FUTURE ATMOSPHERIC NEUTRINO EXPERIMENTS

JAAP PANMAN
CERN
1211 Geneva 23, Switzerland
E-mail: jaap.panman@cern.ch

ABSTRACT

We examine the presently available data on atmospheric neutrino oscillation. A comparison of the possibilities for observations with atmospheric neutrinos and with measurements which can be done with the help of accelerators is made. The remaining open questions are identified and the methods how to get answers are explored. We look at the capabilities of existing experiments and review the requirements and opportunities for the next round of dedicated atmospheric neutrino experiments. The aim is here not to identify the most general atmospheric experiment, but rather to search for a possibility to address very specific questions.

1. Introduction

The Water-Cherenkov experiments Kamiokande-II[1)] and IMB[2)] reported measurements of the ratio of muon-neutrino and electron-neutrino induced events with a value about a factor two smaller than what would be expected from the neutrino flux calculations. Also signs of neutrino oscillation were already visible in the Kamiokande-II zenith angle distributions[3)]. Recently, measurements of atmospheric neutrino events of the Super Kamiokande collaboration confirmed the earlier data from the Kamiokande-II experiment[4)]. Strong evidence for neutrino oscillation phenomena is presented by the measurement of the zenith-angle distributions of electron-like and muon-like events[5)]. The muon-like events show a depletion for upward going muon-neutrinos, while electron-like events show no oscillation effect. The measurements of upward going muons are consistent with this picture[6)]. Upward going muon data[7,8,9,10)], are consistent with the Super Kamiokande data, although these are much less significant.

Super Kamiokande will continue to produce more atmospheric neutrino data and resolve many of the questions which are now still open. In this paper we will explore whether there are issues related to oscillation which will not be settled by the Super Kamiokande experiment and should be addressed by other, *complementary* measurements with atmospheric neutrinos.

We will concentrate here on one particularly important measurement, the determination of Δm^2. Of course, also other studies with atmospheric experiments are possible and should be pursued.

1.1. Present Data

Although more results are available, the most constraining data at present are the measurements by the Super Kamiokande collaboration. The evidence for oscillation is given by the ratio, R, of ν_μ and ν_e-like events (*"double ratio"*), the angular distribution of upward going muons, and most convincingly, the zenith angle distributions of ν_μ and ν_e-like events. The *double ratio* can be interpreted as a loss of ν_μ-events, and is consistent with earlier measurements by IMB[2], Kamiokande-II[1], and with new Soudan-II[8] data. It is not in contradiction with earlier measurements[11,12] with smaller statistical significance which did not show any effect.

The most convincing data set to support the neutrino oscillation hypothesis is the measurement of the zenith angle distributions of fully contained (FC) and partially contained (PC) electron-like and muon-like events by Super-Kamiokande[5]. The zenith angle distributions of muon-like events show features typical for neutrino oscillation without having to rely on knowledge about details of the calculations of the spectra. These distributions support the interpretation that there is a deficit of ν_μ for events coming from below. No such angular dependence is observed for the electron-like events, strengthening the hypothesis of ν_μ-disappearance. The absence of a large oscillation signal in the Super Kamiokande electron neutrino events is supported by measurements at the CHOOZ reactor[13], which exclude a large mixing of ν_μ with ν_e for $\Delta m^2 > 10^{-3}\ eV^2$. Of course a small $\nu_\mu \leftrightarrow \nu_e$-mixing cannot be excluded[14,15].

The *double ratio* is given for different energy samples (sub-GeV and multi-GeV events). The value of the double ratio of the multi-GeV events sets a lower bound[16] for Δm^2 around $10^{-3}\ eV^2$. Similarly, the sub-GeV double ratio give a constraint $\Delta m^2 < 10^{-2}\ eV^2$. The measurement of the zenith-angle distribution of upgoing muons from Super-Kamiokande shows a pattern consistent with $\nu_\mu \leftrightarrow \nu_\tau$ oscillation with $sin^2\ 2\theta > 0.4$ and $10^{-3} < \Delta m^2 < 10^{-1}\ eV^2$. This result is similar to previously published data on upgoing muons by Kamiokande[9] and MACRO[7]. The comparison with the results from the Baksan experiment[17] shows some inconsistencies which need to be resolved. A precise determination of the oscillation parameters from these data is not yet possible.

The bounds given by the flavour ratio measurement depend on calculations of the expected flavour ratios of the atmospheric neutrino flux and experimental efficiencies for different topologies. The measurements rely on the neutrino spectra at low energy (*i.e.* below $2\ GeV$). An experimentally cleaner measurement can be obtained by using the zenith angle distribution of muon-like events, and in particular the up-down ratio. In this case one compares identical topologies and many experimental uncertainties cancel. Present measurements of the zenith angle distributions[16] still allow a large range of Δm^2. As expected, the measured distributions of the low energy events

($E < 400\ MeV$) are almost insensitive to Δm^2. In summary, the probable value of Δm^2 lies between $10^{-3}\ eV^2$ and $10^{-2}\ eV^2$, while values down to $3 \times 10^{-4}\ eV^2$ are not excluded by the zenith angle distributions. The mixing angle of the dominant process is large. The bounds on sub-dominant processes are still weak.

Although the global features in the present data are rather clear, questions about details of the measurements remain. Details of the calculations of the neutrino spectra, especially at low energies, are uncertain[18,19,20]. The absolute scale of the flux is badly known. Recent improvements in the analysis of the data together with an increase in the statistics have also lead to significant changes in the results[16]. This has recently been pointed out independently[21] and the question was raised whether the neutrino flux can be considered constant in time. It is therefore of great importance to single out measurements which are independent of *external* uncertainties.

1.2. Open Questions

Although the evidence for neutrino oscillation phenomena has now been established by the Super Kamiokande experiment, little is known about the details. A large number of models is still consistent with the experimental facts[22]. In order to be able to gain better understanding, many more observations are needed.

Effects observed today indicate strongly that there is a lack of muon-like events. The remaining choice one has is between oscillation of ν_μ with active (ν_τ) or sterile neutrinos. The only candidate for a light active neutrino involved in this process is the τ-neutrino. Sterile neutrinos appear quite naturally in models for neutrino mass and cannot be easily dismissed[23]. The phenomenology of these two options cannot yet be distinguished. Super Kamiokande attempts to distinguish the two cases by comparing the rate of a neutral-current process (or a *neutral-current enhanced sample*) with the charged-current interactions[16]. This measurement is not yet conclusive. One of the reasons is the lack of calibration of the effective cross-section of the *neutral-current enhanced sample*. The neutral-current rate is not changed for an oscillation between active neutrinos, while it will be suppressed if sterile neutrinos are involved.

The open questions are therefore:

- which is the flavour composition of the oscillation, and
- what are the values of Δm^2 and $sin^2\ 2\theta$.
- Are there also sub-dominant oscillations with smaller mixing present?

We will try to explore which experiment or set of experiments can give these answers. The task is to single out experiments where the *a priori* knowledge of the neutrino spectrum and other input data which can lead to *external* systematic uncertainties are minimised.

2. Experimental Methods

2.1. Atmospheric versus Accelerator Experiments

To define a strategy for future experimentation it is important to keep in mind the relative strengths and weaknesses of the methods at hand. A comprehensive summary of the relative merits has been spelled out by Battistoni and Lipari[24)]. The advantages of neutrino beams made at accelerators are:

- The beam energy spectrum can be modified to suit the experiment. In particular, one can produce beams with a significant part of the neutrino energy spectrum above τ-production threshold.
- The beam intensity of an accelerator based beam can be higher than the atmospheric neutrino flux, depending on the distance from the source.
- The flavour composition of the beam can be controlled to some extent by the focusing system.
- The neutrino flux is well calculable, although not with high precision.
- The possibility exists to calibrate the measurements at the far location with a detector in the same beam line at a near location.
- The time structure of the beam can be used to discriminate the neutrino events from cosmic-ray background, making it possible to operate detectors at the surface.

A limitation is the need to choose the baseline of the facility once and for all. The range of L/E covered with a single facility is an important constraint.

The atmospheric neutrino flux has complementary advantages. The range of energies and neutrino flight paths is very large, such that experiments can be sensitive to a large range in Δm^2. One can exploit the intrinsic symmetries of the flux, to compare the effects at different flight path but with identical initial neutrino spectra. Moreover, atmospheric neutrinos are available even without an accelerator facility.

The largely orthogonal advantages of the accelerator based studies and atmospheric experiments justify the pursuit of both methods. The *a priori* choice of baseline at the construction time of the beam line is a limitation inherent to accelerator facilities. Therefore, it makes sense to build more than one such facility in the world with different properties.

Neutrino beams at muon storage rings can possibly provide fluxes orders of magnitude more intense than present beams[25]. The radically different technique to prepare the neutrino beam decouples the pion and muon *production* energy from the energy at the *decay*. Therefore the neutrino spectrum can be much better tuned to optimise experimental conditions, and is at the same time calculable to any required precision. The decay region, being a storage ring, can be made much shorter than the one of conventional beams, adding flexibility to the choice of the location of the neutrino detector. The flavour composition of the beams is determined by the choice of the charge of the muons stored, and does not have unwanted admixtures of background particles. These beams are, to our knowledge, the only option to allow sensitive measurements in the $\nu_e \leftrightarrow \nu_\tau$ oscillation channel.

2.2. Double Ratio

The double ratio measurements provided the first indications for neutrino oscillation phenomena in the atmospheric sector. If by other means it can be argued that *e.g.* the ν_e-flux is not affected by oscillation, the ν_e's can serve as a calibration for the absolute rate to be expected for the ν_μ flux. The naive expectation is a factor two higher flux of muon neutrinos (ν_μ and $\overline{\nu}_\mu$) compared to electron neutrinos (ν_e and $\overline{\nu}_e$). The argument is simply provided by counting of the decay products of the pion and assuming all pions and muons decay before being absorbed. This ratio is not constant as a function of neutrino energy and zenith angle[18,19]. Effects that play a role are many. The long decay length of muons is one of these, such that a non-negligible fraction of the high energy part reaches the earth surface, especially if produced vertically. Energy spectra of the muons are different from the pions and the decay kinematics show differences. The flux is made of a mixture of neutrinos and antineutrinos, which have different total cross-sections. This introduces a sensitivity to the event sample included in the measurement. At low energies, geomagnetic effects introduce asymmetries in the neutrino flux.

Apart from the flux-related uncertainties, also experimental uncertainties are present. One is introduced by the experimental ability to separate the event samples and to define the efficiencies for the selection.

2.3. Upgoing Muons

The measurement of oscillation parameters using the angular distributions of upgoing muons (entering and stopping or through-going) requires the knowledge of the expected distributions. Ingredients in these calculations are the neutrino flux calculations, and the composition of the rock underneath the detector. The knowledge of the (neutrino-)energy distribution of the sample studied is also obtained by simulation. Some non-understood features are present in the data, *e.g.* details of the MACRO[7]

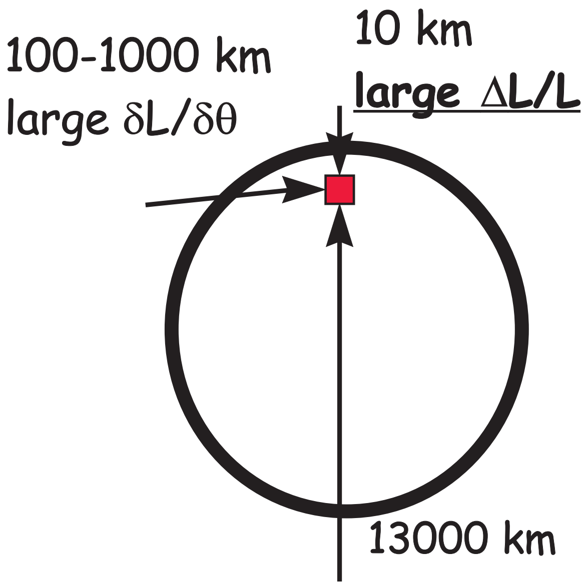

Figure 1: Neutrino flight path as function of zenith angle. The vertical downward direction is characterised by a small distance and a large $\Delta L/L$, the horizontal direction has intermediate distances and a large $\delta L/\delta\theta_\nu$, while the vertical upward direction has a well-determined long flight path.

spectra, and the differences in the comparison of the Baksan[17)] distributions with the others[7,8,9,10)]. It is unlikely that a reliable precision measurement of the oscillation parameters can be obtained from these data.

Owing to their different range of neutrino energies, these distributions provide valuable input for the comparison of the oscillation hypothesis with other mechanisms proposed to explain the suppression of muon-neutrino events[26,27)].

2.4. Zenith Angle Distributions

Zenith angle distributions of neutrino interactions are sensitive to neutrino oscillation by the correlation of the angle with the neutrino flight path. An excursion from a flat distribution indicates a difference in survival probability as function of the distance (L) between neutrino production and interaction. The strength of this method is that it compares processes with similar topologies and identical cross-sections. Thus many systematic uncertainties cancel.

There are three distinct regions in the angular distributions (see Fig. 1 and 2). The first region is formed by the interactions from down going neutrinos with directions near the vertical. In this case the L is determined by the altitude in the atmosphere where the parent particles decayed. The value of L is relatively small (10 km), and the spread relatively large. Any oscillation structure in the L/E spectrum in this

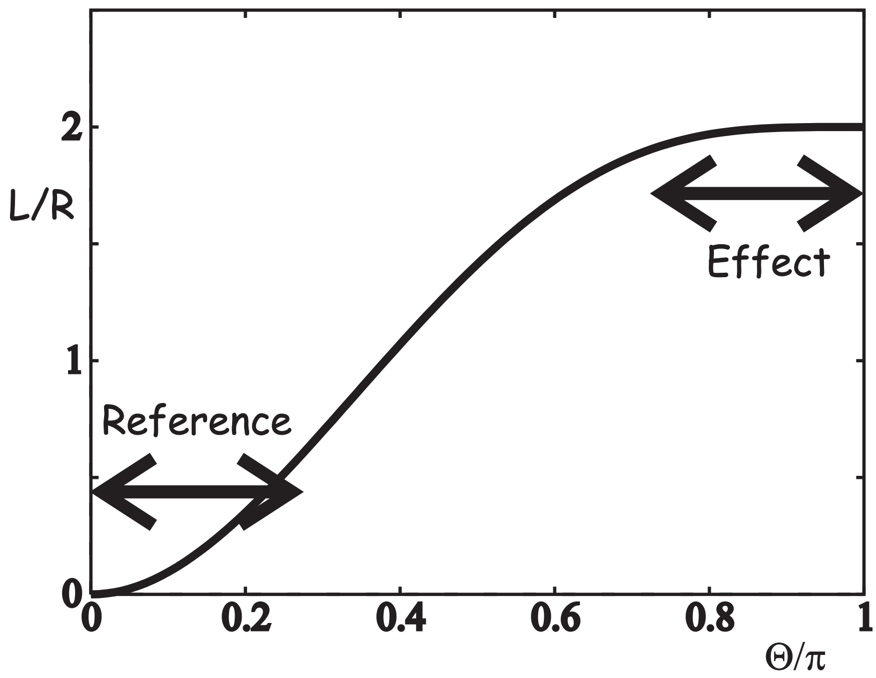

Figure 2: The three regions in the zenith angle distribution. Region one is labelled "reference", region three "effect" and the middle region is region two. The horizontal axis measures the angle in units of π $mrad$, the vertical axis measures the distance L in units of earth radii.

region is washed out by the large $\Delta L/L$, and the sensitivity to Δm^2 is small.

The second region is formed by the interactions from neutrinos with a direction near to the horizontal. These neutrinos span a large range in L. The value of L is derived from a measurement of the zenith angle of the incoming neutrino θ_ν. Due to the large $\delta L/\delta\theta_\nu$ a precise determination of θ_ν is required. Since the kinematical correlation between θ_ν and the direction of the outgoing lepton in a charged-current interaction, θ_l, is weak at low energy, the oscillation pattern only survives at high energy (*i.e.* $E_\nu > 1$ or $2\ GeV$). For low energy different Δm^2 manifest themselves in a small difference in slope of the distribution. It is unlikely that a precise determination of Δm^2 can be obtained with low energy events ($E_\nu < 1\ GeV$) in this region.

The third region is formed by the sample of interactions of neutrinos which come from below near the vertical. These neutrinos have an L close to the diameter of the earth with a relatively small uncertainty. The determination of L is therefore precise in relative sense. In addition, the dependence $\delta L/\delta\theta_\nu$ is small. The energy dependence of the events in this region is therefore a potentially interesting tool to measure Δm^2.

The Super Kamiokande experiment is a detector with a nearly isotropic response, and is therefore well suited to perform measurements of zenith angle distributions.

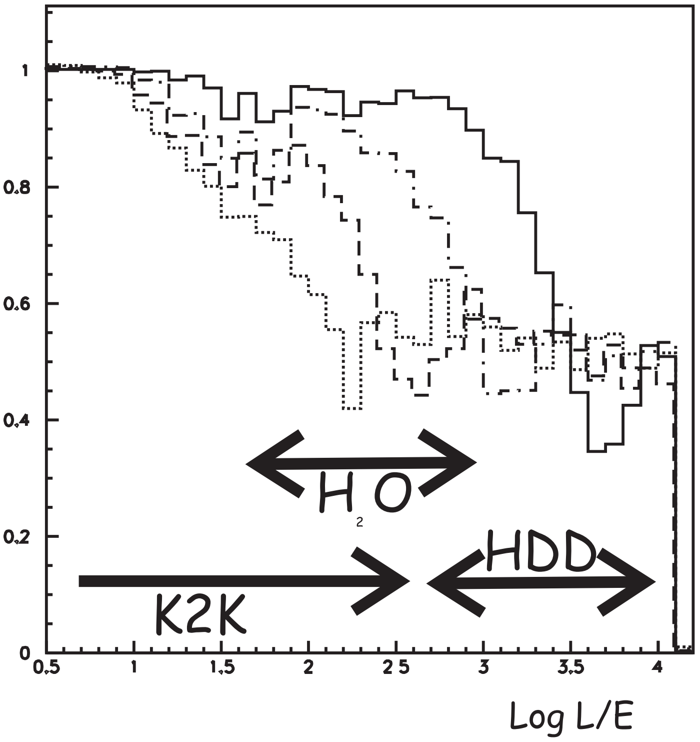

Figure 3: L/E in km/GeV survival ratio spectra (fraction of neutrinos surviving as function of L/E) for different values of Δm^2. The values of Δm^2 are: 10^{-2} eV^2 (dotted line), 3×10^{-3} eV^2 (dashed line), 10^{-3} eV^2 (dashed-dotted line), 3×10^{-4} eV^2 (full line). The arrows indicate the typical range of sensitivity for different experiments (K2K is the long baseline experiment, H_2O stands for the large underwater (or ice) experiments, and HDD stands for high density detectors using the muon range measurement). A realistic experimental scenario with the measurement of the muon kinematics alone is assumed. It is visible that the modulation of the spectrum becomes more significant at lower Δm^2.

Since the most reliable energy measurement is possible for fully contained (FC) events, one can predict in which range of Δm^2 a reliable measurement can be obtained. Region one has a intrinsically large $\Delta L/L$, region two needs a good angular resolution which is kinematically impossible for low energy events, and region three is sensitive to $\Delta m^2 \approx 10^{-4}$ eV^2 or lower.

2.5. L/E Method

The L/E method[28)] is derived from the zenith angle method. The essential ingredients are

- the observation that the neutrino energy distribution of the events in region

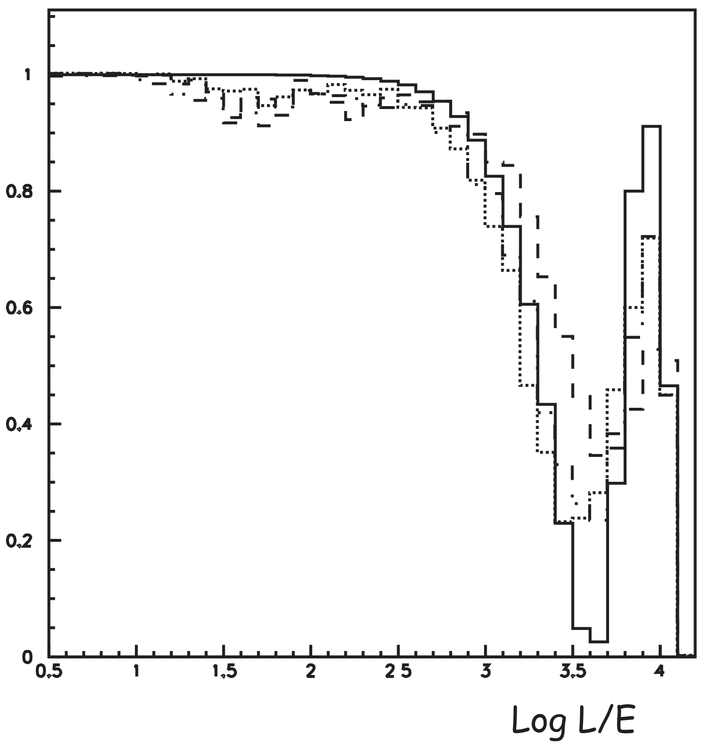

Figure 4: L/E in km/GeV survival ratio spectra for different experimental approaches, for the case $\Delta m^2 = 3 \times 10^{-4}\ eV^2$. The full line is for an ideal measurement, the dotted line for a measurement of all relevant kinematical variables (muon and hadronic energy, and both directions), the dashed-dotted line when only the hadronic direction is not measured, and the dashed line for a measurement of muon parameters alone. It is visible that the measurement with and without hadronic direction is of almost equal quality.

three is sensitive to Δm^2 owing to the good definition of L,

- the use of *high energy* events ($E_\nu >\approx 2\ GeV$) and
- the definition of a *reference* direction to avoid to calculate the neutrino flux.

The direction sensitive to oscillation is taken to be the vertical upward direction. It can be shown[29)] with symmetry arguments, that the neutrino flux from the opposite direction (*i.e.* downward going) is a good measurement of the initial flux of the upward going neutrinos as long as the neutrino energy is high enough. The comparison of charged-current interactions with a neutrino direction near the vertical in opposite directions is then a good measurement of the disappearance of the neutrino flavour due to oscillation.

As shown in Fig. 3[30)], the range of sensitivity of the experiment is determined by the range of neutrino energies of the event sample which can be accurately measured.

For a detector with 1 GeV < E_ν < 10 GeV this range is approximately $10^{-4} < \Delta m^2 < 10^{-3}$.

A study was made by several groups[20,28,31] to identify which are the crucial experimental measurements needed to be sensitive to the value of Δm^2 in the spectral shape of L/E (see Fig. 4[30]). It is shown that a measurement of the direction of the muon, together with the sum of the energy of the muon and the hadronic shower provides almost equal quality to a measurement including the hadronic shower direction in addition. The determination of the latter is notoriously difficult, and results in a large additional complication to the design of an experiment.

3. Existing and Planned Experiments

For the experimenter who plans an experiment it is crucial to predict the context in which the new experiment will operate. It is therefore important to examine the capabilities of presently running facilities and predict which measurements will already be done at the relevant time scale. Moreover, it is also necessary to undertake the difficult assessment of the performance of already planned experiments. Armed with this knowledge one can then decide the aims of a next generation experiment.

In the first category, the *existing facilities*, the Super Kamiokande experiment is the most significant one to take into account. Measurements of atmospheric neutrino interactions are now being supplemented with a low-energy long baseline exposure. The higher statistical significance of the *double ratio* measurement will in principle allow for a larger sensitivity to Δm^2. It is unlikely, that a large improvement can be made with this measurement, since systematic uncertainties will dominate the precision. The zenith angle measurement of muon-like events looks the most promising ingredient for a better determination of Δm^2. In this measurement the limitation will come from the poor correlation between the neutrino direction and the direction of the outgoing lepton at low neutrino energies. Since the energy spectrum of the fully and partially contained events in these samples is low (around 1 GeV) this presents a real limitation. Therefore it is likely that a precise measurement of Δm^2 will not be possible with this technique.

The K2K[32] long baseline experiment is sensitive to oscillation for Δm^2 down to 2×10^{-3} eV^2. The final precision will be reached after three years of data taking, starting in 1999. The experiment consists of a comparison of the spectra and absolute rate of ν_μ-interactions in a *near* detector with the *far* Super Kamiokande detector. The beam energy is below τ-threshold, such that only the disappearance of ν_μ is measurable. The experiment is sensitive to the appearance of ν_e, however, the region probed has already been excluded by CHOOZ data[13]. The near detector will be in the position to *calibrate* the effective cross-sections for the NC-like topologies selected in the atmospheric sample of Super-K. With this calibration, it will be possible to determine the nature of the dominant oscillation channel responsible for the observed oscillation effects. The only *dominant* channels consistent with all data are $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_X$ mixings. The choice between active (ν_τ) and sterile neutrinos (ν_X) can be made by comparing the NC rate with the expectations. The NC rate is suppressed in the $\nu_\mu \leftrightarrow \nu_X$-case, while it is unmodified by $\nu_\mu \leftrightarrow \nu_\tau$ oscillation.

To design and construct a big, new atmospheric neutrino experiment will take in the order of five years. Therefore, one has to try to assess the needs for new experimental data in about five years from now. Extrapolating our present experimental knowledge, the conclusion is that at startup of such a new experiment:

- The nature of the dominant mixing will be known (ν_μ-sterile or ν_μ-ν_τ).
- The value of Δm^2 will only be known if sufficiently high within reach of the K2K experiment.
- The value of $sin^2\, 2\theta$ will be known with reasonable precision, using the zenith angle distributions.
- Little will be known about sub-dominant mixings.

The MINOS[33] long baseline experiment, using the NUMI beam from FNAL to the Soudan mine will have the ability to improve the sensitivity to Δm^2 in a disappearance measurement down to $\approx 10^{-3}\ eV^2$.

From the above, one concludes that it is important to try to measure Δm^2 with atmospheric neutrinos. Of course, if its value turns out to be within reach of the K2K experiment, this conclusion has to be modified. In the following we will examine the possibilities for such a measurement.

Some of the experiments also have capabilities to do measurements relevant to distinguish between $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_X$ oscillations. These are not discussed here, since it is expected that this issue will be resolved prior to the running of these experiments.

4. New Atmospheric Neutrino Experiments

A number of new atmospheric neutrino detectors or detectors with capabilities to measure atmospheric neutrinos have been proposed recently.

Experiments with combined goals for measurements in a long baseline neutrino beam are MINOS[33], ICARUS[34], Aqua-Rich[35], Super-I[36] and NICE[37]. ICARUS and MINOS are being constructed. The former was approved as a proton decay and atmospheric experiment, the latter as a long baseline experiment. The large under-water and ice detectors being constructed for the observation of ultra-high energy cosmic neutrinos have recently explored the possibility to apply this technology to atmospheric neutrino observations[38]. A "High Density Detector" has also been designed as a new dedicated atmospheric neutrino detector[39].

Although other interesting observations can be performed, we will concentrate here on the capabilities of these detectors for the "model-independent" determination of Δm^2 using the L/E method. We will only briefly mention the Super-I and Aqua-Rich detectors; The time scale for the construction of these detectors is longer than for the more conventional options.

Three detector concepts which are based on the L/E method to measure Δm^2 are the *High Density Detector*, *NICE*, and *the large underwater or ice detectors*.

With the exception of the large underwater detectors, where downward going muons cannot be measured accurately, these experiments use the up/down symmetry of the atmospheric neutrino flux. The atmospheric neutrino flux asymmetry due to mainly geomagnetic effects is small for higher energy neutrinos[20,24]. For $\Delta m^2 < 10^{-2}$ the downward neutrinos at these energies are not affected by oscillations and can be used as a reference for the upgoing neutrinos. The experimental method is based on the estimation of the neutrino direction by measuring the direction of the outgoing lepton in charged-current interactions. The approximation improves with energy and is acceptable above 1 to 2 GeV. As explained above, the neutrino direction of upgoing neutrinos near the vertical determines the neutrino flight path with high accuracy.

4.1. MINOS

The MINOS experiment was designed for an exposure in a long baseline neutrino beam[33]. The design is therefore optimised for interactions of neutrinos from the beam direction, which is nearly horizontal. The detector is made of large magnetised iron toroids interspersed with scintillation detectors.

The capabilities of MINOS for atmospheric measurements have been evaluated recently[40]. The sensitivity of the measurement is based on the zenith angle distribution of the muon-like events. The conclusion of the study is a potential sensitivity for the determination of Δm^2 down to values $\Delta m^2 \approx 10^{-4}\ eV^2$. Due to the preferential direction for the detection of the interactions of horizontally incident neutrinos, the sensitivity is provided by relatively low energy neutrinos. The quality of the measurement of the neutrino direction is a very important parameter at these horizontal directions. It is therefore not completely clear yet how model-independent the measurement of Δm^2 can be.

It is interesting to note, that MINOS can also be sensitive to Δm^2 using upward going entering muons down to $1.5 \times 10^{-3}\ eV^2$, without absolute flux normalisation. This is largely supported by the good momentum measurement with magnetic deflection.

4.2. ICARUS

The ICARUS detector[34] was first proposed as a proton decay and atmospheric experiment. The detector is a large volume of liquid Argon read out by a TPC technology. It will be capable of very detailed measurements of event topologies and of the energy. At present a 600 t module is being constructed and should be made operational around 2000 in the Gran Sasso laboratory. Of course, for the model independent determination of Δm^2 with the method outlined here, the detector is too small. If successful, more modules can be installed.

A large (30 kt) version of the ICARUS detector[36)], Super-I, has been proposed mainly for exposure in the NGS long baseline neutrino beam[41)]. The detector will be operated at shallow depth, it therefore needs a good veto for entering muons from above. A preliminary estimate of the capabilities of the detector to detect atmospheric ν_τ-interactions has been made.

4.3. Aqua-Rich

A large water Cherenkov detector to be operated in the NGS long baseline neutrino beam has been proposed recently[35)]. The detector will be located near the Gran Sasso laboratory, but placed outside. The planned volume of water is 125 kt for a cubic version and 180 kt for a spherical version, much larger than Super Kamiokande. The Cherenkov light will be intercepted both directly and by means of a spherical mirror. The focused light will provide a high precision measurement of the track directions. A first study of the capabilities for atmospheric neutrino detection show a sensitivity to the value of Δm^2 in a range $1 \times 10^{-4} < \Delta m^2 < 5 \times 10^{-4}\ eV^2$.

4.4. Under-water and ice detectors

The large under-water detectors are designed for very high energy neutrino detection (TeV energies). They use widely spaced vertical strings of photo-detectors, which measure the Cherenkov light emitted by relativistic particles traversing the medium. Several of these detectors are partly operating, being constructed or planned[42,43,44,45)]. They are optimised to cover a maximum volume for high energy neutrino interactions with a minimum number of detection elements. Therefore a modification of the arrangement is necessary to re-optimise the detectors for the much lower energy atmospheric neutrino interactions. The idea to use these detectors for atmospheric neutrino detection is not new[46,47)]. In this field a new idea was launched to overcome the large spacing of the vertical strings[38)]. If one limits the data sample to muons which travel close to a string nearly parallel to it, one can measure the range of the muon with an accuracy given by the spacing of the photo-detectors along the string. The requirement that the muon travels along the string added to a fiducial volume criterion to determine the starting and stopping point safely inside the detector, provides a good rejection against entering or exiting muons.

In the case of Antares a study has been made for strings with photo-detector spacing of 8 m. The energy of muons can be determined in an energy range $5 < E < 250\ GeV$, given by the threshold and the length of the string. For these topologies, the neutrino flight path is always $1.3 \times 10^4\ km$. One estimates a potential sensitivity for roughly $10^{-3} < \Delta m^2 < 10^{-2}\ eV^2$. One of the problems of this technique is the absence of a reference sample, muons coming from above cannot be used to provide a calibration. One has therefore to rely on the calculation of the shape of the spectrum.

4.5. NICE

The NICE-detector[31,37] was designed to combine a measurement of atmospheric neutrinos with a measurement in the planned NGS long baseline neutrino beam from CERN to the Gran Sasso underground laboratory[41]. The geometry of the detector is a compromise between the need to measure neutrino interactions at nearly horizontal direction, coming from the beam, and isotropic atmospheric neutrino interactions, which require sensitivity to vertical directions. The capabilities of the detector in the beam will not be discussed here.

The choice made here is to measure the neutrino direction by measuring the parameters of the primary muon and the hadronic shower in the charged-current interaction. The event vertex is required to be inside a detector fiducial volume. The muon is not required to be fully contained. Its energy can be measured by range, if it stops inside the detector or by means of magnetic deflection, when it exits. The total energy is obtained by adding the hadronic energy to the muon energy. To improve the measurement of the neutrino direction at lower energies an attempt is made to also determine the direction of the energy flow of the hadronic shower.

The fact that also non-contained events are accepted increases the effective fiducial volume of the detector compared to the case where events are required to be fully contained. At the same time the choice complicates the detector, since a magnetic field is needed around the vertex region. The rejection of background of entering and stopping muons coming from above is a very critical point. About 10^5 muons enter from above for each atmospheric event. This background cannot be removed by a containment criterion, since such criterion would also remove part of the atmospheric neutrino interactions. The experiment therefore needs a very effective method to distinguish upward and downward going muons, *e.g.* by a timing measurement.

The conceptual design is based on a large “isotropic” iron-scintillator calorimeter surrounded on four sides by a magnetised iron spectrometer. The total mass of the calorimeter is at least 10 kt. The calorimeter is made of long, thin rods of iron and bars of scintillator assembled into horizontal planes. The planes are stacked alternately rotated by 90 degrees to form modules of $12 \times 12 \times 8\ m^3$. (A possible arrangement was also proposed separately[48].) Two such modules fit inside the magnet, which looks like a window frame. The momentum measurement is ensured by tracking detectors inserted in slots in the iron of the magnet.

The measurement of Δm^2 is possible by the observation of a modulation of the spectrum in the range $1 \times 10^{-4} < \Delta m^2 < 5 \times 10^{-3}$ eV^2.

4.6. High Density Detector

The High Density Detector[39,49] is designed around the L/E method[28] to measure Δm^2. It is kept as straight-forward as possible. This philosophy allows for a maximum mass.

The neutrino direction is estimated from the track direction of fully contained muons. The other ingredient of the determination of L/E is the total energy of the neutrino, estimated by summing the muon energy and the hadronic energy. The choice is to measure the muon energy by *range*, thus requiring full containment. Together with the simplicity (no magnetic field required) this method has a good precision if the muon path is sufficiently well sampled. An important requirement to the detector is therefore the rejection of incoming tracks by a good veto, mainly for tracks coming from above. Once a clean sample of contained events is isolated, the determination of the up/down direction is not critically difficult.

The detector is made of large 8 cm thick iron plates, 15×30 m^2 surface, oriented horizontally. A stack of 120 such plates with a 2 cm gap for track detectors between them has a height of 12 m and a mass exceeding 34 kt. It requires a total surface of track detectors of 54000 m^2. The up/down direction of the muon is measured with several methods. About half of the events have sufficient hadronic energy at the vertex, to use this energy deposition as a definition of the start of the event. For most of the other events, the relative timing of the hits at both ends of the track reveals the direction. This measurement can be done with sufficiently fast tracking detectors such as RPC's. The direction angle of the muon is measured from a fit to the positions of the hits on the track, and require only moderate measurement precision.

With such a detector arrangement, the sensitivity is optimised for events near the vertical direction. The experiment is sensitive to Δm^2 by the measurement of the L/E neutrino survival spectra. To each event the L/E is assigned as if the neutrino would come from below. The spectra are constructed by the ratio of events coming from below (which have been assigned the "correct" L/E) and the ones coming from above (with a "nominal" L/E), which act as a flux prediction. A significant modulation of the spectrum is obtained for $1 \times 10^{-4} < \Delta m^2 < 5 \times 10^{-3}$ eV^2. The range is given by the range in muon momenta which can be measured in fully contained events.

The principle of the High Density Detector and the NICE detector is shown in Fig. 5.

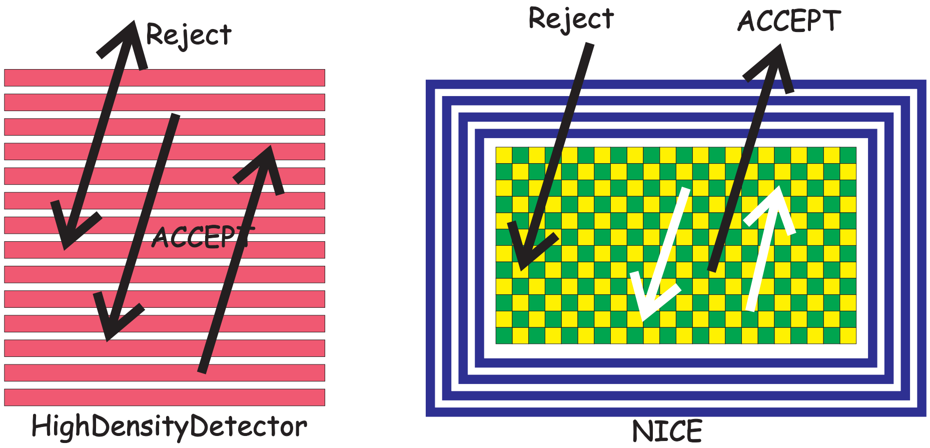

Figure 5: Schematic drawing of the High Density Detector (left) and NICE detector (right) ideas. In the first case only fully contained events are accepted, while NICE with a calorimeter placed inside a magnetic frame accepts also exiting muons.

4.7. Conclusions

The evidence for the existence of neutrino oscillation in the atmospheric data is becoming overwhelming. It is important to perform more measurements to gain more understanding of the phenomenology. The task for new experiments is to concentrate on measurements which cannot be performed by the existing experiments. The most relevant running experiment is Super Kamiokande together with data taken in a low energy neutrino beam with a near detector at KEK.

A particular measurement, the *model independent* determination of Δm^2 has been identified as one of the future challenges. The domain below $10^{-3}\ eV^2$ will remain for some time to come the realm of atmospheric experiments. A concept to attack this problem has been described. Designs for such experiments exist; it is now the time to work out the most powerful and practical solution. The need for big detectors, with a sufficiently large range of measurable muon energies, forces the experimenters to look for simple solutions.

5. Acknowledgements

The author is indebted to J. Brunner, P. Litchfield, A. Para, R. Santacesaria and P. Zucchelli for information valuable for the preparation of this paper.

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