PRAMANA
— journal of
physics

© Printed in India

Supplement to Vol. 41
December 1993
pp. 417–426

Solar and atmospheric neutrinos

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Abstract. Possible explanations of solar neutrino and atmospheric neutrino anomalies are summarized and future tests discussed.

1. Introduction

In the Standard Model (SM) with no singlet right-handed neutrinos and a single Higgs field, all neutrino masses are zero and lepton number (as well as individual flavor quantum numbers) are exactly conserved. It follows that the charged leptonic current is diagonal in both mass and flavor basis and the mixing angles are zero. Hence any evidence for non-zero neutrino masses or for non-trivial mixings is evidence for physics beyond the Standard Model. This makes the searches for neutrino masses and mixings doubly important: as measurements of fundamental parameters of intrinsic interest and as harbingers of new physics.

2. Solar neutrinos

The current status of the data on solar neutrino observations from the four on-going experiments is summarized in the Table 1. The Kamiokande detector is sensitive only to ^8B neutrinos; and the Homestake detector is sensitive to ^8B (77%) as well as ^7Be(14%), pep (2%) and CNO (6%) neutrinos [1]. If the observations need no new neutrino properties, then the ^8B $\nu's$ are not distorted in their spectrum and the flux seen by Kamiokande (over a limited energy range), can be assumed uniform and hence applicable to Homestate as well. In that case a minimum of $(38 \pm 8)\%$ of SSM counting rate is contributed by ^8B neutrinos alone and adding pep neutrinos it is $(40\pm8)\%$ to be compared to the observed $(28\pm4)\%$. It is obvious that something must reduce the ^7Be neutrino flux drastically to obtain agreement. Since the effective temperature dependence of ^7Be ν flux is much weaker than for ^8B flux [2], it is difficult to arrange for a stronger suppression for ^7Be than for the ^8B flux. This is borne out in calculations where the core temperature is allowed to be a free parameter and it is found that a good fit to all the data cannot be obtained [3]. Furthermore, no solar model has been found which can reproduce the Chlorine rates even with the reduced ^8B flux or even come close [4]. There is general agreement that with the Chlorine data averaged over the whole period some neutrino properties are called for [5].

I will summarize the solutions to the solar neutrino deficit with emphasis on the non-MSW options. For definiteness and simplicity I will assume (i) SSM fluxes of Bahcall and Pinsounnent, (ii) two flavor mixing, (iii) and ignore mixing with sterile neutrinos and neutrino flavor changing neutral currents. I will briefly discuss the solutions and how each may be distinguished in future experiments especially in Borexino, SNO, Superkamiokande and ICARUS [6].

Table 1. The solar neutrino data [7-10] compared to the SSM predictions [1]

Experiment	Data/SSM
Kamiokande	0.49 ± 0.01
Gallex	0.63 ± 0.17
Sage	$0.44 \pm^{0.17}_{0.21}$
Homestake	0.28 ± 0.04

MSW:

This is the case in which δm^2 and $\sin^2 2\theta$ lie in the range in which the solar matter effects are very important [11]. A fit to all four experiments leaves three allowed regions [12]. One is the small angle ($\sin^2 2\theta \sim 4.10^{-3}, \delta m^2 \sim 10^{-5} eV^2$) region; in this region the rate for ^7Be νe scattering in Borexino varies rapidly between 0.2 and 0.5 of SSM and ^8B spectrum as seen in SNO or Superkamiokande will show distortion. Another is the large angle large δm^2 region ($\sin^2 2\theta \sim 1, \delta m^2 \overset{\sim}{>} 10^{-5} eV^2$); in this region ^7Be is suppressed between 0.35 and 0.7 and there is no distortion of ^8B spectrum. Finally there is a small region at large angle small $\delta m^2 (\sin^2 2\theta \sim 1, \delta m^2 \overset{\sim}{<} 10^{-6} eV^2)$; here there is a strong day-night variation in ^7Be line as seen in Borexino [13].

Large Angle Long Wavelength:

The large angle long wavelength ("just so") [14] continues to fit all the data [15] with $\delta m^2 \sim 10^{-10} eV^2$ and $\sin^2 2\theta \overset{\sim}{>} 0.8$ [Fig. 1]. Matter effects are negligible. This has striking predictions testable with future detectors: (i) suppression of ^7Be in Borexino between 0.2 and 0.5, (ii)sharp distortion of ^8B spectrum and most importantly, (iii) visible oscillations of ^7Be line with time of the year with upto factor of 2 variations. This maybe the only chance [16] to see true quantum mechanical neutrino oscillations [Fig. 2].

Akhmedov et al. [17] have given an interesting possible justification of such a scenario. They suppose that (i) there are only LH $\nu's$, (ii) lepton number is conserved except by gravity; then at Planck scale there may be lepton number violating terms such as

$$\frac{g_{ij}}{m_p} \bar{\psi}^c_{Li} \underline{\tau} \psi_{Lj} \cdot \bar{\phi} \underline{\tau} \phi \tag{1}$$

where ϕ is the standard Higgs doublet, m_p Planck mass, i and j are family indices. Then the neutrino masses are Majorana and the mass matrix is

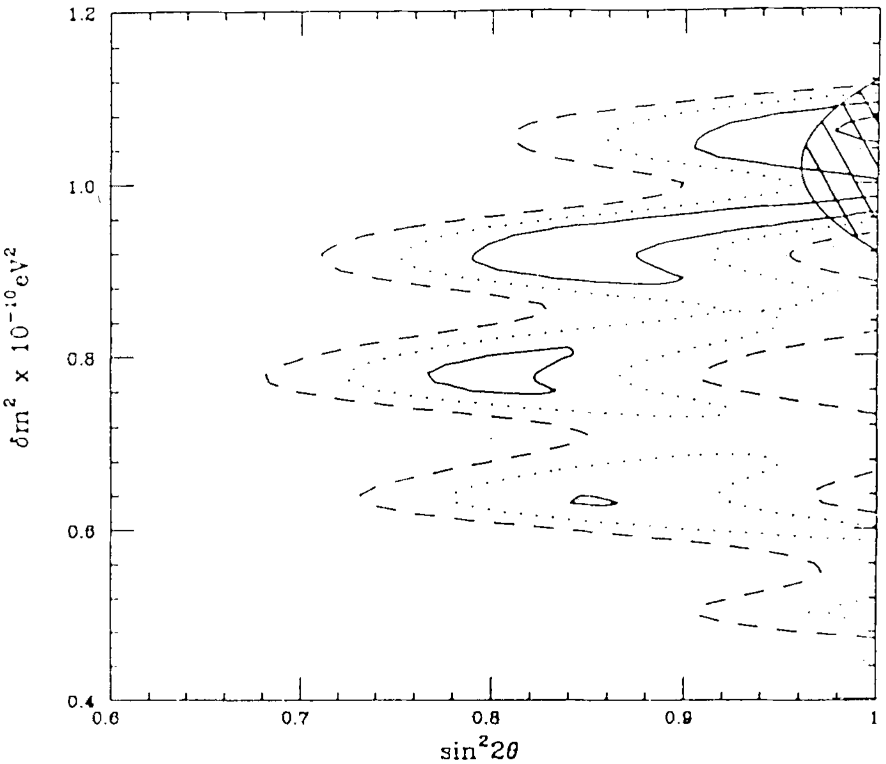

Figure 1. Contour plot showing the allowed parameter regions at the 68% (solid line), 90% (dotted line(and 99% (dashed line) confidence levels for the two neutrino flavor vacuum oscillation solution to the solar neutrino problem based on data from Cl^{37}, K-II and Gallex. The shaded region is excluded at the 68% confidence level.

$$M_{\nu_{ij}} = g_{ij} v^2 / m_p \tag{2}$$

If one makes the further assumption that gravity is flavor-blind and $g_{ij} = g$ and $g \sim 0(1)$, then the matrix is

$$m_\nu = \frac{v^2}{m_p} \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}, \tag{3}$$

which has as mass eigenvalues $m_1 = 0, m_2 = 0$ and $m_3 = m = 2v^2/m_p \cong 10^{-5} eV$. Hence δm^2 is about $10^{-10} eV^2$. The mixing matrix is easily calculated and it can be shown that

$$P(\nu_e \rightarrow \nu_e, L) = 1 - \frac{8}{9} \sin^2 \frac{m^2 L}{4E}, \tag{4}$$

which corresponds to an effective $\sin^2 2\theta$ of 0.89.

Decay with Mixing:

A very old proposal is to have the neutrinos decay on the way to the earth [18]. The SN1987A observation of $\bar{\nu_e}'s$ require that there be a stable component in

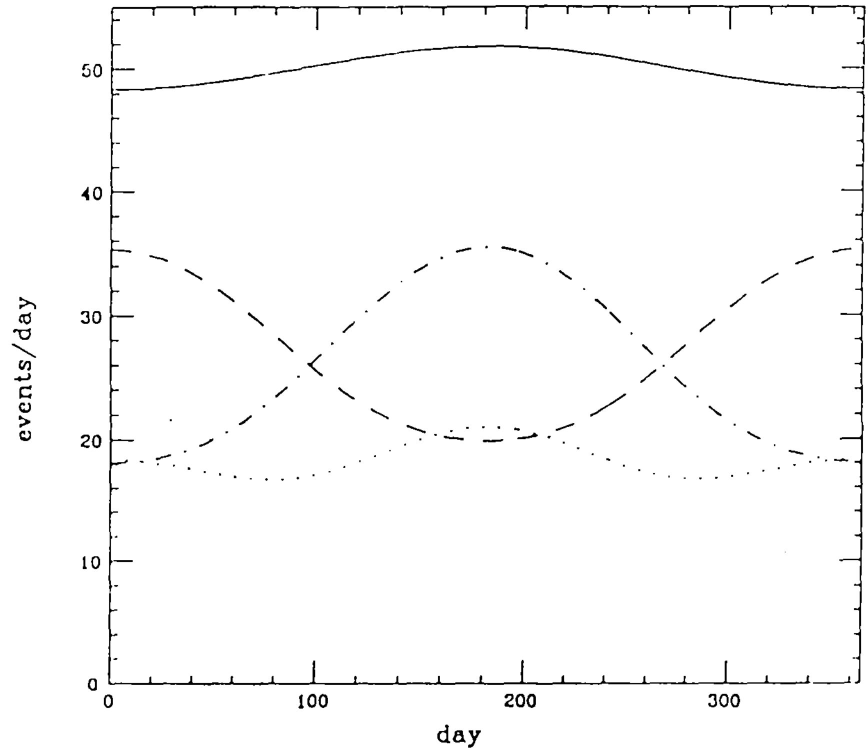

Figure 2. Seasonal variations in ^7Be neutrino flux. The solid line is the SSM prediction showing the $1/r^2$ effect. The dashed, dot-dashed and dotted lines represent 3 vacuum oscillation solutions to the solar neutrino problem with $\sin^2 2\theta = 0.8$ and $\delta m^2 = .81 \times 10^{-10}\ eV^2$, $.76 \times 10^{-10}\ eV^2$ and $.782 \times 10^{-10}\ eV^2$ respectively.

ν_e and the mixing be not too small [19]. There must be also some new physics for the decay into another neutrino and a light or massless boson. In any case, phenomenologically, with the Gallex data in hand, very little parameter space is left for the decay solution [Fig. 3]: the mixing element $\mid U_{e2} \mid$ $(or \sin\theta)$ has to be between 0.6 and 0.7 and the (Laboratory) lifetime for ν_2 has to be less than 1000 sec. [20]. The clear cut predictions are: (i) ^7Be suppression between 0.2 and 0.4, (ii) the NC rate in SNO suppressed by 0.7 ± 0.1, (iii)^8B spectrum distorted but not by much; (iv) for Majorana ν_e decay a sizeable $\bar{\nu}_e$ signal detectable in Borexino ($\gtrsim$ 40 events/yr) [21].

Flavor Violating Gravity:

If the gravitational interaction of neutrinos is not diagonal in flavor, then even for massless neutrinos there are oscillations induced by this flavor dependent gravitational potential [22]. The survival probability for ν_e is given by

$$P(\nu_e \rightarrow \nu_e, L) = 1 - sin^2\,(2\theta_G)\sin^2[\delta\bar{\phi}EL], \tag{5}$$

where $\bar{\phi}$ is the gravitational potential averaged over the neutrino path-length, δ is the departure from flavor independence of gravity: $\delta = f_e - f_\mu$.

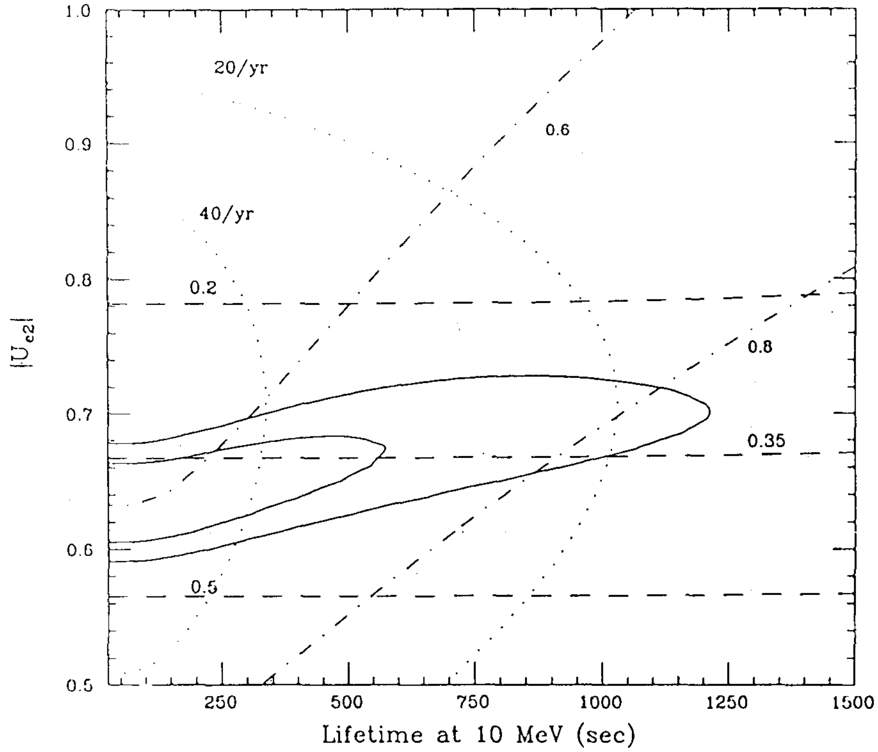

Figure 3. Allowed region at 90% and 99% C.L. for the decay solution. The dashed lines show the expected suppression in ^7Be νe signal, the dashed-dotted lines the suppression in NC signal and the dotted line shows the $\bar{\nu}_e p$ rate in Borexino.

The quantity $(\delta\phi EL)$ can be written as $(\pi L/\lambda_G)$ where $\lambda_G = 6$ km $(10^{-20}/\delta\phi)$ $[1/(E/10\ GeV)]$. The precise value of ϕ at the earth and the sun is very uncertain due to potentially large contributions from "nearby" large masses such as the Virgo cluster or the local super cluster. Current limits on $\delta\phi$ from re-interpretations of $\delta m^2 - sin^2 2\theta$ bound are (for $\nu_e - \nu_x$) 10^{-19} for $\sin^2 2\theta_G \sim 1$. It turns out that $\delta\phi$ in the range $10^{-20} - 10^{-21}$ and $\sin^2 2\theta_G \sim 1$ can provide a simultaneous good fit to all the solar neutrino data as well as the atmospheric anomaly. Future long-baseline experiments can extend the bounds on $\delta\phi$ to 10^{-22} or better and test this hypothesis [23].

To summarize, future detectors such as SNO, Superkamiokande, Borexino, and ICARUS will have real time event rates of several thousand per year. They will measure the ^8B neutrino energy spectrum accurately, ^7Be line rate and the ratio of NC/CC in $\nu_e D$ reaction. With this information at hand it should be possible to establish that (a) neutrino properties are relevant, (b) distinguish between MSW, long wavelength, decay etc., (c) pin down the parameters narrowly and (d) deduce more precise information about the sun such as the core temperature.

3. Atmospheric neutrinos

Neutrinos are produced by cosmic rays interacting in the atmosphere. A primary (P) reacts with "air" nucleus as:

$$\text{“}P\text{”} + \text{“air”} \rightarrow \pi + x. \qquad (6)$$

The π may interact or decay; if it decays:

$$\pi \rightarrow \mu + \nu_\mu \qquad (7)$$

and at low energies (few GeV) the μ can also decay before it hits the ground:

$$\mu \rightarrow e + \nu_e + \nu_\mu. \qquad (8)$$

If all the $\mu's$ decay we are led to expect $N(\bar{\nu}_\mu)/N(\nu_e)$ of 2 (ignoring the distinction between ν and $\bar{\nu}$). This ratio, furthermore, is expected to be essentially independent of the zenith angle at low energies. Neutrinos of energies below 2 GeV give rise to "contained" events in typical kiloton underground detectors. The results from the two large water-Cerenkov detectors suggest that the ratio $R = N(\nu_\mu)/N(\nu_e)$ is smaller than expected by almost a factor of two. Kamiokande finds (based on 310 events) for the ratio of ratios [24].

$$R_{obs}/R_{MC} = 0.60 \pm 0.07 \pm 0.05, \qquad (9)$$

while IMB finds (based on 507 events) [25]

$$R_{obs}/R_{MC} = 0.54 \pm 0.05 \pm 0.12. \qquad (10)$$

The result of Frejus (for contained events) and Nusex is respectively 0.87±0.16±0.08 (based on 133 events) and $0.99^{+0.35}_{-0.25}\pm ?$(based on 50 events) [26,27] Finally very recently SOUDAN II has found a result of 0.46 ± 0.23 based on a $0.5K$-ton-year exposure [28].

The ratio $N(\nu_\mu)/N(\nu_e)$ is considered more reliably calculated than the individual fluxes: the ratio is stable to about 5% amongst different calculations whereas the absolute fluxes vary by as much as 20 to 30% [29]. The μ/e identification in the water $\hat{c}$ detectors is expected be quite reliable; in any case future calibration tests planned at KEK should settle the issue. Nuclear physics uncertainties in the cross-sections or y-distributions are unlikely to be relevant provided the kinematic region near muon threshold is avoided. Finally, in all the new calculations the μ-polarization is taken into account.

The deviation of R_{obs}/R_{MC} from 1 is fairly uniform over zenith angle and is most pronounced in the charged lepton energy range 200-700 MeV which corresponds to neutrino energies from 300 MeV to 1.2 GeV. If we are to interpret this deficit of $\nu_\mu' s$ (and/or excess of $\nu_e' s$) as being due to neutrino oscillations, the relevant parameters are determined rather easily [30]. The typical height of production, h, is about 15-20 km above ground and for a zenith angle θ the distance travelled by the neutrino before reaching the detector is

$$L(\theta) = R\left[\sqrt{(1 + h/R)^2 - \sin^2\theta} - \cos\theta\right], \qquad (11)$$

where R is the radius of the earth. Allowing for angular smearing due to the scattering and finite angular resolution one finds that neutrino path lengths can vary between 30km to 6500 km, and hence L/E can vary between 25 km/GeV and 20,000 km/GeV. Since the data do not show any L (i.e. θ) or E dependence we may infer that the oscillations have already set in at $E_\nu \sim 1\ GeV$ and $L \sim 30km$ and hence δm^2 cannot be much smaller than $3.10^{-2}eV^2$. As for the mixing angle θ, if P denotes the average oscillation probability i.e. $P = \sin^2 2\theta < \sin^2 \delta m^2 L/4E >\approx \frac{1}{2}\sin^2 2\theta$; then $R = 1 - P$ in case of $\nu_\mu - \nu_\tau$ oscillations and for $\nu_\mu - \nu_e$ oscillations

$$R = \frac{1-(1-r)P}{1+(1/r-1)P}, \tag{12}$$

where $r = N(\nu_e)/N(\nu_\mu)$ in absence of oscillations and most flux calculations yield $r \sim 0.45$. Since R is nearly 0.6, large mixing angles of order 30^0 to 45^0 are called for, $\nu_\mu - \nu_e$ mixing needing somewhat smaller ones. Detailed fits by Kamiokande bear these expectations out although somewhat bigger range of parameters (δm^2 up to $4.10^{-3}eV^2$ and mixing angles up to 20^0) are allowed [24].

There are also higher energy muons in the underground detectors. Typically in IMB and Kamiokande detectors events are classified as thrugoing muons and stopping muons. The average ν_μ energy for these correspond to about 100 GeV and 10 GeV respectively. These events are expected to have the famous $sec\theta$ zenith angle distribution due to the competition between π decay and interaction and the ν_e flux is very small since the high energy $\mu's$ do not have time to decay in 20 km [31]. If the above explanation of the low energy anomaly is correct then for the thrugoing events (a) the zenith angle distribution should be distorted since for horizontal events oscillations will not have set in ($\delta m^2 L/4E \ll 1$) but for vertical events there should be depletion (b) the total muon event rate itself should be decreased by the depletion and (c) in case of $\nu_\mu - \nu_e$ oscillations there should be an enhancement of ν_e (and hence showering) events especially at energies where there might be matter enhancement [30,32]. Four detectors, IMB, Kamiokande, Baksan and KGF have data of the order of a few hundred events each [33-36]. There is no clear distortion of the zenith angle distribution or depletion of the total rate seen in any data. However, since the comparison has to be made to absolute flux calculations, the limits on $\delta m^2, \theta$ derived are not yet strong enough to rule out the values needed to explain the low energy anomaly [37]. IMB has derived forbidden regions [33] by taking ratio of stoppers/thrugoers which is largely flux independent and which rules out the large angle region ($\sin^2 2\theta \sim 0.6$ to 1) for $\delta m^2 \sim 3.10^{-3}$ to 8.10^{-3}. The same data can also be used to constrain $\nu_\mu - \nu_e$ mixing but here the matter effects are important and have to be taken into account. Such calculations are now in progress [38].

If the mixing is $\nu_\mu - \nu_\tau$ with δm_{23}^2 in the range $10^{-2}eV^2$ and an effective $\sin^2 2\theta_{23} = 4(U_{\mu 2}\ U_{\mu 3}\ U_{\tau 2}\ U_{\tau 3})$ near 0.6 or so what is implied for other mixings and oscillations? The only general model-independent proposal for neutrino masses is the see-saw mechanism [39]. Assuming that the neutrino masses scale with generation as $m_{\nu_i} \sim m_i^2/M$, and if one uses the up-quark masses for m_i, then $\delta m_{12}^2 \sim 10^{-10}eV^2$ and the solar neutrino puzzle can be solved with long wavelength oscillations (if the effective mixing $\sin^2 2\theta_{12} = 4 \mid U_{e_1}U_{e_2} \mid^2$ is large ($\gtrsim 0.8$)). On the other hand, if one uses $m_i = m_{down}$, then $\delta m_{12}^2 \sim 10^{-5}eV^2$ and the MSW effect may be important for solar neutrinos.

I personally favor the possibility that it is $\nu_\mu - \nu_e$ mixing with δm^2 near $10^{-2}eV^2$ and $\sin^2 2\theta$ in the range 0.6 to 0.8 which is responsible for the atmospheric anomaly [32]. In this case for high energy upcoming $\mu's$ there are unusual showering events due to matter enhanced $\nu_\mu \rightarrow \nu_e$ conversion as a signature. For solar ν_e's there is a uniform, energy independent depletion of flux by about 0.5 to 0.6 (this can be lowered to 0.4 for three flavor mixing) and somewhat less (0.55 to 0.66) for ν_e-scattering detectors. Such an energy independent solution for solar neutrinos is allowed at about 3σ level. The application of the see-saw formula leads to a mass of ν_τ from 10 eV upwards. A ν_τ of mass in the range of 10 eV to 30 eV is very attractive in terms of providing some (or most) of the dark matter in the universe. Also a δm^2_{32} in the range $100 - 1000eV^2$ is potentially detectable in several proposed experiments [40].

Further long baseline experiments and new reactor experiments are absolutely essential to confirm or rule out this interpretation of the atmospheric neutrino data.

Acknowledgements

I am grateful to Andy Acker, Gary McGrath, John Learned, Jim Pantaleone, Raju Raghavan, Xerxes Tata and Tom Weiler for many enjoyable discussions and the organizers of the DAE Symposium for their outstanding hospitality. This work was supported in part by US DOE under contract DE-AM03-76SF-00325 and by the International Centre for Theoretical Physics, Trieste.

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Discussion

Probir Roy : Comments please on $\Theta_{\nu_\mu-\nu_\tau}$ and $\Theta_{\nu_e-\nu_\tau}$ needed for $\nu_{e,\mu}-\nu_\tau$ oscialation experiments proposed at accelerators to see signals!

S. Pakvasa : The proposals at Fermilab and CERN which will probe δm^2 in the 100-1000 eV^2 range for $\nu_\mu - \nu_\tau$ oscallations claim a sensitivity range for $\sin^2 2\theta_{\mu\tau}$ better than 10^{-3}, as I recall.