Study of the Interaction Model Using Atmospheric Muons for the Calculation of Atmospheric Neutrino Flux

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The atmospheric neutrino and the muons are produced simultaneously in the decay of mesons, which is created by the hadronic interaction of cosmic rays and air nuclei. The study of atmospheric muon is important for the calculation of the atmospheric neutrino spectra. Especially when the cosmic ray spectra (CRS) are known well, the study of the atmospheric muon is the study of the hadronic interaction model. In this paper, we construct CRS models with recent observations above 100 GeV/n, and modify the hadronic interaction model so that it reconstruct the observed atmospheric muon spectra for the most different CRS model from our previous CRS model. It is found the atmospheric neutrino spectra calculated with the CRS models and the interaction model which reproduce the obaserved atmospheric muon spectra are virtually the samme as our previous calculation.

1 Introduction

The main source of the atmospheric neutrino is $\pi - \mu$ decay at low energies ($\lesssim$ 100 GeV). When there are accurate measurement of atmospheric muon spectra, they help the calculation of the atmospheric neutrino flux largely. Especially when the primary cosmic ray spectra (CRS) is determined accurately, the study of the atmospheric muon is the study of the pion production in the p-Air hadronic interactions.

Based on this idea, we have carried out the study of the interaction model. We used the cosmic ray spectra (CRS) model constructed with AMS-01 [1] and BESS [2,3] observations, and atmospheric muon spectra observed mainly by BESS [4,5,3]. In this study we selected DPMJET-III [6,7], and modified it so that it reproduce the observed atmospheric muon spectra accurately [8].

Note, the statistics of AMS-01 and BESS date above 100 GeV/n were still poor. For the CRS model above 100 GeV/n, we extrapolated the spectra by power law functions with experimental data at much higher energies ($\gtrsim$10 TeV/n) [10,11]. Recently, new observations; ATIC-2 [12], CREAM-I [13], and PAMELA [14] are improving the situation. They have reported the cosmic rays spectra data above 100 GeV/n with large statistics. They are not largely different from our CRS model, but the difference is enough to make a sizable difference in the atmospheric muon and neutrino spectra. On the other hand, their results are not in a good agreement yet. We construct 3 possible CRS models, and study the hadronic interaction model with them.

2 CRS models in HKKMS and the study of interaction model

In the study of the hadronic interaction with the atmospheric muons, we used a CRS model constructed as an extension of the work of Gaisser et al. [15]. The CRS model is mainly based on the data observed by AMS-01 [1], BESS [2], and BESS-TeV [3] at energies $\lesssim$ 100 GeV/n, and the

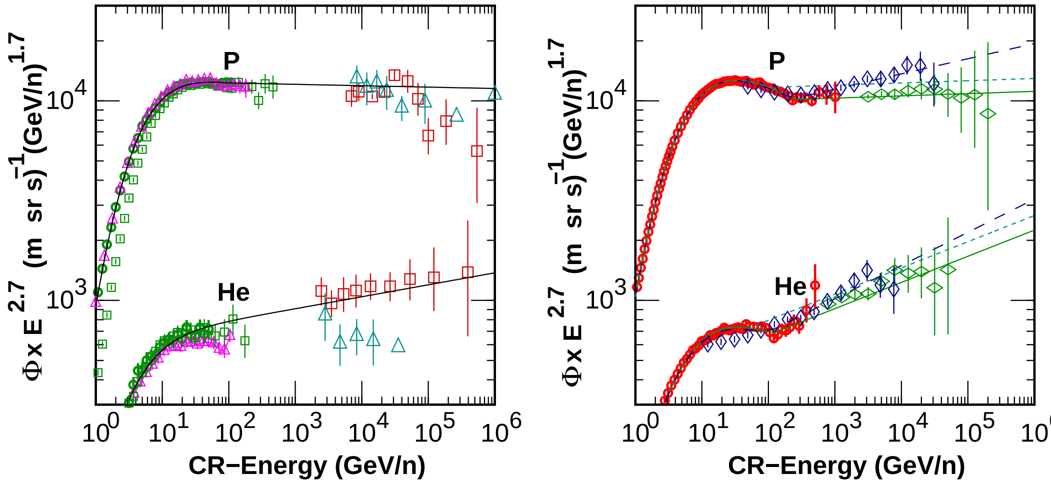

Figure 1: Primary cosmic ray data and the spectra models. Left panel: the CRS model used in HKKMS and the data used to construct it. Small triangles show the AMS-01 data, small circles BESS, small squares BESS-TeV, Large triangles JACEE, and large squares RUNJOB. The solid lines stand for CRS model used in HKKMS. Right panel: possible CRS models and data used to construct them. Small circles show the data of Pamela, horizontal diamonds CREAM-I and vertical diamonds ATIC-2. The solid lines are CREAM model, the dashed lines ATIC model, and the dotted lines are CREAM-power model. The CRS models are explained in section 3.

JACEE [10] and RUNJOB [11] at high energies $\gtrsim$ 10 TeV/n. Then we assumed power law spectra connecting high and low energy data [7]. We show the data and the CRS model in the left panel of Fig. 1 for cosmic ray protons and helium's, since they are the major component of the cosmic rays at these energies. In the right panel of the figure, We show the recent data observed by CREAM-I [13], ATIC-2 [12], and PAMELA [14], and the CRS models constructed from those data for the comparison. Those CRS models will be explained in the next section.

Note, the variation of proton spectra by BESS-TeV from AMS and BESS at low energies ($\lesssim$10 GeV) is due to the solar modulation of cosmic rays. AMS and BESS observed the cosmic rays nearly at the solar minimum, while BESS-TeV observed nearly at the solar maximum. Considering the solar modulation, the agreement of AMS01, BESS, and BESS-TeV is very good at the energies $\lesssim$ 100 GeV for cosmic ray protons. On the other hand, the agreement of AMS01 and BESS or BESS-TeV is not so good for cosmic ray helium's. We selected the BESS and BESS-TeV spectra rather than the AMS-01 one, since the extension agree better with the data at higher energies $\gtrsim$ 10 TeV/n.

Using this CRS model, we had picked DPMJET-III [6] up, since it reproduced the observed muon flux at balloon altitude better than others [4,7]. However, when we compared the calculated and the observed atmospheric muon spectra at lower altitude with much larger statistics, we found the calculated muon spectra with DPMJET-III is significantly lower than the observed ones by BESS and others above 10 GeV/c. Therefore, we decided to modify the secondary spectra of DPMJET-III, so that we can reconstruct the observed atmospheric muon spectra. The modified secondary spectra are shown in the left panel of Fig. 2 at the energy where the the accelerator data [16] are available. The atmospheric muon spectra calculated with the modified interaction model agree well with the observations as shown in the right panel of Fig. 2 for different observation conditions. The data points Norikura are from T. Sanuki et al. [5], Tsukuba from S. Haino et al. [3], L3+c from P. Achard et al. [17], DEIS from O.C. Allkofer et al. [18], and MUTRON from S. Matsuno et al. [19].

With the modified interaction model, and the CRS model shown in the left panel of Fig. 1, we have calculated the atmospheric neutrino spectra [9]. Here after, we refer this calculation as HKKMS calculation, the interaction model as HKKMS int model, and the CRS model as

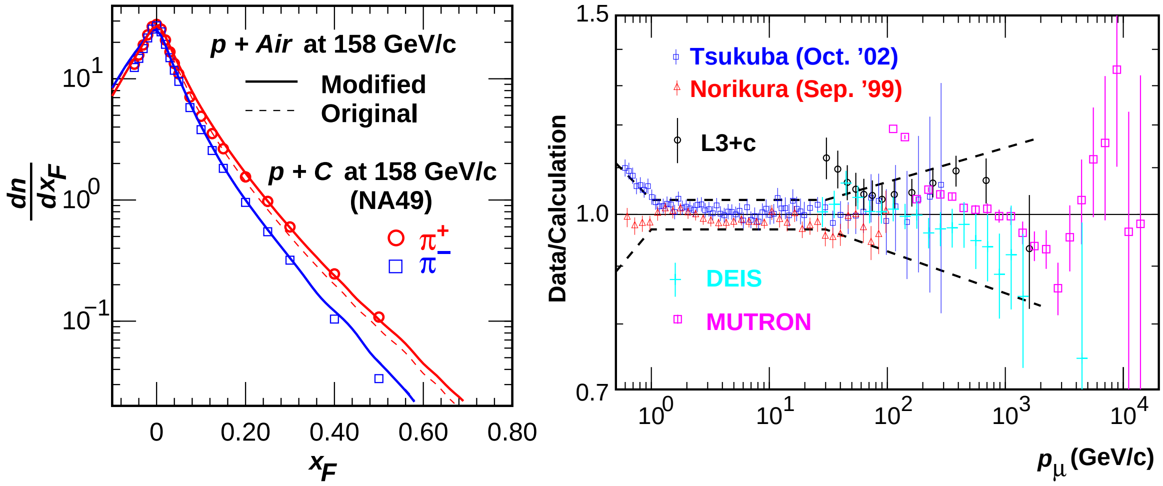

Figure 2: Left panel: HKKMS int. model at the energy where accelerator data are available. Right panel: comparison of calculated atmospheric muon spectra with observed one.

HKKMS CRS model. We note that we have updated the calculation scheme to understand the atmospheric muon flux at balloon altitude better [20]. However, this update is limited to lower energy hadronic interactions ($\lesssim$ 32 GeV).

3 CRS models with recent observations

In the right panel of Fig. 1, we have shown the cosmic ray data with recent observation by ATIC-2 [12], CREAM-I [13], and PAMALA [14] for cosmic ray protons and helium's. ATIC-2 observed cosmic rays from a few 10 GeV to a few 10 TeV in the total energy for many kind of chemical compositions. CREAM-I observed cosmic ray protons and helium's from a few TeV to a few 100 TeV in total energy. ATIC-2 and CREAM-I have a large overlap in the observation energies, but their data show a large differences beyond the statistical error.

PAMELA observed cosmic ray protons and helium's up to $\sim$ 1 TeV/n, especially in a very good statistics below 100 GeV/n. Their observation energy does not overlap with CREAM, but largely with AMS-01, BESS and ATIC-2. For cosmic ray protons, the observation of PAMELA agrees well with that of AMS-01 and BESS below 100 GeV, and is consistent with that of ATIC-2 within the statistical error. For cosmic ray helium's, the observation of PAMELA agrees well with BESS below 100 GeV/n, but not with AMS-01. ATIC-2 observation is somehow in between PAMELA and AMS-01 below 100 GeV/n. Note, PAMELA observed kinks in the cosmic ray spectra, at $\sim$ 250 GeV for cosmic ray protons and at $\sim$ 125 GeV/n for cosmic ray helium's. As the statistics of PAMELA above the kinks are poorer, it is possible to draw power law spectra either to ATIC-2 or CREAM-I spectra from the kinks within the statistical error, both for cosmic ray protons and helium's.

Here, we construct 3 CRS models with these recent observations. 1) Use the spectra suggested by PAMELA below 250 GeV for protons and below 125 GeV/n for helium's, and the spectra above the kinks are the ones suggested by CREAM approximated by single power law spectra, both for protons and helium's. This model gives lowest nucleon flux among all the CRS models including HKKMS from 100 GeV to $\sim$ 1 PeV. We call this model as CREAM CRS model. 2) Use the spectra suggested by PAMELA below 250 GeV for protons and below 125 GeV/n for helium's, and the spectra above the kinks are the ones suggested by ATIC-2 approximated by single power law spectra, both for protons and helium's. This model gives lower nucleon fluxes than that of HKKMS CRS model from 100 GeV to 1 TeV. We call this model as ATIC CRS model. 3) Use the spectra suggested by PAMELA below 100 GeV for protons and below 50

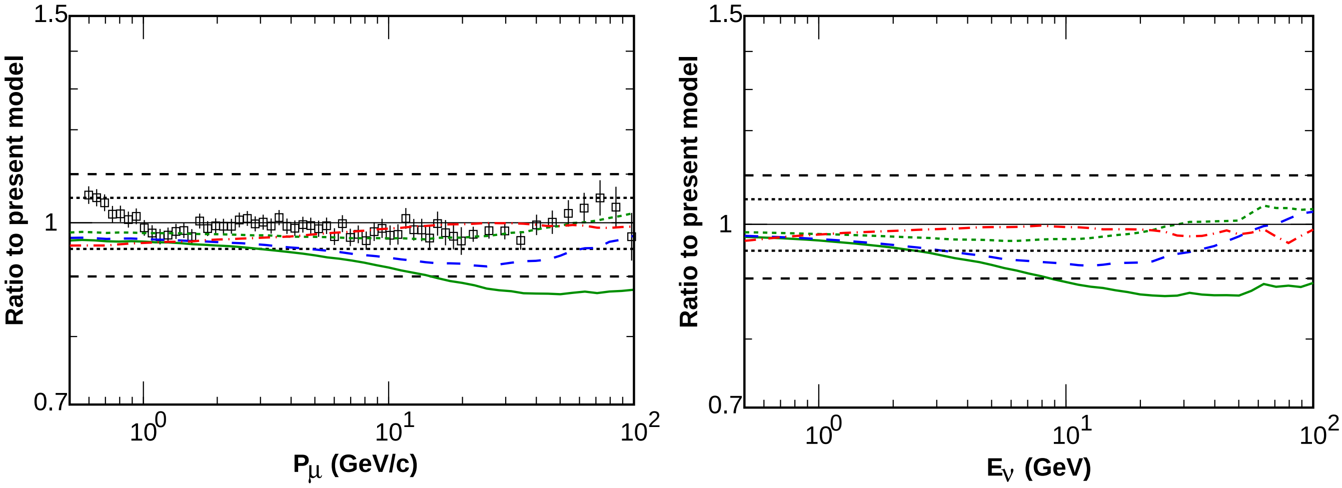

Figure 3: Comparison of the atmospheric muon ($\mu^+ + \mu^-$) spectra in the ratio to the muon spectrum in HKKMS (left panel) and the comparison calculated atmospheric neutrino spectra in the ratio to the neutrino ($\nu_\mu + \bar{\nu}_\mu + \nu_e + \bar{\nu}_e$) spectrum in HKKMS (right panel). The marks in the left panel are the observed data by BESS at Tsukuba. In the both panel, solid line stands for the calculation with CREAM CRS and HKKMS interaction models, dashed line for that with ATIC CRS and HKKMS int. models, dotted line for that with CREAM-power CRS and HKKMS int. models, and dash-dot for that with CREAM CRS and CREAM interaction models.

GeV/n for helium's and extend them by power indexes suggested by the CREAM-I data. This model gives a little lower, but very close nucleon flux to that of HKKMS CRS model. We call this model as CREAM-power CRS model.

4 Study of hadronic interaction with the new CRS models

With these CRS models, we calculate the atmospheric muon spectra in the following combinations: 1) CREAM CRS and the HKKMS int. models, 2) ATIC CRS and the HKKMS int. models, 3) CREAM-power CRS and the HKKMS int. models, and 4) CREAM CRS and the interaction model modified to reproduce the observed atmospheric muon spectra with CREAM CRS model. We call this interaction model as CREAM int. model. Summing μ^+ and μ^+ spectra, we compare the calculated atmospheric muon spectra in the ratio to that calculated in HKKMS scheme in the left panel of Fig. 3. We also plotted the observed data by BESS at Tsukuba [3], as the most reliable data in this momentum range.

The calculation with CREAM CRS and HKKMS int. models gives the lowest atmospheric muon spectrum among all the calculations. The difference of the observed and calculated muon spectra exceed 10% in a wide momentum range, which is not acceptable to use in our calculation of atmospheric neutrino spectra. The calculation with ATIC CRS and HKKMS int. models gives also lower muon spectra in this momentum range, showing the maximum difference of ~ 7 % at ~ 25 GeV, corresponding to the maximum difference of cosmic ray nucleon spectra to the HKKMS CRS model at ~ 250 GeV. The calculated atmospheric muon spectra with CREAM-power CRS and HKKMS int. models is almost consistent with the observed muon spectra and calculated ones in HKKMS. It is also true for the calculation with CREAM CRS and CREAM int. models as intended.

We also calculate the atmospheric neutrino spectra with CREAM CRS and HKKMS int. models, ATIC CRS and HKKMS int. models, CREAM-power CRS and HKKMS int. models, and CREAM CRS and CREAM int. models. Again summing ν_μ, $\bar{\nu}_\mu$, ν_e, and $\bar{\nu}_e$, we compared them in the ratio to that calculated in HKKMS scheme in the right panel of Fig. 3.

We find that the calculations which can reconstruct the observed atmospheric muon spectra

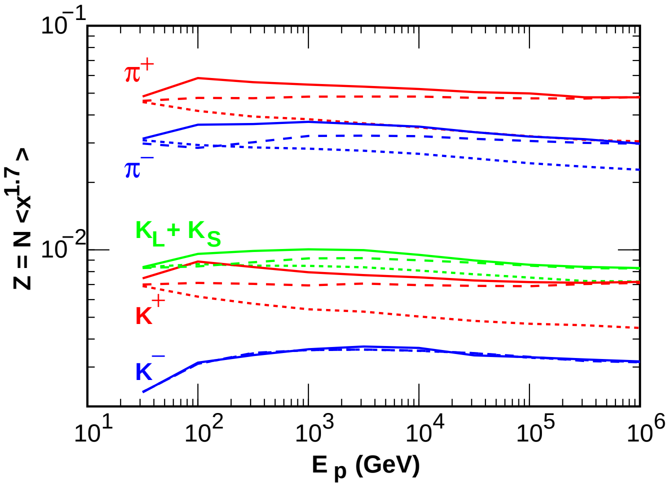

Figure 4: Comparison of the interaction model in terms of Z-factor defined by eq. 1. Solid thick line stands for the CREAM int. model, thin line for the HKKMS int. model, and dashed line for the original DPMJET-III.

give very close atmospheric neutrino spectra to the HKKMS calculation. This is a demonstration of the conclusion of our former study [8], that when we can calculate the atmospheric muon correctly with a cosmic ray spectra model and a hadronic interaction model, they will give the correct atmospheric neutrino spectra.

The magnitude of the modification is shown by the variation of the of the Z-factor defined as;

$$Z_i \equiv N_i < x_i^{1.7} >, \quad \text{and} \quad x_i \equiv \frac{p_i}{p_{proj}}. \tag{1}$$

In Fig. 4, the Z-factors of original DPMJET-III, HKKMS int., and CREAM int. models are shown as the function of projectile energy for p – air interactions.

5 summary

After we summarized the former study of hadronic interaction with the atmospheric muons, we have constructed 3 possible CRS models; CREAM, ATIC, and CREAM power models, with recent cosmic ray observations by ATIC02, CREAM-I, and PAMELA. Then we calculate the atmospheric muon and neutrino spectra with these CRS models using the interaction model used in HKKMS. As the CREAM power CRS model is very close to the HKKMS CRS model, the resulted atmospheric muon and neutrino spectra are very close to those in HKKMS. Also even with the CREAM CRS model, when the interaction model is modified so that it reproduce the observed atmospheric muon spectra, resulted atmospheric neutrino spectra are very close to the one calculated in HKKMS.

The CREAM CRS model gives the lowest cosmic ray nucleon flux, and is most different model from the HKKMS CRS model among all the models we considered here. For any CRS model closer to HKKMS CRS model, we would be able to modify the interaction model so that it reproduce the observed atmospheric muon spectra, and the atmospheric neutrino spectra calculated with it would be very close to those calculated in HKKMS at the energies where the main sopurce is $\pi - \mu$ decay. This is a demonstration of the one of the conclusion stated in Sanuki et al. [8].

Here, we would like to note that AMS-02 [21] has started the observation on the ISS [22], and expected to collect huge primary cosmic ray data in 100 GeV/n – 1 TeV /n. Also balloon borne cosmic ray observation series experiments, such as CREAM, are being carried out. Those experiments will improve the knowledge of the of the cosmic rays above 100 GeV/n largely, and determine the cosmic ray spectra there like the AMS and BESS achieved at energies below 100 GeV/n. When the cosmic ray spectra at energies above 100 GeV/n are known well, we will repeat the study for the hadronic interaction model, and improve the calculation of atmospheric neutrino spectra.

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