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Atmospheric muon and neutrino flux from 3D simulation

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Abstract. The muon and neutrino flux are simulated. The program used has successfully reproduced the proton, helium, and e^+/e^- spectra measured by AMS. An improved parametrization of the pion production cross section induced by proton on nuclei obtained from a set of data over a broad incident kinetic energy range (0.73-200 GeV), has been used. The simulated muon flux accounts fairly well for the recent measurements at various altitude between sea level and 38 km. The simulated neutrino flux obtained are lower than those reported previously by other groups.

1 Introduction

Neutrino physics has been a most active and exciting field of research in the past few years. The high statistics data on atmospheric neutrinos reported by the Super-Kamiokande Collaboration (Fukuda et al., 1998a; 1998b; 1998c), together with the long-standing solar neutrino problem (Davis et al., 1968; Bahcall et al., 1998; Cleveland et al., 1998; The SAGE Collaboration, Davis et al., 1996; The GALLEX Collaboration, Hampel et al., 1996; Kamiokande Collaboration, Fukuda et al., 1996; Super-Kamiokande Collaboration, Fukuda et al.,1998d), led to the general agreement that neutrinos could be massive and hence oscillate from one flavor to another. This is claimed as the first conclusive evidence which indicates the existence of some new physics beyond the standard model.

However, the interpretation of the data depends closely on the simulation result for the atmospheric neutrino flux. Many uncertainties make it difficult to obtain the atmospheric neutrino flux precisely. Several groups have done simulation works independently (Bugaev et al., 1989; Gaisser et al., 1988; Barr et al., 1989; Honda et al., 1990; Honda et al., 1995; Lee and Koh, 1990). Although the flavor ratio reported by these groups are in good agreement with each other, the absolute flux obtained largely differ from each other (Gaisser et al., 1996). In order to extract from data accurate informations on the relevant parameters in the neutrino sector such as the mixing angles and the mass square differences, the absolute flux and their detailed features, for example the zenith angle distribution, must be very well known (Fogli et al., 1998). Hence, to fix the problem of the absolute atmospheric neutrino flux, new one-dimensional calculations making use of a more dependable interaction model in the program (Fiorentini et al., 2001), and new 3-dimensional calculations (Honda et al., 2001; Battistoni et al., 2000; Tserkovnyak et al., 1999; Plyaskin, 2001; Derome et al. 2001a; Favier, 2001), have been performed recently. Moreover, either analytical (Lipari, 1994; Lipari, 2001) or semi-analytical methods (Gaisser, 2001) as well as that starting out directly from the kinematical relationship between muons and neutrinos (Perkins, 1994), are used.

In the reaction chain $p+A \to \pi^\pm + X$, $\pi^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$ and $\mu^\pm \to e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$ leading to the atmospheric neutrinos, studying the $\mu^\pm$ flux can be an important cross check for the neutrino flux. Some experimental groups have joined this effort with several contributions (Bellotti, et al., 1999; Kremer, et al., 1999; Boezio, et al., 1999; Coutu, et al., 2000). However, $\mu^\pm$ being short-lived charged particles, their motion is affected by the geomagnetic field while neutrinos are not, the relation between muon and neutrino flux is not straightforward (Gaisser, 2000). Actually, almost all the calculations reported fit reasonably well the muon flux data, at least at sea level. Therefore, further constraints are needed in addition to the condition on muon flux data, in order to identify the best approach. The other species involved in the reaction chain, like the proton and $e^\pm$ flux can clearly provide such additionnal requirement.

In previous works by the authors, the proton spectra, $e^\pm$ spectra and flux ratio, as well as their dependence on geomagnetic latitude reported by AMS collaboration (J. Alcaraz et al., 2000a; 2000b), were reproduced very well using 3D MonteCarlo simulation approach (Derome et al., 2000; 2001b; 2001c). These successful analysis give confidence in the general approach and in the implementation of the com-

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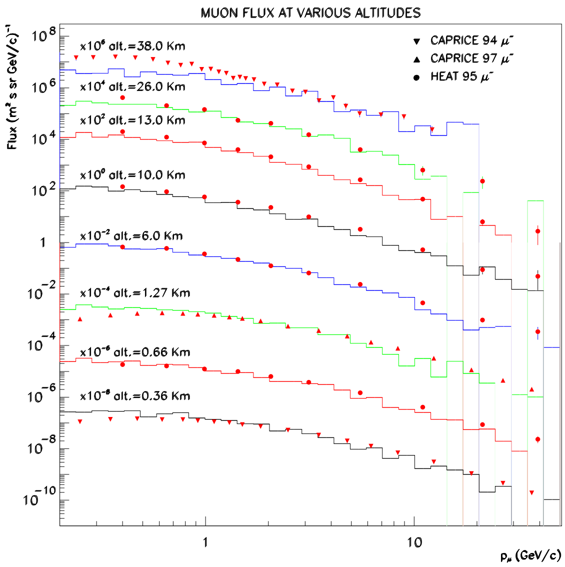

Fig. 1. Comparison of the μ^- flux data at various altitudes, from CAPRICE 94, CAPRICE 97, and HEAT 95 (Boezio, et al., 1999; Kremer, et al., 1999; Coutu, et al., 2000) with the simulation results reported here (histograms)
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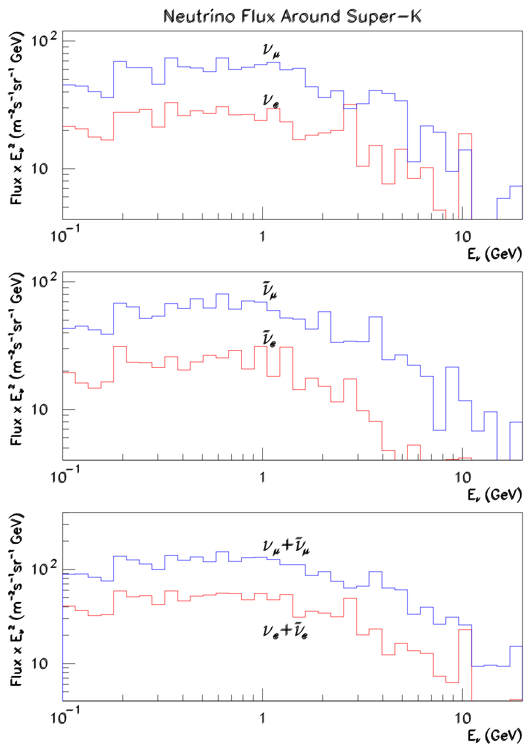

Fig. 2. Neutrino spectrum around the Super-Kamiokande detector weighted by E_ν^2 and averaged over all directions, calulated in the present work.

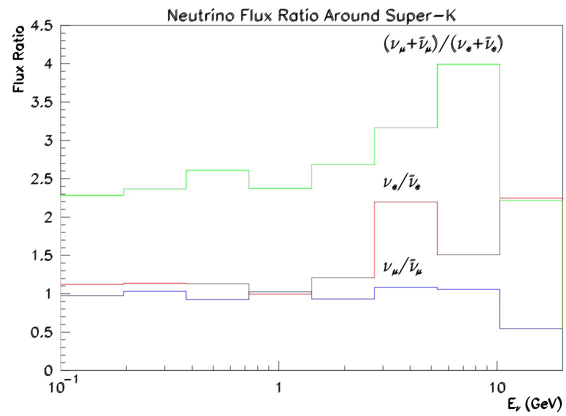

Fig. 3. Calculated dependence of Neutrino flux ratio on neutrino energy around the Super-Kamiokande detector.

puting technique, in particular for the processing of particle trajectories in the geomagnetic field and of the dynamical processes involved. Besides, AMS has performed accurate measurements of the primary cosmic proton and helium spectra. Finally, if the inclusive pion production cross section is known with a good accuracy, the three main uncertainties resulting from the primary spectrum, pion production cross section, and geomagnetic field (Gaisser et al., 1996), are under control, a most reliable neutrino flux evaluation could then be expected from the present approach.

2 Simulation program

A presentation of the simulation program can be found in (Derome et al., 2000; Derome et al., 2001b). The broad success of this approach strengthens its reliability. Some of its main features are:

1. The simulation is full 3-dimensional. The primary cosmic rays are generated according to the spectra measured by AMS. Solar modulation is considered. Each particle propagates in the geomagnetic field and interacts with atmospheric nuclei. The nucleons and pions are produced in each interaction with the respective cross section and multiplicities. Every secondary particle is processed in the same way as its parent particle. Each particle history is traced and recorded in the program.

2. For $\pi^\pm$ production, an improved Mokhov-Striganov parametrization obtained by the authors from fitting data directly (Mokhov and Striganov, 1998; Liu et al., 2001), was used instead of the existing version.

3. For the three body decay of muons, the exact formulae derived from Fermi theory was used, leading to the correct energy and angular distribution of neutrino production. Note that this is not the case with GEANT (GEANT4, 2000).

4. The polarization effect of muons has not yet been included at this stage.

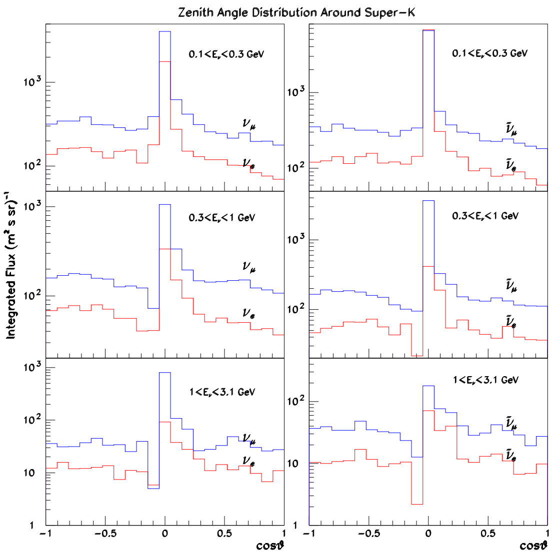

Fig. 4. Calculated zenith angle distribution of the neutrino flux for different energy bins around the Super-Kamiokande detector (θ, zenith angle with $\theta = 0$ for downward going neutrinos).

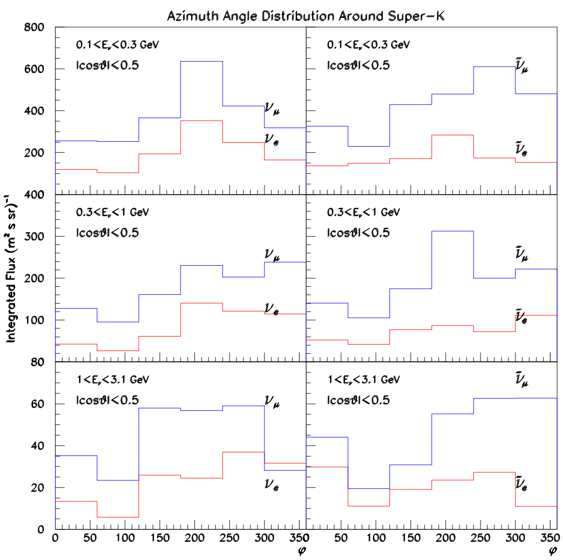

Fig. 5. calculated azimuth angle distribution of the neutrino flux for different energy bins around the Super-Kamiokande detector (ϕ azimuth angle with $\phi = 0^o$, and 90^o for $magnetic$ southern and eastern directions respectively).

3 Result and discussion

In Fig.1, the simulation results are compared with the muon flux data measured by different groups at various altitudes from sea level to the highest balloon altitude (near 40 km) (Boezio, et al., 1999; Kremer, et al., 1999; Coutu, et al., 2000).

It is clearly seen that the calculations account very well for the data, with however a significant difference observed at the highest float altitude, where the low energy muon flux is underestimated. It must be noted that this is a common characteristic to almost all of the simulation results, either 1-dimensional or 3-dimensional (Gaisser et al., 1988; Honda et al., 1995; Fiorentini et al., 2001). However, a weakness of the parametrization, found recently, used here is that the multiplicity of low energy $\pi^{\pm}$ production for high incident energy is underestimated by a factor of probably about 2 in comparison with DTUNUC result (DTUNUC, 1999). Since the first interaction of vertical cosmic rays occurs at around $15 \sim 20$ Km altitude on the average (Honda et al., 1995), at higher altitudes, muons originate from decay of the $\pi^{\pm}$s produced in the first collision of primary cosmic rays which occur on the average at higher energy and then suffer more significantly from the quoted defect of the generator. This could contribute to the observed discrepancy. Further studies and more experimental data are needed to understand this systematic discrepancy.

The calculated $\nu_e, \bar{\nu}_e, \nu_\mu$ and $\bar{\nu}_\mu$ spectra, flavor ratios, zenith and azimuth angle distribution around the Super-Kamiokande detector are shown in Fig. 2, 3, 4, and 5 respectively, with the normalization area taken as $(36^o25'33'' \pm 7.5^o)$ N for geographic latitude and $(137^o18'37'' \pm 10^o)$ E for longitude and count of neutrinos arriving in this area.

Comparing with the results reported by (Gaisser et al., 1988; Barr et al., 1989; Honda et al., 1990; Honda et al., 1995), the present neutrino flux are lower by a factor of about 1.5. However, some recent calculations (Fiorentini et al., 2001) also found neutrino flux with smaller than the value used for the standard analysis of the neutrino induced events in underground detectors. This is not surprising for the following reason.

It was pointed out by (Gaisser et al., 1996; Engel et al, 2000), that proton induced pion production on atmospheric nuclei is the most important input in the simulation. It is easy to see, for example in Fig.8 in (Honda et al., 1995), the $\pi^{\pm}$ production cross section was overestimated by more than a factor of 3 for production momenta less than 6 GeV/c. It must be realized that this is by far the largest part of the production cross section which determines the magnitude of the multiplicity used in the calculation (Derome et al. 2001a; Liu et al., 2001). This overestimated neutrino flux could result from the overestimation of the pion production.

4 Conclusion

In summary, the muon flux data at various altitudes are reproduced with a good accuracy except at the highest altitude by new simulation calculations. The neutrino spectra, flux ratio, zenith and azimuth angle distributions at the Super-Kamiokande detector have also been simulated. The simulated neutrino fluxes obtained here are lower by a factor of about 1.5 than those reported previously by other groups. Should this smaller neutrino flux be confirmed ultimately, the atmospheric neutrino problem should then be revisited, and the data reanalyzed with the corrected value of flux. More work is in progress on the issue.

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