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Results from atmospheric neutrinos

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Abstract. With the announcement of new evidence for muon neutrino disappearance observed by the super-Kamiokande experiment, the more than a decade old atmospheric neutrino anomaly moved from a possible indication for neutrino oscillations to an apparently inescapable fact. The evidence is reviewed, and new indications are presented that the oscillations are probably between muon and tau neutrinos. Implications and future directions are discussed.

Keywords. Neutrino; oscillation.

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1. Introduction

Herein we attempt to review the present understanding of the resolution of the atmospheric neutrino anomaly, put it in context with other results, and speculate upon future directions.

This paper documents the talk given by the author at the WHEPP-99 Workshop in Chennai, India in January 2000. The subject to be covered was generally the situation with respect to the atmospheric neutrino oscillations. The understanding of this phenomenon is now dominated by the data announced by the super-Kamiokande collaboration in June 1998, of which group the present author is a member. Much of this report dwells upon those results and updates to them, and so credit for this work is due to the whole collaboration, listed in the Appendix, who have labored hard to bring this experiment to fruition and who have been ably lead by Prof. Yoji Totsuka of the University of Tokyo. That said, some of this report is the personal opinion of the author, particularly in matters of the previous history, the interpretation and future prospects for this line of research.

1.1 *The atmospheric neutrino anomaly*

We will not dwell upon the past history, but note that the atmospheric neutrino anomaly has been around for some time, roughly fifteen years. Indeed the first notice of something peculiar going on was in the 1960's when the seminal underground experiments in South Africa and South India first detected the natural neutrinos and observed somewhat of an absolute rate deficit, but not convincingly as the flux predictions were rough and the statistics small.

The problem became serious after the activation of the IMB experiment and by 1983 the realization that the number of events containing muon decays was lower than expected [1]. Soon this was confirmed by the Kamioka experiment, which group extended the results with good particle identification giving a redundant measure of the relative muon deficit (as also did IMB). Some members of the IMB group [2] and the Kamioka group [3] began to proclaim that oscillations were the cause of the deficit, but the claim was not widely taken seriously. This author acknowledges being one of the skeptics at that time.

The deficit in the ratio is characterized usually as an R value, the ratio of muon to electron neutrinos, observed to expected. This ratio of ratios is thus independent of the 20–25% uncertain absolute flux prediction, and itself systematically uncertain by less than 10%.

With the initial evidence, the oscillations could have been from muon neutrinos to others (eg. ν_τ) or between muon and electron neutrinos, as it was the ratio that was in deficit: one could not be sure whether there was an excess of electron neutrinos, a deficit of muon neutrinos, or some of both. This lead to suggestions of other ‘physics’ causes, such as nucleon decay favoring electron modes (since the anomaly was not detected above the nucleon mass), or an excess of extraterrestrial electron neutrinos. See table 1 for a graphical summary of the situation. There were also suggestions of systematic problems, such as problems in muon identification, something wrong with flux calculations or neutrino interaction cross-sections, entering backgrounds, or with the water Cherenkov detectors.

Over the intervening years between the emergence of this ‘atmospheric neutrino anomaly’, as it became known, and last year’s announcement, a great deal of effort went into study of the possible systematic causes of the anomaly. One troubling problem was that two European experiments, the NUSEX and the Frejus detectors, did not observe any anomaly. Hence some people suspected a peculiarity of water as a target or with the employment of the Cherenkov radiation in vertex location. Not only were the statistics of the European detectors rather small, but as indicated by more recent work from the similar type of instrument in the US, the Soudan II detector, the presence of a surrounding veto counter is vital for the more compact type of slab detectors. As well, the MACRO experiment has elucidated the production of low energy (hundred MeV) pions by nearby cascades in rock, which particles enter cracks in non-hermetic detectors and appear to be neutrino interactions. In any case the Soudan II with now significant exposure (several kiloton-years) finds an R value close to that of SuperK (and IMB and Kamioka).

2. The super-Kamiokande revolution

We now proceed to summarize the new evidence for oscillations which comes from the SuperK experiment. Before going on it may be worthwhile to point out what permitted the big break-through, which is not so obvious. The increase in size of detector, from near kiloton fiducial volumes for Kamioka and Soudan, and three kilotons for IMB to the twenty two kilotons of SuperK is not the whole story. As will be seen below, the progress comes from the recording of muon events with good statistics in the energy region above 1 GeV. This is due to detector linear dimensions as well as gross target volume: muon events with energy more than 1 GeV and thus 5 m range were not likely to be fully contained in the Kamioka detector (or the IMB detector). SuperK in contrast has decent muon statistics up to almost 5 GeV, and this turns out to be crucial.

Most of the data to be discussed below is the ‘fully contained’ (FC) event sample, consisting of those events in which both vertex and track ends remain in the fiducial volume. There are also ‘partially contained’ (PC) events, in which a muon may exit the fiducial volume from a contained vertex location. Such events are useful even though the total energy is not known, the energy observed being a lower limit. Of course this is the case even with FC events, though to a lessor degree, because the observed particles are not of the same energy (or direction) as the incident neutrino, which of course is what one would desire to observe.

The particle types are identified by pattern recognition software, now well tested and verified by experiment with known particle beams at the accelerator. Fortunately most of the events (roughly 2/3) are single (Cherenkov radiating) tracks, in which the identification is quite clean (at the 98% level). To be clear and cautious we usually refer to the reconstructed events as ‘muon-like’ and ‘electron-like’, though a safe approximation is that these represent muon and electron neutrino charged-current interactions.

The other two categories of events of which we shall report are the through-going upwards moving muons (UM), produced by neutrino interactions in the rock or outer detector, and which are coming from directions below the horizon (as those from above the horizon can be confused with down going muons from cosmic ray interactions in the atmosphere near overhead). Another category of event is the entering-stopping muon (SM). It is useful that these event categories probe approximately three different energy ranges of neutrinos: FC $\simeq$ 1 GeV; PC and SM $\simeq$ 10 GeV; UM $\simeq$ 100 GeV. It should be understood that as far as we know, these neutrinos are all produced in the upper atmosphere by cosmic ray interactions, and are reasonably well described by models in content, energy, and angular dependence (to a few per cent) [5].

We shall not take up limited space here with the description of the SuperK detector, which is well documented elsewhere. The interested reader would do well to look at some of the theses from SuperK, which, though large files, are available on the web [6]. The short summary is that the SuperK detector consists of a large stainless steel cylinder (37 m high by 34 m diameter inside the inner detector) with extremely high photo-tube coverage (40%), ten times more pixels than any earlier instrument, and a remarkable sensitivity of roughly eight photoelectrons per MeV of deposited (Cherenkov radiating) energy. The latter permits detection of events down to about 5 MeV, so for the present discussion detection efficiency versus energy is not important because the events we are discussing are all above $\simeq$ 100 MeV. The inner volume is also well protected by a 2 m thick, fully-enclosing veto counter, populated by the recycled IMB photomultipliers and wavelength shifters. The inner ‘fiducial’ volume is further taken as 2 m inside the photomultiplier surface, resulting in the 22 kiloton volume used for most reported data.

The SuperK oscillations claim was first formally presented to the physics community in June 1998 at the Neutrino98 meeting in Takayama, in a talk by Professor Takaaki Kajita, leader of the on-site contained event analysis group. The data was presented in several papers to the community [7–9], building upon past data from Kamioka [3] and IMB [2], and culminating in the claim of observation of oscillations of muon neutrinos, published in *Phys. Rev. Lett.* in August 1998 [10]. We now proceed to review the evidence, which has changed little except for new indications that the ν_μ oscillating partner is probably the ν_τ, and not a sterile neutrino.

2.1 *Up-down asymmetry*

One way to look at the FC (and PC) data is in terms of a dimensionless up-to-down ratio, difference over sum (which has symmetrical errors in contrast to just up/down) [12]. This quantity is exhibited as a function of charged particle momentum in figure 1, for both electrons and muons, with the PC data shown as well (for which we know only a minimum momentum). One sees that the electron data fits satisfactorily to no asymmetry, whilst the muon data shows strong momentum dependence, starting from no asymmetry to about $-1/3$ $(-0.311 \pm 0.043 \pm 0.01)$ above 1.3 GeV.

From this figure alone, without need for Monte Carlo simulation, assuming the cause to be neutrino oscillations, one can deduce that:

1. The cause of the atmospheric neutrino anomaly is largely due to disappearing muons, not excess electrons.
2. There is little coupling of the muon neutrino to the electron neutrino in this energy/distance range.
3. The oscillations of the muon neutrinos must be nearly maximal for the asymmetry to approach one third.
4. The scale of oscillations must be of the order of 1 GeV/200 km, plus or minus a factor of several.

In fact, as seen by the dashed lines overlying the data points, the simulations do produce an excellent fit to the muon neutrino oscillation hypothesis, while the no-oscillations hy-

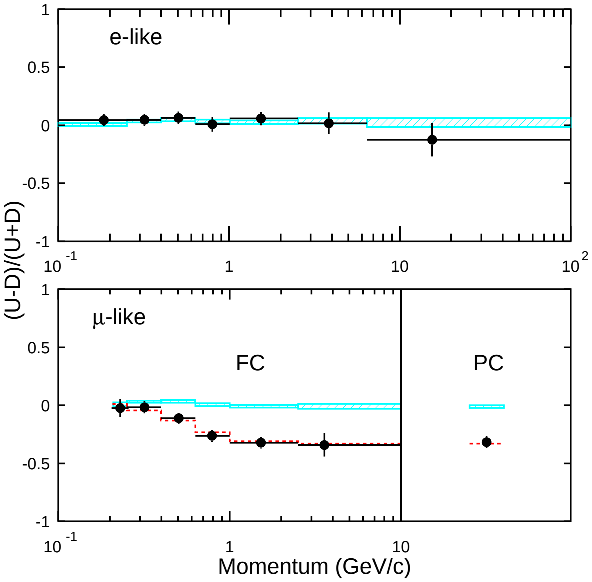

Figure 1. The up-down asymmetry for muon and electron type events in SuperK, from 848 days of live time (analysed by 6/99), as a function of observed charged particle momentum. The muon data includes a point for the partially contained data (PC), which is more than about 1 GeV.

pothesis is strongly rejected. The latter is so strong that statistical fluctuations are not in question, one must look for systematic problems to escape the oscillations explanation.

One concern for some people has been the fact that the asymmetry is indeed maximal, which makes it appear that we are very lucky that the earth size and cosmic ray energies are ‘just so’ to produce this dramatic effect. This appears to this author to fall in the category of lucky coincidences, such as the angular diameter of the moon and sun being the same from earth. (There is another oscillations related peculiar coincidence that the matter oscillation scale turns out to be close to one earth diameter, and this depends upon the Fermi constant and the electron column density of the earth.) The phase space for ‘coincidences’ is very large, and we humans are great recognizers of such patterns.

2.2 *East–West asymmetry*

The effect of the earth’s magnetic field is a little complicated. For example for energies to a few GeV, it provides some shielding from straight downwards going charged cosmic rays in regions near the magnetic equator. For higher energies and incoming trajectories near the horizon, the magnetic field still prevents some arrival paths. As the SuperK detector location is not on the magnetic equator the effect is not up-down symmetric, and this spoils the symmetry otherwise expected from the neutrinos about the horizontal plane (where there is some peaking due to longer flight paths for pions in the atmosphere). However, the effects are mostly limited to neutrino energies below about 1 GeV, corresponding to cosmic ray primaries below about 10 GeV. The picture is made a bit more complicated by the earth’s magnetic field not being a nice symmetrical dipole. Fortunately there are good models of the magnetic field and the people who have made flux calculations take this into account. The SuperK group has published a paper [9] showing the azimuthal variation of the SuperK data ($\pm 30\,\mathrm{deg}$ about the horizon) for intermediate to higher energies (400–3000 MeV), where the calculations are reliable. (Certain simplifications such as a one dimensional cascade model have been regularly used, which surely is not a good approximation at the lowest energies.) The SuperK data exhibit significant variation from uniformity yet fit the flux predictions very well, giving one confidence in the modeling [9].

2.3 *Natural parameters for oscillations: L/E*

In an ideal world, one would assuredly present this data as a function of distance divided by energy, L/E, since that is the parameter in which one expects to see oscillatory behavior. Since we observe only the secondary charged particle’s energy and direction, badly smeared at the energies available, plots in which one would wish for visible oscillations can at best show a smooth slide from the no-oscillations region to the oscillating regime. This is illustrated in figure 2, where the ratio of numbers of events observed to those expected with no-oscillations is plotted versus ‘L/E’ [13], for muon and electron (type) events.

The plot is not ‘normalized’, and since we see somewhat of an excess of electron type events overall, the solid circle indicated electron points are a bit greater than one on average ($+14\%$). This is a little worrisome, but acceptable since (as already noted) the absolute flux is uncertain to a larger value. In contrast to the electron data, the muon points fall with increasing L/E, reaching a plateau at about one half their initial value, again consistent with oscillations. Muon neutrino oscillations in the Monte Carlo simulation are indicated by dotted line, and fit the data reasonably well.

As noted, the data does not show oscillations, presumably due to convolutions washing out the oscillatory behavior. It was this smooth falloff that got us wondering if another model might fit the data, one in which one component of the muon neutrino decays with distance. We wrote a paper [14], and a second version [15], suggesting decay to explain the atmospheric neutrino anomaly. I will not discuss details here, but note that in order to get a model that fit the available facts we had to push on all available limits, and we invoke neutrino mass and mixing in any case. Consequently such models do not pass the economy test of Occam's Razor, though most annoyingly they remain not ruled out as yet.

Considering future experiments, this is one area in which improvement may indeed be made. A hypothetical detector, such as a megaton version of the Aqua-RICH instrument studied by Ypsilantis and colleagues could have the resolution to see a multi-peaked L/E plot [16].

2.4 *Fits in energy and angle*

The SuperK Collaboration's preferred method of fitting the ensemble data is to employ a χ^2 test to numbers of events binned by particle type, angle, and energy, a total of 70 bins.

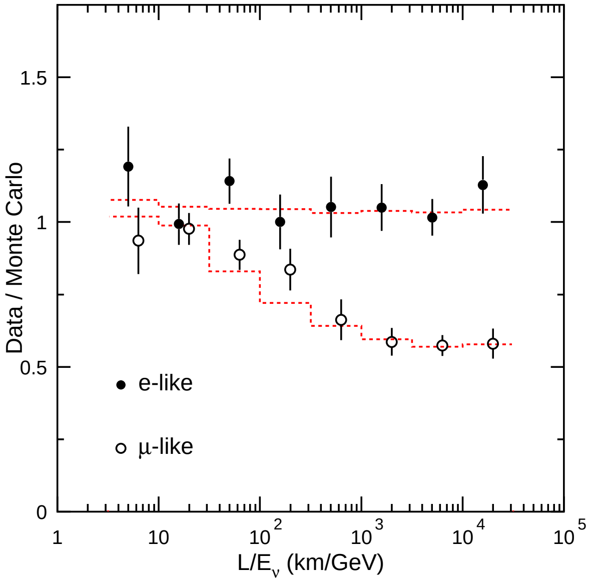

Figure 2. The ratio of numbers of events observed compared to predicted as a function of the natural oscillations parameter, distance divided by energy. The results are not normalized and overall there is a slight excess (not significant) compared to expectations. Electrons show no evidence for oscillations, while muons exhibit a strong drop with L/E. This is consistent with oscillations, as indicated by the dashed lines from simulations.

The bin choices may seem a bit peculiar, but they have historical precedent (they are as employed for Kamiokande) and though not optimal for the new data set, this choice allows us to avoid paying any statistical (or confidence) penalty for choosing arbitrary bins. The fit employs a set of parameters to account for potential systematic biases. Details cannot be presented here, but it has been shown that the numerical results are quite insensitive to the selection of the parameters or their supposed 'errors' (except for the overall normalization) [17].

Figure 3 illustrates the data plotted for two energy intervals (sub-GeV and multi-GeV, more or less than 1.3 GeV) for single track events identified as either electron-like or muon-like. The partially contained data is added to the multi-GeV muon data. The data is shown as a function of the cosine of the zenith angle, with $+1$ being down-going. One sees that the data very well fits the curves gotten from the Monte Carlo simulation, at the values gotten from the grand ensemble fit ($\delta m^2 = 0.003\,\mathrm{eV}^2$ and $\sin^2(2\theta) = 1.0$).

The results of the fits are often presented in terms of an inclusion plot, showing an acceptable region(s) in the space of mixing angle ($\sin^2 2\theta$) and mass squared difference (δm^2), as presented in figure 4. The minimum in δm^2 has moved a little upwards with accumulated statistics, though not much, (good news for long baseline experiments anyway) but remains uncertain to about a factor of two.

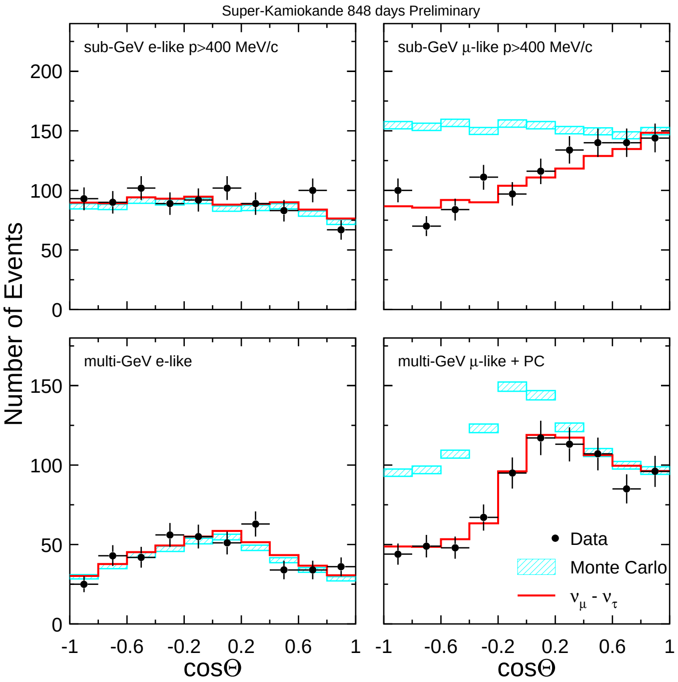

Figure 3. Cosine of zenith angle distributions of the contained event data for two different energy ranges, electron and muon events. Shaded region shows no-oscillations simulation, and heavy line for oscillations between muon and tau neutrinos.

2.5 *Muon decay events*

It is not often emphasized, but the original indication of the anomaly, a deficit in stopped-muon decays ($\simeq 2.2\,\mu$ sec after the initial neutrino event), remains with us, and constitutes a nice alternate, almost independent, sample with quite different systematics. It is not so clean a sample and the statistics are lower, but the complete consistency of the muon decay fraction remains a reassuring complement to the energy and angle analysis employing track identification.

2.6 *Through-going and entering-stopping muons*

Another cross check comes from the UM and SM samples, particularly nice as the source energies are factors of 10 and 100 higher and the detector systematics rather different (for example, the target is mostly rock not water). In going from the earlier instruments to SuperK, however, the gain is not so great (about a factor of 2.5 times over IMB, for example), since the rate of collection of through-going muons depends upon area not volume. However, the much greater thickness of the detector and the good tagging of entering and exiting events in the veto layer yields many more stopping (SM) events.

The angular distribution for UM events from below the horizon is shown in figure 5, where one sees that the angular distribution is nicely consistent with oscillations and not with no-oscillations. However, since much of the effect is close to the horizon, where oscillations for the energies in question are just setting in, one worries about contamination

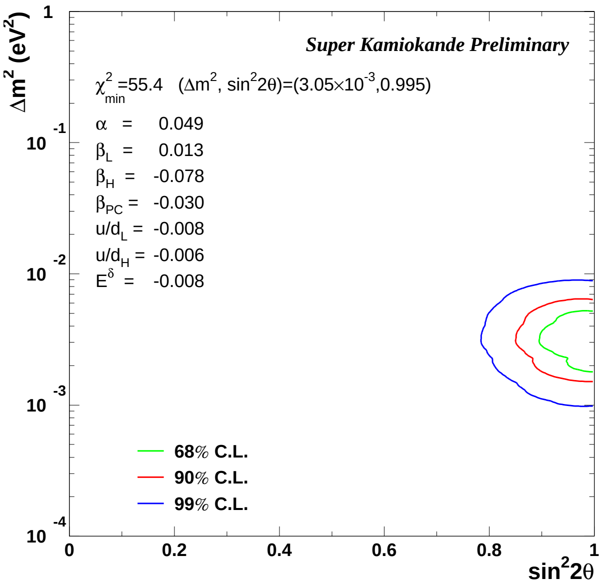

Figure 4. Inclusion plot, showing the regions for various degrees of statistical acceptability in the plane of mixing angle and mass squared difference. Contained event data analysis of June 1999.

of the near horizon events with in-scattered events from the much greater numbers of down going muons. There is no room for details here, but we find no evidence for significant contamination [11].

The SM sample was predicted to be 35–40% of the UM sample, as indicated in figure 6, yet in fact we see only about $24\% \pm 3\%$. Fitting the data to the oscillation hypothesis one can make the now usual inclusion plot, which shows that the UM and SM results are completely in accord with those from the FC and PC data. However, as the statistics are smaller and the physics leverage not as great, the muon result does not add much to the FC and PC constraints, though it does stiffen the lower bound in δm^2.

There is a lengthy tale about an SM/UM analysis from the IMB experiment [2], which claimed an exclusion region very close to the now preferred solution. This result seems to have been flawed due to older flux models and Monte Carlo simulations. Work is in progress to reassess the old data with new flux calculations and an updated quark model. Thus there remains a cloud upon the horizon, but one which I expect will fade away in reanalysis.

2.7 *The muon neutrino's oscillation partner*

Given that the muon neutrino is oscillating, is it oscillating with a tau neutrino or a new sterile neutrino which does not participate in either the charged (CC) or neutral current (NC) weak interaction? Fortunately we have several means to explore this with SuperK data. The NC events should show an up-down asymmetry for sterile neutrinos but not for tau neutrinos (as the NC events for all ordinary neutrinos are the same). Another av-

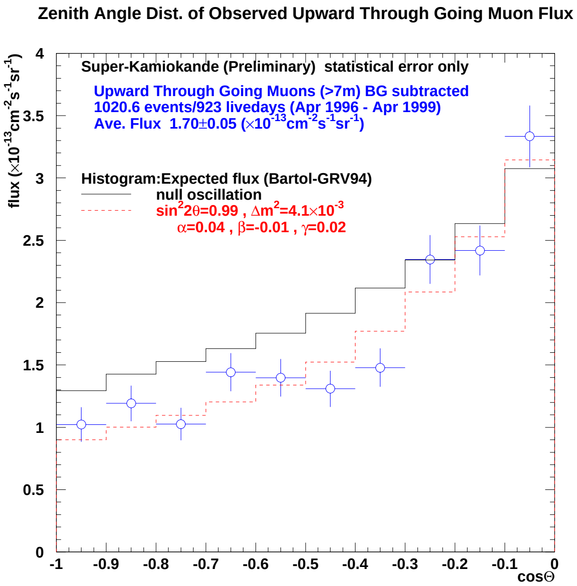

Figure 5. The angular distribution of upcoming muons from 902 days of SuperK data. Expectations for no-oscillations and best fit from contained events are indicated.

enue for discrimination is that sterile neutrinos would have an additional oscillation effect due to ‘matter oscillations’. The consequence would be a unique signature in the angular distribution of intermediate energy muons.

Early SuperK efforts focussed upon the attempt to collect a clean sample of π^0 events. As it turns out, this has been frustrating because the rings (from the two decay γs) cannot be separated at energies above $\simeq$ 1 GeV, and in net there are not so many reconstructed events as to permit a good discrimination. In fact the absolute rate is consistent with expectations, but the cross section is uncertain to about 20% making the hint at tau coupling not significant.

More recently, tests have been devised employing the PC event sample and the UM sample. The PC sample can be cut on energy to yield a somewhat higher mean source energy, and the upwards going number compared to downwards number of events. For the muons a near horizontal number can be compared to number of nearly straight upcoming events. Preliminary results from SuperK give no encouragement for sterile neutrino model builders. It appears that the tau neutrino hypothesis fits the data, while the sterile neutrino hypothesis is rejected at about the 2 standard deviation level. A publication will be forthcoming from SuperK.

2.8 *Hypotheses to explain anomaly*

We conclude with a summary table 1 of all hypotheses put forth to explain the atmospheric neutrino anomaly. Space does not permit a full discussion here, but it is the case that with

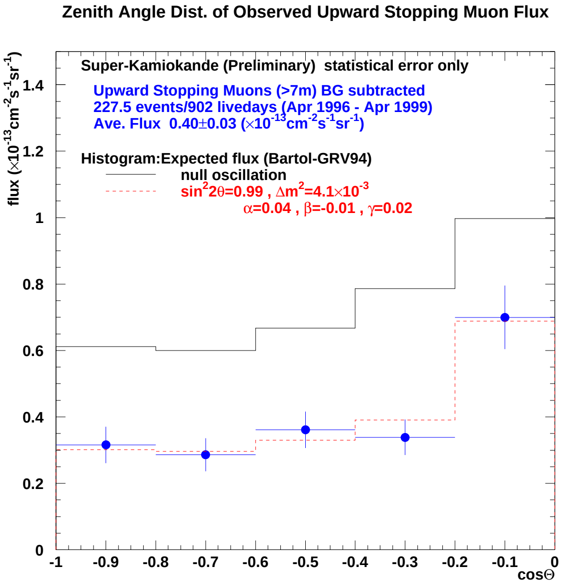

Figure 6. The rate of stopping muons versus zenith angle in 902 days of SuperK data. The large deficit is less significant than it appears because of a 20% uncertainty in absolute flux.

the SuperK data we now have eliminated almost all alternate hypotheses to explain the results. The only exception of which the author is aware involves the peculiar decay model, but it is one that nobody takes very seriously (including the author who is co-author of the model). The only hypothesis which fits the evidence, and it fits very well, is that muon neutrinos maximally mix with tau neutrinos with a δm^2 in the range of 2–5 $\times 10^{-3}$ eV^2.

3. Implications

The ramifications of the atmospheric neutrino anomaly are great and span the known realms of fundamental physics from large to small. We have not discussed in this short paper the links to solar neutrinos, nor the LSND results. Certainly there is no conflict between the atmospheric muon neutrino results and the possible (nay likely) solar oscillations. If, however, the LSND results are correct, then we have surely some interesting physics to untangle, as it is generally admitted that no simple three neutrino model can incorporate all three neutrino anomalies, and that new degrees of freedom would be required.

Table 1. List of hypotheses invoked to possibly explain the atmospheric neutrino anomaly. The first 3 columns are criteria available prior to SuperK, and the last 4 after the 1998 SuperK publication. The hypotheses divide into 5 systematics issues and 7 potential physics explanations. As indicated in the text, the only remaining likely hypothesis is the oscillation between muon and tau neutrinos. The 'x' schematically indicates which evidence rules out the hypothesis in that row.

Evidence	Old			New			
Hypothesis	R $(E < 1$ GeV)	μ decay Frac	Vol. Frac	R $(E > 1$ GeV)	A_e $\simeq 0$	A_μ < 0	$R(L/E)$ $\simeq 0.5$
Atm. flux calc.	xx			x		x	x
Cross-sections	xx			x		x	
Particle ident.		xx	xx				
Entering bkgrd.			xx			x	
Detector asym.			xx				
X-ter. ν_e						x	x
Proton decay				x		x	x
ν_μ decay							$\simeq$x
ν_μ abs.							x
$\nu_\mu - \nu_e$					x		
$\nu_\mu - \nu_s$						x	
$\nu_\mu - \nu_\tau$							

3.1 *Astrophysics and cosmology*

The implications of the oscillations results have been explored in other talks at this meeting as well. First, it appears that neutrinos with summed masses of the order of 0.1 eV will not make any major contribution to resolving the dark matter quandary. Nonetheless with a ratio of 2 billion to one for photons (and neutrinos) to nucleons from the Big Bang, even such a small neutrino mass may be greater in total than all the visible stars in the sky. Hence one must account for neutrino mass in further cosmological modeling, but neutrinos are not likely to constitute the bulk of the 'missing matter'. However if the neutrinos should be nearly degenerate in mass and all have masses in the range near 1 eV (and hence we are observing only small splittings with the oscillations), then neutrino mass may dominate the universe. While neutrinos are not favored by astrophysical modelers (fitting the spatial fluctuations in the cosmic microwave background for example), large neutrino masses are not ruled out. Nearly degenerate neutrino masses would not present a consistent picture with the quark and charged lepton masses, which make large mass jumps between generations. But who knows? We do not have a viable GUT with mass predictions, so an open mind is appropriate.

The other major area of significance, perhaps of the deepest significance has to do with baryogenesis, the origin of the predominance of matter by one part per billion over anti-matter at Big Bang time. There are claims that the old idea of accumulation of net baryon number will not survive the early stages of universe expansion [18,19]. If that is indeed the case, it may be that neutrinos provide the avenue for net baryon asymmetry generation, relatively late in the game [20].

Neutrino masses and possible sterile neutrinos have also been invoked to help resolve problems in understanding heavy element synthesis in supernovae.

3.2 *Theoretical situation: Why so important?*

There have been a number of talks at this Workshop about the particle theory situation, so I can add little. In figure 7, I show the masses of the fundamental fermions in three generations, on a logarithmic scale in mass. Dramatically, one sees that if the neutrino masses are near the lower bounds (that is at the presumed mass differences from present atmospheric and solar results), they lie 10–15 orders of magnitude below the other fundamental fermions (charged quarks and leptons). Graphically one notes the spacing between the neutrino masses and the charged fermion masses is just about the same as the distance (on the log scale) to the unification scale. This is a pictorial representation of the see-saw prediction, as we noted more than ten years ago [4]. This points up the task for grand unification, and highlights the deep link between neutrino masses and nucleon decay.

3.3 *Future*

During the last year the physics community seems to have largely accepted the inevitability of neutrino mass and oscillations [**?**]. Of course the game has hardly begun and many a sublety may await our exploration. But if the LSND claims will go quietly away, the mass and mixing may settle into the simple hierarchical pattern explored in the bi-maximal mixing scenario (or similar versions). To my taste this highlights the importance of experiments to follow up on the LSND results as one of the first agenda items in the neutrino business.

Given present indications, it would seem that the K2K and MINOS experiments should confirm the SuperK results and make the oscillation parameters more precise. Of course, one would really like to see tau appearance, not just muon disappearance to be sure we are not being misled. There are many arguments in the community as to what constitutes appearance. Because of the complexity of tau final state identification, this author would prefer to see a real tau track recorded. In any case plans are in progress in the US, Japan and Europe for the obvious follow up experiments to nail things down.

More interesting for the long range physics is filling in the MNS matrix (lepton equivalent of quark CKM matrix) for neutrinos. This is not an easy business. The atmospheric neutrino measurements really are only defining, at best, three of the nine elements! Solar neutrinos get us another, perhaps a constraint on two. Measuring the tau related components directly seems pretty hopeless. Of course if we can assume the matrix to be unitary and real we are, or soon will be, in good shape as there are then only three independent parameters (plus the masses). But we do not know this, and if there exist CP violations we then have a total of three angles and two phases (but only one measurable). If there are more (heavy or sterile) neutrinos, then things could be much more complicated (as the 3 by 3 sub-matrix will not be unitary). By analogy with the quarks (where the 3 by 3 CKM with small mixing angles and one CP violating phase seems to do the job), perhaps we should not worry too much, except for lack of any guidance whatsoever from theory. CP violation is only very weakly constrained experimentally in the neutrino sector at present, so we could be in for big surprises, and given the neutrino connection with cosmology and baryogenesis, one should indeed be suspicious, I believe. As a whole, the particle physics community is just beginning to explore this avenue, but it looks as though muon colliders

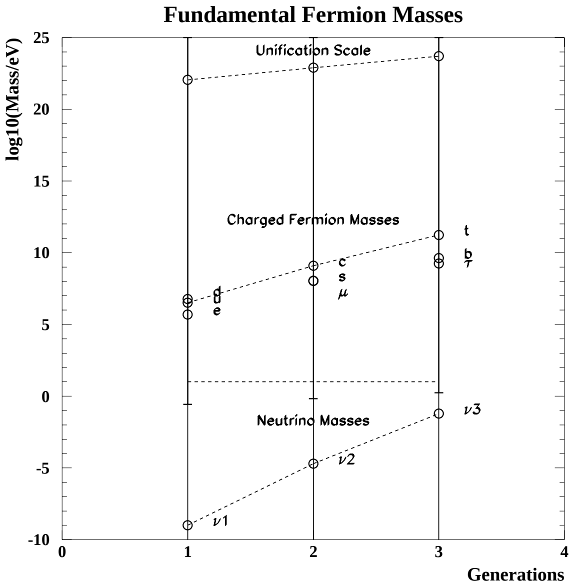

Figure 7. The masses of the fundamental fermions.

may provide our best route for exploring this new realm. Measuring absolute mass remains a frustrating problem, which will not be resolved in the near future it seems.

It seems to me that a next generation (megaton) scale nucleon decay and neutrino detecting instrument would do wonders for advancing this line of investigation. To my view, simply building a larger version of SuperK will not suffice because we need greater resolution as well as size. The only candidate I see at the moment is something like the AQUA-Rich style of imaging water Cherenkov detector [16]. In any case we can expect a long and interesting exploration into neutrino mass and mixing now that the door has been opened.

Appendix

Super-Kamiokande Collaboration, 6/99

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