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Distinction of atmospheric ν_μ–ν_τ and ν_μ–$\nu_{\rm s}$ oscillations using short or intermediate baseline experiments

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Abstract. The current case for atmospheric ν_μ oscillations in active or sterile neutrinos is reviewed. It is argued that neither the study of neutral current events at Super-Kamiokande, nor the information obtained from future long baseline experiments might be sufficient to unambiguously decide between these two scenarios. However, a combination of these results with the results from future short or intermediate baseline τ appearance experiments would clearly resolve most of the remaining ambiguities. This conclusion does not strongly depend on whether the results from the LSND experiment will be confirmed or not. In the case that LSND would be confirmed, a negative result in such a short or intermediate baseline experiment would also unambiguously exclude the interpretation of LSND as indirect ν_μ–ν_τ–$\nu_{\rm e}$ oscillations.

1 Introduction

In the wake of the recent evidence for atmospheric ν_μ oscillations by Super-Kamiokande [1], one of the crucial issues is to clarify whether the observed effect is due to ν_μ–ν_τ, ν_μ–$\nu_{\rm e}$ or ν_μ–$\nu_{\rm s}$ (sterile) oscillations. The pure ν_μ–$\nu_{\rm e}$ case is strongly disfavoured [2] by CHOOZ [3] and Super-Kamiokande [1], while pure ν_μ–ν_τ and ν_μ–$\nu_{\rm s}$ oscillations are equally possible [4]. Within the restrictions imposed by CHOOZ, complicated mixtures of the three cases can also not be excluded experimentally [5,6]. In fact, most models favouring the sterile neutrino interpretation [7–10] do suggest some (small) contribution from standard flavour oscillations. Due to the fundamental implications of the existence of a sterile neutrino for new physics, we will assume that a separation power of three to five σ is desired to rule out the mainly sterile oscillation scenario, and that a significance of at least five σ is required to establish it.

The paper is organized as follows: first, we will review the current experimental status of the active versus sterile oscillation hypothesis. We will then give some arguments as to why it is likely that future improvements on these measurements by atmospheric and long baseline neutrino experiments will leave important loopholes in the confirmation of either of the two hypotheses, and how a modest admixture of ν_μ–ν_τ to mainly ν_μ–$\nu_{\rm s}$ oscillations can mimic the pure ν_μ–ν_τ oscillation case. Finally, we will show how these loopholes can be closed by using the (positive or negative) results from short or intermediate baseline τ appearance (SIBTA) experiments [11–13].

Furthermore, we will argue that this conclusion does not depend strongly on whether the LSND [14] observation of ν_μ–$\nu_{\rm e}$ oscillations will be confirmed or not. If LSND were to be confirmed, a negative result in a SIBTA experiment would also unambiguously exclude the interpretation of LSND as indirect ν_μ–ν_τ–$\nu_{\rm e}$ oscillations, therefore ruling out all oscillation scenarios invoking this option [15]. This includes essentially all models trying to reconcile LSND with the atmospheric and solar neutrino result in the standard three-neutrino framework [16].

2 Discussion of Super-Kamiokande indications

Results of neutrino oscillation experiments are often expressed in terms of an effective two-flavour oscillation scheme with a mixing angle $\sin^2 2\theta$ between the two flavours and a mass difference δm^2 between the two relevant mass eigenstates. The most popular interpretation of the Super-Kamiokande results is to invoke maximal or close to maximal ν_μ–ν_τ oscillations with a δm^2 in the 10^{-2}–$10^{-3}\,{\rm eV}^2$ range. Clearly, if this interpretation is correct, the low δm^2 excludes any observation of a ν_μ–ν_τ oscillation signal in current [17,18] and future [11] short baseline experiments. However, a significant ν_μ–$\nu_{\rm e}$ contribution to the angular dependence of the atmospheric neutrino result is not completely excluded, and even suggested by some of the models [16] trying to reconcile the atmospheric neutrino anomaly with LSND. In this case the constraint on $\delta m^2_{\mu\tau}$ could be considerably diluted, and τ appearance signals in short or intermediate baseline experiments could be possible.

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Alternatively, several theoretical models suggest the interpretation of the Super-Kamiokande results as ν_μ–ν_s oscillations. In this case, the sterile neutrino could either be the right-handed (sterile) partner of the left-handed (active) muon neutrino (or its antiparticle), leading to maximal ν–$\bar{\nu}$ oscillations analogous to K^0–$\bar{K}^0$ oscillations [7,8], or the light remnant of very massive neutrinos in grand unified theory (GUT) extensions of the standard model usually involving extra neutrino multiplets [9,10]. In most of these models the observation of ν_μ–ν_s oscillations could be further complicated by non-negligible admixtures of ν_μ–ν_τ or ν_μ–ν_e oscillations.

Since, due to the high τ mass threshold, neither ν_τ nor ν_s produce a visible charged current (CC) signal in Super-Kamiokande, the two cases are experimentally almost indistinguishable in the standard Super-Kamiokande analysis of e-like and μ-like events [1,4]. However, ν_τ do produce neutral current (NC) interactions while sterile neutrinos do not. This could lead to a visible distinction in two kinds of measurements: in the ν_μ–ν_s case the up/down asymmetry observed in the CC sample should also be present for NC events, while no NC up/down asymmetry should occur in the ν_μ–ν_τ (or ν_μ–ν_e) case [19]. This effect also yields differences for the up/down asymmetry in inclusive event samples [20]. Furthermore, the NC suppression in the ν_μ–ν_s case modifies the predicted NC/CC ratios [21].

Unfortunately a clean NC/CC separation is experimentally difficult, and the expected effects are diluted by the (supposedly) unaltered contribution from ν_e NC events. The cleanest way to identify NC events in Super-Kamiokande is to require a single π^0 from the process $\nu + N \to \nu + N + \pi^0$, with N being either a neutron or a proton below the Čerenkov threshold. The π^0 is detected via its decay into two photons which convert and yield two electron-like (double) rings whose invariant mass is consistent with the π^0 mass. This procedure reduces statistics by so much that currently no significant measurement of the up/down asymmetry can be obtained [22]. The ratio of two-ring (π^0-like, NC) to single-ring (e-like, CC) events compared to the prediction for the no-oscillation case is measured to be [22][1]

$$\frac{(\pi^0/e)_{\rm data}}{(\pi^0/e)_{\rm pred}} = 0.88 \pm 0.08_{\rm stat} \pm 0.19_{\rm sys} \qquad (1)$$

where the systematic error is dominated by the poorly known single π^0 cross-section, and the statistical error is based on 535 days (2 years) of running. Assuming an initial ν_μ/ν_e ratio of 2.0, using the measured average ν_μ/ν_e ratio suppression of 0.63 [1], and assuming no background, the ratio in (1) is expected to be 1.00 for ν_μ–ν_τ oscillations (neither of the two contributions is affected), 0.75 for ν_μ–ν_s oscillations (the π^0 contribution is suppressed), 0.75 for ν_μ–ν_e oscillations (the e contribution is enhanced) and 0.94 for mainly ν_μ–ν_τ oscillations with a 10% ν_μ–ν_e contribution. If there is significant background contamination these differences will be further reduced.

[1] The value of 0.94 quoted e.g. in [23] does not include background subtraction.

In order to disentangle ν_μ–ν_τ from ν_μ–ν_s at the three σ level, the combined statistical and systematic error must therefore be reduced to 8% or less. If a 10% ν_μ–ν_e contribution is allowed, the required maximal uncertainty is reduced to 6%. Arbitrarily assuming 2140 days (8 years) of running, the statistical error will be about 4%. In order not to exceed the 6% total error this implies a systematic uncertainty of the order of 5% or less. Even with the planned measurement of the π^0 production cross-section in the near detector of the K2K experiment [24] this seems to be very hard to achieve. We therefore conclude that this measurement will probably yield a useful indication, but is unlikely to firmly establish one of the two options.

Similar arguments hold for the π^0 up/down asymmetry. From a simple extrapolation of existing data [22], it looks unlikely that this method will distinguish the two cases by more than about two standard deviations.

The possibility to separate ν_τ and ν_s from the measurement of the inclusive up/down asymmetry of multi-ring events, which also depends on the suppression of the NC contribution, is discussed in [20]. Here, the statistical and systematic errors are smaller, but the differences are also small, again yielding a potential effect of about two σ. Furthermore, ν_μ–ν_s oscillations with a significant ν_μ–ν_e admixture could yield the same asymmetry as pure ν_μ–ν_τ oscillations.

3 Other atmospheric neutrino experiments

None of the currently planned atmospheric neutrino experiments [25–28] has a τ detection efficiency which is sufficiently large to see a significant pure charged current oscillation signal. In addition to the small cross-section (τ mass threshold), the unknown direction of the incoming neutrino makes a significant kinematical analysis 'à la NOMAD' [17] impossible. Emulsion techniques 'à la CHORUS' [18] cannot be used due to the inherently small target mass.

As in Super-Kamiokande, any efforts to distinguish between ν_s and ν_τ must therefore focus on neutral current events or on inclusive event rates. In a detector like NICE [26] there is a small window at $\delta m^2 \sim$ few $\times 10^{-4}\,{\rm eV}^2$ where the oscillation pattern could actually be resolved, opening the possibility of comparing the energy dependence of the CC and NC event rates. In addition, such a low δm^2 would in itself be an indication for oscillations into active neutrinos, since the sterile case is somewhat disfavoured for such low δm^2 values due to earth matter effects which start to play a role [4].

Reference [27] outlines an atmospheric neutrino detector concept which would allow measurement of the appearance of ν_τ via an enhancement of muon-less events from τ decays at the highest accessible neutrino energies, where τ production is least suppressed. The nice feature of this concept is that ν_e events are effectively filtered out, therefore removing most of the ν_e background and the ν_μ–ν_τ/ν_μ–ν_e ambiguity. Combined with the NC suppression for ν_s this yields a ν_μ–ν_τ/ν_μ–ν_s separation of several standard deviations for $\delta m^2 \sim 5 \times 10^{-3}\,{\rm eV}^2$ or larger [27]. For

$\delta m^2 \sim 3\times10^{-3}$ the sensitivity is significantly reduced (oscillations of high energy ν_μ are suppressed), while for even lower δm^2 the difference becomes marginal.

For the Super-Kamiokande most favoured case of $\delta m^2 \sim 2\times10^{-3}\,\mathrm{eV}^2$ it is not clear at present whether the difficulties outlined above will allow any firm conclusions concerning the distinction of active and sterile neutrino oscillations. Furthermore, no detector of the types discussed above has been endorsed or approved so far.

In principle ν_μ–ν_τ and ν_μ–$\nu_{\rm s}$ oscillations can also be distinguished through the distortion of the momentum spectra of upward going muons due to matter effects [29]. No conclusion has been reached so far from ongoing experiments [30] due to large systematic errors. It is not clear at present whether these measurements can be improved sufficiently well to eventually allow a clear distinction.

4 Accelerator neutrino experiments

The best way to establish the ν_μ–ν_τ interpretation of the atmospheric neutrino result obviously seems to be the detection of the appearance of ν_τ in long baseline accelerator experiments [28,31–33,25]. Here, appearance could be established either directly through the observation of τ production, or indirectly via an enhancement of the NC/CC ratio, together with the non-observation of a large electron appearance effect. But, it turns out that a positive τ signal in e.g. ICARUS [28], OPERA [31] or MINOS [32] would *not* automatically prove the ν_μ–ν_τ hypothesis for atmospheric neutrinos, unless the corresponding δm^2 can be measured directly from this signal. The basic argument is that, as illustrated in Fig. 1, even a small ν_μ–ν_τ contribution ($\sin^2 2\theta \sim \mathrm{few}\times10^{-3}$ or larger) at large δm^2 (order eV^2) can yield a signal in long baseline experiments (for both appearance and disappearance) that is similar in size or even larger than the expected effect from maximal ν_μ–$\nu_{\rm s}$ oscillations, and can therefore mimic maximal ν_μ–ν_τ oscillations at small δm^2. This argument is discussed in detail below.

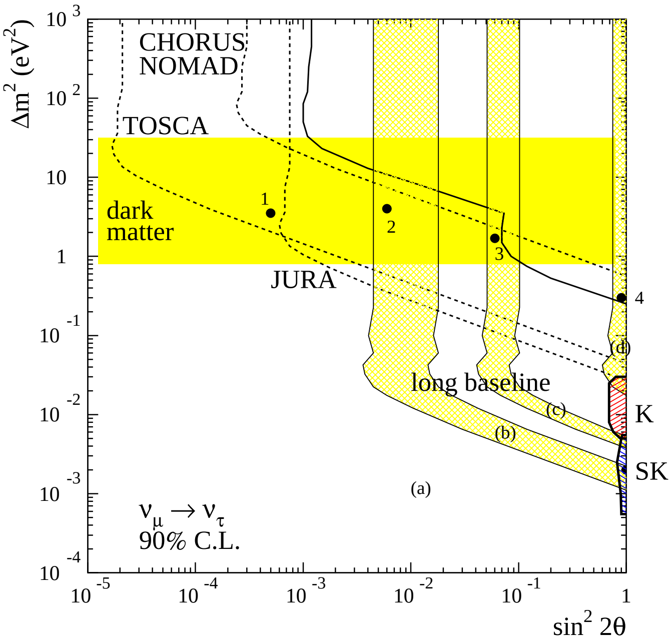

Fig. 1. Parameter space for ν_μ–ν_τ oscillations. Indicated are the current combined limit from NOMAD [17], CHORUS [18], E531 [34] and CDHS [35] (thick continuous line) as well as the potential future limits from CHORUS/NOMAD, TOSCA [11], and a generic intermediate baseline experiment in the Jura [13] experiment (dashed lines). The allowed regions of the Kamiokande (K) [36] and Super-Kamiokande (SK) [1] experiments, if interpreted as ν_μ–ν_τ oscillations, are also shown. The bands labelled **b**, **c** and **d** correspond to allowed regions from different potential τ appearance results of a generic long baseline experiment as discussed in the text, while **a** stands for a null result. The shaded area indicates the region favoured by mixed dark matter scenarios [37] while the points indicate test points used for the discussion in the text. They correspond to a specific prediction of ν_μ–ν_τ oscillations (in addition to maximal ν_μ–$\nu_{\rm s}$ oscillations) of [8] (1), a generic test point compatible with most of the models in [7,9,10] (2), and two test points corresponding to indirect oscillation solutions for LSND [15] (3 and 4). In addition, point 3 can be considered a variant of point 2

4.1 Motivation for mixed ν_μ–$\nu_{\rm s}$ and ν_μ–ν_τ scenarios

One of the most general arguments brought forward in favour of ν_μ–$\nu_{\rm s}$ oscillations in the context of some models [7,9] is the possibility to combine a neutrino mass hierarchy and mixing pattern which are similar to the one observed in the quark and charged lepton sector (i.e. the third generation is heaviest, mixing angles are small) with maximal ν_μ–$\nu_{\rm s}$ oscillations, while retaining a significant contribution to hot dark matter. In mixed dark matter models, this would suggest a ν_τ mass of order eV. Similarity with the CKM matrix [38] would suggest a $\sin^2 2\theta_{\mu\tau}$ of order 10^{-2} (e.g. test point 2 in Fig. 1). Once sterile neutrinos are considered at all this is in some sense a 'natural' possibility which should not be dismissed *a priori*, although it is by no means a necessity. Without requiring mass hierarchy, similar arguments for a possible $\nu_\mu \rightarrow \nu_\tau$ admixture apply for the models of [10].

If LSND [14] were to be confirmed this argument would be strengthened further, since the observation of ν_μ–$\nu_{\rm e}$ oscillations in the range $\delta m^2 \sim 0.2$–$2\,\mathrm{eV}^2$, combined with the hierarchy assumption, would again suggest a ν_τ mass in the eV range. In addition, it would make the sterile scenario more attractive, since the LSND result is hard to combine with the evidence from atmospheric and solar neutrinos in a three-neutrino scheme. However, the argument given in the previous paragraph would *not* vanish if LSND were disproven. Instead, ν_μ–$\nu_{\rm e}$ oscillations might play a significant role at lower δm^2, either as an admixture to mainly ν_μ–$\nu_{\rm s}$ atmospheric neutrino oscillations or as the solution of the solar neutrino problem [39].

Finally, let us digress and consider the case of indirect ν_μ–ν_τ–$\nu_{\rm e}$ oscillations in LSND [15,40]. Assuming mass hierarchy and denoting the dominant mass components of ν_e, ν_μ and ν_τ by m_1, m_2 and m_3 yields the mass relation $\delta m_{12}^2 \ll \delta m_{23}^2 \sim \delta m_{13}^2 \sim m_3^2$ known as one mass scale dominance [41]. In order for indirect oscillations to be detectable, m_3^2 must be in the range relevant for LSND, i.e. of order $1\,\mathrm{eV}^2$, and the rate proportional to

$$\sin^2 2\theta_{\mathrm{LSND}} = 4|U_{e_3} U_{\mu_3}|^2 \quad (2)$$

must be sufficiently large. Here, U_{e_3} and U_{μ_3} are the relevant matrix elements of the general three-neutrino mixing matrix. Bounds on U_{e_3} from Bugey [42] combined with the LSND measurement of the rate in (2) yield a prediction for U_{μ_3} as a function of m_3^2. All possible solutions are close to the limit from CDHS [35]. Two (marginally) allowed solutions, translated into $\sin^2 2\theta_{\mu\tau}$, are shown as test points 3 and 4 in Fig. 1.

Test point 3 corresponds to a scenario very similar to that of test point 2, where ν_μ–ν_τ oscillations happen in addition to the ν_μ–ν_s oscillations responsible for the atmospheric neutrino deficit. It is therefore also relevant outside of the LSND context.

Test point 4 represents the region of very large ν_μ–ν_τ mixing used, among others, for the Cardall/Fuller, Acker/Pakvasa and Thun/McKee schemes [16] without the need for sterile neutrinos.

4.2 Interpretation of long baseline observations

For the purpose of this study we will consider close to maximal ν_μ disappearance of atmospheric neutrinos to be an established fact, and anticipate that this will be confirmed[2] through a positive effect in the ratio of the ν_μ CC rate in near and far detectors of the long baseline programme (K2K [24], MINOS [32], NICE [26], etc.). Whenever atmospheric ν_μ–ν_τ or ν_μ–ν_s oscillations are mentioned in the next few paragraphs, it is understood that there could be a small (up to 10%) contribution from ν_μ–ν_e. A potentially even larger ν_e contribution is assumed to be measured and corrected for. Finally, Fig. 1 implies that very similar conclusions can be obtained from short and intermediate baseline experiments. We will therefore often refer to a generic SIBTA experiment in the discussion.

Case (a): Long baseline experiments do not observe ν_τ appearance.
A positive signal in a SIBTA experiment would then *establish* that ν_μ–ν_τ oscillations are outside of the range accessible to long baseline experiments, but within the range relevant to mixed dark matter (e.g. test point 1 in Fig. 1 for the short baseline case), and *force* the ν_μ–ν_s interpretation of the atmospheric neutrino result. The measured long baseline disappearance rate would yield a measurement of the δm^2 for ν_μ–ν_s oscillations, to be compared to the Super-Kamiokande result.

A negative result in a SIBTA experiment would *exclude* any ν_μ–ν_τ contribution to the long baseline signal from the cosmologically relevant range. It would therefore *strongly suggest* the ν_μ–ν_τ interpretation of the atmospheric neutrino oscillations at the low end of the Super-Kamiokande allowed δm^2 range, provided the observed long baseline disappearance signal (from a low-energy beam) is consistent with this low δm^2 hypothesis.

Case (b): Long baseline experiments observe a small ν_τ appearance signal.
Since the appearance signal is small (e.g. a handful of events in the case of direct τ appearance), it would supposedly *not* be possible to reliably measure the δm^2 from the energy distribution of the appearance signal alone. Again, a positive signal in a SIBTA experiment would *establish* that ν_μ–ν_τ oscillations occur in the cosmologically relevant range (e.g. test point 2 in Fig. 1), and *force* the ν_μ–ν_s interpretation of the atmospheric neutrino result. The combination of the SIBTA and long baseline results would unambiguously fix the ν_μ–ν_τ oscillation parameters. If the ν_μ–ν_s oscillations were to occur at the Super-Kamiokande best fit point of $\delta m^2 \sim 2\times10^{-3}\,\mathrm{eV}^2$ (SK), they would be partially masked by the ν_μ–ν_τ signal in the long baseline disappearance search. On the other hand, if the disappearance rate turned out to be significantly larger than the appearance rate ($\delta m^2 > 2\times10^{-3}\,\mathrm{eV}^2$), the former could be used to measure the δm^2 of the ν_μ–ν_s oscillations.

A negative SIBTA result would again *exclude* any ν_μ–ν_τ contribution to the long baseline signal from the cosmologically relevant range, and therefore *strongly suggest* the ν_μ–ν_τ interpretation of the atmospheric neutrino oscillations with parameters close to the Super-Kamiokande best fit point. This can be cross-checked by requiring the appearance and disappearance rates to agree. The combination of the long baseline with the atmospheric neutrino results then yields a precise measurement of the ν_μ–ν_τ oscillation parameters.

Case (c): Long baseline experiments observe a large ν_τ appearance signal.
Given a large ν_μ–ν_τ appearance signal, it might be possible to extract δm^2 from the energy distribution of the appearance signal alone, or at least to exclude a significant fraction of the available parameter space. However, the example of the LSND experiment [14] shows that this possibility cannot be taken for granted. Despite a claimed excess of 50 events over a small background, LSND is not able to differentiate the low and high δm^2 cases for their ν_μ–ν_e oscillation signal. Definitely, a low/high δm^2 distinction at the five σ level would not be obvious for the long baseline results.

A preference for the low δm^2 case could e.g. suggest the ν_μ–ν_τ interpretation of the atmospheric neutrino deficit with a δm^2 in the Kamiokande/Super-Kamiokande overlap region ($\sim 6\times10^{-3}\,\mathrm{eV}^2$). The requirement of *not* observing a SIBTA signal would essentially *eliminate* the whole large δm^2 range, including the regions suggested by dark matter and/or LSND (test point 3), and therefore strongly enhance the confidence in the low δm^2 result. Compatibility of the observed long baseline appearance and disappearance rates, although required, would

[2] However, note some caveats explained later in the text.

not yield any further separation power, since a large τ appearance signal from e.g. test point 3 in Fig. 1 would completely mask the atmospheric oscillation effect, and also yield a consistent appearance/disappearance rate.

A preference for the high δm^2 case would imply the interpretation of the atmospheric neutrino anomaly as mainly ν_μ–ν_s oscillations. If LSND were confirmed, it could in addition imply the compatibility of the ν_μ–ν_τ oscillation parameters with the indirect oscillation hypothesis for LSND (test point 3). Given the importance of such a result, the cross-check from the requirement of a positive SIBTA result would be absolutely *essential*.

Case (d): Long baseline experiments observe a close to maximal (>30%) ν_τ appearance signal.
Such a signal would be really spectacular, and inconsistent with the analysis of the Super-Kamiokande data in terms of two-flavour oscillations. Since it would point to a δm^2 larger than $10^{-2}\,\text{eV}^2$ it would either indicate a serious flaw in the Super-Kamiokande analysis, or require a three- (or more) flavour scheme with significant contributions from two different δm^2, one high and one low.

The energy distribution of the observed τ spectrum could already give a serious indication of the relevant high δm^2. The rate of a positive SIBTA signal would, however, unambiguously fix the δm^2 for ν_μ–ν_τ oscillations, and could decide whether it corresponds to the Cardall/Fuller or Thun/McKee solutions (test point 4) or to some lower δm^2 value.

A negative SIBTA result would *constrain* the δm^2 to about $2 \times 10^{-2}\,\text{eV}^2$.

In either case the up/down asymmetry pattern of the Super-Kamiokande data suggesting a significant low δm^2 contribution would either have to be disproven, attributed to ν_μ–ν_e oscillations through a corresponding observation in long baseline experiments or attributed to a complicated mixture of ν_μ–ν_τ, ν_μ–ν_e and ν_μ–ν_s oscillations.

5 Compatibility with LSND

As outlined in the cases discussed above, none of the scenarios discussed essentially requires the confirmation of LSND. On the other hand, a confirmation of LSND would significantly enhance the interest in the ν_μ–ν_τ/ν_μ–ν_s distinction, since the addition of one or more sterile neutrinos might then be the only solution to simultaneously describe all the data. Also, the question of whether the LSND signal is caused by direct or indirect oscillations becomes very relevant. As can be seen from Fig. 1, a negative SIBTA signal would unambiguously exclude the indirect oscillation possibility (test points 3 and 4), while a positive signal might allow it. A positive ν_μ–ν_τ signal of kind (c) or (d) in the long baseline experiments could confirm this scenario, while a signal of kind (b) or (a) (no signal) would again exclude it. Finally, reversing the argument, the observation or non-observation of a signal in a SIBTA experiment before the LSND case is settled could, depending on the context of the results of other experiments, indirectly contribute to the LSND verification.

6 Conclusion

It has been shown that, whatever the outcome of future atmospheric and long baseline neutrino experiments, the complementary information from a short or intermediate baseline τ appearance experiment could be crucial for the unambiguous interpretation of the long baseline results. Such an experiment is therefore needed to distinguish clearly between the ν_μ–ν_τ and ν_μ–ν_s interpretations of the atmospheric neutrino anomaly, and even a negative result is very relevant in this context. In the absence of this cross-check, a small ν_μ–ν_τ contribution at high δm^2 could mask the long baseline ν_μ–ν_s signal, therefore yielding a false confirmation of the interpretation of the atmospheric neutrino anomaly in terms of ν_μ–ν_τ oscillations. This conclusion does not depend on whether LSND is confirmed or not, although a confirmation of LSND would enhance the interest in resolving this ambiguity. If LSND were confirmed, a negative signal in such a short or intermediate baseline experiment would definitively rule out the indirect oscillation interpretation of the LSND result.

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References

1. Super-Kamiokande Collaboration, Y. Fukuda et al., Phys. Rev. Lett. **81**, 1562 (1998);
   Super-Kamiokande Collaboration, Y. Fukuda et al., Phys. Lett. B **436**, 33 (1998);
   Super-Kamiokande Collaboration, Y. Fukuda et al., Phys. Lett. B **433**, 9 (1998)
2. M.C. Gonzalez-Garcia et al., Phys. Rev. D **58**, 033004 (1998)
3. CHOOZ Collaboration, M. Apollonio et al., Phys. Lett. B **420**, 397 (1998)
4. R. Foot, R.R. Volkas, O. Yasuda, Phys. Rev. D **58**, 013006 (1998);
   M.C. Gonzalez-Garcia et al., FTUV-98-56 and hep-ph/9807305, July 1998.
5. G.L. Fogli et al., Phys. Lett. B **425**, 341 (1998);
   G.L. Fogli et al., Phys. Rev. D **59**, 033001 (1999);
   S.M. Bilenky, C. Giunti, DFTT 05/98 and hep-ph/9802201, Feb. 1998;
   R. Foot, R.R. Volkas, O. Yasuda, Phys. Lett. B **433**, 82 (1998)
6. V. Barger et al., Phys. Rev. D **58**, 093016 (1998)
7. A. Geiser, Phys. Lett. B **444**, 358 (1999);
   M. Kobayashi, C.S. Lim, M.M. Nojiri, Phys. Rev. Lett. **67**, 1685 (1991);
   C. Giunti, C.W. Kim and U.W. Lee, Phys. Rev. D **46**, 3034 (1992)
8. Y. Koide, H. Fusaoka, US-98-06 and hep-ph/9806516, June 1998;
   Y. Koide, Phys. Rev. D **57**, 5836 (1998)

9. J.P. Bowes, R.R. Volkas, J. Phys. G **24**, 1249 (1998); R. Foot, R.R. Volkas, Phys. Rev. D **52**, 6595 (1995); R. Foot, Mod. Phys. Lett. A **9**, 169 (1994)
10. Q.Y. Liu, A.Yu. Smirnov, Nucl. Phys. B **524**, 505 (1998); Q.Y. Liu, A.Yu. Smirnov, IC-98-14, Feb. 1998; E.J. Chun, C.W. Kim, U.W. Lee, Phys. Rev. D **58**, 093003 (1998); A.S. Joshipura, A.Yu. Smirnov, Phys. Lett. B **439**, 103 (1998); M. Bando, K. Yoshioka, KUNS-1516 and hep-ph/9806400, June 1998
11. TOSCA Letter of Intent, CERN-SPSC/97-5, SPSC/I 213 (1997); Addendum to Letter of Intent, CERN-SPSC/98-20, SPSC/I 213 add., May 1998
12. R.A. Sidwell (COSMOS Collaboration) in Neutrino '96, Proceedings of the 17th International Conference on Neutrino Physics and Astrophysics, Helsinki, Finland, June 13, 1996, edited by K. Enqvist, K. Huitu, J. Maalampi, (World Scientific, Singapore, 1997), p. 152
13. Proposal for ICARUS in the Jura, CERN/SPSLC 96-58 (1996); D. Autiero et al., Expression of Interest for Jura experiment, CERN/SPSC/97-23, SPSC/I 217, Oct. 1997
14. LSND Collaboration, C. Athanassopoulos et al., Phys. Rev. Lett. **75**, 2650 (1995); J.E. Hill, Phys. Rev. Lett. **75**, 2654 (1995); LSND Collaboration, C. Athanassopoulos et al., Phys. Rev. C **54**, 2685 (1996); LSND Collaboration, C. Athanassopoulos et al., Phys. Rev. Lett. **77**, 3082 (1996); LSND Collaboration, C. Athanassopoulos et al., LA-UR-97-1998, UCRHEP-E191, and nucl-ex/9706006, June 1997, submitted to Phys. Rev. **C**; LSND Collaboration, C. Athanassopoulos et al., Phys. Rev. Lett. **81** (1998) 1774
15. K.S. Babu, J.C. Pati, F. Wilczek, Phys. Lett. B **359**, 351 (1995)
16. C.Y. Cardall, G.M. Fuller, Phys. Rev. D **53**, 4421 (1996); G.L. Fogli et al., Phys. Rev. D **56**, 4365 (1997); A. Acker, S. Pakvasa, Phys. Lett. B **397**, 209 (1997); T. Teshima, T. Sakai, O. Inagaki, CU-TP-98-01 and hep-ph/9801276, Jan. 1998; R.P. Thun, S. McKee, Phys. Lett. B **439**, 123 (1998); G. Barenboim, F. Scheck, Phys. Lett. B **443**, 317 (1998); G. Conforto, M. Barone, C. Gramini, UB-FI-98 and hep-ph/9809501
17. NOMAD Collaboration, J. Altegoer et al., Phys. Lett. B **431**, 219 (1998); D. Autiero (NOMAD Collaboration), talk at ICHEP98 Vancouver, Canada, July 23-29 1998
18. CHORUS Collaboration, E. Eskut et al., Phys. Lett. B **424**, 202 (1998); CHORUS Collaboration, E. Eskut et al., Phys. Lett. B **434**, 205 (1998); P. Migliozzi (CHORUS Collaboration), talk at ICHEP98 Vancouver, Canada, July 23–29 1998
19. J.W. Flanagan, J.G. Learned, S. Pakvasa, Phys. Rev. D **57**, 2649 (1998); J.G. Learned, S. Pakvasa, J.L. Stone, Phys. Lett. B **435**, 131 (1998)
20. L.J. Hall, H. Murayama, Phys. Lett. B **436**, 323 (1998)
21. F. Vissani, A.Yu. Smirnov, Phys. Lett. B **432**, 376 (1998)
22. W. Gajewski (Super-Kamiokande Collaboration), talk at Neutrino Oscillation Workshop (NOW 98), Amsterdam, Netherlands, 7–9 September 1998
23. T. Kajita (Super-Kamiokande Collaboration), talk at 18th International Conference on Neutrino Physics and Astrophysics, Takayama, Japan, June 1998
24. Y. Suzuki (E362 (K2K) Collaboration), in Neutrino '96 [12], p. 237
25. NOE Collaboration, M. Ambrosio et al., Nucl. Instrum. Methods A **363**, 604 (1995)
26. NICE proposal, G. Baldini et al., LNGS-LOI 98/13 (1998)
27. A. Curioni et al., ICGF-98-05 and hep-ph/9805249, May 1998
28. ICARUS Collaboration, P. Benetti et al., Nucl. Instrum. Methods A **327**, 327 (1993); Nucl. Instrum. Methods A **332**, 332 (1993); P. Cennini et al., Nucl. Instrum. Methods A **333**, 567 (1993); Nucl. Instrum. Methods A **345**, 230 (1994); Nucl. Instrum. Methods A **355**, 355 (1995); ICARUS-CERN-Milano Collaboration, CERN/SPSLC 96-58, SPSLC/P 304, December 1996
29. P. Lipari, M. Lusignoli, Phys. Rev. D **58**, 073005 (1998); Q.Y. Liu, S.P. Mikheyev, A.Y. Smirnov, Phys. Lett. B **440**, 319 (1998)
30. MACRO collaboration, M. Ambrosio et al., Phys. Lett. B **434** (1998) 451; MACRO Collaboration, S. Ahlen et al., Phys. Lett. B **357**, 481 (1995); Kamiokande Collaboration, S. Hatekayama et al., Phys. Rev. Lett. **81**, 2016 (1998); Baksan Collaboration, review by T. Gaisser, in Neutrino '96 [12], p. 211; IMB Collaboration, R. Becker-Szendy et al., Phys. Rev. D **46**, 3720 (1992)
31. OPERA letter of intent, S. Shibuya et al., CERN-SPSC/97-24, SPSC/I 218, LNGS-LOI-8-97 (1997).
32. MINOS Collaboration, Fermilab proposal P875; MINOS Collaboration, 'Neutrino Oscillation Physics at Fermilab: The NuMI-MINOS Project', NuMI-L375, May 1998; S.G. Wojcicki, in Neutrino '96 [12], p. 231
33. AquaRICH Collaboration, T. Ypsilantis et al., Nucl. Instrum. Methods A **371** (1996) 330
34. E531 Collaboration, N. Ushida et al., Phys. Rev. Lett. **57**, 2897 (1986)
35. CDHS Collaboration, F. Dydak et al., Phys. Lett. B **134**, 281 (1984)
36. Kamiokande Collaboration, Y. Fukuda et al., Phys. Lett. B **335** (1994) 237
37. See e.g. J. Primack, A. Klypin, Nucl. Phys. Proc. Suppl. B **51**, 30 (1996)
38. N. Cabibbo, Phys. Rev. Lett. **10**, 531 (1963); M. Kobayashi, T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973); F.J. Gilman, K. Kleinknecht, B. Renk, in Review of Particle Physics, Phys. Rev. D **54**, 94 (1996)
39. N. Hata, P. Langacker, Phys. Rev. D **56**, 6107 (1997)
40. C.Y. Cardall, G.M. Fuller, D.B. Cline, Phys. Lett. B **413** (1997) 246
41. G.L. Fogli, E. Lisi, G. Sciosia, Phys. Rev. D **52**, 5334 (1995)
42. Bugey Collaboration, B. Achkar et al., Nucl. Phys. B **434**, 503 (1995)