Summary of the meeting[1]

1 Introduction

An informal meeting on “Atmospheric neutrino flux” was held on Feb.8th and 9th, 2000 at the Institute for Cosmic Ray Research, Univ. of Tokyo. This is a “telegraphic” summary of some of the discussion we had during the meeting.

There was an agreement that the data of Super–Kamiokande on atmospheric neutrinos give clear evidence for the existence of neutrino oscillations. The next step for SK and the other atmospheric neutrino experiments is to perform detailed studies of neutrino oscillations. However, for these further studies, a better understanding of the neutrino flux is essentially important.

The main purposes of the meeting was to assess the status and understand of the calculations of the atmospheric neutrino fluxes, and to determine which are the most “urgent” questions that are important for an understanding and correct interpretation of the neutrino data and in which directions we can expect to have progress in the near future.

In this program there is a strong need for INPUT data. On the primary cosmic rays, and on the fluxes of other “secondary” particles in the atmosphere (especially muons but also photons). Also data on particle production in hadronic interactions with nuclear targets, and new high precision data on the neutrino cross section in the relevant energy range would help the field.

How important are the studies of ν oscillations with atmospheric neutrinos? We all know that that the experimental program on atmospheric neutrinos will be very intense in the next few years and that LBL programs (starting with K2K) will give very valuable information on the neutrino oscillation parameters, however the results from atmospheric neutrinos could give very important information still for several years (possibly longer). The measurement of $\sin^2 2\theta$ from the up–down asymmetry of muon events is likely to remain the best determination for a long time. The measurement of Δm^2 with atmospheric neutrinos is more difficult, “theoretical biases” can more easily be introduced in the estimate and on paper LBL experiments should provide a more precise measurement (especially if Δm^2 is large).

In any case one should try hard to “get the most” out the experimental studies of atmospheric neutrinos.

The structure of the workshop was organized around the following themes:

- Discussion of the SK experimental data.
- New measurements of the primary cosmic ray data.

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[1] List of the participants: T.K.Gaisser (Bartol Research Institute, Univ. of Delaware); A.Kibayashi (Univ. of Hawaii); S.Torii (Kanagawa Univ); M.Motoki (KEK); A.Ferrari (Univ of Milano), K.Kasahara (Shibaura Inst. Tech.); J.Nishimura, T.Sanuki (Univ. of Tokyo); H.Matsumoto (ICEPP, Univ. of Tokyo); S.A.Stephens (ICEPP, Univ. of Toyko and Tata Institute); M.Honda, M.Ishitsuka, T.Kajita, J.Kameda, K.Kaneyuki, K.Kobayashi, A.Okada, S.Moriyama, Y.Obayashi, M.Shiozawa, T.Toshito, (ICRR, Univ. of Tokyo); P.Lipari (ICRR, U.Tokyo, and Univ of Rome)

- Hadronic interaction models
- Method of calculations (1D versus 3D), particle propagation and so on.
- The neutrino cross section.
- Constraints from muon and γ measurements in the atmosphere.
- The atmosphere, the mountain and other effects.

2 Experimental data

We heard two presentation about Super–Kamiokande. K. Kaneyuki presented a summary of the SK atmospheric neutrino data, and he discussed what we can expect from the future. He estimated that after 10 years of data taking Δm^2 will be measured to a 20% accuracy, $\sin^2 2\theta$ to 5% accuracy (in a two flavor $\nu_\mu \leftrightarrow \nu_\tau$ scenario). The systematic uncertainties on up–down asymmetry need to be kept small not to bias the estimate of $\sin^2 2\theta$.

T. Toshito discussed the $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_{sterile}$ interpretations of the SK data.

The conclusion, recently reached by the SK collaboration is that oscillation into a sterile neutrino is disfavored at 99% C.L. This important result does rely on the details of the flux calculation and on the estimate of the "theoretical" uncertainty in the calculation. The π/K ratio plays a very important role as it is recognized as the most important source of uncertainty in determining the *shape* of the zenith angle distributions of the upward going muons.

3 Primary cosmic ray flux

3.1 The proton flux

Significant progress has been obtained in recent times. Before 1990, the measurements of the primary proton flux below about 100 GeV were ambiguous and there where discrepant results (the "high flux" results of Webber et al, and the "low flux" result of LEAP) In the 1990's, several new measurements have been carried out. All the new results agrees with the "low flux".

We have heard detailed presentations of the BESS data from T.Sanuki and of the CAPRICE data from S.Stephens.

There was some discussion on the data of AMS. Several of us have noted that the data seems to show the presence of a magnetic latitude dependence of the primary proton flux (P.Lipari had circulated a note about this). The effect seems statistically significant. However there are reasons to be cautious. The BESS muon data at ground taken at Tsukuba and Lynn Lake do not show any evidence for flux difference in the high-energy region. The result is therefore not confirmed by any other experiment. We conclude that it is too early to include the AMS latitude dependence in the neutrino flux calculation.

3.2 The Helium flux

The picture of the determination of the proton flux seems to be converging to a consistent picture at least for $E_0 \lesssim 100$ GeV. There seem to be some significant discrepancy for the Helium data. The results of Caprice and BESS do not seem to be in good agreement. This could have a relatively small impact for the atmospheric neutrino calculation, but we believe that a full understanding of this question is important.

3.3 High energy fluxes

A question that is important (especially for upward–going muons) is the estimate of the cosmic ray fluxes at high energy. BESS in the future will measure the proton flux up higher energy. In the mean time one has to use the results of emulsion experiments on balloons (JACEE and RUNJOB) and the constraints obtained from indirect measurements at ground level. How stringent these contraints are is the subject of some discussion.

The data on the photon fluxes (BETS) high in the atmosphere has been suggested as an important measurement strictly related to the primary flux (see later).

3.4 Fits to the data

The time is ripe to use the very valuable new data for a new estimate of the primary fluxes to be used in the calculation of the ν fluxes.

T. Gaisser noted that the Bartol group is planning to perform a careful fit of all world data, discarding the "high flux" results of Webber to have a best estimate to be used for atmospheric neutrino calculations.

M. Honda has discussed the merits of using the results of a single experiment (BESS) that in the judgment of several of the participants has the best control of systematics and the smallest statistical errors.

It will be very interesting and instructive to compare the "world average" of the Bartol group with BESS results to see how they match each other.

4 Atmospheric muons and gammas

Several measurements of the atmospheric muon flux are carried out. These muon data are very useful for the calibration of the atmospheric neutrino flux calculation which starts from the primary cosmic ray fluxes. CAPRICE muon data (presented to us by S. Stephens) are very useful since they have data at ground level, during the ascent and at float. BESS has similar data (presentation of M. Motoki) they have presented the data at ground level and are working on the data taken during flight and at Mt. Norikura (at an atmospheric depth of 720 g cm^{-2}).

The ground level data of BESS and Caprice seem in good agreement. It is important to note that the flux seems approximately 20% lower in normalization than previous data. Since the old normalization was well reproduced by the HKKM (Honda, Kajita, Kasahara and Midorikawa) and Bartol calculations, this result suggests that the calculated atmospheric neutrino fluxes may also be lowered by a similar amount.

The data taken during the balloon ascent, and at float altitude are also of great interest and probe in different ways the development of the hadronic showers. There is some discrepancy between the muon data taken in flight and the calculations. The significance and interpretation of these discrepancies are still the object of discussion. The importance of using the real air density profile (as determined during the flight) for the data analysis was discussed. The importance for the calculations of accounting for bending of muons in the geomagnetic field and of matching as closely as possible the acceptance of the individual muon detector was also noted. The effects of the air density profile, and of the bending of charged particles in the geomagnetic field are stronger for muons than for neutrinos.

Since the muon data (especially μ^+ data) are limited to a relatively low energy region, the gamma ray data can be used as another source of the calibration of the neutrino flux in the high energy range. An advantage of the use of measurement of photons (with the respect to the case of atmospheric muons) is the fact that the flux of γ's does not depend on the details of the atmospheric structure, but only on the column density at the detection point that is directly measurable. Because of these different characteristics the measurements of atmospheric μ's and γ's can be seen as complementary. K. Kasahara presented some preliminary results of the balloon experiment BETS on the flux of gamma rays in the atmosphere. J. Nishimura discussed the relevance of these measurements and the relation between the photon flux and the primary radiation. He also presented other data on the gamma–ray spectrum obtained together with measurements of the primary electron spectrum.

5 Hadronic Interactions

The modeling of hadronic interactions is very important in the calculation of the atmospheric neutrino fluxes.

We have heard presentations about FLUKA (from A. Ferrari) and TARGET (from T.Gaisser) and by K. Kasahara about the models used in calculations performed in Japan. There are important differences in the way models are built and in the results they provide. The models are constructed according to different theoretical frameworks, and have different underlying dynamics. The models give different descriptions of the average multiplicity of different particle types in the final state, and of the momentum distributions of these particles. These differences are reflected on the neutrino fluxes. The largest effect is a different normalization for the fluxes, but other effects are also introduced that are smaller but possibly more important for the interpretation of the data in terms of ν oscillations.

To judge the quality of the models one of course need a detailed comparison with the available experimental data. This work of comparison with accelerator data is underway. Gaisser showed comparisons which suggest that TARGET gives somewhat too high pion multiplicity for small x. Ferrari showed extensive comparisons of FLUKA with a variety of data with various beams and targets that demonstrate the power and wide range of applicability of the code. Comparisons among these groups are continuing with the goal of identifying the sources of the differences in their calculated neutrino fluxes, and eventually clarify which models are better reproducing the available experimental data. These comparisons will also allow further improvements if required.

We can expect the uncertainties from interaction models to be reduced, but not eliminated entirely because accelerator experiments do not presently cover all of relevant phase space; moreover not all of the available data is entirely consistent. In this connection we note that the newly approved experiment HARP at CERN will explore pion and kaon production on various nuclear targets over a large fraction of relevant phase space with beam energies up to 15 GeV. Other new experiments at higher energies are also desirable.

As pointed out by T.Toshito, the analysis of $\nu_{sterile}$ by upward going muons strongly depends on the shape of the calculated zenith angle distribution of the neutrino flux. The uncertainty of this shape mainly comes from the uncertainty of the K/π production ratio. The uncertainty on the K/π ratio was estimated as of order $\pm 20\%$.

The new calculation of FLUKA shows a μ/e ratio (for contained charged current ν interactions) significantly larger than the results of Bartol and HKKM (nearly 7%–8% larger for $E_\nu \gtrsim 1$ GeV). This is a very important point. A full understanding of the origin of this discrepancy has not yet been achieved. In particular, it is not yet clear if it results from a difference between the interaction models or a difference in the treatment of the atmospheric cascades.

The computer codes for the development of the cosmic ray showers include not only a model for the hadronic interactions, but also algorithms for particle propagation, energy loss, decay probability and so on (see also the discussion in the next section). A comparison of the "shower development codes" used by the different groups can also be important. Useful tests that have been discussed and that could be performed in the near future are the inclusion of the TARGET model for hadronic interactions inside FLUKA, and the use of the inclusive secondary particle distributions of FLUKA and TARGET in the shower code developed by Honda, Kasahara et al.

It is clear that the data on atmospheric muons (and photons) provide an extremely valuable constraint for the entire calculation of the neutrino fluxes. It is of course necessary to clearly establish which sets of data are reliable and can be used as a reference (see the discussion in section 4). All elements discussed in this workshop (primary spectrum, interaction model, atmospheric density profile, treatment of shower development) play a role in the results of a calculation. The failure of a calculation in reproducing the data on atmospheric muons and photons would of course require a detailed analysis to identify the possible source(s) of the discrepancy. A successful description of the data would be a strong indication of the reliability of a calculation. It has been noted that the agreement with the muon and photon data in order to be really significant should be obtained with all different elements of the calculation (primary flux, interaction model etc.) in agreement with the relevant data (direct measurements, accelerator experiments).

6 1 dimensional versus 3 dimensional calculations

The most significant difference between 1D and 3D calculations is the enhancement of the flux near the horizon in the 3D calculation. This effect was demonstrated in the 3D calculation of FLUKA. Honda and Kasahara presented new results that confirm the existence of this geometrical enhancement. In this meeting, it was recognized that the enhancement of the horizontal flux is a real effect. This enhancement is significant and we think that the future calculations should be done in the 3D framework.

It was pointed out by P.Lipari, that a detectable signature of the 3D effects could be obtained from the analysis of the east–west effect for atmospheric neutrinos already observed by Super–Kamiokande. In fact the Super-Kamiokande data on the east-west effect presented by K.Kaneyuki showed the hint of a discrepancy between data and the 1D prediction. A 3D calculation including the bending of secondary particles in the geomagnetic field would (qualitatively at least) explain better the data.

7 Neutrino interaction cross sections

The modeling of neutrino cross section is important in the prediction of the neutrino event rate, and has to be discussed as carefully as the neutrino fluxes. There are several good Monte Carlo programs which simulate neutrino interactions. A careful work of comparison between these different codes would be useful and instructive. We discussed a preliminary comparison between the NEUT and NUANCE programs which are used in Super-Kamiokande, the code developed for MACRO and the code developed by A.Ferrari and A.Rubbia for Nomad and ICARUS. The rates predicted by NEUT and NUANCE (for the same ν–fluxes) seem a little smaller.

A. Ferrari noted that some of the nuclear physics needed for the calculation of the neutrino cross sections (like particle rescattering in a nucleus) is also relevant for the simulation of proton decay.

8 The Atmosphere and the Mountains

The density profile of the atmosphere depends (weakly) on the geographycal position and time (day–night and seasonal variations). These differences can in principle be reflected on the atmospheric neutrino fluxes. Note also that if it is summer for the detector site it could be winter for the “up–going” neutrinos. M.Honda presented results of calculations performed using detailed profiles that depend on the position and the time (season). His results show effects of the order of a few percent. (smaller of course when integrated over an entire year). If these results are confirmed by Monte Carlo calculations with larger statistics, they could be observable by Super–Kamiokande. The “atmosphere” effects are larger for electron neutrinos than for muon neutrinos.

The presence of a mountain above the Super–Kamiokande detector reduces (by at most a few percent) the flux of down–going neutrinos in Super–Kamiokande. M.Honda presented a calculation of the effect in agreement with the first rough estimate by the Super-Kamiokande collaboration. The effect is largest for e–like events (all coming from muon decay).