Calculation of Atmospheric Neutrino Flux Based on AMS02 Observation

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1. Cosmic Ray Observation of AMS02 and Some Others
2. Cosmic Spectra Model
3. Muon Calibration of Hadronic Interaction Model
4. Calculation of Atmospheric Neutrino Flux
5. Comparison with Previous Calculation and Estimation of Errors.
6. Summary
Other chemical compositions are also considered in the calculation, but they give small contributions.
Direct Observation

Balloon Borne (BESS)

Satellite (ISS, AMS02)
Recent Cosmic Ray observation and Available High Energy data
Proton Closeup
Helium Closeup
Cosmic Ray Spectra Model Based on AMS02 Observation

Looking forward to hearing from CALET and ISS-CREAM
Solar Modulation and Neutron Monitor

![Graph showing neutron monitor counts over years with data from CLIMAX, Newark (Bartol), PAMELA, AMS02, and BESS group flights. The graph also includes data from BESS 97 to 02 on a log-log scale for particle flux.]
Solar Modulated Flux at Fixed Energy
Practical Formula for Solar Modulation

\[ \phi(E, N) = \begin{cases} 
\phi(E, 3710) \exp(a \cdot (N - 3710)) \\
\phi(E, 3710) 
\end{cases} \]

Where \( a \) is from right figure, and \( N \) is the Count of Newark Neutron Monitor.
Muon Calibration

Primary cosmic ray flux
Interaction model

Calculation scheme
(include rigidity cutoff)
Atmosphere model

Atmospheric $\nu$ flux
+ related primary cosmic ray $\mu$

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G. Battiston, A. Ferrari, T. Montaruli, R. Engel

$\Phi_\nu = \Phi_{\text{primary}} \otimes R(B_\odot) \otimes \text{Yield}(\text{Nuv})$

$\Phi_\mu = \Phi_{\text{primary}} \otimes R^*(B_\odot) \otimes \text{Yield}(\text{Nuv})$

Outline of talks
1) Cutoff + $B_\odot$
2) Primary spectrum
3) Muons
4) Yields
Muons Calibration of Interaction Model

Quick 3D Calculation for Muon flux.

As the muon flux is a “local quantity” ($\gamma ct \sim 60\text{km at}10\text{ GeV}$), we can calculate it in a quick calculation method:

1. Inject cosmic rays just above the observation point,
2. Analyze all muons reach the surface of Earth.
Comparison of **Quick 3D** and **Full 3D** calculations

This method works above 0.2 GeV/c.
Muon Calibration of inclusive DPMJET-III

Data are larger by ~15%

Data are larger by ~0.05

Data are smaller by ~0.05

~15% scatter?

=> DPMJET-III Should be Modified
Comparison AFTER the modification
JAM + Modified DPMJET-II vs Muons at the Balloon altitude (HKKM2011)

Good agreement!

Use DPMJET-III above 32 GeV and JAM below 32 GeV
With Cosmic ray spectra model based on AMS02 observation

Before muon re-calibration

After muon re-calibration
The neutrino flux is calculated from the number of neutrinos path through with virtual detector correction.

Re = 6378km

Simulation Sphere ($R_s = 10 \times Re$)
Cosmic ray go out this sphere are discarded.
Cosmic rays go beyond are pass the rigidity cutoff test

Injection Sphere ($Re +100lm$)
Cosmic Rays are sampled and injected here

Virtual Detector
US-standard '76 may be used as the global approximation of the Atmosphere.
Atmosphere model (NRLMSISE-00) and seasonal variations
IGRF10 Geomagnetic Horizontal Field Strength
Based On AMS02 Observation (Preliminary)
Estimated Error in Atmospheric $\nu$-flux Calculation (HKKMS07)

Possible Error with JAM (HKKM11)

- $\delta_\pi$: observation error + Residual of reconstruction
- $\delta_K$: Kaon production uncertainty
- $\delta_\sigma$: Mean free path (interaction crosssection) uncertainty
- $\delta_{air}$: Atmosphere density profile uncertainty
Summary

• According to the new cosmic ray data provided by AMS02 and some others, we have renewed the Cosmic Ray Spectra Model including the practical formula for the Solar Modulations.
• The Muon Calibration of Hadronic Interaction Model was repeated again, with the newly constructed Cosmic Ray Spectra Model.
• The atmospheric neutrino flux calculated with New Cosmic Ray Spectra Model and the Muon-Calibrated Hadronic Interaction Model is generally similar to the previously calculated one, considering the difference of the Muon-Calibration Policy.
• However, a ~ 5% deficit of the flux at ~ 10GeV is seen in the newly calculated atmospheric neutrino flux irrespective of arriving directions or kind of neutrinos.
Comparison with Neutrino Data
Super-K Preliminary

From K. Okumura in ICRC2015
Solar Modulation of Atmospheric Neutrinos

From PHD thesis of E. Richard

Best fit corresponds to 62% of the predicted variations

Poor Statistics

Picked up mainly the forbush decrease?
Observed Azimuthal Variation of $\nu_e$ flux (from PHD thesis of E. Richard)

Energy Binned All Azimuth angles

Zenith Angle Binned All Energies
Observed Azimuthal Variation of $\nu_\mu$ flux (from PHD thesis of E.Richard)

Energy Binned All Azimuth angles

Zenith Angle Binned All Energies
Comparison in [Flux/depth]

DPMJET-III show the best agreement
Phase Space Study

\[ p + N(air) \rightarrow \pi^{\pm} + X \]

\[ \pi^{\pm} \rightarrow \nu_{\mu}(\bar{\nu}_{\mu}) + \mu^{\pm} \]

\[ \mu^{\pm} \rightarrow \bar{\nu}_{\mu}(\nu_{\mu}) + \nu_{e}(\bar{\nu}_{e}) + e^{\pm} \]

At \( P_{\nu} = 0.32 \text{ GeV/c} \)
$p + N(\text{air}) \rightarrow \pi + X$

$\pi \rightarrow \nu_\mu + \mu$

Size of Phase space to give the variation

At $P_\mu = 0.32$ GeV/c
Vertical neutrino flux

\[ \nu_\mu \]

\[ \bar{\nu}_\mu \]

\[ \nu_e \]

\[ \bar{\nu}_e \]

\[ \Delta \phi_v / [\Delta \phi_{\mu}]_{\text{Max}} \]

\[ \sqrt{\langle \Delta \phi_v / [\Delta \phi_{\mu}]_{\text{Max}} \rangle^2} \]

\[ \log (E_v) \]
Horizontal neutrino flux
Horizontal enhancement of neutrino flux
Sub-GeV flux at Kamioka

(Battistoni et al. Astropart. Phys 1999)
Interpretation of horizontal enhancement

Longer integration length in the neutrino production zone for horizontal directions