DANSS Calibration With Michel Electrons

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DANSS experiment

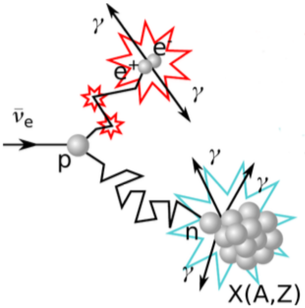
The number of active neutrino is limited to 3, but the existence of sterile ones is not excluded. There are some indications of their excistence (RAA, GA).

The DANSS experiment goal is the search for sterile neutrinos. Antineutrino oscillations to sterile neutrinos should change the antineutrino spectrum at different distances from the reactor core.

Antineutrino energy is determined by measuring energy of positrons produced in inversed beta decays (IBD).

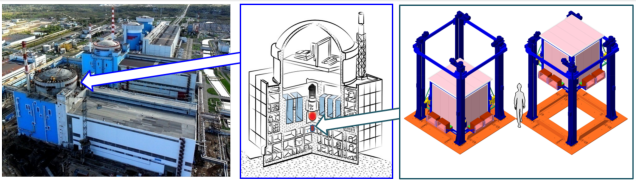
$$\overline{\nu}_e + p \to e^+ + n$$

$$E_{\overline{\nu}} \approx E_{e^+} + 1.8 \text{ MeV}$$

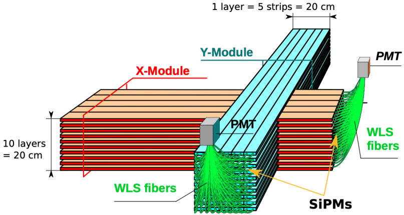


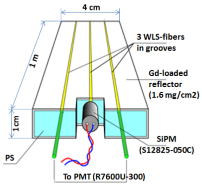
The detector energy scale is a key parameter for the experiment result.

DANSS experiment



The detector is installed on a movable platform under the reactor core at the Kalinin Nuclear Power Plant (KNPP). DANSS consists of 2500 scintillator strips arranged in 100 layers of 25 strips. The strips in the adjacent layers are orthogonal that allows 3D track reconstruction. Light from the strips is collected with wavelength shifting fibers read out with SiPMs and PMTs.

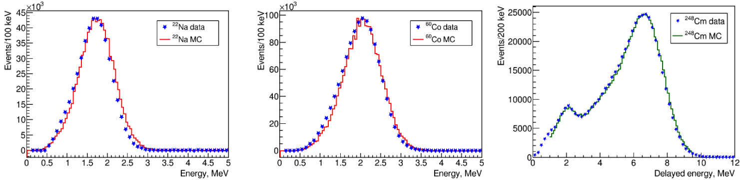




Calibration sources

- decays of ^{22}Na (3γ), ^{60}Co (2γ);
- captures of neutrons, produced by ^{248}Cm, on Gd;
- the main source: decay of ^{12}B, produced in the reaction $n +^{13} C \rightarrow p +^{12} B$.
  In ^{12}B decays there are no soft electrons. Therefore correction for the non-linearity of the response is small.

MC simulation spectrum requires the additional blur of $12\%/\sqrt{E} \oplus 4\%$. MC with energy scale fixed by ^{12}B slightly overestimates energies of ^{22}Na, ^{60}Co and ^{248}Cm sources (by 1.5%, 1.0% and 0.5% correspondingly). Most probably this is related to a non-perfect description of the low energy electron/photon detection in the simulation. The search for a new calibration source is extremely important for the experiment.



Comparison of measured and simulated source spectra: ^{22}Na (3γ), ^{60}Co (2γ), ^{248}Cm.

Processes caused by stopped muons

DANSS detects cosmic muons ($\sim 10^6$ per day). Some of them stop inside the detector ($\sim 2 \cdot 10^3$ per day).

Stopped muons could **decay** ($\approx 97\%$)

$$\mu^+ \to e^+ + \nu_e + \overline{\nu}_\mu; \qquad \mu^- \to e^- + \overline{\nu}_e + \nu_\mu$$

or **be captured** ($\approx 3\%$ mainly on carbon)

$$\mu^- + p \to n + \nu_\mu.$$

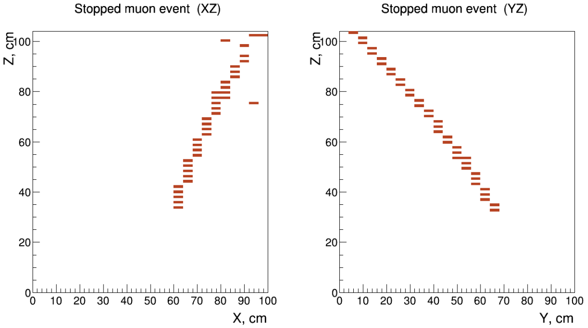
Mean muon lifetime: $\approx 2.2\ \mu s$.

DANSS registers e^- and e^+ produced in these processes, which have known spectra and can be used for the energy scale determination.

Search for stopped muons

- search for the lowest strip of the muon event (Z is considered);
- X, Y coordinates of the stopping point reconstruction by parameters of the previously built track line

If stopping point is on the boundary of the detector, the muon is considered as passing one.



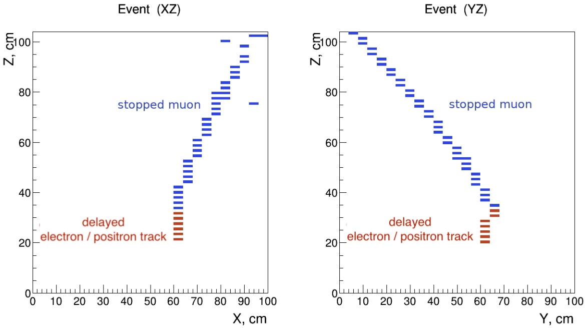
Example of stopped muon.

In the further analysis we consider muons stopped in the central part of the detector (cube with a side of 50 cm).

Decays of stopped muons selection criteria

- time span between the event and the muon stop is less than 8 μs (mean muon lifetime $\approx 2.2\ \mu s$);
- at least one strip close to the stop point responded;
- energy of each hit is less than 10 MeV (to avoid saturation effect in each channel)

We register $\approx 3.5 \cdot 10^3$ events per day in the central part of the detector.



Example of decay event.

Random coincidence rate is consistent with zero within errors.

The goal is to compare the energy spectrum of the selected events with the simulated one at different energy scales and blur correction coefficients.

Determination of muon lifetime

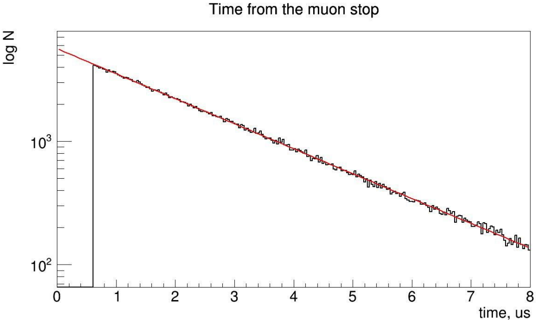
The distribution of time from the muon stops was fitted with the following function: $f(t) = p_0 + \exp(p_1 \cdot t + p_2)$.

Free muon lifetime (PDG): $2.196981 \pm 0.000002\ \mu s$

Measured muon lifetime (from fit parameter p_1): $2.150 \pm 0.007\ \mu s$

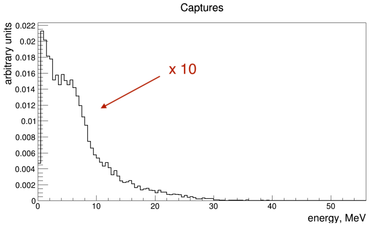
Expected muon lifetime ($\frac{\mu^-}{\mu^+}$ is taken into account): $\approx 2.131\ \mu s$

Measured muon lifetime is smaller than free muon life time because of captures and is close to the expected.



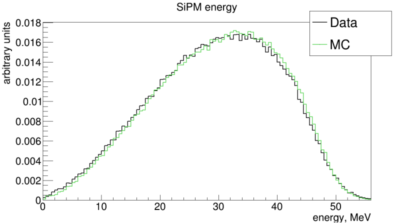
Distributions of time from the muon stops.

MC spectrum of captures



MC spectrum of captures.

Captures of stopped muons are hard to describe in modeling because of saturation effects.

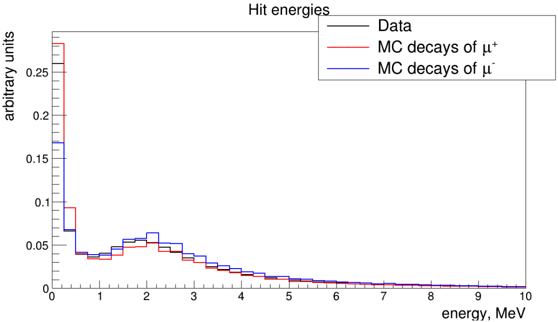


Measured spectrum of decays and captures and MC spectrum of decays.

For further analysis we use only **decay** spectra from the simulation. The comparison is carried out at high energies (≥ 20 MeV) where the contribution of captures is almost zero.

Hit energies

Energies of SiPMs in the selected events are similar to signal energies in positron events from IBD (target reaction of the experiment). Therefore for the further analysis all energy spectra are constructed by SiPM signals.
SiPM energies are less than 10 MeV to avoid saturation effect.

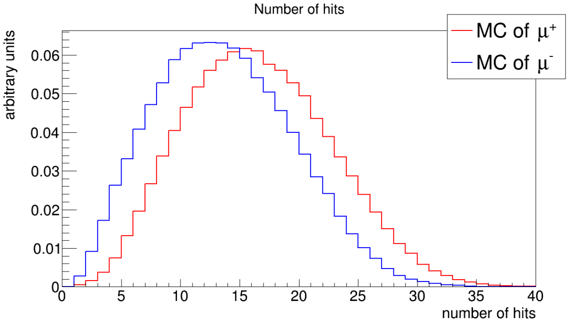


Energy distributions of SiPM signals
for experimantal data and simulated decays of μ^+ and μ^-.

Energy spectrum of decays

Energy spectrum of decays of negative and positive stopped muons are slightly different.

Positive muon spectrum is shifted to higher energies and has larger hit multiplicity than negative muon spectrum due to positrons annihilation. Negative muon spectrum has a less sharp decrease at high energies because of decays in orbit.

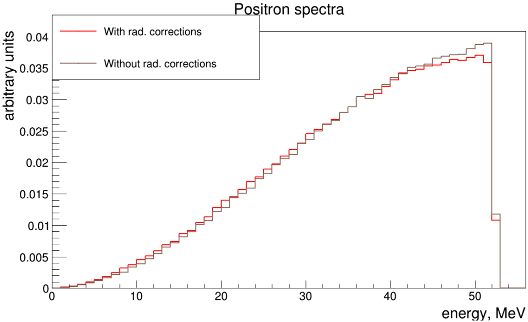


MC distributions of number of hits for μ^+, μ^-.

Energy spectrum of decays

Simulation requires taking into account radiative corrections. To correct positive muon spectrum formulas from the artcile *Radiative Corrections and Semileptonic B Decays*[1] were used.

Radiative corrections for negative muon spectrum have not yet been made. We expect that the corrections for negative muons change the final energy scale not significantly. Radiative corrections for positive muons change the scale by at most 0.3%.



Simulated energy spectra of positrons from stopped muon decays with radiative corrections and without radiative corrections.

[1] https://lib-extopc.kek.jp/preprints/PDF/1990/9003/9003317.pdf

Comparison with MC simulation

Comparison procedure:

- the measured energy spectrum is scaled with an additional coefficient c;
- the spectrum from the simulation is blurred;
- these spectra are compared for different calibration and blur coefficients

The blur is set by a non-stochastic coefficient b and a stochastic coefficient a and added to the simulation according to the formula for relative resolution

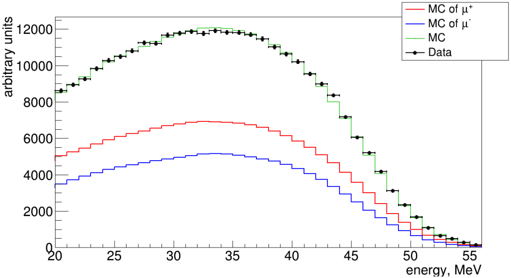
$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b.$$

By default, one free parameter is considered - normalization of the total MC spetrum of decays. The ratio μ^-/μ^+ is fixed to the ratio on the surface, taking into account the passage through the matter to the experimental setup.

Comparison with MC simulation

Non-stochastic blur coefficient is fixed to the optimal for other calibrations: $b = 4\%$. Energy scale correction coefficient c and stochastic blur coefficient a were found by grid search.

Optimal coefficients (after averaging over different periods of data acquisition): $a = 3.1\%,\ b = 4\%,\ c = 101.5\%$.



Spectra for optimal coefficients. μ^+ and μ^- decay histograms are summed up to the total MC spectrum. Data is perfectly described by the MC simulation ($\chi^2/\mathrm{NDF} = 0.94$).

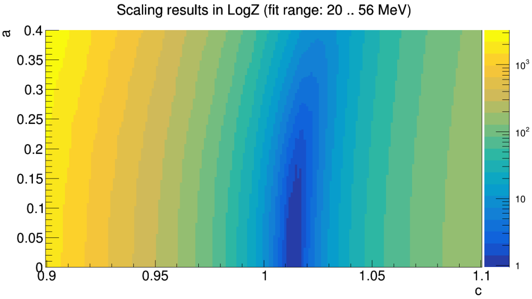
The determined energy scale is 1.5% lower than the scale from ^{12}B decays. Most probably this is due to saturation effects for many soft gammas/electrons produced in positron annihilation.

Comparison with MC simulation

Non-stochastic blur coefficient is fixed to the optimal for other calibrations: $b = 4\%$.

χ^2/NDF increases sharply with the distance from the optimal point in coordinates (c, a). p-value is smaller than 0.05 outside the rectangular area 0.04×0.16 around the optimal values.

Therefore, the detector energy scale is determined with a high accuracy of about 0.2% in 50 days.



χ^2/NDF for different pairs c, a (logarithmic scale).

Study of systematics and the final result

The following systematics were considered:

- limits for energies of SiPM signals in selected decay events ($\leq$ 10 MeV, $\leq$ 9 MeV, $\leq$ 8 MeV);
- dead channel map overlaid on the simulation (coinciding with the map according to experimental data or averaged map);
- number of free parameters of the comparison (1: normalization of the total MC decay spectrum, 2: normalization of the total MC decay spectrum and ratio μ^-/μ^+ in the simulation);
- energy ranges of the comparison (20..56 MeV, 20..48 MeV, 24..56 MeV);
- different periods of data acquisition.

While studying systematics, the energy scale correction coefficient remained constant within $\pm$0.5%, while the stochastic blur coefficient varied more strongly and took values from the range 0% - 18%.

The energy scale is determined with a high statistical accuracy.

Since number of detected Michel electrons is large the stability of the detector energy scale with time can be tested by this method.