Atmospheric Neutrino Fluxes

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Synopsis

Section 1: Features of atmospheric neutrino fluxes
  – Cosmic ray cascades
  – 3D effects
  – Fluxes, flux ratios

Section 2: Systematics
  – Primary fluxes
  – Hadron production
  – Other effects
Section 1: Features of Atmospheric neutrino fluxes
Neutrinos produced from a shower

- Primary cosmic ray: proton or heavier nucleus
- Interacts in $\sim 90\text{g/cm}^2$
- Atmosphere depth $1050\text{g/cm}^2$
- Cascade
- Most hadrons don’t reach ground.
Through Going \textit{induced} \textit{in}

Partially C

Contained

$E_\parallel$ (GeV)

0.1 1 10 100 1000

Osc Max Down

Osc Max Horizontal

Osc Max Up

m^2 = 2.5 \times 10^{-3} \text{ eV}^2
### Summary of Atmospheric Neutrino Calculations

<table>
<thead>
<tr>
<th>Authors</th>
<th>Journal Reference</th>
<th>Dimensionality</th>
<th>Code/Other Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zatsepin, Kuz'min</td>
<td>SP JETP 14:1294(1961)</td>
<td>1D</td>
<td></td>
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<tr>
<td>E. V. Bugaev and V. A. Naumov,</td>
<td>PL B232:391 (1989)</td>
<td>1D</td>
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<tr>
<td>Agrawal, Gaisser, Lipari, Stanev</td>
<td>PRD 53:1314 (1996)</td>
<td>1D</td>
<td>Target</td>
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<tr>
<td>P. Lipari</td>
<td>Asp.Phys 14:171 (2000)</td>
<td>3D</td>
<td></td>
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<tr>
<td>V. Plyaskin</td>
<td>PL B516:213 (2001)</td>
<td>3D</td>
<td>GHEISHA</td>
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<tr>
<td></td>
<td>hep-ph/0303146</td>
<td></td>
<td></td>
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<tr>
<td>Wentz et al</td>
<td>PRD 67 073020 (2003)</td>
<td>3D</td>
<td>Corsika: DPMJET, VENUS, UrQMD</td>
</tr>
<tr>
<td>Liu, Derome, Buénerd</td>
<td>PRD 67 073022 (2003)</td>
<td>3D</td>
<td></td>
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<tr>
<td>Favier, Kossalsowski, Vialle</td>
<td>PRD 68 093006 (2003)</td>
<td>3D</td>
<td>GFLUKA</td>
</tr>
<tr>
<td>Barr, Gaisser, Lipari, Robbins, Stanev</td>
<td>PRD (July 2004)</td>
<td>3D</td>
<td>Target</td>
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<tr>
<td>Honda, Kajita, Kasahara, Midorikawa</td>
<td>PRD 64 053011 (2001)</td>
<td>3D</td>
<td>DPMJET</td>
</tr>
</tbody>
</table>
Path length distributions

From Honda et. al. astro-ph/040445
Solid 3D at Kamioka, Dashed 1D at Kamioka, Dot 3D at Soudan

\[
\nu_\mu + \bar{\nu}_\mu \\
0 < \cos \theta < 0.05
\]

\[
\nu_e + \bar{\nu}_e \\
0 < \cos \theta < 0.05
\]
Azimuth angle distribution
East-West effect

Kamioka, $v_e$
$E_t > 315$ MeV

Kamioka, $v_\mu$
$E_t > 315$ MeV

ratio

azimuth angle $\phi_v$

ratio

azimuth angle $\phi_{\nu_e}$
Flavour ratio

Kamioka

$\frac{E_{\nu} / (\text{GeV})}{(\nu_e + \bar{\nu}_e) / 2}$

1D  
3D  
NM

Kamioka $\nu_\mu$

$E_{\nu} / (\text{GeV})$

$E_{\nu} / (\text{GeV})$

Kamioka $\nu_\mu$

$E_{\nu} / (\text{GeV})$

Kamioka $\nu_e$

$E_{\nu} / (\text{GeV})$

NM=3D with no bending of secondaries in Earth's mag field
Section 2: Systematics
Primary fluxes

\[ \Phi(E_K) \propto K \frac{1}{E_K^{1/2}} b \exp \left[ c \sqrt{E_K} \right] \]

<table>
<thead>
<tr>
<th>Element</th>
<th>( K )</th>
<th>( b )</th>
<th>( c )</th>
</tr>
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<tr>
<td>H</td>
<td>2.74</td>
<td>14900</td>
<td>2.15</td>
</tr>
<tr>
<td>He</td>
<td>2.64</td>
<td>600</td>
<td>1.25</td>
</tr>
<tr>
<td>CNO 14</td>
<td>2.70</td>
<td>62.4</td>
<td>1.78</td>
</tr>
<tr>
<td>Ne-Si 24</td>
<td>2.70</td>
<td>21.4</td>
<td>1.78</td>
</tr>
<tr>
<td>Fe(56)</td>
<td>2.70</td>
<td>5.1</td>
<td>1.78</td>
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</table>

- Protons = 75% of all nucleon fluxes
- Helium = 15% of all nucleons = 60% of all nuclei.
Residuals: Oldest measurements
Residuals: Newer measurements
Residuals: Newest measurements
Effect on neutrino fluxes

This includes helium uncertainty shown on next slide
Helium Fluxes
Hadron production measurements

Population of hadron-production phase-space for pA X interactions.

$\mu_\mu$ flux (represented by boxes) as a function of the parent and daughter energies.

Measurements.
- 1-2 p$_T$ points
- 3-5 p$_T$ points
- >5 p$_T$ points

Can attempt fit all the data simultaneously.

Antiproton example: Duperray, Huang, Protasov, Buénerd astro-ph/0305274
Hadron production: MC comparison
Muon fluxes

From: Wentz et al

Ratio $\left( \frac{\mu^-}{e^-} \right) / \left( \frac{\mu^+}{e^+} \right)$

(Sea level muon fluxes) $\times p$

Graph showing the comparison of muon fluxes at different locations.
• Effect of a **15% reduction in $\bar{K}^+$ production**
Future hadron-production results

HARP 3-15 GeV at CERN PS
MIPP 5-120 GeV at FNAL MI
NA49 100,160 GeV at SPS
Cross section change

Effect of artificial increase in total cross section of 15%
Other effects: Atmospheric Density
Other effects: Magnetic field


Method A: Generate far from Earth, propagate in (Circles)
Method B: Generate near earth and propagate charge-reversed out.
Return to 3D: Is it important?

SuperKamiokande Collaboration  
hep-ex/0404034

Difference between 3D and 1D calculations
Return to 3D: Is it important?

SuperKamiokande Collaboration
hep-ex/0404034

<table>
<thead>
<tr>
<th>3D</th>
<th>1D</th>
</tr>
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<tbody>
<tr>
<td>bigger</td>
<td>bigger</td>
</tr>
<tr>
<td>&gt;30%</td>
<td>3%-10%</td>
</tr>
<tr>
<td>10%-30%</td>
<td>&lt;3%</td>
</tr>
</tbody>
</table>

Difference between 3D and 1D calculations
Conclusions

• Since early days of nucleon decay expts and the atmospheric neutrino ‘anomaly’:
  - Large increase in calculation sophistication
  - Much improved primary fluxes
  - Hadron production data still needed

• 3D effects now well understood.