Muons and neutrinos

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Abstract. This report reviews several selected topics presented in SH1.01 and HE2.01 – HE2.06 sessions dedicated to muons and neutrinos. There were 118 papers in these sessions. Many of them deserve discussion and presentation in rapporteur talks. However, I put the priority to exciting new results, primary the results on neutrino oscillations from solar and atmospheric neutrinos.

The first results from the SNO experiment combined with the Super-Kamiokande solar neutrino data give essential information toward the understanding of the 30-year-old “solar neutrino problem”. Increased statistics of the atmospheric neutrino data make it possible to study details of muon neutrino oscillations. Recent precise atmospheric muon data give very important constraint to the absolute flux of the atmospheric neutrinos. The results from recent muon measurements are reviewed and the status of the new generation of atmospheric neutrino experiments is discussed.

1 Introduction

In solar and atmospheric neutrino measurements, there have been well-known problems. One is the “missing solar neutrino problem” (Davis et al., 1968) since the late 1960’s. The other is the “atmospheric muon neutrino deficit” (Hirata et al., 1988). The later was confirmed to be due to neutrino oscillations in 1998 (Fukuda et al., 1998).

In this conference, a result from a D2O solar neutrino experiment, SNO, (Waltham, 2001) (Ahmad et al., 2001) was reported. This result combined with a precise measurement of the solar neutrino flux by neutrino electron scattering in Super-Kamiokande provides evidence for solar neutrino oscillations.

Neutrino flavor oscillations (Maki, Nakagawa, Sakata, 1962)(see also (Pontecorvo, 1957)) is one of a few ways to study small neutrino masses and mixings. For simplicity, we consider two-flavor neutrino oscillations. If neutrinos are massive, the flavor eigenstates, $\nu_\alpha$ and $\nu_\beta$, are expressed as combinations of the mass eigenstates, $\nu_i$ and $\nu_j$. The probability for a neutrino produced in a flavor state $\nu_\alpha$ to be observed in flavor state $\nu_\beta$ after traveling a distance $L$ through a vacuum is:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_{ij} \sin^2 \left( \frac{1.27 \Delta m^2_{ij} (eV^2) L (km)}{E_\nu (GeV)} \right)$$

where $E_\nu$ is the neutrino energy, $\theta_{ij}$ is the mixing angle between the flavor eigenstates and the mass eigenstates, and $\Delta m^2_{ij} = m^2_{\nu_j} - m^2_{\nu_i}$.

Three neutrino flavors have been observed. Therefore, the above description has to be generalized to three-flavor oscillations. In the three-flavor oscillation framework, neutrino oscillations are parameterized by three mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$), three mass squared differences ($\Delta m^2_{12}, \Delta m^2_{23}$, and $\Delta m^2_{13}$; among the three $\Delta m^2$’s, only two are independent) and one CP phase ($\delta$). However, if a neutrino mass hierarchy is assumed, the three $\Delta m^2$’s are approximated by two $\Delta m^2$, and neutrino oscillation lengths are significantly different for the two $\Delta m^2$’s. One $\Delta m^2 (\Delta m^2_{13})$ is related to solar neutrino experiments. The other $\Delta m^2 (\Delta m^2_{23})$ is related to atmospheric neutrino oscillation experiments. It is known that it is approximately correct to assume two-flavor oscillations for analyses of the present neutrino oscillation data. Therefore, in this article, we mainly discuss two flavor neutrino oscillations assuming two significantly different $\Delta m^2$’s.

2 Solar neutrinos

Solar neutrinos have been observed by six experiments (Cleveland et al., 1998) (Fukuda et al., 1996) (Abdurashitov et al., 1999) (Hampel et al., 1999) (Fukuda et al., 2001) (Altman et al., 2000). However, the observed fluxes from these experiments (see Fig. 1) have been significantly lower than
the Standard Solar Model (SSM) predictions (Bahcall, Pinsonneault, Basu, 2001). It is known that the present solar neutrino data cannot be explained by reasonable modifications of the solar model. On the other hand, it is possible to explain the solar neutrino data by neutrino oscillations in the Sun (Mikheyev, Smirnov, 1985, 1986) (Wolfenstein, 1978) or in the vacuum. Figure 2 shows the allowed parameter regions of neutrino oscillations based on a combined analysis of the flux measurements (Fogli et al., 2001). Because of the matter effect for oscillations between $\nu_e$ and $\nu_x$, where $x = \mu$ or $\tau$, the mixing angle smaller and larger than 45° can be distinguished, and therefore, the horizontal axis shows $\tan^2\theta_{12}$. Several allowed parameter regions are observed. (Hereafter, in the solar neutrino section, if an explicit mention is not made, we always assume $\nu_e \rightarrow \nu_x$ oscillations.)

For a definite confirmation of the solar neutrino oscillations, experimental results that cannot be predicted by any solar models are highly desirable. Furthermore, the parameter region of neutrino oscillations should be uniquely determined. It is predicted that the spectrum of the $^8$B solar neutrinos should be distorted significantly and the $^7$Be solar neutrinos are almost completely oscillated to the other neutrinos for the “small-mixing MSW solution” and the “vacuum oscillation solution”, or a day–night effect in the $^8$B neutrino flux should be observed for a region of the “large-mixing MSW solution”.

2.1 Super-Kamiokande

$^8$B solar neutrinos are detected by Super-Kamiokande through neutrino-electron scattering, $\nu e \rightarrow \nu e$ (Fukuda et al., 2001; Blaufuss, 2001). The threshold energy is 5.0 MeV. The observed number of events during 1258 days of the data is $18.464 \pm 204$ (stat.) +646$^{\text{syst.}}$, which corresponds to 0.459 $^{\text{stat.}}$+0.016(stat.) +0.013$^{\text{syst.}}$ of the predicted flux by the SSM (Bahcall, Pinsonneault, Basu, 2001). This experiment provides information for both the energy spectrum and the day-night effect. The day-night data are shown in Fig. 3 (upper). The day-time and night-time fluxes are compared as: $(N - D)/((N + D)/2) = 0.033 \pm 0.22$ (stat.) $^{+0.013}_{-0.012}$ (syst.), where $N$ and $D$ show the fluxes in the night- and day-time, respectively. The possible excess of the flux in the night time is about 1.3 standard deviations and is not significant. Furthermore, the data do not show any evidence for an enhancement of the flux for neutrinos passing through the core of the Earth (see the sixth night bin in the figure). Fig. 3 (lower) shows the observed energy spectrum of the recoil-electrons relative to the SSM prediction. A fit to an undistorted energy spectrum gives $\chi^2/DOF = 19.0/18$. The shape of the energy spectrum is consistent with the SSM prediction.

The present day-night and energy spectrum data from Super-Kamiokande do not show any SSM independent evidence for neutrino oscillations. However, these precise data are useful to constrain neutrino oscillation parameters. Indeed, most of the “small-mixing MSW” and “vacuum oscillation” regions are excluded at 95% C.L. (Fukuda et al., 2001) (Blaufuss, 2001).

2.2 SNO

One of the highlights of this conference was the first results from the SNO heavy water Cherenkov experiment. It is pos-

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**Fig. 1.** Summary of the observed solar neutrino flux by various experiments (before SNO). The uncertainties in the SSM prediction are also shown.

**Fig. 2.** Allowed parameter regions of $\nu_e \rightarrow \nu_x$ oscillations obtained by the measured rate of solar neutrinos from Ga, Cl and H$_2$O experiments (Fogli et al., 2001). The constraints from the predicted flux from the standard solar model are included. $\delta m^2$ and $\tan^2 \theta_{12}$ in this figure and in Fig. 5 correspond to $\Delta m^2_{12}$ and $\tan^2 \theta_{12}$ in the text, respectively.
possible to measure the flux of $^8$B solar $\nu_e$ by $\nu_e D \rightarrow e^- pp$ (CC interaction). The SNO experiment reported the rate of the CC interactions of $^8$B solar neutrinos using this reaction. Figure 4 shows the angular distributions of observed electrons relative to the direction vector from the Sun to the Earth. The forward peak shows events due to neutrino-electron scattering, and the backward enhanced distribution shows the evidence for events due to $\nu_e D \rightarrow e^- pp$. 975.4 ± 39.7 CC events and 106.1 ± 15.2 neutrino-electron scattering events (plus 87.5 background events) have been observed above 6.75 MeV electron energy during 241 days of the detector exposure. The observed flux by the CC interaction was $0.347 \pm 0.029$ (stat. + syst.) of the Standard Solar Model prediction. The measured energy spectrum was also consistent with the prediction, see Fig. 4.

2.3 SNO + Super-Kamiokande combined analysis

SNO measures the flux of electron neutrinos, while Super-Kamiokande measures the flux by neutrino electron scattering. The neutrino-electron scattering primary measures the $\nu_e$ flux, but is also sensitive to the other neutrinos with a reduced sensitivity. (The $\nu_{\mu,e}$ and $\nu_{\tau,e}$ cross sections are about 1/7 of that of $\nu_{e,e}$) The measured flux in Super-Kamiokande was $0.459 \pm 0.016$ (stat. + syst.) of the SSM prediction. The observed flux by SNO is 3.3 $\sigma$ smaller than that by Super-Kamiokande. This discrepancy gives the first direct evidence for solar neutrino oscillations, because the higher flux observed in the neutrino-electron scattering is interpreted as due to $\nu_{\mu,e}$ and $\nu_{\tau,e}$ scattering.

From the measurements of SNO and Super-Kamiokande, it is possible to estimate the total $^8$B solar neutrino flux independent of neutrino oscillations. The estimated total $^8$B solar neutrino flux is $5.44 \pm 0.99 \times 10^6$ cm$^{-2}$s$^{-1}$. This value is in excellent agreement with the predicted value by the SSM ($5.05 \pm 0.99 \times 10^6$ cm$^{-2}$s$^{-1}$) (Bahcall, Pinsonneault,
Cosmic ray interactions in the atmosphere produce neutrinos. Although the absolute flux is uncertain by ±20% there are various accurate predictions such as, zenith-angle distribution of the flux and the $\nu_\mu/\nu_e$ flux ratio.

Atmospheric neutrino events detected in underground detectors can be classified as: (1) fully-contained (FC) events, (2) partially-contained (PC) events, (3) upward stopping muon events, and (4) upward through-going muon events. Events in class (1) and (2) are due to neutrino interactions within a detector, and events in class (2) contain energetic muons from these interactions that exit the detector. Events in class (3) and (4) are due to neutrino interactions in the rock below the detector which initiate highly energetic muons that enter the detector. The typical neutrino energies for FC, PC, upward stopping and upward through-going muon events are of the order of 1, 10, 10, and 100 GeV, respectively. Super-Kamiokande, a 50 000 ton water Cherenkov detector, observes all these types of events. Soudan-2, a 1 kton fine-grained iron calorimeter, observes FC events. However, upward going muons have not been identified due to the lack of the fast timing and the resulting ambiguity between upward and downward going muons. MACRO, a liquid scintillator detector combined with tracking devices, detects upward-going muons and PC events.

The flight length of the atmospheric neutrinos varies from ~15 km to 13 000 km depending on the zenith angle of the neutrino direction. For some oscillation parameters, it should be possible to observe a zenith angle-dependent deficit (and possibly excess) of the neutrino flux. However, the direction of the neutrino must be estimated from the reconstructed direction of the products of the neutrino interaction. Typically, for lepton momentum below ~400 MeV/c, the lepton direction has little correlation with the neutrino direction. Therefore, the zenith angle dependence of the flux as a consequence of neutrino oscillations is largely washed out below 400 MeV/c. The correlation angle gets smaller with increasing lepton momentum.

3 Atmospheric neutrinos

The zenith angle distributions for $e$-like and $\mu$-like events observed in Super-Kamiokande (79 ktone-yr) (Kamada, 2001) are shown in Fig. 6. The $\mu$-like data have exhibited a strong deficit of upward going events while no significant deficit has been observed in the $e$-like data. It is known that the flux is essentially up-down symmetric in the absence of neutrino oscillations in the multi-GeV energy range. We define the up-down double-ratio, $(U/D)_{\text{Data}}/(U/D)_{\text{MC}}$, where $U$ and $D$ are the numbers of upward ($-1 < \cos \Theta < -0.2$) and downward ($0.2 < \cos \Theta < 1$)-going events, respectively. For the multi-GeV, single-ring $\mu$-like plus PC events from Super-Kamiokande, this double-ratio is $0.53 \pm 0.04$ (stat.) $\pm 0.01$ (syst.). The Kamiokande value for the multi GeV FC+PC $\mu$-like events was $0.59^{+0.13}_{-0.11}$ (stat.) (Fukuda et al., 1994) and is in good agreement with the Super-Kamiokande result.
number of events
120
0
40
80
µ
-1 -0.5 0 ... (including the old Kamiokande data (Hatak e yama
et al., 1998)) have similar shapes: these experiments have ob-
erved lower fluxes near the vertical direction compared with the predicted flux. If the oscillation effect is taken into ac-
count, the observed zenith angle-dependent deficit of µ-like events is consistent with the Super-Kamiokande data.

3.2 Upward going muon events

The typical energy of a neutrino that produces an upward through-going muon is about 100 GeV. Neutrinos arriving vertically travel 13,000 km, while those arriving horizontally travel only ~500 km. These numbers, together with the estimated $\Delta m^2_{23}$ region from the FC+PC data ($\sim 3 \times 10^{-3}$ eV$^2$), suggest that the neutrino oscillation effect can be seen in the zenith angle distribution of the upward through-going muon events. Namely, a larger deficit for vertically upward through-going muon events is expected than for almost horizontally going muons. Figures 6 (h) and 8 (top) show the zenith angle distributions for the upward through-going muon flux observed in Super-Kamiokande (Kamda, 2001) and MACRO (Montaruli, 2001), respectively. The shape of the zenith angle distribution is predicted accurately (Lipari, 2001). The measured zenith-angle distributions in these experiments (including the old Kamiokande data (Hatakeyama et al., 1998)) have similar shapes: these experiments have observed lower fluxes near the vertical direction compared with the predicted flux. If the oscillation effect is taken into account, the observed zenith-angle distributions are explained well.

The typical energy of a neutrino that produces an upward-stopping muon is about 10 GeV. Therefore, for some neutrino oscillation parameters, the observed flux for the upward stopping muons should be significantly smaller than the calculated flux. Fig. 6(g) shows the zenith angle distribu-
tion for the upward stopping muon flux observed in Super-Kamiokande (Kamada, 2001). Also, shown in the same figure are the predicted fluxes with and without neutrino oscillations. Clearly, the predicted flux without neutrino oscillations disagrees with the data beyond the systematic uncertainty of the prediction (22%). In addition, the MACRO data on (upward stopping muons + downward PC events) and upward PC events also show deficits and are consistent with neutrino oscillations (Spurio, 2001), see Fig. 8 (middle and bottom).

Finally, we mention the upward through going muon data from SNO (Waltham, 2001a). Because of the great depth of the SNO detector (6000 m.w.e.), most of the downward going muons with $\cos \Theta < 0.4$ are due to neutrinos. Since these neutrino induced downward going muons have minimal effect of neutrino oscillations, the data constrain the absolute flux of the high energy neutrinos.

### 3.3 Neutrino oscillation analysis

The contained and the upward going muon events are consistently explained by $\nu_\mu \rightarrow \nu_\tau$ oscillations. Therefore, we discuss allowed regions of neutrino oscillation parameters. The allowed parameter regions are shown in Fig. 9. The best fit parameter point for the Super-Kamiokande data (Kamada, 2001) has been found at $\sin^2 2\theta_{23} = 1.00$ and $\Delta m^2_{23} = 2.5 \times 10^{-3} \text{eV}^2$. The $\chi^2$ value of the fit for this oscillations parameter set is 157.5/170 d.o.f., thus, the data are explained well by the $\nu_\mu \rightarrow \nu_\tau$ oscillation assumption. The 90% C.L. allowed parameter region is: $\sin^2 2\theta_{23} \geq 0.90$ and $1.6 \times 10^{-3} \leq \Delta m^2_{23} \leq 3.6 \times 10^{-3} \text{eV}^2$. The allowed regions obtained by the analyses from Kamiokande (Hatakeyama et al., 1998), Soudan-2 (Goodman, 2001) and MACRO (Montaruli, 2001) are also shown in Fig. 9.\(^2\)

\(^2\)The allowed region obtained by upward through-going muons in Super-Kamiokande (which is not shown in this figure) is much greater than that on through-going muons, and is not shown.) In Soudan-2, high-resolution FC events are used.
As an extension of the oscillation analysis, we discuss three flavor neutrino oscillations. We assume that the mass difference between the lightest and the second lightest neutrinos is very small and, therefore, the effect of the oscillations between these two neutrino eigenstates is invisible in atmospheric neutrino experiments. This is a reasonable assumption, because the solar neutrino data suggest that $\Delta m_{12}^2$ is less than $\sim 10^{-3}$ eV$^2$, see Fig. 5. Under this assumption, there are only three oscillation parameters; $\theta_{13}$, $\theta_{23}$ and $\Delta m_{23}^2 \equiv \Delta m_{12}^2 = \Delta m_{23}^2$. Only $\theta_{13}$ is the new parameter, and it represents the first and third generation neutrino mixing. The data from Super-Kamiokande have been analyzed along this line. To date, no evidence for finite $\theta_{13}$ has been observed, and pure two flavor $\nu_{\mu} \rightarrow \nu_{\mu}$ neutrino oscillations is completely consistent with the data. This result is also consistent with results from reactor neutrino oscillation experiments (Apollonio et al., 1999) (Boehm et al., 2001).

An important question to ask is whether neutrino oscillations generated by neutrino mass and mixing are the only possible explanation of the atmospheric neutrino data. Indeed, there have been several proposals for alternative explanations of the atmospheric neutrino data. However, detailed studies of the atmospheric neutrino data have already excluded these possibilities at more than 99% C.L. In this conference, we have heard that the $\nu_\mu \rightarrow \nu_{\text{sterile}}$ oscillations have been excluded using high-energy $\nu_\mu$ events (Habig, 2001) (Montaruli, 2001) and using neutral current events (Habig, 2001). Also, neutrino decay has been excluded using neutral current events (Kamda, 2001). In addition, Super-Kamiokande reported preliminary results on a search for CC $\nu_\tau$ events in the detector (Habig, 2001). The observed data are consistent with the existence of $\nu_\tau$ events generated by neutrino oscillations at the 2 standard deviation level. We summarize that the neutrino oscillations between $\nu_\mu$ and $\nu_\tau$ is essentially the only explanation for the atmospheric neutrino data.$^3$

4 Atmospheric muons

Present atmospheric neutrino experiments usually use fluxes calculated by (Honda et al., 1995) and (Agrawal et al., 1996) for the Monte Carlo prediction. These calculations were carried out more than 5 years ago, and suffer from relatively large uncertainties in the absolute flux ($\sim 20\%$) due to the limited data on primary cosmic ray and secondary muon fluxes. In order to study neutrino oscillations in more detail, (about a factor 3 in $\sin^2 2\theta_{23}$) larger than that from MACRO. In my understanding, this is mainly due to difference in the statistical methods. Super-Kamiokande uses a method recommended in (Particle Data Group, 1996), while MACRO uses a method recommended in (Particle Data Group, 1998).

$^3$Some alternative explanations suggest that the $\nu_\mu$ survival probability has an exponential form rather than a sinusoidal form. The proposed MONOLITH experiment (MONOLITH collab., 2001) should be able to distinguish these possibilities by accurately observing $P(\nu_\mu \rightarrow \nu_\mu)$ as a function of $L/E_\nu$.

better knowledge on the neutrino flux is necessary. For this purpose, it is important to have an accurate knowledge on the fluxes of primary cosmic rays and atmospheric muons. (Atmospheric gamma’s that are produced by $\pi^0$ decay are also important for constraining the neutrino flux (Kasahara et al., 2001)).

Primary cosmic rays up to 100 GeV have been measured accurately by recent balloon borne and Space Shuttle experiments (Sanuki et al., 2001) (Alcaraz et al., 2000) (Mochizuki et al., 2001). Since this topic is discussed in detail by other authors, I only refer the other papers (see, for example, (Gaisser et al., 2001)).

Because of the direct relation between muon and neutrino production in the atmosphere, accurate data on the muon flux at various altitudes are very important to predict the absolute neutrino flux. Cosmic ray muons at the ground level have been measured by many experiments. However, it is only recent days that precise muon data at the balloon altitudes get available. All these data are very useful for constraining the atmospheric neutrino fluxes. In this conference, new muon measurements were reported by various experiments such as BESS (Motoki et al., 2001) (Sanuki et al., 2001), CAPRICE (Hansen et al., 2001), and (Tsujii et al., 2001). In order to select muons with a high purity, these experiments comprised a variety of particle identification techniques. As a few examples, Figs. 10, 11 and 12 show the measured muon fluxes on the ground, during the ascend of the balloon.
experiments, and at 4–5 g/cm² altitude, respectively. (There are more data, however, I have not included measurements which are normalized to some other results.) In addition, in relatively shallow underground, two LEP experiments (Le Coulter, 2001; Maio et al., 2001) reported precise measurements of cosmic ray muons up to 1000 GeV/c. It is clear from Fig. 10 that the muon data on ground is very accurate. The data from BESS and CAPRICE taken at Lynn Lake in Canada agrees within 5%. Furthermore, we clearly see altitude and geomagnetic cutoff dependence of the measured fluxes.

In the GeV energy range, most of the muons decay before reaching to the ground. Therefore, the comparison of the data and calculation of the ground muon flux is sensitive to experimental conditions such as the temperature or the atmospheric pressure. It could be more important for the normalization of the neutrino flux to compare the calculation and the data at high altitude. The flux measurement at very high altitude is more difficult due to higher proton flux. Especially, in the high momentum range, the separation of muons and protons is difficult. In this conference, CAPRICE reported the measurement of the \( \mu^- \) flux in the atmosphere up to 18 GeV/c for the first time (Hansen et al., 2001). However, the high altitude muon data are still limited in the statistics and the momentum range as seen in Figs. 11 and 12. We really hope to have higher statistics data in the near future.

One good news we have heard in this conference is a plan to have dedicated atmospheric muon measurement by the Wizard/CAPRICE collaboration in 2002 (Circella et al., 2001). Our knowledge on the flux of atmospheric muons will be improved significantly by these future measurements.

5 Atmospheric neutrino flux calculations

Because of the need for a precise prediction of the neutrino flux for the atmospheric neutrino experiments, there are several new flux calculations. In this conference, 7 new flux calculation activities have been reported (Battistoni et al., 2001, 2000; Honda et al., 2001; Engel et al., 2001; Wenz et al., 2001; Tserkovnyak et al., 2001; Fiorentini et al., 2001; Liu et al., 2001).

Three dimensional calculations of the flux are particularly emphasized recently. The fluxes typically used in the present atmospheric neutrino experiments are calculated by one dimensional approximations (Honda et al., 1995; Agrawal et al., 1996). Namely, after an interaction of a primary cosmic ray particle with an air nuclei, all the secondary particles are assumed to be on the line of the primary particle’s motion. The three-dimensional flux calculations have found a significant enhancement of the flux near the horizon in the sub-GeV energy range. Fig. 13 compares the fluxes by the one-dimensional and three dimensional calculations (Battistoni et al., 2001, 2000). The enhancement can be explained by a bigger target mass per solid angle near the horizon, see (Lipari, 2000) for a more complete discussion.

Another important quantity that is related to neutrino oscillations is the \( \nu_\mu/\nu_e \) flux ratio. Fig. 14 shows the \( (\nu_\mu + \nu_\tau) / (\nu_e + \nu_\tau) \) flux ratio as a function of \( E_\nu \), integrating over the solid angle. Within 5%, there is no difference between the three dimensional and one dimensional calculation results below 30 GeV. Above 30 GeV, the difference is larger than 5%. However, this must be due to the difference in the hadronic interaction model, especially in the Kaon production.

Although the three dimensional flux calculations predict a horizontal enhancement for the sub-GeV flux, the present atmospheric neutrino experiments do not have enough angular resolution to detect this effect. Consequently, the enhancement does not have any significant effect to the present neutrino oscillation studies. Indeed, Super-Kamiokande has
Fig. 13. Calculated zenith angle distributions of the atmospheric neutrino flux at the Super-Kamiokande site for each neutrino flavor by the Fluka group (Battistoni et al., 2001, 2000). Black circles and white squares show the calculated fluxes based on three dimensional and one dimensional simulations, respectively.

Fig. 14. Calculated $g(\nu_{\mu} + \bar{\nu}_{\mu})/(\nu_e + \bar{\nu}_e)$ flux ratio as a function of $E_\nu$ integrating over the solid angle. Results from one dimensional calculations are shown by a dotted line (Agrawal et al., 1996) and a thin-solid line (Honda et al., 1995). Results from three dimensional calculations are shown by a dashed line (Battistoni et al., 2001, 2000) and a thick-solid line (Honda et al., 2001).

compared the allowed regions of neutrino oscillation parameters based on fluxes by a one-dimensional calculation (Honda et al., 1995) and a three-dimensional calculation (Battistoni et al., 2001, 2000), and has found no big difference in the allowed regions.

As we have discussed in the previous section, there are precise data on primary cosmic ray fluxes, especially below 100 GeV. Therefore, the absolute neutrino flux in the GeV region can be predicted precisely. We had heard that recent calculations by (Battistoni et al., 2001, 2000; Honda et al., 2001; Engel et al., 2001; Tserkovnyak et al., 2001; Fiorentini et al., 2001) predict about (10 – 20)% smaller fluxes than those of (Honda et al., 1995) and (Agrawal et al., 1996) near 1 GeV. One calculation (Wenz et al., 2001) has found a similar absolute flux to those of (Honda et al., 1995) and (Agrawal et al., 1996). One calculation (Liu et al., 2001) has found about 30% smaller flux, however, this is likely to be due to the neglect of the primary Helium and heavier nuclei. We expect that the absolute flux could be similar to the others if the heavier primaries are included in the calculation. Figure 15 shows the calculated absolute fluxes by several authors. In summary, the new calculations predict about (10 – 20)% smaller fluxes near 1 GeV. The general agreement among the calculations is about ±10%. I estimate that the uncertainties in the flux and the cross section in neutrino interactions (±10 – 15 %) almost equally contribute to the uncertainty in the neutrino event rate in the GeV energy region.

Unfortunately, below 1 GeV energy region the calculated flux seems to have larger uncertainty mainly due to the limited knowledge on low energy (<10 GeV) hadron interactions. The HARP experiment (Barr, 2001) shall provide precise information on hadron interactions in this energy range. Since this experiment has already started taking data, we expect that the ambiguity in the low energy neutrino flux will be significantly reduced in a few years.

The high energy (>1 GeV) neutrino flux still has a large uncertainty due to the limited accuracy in the measured cosmic ray fluxes above 100 GeV. The BESS experiment has been upgraded to have the maximum detectable momentum of 1 TeV (and had the first flight with this detector configuration in Sep. 2001). Also, the AMS detector on Space Station will have the similar momentum coverage and provide high statistics data in about 5 years. These data shall significantly improve the accuracy in the predicted neutrino flux in the high energy range. However, in order to improve the accuracy in the flux of upward through going muons substantially, the neutrino flux up to ~1 TeV needs to be predicted accurately. This requires accurate primary cosmic ray flux measurements up to ~10 TeV and precise knowledge on the hadron interaction (especially on the Kaon production). We hope that future cosmic ray experiments could provide accurate flux data in this energy range.
The spectrum of the astronomical neutrinos are generally expected to be harder. For upward going muon events from these neutrino sources, the typical energy of the muons are higher, and, therefore, $dE/dx$ of the muons are larger. Large $dE/dx$ upward going muons have been searched for in the MACRO (Perrone, 2001), and AMANDA (Hill, Leuthold, 2001) experiments. Also, high energy $\nu_e$ events have been searched for in the Baikal (Balkanov et al., 2001; Balkanov et al., 2001) and AMANDA (Taboada, Kowalski, 2001) experiments. High energy $\nu_e$ events should look like isolated cascades. These experiments have not found any evidence for these neutrinos. Figure 16 summarizes the present limits on astronomical neutrinos. The present limits are of the order of $E_{\nu}^{2} \cdot \Phi < 10^{-6} \text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{GeV}$, where $\Phi$ is the neutrino flux. A similar limit was obtained by AMANDA (Wiebusch, 2001). It should be mentioned that the present limits are only about an order of magnitude higher than the TeV gamma ray flux during Markarian 501’s high gamma-ray emission state in 1997. Therefore, these experiments are almost reaching to the level of sensitivity where models that predict neutrino emissions of the order of the gamma ray emissions can be tested.

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6 Neutrino astronomy

Observation of high energy gamma rays from various astronomical sources strongly suggests that high energy neutrinos might also originate from these sources. However, detailed theoretical studies predict that very large detectors are necessary to detect these neutrinos. In the GeV energy region, the flux of the atmospheric neutrinos is dominant, and, therefore, it is not realistic to search for astronomical neutrinos in this energy range. However, the flux of the astronomical neutrinos is expected to behave like, $E_{\nu}^{-0.2-2.5}$, whereas the spectrum of atmospheric neutrinos above 100 GeV falls rapidly like, $E_{\nu}^{-3.7}$, resulting in a improved signal to noise ratio at higher energies. In addition, the neutrino interaction cross section and the muon range increase with energy. Therefore, astronomical neutrinos are typically searched for using high energy upward going muons.

The topics of neutrino astronomy were extensively discussed at the Plenary Session (Learned, 2001). Therefore, I will only summarize the present status and future prospect of the field briefly.

Neutrino point sources have been searched for by underground experiments. The upward going muon samples observed in MACRO and Super-Kamiokande have been used. MACRO (Perrone, 2001) and Super-Kamiokande (Matsuno, 2001) have observed 1356 and 1761 upward going muons, respectively. However, these experiments have not observed any directional clustering of events, and, therefore, found no evidence for neutrino point sources. The typical upper limit on the flux of upward going muons is of the order of $10^{-15-14} \text{cm}^{-2}\text{s}^{-1}$. This limit can be translated to the neutrino flux limit assuming $E_{\nu}^{-2}$ spectrum. The flux limit is of the order of $E_{\nu}^{2} \cdot \Phi < 10^{-6} \text{cm}^{-2}\text{s}^{-1}\text{GeV}$, where $\Phi$ is the neutrino flux. A similar limit was obtained by AMANDA (Wiebusch, 2001). It should be mentioned that the present limits are only about an order of magnitude higher than the TeV gamma ray flux during Markarian 501’s high gamma-ray emission state in 1997. Therefore, these experiments are almost reaching to the level of sensitivity where models that predict neutrino emissions of the order of the gamma ray emissions can be tested.

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To date, there has been still no evidence for astronomical neutrinos. However, there is a very impressive progress in the preparation and construction of the next generation neutrino telescopes. Also, shown in Fig. 16 are the expected sensitivities in the neutrino astronomy in various next generation neutrino telescopes (Barwick, 2001; Capone, 2001; Tzamarias, 2001; Goldschmidt, 2001) and the expected starting date of the operation of these telescopes. We find that, in general, the sensitivity of these experiments largely covers many of the theoretical models that predict astronomical neutrinos. I hope that big news will be reported from these experiments in the next ICRC’s.

Before ending this section, I would like to make two comments. Because of $\nu_\mu \rightarrow \nu_\tau$ oscillations with almost the full mixing, we expect that a half of $\nu_\mu$ that are produced at an astronomical neutrino source should oscillate to $\nu_\tau$. On the other hand, because of the relatively small diameter of the Earth, high energy ($> O(1 \text{TeV})$) atmospheric $\nu_\mu$’s cannot oscillated to $\nu_\tau$ while propagating in the Earth. Therefore, an observation of one very high energy $\nu_\tau$ event is almost enough to prove the existence of astronomical neutrinos. These $\nu_\tau$ events in these high energy regions have been discussed by several authors in this conference (see discussions in Sessions HE2.04 and HE2.05). For example, a tau lepton produced by a $\nu_\tau$ with $E_{\nu_\tau} \sim 10^{15-16} \text{eV}$, should typically travel $O(100 \text{m})$ before decay. These neutrino events
Fig. 16. Present upper limits on astronomical neutrino flux and various theoretical calculations are compared. Also, shown are the sensitivities of next generation neutrino telescopes. (The original figure was taken from Balkanov et al., 2001. See Balkanov et al., 2001 for the references of the theoretical calculations.)

should be observed as “double-bang” events (Learned, Pukhovas, 1995) (one cascade shower is produced at the neutrino interaction point and the other is produced at the tau decay point) in large neutrino telescopes.

If the energy of neutrinos is much higher than 10^10 eV, the Earth is no more transparent to neutrinos. In the energy region higher than 10^{18} eV, the probability of a neutrino interaction in the air is not negligible. These extremely high energy neutrinos have been searched for in an air shower experiment, AGASA (Yoshida et al., 2001). Penetrating, horizontal air shower events have been searched for. This experiment has observed 1 candidate event, which is consistent with the estimated background of 0.52^{+0.31}_{-0.20}. This result has set a flux limit of \( E^2 \cdot \Phi < 10^{-5.5} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV} \) in the energy range of \( 10^{18} - 20 \) eV assuming \( E\nu^{-2} \) energy spectrum. Also, a result from the RICE (Seckel et al., 2001) was presented.

7 Summary

These have been a lot of progress in the neutrino and muon fields in the last two years. One of the biggest news in this conference was the first results from the SNO solar neutrino experiment. SNO has observed a clear CC signal. The combined results from SNO and Super-Kamiokande give evidence for solar neutrino oscillations, \( \nu_e \rightarrow \nu_\mu \) or \( \nu_\tau \). In addition, combined analyses of recent precise solar neutrino data exclude “small mixing MSW solution” of the solar neutrino problem. Only a large \( \theta_{12} \) is allowed. However, both a large \( \sim 10^{-4} \text{eV}^2 \) and a small \( \sim 10^{-7} \text{eV}^2 \) \( \Delta m^2_{23} \) are still allowed.

The atmospheric neutrino data have been improved significantly in statistics. These high statistics data are used to study details of neutrino oscillations. In fact, many of the non-standard explanations of the atmospheric neutrino data have already been excluded. On the other hand, two flavor \( \nu_\mu \rightarrow \nu_\tau \) oscillations still explain all the data. The 90\% C.L. allowed parameter region from Super-Kamiokande is \( 1.6 \times 10^{-3} < \Delta m^2_{23} < 3.6 \times 10^{-3} \text{eV}^2 \) and \( \sin^2 2\theta_{23} > 0.90 \). In order to further improve the understanding of the atmospheric neutrino oscillations, it is very important to have accurate predictions of the flux. In this conference, there have been many presentations on primary and secondary cosmic ray measurements and new flux calculations. The high activity of these fields together with increased statistics of the neutrino data and new atmospheric neutrino experiments, ensures that atmospheric neutrinos shall continue to contribute to the understanding of neutrino mass and mixing.

To date, no evidence for astronomical neutrinos has been observed. However, the construction of neutrino telescopes has been in progress steadily. Therefore, we expect that these neutrino signals could be observed in a relatively near future. Finally, we would like to stress that the basic information on neutrino mass and mixing, which are the key elements to “beyond the standard model” of elementary-particle physics, has been obtained by the cosmic ray experiments.

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