REVIEW OF ATMOSPHERIC NEUTRINOS

T.K. GAISSER
Bartol Research Institute, University of Delaware
Newark, DE 19716, USA

In this talk I review measurements and calculations of the flux of neutrinos produced by interactions of cosmic rays in the atmosphere. The main reason for interest in this subject is the apparent anomaly between the predicted and the observed ratio of $\nu_e$ to $\nu_\mu$. With the advent of Super-Kamiokande, we are on the threshold of an order of magnitude increase in the amount of data available to study the problem. My goal in this talk is to describe the current status of the subject, both for contained events and for neutrino-induced upward muons.

1 Introduction

Because of their small cross sections neutrinos were the last component of the secondary cosmic radiation to be measured, although they are the most numerous particles in the GeV energy range at sea level. Markov suggested how upward and horizontal muons deep underground could be used as a signal of high energy neutrinos, and Greisen described a neutrino detector like the modern water detectors in which neutrino interactions could be observed directly. Neutrino-induced horizontal muons at the predicted level were observed a few years later in deep mines in India and in South Africa.

The deep detectors built to search for proton decay have now accumulated more than a thousand contained events. The large water Cherenkov detectors, IMB and Kamiokande, dominate the statistics. Although the total events rates are consistent with the expectation for interactions of atmospheric neutrinos, the ratio of electron-type to muon-type neutrinos is significantly higher than predicted for the water Cherenkov detectors. The first hint of this anomaly came already in 1986 with the observation by IMB of fewer than expected muon decays among their events. The most well-defined class of events is the contained single-ring events. These are mostly charged-current quasi-elastic events (e.g. $\nu_\mu + n \rightarrow p + \mu^-$) with an admixture of neutral-current events in which a single pion is produced. A recent statement of the anomaly for $\lesssim 1$ GeV neutrinos at Kamiokande is:

$$\frac{(\mu/e)_{\text{data}}}{(\mu/e)_{\text{calculated}}} = 0.60^{+0.06}_{-0.05}$$

for contained single-ring events. The iron tracking calorimeters, however, find results consistent with no anomaly or with a smaller anomaly.
The rate of interactions for neutrinos $\nu_i$ inside a detector of mass $M$ (in g) is

$$\text{Rate} = N_A M \int dE_\nu \int dE_\ell \int d\Omega \phi_i(E_\nu, \Omega) \frac{d\sigma_i}{dE_\ell} \epsilon(E_\ell),$$

(1)

where $N_A$ is Avogadro’s number. The factors in the integrand are the differential flux of $\nu_i$; the differential cross section to produce the corresponding lepton, $\ell$; and the efficiency, $\epsilon$, for its identification and detection. The expression for the rate of neutrino-induced muons is similar except that the target mass is

$$M(\Omega) = R_\mu(E_\mu) \times A(\Omega),$$

(2)

where $R_\mu(E_\mu)$ is the muon range and $A(\Omega)$ is the projected area of the detector as seen from the direction $\Omega = (\theta, \phi)$.

Explanations for the anomaly in the contained events have been sought in all three factors of Eq. 1. I will discuss calculation of the flux $\phi_i$ of atmospheric neutrinos separately in the next section. Several approximations have been made in the treatment of the cross sections for neutrino interactions in oxygen inside the water detectors. Engel et al.\textsuperscript{14} conclude, however, that the neglected physics cannot account for the anomalous $\mu$-to-$e$ ratio observed at Kamiokande and IMB. The reason is that the lepton momenta are high enough that corrections affect muons and electrons in very nearly the same way. Beam tests at KEK\textsuperscript{15,16} confirm the efficiencies determined from simulations for misidentifying muons as electrons and vice versa.

Another possibility is that there is some contamination of events that are not due to interactions of atmospheric neutrinos. The suggestion that there was an excess of events due to $p \rightarrow \nu\ell\bar{\nu}$ is presumably eliminated by the fact that the anomaly persists at higher energy.\textsuperscript{17} Ryazhskaya\textsuperscript{19} has suggested that extra electron-like events are really cascades from neutral pions produced inside the detector by interactions of entering neutrons generated outside the detector in interactions of atmospheric muons in the rock. Kamiokande argues against this by showing\textsuperscript{16} that they have a $\pi^0$ production rate consistent with neutral current production by neutrinos at the level expected and already accounted for in their simulations. Soudan argues against this explanation by analysis of their shield events\textsuperscript{12,13}.

Such possibilities highlight the importance of internal checks on the data. Various analyses\textsuperscript{20,21} agree that the Kamiokande and IMB data are consistent with each other after accounting for differences in exposure, geomagnetic cutoff and energy threshold, although Beier and Frank\textsuperscript{22} note a possible small discrepancy in the electron spectra at low momentum. There is a hint of the expected smaller interaction rate at the IMB detector during the period of maximum solar activity between 1989 and 1991 as compared to the earlier
part of their data collection from 1986-88, a period of minimum solar activity. One expects fewer events during solar maximum when the low energy primary cosmic rays are partially excluded from the inner solar system. The effect should be more noticeable in the overall rate at IMB than at Kamiokande because of the higher local geomagnetic cutoff at Kamiokande, which excludes a large fraction of the lower energy primaries in any case. During the first period (exposure of 3.4 kT yrs) IMB found 236 events (139 e-like and 97 µ-like). The corresponding numbers for the last 4.3 kT yrs of the 7.7 kT-yr. exposure were 271 (186 e-like and 85 µ-like). The total expected by simple extrapolation of the first period would be 297 ± 20. The difference (297 − 271), though not statistically significant, is about what would be expected due to solar modulation effects. The fact that the decrease shows up only in the µ-like events is not consistent with solar modulation. Presumably it is an accident of low statistics. Stanev has emphasized the importance of using the expected solar cycle variations as a probe of atmospheric neutrino data, which will be possible with larger data samples.
Before turning to the discussion of the neutrino fluxes, I display the integrand of Eq. 1. Fig. 1 shows the “response-curves” for observed neutrino-induced muons. What is plotted is the rate of muons integrated over muon energy per logarithmic interval of neutrino energy. The four classes of events are fully-contained interactions, Kamiokande “multi-GeV” events entering muons that stop in the detector and neutrino-induced throughgoing muons. The figure is specific to the Kamiokande detector, but similar distributions could be constructed for any detector. The curves rise from low energy as the neutrino cross section increases with energy. For \( \nu \)-induced muons the effective volume also increases with energy as the range increases. Eventually the growth of range and cross section slow and the steep cosmic-ray spectrum (together with pion interaction) cuts off the signal of atmospheric neutrinos at high energy. The response curves are useful when considering possible explanations of the flavor anomaly in terms of neutrino oscillations.

## 2 Flux of atmospheric neutrinos

The analysis of atmospheric neutrino experiments has depended mainly on four calculations of atmospheric neutrinos. The calculations of G. Barr, Gaisser and Stanev (BGS), Honda et al. (HKHM) and Bugaev and Nau-mov (BN) are completely independent of each other. The neutrino flavor ratio is the same within 5% in all these calculations, but there are some significant differences in normalization and shape of the calculated neutrino energy spectra. Many sources of uncertainty cancel in the calculation of the ratio of \( \nu_e/\nu_\mu \). Thus the theoretical uncertainties are much smaller in the ratio than in the normalization. Fogli and Lisi have shown how to make the comparison between expected and measured neutrino interactions in this situation.

Suzuki has compared the measured spectra of electrons and muons in single ring neutrino interactions with full simulations starting from the fluxes of HKHM, BGS and BN. The calculation of BGS gives the steepest spectrum, predicting more muons with momenta below 600 MeV/c than observed, but agreeing with the measured spectrum of electrons. In contrast, the neutrino spectra of BN are nearly in agreement with the muon spectrum down to 200 MeV/c but predict fewer electrons than observed. The calculation of HKHM is intermediate but closer to the results of BGS.

Table 1 compares the neutrino fluxes of the three calculations. The first part of the table shows the neutrino spectra separately for \( \nu_e \) and \( \nu_\mu \) in three energy intervals, normalized to BGS= 1.00. The second part of the table shows
Table 1: Comparison of calculated neutrinos fluxes at Kamioka

|       | $\nu_\mu + \bar{\nu}_\mu$ | $\nu_e + \bar{\nu}_e$ |
|-------|-----------------------------|------------------------|
|       | 0.4 – 1 1 – 2 2 – 3         | 0.4 – 1 1 – 2 2 – 3    |
| BGS   | 1.00 1.00 1.00              | 1.00 1.00 1.00         |
| HKHM  | 0.90 0.95 1.04              | 0.87 0.91 0.97         |
| BN    | 0.63 0.79 0.95              | 0.62 0.74 0.87         |

|       | $\bar{\nu}_\mu/\nu_\mu$ | $\bar{\nu}_e/\nu_e$ | $R_{e/\mu}$ ($\leq E_\nu \leq 1$ GeV) |
|-------|---------------------------|---------------------|----------------------------------------|
| BGS   | 0.99                      | 0.89                | 0.49                                   |
| HKHM  | 0.99                      | 0.84                | 0.48                                   |
| BN    | 0.98                      | 0.76                | 0.50                                   |

the neutrino ratios in the energy interval between 0.4 and 1 GeV. Here

$$ R_{e/\mu} = \frac{\bar{\nu}_e + \frac{1}{3} \bar{\nu}_\mu}{\nu_\mu + \frac{1}{3} \nu_\mu} $$

to reflect the smaller interaction cross section for antineutrinos. This crucial ratio is nearly the same in all cases.

We have investigated the sources of difference among the calculations by substituting one-by-one different sets of assumptions from the various papers into the framework of the BGS calculation. In that work, the spectrum of neutrinos $\nu_i$ was expressed as a convolution of the primary cosmic-ray spectrum, the geomagnetic cutoffs and the yield per nucleon of $\nu_i$:

$$ \phi_{\nu_i}(\Omega) = \phi_p \otimes R_p \otimes Y_{p\rightarrow\nu_i} $$

In this equation $R_p(R_A)$ is the geomagnetic cutoff for protons (nuclei) incident on the atmosphere from the direction $\Omega = \{\theta, \phi\}$. The three terms on the right-hand-side represent respectively neutrinos from primary hydrogen, from protons bound in incident nuclei and from neutrons bound in incident nuclei. The separation is necessary because neutrino production depends on energy-per-nucleon of the incident cosmic rays but the geomagnetic cutoff depends on magnetic rigidity (gyroradius). Nuclei and protons of the same energy per nucleon differ by a factor of $A/Z$ in magnetic rigidity. To a good approximation, the yields of neutrinos from nuclei can be calculated as if the incident nucleons...
were unbound. (This approximation somewhat overestimates the production of neutrinos from pions produced in the target fragmentation region for the fraction of the flux due to incident nuclei. It is not used in Ref. 29.) In the energy region important for contained events, approximately 80% of the neutrinos are produced by cosmic-ray hydrogen (free protons) and most of the rest come from helium nuclei.

The form of the BGS calculation (Eq. 3) makes it possible to trace the effects of different assumptions through the calculation. As an example, consider the 1 GeV neutrino flux at Kamiokande at solar minimum. (Kamioka has the highest cutoff for downward cosmic rays of the nucleon decay detectors, so the effect of differences in cutoff is maximum. Comparison at solar minimum maximizes the effects of differences in assumed primary spectrum.) We compare the calculation of BGS 26 with that of HKHM 27. The treatment of the geomagnetic cutoff in BGS neglected the “penumbra” effect. A more accurate treatment of the cutoffs in by HKHM reduces the 1 GeV flux by a factor 0.87. The primary spectrum assumed in HKHM is higher than in BGS, which gives a factor 1.25. Yields of GeV neutrinos are approximately 15% lower in HKHM, giving a factor of 0.85. The product $0.87 \times 1.25 \times 0.85 = 0.93$ gives a net 7% lower GeV neutrino flux in HKHM than in BGS.

The main result of our comparison is that the biggest source of difference among the three independent calculations 26, 27, 29 is the treatment of production of low energy pions in collisions of 10 to 30 GeV protons with nuclei of the atmosphere. In the BN calculation the inclusive cross sections for production of $< 3$ GeV pions is significantly lower than in the calculations of BGS and HKHM. In fact, it is quite similar to the spectrum of pions in proton-proton interactions. In contrast, both HKHM and BGS use representations of pion production that give significantly more low energy pions in collisions on nitrogen than for $pp$ collisions. It is this feature of the BN calculation that gives rise to their characteristically harder neutrino spectra with relatively few low energy ($< 2$ GeV) neutrinos. At higher energy the neutrino fluxes of the three calculations are in better agreement.

Measurements of muons at high altitude can be used to constrain the neutrino spectra. Perkins 33 has calculated neutrino spectra starting from measured muon spectra, including preliminary results of the MASS 34 experiment. He concludes that the higher flux is preferred. Several groups have now measured the muon flux during the ascent of their balloon-borne detectors. The spectra of negative muons first reported in Ref. 34 have now been published. 35 The IMAX experiment has given a preliminary report of their measurements of muons 36, and the HEAT experiment is in the process of analyzing their measurements. 37
Both the Japanese group and we have now published calculations of the neutrino fluxes over the whole energy range from 0.1 MeV to 10^4 GeV. Our calculations now include a correct treatment of the geomagnetic cutoff effects, as described by Lipari and Stanev. Because of the large range of energies they cover, these calculations each give a consistent set of neutrino fluxes for simulating the full range of experimental data, from contained events to neutrino-induced muons at high energy. The algorithms used for these and other calculations of the atmospheric neutrino flux should be checked by comparing their corresponding muon fluxes with the full set of measurements of muons at high altitude that are becoming available.

3 Neutrino oscillation interpretation of the flavor anomaly?

As shown in the previous section, the predicted neutrino flavor ratio is quite robust because many sources of uncertainty cancel in the ratio. The most intensively investigated physics explanation of the atmospheric neutrino anomaly is the possibility of neutrino oscillations. As an example, consider oscillations, which occur with probability

\[ P_{\nu_\mu \leftrightarrow \nu_\tau} = \sin^2 2\theta \sin^2 \left( 1.27 \frac{\delta m^2 L(km)}{E(\text{GeV})} \right). \]

There is no visible up/down difference in contained events, for which \( E_\nu \sim 1 \text{ GeV} \). Since \( L \sim 20 \text{ km} \) for downward neutrinos this gives a lower limit of approximately, \( \delta m^2 \geq 0.005 \text{ eV}^2 \). If the effect begins to disappear for higher energy, there would then be an upper limit on \( \delta m^2 \). This is the significance of the Kamiokande extended analysis that includes a multi-GeV sample of data. In the multi-GeV sample there is an apparent up/down difference in the comparison between calculated and observed flavor ratio. The anomaly is largest for upward neutrinos with pathlength \( L \sim R_\oplus \approx 6000 \text{ km} \). The ratio is consistent with expectation for vertically downward events.

The Kamiokande combined analysis defines allowed regions for both \( \nu_e \leftrightarrow \nu_\mu \) and \( \nu_\mu \leftrightarrow \nu_\tau \) oscillations with large mixing angle and \( \delta m^2 \) in the range 0.01 to 0.02 eV^2. The preferred interpretation depends both on the normalization and the shape of the calculated neutrino flux. For the contained and sub-GeV events the calculations with high normalization suggest oscillations primarily in the \( \nu_\mu \leftrightarrow \nu_\tau \) sector whereas the calculation of BN prefers \( \nu_\mu \leftrightarrow \nu_e \).

There is an interesting energy-dependence that shows up in the multi-GeV events which has been noted previously (e.g. in Refs. and ). When compared to the HKHM neutrino fluxes, the ratio of measured/calculated for
electron-like events is $\sim 1.5$ as compared to $\sim 1.1$ for the sub-GeV sample. The corresponding numbers for muon-like events are $\sim 0.83$ and $\sim 0.66$. A neutrino spectrum that is sufficiently harder could be made to give the same ratios of measured/calculated for the sub-GeV and multi-GeV samples\textsuperscript{(a)} (The statistical significance of the anomaly would not be changed, only its interpretation.) Inspection of Table 1 shows that the BN spectrum has roughly the right degree of hardness to keep the ratio of measured/calculated constant for each neutrino flavor, but at the cost of a rather extreme assumption about the nature of production of low-energy pions in collisions of 10—30 GeV protons on oxygen; namely, that the yield is about the same below $\sim 2$ GeV as for collisions on protons. In a recent comprehensive three-flavor treatment of the atmospheric neutrino anomaly, Fogli et al.\textsuperscript{43} find that in fact $\nu_\mu \leftrightarrow \nu_e$ oscillations provide a better fit to the atmospheric neutrino anomaly than $\nu_\mu \leftrightarrow \nu_\tau$.

4 Neutrino-induced upward muons

Another way to explore higher neutrino energies is to use upward muons. Table 2 summarizes some comparisons between experiments and calculations for the flux of neutrino-induced muons with energy greater than a few GeV (the exact value depends on the experimental cut). The calculations are shown for two different assumed neutrino spectra, Volkova\textsuperscript{44} and Bartol,\textsuperscript{39} and assuming no oscillations. The calculations also depend on the structure functions used to obtain the cross section for $\nu + N \rightarrow \mu + X$.

The IMB calculation is an early result\textsuperscript{45} which uses the EHLQ\textsuperscript{46} structure functions which probably give too low a value of the cross section and hence underestimate the expected rate by some amount\textsuperscript{25}. Baksan\textsuperscript{47} and MACRO\textsuperscript{48} both calculate the cross section using Morfin & Tung structure function B1-DIS\textsuperscript{49}, while Kamiokande\textsuperscript{9} use MRS set G.\textsuperscript{50} The results are inconclusive because interpretation depends on comparison with an absolute calculation.
For example, Frati et al. \cite{25} considered an oscillation purely in the $\nu_\mu \leftrightarrow \nu_\tau$ sector. Using Owens'\cite{51} structure function for the cross section, they found $1.61, 1.97, \text{and } 2.33 \times 10^{-13} \text{cm}^{-2}\text{sr}^{-1}\text{s}^{-1}$ for $\delta m^2 = 0.01 \text{ eV}^2$ and $\sin^2(2\theta) = 1.0, 0.5 \text{ and } 0.0$ (no oscillations) respectively.

Comparison to the muon flux is also relevant for high energy neutrino fluxes, though the constraint becomes less restrictive as energy increases because at high energy ($> 100 \text{ GeV}$) a relatively larger fraction of neutrinos comes from kaon decay as compared to the muons, which are always dominated by pion decay. The muon fluxes corresponding to several different calculations of the neutrino flux at high energy \cite{52,53} are compared with a compilation of measured vertical muon fluxes from 1 to $10^4 \text{ GeV}$ in Ref.\cite{3}. All these calculations show some tendency to be higher than the measurements from 10 to 100 GeV and somewhat below the data from 100 to 1000 GeV. This small systematic effect, which is also noted in Ref.\cite{39}, is not presently understood.

The angular dependence of the upward (neutrino-induced) muon flux also contains in principle information relevant to an oscillation interpretation because the path length changes with angle. There are, however, significant systematic uncertainties because the experiments in general have acceptances that depend on direction. \cite{48} See for example the discussion of the angular-dependence of the MACRO data.\cite{58} There is also some difference in angular dependence among the calculations. In this situation it might be useful to carry out a two-dimensional analysis of the comparison between data and calculation, following the example of Fogli and Lisi\cite{30} for contained events. The variables might be total rate and the ratio of “horizontal”/“upward.”

Concerning angular dependence, it is interesting to note that the recent Kamiokande data set (364 events)\cite{9} does not fit any calculation as well as the earlier set \cite{56} with poorer statistics (252 events). For example, the $\nu_\mu \leftrightarrow \nu_\tau$ oscillation referred to above with $\delta m^2 = 0.01$ gives reduced $\chi^2$ values of 2.9, 2.6, and 3.2 respectively for $\sin^22\theta = 1.0, 0.5$, and 0 (no oscillation). The corresponding $\chi^2$ values for the earlier data set were 1.9, 1.1 and 2.0 (no oscillation).

Another way to remove some of the model-dependence from a comparison between expectation and observation of neutrino-induced muons is to compare the ratio of stopping to throughgoing muons.\cite{45} The stopping muons depend significantly on the neutrino cross section in the few GeV region, which is below the deep-inelastic scattering regime. Lipari et al.\cite{57} have pointed out that the cross section is poorly known in the low energy region. They make a careful evaluation of the cross section in the resonance region and find that the exclusion region is less restrictive than originally estimated in Ref.\cite{45}. There is almost no overlap between the excluded region they find and the “allowed”
region for oscillations in the $\nu_\mu \leftrightarrow \nu_\tau$ sector found by Kamiokande.

5 Conclusion

Results from the two large water detectors are consistent with each other, and they report a significant anomaly in the ratio of e-like to $\mu$-like events as compared to what is expected if all the events are due to interactions of atmospheric neutrinos inside the detectors. Iron (tracking) detectors are consistent with no anomaly but with low statistics. Preliminary results of the Soudan experiment are intermediate. Calculated ratios of $\nu_e/\nu_\mu$ are the same within $\pm 5\%$ in all calculations. Main sources of difference in overall normalization and shape among the calculations of the flux of atmospheric neutrinos have been identified. There are updated calculations which cover the whole neutrino energy range from $<100$ MeV to $10^4$ GeV. Further work is needed to compare these calculations with measurements of muons in the atmosphere at various cutoffs, times and altitudes.

The angular dependence of the Kamiokande multi-GeV events in combination with their sub-GeV events suggests a limited range of oscillation parameters with large mixing angles and $\delta m^2$ in the range $\sim 10^{-2}$ eV$^2$. Because they require comparison to an absolute calculation (rather than a ratio as for the contained events), the measurements of neutrino-induced upward muons are inconclusive at present.

First results from Super-Kamiokande are expected very soon. Because of its large fiducial volume Super-K will be able to accumulate of order $10^4$ events in a few years. This is enough to give $\sim 100$ events from each cone of half-angle $10^\circ$ in the sky. Super-K should therefore be able to pick out directions with particularly high and particularly low values of geomagnetic cutoff and therefore demonstrate that they can see the appropriate changes of rate characteristic of neutrinos produced by cosmic rays in the atmosphere. Similar remarks can be made about effects of solar modulation as we go from the current epoch of minimum solar activity into the next solar maximum in $\sim 1999$. In addition the systematics will improve as higher energy events will be fully contained.

Acknowledgments

I am grateful to Paolo Lipari, G.L. Fogli, Todor Stanev, Francesco Ronga and S. Mikheyev for discussions and data that helped me prepare this talk. This work is supported in part by the U.S. Department of Energy under Grant No. DE-FG02-91ER40626.
References

1. M.A. Markov in Proc. 1960 Annual Int. Conf. on High Energy Physics at Rochester (ed. E.C.G. Sudarshan, J.H. Tinlot and A.C. Melissinos).
2. K. Greisen, Ann. Revs. Nucl. Sci. 10, 63 (1960).
3. I have reviewed the history of atmospheric neutrinos in Phil. Trans. Roy. Soc. Lond. A346, 75 (1994).
4. C.V. Achar et al., Phys. Letters 18 196 and 19 78 (1965).
5. F. Reines et al., Phys. Rev. Letters 15, 429 (1965).
6. R. Becker-Szendy et al., (IMB Collaboration) Phys. Rev. D46, 3720 (1992).
7. K.S. Hirata et al. (Kamiokande Collaboration) Physics Letters B280, 146 (1992).
8. T.J. Haines et al. (IMB Collaboration) Physical Review Letters 57, 1986 (1986).
9. A. Suzuki, Proc. 7th Int. Workshop on Neutrino Telescopes (Venice) 1996.
10. Ch. Berger et al. (Frejus Collaboration) Physics Letters B227, 489 (1989) and 245, 305 (1990).
11. M. Aglietta et al. (NUSEX) Europhysics Letters 8, 611 (1989).
12. M. Goodman (Soudan Collaboration), talk given at the meeting of the American Physical Society, Indianapolis, May, 1996.
13. Earl Peterson, this conference.
14. J. Engel, E. Kolbe, K. Langanke and P. Vogel, Phys. Rev. D48, 3048 (1993).
15. S. Kasuga et al. (Kamiokande Collaboration) Phys. Letters B374, 238 (1996).
16. Y. Totsuka ICRR-Report-359-96-10.
17. W.A. Mann, T. Kafka and W. Leeson, Phys. Letters B291, 200 (1992).
18. Y. Fukuda et al., Physics Letters B335, 237 (1994).
19. O.G. Ryazhskaya, Nuovo Cimento C18, 77 (1995); Pis’ma Zh. Eksp. Teor. Fiz. 61, 226 (1995) [JETP Lett. 61, 237 (1995)].
20. E.W. Beier et al., Phys. Letters B283, 446 (1992).
21. T.K. Gaisser, Francis Halzen and Todor Stanev, Physics Reports 258, 174 (1995).
22. E.W. Beier and E.D. Frank, Phil. Trans. Roy. Soc. Lond. A346, 63 (1994).
23. D. Casper et al. (IMB Collaboration), Phys. Rev. Letters 66, 2561 (1991).
24. Todor Stanev, Nucl. Phys. B (Proc. Suppl.) 48, 165 (1996).
25. W. Frati et al., *Phys. Rev. D* **48**, 1140 (1993).
26. G. Barr, T.K. Gaisser and Todor Stanev, *Phys. Rev. D* **39**, 3532 (1989).
27. M. Honda, K. Kasahara, K. Hidaka and S. Midorikawa, *Phys. Letters B* **248**, 193 (1990).
28. H. Lee and Y.S. Koh, *Nuovo Cimento* **105B**, 883 (1990).
29. E.V. Bugaev and V.A. Naumov *Phys. Letters B* **323**, 391 (1989).
30. G.L. Fogli and E. Lisi, *Phys. Rev. D* **52**, 2775 (1995).
31. T.K. Gaisser, M. Honda, K. Kasahara, H. Lee, S. Midorikawa, V. Naumov & Todor Stanev, *Phys. Rev. D* (to be published).
32. J. Engel et al., *Phys. Rev. D* **46**, 5013 (1992).
33. D.H. Perkins, *Astroparticle Physics* **2**, 249 (1994).
34. M. Ciricella et al., Proc. 23rd Int. Cosmic Ray Conf. (Calgary) vol. 4, p. 503 (1993).
35. R. Bellotti et al., *Phys. Rev. D* **53**, 35 (1996).
36. J.F. Krizmanic et al., Proc. 24th Int. Cosmic Ray Conf. (Rome) vol. 1, p. 593 (1995).
37. S. Barwick, private communication.
38. M. Honda et al., *Phys. Rev. D* **52**, 4985 (1995).
39. Vivek Agrawal et al, *Phys. Rev. D* **53**, 1314 (1996).
40. T.K. Gaisser and Todor Stanev, Proc. 24th Int. Cosmic Ray Conf. (Rome) vol. 1, p. 694 (1995).
41. Paolo Lipari and Todor Stanev, Proc. 24th Int. Cosmic Ray Conf. (Rome) vol. 1, p. 516 (1995).
42. T.K. Gaisser and M. Goodman, Proceedings of the 1994 Snowmass Summer Study *Particle and Nuclear Astrophysics and Cosmology in the Next Millennium* (World Scientific, 1995) p. 220.
43. G.L. Fogli, Proc. 7th Int. Workshop on Neutrino Ades (Venice) 1996; G.L. Fogli, E. Lisi, D. Montanino and G. Scioscia, IASSNS-AST 96/41.
44. L.V. Volkova, *Yad. Fiz.* **31**, 1510 (1980) [Sov. J. Nucl. Phys. **31**, 784 (1980)].
45. R. Becker-Szendy et al. (IMB Collaboration) *Phys. Rev. Letters* **69**, 1010 (1992).
46. E. Eichten, et al., *Revs. Mod. Phys.* **56**, 579 (1984); **58**, 1065(E) (1986).
47. M.M. Boliev et al., Proc. 24th Int. Cosmic Ray Conf. (Rome) vol. 1, p. 722 (1995) and S. Mikheyev (private communication).
48. S. Ahlen et al. (MACRO Collaboration) *Phys. Letters B* **357**, 481 (1995) and F. Ronga, this conference.
49. J.G. Morfin and W.K. Tung, *Z. Phys. C* **52**, 13 (1991).
50. A.D. Martin, R.G. Roberts and W.J. Stirling, *Phys. Rev. D* **50**, 6734
(1994).
51. J.F. Owens, Philosophy Letters B266, 126 (1991).
52. Paolo Lipari, Astroparticle Physics 1, 195 (1993).
53. T.K. Gaisser, Todor Stanev & Paolo Lipari, Proc. 23rd Int. Cosmic Ray
   Conf. (Calgary) vol. 4, p 495 (1993).
54. K. Mitsui, Y. Minorikawa and H. Komori, Nuovo Cimento C9, 995
   (1986).
55. A.V. Butkevich, L.G. Dedenko and I.M. Zheleznykh, Yad. Fiz. 50, 142
   (1989) [Sov. J. Nucl. Phys. 50, 90 (1989)].
56. M. Mori et al. (Kamiokande Collaboration) Phys. Letters B270, 89
   (1991).
57. Paolo Lipari, Lusignoli and F. Sartogo, Phys. Rev. Letters 74, 4384
   (1995).
58. Y. Suzuki, this conference.
