Borexino is a particle physics experiment with a large liquid scintillator neutrino detector, located in Gran Sasso National Laboratory (LNGS), Italy. Together with its main goal – studying solar neutrinos – the exceptional levels of radioactivity have made it possible to also produce many other interesting results both within and beyond the Standard Model of particle physics.

Atmospheric neutrinos are generated in decays of secondary particles produced in cosmic rays interactions with atomic nuclei of atmosphere. They interact with the neutrino in the following processes:

\[ p(\alpha, \ldots) + A \rightarrow \pi^{\pm}(K^\pm) + \ldots + X \]

\[ \pi^{\pm}(K^\pm) \rightarrow \mu^{\pm} + \nu_\mu \]

\[ \mu^{\pm} \rightarrow e^{\mp} + v_e + \bar{\nu}_\mu \]

\[ \mu^{\pm} \rightarrow e^{\mp} + v_e + v_\mu \]


**How?**

**Initial fluxes**

Combination of HKKM2014 [1] (for energies above 100 MeV) and FLUKA [2] (below 100 MeV) models for LNGS.

**Fluxes in detector**

Using ROOT [3] and modified ProB++ software [4] we developed special software to calculate the neutrino flavor oscillations during propagation through the Earth.

**Simulation**

Calculated atmospheric neutrino spectra are then used in GENIE [5] (version 3.0.0, tune G18_10b) to generate neutrino interactions with $^6$Li, $^{12}$C and $^{14}$C nuclei of Borexino target medium. GENIE output final state particles are used as input particles for the BxMC – Borexino Monte-Carlo [24] that allows us to reproduce the detector response.

**Results**

**Observed events, expected background events and 90% C.L. upper limits on the $\nu_e$ DSNB flux. Without or (with) atmospheric neutrino contributions**

<table>
<thead>
<tr>
<th>Energy range [p.e.]</th>
<th>Signal [events]</th>
</tr>
</thead>
<tbody>
<tr>
<td>408-1500</td>
<td>2.2±1.1</td>
</tr>
<tr>
<td>408-4000</td>
<td>3.3±1.6</td>
</tr>
<tr>
<td>408-8000</td>
<td>9.2±4.6</td>
</tr>
</tbody>
</table>

** Expected number of atmospheric $\nu_e$ events**

<table>
<thead>
<tr>
<th>Energy range [p.e.]</th>
<th>Signal [events]</th>
</tr>
</thead>
<tbody>
<tr>
<td>408-1500</td>
<td>2.2±1.1</td>
</tr>
<tr>
<td>408-4000</td>
<td>3.3±1.6</td>
</tr>
<tr>
<td>408-8000</td>
<td>9.2±4.6</td>
</tr>
</tbody>
</table>

**Geo-$v$ analysis**

We estimate the respective systematic uncertainty due to atmospheric neutrinos on geoneutrinos as +0.00 % and on reactor antineutrinos as −0.38 %.

**References:**


