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IMPLICATIONS OF THE NEW NEUTRINO OSCILLATION RESULTS

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The new results on atmospheric neutrinos, particularly the latest results from SUPER-KAMIOKANDE, clearly imply large mixing for ν_μ at the atmospheric scale $\Delta m^2 \sim 10^{-3}$ eV^2. It is argued that the existing solar neutrino results point strongly to large mixing for ν_e also, with no (convincing) energy-dependence seen and no seperate scale determined. Accounting for constraints from reactor experiments especially CHOOZ, various maximal and near-maximal mixing schemes are compared to data and the implications for long-baseline experiments explored. It is emphasised that terrestrial matter effects tend to supress ν_e mixing in atmospheric and long-baseline accelerator experimensts at multiGeV energies.

1 Introduction

The most convincing evidence for neutrino oscillations comes from the atmospheric [1] and solar [2] neutrino data, which show large ($\sim 50\%$) departures from the expected rates with no oscillations, for ν_μ and ν_e respectively:

$$P(\mu \to \mu) \sim 1/2 \tag{1}$$

$$P(e \to e) \sim 1/2 \tag{2}$$

The atmospheric and solar neutrino deficits (Eqs. 1-2) being each independently confirmed in several experiments, are considered here established effects, and are taken as the basic experimental input for this review.

The LSND results [3] on $\bar{\nu_e}/\nu_e$ appearance still (it may reasonably be said) require independent experimental confirmation, and on these grounds will not be included here. The LSND results will be discussed by I Stancu at this meeting (and see also the talk by D. Caldwell).

2 Atmospheric Neutrinos

Of course the undisputed 'Star-of-the-Show' at this point in time is the SUPER-KAMIOKANDE experiment, especially regarding the very beautiful recent results on atmospheric neutrinos. We shall all have the opportunity to hear about these first-hand from Prof. Nakahata tomorrow. Allow me to observe right away that these latest results from SUPER-K are so striking and convincing both statistically and systematically that (at least as far as I am concerned) it really is quite inconceivable that they are anything other than substantially 'correct' (ie. this effect is not just going to 'go away').

Atmospheric neutrinos (ν_μ) are produced by in-flight decays of mesons (mainly pions) generated by hadronic interactions of high energy cosmic-rays (mainly protons) in the Earth's atmosphere, see Fig. 1. Since the muons produced in the decays are themselves unstable contributing both ν_μ and ν_e it turns out that the overall initial flavour ratio for atmospheric neutrinos is $\nu_\mu/\nu_e \sim 2/1$ (and $\gg 2/1$ at high energies).

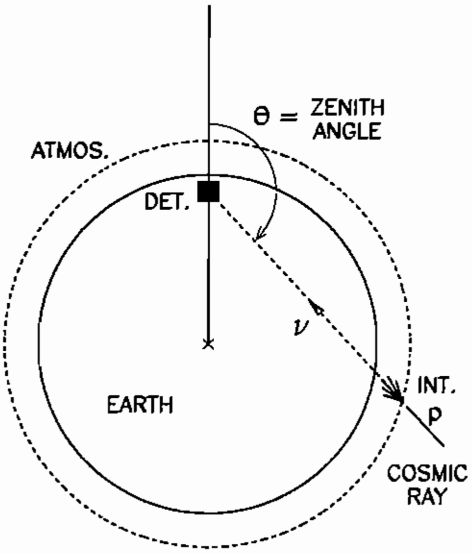

Figure 1: Atmospheric neutrino production and the definition of zenith angle (not to scale).

The atmospheric neutrino anomaly was first reported in the old KAMIOKA experiment. In essence the observed rate of 'μ-like' events in atmospheric neutrino experiments was found to be depressed relative to the rate of 'e-like' events, by an average factor $R \sim 0.60 - 0.70$ (where admittedly some of the experiments were reporting no effect, ie. $R \sim 1$). The latest and most precise value of R comes from the SUPER-K 'sub-GeV' events ($E \sim 0.2 - 1.5$ GeV): $R = 0.63 \pm 0.03 \pm 0.05$ and is clearly significantly different from unity, despite the relatively large systematic error ($\pm 8\%$) from ν_μ/ν_e flux uncertainties.

But the most impressive aspect, now dramatically confirmed by the new SUPER-K data, concerns the zenith angle distributions of the 'multi-GeV' events ($E \gtrsim 1.5$ GeV). (For the definition of zenith angle, see again Fig. 1).

Specificly (see Fig 2) μ-like events show a clear $\sim$ 50%-suppression for upward-going ($\cos\theta \sim -1$) neutrinos ie. in the case that the neutrinos have travelled the $\sim 12,000$ km through the Earth, relative to downward-going ($\cos\theta \sim +1$) neutrinos, which have travelled only the $\sim$ 20 km down through the atmosphere.

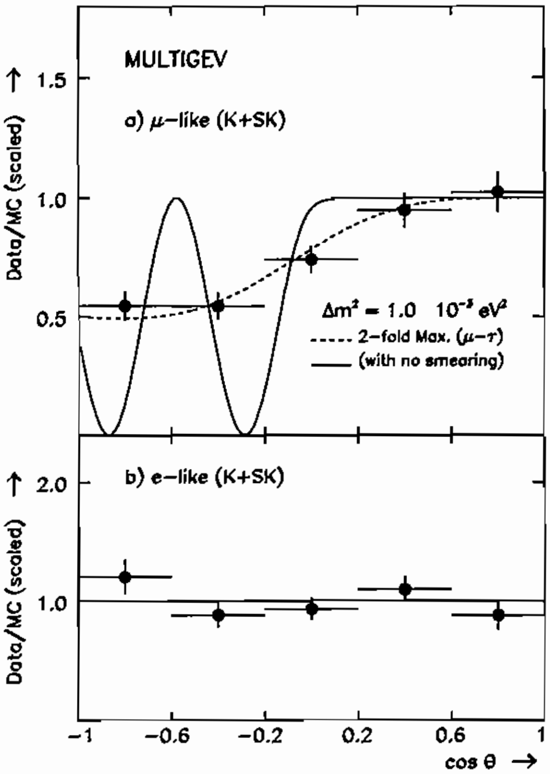

Figure 2: The combined KAMIOKA and SUPER-K multi-GeV zenith angle distributions for a) μ-like and b) e-like events. We plot the ratio of observed to predicted events rescaled for comparison with theory, independent of fluxes. The solid curve is the full oscillation curve for 2-fold maximal mu-tau mixing for a representative neutrino energy $E = 3$ GeV, while the dashed curve includes angular smearing and averaging over neutrino energies.

At the same time the rate of e-like events seems to be largely unaffected (if anything e-like events show an excess with respect to expectation).

Probably like lots of other people outside the SUPER-K collaboration, I have been reading-off the SUPER-K data points and (together with my collaborators) trying to fit them too. In Fig. 2 we plot the ratio of observed to expected rates for a) μ-like and b) e-like events vs. the cosine of the zenith angle. We saw no really significant discrepancies between the new SUPER-K data and the old KAMIOKA data, and for Fig. 2 we combined both data sets for maximum statistics. To minimise any dependence on atmospheric flux models, we incorporated in our fits (and in the plotted observed/expected ratios in Fig. 2) separate overall scale factors for μ-like and e-like events respectively, so that only the shape of the zenith angle dependence is being tested here.

So far the SUPER-K collaboration have reported that the SUPER-K data are consistent with 2-fold maximal $\nu_\mu \leftrightarrow \nu_\tau$ mixing, eg. with a mixing matrix:

$$\begin{array}{c} \\ e \\ \mu \\ \tau \end{array} \begin{array}{c} \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \left(\begin{array}{ccc} 1 & . & . \\ . & 1/\sqrt{2} & 1/\sqrt{2} \\ . & 1/\sqrt{2} & -1/\sqrt{2} \end{array} \right) \end{array} \tag{3}$$

The allowed range of Δm^2 extracted on that basis is:

$$5\ 10^{-4}\, eV^2 \ < \ \Delta m^2 \ < \ 6\ 10^{-3}\, eV^2 \qquad (90\% CL) \tag{4}$$

where the best-fit value is: $\Delta m^2 \sim 2.2\ 10^{-3}$ eV^2.

Of course a non-zero mass-squared difference implies at least one non-zero neutrino mass:

$$m_3 \gtrsim 20 - 80\ meV \tag{5}$$

where the inequality would become an approximate equality in the case of a 'hierachical' neutrino mass spectrum. While a dominant cosmological role for neutrinos seems to me far from guaranteed, it is probably reasonable to assume that there are non-relativistic relic neutrinos around today and that they contribute more to the total energy density than for example the CMB photons (cf. a typical CMB photon energy $kT \sim 0.25$ meV).

In Fig. 2 the dashed curve is the expected supression assuming 2-fold maximal mu-tau mixing (Eq. 3) including the energy distribution and the expected angular smearing, while the solid curve shows the actual oscillations with no angular smearing for a fixed neutrino energy $E = 3$ GeV (all curves here are calculated for a representative Δm^2 value $\Delta m^2 = 10^{-3}$ eV^2, not necessarily the best-fit). In accord with the conclusion reached by the SUPER-K experimenters, we see that the fit to 2-fold mu-tau mixing (with smearing) is very good indeed (eg. χ^2/DOF $= 1.5/4$, for $\Delta m^2 \sim 10^{-3}$ eV^2).

Of course as it stands the 2-fold maximal mu-tau mixing matrix (Eq. 3) predicts no ν_e mixing at any scale, and so without making some modifications to the 2-fold maximal mu-tau mixing hypothesis there is no possibility at all to account for the solar data.

3 Solar Neutrinos

The solar neutrino data are shown in Fig. 3. For each of the five (current) experiments we show the ratio S of observed to expected rates based on the BP98 fluxes. The SAGE and GALLEX results (rightmost points) are by far the most important quantitatively, because gallium experiments sample mainly the *pp* flux which is highly constrained by the solar luminosity. On the other hand the KAMIOKA, SUPER-K and HOMESTAKE ratios (leftmost points) depend almost exclusively on the ^{8}B-flux which is highly temperature-dependent and varies by up to a factor of two between different flux models.

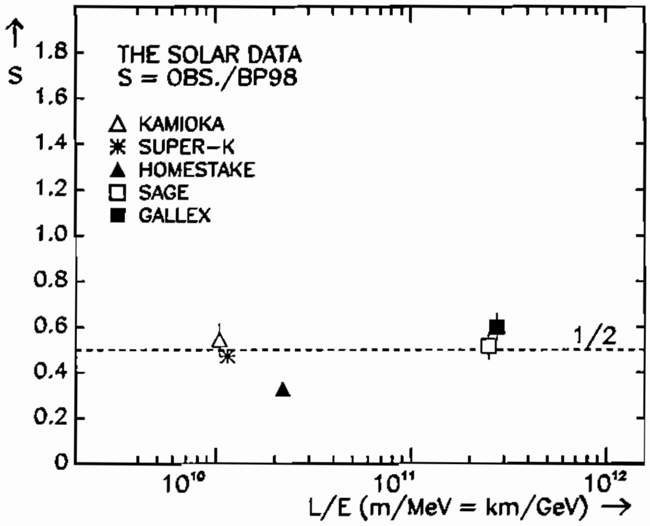

Figure 3: The solar results calculated using BP98 fluxes plotted vs. L/E. While perhaps not entirely mutually consistent, all experiments see a large ($\sim$ 50%) supression.

The dashed line $P(e \to e) = 1/2$ is a reasonable description of the data. But there are complications. The KAMIOKA and SUPER-K rates based on $\nu e \to \nu e$ scattering ($E_e > 7.5, 6.5$ MeV respectively) include a neutral current (NC) contribution which has to be taken into account (-0.14). While using BP98 fluxes this might seem to be just what is needed to fix the SUPER-K/HOMESTAKE discrepancy (Fig. 3), one would clearly still be left with a discrepancy with the gallium experiments, pointing to a smaller ^{8}B-flux (for which the relative NC correction would be less). The HOMESTAKE point is based on the excitation of ^{37}Cl and should include a $\sim$ 15% contribution from the ^{7}Be line (E = 0.86 MeV), whereby a real SUPER-K/CHLORINE discrepancy would imply an energy-dependent suppression.

3.1 The MSW Solution

Remarkably a mechanism exists[4] for acheiving just the required energy dependence, effectively deleting the contribution of the ^{7}Be line as far as the experiments are concerned. The physics is perhaps best understood by restricting to the hypothetical case of 2×2 mixing (eg. $\nu_e \leftrightarrow \nu_\mu$, say). Off-diagonal mixing elements are assumed small with $\nu_e \sim \nu_1$ and $\nu_\mu \sim \nu_2$ in vacuum. In matter however the ν_e interacts with the ambient electron density (via W exchange - CC) and at sufficiently high matter densities (eg. as in the solar core) the ν_e becomes the heavy mass eigenrnstate $\nu_e \sim \nu_2$ thus:

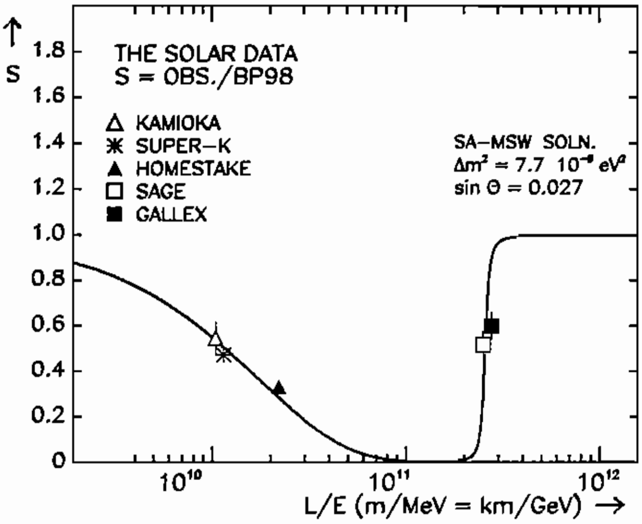

Figure 4: The MSW curve fits the solar data well, but is less than convincing (see Ref. 6).

$$\begin{array}{cc} & \begin{array}{cc}\nu_1 & \nu_2\end{array} \\ \begin{array}{c} e \\ \mu \end{array} & \left(\begin{array}{cc} 1 & . \\ . & 1 \end{array}\right) \end{array} \longrightarrow \begin{array}{cc} & \begin{array}{cc}\nu_1 & \nu_2\end{array} \\ \begin{array}{c} e \\ \mu \end{array} & \left(\begin{array}{cc} . & 1 \\ 1 & . \end{array}\right) \end{array} \qquad (6)$$

(where the dots represent some small but non-zero mixing angle in this case). The really beautiful thing is that with the solar density falling-off smoothly with radius the neutrino remains a heavy mass eigenstate (in the adiabatic approximation) and exits from the Sun as a ν_μ. By judicious choice of Δm^2 and mixing angle one may arrange for a $\sim 50\%$ supression in the gallium experiments and a $\sim 30-50\%$ supression in the HOMESTAKE and KAMIOKA experiments in excellent agreement with the data (Fig. 4).

While a small $e2$ element is readily incorporated into the 2-fold maximal mu-tau matrix (Eq. 3) to exploit [5] the small-angle MSW solution, I take the view that $P(e \rightarrow e) = 1/2$ is the 'conservative' conclusion based on the existing solar data and that energy-dependence remains to be demonstrated [6].

3.2 Bi-Maximal Mixing

If you accept that the solar data are more naturally interpreted in terms of an energy-independent supression then the form of the lepton mixing matrix might appear to be essentially determined:

$$\begin{array}{cc} & \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \begin{array}{c} e \\ \mu \\ \tau \end{array} & \left(\begin{array}{ccc} 1/2 & 1/2 & . \\ 1/4 & 1/4 & 1/2 \\ 1/4 & 1/4 & 1/2 \end{array} \right) \end{array} \tag{7}$$

(we give here the matix of the moduli squared of the mixing matrix elements, which turns out to be much more useful generally, than the mixing matrix itself). With no ν_e mixing yet seen at the atmospheric scale, the crucial feature of Eq. 7 is that the $e3$ entry (the top rightmost element) has been set equal to zero. The mixing matrix then becomes real (ie. no CP-violating phase) and is expressible in terms of only two non-zero parameters eg. $\mu 3 \sim 1/2$ and $e2 = 1/2$ fixed by the atmospheric and solar results Eq. 1 and Eq. 2 respectively. Explicitly with the top rightmost three elements fixed by experiment, all the other elements follow immediately: $\tau 3 = 1/2$ and $e1 = 1/2$ (from unitarity) whence $\mu 1 = \mu 2$ (for orthogonality), so that $\mu 1 = 1/4$ and $\mu 2 = 1/4$ and similarly $\tau 1 = \tau 2 = 1/4$.

Now from the second row of Eq. 7 the survival probability for ν_μ at the atmospheric scale ($\Delta m^2 \sim 10^{-3}$ eV^2) is given by:

$$I(\mu \rightarrow \mu) = (1/4 + 1/4)^2 + (1/2)^2 = 1/2 \tag{8}$$

while from the first row of Eq. 7 the survival probability for ν_e at the second scale ($\Delta m'^2$ yet to be determined) is given by:

$$II(e \rightarrow e) = (1/2)^2 + (1/2)^2 + (0)^2 = 1/2 \tag{9}$$

as required by the solar data (where 10^{-3} eV$^2 \gtrsim \Delta m'^2 \gtrsim 10^{-11}$ eV^2).

The matrix Eq. 7 corresponds to the famous 'bi-maximal' mixing scheme proposed now by a number of authors [7] and which surely has to be taken seriously as a valid description of the current solar and atmospheric data. The phenomenology of the 'bi-maximal' scheme is identical to that of 2-fold maximal mu-tau mixing at the atmospheric scale and is similarly completely unaffected by matter effects in the Earth (and in the Sun).

4 Threefold Maximal Mixing

Threefold maximal mixing (or 'trimaximal' mixing) is the simplest of all mixing schemes and has long been considered a likely lepton mixing matrix[8]:

$$\begin{array}{c|ccc} & \nu_1 & \nu_2 & \nu_3 \\ \hline e & 1/3 & 1/3 & 1/3 \\ \mu & 1/3 & 1/3 & 1/3 \\ \tau & 1/3 & 1/3 & 1/3 \end{array} \tag{10}$$

All charge-lepton to neutrino transitions have equal strength so that a perfect knowledge of charged-lepton flavour implies no knowledge of the neutrino mass-eigenstate and vice-versa (cf. the Heisenberg Uncertainty Principle).

In threefold maximal mixing all (vacuum) survival/appearance probabilities are universal ie. flavour independent. The standard scenario[9] exploits only one scale (the atmospheric scale) to fit both the atmospheric and solar data:

$$I(\mu \to \mu) = (1/3 + 1/3)^2 + (1/3)^2 = 5/9 \tag{11}$$

$$I(e \to e) = (1/3 + 1/3)^2 + (1/3)^2 = 5/9 \tag{12}$$

However $\nu_\mu \leftrightarrow \nu_e$ mixing is predicted at the atmospheric scale:

$$I(\mu \to e) = I(e \to \mu) = 2 \times (\mu 3)(e3) = 2 \times (1/3)(1/3) = 2/9 \tag{13}$$

and one may reasonably ask why this is not seen. Of course in vacuum, in the approximation that $\nu_\mu/\nu_e = 2/1$, the loss of ν_e in 3-fold maximal mixing is exactly compensated by $\nu_\mu \to \nu_e$ appearance $(5/9 + 2 \times 2/9 = 1)$.

4.1 Terrestrial Matter Effects

Matter effects[10] first lift the degeneracy between ν_1 and ν_2 and ultimately decouple the ν_e in the mixing matrix ($\nu_e \to \nu_3$), which in the case of 3-fold maximal mixing tends to a 2-fold maximal mu-tau mixing matrix:

$$\begin{array}{c|ccc} & \nu_1 & \nu_2 & \nu_3 \\ \hline e & . & 2/3 & 1/3 \\ \mu & 1/2 & 1/6 & 1/3 \\ \tau & 1/2 & 1/6 & 1/3 \end{array} \longrightarrow \begin{array}{c|ccc} & \nu_1 & \nu_2 & \nu_3 \\ \hline e & . & . & 1 \\ \mu & 1/2 & 1/2 & . \\ \tau & 1/2 & 1/2 & . \end{array} \tag{14}$$

with identical phenomenology to Eq. 3. In fact the perfect compensation of the ν_e rate persists in the presence of matter effects provided only that $\nu_\mu/\nu_e = 2/1$ and similarly the compensated ν_μ rate is always $1/2$ just as for 2-fold maximal mu-tau mixing (eg. $7/18 + 1/2 \times 2/9 = 1/2$).

We calculate terrestrial matter effects for atmospheric neutrinos in 3-fold maximal mixing using a general numerical program already described [9]. The calculation proceeds in 100km steps through the Earth with the density of the Earth input as a function of radius from the Standard Earth Model [11]. Fig. 5 shows the 3-fold maximal mixing predictions including smearing etc. with and without terrestrial matter effects (solid curve and dotted curve respectively) superposed on the combined KAMIOKA/SUPER-K multiGeV zenith angle distributions (cf. Fig. 2). The expectation for 2-fold maximal mu-tau mixing (dashed curve) is also shown for comparison. Clearly 3-fold maximal mixing with matter effects (χ^2/DOF = 3.6/4) fits almost as well as 2-fold maximal mu-tau mixing (or equivalently 'bi-maximal' mixing).

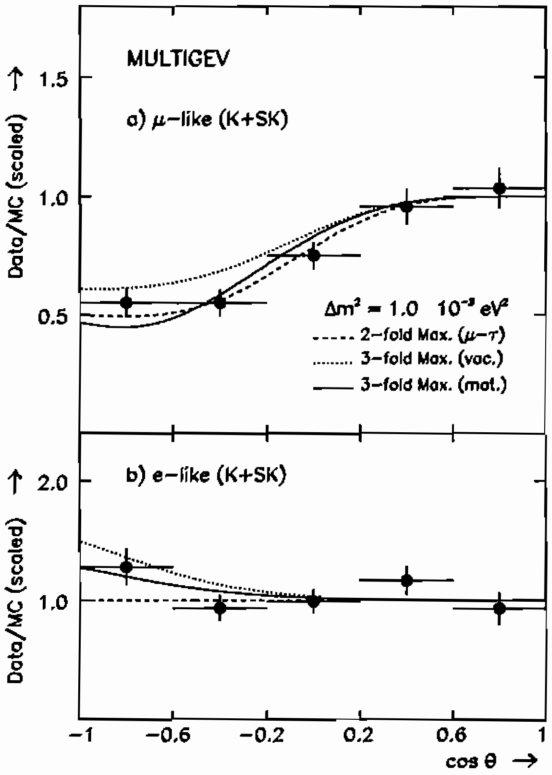

Figure 5: The combined KAMIOKA/SUPER-K multi-GeV zenith angle distributions (see also Fig. 2). The solid curve is now the 3-fold maximal mixing prediction including terrestrial matter effects which approaches 2-fold maximal mu-tau mixing (broken curve). The dotted curve is 3-fold maximal mixing neglecting matter effects.

In an up-down symmetric detector the ratio of up to down rates is likely to be rather insensitive to systematic errors, eg. flux uncertainties etc. [12] Fig. 6 shows the up/down ratio for e-like and μ-like events defined by the rates with $|\cos\theta| > 0.2$ measured using the combined multi-GeV data sets above. The solid curve shows the 3-fold maximal mixing prediction including matter effects, while the dotted and dashed curves show the 3-fold maximal vacuum and 2-fold maximal mu-tau predictions respectively. For multiGeV events $\nu_\mu/\nu_e \gtrsim 2/1 \sim 3/1$, but excessive overcompensation of the ν_e rate is inhibitited naturally here (ie. without assuming an arbitrary zero, cf. Eq. 7) by terrestrial matter effects, which supress ν_e appearance (see also Fig. 5) as the complete decoupling limit Eq. 14 is approached ($\Delta m^2/E \ll GN_e$).

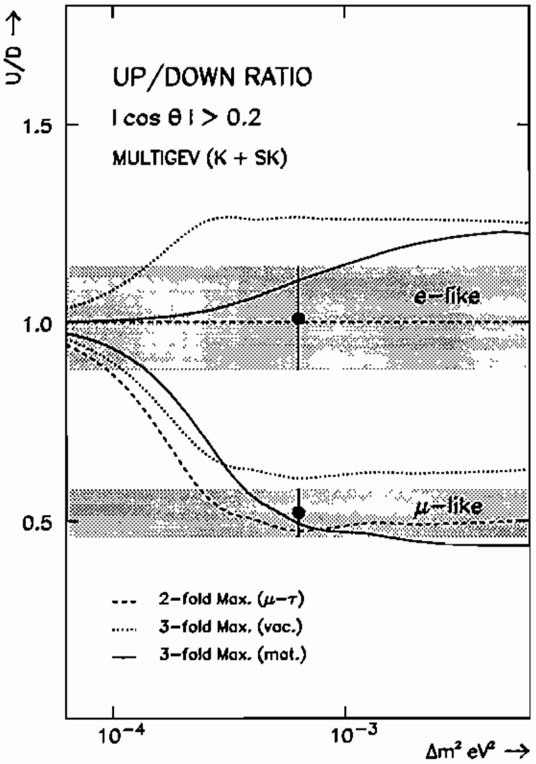

Figure 6: The predicted up/down ratio for multiGeV events as a function of Δm^2. Terrestrial matter effects in 3-fold maximal mixing (solid curves) give a compensated μ-rate $\sim 1/2$ and supress ν_e appearance naturally (for $\Delta m^2 <\sim 10^{-3}$ eV^2), consistent with the data.

5 Future Prospects

I believe the real race now is between 'bi-maximal' and 'tri-maximal' mixing. From this point of view the crucial experimental question is whether or not there is large vacuum ν_e mixing at the atmospheric scale.

Reactor experiments such as CHOOZ, PALO-VERDE [13] [14] and KAMLAND [15] play a unique role here. With their low energies (and short baselines) reactor experiments are effectively immune to matter effects. If three-fold maximal mixing is right, these experiments must see $P(e \longrightarrow e) < 1$, as shown in Fig. 7. Interestingly, the published CHOOZ limit for maximal mixing ($\Delta m^2 > 0.9 \times 10^{-3}$ eV^2 at 90% CL) seems to be weakening (cf. M. Grassi[13]). We shall hear about the KAMLAND project from Prof. Shirai on Thursday[15].

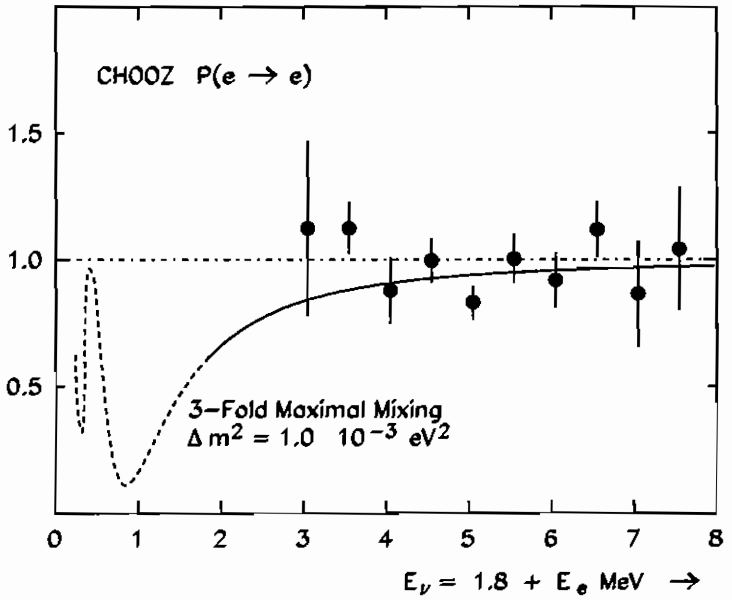

Figure 7: If 3-fold maximal mixing is right then reactor experiments must see $P(e \rightarrow e) < 1$.

Clearly terrestrial matter effects can strongly influence long-baseline accelerator experiments such as K2K [16], ICARUS[17], MINOS [18], OPERA [19] etc. As we have seen ν_e mixing can get completely switched-off at multi-GeV energies, and if one is interested in ν_e appearance[17] sub-GeV experiments such as K2K[16] seem much safer. Of course if $\nu_\mu \longrightarrow \nu_e$ is supressed $\nu_\mu \longrightarrow \nu_\tau$ is enhanced and this could perhaps be considered advantageous[19].

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References

[1] K. S. Hirata et al. Phys. Lett. B 205 (1988) 416; R. Becker-Szendy et al. Phys. Rev. D 46 (1992) 3720; W. W. M. Allison et al. Phys. Lett. B 39 (1997) 491. E. Peterson. Neutrino '98. T. Kajuta. Neutrino '98, hep-ex/9810001; M. Nakahata. These Proceedings.

[2] B. T. Cleveland et al. Nucl. Phys. B (Proc. Suppl.) 38 (1995) 47; Y. Fukuda et al. Phys. Rev. Lett. 77 (1996) 1683. J. N. Abdurashitov et al. Phys. Rev. Lett. 77 (1996) 4708. W. Hampel et al. Phys. Lett. B 420 (1998) 114. Y. Fukuda et al. hep-ph/9805021. Y. Suzuki. Neutrino '98

[3] C. Athanassopoulos et al. Phys. Rev. Lett. 75 (1995) 2650; 81 (1998) 1774. Phys. Rev. C 54 (1996) 2685. I. Stancu. These Proceedings.

[4] L. Wolfenstein. Phys Rev. D 17 (1978) 2369.
S. P. Mikheyev and A. Yu. Smirnov, Il Nuovo Cimento 9C (1986) 17.

[5] S. P. Rosen and W. Kwong. UTAPHY-HEP-13.

[6] W. G. Scott. Nucl. Phys. (Proc. Suppl.) 66 (1998) 411.

[7] V. Barger et al. hep-ph/9806382.
A. J. Bahz, A. S. Goldhaber and M. Goldhaber. hep-ph/9806540.
H. Giorgi and S. L. Glashow. hep-ph/9808293.

[8] L. Wolfenstein. Phys. Rev. D18 (1978) 958.
N. Cabibbo. Phys. Lett. B72 (1978) 333.
P. F. Harrison and W. G. Scott. Phys. Lett. B333 (1994) 471.

[9] P. F. Harrison, D. H. Perkins and W. G. Scott. Phys. Lett. B349 (1995) 137; B374 (1996) 111; B396 (1997) 186.

[10] C. Giunti, C. W.Kim and M. Monteno. Nucl. Phys. B521 (1998) 3.
R. Foot, R. R. Volkas and O. Yasuda. Phys. lett. B433 (1998) 82.

[11] J. A. Jacobs. The Earth's core. Academic Press (1987).

[12] R. Foot, R. R. Volkas and O. Yasuda. Phys. Lett. B 421 (1998) 245.

[13] M. Apollonio et al. Phys. Lett. B 420 (1998) 397.
M. Grassi. These Proceedings.

[14] F. Boehm et al. The Palo-Verde Experiment. (1995).

[15] J. Shirai. These Proceedings.

[16] Y. Oyama et al. hep-ex/9803014.

[17] D. Cline and S. Otwinovski. ICARUS-TM-98/15.

[18] W. W. M. Allison et al. Fermilab Proposal P-822 (1995).

[19] G. Iovane. These Proceedings.