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To cite this article: V S Atroshchenko and E A Litvinovich 2017 J. Phys.: Conf. Ser. 798 012108

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Sub-GeV atmospheric neutrinos background in organic liquid scintillation detectors

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Abstract. Atmospheric neutrinos are produced in interactions of cosmic rays with atomic nuclei in the Earths atmosphere. In low energy neutrino experiments they are mainly considered as a background for studied processes. For atmospheric neutrinos in sub-GeV range we present semi-analytical expected yield for four neutrino detection reactions: $\nu_e$-ES, $\nu_p$-ES, inverse $\beta$-decay and $^{12}\text{C}(\nu,\nu')^{12}\text{C}^*(15.11\text{ MeV})$, as well as results of Monte-Carlo simulation for other $\nu^{12}\text{C}$ interaction channels. Calculations are made for 4 neutrino experiments and include neutrino oscillation averaged over neutrino arrival directions.

1. Introduction
Atmospheric neutrinos background in MeV energy range is crucial for different tasks, such as searches for proton decay or diffuse supernova neutrino background. Meanwhile, atmospheric neutrinos are mostly considered in GeV energy range. In this article background from sub-GeV (including below 100 MeV) atmospheric neutrinos is estimated for 4 organic liquid scintillation neutrino detectors: Borexino (Gran Sasso, Italy), KamLAND (Kamioka, Japan), SNO+ (Sudbury, Canada) and JUNO (Jiangmen, China). We consider neutrino interactions with electrons, protons and carbon-12 nuclei as the most numerous particles in organic scintillators.

2. Scintillators properties
One of the features of scintillators is energy scale non-linearity and lightyield suppression. Because of the effect of scintillation quenching different particles with the same kinetic energy give different lightyield. Obtained from lightyield visible energy is smaller than real deposited energy, reduction depends on the energy, and it can be expressed by Birks' law as [1]

$$E_{\text{vis}}(T) = \int_0^T \frac{dE}{1 + kB \frac{dE}{dx}(E)}$$

(1)

where $E_{\text{vis}}$ is visible energy, $T$ is kinetic energy of particle, $dE/dx$ is stopping power of given scintillator material with respect to given particle, and $kB$ is Birks parameter (different for different scintillators and particles too).
Another feature, which is directly related to the organic scintillators, is their low energy threshold. Natural carbon has traces of carbon-14 isotope, which is beta-decayer with maximum emitted electron energy of 156 keV. Unavoidable presence of carbon-14 results in extremely high rate of such decays, it means that any good event is indistinguishable if its energy is below 200-300 keV, depending on energy resolution. In following analysis low energy threshold for all scintillators is chosen as 250 keV.

Properties of scintillators (targets) in considered detectors are shown in table 1.

| Table 1. Scintillators properties. |
|-----------------------------------|
| **Composition** | Borexino | KamLAND | SNO+ | JUNO |
| PC + 1.5 g/l PPO | 80% dodecane + 20% PC + 1.36 g/l PPO | LAB + 2 g/l PPO + 15 mg/l bisMSB | LAB + 3 g/l PPO + 15 mg/l bis-MSB |
| **Density, kg/m³** | 876 | 780 | 860 | 860 |
| **Target mass, tons** | 278 | 900 | 780 | 20000 |
| **Energy resolution (at 1 MeV), %** | 5 | 6.4 | 5 | 3 |
| kB(e⁺/γ), μm/MeV | 115 | 138 | 74 | 74 |
| kB(p), μm/MeV | 115 | 100 | 97 | 98 |
| kB(α), μm/MeV | 92 | 148 | 76 | 74 |

3. Atmospheric neutrinos fluxes

3.1. Initial fluxes

For sub-GeV and few GeV neutrino energies solar modulation and geomagnetic cutoffs become important. It means atmospheric neutrinos fluxes are different over time and locations.

For energies above 100 MeV HKKM2014 [2] fluxes are used. For every experiment site mean fluxes between solar min and solar max are taken. For JUNO, as HKKM simulation is not performed for its location, fluxes are taken as mean between those for Kamioka and INO site.

For energies below 100 MeV FLUKA fluxes from [3] are used. Since FLUKA and solar mean HKKM fluxes appeared to be almost the same in range 100-1000 MeV, and HKKM fluxes are more precise, FLUKA fluxes were scaled to be equal with corresponding HKKM fluxes at 100 MeV. Fluxes below 100 MeV for SNO+ and JUNO were obtained by taking mean between Gran Sasso and Kamioka FLUKA fluxes and scaling them to HKKM fluxes.

Flux spectra shown in figure 1 as per flavor fluxes in Gran Sasso, and in figure 2 as total fluxes per experiment. Smooth curves were obtained by logarithmic quadratic spline interpolation.

3.2. Oscillated and integrated fluxes

Fluxes considered in section 3.1 are different from fluxes passing through detectors. Neutrino oscillations and Mikheyev-Smirnov-Wolfenstein effect change probability of neutrino flavors to be detected. Thus two main factors affect the probability: path length between points of neutrino birth in atmosphere and interaction in the detector, and density profile of matter along the path.

As the first order approximation, assuming that the Earth is a sphere and that atmosphere properties do not depend on location, neutrino path length depends only on neutrino production height above the Earth’s surface, and on zenith angle – angle between line from the Earth’s center passing through the detector, and direction from the detector to the point of neutrino birth. Production points distribution over zenith angle is uniform, while production height values were
taken from [3] and approximated with probability density function

\[ P_h(h) = c_1 \exp(-a h) + \frac{c_2}{\beta} \exp\left(\frac{\alpha - h}{\beta} - \exp\left(\frac{\alpha - h}{\beta}\right)\right) \]  

where \( h \) is for production height, and \( c_1, c_2, a, \alpha, \beta \) are free fit parameters. The Preliminary reference Earth model (PREM) [4] is used for the Earth’s density profile.

Prob3++ software [5] is chosen for propagating neutrino through the Earth. It was modified to correctly handle neutrino path in the atmosphere, and also to use constant density layers of 1 km width with density values for each obtained from PREM.

Since liquid scintillator detectors do not preserve the information about neutrino arrival direction, and due to chosen approximation of the Earth and atmosphere, fluxes passing through the detector can be calculated as

\[ F_i(E) = F_{i}^{ini}(E) \sum \langle P_{j \rightarrow i}^{osc}(E) \rangle = F_{i}^{ini}(E) \frac{1}{\pi h_{\text{max}}^{\text{atm}}} \sum \int_{0}^{\pi} \int_{0}^{h_{\text{max}}^{\text{atm}}} d\theta_z dh P_{j \rightarrow i}^{osc}(E, \theta_z, h) \]  

where \( i \) and \( j \) are for (anti-)\( \nu_e, \nu_\mu, \nu_\tau \), \( F \) is flux in the detector, \( F^{ini} \) is initial flux, \( P^{osc} \) is oscillation probability, \( \theta_z \) is zenith angle, \( h \) is production height and \( h_{\text{max}}^{\text{atm}} \) is the maximum considered atmosphere height.

In order to speed up the calculations, integration was replaced by summing on a grid of points over zenith angle and production height. For zenith angle 180 equidistant points were taken, thus every point corresponds to 1°. For production height cumulative distribution function was obtained from (2), and 100 points were chosen which are equidistant on probability axis, resulting in that each height point corresponds to the probability part of 1%. Energy was discretized as 10000 points per decade in logarithmic scale from 1 keV up to 10 GeV.

4. Semi-analytical calculations of reaction channels yield

If one knows differential cross-section of neutrino interaction reaction over the kinetic energy of outgoing particle \( \frac{d\sigma}{dT} \), neutrinos flux over energy \( dN_\nu/dE_\nu \), and transformation law of particle kinetic energy to the visible energy \( E_{\text{vis}}(T) \) (see (1)), and number of particles \( n \) which neutrino interacts with in scintillator, one can calculate energy spectrum of reaction yield in the detector as

\[ \frac{dN}{dE_{\text{vis}}} = n \frac{dT}{dE_{\text{vis}}} \frac{dN}{dT} = n \frac{dT}{dE_{\text{vis}}} \int dE_\nu \frac{dN_\nu(E_\nu)}{dE_\nu} \frac{d\sigma(E_\nu, T)}{dT} \]  

Figure 1. Atmospheric neutrino flux spectra in Gran Sasso. Top to bottom: total, \( \bar{\nu}_\mu, \nu_\mu, \bar{\nu}_e, \nu_e \).

Figure 2. Total atmospheric neutrino flux spectra for 4 experiments. Top to bottom: SNO+, Borexino, KamLAND, JUNO.
with proper limits on integral over $E_{\nu}$, where $dT/dE_{vis}$ is derivative of inverse function of $E_{vis}(T)$.

Yields are calculated for neutrino electron elastic scattering (5), neutrino proton elastic scattering (6), inverse beta-decay (7) and neutrino carbon-12 excitation (8). Cross-sections are taken from Standard Model, [6], [7], and [8], correspondingly.

\begin{align*}
\nu + e^- & \rightarrow \nu + e^- \quad (5) \\
\nu + p & \rightarrow \nu + p \quad (6) \\
\bar{\nu}_e + p & \rightarrow n + e^+ \quad (7) \\
\nu + ^{12}\text{C} & \rightarrow \nu + ^{12}\text{C}^{*} \rightarrow \nu + ^{12}\text{C} + \gamma (15.11 \text{ MeV}) \quad (8)
\end{align*}

Stopping power function $dE/dx$ from (1) is calculated using ESTAR [9] for electrons and positrons, and using SRIM [10] for protons.

Detection of inverse beta-decay (IBD) reaction is based on the method of time coincidences, providing clear double event signature. Prompt event is the positron annihilation in scintillator, and delayed event is the neutron capture mostly by hydrogen, producing deuterium and de-excitation photon with energy 2.22 MeV. Mean time of neutron capture depends on scintillator’s type and density.

Calculated event rates in different visible energy ranges are shown in table 2.

**Table 2.** Reactions yield for atmospheric neutrinos (events per year per 100 tons of scintillator). Low energy threshold for visible energy is 250 keV.

| Reactions                  | $E_{vis} \leq \ldots$ MeV | Borexino | KamLAND | SNO+   | JUNO   |
|----------------------------|----------------------------|----------|---------|--------|--------|
| $\nu_e$-ES                 | 1  4.47E−5                  | 3.37E−5  | 6.07E−5 | 2.89E−5 |
|                           | 10 5.36E−4                  | 4.05E−4  | 7.26E−4 | 3.47E−4 | 4.05E−4 |
|                           | 100 3.26E−3                 | 2.52E−3  | 4.31E−3 | 2.17E−3 | 4.31E−3 |
|                           | 1000 7.11E−3                | 5.86E−3  | 8.76E−3 | 5.12E−3 | 8.76E−3 |
| $\nu_p$-ES                 | 1  2.61E−2                  | 2.54E−2  | 4.01E−2 | 1.93E−2 | 4.01E−2 |
|                           | 10 1.53E−1                  | 1.57E−1  | 2.38E−1 | 1.18E−1 | 2.38E−1 |
|                           | 100 4.59E−1                 | 5.05E−1  | 6.93E−1 | 3.80E−1 | 6.93E−1 |
|                           | 1000 5.92E−1                | 6.70E−1  | 8.72E−1 | 5.07E−1 | 8.72E−1 |
| IBD                       | 10 4.54E−5                  | 4.99E−5  | 7.94E−5 | 3.50E−5 | 7.94E−5 |
|                           | 100 4.08E−2                 | 4.13E−2  | 6.67E−2 | 2.95E−2 | 6.67E−2 |
|                           | 1000 2.44E−1                | 2.72E−1  | 3.59E−1 | 2.00E−1 | 2.72E−1 |
| $^{12}\text{C}(\nu,\nu')^{12}\text{C}^{*}$ (15.11 MeV) | — 2.93E−2                  | 2.08E−2  | 3.71E−2 | 1.89E−2 | 2.08E−2 |
| $\nu^{^{12}\text{C}}$ MC single-like | 1  4.12E−2                  | 2.83E−2  | 4.94E−2 | 2.61E−2 | 4.94E−2 |
|                           | 10 4.62E−1                  | 3.25E−1  | 5.55E−1 | 3.04E−1 | 5.55E−1 |
|                           | 100 1.42E+0                 | 1.04E+0  | 1.70E+0 | 9.52E−1 | 1.70E+0 |
|                           | 1000 5.74E+0                | 4.40E+0  | 6.60E+0 | 4.06E+0 | 6.60E+0 |
| $\nu^{^{12}\text{C}}$ MC IBD-like | 10 4.35E−1                  | 3.10E−1  | 5.11E−1 | 2.82E−1 | 5.11E−1 |
|                           | 100 1.36E+0                 | 1.03E+0  | 1.63E+0 | 9.39E−1 | 1.63E+0 |
|                           | 1000 3.71E+0                | 2.95E+0  | 4.30E+0 | 2.68E+0 | 4.30E+0 |
5. Monte-Carlo simulation of neutrino carbon-12 reactions channels
Because of the large number of possible $\nu^{12}C$ reactions channels, GENIE Neutrino Monte-Carlo Generator (version 2.10) [11] was used. Samples of 2 millions neutrino interaction events were obtained for each experiment, and normalized by integrating flux times cross-sections, implemented in GENIE. Nuclear remnants, tagged by GENIE as “low energy hadronic blob”, were assumed as ground state nuclei, because there is no nuclear excitation and de-excitation implemented in GENIE.

Geant4 based Monte-Carlo generator as simple full sphere detector with scintillator material was written to track final state particles from GENIE output. Scintillation quenching was implemented by modifying G4EmSaturation using Birks’ law (1) with pre-calculated $dE/dx$ tables (by ESTAR [9] and SRIM [10]) for speed.

Obtained event rates are shown in table 2 for single-like and IBD-like event signatures. Single-like rates include delayed events from IBD-like for which energy of prompt event is below than 250 keV (see section 2).

6. Results
Table 2 shows expected event rates for all considered atmospheric neutrinos interaction reactions for 4 neutrino experiments in several visible energy ranges. Detection efficiency was assumed to be 100%.

Acknowledgments
This work was supported by RFBR grant 14-22-03031.

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