JOURNAL OF THE FACULTY OF INTERNATIONAL STUDIES OF CULTURE,
KYUSHU SANGYO UNIVERSITY. NO. 12, 109-118 (1998)

Neutrino Properties From Atmospheric Neutrino Experiments

Kunio SHIGA

Physics Department, Kyusyu Sangyo University
2-3-1 Matsukadai, Higashiku, Fukuoka, Japan
(e-mail: shiga@phys.kyusan-u.ac.jp)
(Received May 20, 1998)

Abstract:

Atmospheric neutrinos originating from the interaction of the primary cosmic rays with the globe's atmosphere provides useful means of studying the intrinsic properties of neutrinos, especially to the sensitive search of neutrino oscillation in particularly very small Δm^2 region inaccessible to the present accelerator and reactor experiments. Prospects of various long baseline experiments under construction are commented at the end of this paper.

§ 1 The basic scheme of atmospheric neutrino production

The intensity of cosmic rays which have enough energy for neutrino production is almost equal all over the surface of the earth. But it is not true for the atmospheric neutrino being created in the atmospheric zone of the earth. Primary cosmic rays interacting with atmospheric nuclei produce complex hadronic showers. Neutrinos are created through the decays of the unstable secondaries. The basic scheme for atmospheric neutrino production is as follows. Primary cosmic rays striking the atmospheric pions and kaons which subsequently decay into muons and muon-neutrinos and much less abundantly, electrons and electron-neutrinos. At the height of several teen kilo-meters, the muons further decay into electron-neutrinos and muon-neutrinos in the following ways.

$$\pi^{+}\text{or } K^{+} \rightarrow \mu^{+}\nu_{\mu} \quad , \quad \mu^{+} \rightarrow e^{+}\bar{\nu}_{\mu}\nu_{e}$$
$$\pi^{-}\text{or } K^{-} \rightarrow \mu^{-}\bar{\nu}_{\mu} \quad , \quad \mu^{-} \rightarrow e^{-}\nu_{\mu}\bar{\nu}_{e}$$

The atmospheric muon and electron fluxes has been calculated by many peoples using different methods. Due to the uncertainties about the primary flux and to the incomplete knowledge of the details of primary interactions with atmospheric nuclei, the expected neutrino fluxes have large systematic errors. But it is interesting to notice that the ratio $(\nu_\mu+\bar{\nu}_\mu)/(\nu_e+\bar{\nu}_e)$ is predicted to be nearly two within five percent uncertainties in many theoretical calculations[1)]. The energy spectrum of atmospheric neutrinos detected in experiments, peaks at around one GeV, although the peak of the energy spectrum of solar neutrino is around 10 MeV. Providing the average energy of the atmospheric neutrino is about one GeV and the neutrino mass is larger than 0.001 eV, we can investigate the neutrino mass through the observation of the neutrino oscillation phenomena.

In fact, there is a difference in the travelling distance between the down-going neutrino and the up-going neutrino penetrating through the earth. That is, the travelling distance is about 20 (13000) kilometer for the former (latter) neutrino. A long flight in the latter case may cause the neutrino oscillation and bring some modification into the ratio $(\nu_\mu+\bar{\nu}_\mu)/(\nu_e+\bar{\nu}_e)$. For instance, providing the conditions with the neutrino energy being 5 GeV and the mass difference $\Delta m^2=0.005$ eV^2, the neutrino oscillation phenomena for the latter neutrino case can be visible after the flight of nearly ten thousands kilometers, but not in the former case with about 20 kilometers travelling distance. Then it is noted that the search of neutrino oscillation is particularly important for the case of the up-going neutrino penetrating through the earth. Then the atmospheric neutrino gives us a unique opportunity to study neutrino oscillations with particularly low Δm^2 region. Specifically, the sensitive searches for neutrino oscillations are made possible by the well-understood ratio $(\nu_\mu+\bar{\nu}_\mu)/(\nu_e+\bar{\nu}_e)$ and by the long distances traveled about $1.3\text{x}10^4$ km, to reach the detector on the earth. Using this long base line, atmospheric neutrino propagation may be studied over much longer distances than neutrinos produced in the laboratory.

Before proceeding to the next section, it is noted that the intensity of the atmospheric neutrino is extremely small in the contrast of accelerator beams. Then the experiment of examining the atmospheric neutrino requires the huge fiducial mass detector, although which is available in 1980's, having the large detection efficiency for physical events. This efficiency is often expressed in terms of

events/kton•year

which stands for the sensitivity in the atmospheric neutrino experiment.

§ 2 The atmospheric neutrino interactions with matter

As we discussed in earlier papers[2)], the oscillation probability in vacuum after a flight distance of relativistic neutrinos is provided as follows,

$$P\ (\nu_\mu \rightarrow \nu_\tau) = 1/2 \cdot \sin^2\ (2\theta) \cdot \{1 - \cos(E_1 - E_2)\ t\}$$

Considering the relativistic neutrino and putting $|E_1 - E_2| = \Delta m^2/2p_\nu$, $\Delta m^2 = |m_1{}^2 - m_2{}^2|$, $L = ct$ and $\lambda = 4\pi p_\nu/\Delta m^2$ (the wavelength of neutrino oscillation), the above probability is modified as follows, which means the probability for finding tau-neutrino at the distance L,

$$P(\nu_\mu \rightarrow \nu_\tau) = 1/2 \cdot \sin^2(2\theta) \cdot \{1 - \cos(2\pi L/\lambda)\}$$
$$= \sin^2(2\theta) \cdot \sin^2(1.27L/E_\nu \cdot \Delta m^2)$$

in the case of taking L, $E_\nu = p_\nu$, Δm^2 in m, MeV, eV^2 unit system, respectively.

In this derivation, the neutrino mass is essential. The massive neutrino are mixed in the mass term of the Lagrangian. Especially in the two-flavor hypothesis, the mixing matrix is a 2x2 matrix specified by the mixing angle θ. Due to the $W^\pm$ particle exchange with atomic electrons,

$$\nu_{\text{lepton}}\ N \rightarrow \text{lepton}\ N'$$
$$\nu_{\text{lepton}}\ N \rightarrow \text{lepton}\ N' + \pi\text{'s}$$

and Z^0 particle exchange with atomic electrons

$$\nu_{\text{lepton}}\ N \rightarrow \nu_{\text{lepton}}\ N'$$
$$\nu_{\text{lepton}}\ N \rightarrow \nu_{\text{lepton}}\ N' + \pi\text{'s}$$

the resonant amplification and/or suppression of the vacuum oscillations will be provided. Then, the electron neutrinos have a different index of refraction in matter than the other flavors. As a results, The presence of matter in the path of the atmospheric neutrino, bring a little changes into the above picture in the vacuum. These facts are indicated by Mikheyev and Smirnov[3] and Wolfenstein[4], usually called as MSW effect.

The atmospheric neutrino having the peak energy at one GeV, interacts directly with nucleons consisting of nucleus in the detector. The reaction cross section is proportional to the neutrino energy like,

$$\sigma_{\nu \mathrm{lepton} N} = 0.8\mathrm{x}10^{-38}\mathrm{x}\,(E_\nu/\mathrm{GeV})\,\mathrm{cm}^2$$

which is considered to be valid in the energy range of the atmospheric neutrino. The validity of this formula, however, to what energy it is well described, is still controversial.

§ 3 Worldwide measurements of the atmospheric neutrinos

The observation of the atmospheric neutrino has started in 1690's, but the great progress on the experimental accuracy has been achieved in 1980's with the successive appearance of the huge mass detector inspired by the search of proton's decay predicted in the grand unified theory[5]. Since then, the experiments of the atmospheric neutrino have been done in accordance with the experiment planned for the survey of proton's decay. Also these experiments are executed in deep underground for the purpose of avoiding and minimizing the background effects caused by the cosmic muon. In particular, the foundation of neutrino physics has been established after the proposal of the standard model.

In the experiment of the atmospheric neutrino, there are two different kinds of experiments in the present stage, as summarized below.

Experimental Groups (Location)	Method & Target	Running Years
IMB[6] (Cleveland, Ohio)	Water Cerenkov	1982-1991
KamiokaNDE[7] (Kamioka, Japan)	Water Cerenkov	1983-1995
FREJUS[8] (Alps, France)	Iron Calorimeter	1984-1988
NUSEX[9] (Mont Blane, France)	Iron Calorimeter	1982-1988
SOUDAN2[10] (Soudan Mine, Minnesota)	Iron Calorimeter	1989-1993-
SuperKamiokaNDE[11] (Kamioka, Japan)	Water Cerenkov	1996-
MACRO[12] (Gran Sasso, Italy)	Liquid Scintillator	1991-
ICARUS[13] (Gran Sasso, Italy)	Liquid Scintillator	1999-

<acronyms of collaborations>
IMB: Irvine, Michigan, Brookhaven
KamiokaNDE: Kamioka Nucleon Decay Experiment
NUSEX: NUcleon Stability EXperiment
MACRO: Monopole Astrophysics and Cosmic Ray Observatory
ICARUS: Imaging of Cosmic And Rare Underground Signals

The first one is the huge pure water tank attached with many photomultiplier adopted by IMB[6] and KamiokaNDE[7] groups. The second one is the iron calorimeter adopted by FREJUS[8] and NUSEX[9] groups. The IMB-3 detector with a 3.3-kt fiducial mass and 2048 8-inch photomultiplier augmented with wavelength-shifting plates, has been operated since May 1986. KamiokaNDE is a 3000t water Čerenkov detector located 1000 m underground in the Kamioka mine in Japan. The fiducial volume in this analysis is defined to be 2 m inside from the PMT planes for KAM-1 and 1.5 m for KAM-II. The corresponding fiducial masses are 880 t and 1040 t for KAM-1 and KAM-II, respectively. In the early stage of KamiokaNDE experiment, 277 events are observed in KamiokaNDE detector. The number of electron-like single—prong events shows a good agreement, but the discrepancies is observed in the number of the muon-like single-prong events, which discrepancy will bring the possible existence of neutrino oscillation. Experimental data are also taken in the KamiokaNDE detector in an exposure of 4.92 kt•yr. The observed ν_μ/ν_e ratio is smaller than the value expected in the theory, which difference leads to the existence of neutrino oscillation.

On the other hands, the FREJUS Collaboration has analysed charged-current interaction in their detector and find a fraction of 0.64 ± 0.04(stat) $\pm$ 0.02(syst) in which the final-state is a muon. The NUSEX Collaboration has studied contained interactions (charged- and neutral-current interactions are not separated) in their detector and find a 0.64 ± 0.07(stat) fraction of muon-like events. Both teams used fine-grain ion calorimeters, in which detector all lepton momenta and multiprong topologies are carefully analysed. Therefore it is difficult to see the quantitative comparison between the former two groups, IMB and KamiokaNDE and the latter two groups, FREJUS and NUSEX.

Experimental Groups	Ratio of Ratios	Sensitivity
	$(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$	(kiloton year exposured)
IMB[6]	0.54±0.05±0.07	7.7
KamiokaNDE[7]	0.60±0.06	6.1
FREJUS[8]	0.99±0.13±0.08	2.0
NUSEX[9]	1.0±0.3	0.74
SOUDAN2[10]	0.61±0.14±0.07	1.52
SuperKamiokaNDE[11]	0.54±0.07±0.05±0.05	12.8

From above table, there is a clear evidence of anomaly in neutrino events in IMB[6], KamiokaNDE[7], SOUDAN2[10], SuperKamiokaNDE[11] experiments. On the contrary, no definite anomaly is seen in FREJUS[8] and NUSEX[9] experiments, although these two experiments are inferior to the former experiments in the experimental sensitivity.

Before concluding this section, we give a few comments on the mesurement using water Čerenkov counter. Because of neutrino having no electric charge, therefore, the search of neutrino interaction is supposed to be done indirectly through the survey of charged particle interacted with neutrino. It is true in the water Čerenkov detector adopted in IMB and KamiokaNDE. When charged particle created in the interaction with neutrino and run through water with velocity larger than the light velocity, we can observe the Čerenkov radiation using photomultiplier attached in wall. Čerenkov radiation produced by charged particle with the light velocity, is radiated to the direction with 42 degrees along with the direction of incident particle. Then Čerenkov radiation is observed on the wall, in the form of ring. The energy of the incoming charged particle is determined from the total radiation on the wall, and also its direction is found by taking account of the direction of Čerenkov radiation. A number of rings of Čerenkov light make possible to count the number of charged particles.

§ 4 Miscellaneous problems and concluding remarks

Since the proposal of the standard model, many attempts of searching for proton decay are planned and executed in this decade. These trend brought the development of huge fiducial mass detector which brought the progressive steps into the observation of cosmic neutrino physics. In an early days, the neutrino experiment took a long time to accumulate the data, for example in the experiment by Davis et al.[14]. After the appearance of the huge mass detector starting at KamiokaNDE, the solar and atmospheric neutrino experiment have become possible to be achieved in relatively shorter period and also reveals the new aspects in the field of neutrino physics.

Concerning neutrino properties, it has been established at present that there are three kinds of neutrino corresponding to three generations in the standard model. But for the mass of these three neutrinos, attempts at direct measurements have yielded up to now the following sort of upper limits[15],

$$m_e < 3.9 \text{ eV}, \quad m_\mu < 170 \text{ keV}, \quad m_\tau < 18.2 \text{ MeV}.$$

The existence of small mass can be examined through the oscillation phenomena in quantum mechanics. We can learn a good example in history from the oscillation between neutral K_L and K_S mesons. The neutrino state is normally expressed in terms of mass eigenstates when it is created through the decay of particle. The mass eigenstates with different masses develop with different time in their progress owing to their different velocities being resulted from different masses. Therefore after the long flight, the combination of the mass eigenstates becomes another combination from the initial one. This is a particle oscillation phenomena, which is often used as a useful tools of finding small mass. It is noted that the necessary conditions for the existence of neutrino oscillation are (a) three neutrinos have different masses and also (b) mass eigenstates differ from flavor eigenstates. Under these two conditions, the searchable region for the small mass squared needs a long flight of neutrino, because of its proportionality of the quantity E/L (E: neutrino energy, L: propagation distance).

In the below, we summarize the results of the solar neutrino and atmospheric neutrino experiments executed so far. In particular, there are several hints for a nonvanishing mass for at least two or three known neutrinos which look very promising and credible. These facts are concluded from the observation of the solar neutrinos in various experiments and their disagreement with the predictions of the solar standard model[16]: the earlier experiments from Homestake[14], KamiokaNDE[7], SAGE[17] and GALLEX[18] and the most recent high statistics confirmation of the earlier results by the super-KamiokaNDE[11] experiments. The deficit in the solar neutrino experiments are in the range of thirty to forty percent, which is reasonably interpreted as a occurrence of neutrino oscillation between ν_e and ν_μ.

In addition, there are a few observations of the atmospheric neutrinos by IMB and KamiokaNDE and the most recent confirmation of the earlier results by the super-KamiokaNDE collaboration. Futhermore the first laboratory evidence for the neutrino oscillation of both $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ as well as $\nu_\mu \rightarrow \nu_e$ by Los Alamos Liquid Scintillator Neutrino Detector (LSND)[19]. About forty percent deficit in the $(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$ is reported at present in the atmospheric neutrino experiments, which is reasonably interpreted as a occurrence of neutrino oscillation between ν_μ and ν_τ. The present data suggests the target mass squared region in the range 0.001 to 0.01 eV^2 and quite a large mixing. A long flight of the up-going neutrino penetrating through the earth made it possible to search in particularly very small Δm^2 region inaccessible to the present accelerator and reactor experiments. But the atmospheric neutrino experiments are suffering from the smallness of neutrino flux.

Accelerator beams are however well focused and we can expect to go to hundreds of kilometers of path length with them. Various long baseline experiments using accelerator neutrino beams are under construction. K. Zuber[20] gave a beautiful reports of these experiments. We give a brief summary of them in the following. The first one is KEK-E362(K2K) project[21], in which the beam line will be finished by 1998 and data should be expected by 1999. This project is figured between KEK laboratory and the Kamioka mine, the distance between them is about 235 km. KEK labolatory is supposed to send the neutrino beam to Kamioka, with an average energy of one GeV. Similar plans between Fermilab and Soudan mine (735 km), and between CERN and Gran-Sasso mine (732 km) are under construction. The former project may start at the beginning of 2000.

The cosmic neutrino flux with energies above one TeV carries an unavoidable background for many of the astrophysical experiments with the full-size underwater/ice neutrino telescopes. The status of the present situation of these neutrino telescope experiments will be discussed in the following paper.

(Note added in proof)

The XVIII International Conference on Neutrino and Astrophysics was held in Takayama, Japan, June 4-9, 1998. Many intriguing results about neutrino properties were reported by many speakers. Especially the Supernamiokande group in Japan established the nonzero neutrino mass through the search of neutrino oscillation. Also the CHORUS collaboration reported the possible evidence of tau neutrino. The parameters of long base line experiments, Kamioka-KEK, Fermilab-Soudan and CERN-Gran Sasso, were reported in details. Transparencies of all talks given in this conference are accessible in the following pages.

http://www-sk.icrr.u-tokyo.ac.jp/nu98/scan/index.html.

References

1) G. Barr, T. K. Gaisser and T. Stanev, Physical Review **D39**, 3532 (1989); M. Honda, K.Kasahara, K. Hidaka and S. Midorikawa, Physics Letters **B248**, 193 (1990); H. Lee and Y. S. Koh, Nuovo Cimento **105B**, 883 (1990).
2) K. Shiga: Journal of the Faculty of International Studies of Culture, **9**, 167 (1997); K. Shiga: Journal of the Faculty of International Studies of Culture, **10**, 149 (1997).
3) S. P. Mikhehev and A. Yu. Smirnov, Soviet Journal of Physics **42** 913 (1985); Nuovo Cimento **9C** 17 (1986).
4) L. Wolfenstein, Physical Review **D17**, 2369 (1978).
5) P. Langacker, Physics Reports **72**, 185 (1989) and references therein.
6) D. Casper, et al., Physical Review Letters **66**, 2561 (1991); D. W. Casper, Doctor Thesis, University of Michigan (September 1990); R. Becker-Szendy, *et al*, Physical Review

D46, 3720 (1992).

7) K. S. Hirata, *et al.*, Physics Letters **B205**, 416 (1988); K. S. Hirata, *et al.*, Physics Letters **B280**, 146 (1992); Y. Fukuda, *et al.*, Physics Letters **B335**, 237 (1994); Y. Suzuki, in Proceeding of Neutrino **96**, ed. K. Enqvist and K. Huitu and J. Maalampi (World Scientific, Singapore, 1996) p. 73.

8) C. Berger, *et al.*, Physics Letters **B227**, 489 (1989).

9) N. Aglietta, *et al.*, Europhysics Letters 8, 611 (1989).

10) Soudan 2 *http://hepwww.rl.ac.uk/soudan2/index.html*, S. M. Kasahara *et al.*, Physical Reviews **D55**, 5282 (1997).

11) Y. Suzuki, Invited talk at Erice Neutrino workshop, Sept. 17-22, 1997; SuperKamiokande *http://www-sk.icrr.u-tokyo.ac.jp/doc/sk/*.

12) MACRO: *http://www.lngs.infn.it/lngs/htexts/macro.html*.

13) ICARUS: *http://www.aquila.infn.it:80/icarus/exp.html*.

14) K. Lande, B. Cleveland, T. Daily, R. Davis, C. K. Lee, A.Weinberger, P. Wildenhaim, J. Uhlman, Status and Future of Solar Neutrino Observations, Proceedings of the International School on Astro-Particle Physics (World Scientific, Singapore 1991); R. Davis, Proceedins of the 6th International Workshop on Neutrino Telescopes, Venezia, Feb. 22-24, 1994.

15) *http://neutrino.pc.helsinki.fi/neutrino/nd-mass.html*.

16) J. N. Bahcall and M. H. Pinsonneault, Review Modern Physics **67**, 781 (1995); S. Turck-Chieze *et al.*, Physics Report **230**, 57 (1993); V. Castellani *et al.*, Physics Report **281**, 309 (1997); A. Dar and G. Shaviv, Nuclear Physics **B48**, 335 (1996).

17) The Russian-American Gallium Experiment (SAGE): *http://www.npl.washington.edu/npl/ar96/ch2 9.html*.

18) *http://kosmopc.mpi-hd.mpg.de/gallex/gallex.htm*.

19) C. Athanassoupoulos *et al.*, Physical Review Letters **75**, 2650 (1995); ibid nucl-ex/9706006.

20) K. Zuber, to appear in Proceeding of COSMO'97, Ambleside (UK), September 1997; ibid hep-ph/9712378; P. B. Pal, Plenary talk given at the B and Nu Workshop held at the Mehta Research Institute, Allahabad, India, Jan. 4-8 1998.

21) KEK-E362 (K2K) project: *http://pnahp.kek.jp/*.