Future Atmospheric Neutrino Detectors

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Future experiments focusing on atmospheric neutrino detection are reviewed. One of the main goals of these experiments is the detection of an unambiguous oscillation pattern ($\nu_\mu$ reappearance) to prove the oscillation hypothesis. Further goals include the discrimination of $\nu_\mu - \nu_\tau$ and $\nu_\mu - \nu_{\text{sterile}}$ oscillations, and the detection of a potential small $\nu_\mu - \nu_e$ contribution. The search for matter effects in three or more flavour oscillations can be used to constrain hybrid oscillation models and potentially measure the sign of $\delta m^2$. The detectors and measurement techniques proposed to achieve these goals are described, and their physics reach is discussed.

1. Introduction

At the Neutrino '94 conference in Eilat, Israel, the title of the summary talk on atmospheric neutrinos [1] was: “Is There an Atmospheric Neutrino Anomaly?”. Already then, B.C. Barish concluded that “it seems strongly indicative that the anomaly is indeed real, and that it is due to a deficit in the number of observed muon neutrinos.” This conclusion was beautifully confirmed by the presentation of “Evidence for $\nu_\mu$ oscillations” by Super-Kamiokande [2] in Takayama, Japan, 4 years later [3], implying the disappearance of muon neutrinos into some other neutrino flavour.

In the two flavour approximation, the survival probability for muon neutrinos in vacuum can be expressed by the well known oscillation formula

$$P(L/E) = 1 - \sin^2(2\Theta) \sin^2(1.27 \Delta m^2 L/E)$$

where $L$ is the distance travelled in km, $E$ is the neutrino energy in GeV, $\Theta$ is the neutrino mixing angle, and $\Delta m^2$ is the difference of the mass square eigenvalues expressed in eV$^2$. This simple relation could be modified by a contribution of additional flavours, and by matter effects [?] which depend on the neutrino flavour.

Oscillations into $\nu_\tau$ are the currently preferred hypothesis. A large contribution of oscillations into $\nu_\tau$ is excluded by the CHOOZ reactor results [4], and recent indications from Super-Kamiokande strongly disfavour pure $\nu_\mu - \nu_{\text{sterile}}$ oscillations [5]. Hybrid oscillations into both $\nu_\tau$ and $\nu_{\text{sterile}}$, and a small contribution of $\nu_\mu - \nu_e$ oscillations are however still allowed [5]. Furthermore, due to the limited L/E resolution, exotic alternatives to the oscillation hypothesis such as neutrino decay [7], large extra dimensions [8] or neutrino decoherence [9] remain fully valid explanations [6].

Over the last few years, an impressive effort has been made towards the further clarification of the atmospheric neutrino anomaly with the help of long baseline neutrino beams in Japan [10,11], the US [12,13] and Europe [14–17]. This program is starting to yield first results [11]. Here, we would like to present the case why these measurements need to be complemented by further, more precise atmospheric neutrino measurements, and how these measurements can be achieved.

1.1. Why atmospheric neutrinos?

Atmospheric neutrino experiments offer several advantages over currently operational or planned long baseline neutrino beam programs.

- A very large $L/E$ range (from about 1 km/GeV to $10^5$ km/GeV; a typical long baseline beam covers only one or two orders of magnitude). Therefore, a very large range of oscillation parameters can be studied simultaneously.
- Two identical sources for a single detector:
a near (downgoing neutrinos) and a far (up-going neutrinos) one.

- For some of the measurements, e.g. the confirmation of the oscillation pattern, there is currently no alternative to atmospheric neutrino detectors if the atmospheric $\Delta m^2$ is low. The pattern measurement is sensitive to test and exclude alternative explanations and is competitive to long baseline studies even at high $\Delta m^2$.

- During the next decade large matter effects with high energy neutrinos can only be observed in atmospheric neutrino experiments, since the current long baseline distances are too short for a significant effect. The measurement of the presence or absence of such effects can significantly constrain complicated hybrid oscillation models. The measurement of a difference in the neutrino and antineutrino oscillation parameters might allow the measurement of the sign of $\Delta m^2$, i.e. the neutrino mass hierarchy (matter effects are expected to dominate over CP violation effects).

2. Future atmospheric neutrino detectors

Most future detectors able to make significant contributions to the detection of atmospheric neutrinos are multi-purpose detectors which also cover many other physics topics, like the detection of neutrinos from long baseline beams, detection of solar neutrinos, supernova neutrinos, and nucleon decay, or the study of cosmic ray muons and other astrophysics topics.

The reference against which future improvements should be evaluated is given by the results of Super-Kamiokande [2,5], a 50 kt (23 kt fiducial) water Cherenkov detector.

2.1. Water Cherenkov detectors: UNO, AQUA-RICH

Some of the atmospheric neutrino measurements (e.g. $\nu_\tau/\nu_\mu$ separation) are still statistically limited, and could be improved by extending the Super-Kamiokande concept to a larger detector mass.

![Figure 1. The UNO detector concept.](image)

The concept of a 650 kt (450 kt fiducial) water Cherenkov detector, tentatively called UNO [18] (Ultra underground Nucleon decay and neutrino Observatory detector), is currently being discussed (fig. 1). It would be subdivided into three cubic compartments of $60 \times 60 \times 60$ m$^3$. The walls of the central compartment would be equipped with photomultipliers “a la Super-K”, to be fully sensitive also to low energy (MeV) neutrinos. A less dense photomultiplier coverage is foreseen for the two outer compartments, dedicated to higher energy events. Apart from Super-K-like measurements with 20-fold increased statistics, the $\tau$ production rate from $\nu_\mu - \nu_\tau$ oscillations might be large enough in such a detector to extract an explicit $\tau$ appearance signal from atmospheric neutrinos [15]. Optionally, an external muon momentum and charge identifier could be addeed.

A different detector concept, based on the Ring Imaging Cherenkov (RICH) technique, is envisaged by the AQUA-RICH project [19]. This project is currently in the R&D phase (fig. 2). Two spherical detector structures equipped with Hybrid Photo-Detectors (HPD’s) are immersed into a large water tank (fig. 2). The upper part of this tank is used as a shield against low energy...
cosmic rays. The inner surface of the outer sphere is equipped as a mirror to focus the Cherenkov light onto the outer surface of the inner sphere. This inner sphere (dome) is densely covered with HPD’s to detect the focused Cherenkov rings. In addition, the mirror sphere is sparsely equipped with additional HPD’s to also directly detect the non-focused Cherenkov light. A fiducial mass of 1 Mt is envisaged for this project.

While the mirror HPD’s can be used to reconstruct the neutrino interaction vertex and the particle flight direction, the space-time structure of the Ring Image on the dome HPD’s yields a measurement of the particle momentum through multiple scattering. A momentum resolution of 7% can be achieved [20]. This yields an L/E resolution which is good enough to resolve the sinusoidal oscillation pattern [19] over the complete Super-Kamiokande allowed range.

2.2. Magnetised tracking calorimeters: MONOLITH

The water detectors discussed above have the advantage of a very large mass, and therefore large statistics, but two main drawbacks. The time scale for their realization spans at least 10 years, and the implementation of a magnetic field (if any) to measure the muon charge is complicated and costly. A different detector concept is being followed using large magnetised tracking calorimeters.

The advantage of such detectors is that they can easily measure the muon charge, and therefore separate the neutrino and antineutrino components. In the context of atmospheric neutrinos, this is very useful to study matter effects, which can be significantly different in the two cases. Furthermore, the energy of the hadronic system and the momentum of semi-contained muons can be measured. This yields a good reconstruction of the neutrino energy up to the highest energies. At these energies the neutrino angular resolution, which determines the resolution on L, is also good. Hence, very good L/E resolution can be obtained [21], which is needed to resolve the oscillation pattern.

Two such detectors, the approved MINOS detector at Fermilab [12] and the NOE part of the proposed ICANOE detector at Gran Sasso [16], have been primarily designed as long baseline beam detectors. They are described in other contributions to this conference [13,17]. Their small fiducial mass (3.5 kt or less) severely limits the statistics, and therefore their potential contribution to atmospheric neutrino measurements.

MONOLITH (Massive Observatory for Neutrino Oscillations or LImits on THeir existence), a 34 kt magnetised iron detector dedicated to the measurement of atmospheric neutrinos in the Gran Sasso lab in Italy, has been officially proposed this summer [22]. Its fiducial mass of about 26 kt matches the mass of Super-Kamiokande, while its superior L/E resolution allows the reconstruction of the oscillation pattern. The de-
Detector consists of two modules with dimensions of $14.5 \times 15 \times 13$ m$^3$ each (fig. 3). Each module is made of 125 horizontal iron layers (8 cm thick) interleaved with active planes of Glass Spark Counters (Glass RPC’s), and surrounded by external scintillation counters to help reducing the background from cosmic ray muons. A magnetic field of 1.3 T, fully contained within the iron plates, is applied. Optionally, and end cap of vertical planes could improve the performance for auxiliary measurements in the CERN to Gran Sasso beam. If approved promptly, the experiment could start data taking towards the end of 2004.

Finally, a similar detector concept is also discussed in the context of a 50 kt detector for a future neutrino factory [23]. Such a detector would have a performance on atmospheric neutrinos similar to MONOLITH, but with a larger mass, and on a longer timescale.

2.3. Liquid Argon TPC’s: ICARUS

Liquid Argon Time Projection Chambers (TPC’s) are a further technique well suited to the detection of atmospheric neutrinos. Their advantage with respect to massive iron detectors is their sensitivity to both electron and muon neutrinos down to the lowest possible energies for atmospheric neutrinos, and their sensitivity to $\tau$ appearance. Their disadvantage is the much higher price per kton. The proposed ICANOE detector [16], combining a 7.6 kt (5.6 kt fiducial) liquid Argon TPC (ICARUS, split into 4 modules) with a 3.2 kt iron calorimeter (NOE), is described in a separate contribution to this conference [17]. This detector is designed both for the detection of $\nu_\tau$ and $\nu_e$ appearance in the CERN to Gran Sasso neutrino beam [14] and for the detection of atmospheric neutrinos of all flavours. For some atmospheric neutrino measurements its better resolution with respect to Super-Kamiokande compensates the reduced statistics due to the lower mass.

A 600 t ICARUS module has already been approved and is scheduled to start data taking in 2001. If approved promptly, the first (out of 4) ICANOE modules could be operational in 2003. A future 30 kt version (Super-ICARUS) has also been considered at the Letter of Intent level [24].

3. Detection of the oscillation pattern

If detected with sufficiently high resolution, the observation of neutrino oscillations should yield a sinusoidal oscillation pattern (eq. (1)). However, none of the experiments which have yielded indications for neutrino oscillations have so far succeeded to measure such a pattern. Figure 4 shows the $L/E$ distribution obtained by Super-Kamiokande compared to the expectation for neutrino oscillations and to a functional form suggested by a recent neutrino decay model [7]. Once the detector resolution is taken into account, the two hypotheses are essentially indistinguishable [7]. Even though the current evidence is very suggestive of neutrino oscillations, a more precise measurement of the oscillation pattern is the only way to actually prove the oscillation hypothesis for atmospheric neutrinos. In particular, it should be proven that muon neutrinos do not only disappear, but actually reappear at some larger $L/E$.

![Figure 4. $L/E$ distribution from Super-Kamiokande compared to the best fit oscillation hypothesis (continuous line), and to a parametrization corresponding to the neutrino decay model of ref. 7 (dashed line).](image)

The proposed MONOLITH experiment [22] is explicitly designed to achieve this goal. Having a similar mass as Super-Kamiokande, significantly
larger acceptance at high neutrino energies and better \( L/E \) resolution, the experiment is optimized to observe the full first oscillation swing, including \( \nu_\mu \) "reappearance". Therefore, the oscillation hypothesis can be clearly distinguished from other hypothesis which yield a pure threshold behaviour (figure 3).

A similar measurement is also being pursued by the ICANOE experiment (figure 6) and, on a somewhat longer timescale, by the AQUA-RICH project [19].

Furthermore, the sensitivity to detect the oscillation pattern does not strongly depend on the oscillation parameters. This is in contrast to long baseline experiments like MINOS, which can do a similar measurement at the highest allowed \( \Delta m^2 \) if the low energy beam is used [25], but for which the observation of a reappearance signal in the lower \( \Delta m^2 \) range is not obvious.

Fig. 7 shows the expected pattern in MONOLITH for \( \Delta m^2 = 2 \times 10^{-3} \text{ eV}^2 \). This figure also illustrates the result of normalizing the sample of upgoing (oscillated) neutrinos to the sample of downward going (unoscillated) ones. Taking the
ratio eliminates most of the systematic error due to the atmospheric neutrino flux and the detector response [22,21].

Fig. 8 gives an example how the atmospheric neutrino measurement could be complemented by a disappearance measurement in a high energy neutrino beam. This possibility is particularly attractive for high \( \Delta m^2 \) (here: \( 5 \times 10^{-3} \text{ eV}^2 \)).

\[ \frac{L}{E} \text{ distribution (} \nu_\mu \text{ survival probability)} \]

Figure 8. Example for the expected \( \frac{L}{E} \) distribution (\( \nu_\mu \) survival probability) in MONOLITH with 2 years of data taking of atmospheric neutrinos and 1 year with the CERN-Gran Sasso neutrino beam for \( \Delta m^2 = 5 \times 10^{-3} \text{ eV}^2 \) (points) [22]. Also shown is a fit of the expected oscillation hypothesis (continuous line). Beam neutrinos dominate the \( \frac{L}{E} \) region below \( 10^2 \text{ km/GeV} \). For \( \frac{L}{E} > 10^2 \text{ km/GeV} \) only atmospheric neutrinos contribute. Only statistical errors are shown.

Finally, the pattern measurement can be used to significantly improve the measurement of the oscillation parameters (fig. 3). Again, the result could potentially be improved by combining beam measurements, including the potential \( \tau \) appearance rate, with atmospheric measurements (fig. 10). In such a combination, \( \sin^2 2\theta \) is mainly constrained by the atmospheric neutrino measurement, which allows a precise \( \Delta m^2 \) determination from the beam information if \( \Delta m^2 \) is not too low.

Figure 9. Expected sensitivity contours for \( \nu_\mu \) disappearance for K2K [10,26] (5 years), MINOS [12] (3 years reference beam) and MONOLITH [22] (4 years). Also shown are the exclusion contour from CDHS [27], the recent allowed areas from Super-Kamiokande [5] and Kamiokande [28] and the expected allowed area of MONOLITH (dark shaded, four years) for the current Super-Kamiokande central value.

Figure 10. Overall combined fit (beam + atmospheric, appearance + disappearance) expected by ICANOE [16], compared to Kamiokande [28] and Super-Kamiokande [4].
4. Detection of $\nu_\tau$ appearance

For maximal $\nu_\mu - \nu_\tau$ oscillations in the $\Delta m^2$ range $2-5 \times 10^{-3} \text{ eV}^2$, the expected $\tau$ appearance rate in atmospheric neutrinos is about 1 per kty [16].

Such events could be directly observed in ICANO, but the low rate limits the statistical significance to about 2.5 $\sigma$ in 4 years [16]. In MONOLITH the rate is larger due to the larger mass, but the $\tau$ candidates can only be detected indirectly through an apparent enhancement of the NC up/down ratio at high energies (hadronic decays of upward going $\tau$’s). Again, the significance is limited to about 2-3 $\sigma$ in 4 years. The best results on $\nu_\tau$ appearance are therefore expected to be obtained from long baseline beams. However, these atmospheric neutrino measurements could yield useful complementary information in the case of complicated hybrid oscillation models.

To obtain a significant sample of atmospheric $\tau$ neutrinos, bigger detectors like Super-ICARUS [24] or UNO [18] might be needed.

5. Detection of matter effects

Matter effects can play an important role if there are significant contributions of $\nu_e$ or $\nu_{\text{sterile}}$ to atmospheric neutrino oscillations. Already now, Super-Kamiokande uses the nonobservation of large matter effects to exclude the pure $\nu_\mu - \nu_{\text{sterile}}$ oscillation hypothesis at 99% c.l. [5].

For a contribution of nonmaximal $\nu_\mu - \nu_{\text{sterile}}$ oscillations, matter effects would also manifest themselves in differences in the oscillation patterns for neutrinos and antineutrinos. Such differences could be measured with MONOLITH [22], and could yield important constraints on hybrid oscillation scenarios [6, 30].

Interestingly, such effects could be detectable even in standard three flavour oscillation scenarios (Figs. 11 and 12). A small $\nu_\mu - \nu_e$ contribution, close to the CHOOZ limit [4], could be strongly enhanced in particular regions of phase space through matter resonances, such that it could be measured in $\nu_\mu$ disappearance. Depending on the sign of $\Delta m^2$, such enhancements occur either for neutrinos or for antineutrinos only. By Figure 11. Muon neutrino survival probability (black=1, white=0) for three flavour oscillations assuming the Super-Kamiokande “best fit” parameters [5] of $\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$, $\sin^2 \theta_{23} = 0.55$ ($\sin^2 2\theta_{23} = 0.99$) and $\sin^2 \theta_{13} = 0.02$ ($\sin^2 2\theta_{13} = 0.08$). Left: neutrinos. Right: antineutrinos. Formulas are taken from an analytic two-density earth model including core effects [29]. For negative $\Delta m^2$, the two plots would be reversed.

Figure 12. Reconstructed neutrino energy distributions (points) for the oscillation parameters of fig. 11, for a 50 kt magnetized iron detector (5 years of atm. $\nu_\mu + \nu_e$). Only the events crossing the inner mantle ($3200 < L < 10600 \text{ km}$) are used here. The dashed line shows the same distribution for $\sin^2 \theta_{13} = 0$ ($\nu_\mu - \nu_\tau$ mixing only).
comparing the neutrino and antineutrino distributions in a magnetized iron detector, the sign of $\Delta m^2$, and therefore the neutrino mass hierarchy, could be determined if a signal would be observed. Even a low statistics measurement could be used for this purpose if the $\nu_\mu - \nu_e$ oscillation parameters were already measured by the forthcoming long baseline neutrino experiments for which matter effects are essentially negligible.

Finally, the ICANOE experiment, which is able to detect atmospheric $\nu_e$’s down to the lowest possible energies (but not their charge), has a window of opportunity to detect a subleading $\nu_\mu - \nu_e$ contribution from the “solar” $\Delta m^2$ if the large angle MSW solution of the solar neutrino problem would turn out to be true. Such a contribution would also be strongly affected by matter effects.

6. Conclusion and acknowledgements

In conclusion, several experiments are in preparation which could improve the present atmospheric neutrino measurements. Such measurements should prove (or disprove) the oscillation hypothesis for atmospheric neutrinos by measuring the oscillation pattern, contribute to disentangle potential complicated hybrid oscillation solutions from the simple $\nu_\mu - \nu_e$ oscillation scenario, and potentially determine the neutrino mass hierarchy through the observation of matter effects even in standard three neutrino scenarios.

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