Estimation of atmospheric neutrinos background in Borexino

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Abstract. Atmospheric neutrinos are produced in interactions of cosmic rays with atomic nuclei in the Earth’s atmosphere. Although their flux is too low for studying in Borexino, atmospheric neutrinos act as a background for other processes. This paper presents the theoretical expected yield of atmospheric neutrinos in Borexino for three neutrino detection reactions: $\nu p$-ES, $\nu e$-ES and inverse $\beta$-decay, as well as the status of Monte-Carlo simulation for $\nu ^{12}C$ interaction channels. Calculations were performed based on the only currently known detailed model of atmospheric neutrinos flux at very low energies.

1. Atmospheric neutrinos
Atmospheric neutrinos are produced in the interaction of cosmic rays with atomic nuclei in the Earth’s atmosphere. Muon neutrinos are produced in decays of pions (kaons) and muons, whereas electron neutrinos are produced only in the decay of muons. Thus, a flux ratio of muon neutrinos to electron neutrinos is about 2-to-1 (it is true with energies less than 1 GeV). Spectrum of atmospheric neutrinos is associated with the spectrum of cosmic rays, and extends up to ultrahigh energies.

FLUKA atmospheric neutrinos flux at low energy from [1] was used. According to the article, the overall absolute flux uncertainty does not exceed 25%. Flux spectra shown in figure 1. Smooth curves obtained by quadratic spline interpolation.

The most numerous particles in the Borexino scintillator are electrons, protons and carbon-12 nuclei (see table 1). Neutrino interactions with these particles were considered.

2. Neutrino proton elastic scattering reaction channel
The differential cross section of neutrino on free proton elastic scattering ($\nu p$-ES) in terms of proton kinetic energy $T_p$ is [2]

$$\frac{d\sigma}{dT_p} = \frac{G_F^2m_p^3}{4\pi E_{\nu}^2} \left[ A \mp B \frac{(s-u)}{m_p^2} + C \frac{(s-u)^2}{m_p^4} \right]$$ (1)

In this formula the minus (plus) is for (anti)neutrinos, $s$ and $u$ are Mandelstam variables; and $A$, $B$, $C$ are functions of $Q^2$ - 4-momentum transfer, they contain vector form-factors $F_1$ and $F_2$, and axial form-factor in dipole form.
Figure 1. Atmospheric neutrino flux spectra.

\[ F_A = \frac{g_A}{(1 + Q^2/M_A^2)^2}, \]  

(2)

where \( g_A = F_A(Q^2 = 0) = -1.267 \) is axial-vector coupling constant, and \( M_A = 1.03 \text{ GeV} \) is the axial mass.

Recoil protons kinetic energy distribution in the detector is related with the differential cross-section \( d\sigma/dT_p \) and neutrino spectrum \( dN/dE_\nu \) as

\[ \frac{dN}{dT_p} = N_p \int_{E_{\nu}^\text{min}}^\infty dE_\nu \frac{dN_\nu(E_\nu)}{dE_\nu} \frac{d\sigma(E_\nu, T_p)}{dT_p}, \]  

(3)

where \( N_p \) is the number of free protons in the Borexino detector (see table 1).

Because of the effect of scintillation quenching, the light yield for protons is suppressed. Visible energy for proton \( E_{p,\text{vis}} \) is

\[ E_{p,\text{vis}}(T_p) = \int_0^{T_p} \frac{dE}{1 + kB \frac{dE}{dx}(E)} \]  

(4)

where \( dE/dx \) is stopping power of scintillator material with respect to protons, \( kB \) is Birks parameter, \( kB = 0.0115 \text{ cm/MeV} \) for protons in the Borexino scintillator. Function \( dE/dx \) is computed using the software SRIM [4].

Borexino detector energy resolution \( \delta E_{\text{vis}} = 5\%/\sqrt{E_{\text{vis}} \text{ [MeV]}} \) is also taken into account.

Calculated events number is in table 2. Events energy distribution shown in figure 2.

### Table 1. Particles in Borexino scintillator (number per 100 tons).

| Particle | Number per 100 tons |
|----------|---------------------|
| \( e^- \) | \( 3.30531 \times 10^{31} \) |
| \( p \) | \( 6.00013 \times 10^{30} \) |
| \( ^{12}C \) | \( 4.45652 \times 10^{30} \) |
| \( ^{13}C \) | \( 5.00226 \times 10^{28} \) |
| \( ^2H \) | \( 9.00155 \times 10^{26} \) |
| \( ^{16}O \) | \( 8.52935 \times 10^{26} \) |
| \( ^{14}N \) | \( 8.51840 \times 10^{26} \) |
| \( ^{15}N \) | \( 3.12919 \times 10^{24} \) |
| \( ^{18}O \) | \( 1.70994 \times 10^{24} \) |
| \( ^{17}O \) | \( 3.24888 \times 10^{23} \) |

3. **Inverse beta-decay reaction channel**

Inverse beta-decay (IBD) \( \bar{\nu}_e + p \rightarrow n + e^+ \) is the threshold reaction, possible if

\[ E_\nu > E_{\text{thr}} = \frac{(m_n + m_e)^2 - m_p^2}{2m_p} = 1.806 \text{ MeV} \]  

(5)

Detection of this reaction is based on the method of time coincidences. Prompt event is the positron annihilation in scintillator, and delayed event is the neutron capture mostly by
hydrogen (mean neutron capture time in Borexino scintillator is \((254.5 \pm 1.8)\mu s\) [5]), producing deuterium and photon with energy 2.22 MeV.

The exact inverse beta decay cross-section (including radiative corrections) from [6] is used. Calculated prompt events number is in table 2. Energy distribution shown in figure 3.

4. Neutrino electron elastic scattering reaction channel

According to the Standard Model, (anti)neutrino electron elastic scattering (\(\nu e\)-ES) differential cross-section in terms of electron kinetic energy \(T_e\) is

\[
\frac{d\sigma}{dT_e}(E_\nu, T_e) = \frac{2G_F^2 m_e}{\pi E_\nu^2} \left[ g_L^2 E_\nu^2 + g_R^2 (E_\nu - T_e)^2 - g_L g_R m_e T_e \right] \tag{6}
\]

Coupling constants \(g_R = \sin^2 \theta_W\) for all neutrino types, \(g_L = \sin^2 \theta_W + 1/2\) for \(\nu_e\), \(g_L = \sin^2 \theta_W - 1/2\) for \(\nu_{\mu,\tau}\), \(g_R \leftrightarrow g_L\) for antineutrino.

Calculations are analogous to those for \(\nu p\)-ES with \(kB(e) = kB(p) = 0.0115\) cm/MeV and \(dE/dx\) calculated using ESTAR [7]. Calculated events number is in table 2. Events energy distribution shown in figure 4.

5. Neutrino carbon-12 reactions channels

Because of the large number of possible \(\nu^{12}C\) reactions channels, GENIE Neutrino Monte-Carlo Generator (ver 2.8.6) [8] was used. Sample of more than 600 thousands neutrino interaction events was obtained, and normalized by integrating flux times cross-sections, implemented in GENIE.

A special module was developed for Geant4 based Borexino Monte-Carlo generator (BxMC) to read and track final state particles from GENIE neutrino interactions. Unfortunately, nuclear deexcitation is not implemented in GENIE, and nuclear remnants, tagged by GENIE as ”low energy hadronic blob”, were assumed as ground state nuclei.

Obtained visible events number and energy distributions shown in table 2 and figure 5.

While reactions with pions and muons as final state particles can be easily tagged because of their high deposited energy, reactions producing, for example, low energy protons (and neutrinos) and (pseudo)stable nuclei are hard for tagging. There are also many reactions, that can imitate IBD reaction with protons/electrons/nuclei as prompt events and knocked out neutrons as delayed events. Some residual unstable nuclei have long lifetime (\(\tau(\nu^{10}C, ^8He, ^9Li) \sim 0.2\) s, \(\tau(^8Li, ^8B, ^6He) \sim 1.2\) s, \(\tau(^{10}C) \sim 27.8\) s, \(\tau(^{11}C) \sim 29.3\) min), which means they can be recognized with high efficiency, but with applying long time cut, up to 3 hours for \(^{11}C\).

It all requires a detailed consideration, which is in progress.
Figure 5. Neutrino carbon-12 interaction reactions yield for the atmospheric neutrinos in the Borexino detector. Visible energy distributions of events for: (blue) neutral current reactions, (green) charged current reactions, (black) all reactions in sum.

Table 2. Reactions yield for atmospheric neutrinos in the Borexino detector (events per year per 100 tons).

|          | νp-ES | IBD | νe-ES | ν$^{12}$C-CC | ν$^{12}$C-NC | ν$^{12}$C total |
|----------|-------|-----|-------|--------------|--------------|----------------|
| 0.25 ≤ $E_{\text{vis}}$ ≤ 15 MeV | 0.181443 | 0.000205 | 0.000725 | 0.005962 | 1.282274 | 1.288701 |
| 1 ≤ $E_{\text{vis}}$ ≤ 100 MeV | 0.397184 | 0.033788 | 0.002981 | 0.619615 | 4.156067 | 4.775682 |

6. Conclusions

Table 2 shows expected events rate number for atmospheric neutrinos interaction reactions in the Borexino detector in two visible energy ranges for two Borexino DAQ systems. Visible energy events distributions are shown in figures 2 to 5. Detection efficiency is not taken into account.

Results of the work show that atmospheric neutrinos should be thought as an important source of background for some kinds of processes in Borexino with few expected events per year.

Acknowledgements

This work was supported by RFBR grant 14-22-03031 and partially supported by MEPhI Academic Excellence Project (contract № 02.a03.21.0005, 27.08.2013).

References

[1] Battistoni G et al. 2005 Astropart. Phys. 23 526
[2] Ahrens L A et al. Phys. Rev. D 35 785
[3] Birks J B 1964 The theory and practice of scintillation counting (New York: Macmillan)
[4] Ziegler J F, Ziegler M D and Biersack J P 2010 Nucl. Instrum. Meth. B 268 1818
[5] Bellini G et al. 2011 JINST 6 5005
[6] Strumia A and Vissani F 2003 Phys. Lett. B 564 42
[7] Berger M J et al. 2005 ESTAR, PSTAR, and ASTAR: Computer Programs for Calculating Stopping-Power and Range Tables for Electrons, Protons, and Helium Ions (version 1.2.3) URL http://physics.nist.gov/Star
[8] Andreopoulos C et al. 2010 Nucl. Instrum. Meth. A 614 87