Summary talk on Atmospheric Neutrinos

John G. Learned [a] and Paolo Lipari [b]

[a]Dep't of Phys. and Astron., U. of Hawaii, Honolulu, HI, USA

[b]INFN and Dipartimento di Fisica, Università Roma I

This is a short summary of the presentations and the discussions held during the parallel sessions on the "past, present and future" of atmospheric neutrinos.

1. Atmospheric ν and "New Physics"

The parallel sessions on atmospheric ν's were organized around three main themes:
(a) interpretation of the existing data,
(b) systematic uncertainties in the predictions,
(c) perspectives of future experimental studies.

A consensus has emerged that the existing data show convincing evidence for the "disappearance" of ν_μ and $\overline{\nu}_\mu$ that require the existence of some form of "new physics" beyond the standard model. The reason why the evidence is robust has been spelled out several times. The atmospheric ν fluxes have two properties that can be predicted in a model independent way: (i) the fluxes are up–down symmetric, (ii) the fluxes of ν_e and ν_μ are strictly related. The qualitative results of SK [1] that show a suppression of μ–like relative to e–like events, and of up–going (long L) relative to down–going (short L) events can indeed be considered as a "smoking gun", a model independent result that demands the existence of new physics. The SK results point to ν_μ disappearance, most probably due to oscillation, as the source of the "atmospheric neutrino anomaly" found by the first generation of water Cherenkov detectors IMB and Kamioka. The SK claims are confirmed by the results of Soudan–2 and MACRO [2].

The simple hypothesis of $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with nearly maximal mixing results in a remarkably good fit to all existing data. It is of course very important to see if this explanation is unambiguous and sufficient. Some natural questions are:

– Are other flavors participating in the process?
– How accurately can the oscillation parameters be determined ?
– Do sterile ν's play in the transitions ?
– Can other mechanisms be responsible for the observed effects ?
– Does CP or even CPT violation play any role here?

Regarding the next to last point, it is important to observe that several "alternative models" such as FCNC currents, ν decay (in its simplest versions), and violations of the Equivalence Principle are strongly disfavored. However, some other (perhaps more "ad hoc") explanations, such as a modified version of the decay model, or the presence of de-coherence are still viable. In these models the survival probability of the ν_μ decreases monotonically with growing L/E_ν from unity to $\sim \frac{1}{2}$ without oscillations. (Yet such models also involve neutrino mass and mixing, so are disfavored for lack of parsimony in requiring more new physics.)

The "up–going" muon events, produced by ν_μ with a broad energy distribution between ~ 10 and $\sim 10^3$ GeV (much higher that the typical energy of the contained events), play an important role in determining the energy dependence of the the ν_μ disappearance probability[3]. The shape of the zenith angle distribution of up–going events shows the existence of a distortion that is consistent with the presence of oscillations. It should be noted that this is not a "model independent" statement since one has to compare the data with a calculated prediction, since no equivalent sample of ν_e induced events exists, and only up–going events are detectable without a huge background. The "standard model" shape can however be reliably predicted. The observed distortion also plays an important role in the rejection of the $\nu_\mu \leftrightarrow \nu_{\rm sterile}$ hypothesis.

2. Systematic Uncertainties in the Predictions

A central question discussed during the workshop has been the role of systematic uncertainties in the calculation of the expected rates for the interpretation of the data. These systematic uncertainties arise from different sources:
(i) Knowledge of the primary cosmic ray fluxes;
(ii) Modeling of the hadronic interactions;
(iii) Modeling of the shower development;
(iv) Description of the ν cross section.

The recent years have seen some remarkable progress about point (i). Two new measurements of the primary cosmic ray fluxes have been performed by the BESS balloon experiment [4], and by the AMS–01 detector during a 10 days flight on the Space Shuttle [5]. The measurements of the two detectors (that are limited to $E_0 \lesssim 200$ GeV) are in excellent agreement with each other, better than 5% for p and $\sim 10\%$ for Helium. The Caprice results [6] suggest a slightly smaller flux. Much larger discrepancies exist with some of the earlier measurements, that should very likely be ascribed to the existence of not–understood systematic errors. Uncertainties on the primary flux remains important only for up–going muons, where primaries with energy as high as $\sim 10^5$ GeV give a non negligible contribution. An important contribution of the AMS detector has been the measurement of the fluxes arriving "simultaneously" at different points on the surface of the Earth. The measurements show that for ($p \gtrsim 15$ GeV/Z) the vertical fluxes are position independent, while for lower rigidity the fluxes are suppressed for locations closer to the geomagnetic equator. These results confirm quantitatively the algorithms used in the calculation of the fluxes.

The AMS detector has also found the existence of a population of low momentum protons (and $e^\pm$) that remain trapped in near orbit trajectories for a time as long as several seconds. These particles give a negligibly small contributions to the atmospheric ν rates.

The modeling of hadronic interactions remain a significant source of uncertainty in the prediction. The largest uncertainty is in the absolute normalization of the fluxes (that has little importance for the interpretation of the data), however other smaller effects play a more important role. For example the ratio ν_μ/ν_e decreases for an increase in the π^+/π^- ratio, reflecting the fact that a π^+ (π^-) produces a ν_e ($\overline{\nu}_e$) and that $\sigma_\nu > \sigma_{\overline{\nu}}$. Also the expected no–oscillation up–down asymmetry (that is a significant correction for low E_ν) is the result of a convolution of geomagnetic effects (different primary fluxes reaching points with different geomagnetic coordinates) with the ν yields. A larger (smaller) yield for low energy primaries is reflected in a larger (smaller) no–oscillation asymmetry. This is an important source of uncertainty for the interpretation of the Soudan data where the geomagnetic effects are strongest. Only additional data will allow a reduction of these uncertainties. The program of HARP [7] has interesting potential in this direction, the main limit being the low primary energy available.

Given a primary flux, and a good description of particle production in proton–nucleus (and helium–nucleus) interactions, the calculation of the atmospheric ν fluxes is a straightforward problem, without difficulty in principle, that can be performed with Monte Carlo simulation techniques. This calculation has however intrinsically a very small "efficiency", in the sense that a given detector receives only a tiny fraction of the total number of ν's produced over the entire surface of the Earth, while on the other hand *all* showers can produce a ν that crosses the detector.

The technical solution of this problem used in the first generation calculations, has been the so called "1D" approximation that considers all ν's as exactly collinear with the primary particle. This approximation has been found insufficient to describe accurately the fluxes, since it misses a low energy enhancement on the horizontal plane [8] that is not easily observable directly because of the poor resolution, but that nonetheless modifies the ν path-length distribution. Preliminary investigations have shown that the inclusion of these effects result in only small corrections to the value of the best fit oscillation parameters. However, in future analysis it will be necessary to go beyond the "1D" approximation.

A powerful constraint on the calculation of the ν fluxes come from the measurement of the associated muon fluxes in the atmosphere. Measurement at ground level are very important, and in fact new more precise measurements recently performed (that show a lower normalization with respect to previous results) are of considerable interest. The $\mu^{\pm}$ that are more closely related to the ν's that produce the (semi–)contained events do not reach the ground because they decay in air. Their flux is most intense at an altitude $\sim$ 10–20 Km, where they can be observed by balloon experiments during their ascent (even if with only short exposures). For more discussion about the perspectives of these measurements see [4,6].

The description of the ν cross section is also a significant source of uncertainty, and could in fact remain the dominant source of ambiguity for contained events after a detailed analysis of the cosmic ray muon data. Only additional data from accelerators will result in an improvement of the situation, and would also be very valuable for the interpretation of the long–baseline projects.

3. Future Projects

A significant part of the session has been dedicated to the perspectives of future experimental studies of atmospheric ν. A table with a comparison of the different projects and their physics potential, also compared to the LBL projects can be found in [?]. For three projects we have heard detailed presentations.

The development of large (Km^3 size) detectors for the study of high energy ν of astrophysical origin is one of the main directions of research in ν physics. Obviously these instruments will detect large rates of atmospheric ν origin, that in fact will constitute a major source of background for the astrophysical signals. However the optimization of a detector for astrophysical and oscillation studies is quite different, since in the first case the main interest is higher E_ν and a very large acceptance at the cost of lower resolution. The ANTARES [9] collaboration is developing a "demonstrator" detector with a volume of order 0.1 Km^3. Monte Carlo studies show that this detector has an interesting potential for the study of atmospheric ν's oscillations, studying the distortions in the energy and angular distribution of up–going events. A major difficulty arises however from the fact that the effective volume in the most important energy range (close to the threshold of order $\sim$ 20–30 GeV) is a rapidly growing function of E_ν, therefore the sensitivity to oscillations will depend on the capability of determining accurately and with small systematic uncertainty this energy dependence.

The MONOLITH detector [10] is a large magnetized iron detector, that is proposed for the Gran Sasso laboratory. The detector is composed of a sandwich of 8 cm iron planes with tracking detectors (RPC) with good spatial and time resolution. The basic goal of the detector is the observation of the pattern of oscillation in L/E_ν. As discussed before, such a measurement would exclude "alternative models" with a monotonically falling disappearance probability and is therefore important.

The reason why the oscillation pattern is not observable by SK is that the position of the crucial "last" minimum of the oscillation formula $L/E_\nu = 2\pi/|\Delta m^2|$ has a best fit value $\sim$ 400 Km/GeV. For $E_\nu \sim$ 1 GeV this corresponds to horizontal ν's, for which the resolution in L/E_ν is very poor since a small uncertainty in the ν direction is reflected in a large uncertainty in L. The key to improve the resolution is to go to higher E_ν, so that the minimum moves to less horizontal directions where the geometry is more favorable, furthermore for larger E_ν the directions of the detected μ and the initial state ν have a better correlation. A tracking calorimeter could also offer some advantages over a water Cherenkov detector in the study of multi-particle events (when in water several Cherenkov rings overlap. The magnetized iron also allows measurement of the momentum of the muons in semicontained events, improving the E_ν resolution.

The ICARUS design [11] thanks to the remarkable resolution of its novel technique, allows events to be studied in great detail, with excellent μ/e discrimination. For example it will be possible to observe with good efficiency the recoil protons in quasi–elastic interactions (such as $\nu_e n \to e^+ p$). This allows "closing" the kinematics of the event, obtaining a better resolution for the ν energy and direction. The main limitation is due to nuclear effects, since most of the reactions will happen on a nuclear target, and a certain amount of energy and momentum will be transfered to the spectator nucleons and be unobservable.

Is it possible to design a detector with a very significant (order of magnitude) improvement over the performances of SK? This is clearly an ambitious program considering the size, quality and cost of SK. Several ideas have been proposed, and have been discussed. This problem is also tightly related to the future of experimental studies on p decay. In fact the main scientific motivation for the detectors that have discovered and studied the "atmospheric ν anomaly" was in fact the search for p decay, and the "next generation" p–decay detectors that are currently under discussion could (must) also perform important measurements on the "background" due to the atmospheric ν's.

One possible direction of improvement is an increase in detector mass with only limited degradation of the resolution. This is the direction of the "Hyper–Kamiokande" concept [12] (eg. "UNO"), a water Cherenkov detector with a Megaton mass. For SUSY–SU(5) models the interesting nucleon decay modes involve Kaons in the final state. SK is already background limited for such modes, and hence potential gains in lifetime–reach scale as the square root of detector mass. Achieving the interesting level of 10^{35} *year* at reasonable cost seems difficult.

An interesting variation of the non-imaging water Cherenkov detector concept (SK), proposed and vigorously discussed by Tom Ypsilantis [13], is the AQUA-RICH idea of focusing the Cherenkov light to allow for better resolution and pattern recognition capabilities. The tradeoff here is that higher energy cosmic ray neutrino events (around 10 GeV) are needed, so one also needs an instrument of megaton class, and one may not make much progress for for nucleon decay (where the backgrounds are near the Cherenkov detection threshold).

An alternative direction [14] is to consider a detector with a mass comparable to SK, but significantly better resolution and pattern recognition capabilities, for example an ICARUS–like detector with the SK mass. This could in principle be achieved filling the SK with 70 kilotons of liquid argon. Additional studies are of course necessary to see if these 'dreams" have a realistic chance of becoming reality.

Discussing the future of experimental studies on the flavor transitions discovered in the atmospheric ν data one is tempted to make an analogy with the historical development of particle physics. This field started with cosmic ray studies, and the discoveries of the positron, the muons, the pions of the strange particles all happened in experiments with cosmic ray. Soon after however, particle physics moved to accelerators, where more intense and better controlled beams were available. From that moment the contribution of cosmic rays to the development of particle physics has been marginal (even if things could change again in the near future [15]).

Similarly today the focus of the study of the physics at the origin of "the atmospheric ν anomaly" seems to be moving in the direction of an intense program experiments using long baseline beams ν produced at accelerators [16]. This however does not exclude the possibility that further studies of the atmospheric fluxes will not yield important contributions. Atmospheric neutrinos have a broader range in energy and pathlength with respect to accelerators ones. This is a distinct advantage, that can be particularly important if the "new physics" that is at the origin of the observed effects is more complex that the simplest hypothesis of standard flavor oscillations.

Table 1 shows a rough comparison of the physics capabilities and reach of SuperK and the various present and future long-base-line experiments which are designed to follow up the indications of muon neutrino oscillations in SuperK. This table was initially generated by an informal working group at the 2000 Aspen "Neutrinos with Mass" Workshop. Although the details may annoy proponents of some projects (and please others), the purpose was not to evaluate specific experiments, but to try and gauge the strengths of the various approaches as we move forward in the quest to complete the MNS matrix and explore for CP and CPT violations in the neutrino sector. Since Aspen we have added MONOLITH, changed ICANOE back to ICARUS, adjusted some entries based upon comments from proponents, and added a row on ancillary physics capabilities.

In order to make such a table we have to make some guesses about the physics. We assume $\Delta m^2 = 0.003\ eV^2$ and $\sin^2(2\theta) \simeq 1.0$ with dominantly $\nu_\mu \leftrightarrow \nu_\tau$ mixing, U_{e3} is not zero, large mixing angle MSW solar neutrino oscillations and no LSND/BooNE indication of oscillations. We also assume a $20 - 50\ GeV$ neutrino factory and high quality neutrino detector at a few thousand kilometers distance.

In Aspen there was considerable discussion of whether the new experiments will or will not be able to see at least one dip in the detected neutrino spectrum, unambiguously discriminating oscillations from decay. The present authors conclude that such a detection will be very difficult for all experiments with traditional neutrino beams if the Δm^2 is at the low end of the presently allowed region. ICARUS claims to be able to detect oscillations in the cosmic ray beam, a consequence of their excellent resolution and the larger range of L/E values available from the atmospheric neutrinos than from a fixed distance long-base-line beam.

What we see from this exercise is that there really is a great gulf between what can be accomplished with a neutrino factory and anything prior to that, even with more powerful traditional neutrino beams. It will not be until there is a neutrino factory with detectors at several distances that great progress will be made in filling in the MNS matrix, including testing unitarity.

Slightly further in the future there may well be a neutrino factory somewhere in the world. As indicated in Table 1, it has become inescapable that significant progress in elucidating the MNS matrix as well as testing for CP and CPT violations in neutrinos will require long baseline neutrino factory associated experiments. While there has been much discussion of optimal accelerator-detector range for such experiments, it seems that neutrino detectors with masses of at least tens of kilotons are required. Given that the energy ranges for nucleon decay, contained atmospheric neutrino events, and beams from a neutrino factory (with muon energy 20–50 GeV) are all rather similar, a facility which can study all three categories is very attractive. Note that the need for μ/e separation and muon energy measurement for a neutrino factory experiment, strongly constrains choices. There will certainly be much discussion of the relative merits of the various possibilities in the next few years, since a neutrino factory is thought to be at least a decade away from reality.

The door has been opened by the atmospheric neutrino (and solar neutrino, and perhaps LSND) results and there is now much vigorous pursuit of the avenues which will lead to detailed knowledge of the neutrino sector. We expect that NOW2000 may be the only an early sample of a continuing and exciting campaign probably to require many years.

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Tom Ypsilantis had agreed to discuss this project with us at this workshop. His absence deeply saddened all of us.
14. J. Learned and A. Rubbia, plus D. Cline and K. McDonald, discussions during the "Neutrinos with Mass" Workshop, Aspen Center for Physics, July, 2000.
15. See for example John Ellis, astro-ph/0010474 and references therein.
16. See the contributions of J. Hill, B. Gavela and G. Saitta in these Proceedings.

Table 1: Comparison of SuperK and follow-on ν_μ long-base-line neutrino experiments in terms of physics capabilities and reach. See text for explanation.

Experiment: Test	SuperK (atm ν)	K2K	MINOS	ICARUS	OPERA	MONOLITH	JHF2K	ν Fac
$d(ln(\Delta m^2))$	50%	20%	10%	10%	$> 20\%$	6%	10%	2%
$d(\sin^2 2\theta)$	5%	5%	5%	5%	?	4%	4%	2%
See Osc. Dip?	$\times$	$\times$	$\surd$(?)	$\times(atm\surd)$	?	$\times$	$\times$	$\surd$
τ appear (kink)	$\times$	$\times$	$\times$	$\times$	$\surd$	$\times$	$\times$	$\surd$
τ appear (kinem)	$\surd$?	$\times$	$2\surd$	$3\surd$	$4\surd$	$\surd$	$\times$	$4\surd$
$\sin^2 2\theta_{13}$ limit	0.1	0.03	0.03	0.015	(ident e?)	0.03	0.1	$1-3\times10^{-3}$
$d(\nu_s/\nu_\tau)$	20%	$\times$	5%?	5%	?	20%	$\times$	1%
Elim Decay Models?	$\times$(? NC/CC)	$\times$	$\surd$(NC/CC)	$\times$(atm$\surd$)	?	$\surd$	$\times$	$\surd$
Sign of Δm^2	$\times$	$\times$	$\times$	$\times$	$\times$	?	$\times$	$\surd$
$\nu_e \to \nu_\tau$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$\surd$
CP violation tests	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$\surd$
CPT violation tests	$\times$	$\times$(?)	$\surd$	$\surd$	$\times$	?	$\times$(?)	$\surd$
Signif. Other Phys.	PDK, SN, Sν	σ_ν	σ_ν	PDK?, SN	$\times$	$\times$	?	?