Cosmic muons measurements in the DANSS experiment

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Abstract. DANSS is a highly segmented detector, which contains 2500 one meter long plastic scintillator strips. The DANSS detector is placed under an industrial reactor of the Kalininskaya Nuclear Power Plant. The distance to the core is varied on-line from 10.7 to 12.7 m, and the primary task of the experiment is a search for short-distance neutrino oscillations. This work contains results of the cosmic muons study based on the data obtained with the DANSS detector. In order to achieve these results, the specific algorithm of muon track reconstruction with 97 % efficiency was developed. We also present some preliminary results on the annual variability in the flux of cosmic muons, an evaluation of the $<E_{\theta}, \cos \theta >$ parameter and the correlation coefficient.

1. Introduction
Study of the muon flow is an important subject for the DANSS experiment. Muons could induce backgrounds, like free neutrons or excited nuclei, caused by their interactions in the passive shielding or in the sensitive volume of the detector. To reduce the influence of these effects we should know the space distribution of cosmic muon flux. Besides this, muons are very useful for calibration, because they are flying through the whole detector all the time. Also, it is very interesting to measure the cosmic muon flux seasonal variation, due to the intermediate position of DANSS in terms of the overburden. There are three effects which influence on the cosmic muons intensity: a negative temperature effect, a positive temperature effect and a barometric effect [1]. The negative temperature effect corresponds to the decrease of the muon flux and relates to the fact that when the temperature grows, the atmosphere expands and more muons decay due to the increase of their way through the atmosphere. The barometric effect is caused by the variation of the atmospheric mass above the detector. The positive temperature effect is associated with the fact that higher temperature corresponds to less dense atmosphere and more mesons could fly through it till their decay giving a larger yield of muons. The negative temperature and barometric effects strongly affect low energy muons, and dominate at the ground level. But deep underground the flux consists only of high energy muons and the positive temperature effect starts to dominate. DANSS is located on the ground level, but directly under the reactor core, so the reactor cauldron, cooling pond, concrete and other materials give almost 50 m.w.e. of the overburden. It allows us to observe the combination of all effects.
2. The DANSS experiment

DANSS (Detector of the reactor AntiNeutrino based on Solid Scintillator) is a reactor experiment, and its main task is to search for short-range neutrino oscillations [2, 3]. A sketch of the experiment is shown in the figure 1.

The detector is a 1 m$^3$ cube which consists of 2500 plastic scintillator strips (1 × 4 × 100 cm$^3$) with a thin Gd-containing surface coating. It is surrounded by several layers of passive shielding: copper (5 cm), borated polyethylene (8 cm), lead (5 cm), borated polyethylene (8 cm), and muon active veto system from the 5 sides. The detector is located at Kalininskaya Nuclear Power Plant (57.9°N, 35.1°E) very close to the core of a 3.1 GW$_{th}$ industrial power reactor. It is installed on a lifting system, and typically stays in 3 positions: the up position (10.7 meters under the core), the middle position (11.7 meters under the core) and the down position (12.7 meters under the core), which are switched every several days. For the neutrino registration inverse $\beta$-decay is used: $\nu_e + p \rightarrow e^+ + n$, in which both the positron and the neutron are detected.

3. Muon data

Because of the reactor core we do not detect the hadronic component of the cosmic rays, so we could associate every straight track with a muon. First of all, the algorithm of track reconstruction was developed. To prove its efficiency, it was tested on Monte-Carlo data, with different zenith angles. As one could see from the figure 2, the minimal efficiency is above 97 % for all angles.
Using this algorithm muon angular distributions, shown in figures 3 and 4, were obtained. Smaller intensity for the detector positions closer to the core can be explained by the fact that the closer detector is to the reactor, the more solid angle is occupied by the core. But because of the complex distribution of the reactor infrastructure you could see an opposite situation near $\theta = 70^\circ$, where more muons are observed in the up position. Near azimuth angles $\varphi = 0^\circ, 90^\circ, 180^\circ$ and $270^\circ$ we have a pumping effect due to the fact that the strips in DANSS lie along these directions. With the exception of these areas the distribution on the $\varphi$ angle is close to uniform.

Figure 3. Histogram of the zenith angle. Angle $\theta$ is relative to the Earth plane. Red points are data in the down position, green points are data in the middle position, and blue points are data in the up position.

Figure 4. Histogram of the azimuth angle. Red points are data in the down position, blue points are data in the up position.

4. Seasonal variation of the cosmic muon flux

4.1. Cosmic muon intensity variation over time

Muons data are selected from October 2016 till September 2017. All the data are normalized to the middle position of the detector. The intensity of cosmic muons as a function of time is shown in figure 5. We fit it by a sinusoidal function with a fixed period. A sharp decrease of intensity
from the end of July till the end of August is strongly correlated with the reactor shutdown during this period of time, when about 8 m of water were added above the reactor core for the safe fuel rods transportation. As the fuel replacement procedure influences the overburden and thus the muon flux, we do not use data from this period in the further analysis.

**Figure 5.** Dependence of the cosmic muon intensity on time. Data starts from 01.10.2016, and ends on 27.09.2017. Solid line is the result of the fit.

4.2. **Muons threshold energy**

The correlation between temperature and the muon flux depends on the energy range of the original muons we select and thus on the amount of matter above the detector. An important parameter for the following estimates is the threshold energy $E_{\text{thr}}$. It is the minimum energy that a particle must have on the surface to reach the detector. Since $E_{\text{thr}}$ depends on the zenith angle, an averaged parameter $\langle E_{\text{thr}} \cos \vartheta \rangle$ is preferable. The averaging here occurs over the zenith angle $\vartheta$ which is the angle between the vertical direction and the muon track. The parameter $\langle E_{\text{thr}} \cos \vartheta \rangle$ is required for the effective temperature calculation and for the comparison of our results with models and other experiments. Due to the complex structure of the reactor building above the detector, we can not simply calculate it. So for the calculations of $E_{\text{thr}}$ as a function of zenith angle we took the theoretical prediction of the muon flux on the surface level [4]:

$$\frac{dI(\vartheta, \varphi, p)}{d\vartheta d\varphi dp} = \frac{18(p + 5)}{(p \cos \vartheta + 145)(p + 5 \sec \vartheta)(p + 2.7 \sec \vartheta)^{2.7}}.$$  

Having integrated this formula on the $\varphi$ angle, for every zenith angle $\vartheta$ we picked up such a value of the starting momentum that the theoretical integral flow is equal to the experimental flow. Results are shown in figure 6. Formula works fairly well for the angles $0^\circ \leq \vartheta \leq 85^\circ$, and momentum $1 \leq p \leq 10^5$ GeV/c, but at large angles a sharp unnatural increase is observed. This can be due to the bad sensitivity of DANSS to the horizontal muons. So for now, for $\langle E_{\text{thr}} \cos \vartheta \rangle$ calculations only the data in $0^\circ \leq \vartheta \leq 85^\circ$ range of zenith angles is used. After averaging over the zenith angle $\langle E_{\text{thr}} \cos \vartheta \rangle = 5.7 \pm 0.7$ GeV.
4.3. Correlation analysis

The atmospheric temperature profile data at DANSS location was taken from ERA-Interim database supplied by the European Centre for Medium-Range Weather Forecasts (ECMWF) [5]. These data contain temperature values at 37 pressure levels (from 1 hPa to 1000 hPa), four times per day (midnight, 6 a.m., noon and 6 p.m.). An effective $T_{\text{eff}}$ is the temperature that would cause the observed muon flux if all the atmosphere has the same temperature. It can be estimated as [6]:

$$T_{\text{eff}} = \frac{\int_0^\infty dX T(X)W(X)}{\int_0^\infty dX W(X)} \approx \frac{\sum_i \Delta X_i T(X_i)W(X_i)}{\sum_i \Delta X_i W(X_i)},$$

where $X$ is the atmospheric depth, $T$ is the temperature at this depth and $W(X)$ is the weight function which is sum of the pion weight function and the kaon weight function [7].

Using calculated data of the effective atmospheric temperature, we built a dependence of the relative muon rate variation of the relative effective temperature variation, which is shown in the figure 7. The value of the correlation coefficient is small negative $\alpha = -0.0391 \pm 0.0014$ and that means that the negative effects slightly prevails at our detector position. This could give us an opportunity to separate these effects and to study them one by one. Obvious blur of temperature dependence is likely connected with the barometric effect, which we are going to analyse in the near future.

5. Conclusion

A study of cosmic muons has been performed using the data from the DANSS experiment, which contain almost one year dataset. The algorithm of the cosmic muons selection and track reconstruction was developed with efficiency exceeding 97%. Using this algorithm angular distribution of cosmic muons was built. A seasonal correlation of cosmic muon flux was observed, with maximum of muon intensity at the end of the winter, and minimum at the end of the summer. The important result is the calculation of the parameter $<E_{\text{thr}} \cos \theta > = 5.7 \pm 0.7$ GeV. Though this result could be upgraded in the future, we already can calculate important values like effective atmospheric temperature and compare results on seasonal variations with the theory and other experiments. A preliminary value of the correlation coefficient was obtained using the data from the European Centre for Medium-Range Weather Forecasts: $\alpha = -0.0391 \pm 0.0014$. 

Figure 6. Threshold energy of muons for different zenith angles.
Figure 7. Correlation between the relative muon intensity variation and the relative effective atmospheric temperature variation. Red line is the result of the fit by linear function and gives the correlation coefficient.

This, close to zero, value means that the negative and the positive effects are comparable in magnitude in our case, so at the next step of our work could be in separating these effects.

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