $\nu_2$ have large mixing with $\nu_e$, invisible decay of these states is strongly constrained by the non-observation of its effects in solar neutrinos [12–14], $\tau/m \gtrsim 10^{-4}$ s/eV, which makes it completely unobservable in present atmospheric and LBL experiments. Further simplification arises if one assumes that the decay products are outside of the $(\nu_e, \nu_\mu, \nu_\tau)$ neutrino ensemble. Indeed this is required in order for the decay to be fast enough because in this case the mass difference for the decay $\nu_3 \rightarrow \nu_\tau X$, $\Delta m^2_{32}$, may not be directly constrained by oscillation data. This is the case if, for example, $\nu_3$ decays into a fourth much lighter sterile neutrino $\nu_s$ with which none of the active neutrinos mix [10].

With these assumptions, and neglecting the small allowed $\nu_e$ admixture in the oscillation [15], the atmospheric and LBL neutrino evolution equation involves only two neutrino states $\nu^T = (\nu_\mu, \nu_\tau)$. $\nu_3$ decay can be accounted for by introducing an imaginary part in the Hamiltonian which is proportional to the only relevant decay width

$$i \frac{d\nu^T}{dx} = U_{23} \left[ \frac{\Delta m^2_{32}}{4E} \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} - i \frac{m_3}{2 \tau_3 E} \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \right] U_{23}^\dagger \nu^T, \quad (1)$$

where $\tau_3$ is the $\nu_3$ lifetime\footnote{Equation (1) also describes the oscillation plus decay $\nu_3 \rightarrow \nu_\tau X$ even if $\nu_\tau$ has admixtures of $\nu_\mu$ and $\nu_\tau$ provided that its energy is degraded enough so that it does not contribute to the observed event rates.} and $U_{23}$ is the rotation matrix of mixing angle $\theta_{23}$.

Solving Eq. (1) one gets the survival probability of $\nu_\mu$:

$$P_{\mu\mu} = \cos^4 \theta_{23} + \sin^4 \theta_{23} e^{-\frac{m_3 L}{\tau_3 E}} + 2 \sin^2 \theta_{23} \cos^2 \theta_{23} e^{-\frac{m_3 L}{\tau_3 E}} \cos \left( \frac{\Delta m^2_{32} L}{2E} \right). \quad (2)$$

Equation (2) contains as limiting cases the scenarios explored in Refs. [7,
10] (up to a relabeling $\nu_2 \leftrightarrow \nu_3$, or, equivalently, $\sin \theta_{23} \leftrightarrow \cos \theta_{23}$). If one assumes that $\Delta m_{3i}^2 \gg E/L$ the oscillating term in Eq. (2) averages to zero and $P_{\mu\mu} = \cos^4 \theta_{23} + \sin^4 \theta_{23} e^{-m_3^2 L / 4 \tau_3}$. This was the decay model proposed in Ref. [7]. In the alternative scenario of Ref. [10] $\nu_3$ decays into a sterile state $\nu_j$ with which it does not mix. In this case the mass difference relevant for oscillations is unrelated to the mass difference between the decaying and the daughter neutrino states so one could have fast decays even if $\Delta m_{32}^2$ was very small. In that limit $P_{\mu\mu} = (\cos^2 \theta_{23} + \sin^2 \theta_{23} e^{-m_3 L / 4 \tau_3})^2$. As mentioned above both these limiting cases are now excluded.

In this work we have performed a global analysis of atmospheric and long-baseline neutrino data in the general framework of oscillation plus decay, as described by Eq. (2), leaving free the three parameters $\Delta m_{32}^2$, $\theta_{23}$ and $\tau_3 / m_3$. We have included all the SK-I and SK-II data as well as the latest K2K and MINOS results. Concerning the analysis of atmospheric data, an extensive description with all the technical details of our calculations can be found in the Appendix of Ref. [1]. As for MINOS, we convolve the unoscillated event spectrum given as a function of the true neutrino energy (which we take from Refs. [16, 17]) with the $P_{\mu\mu}$ survival probability, and with a Gaussian smearing function to properly account for the finite energy resolution of the detector. In this way we calculate the charged-current event rates, which we add to the neutral-current background (also taken from Ref. [17]) to obtain the theoretical prediction for each energy bin. As can be seen by comparing our event distribution for pure oscillations (lower panel of Fig. 2) with the corresponding one from MINOS [17], our calculations show good agreement with the MINOS Monte Carlo. The theoretical predictions are then fitted against the experimental results, assuming a Poisson distribution with a total systematic uncertainty of 4%.

Our results are summarized Fig. 1 where we show different projections of the allowed three-dimensional parameter space after marginalization with respect to the undisplayed parameter. The hollow regions in the two lower panels show the allowed domains at 90%, 95%, 99% and 3$\sigma$ CL from the analysis of the atmospheric neutrino data alone; inclusion of the LBL experiments lead to the full regions. The corresponding one-dimensional projections of the $\Delta \chi^2$ functions are shown in the three upper panels. From the figure we see that the best fit in this general oscillation plus decay scenario corresponds to pure oscillations with

$$\Delta m_{32}^2 = 2.4 \times 10^{-3} \text{ eV}^2, \quad \theta = 45^\circ, \quad \tau_3 / m_3 \gg 10^{-8} \text{ s/eV}. \quad (3)$$

However, the figure also shows that a reasonable fit to atmospheric neutrino data is still possible in a oscillation plus decay scenario with

$$\Delta m_{32}^2 = 2.6 \times 10^{-3} \text{ eV}^2, \quad \theta = 34^\circ, \quad \tau_3 / m_3 = 2.6 \times 10^{-12} \text{ s/eV}. \quad (4)$$
Fig. 1. Allowed regions from the analysis of atmospheric and LBL in presence of $\nu_\mu \rightarrow \nu_\tau$ oscillations plus $\nu_3$ decay. The three upper panels show the dependence of $\Delta \chi^2$ on the parameters from the analysis of atmospheric only (dashed) and atmospheric+LBL (full line). The two lower panels show the two-dimensional projection of the allowed three-dimensional region after marginalization with respect to the undisplayed parameter. The different contours correspond to the two-dimensional allowed regions at 90%, 95%, 99% and $3\sigma$ CL. The lines (full regions) correspond to the atmospheric (atmospheric+LBL) analysis.

This solution is well within the 90% CL regions for the analysis of atmospheric data alone (at $\Delta \chi^2_{\text{ATM}} = 3.8$ with respect to the global best fit Eq. (3)), although it becomes more disfavored (at the 99% CL level, $\Delta \chi^2_{\text{ATM+LBL}} = 8.8$) when LBL data are also included in the fit. The one-dimensional projection shows that the required lifetime at this local best fit point lies at the boundary of the $2\sigma$ ($3\sigma$) single parameter range allowed from atmospheric (atmospheric+LBL) data. Indeed this solution is similar to that found in Ref. [10] for the decay and mixing but still allowing for oscillations. Our results show that forcing $\Delta m^2_{32} \ll 10^{-3}$ rules out this solution well beyond $3\sigma$ (at $\Delta \chi^2_{\text{ATM}} = 13.7$ with respect to the global best fit Eq. (3)), in agreement with the analysis of SK [11]. LBL data definitively rules out the mixing plus decay scenario with $\Delta \chi^2_{\text{ATM+LBL}} = 39$.

A better insight on the solutions in Eqs. (3) and (4) can be obtained from Fig. 2, where we show the expected event distributions at SK and MINOS. As seen in the figure both solutions yield rather similar results for the atmospheric neutrino events. For the sake of comparison we also show the corresponding
Fig. 2. Zenith-angle distributions for SK $\mu$-like events and energy spectrum at MINOS (normalized to the no-oscillation prediction) for the global best fit (full line), for the local best fit with oscillations plus decay (dashed line), and for a solution with oscillation plus decay with maximal mixing (dash-dotted line).

distribution for a decay plus oscillation scenario with $\Delta m^2$ and $\tau/m_3$ as in Eq. (4) but the mixing angle still maximal. This last curve illustrates how the introduction of decay produces a strong deficit of atmospheric $\nu_\mu$ events, which can be compensated by the deviation of the mixing angle from maximal. Also, as easily seen from Eq. (2) this compensation is only possible with a mixing angle $\theta \leq 45$. The event distributions for MINOS also show how the oscillation plus decay scenario cannot fully account for the observed dip in the neutrino spectrum; this leads to the worsening of the fit when including the LBL data. Thus this scenario will be further tested by a more precise determination of the $\nu_\mu$ spectrum in MINOS.

Beyond this local minimum, the analysis shows no evidence in favor of a non-
vanishing neutrino decay width, thus it allows to set an upper bound on the decay lifetime

\[ \tau_3/m_3 \geq 2.9 \times 10^{-10} \text{ s/eV} \Rightarrow \tau_3 \geq 6.5 \times 10^{-10} \left( \frac{m_3}{2.2 \text{ eV}} \right) \text{ s} \quad (5) \]

at the 90% [99%] CL where in the right hand side we have normalized to the maximum allowed value on the absolute mass scale of the neutrino from tritium \( \beta \) decay experiments \([18, 19]\), \( m_3 < 2.2 \text{ eV} \).

We now turn to compare the bounds in Eq. (5) with the existing bounds from other experiments. In order to make such comparison, we must first specify the neutrino decay model. The reason for this is that most of the bounds in the literature are not derived exclusively from effects due to the neutrino decay, but also from effects associated with the presence of new neutrino interactions which are responsible for its decay. We will focus on the fast invisible Majorana neutrino decay \( \nu_3 \rightarrow \nu_s J \) induced by the interaction

\[ \mathcal{L}_I = ig_{ij} \bar{\nu}_i \gamma_5 \nu_j J, \quad (6) \]

where \( J \) is the Majoron (pseudoscalar) field \([20–25]\), which has to be dominantly singlet, in order to satisfy the constraints from the invisible decay width of \( Z \) \([26]\). Alternatively for Dirac neutrinos one can have the decay channel \( \nu_3 \rightarrow \bar{\nu}_s \chi \) induced by a new neutrino interaction with a complex scalar field \( \chi \) \([27]\). In both cases the rest-frame lifetime of \( \nu_3 \) for \( m_3 \gg m_s \) is given by

\[ \tau_3 = \frac{16\pi}{g_{s3}^2 m_3}, \quad (7) \]

where \( g_{s3} = \cos \theta_{23} g_{s\tau} + \sin \theta_{23} g_{s\mu} \) is the relation between the relevant coupling constants in the mass and flavor basis (which for Majorana neutrinos is \( g_{ij} = U_{i\alpha}^T g_{\alpha\beta} U_{\beta j} \)). For these modes, the 90% [99%] bounds on Eq. (5) imply:

\[ |g_{s3}| \leq 4.8 \ [8.6] \times 10^{-3} \left( \frac{2.2 \text{ eV}}{m_3} \right). \quad (8) \]

This bound can be directly compared with the constraints on the \( g_{\mu\alpha} \) and \( g_{\tau\alpha} \) (for any flavor or sterile state \( \alpha \)) couplings that have been derived from their effect in meson and charged lepton decay. The most updated analysis \([28]\) yields the model independent 90% bounds

\[ |g_{\mu\alpha}| \leq 9.4 \times 10^{-3}, \quad |g_{\tau\alpha}| \leq 0.33. \quad (9) \]

Also, limits from decay and scattering of Majorons inside supernova yield bounds on \( |g_{\alpha\beta}| \) because for large couplings the supernova energy is drained due to Majoron emission and no explosion occurs. However, for very large coupling the Majoron becomes trapped inside the supernova and no constraint
is possible [29, 30]. As a consequence both ranges

\[ |g_{\alpha\beta}| < 3 \times 10^{-7} \quad \text{or} \quad |g_{\alpha\beta}| > 2 \times 10^{-5} \]  \quad (10)

are allowed [29].

In Ref. [31] a very strong limit was derived from the requirement that the neutrinos are free-streaming at the time of the photon decoupling, as deduced by precise measurements of the CMB acoustic peaks, \(|g_{ij}| \lesssim 0.61 \times 10^{-11} \text{(50 meV}/m_i)^2\). However the robustness of this conclusion has been questioned in [32].

Future experiments can improve the bounds on \(g_{\mu\mu}\) and \(g_{\nu\tau}\) by orders of magnitude, in particular from their cosmological effects [33] and from the observation of diffuse supernova neutrino background [34,35]. Till then the bounds derived in this work, Eqs. (5) and (8), from the analysis of atmospheric and LBL neutrino data are the strongest applicable to the \(\nu_3\) neutrino state with masses \(\mathcal{O}(\text{eV})\). In the flavor basis they represent the strongest bounds on the Majoron coupling to \(\nu_\tau - \nu_s\) in the full range \(2.2 \leq m_3 \leq 0.05 \text{ eV}\) allowed for the normal ordering of the neutrino mass states \(m_3 \geq m_2 \geq m_1\) with \(m_3 \gg m_s\).

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