# $^{144}$Ce – $^{144}$Pr beta-spectra measurement and MC study of sterile neutrino search with an LS detector

PNPI LBML group

Oct 3, 2019

# Project SOX:
# Short baseline Oscillations with BoreXino.

## Searches for neutrino oscillation to the sterile state

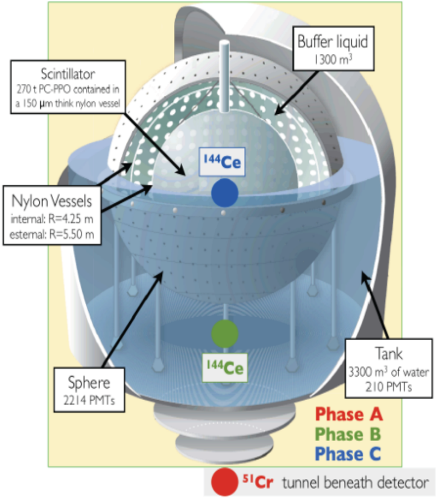
# Project SOX: Short distance Oscillations with BoreXino

***SOX: JHEP 08 (2013) 038; arXiv:1304.7721***

**Neutrino sources in Bx:**
1) To calibrate the energy scale and efficiency of the Bx
2) To search for neutrino magnetic moment

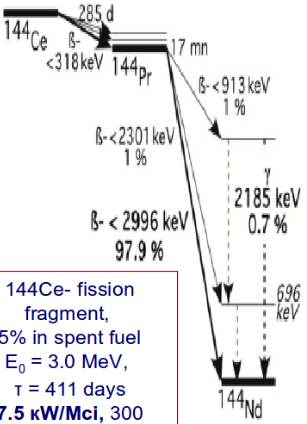
**BX is the best for 1 eV Sterile neutrino searches:**
1) Space resolution is **14 cm at 1 MeV**
2) Energy resolution is **5% at 1 MeV**

Two methods to search for oscillation effect
1) To use absolute count rate of IBD reaction
2) To measure the positron spectra vs distance

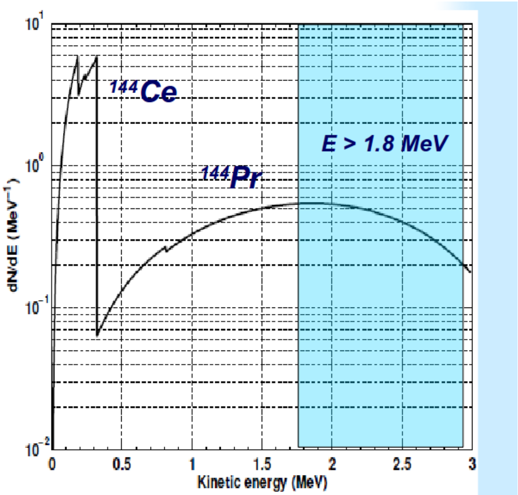



*Three kinds of experiment with neutrino sources was considered*

# First stage with $^{144}Ce$ – $^{144}Pr$ antineutrino source




144Ce- fission fragment,
5% in spent fuel
$E_0$ = 3.0 MeV,
τ = 411 days
**7.5 кW/Mci**, 300 g/MCi
**3 PBq - 0.6 kW**

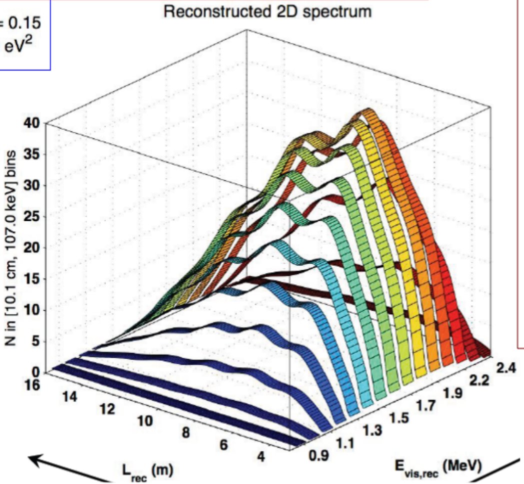



*The maximum neutrino energy for $^{144}Ce$ is 318 keV, for $^{144}Pr$ it is 3.0 MeV. The inverse beta decay reaction threshold is 1.8 MeV.*

# Expected count rate of IBD vs Distance and Energy

$$\mathcal{P}(\theta, \Delta m^2, L, E) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 \frac{L}{E})$$

$\sin^2(2\theta) = 0.15$
$\Delta m^2 = 2\ eV^2$




***100 κCi $^{144}$Ce***

***8.5 m from Bx center.***

***1.5 y data taking.***

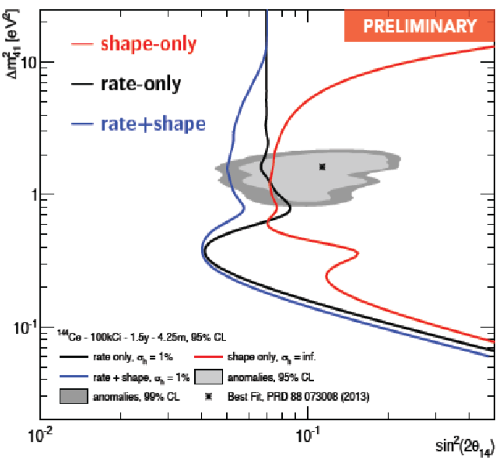
***$10^4$ events of IBD.***

***$\sigma_E$ = 5% (1 MeV).***

***$\sigma_R$ = 15 cm (1 MeV)***

***Background = 0***

# Sensitivity of SOX-Ce to oscillation parameters




**100 кCi at 8.5 m from Bx center 1.5 y data taking**

*Measurement of **Shape**(R,Ev)*

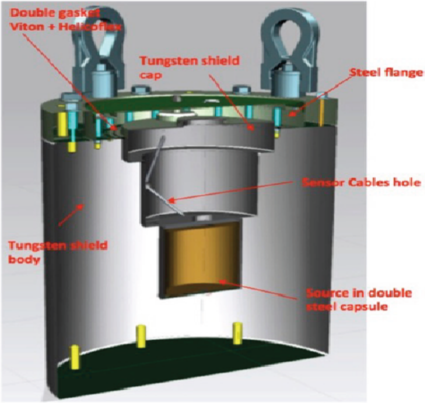
1. *Smoking-gun*
2. *Sensitive to $\delta m^2 \approx 0.5$ -5 эВ²*
3. *High energy and space resolution are needed*
4. *Sensitivity is determined by statistics.*

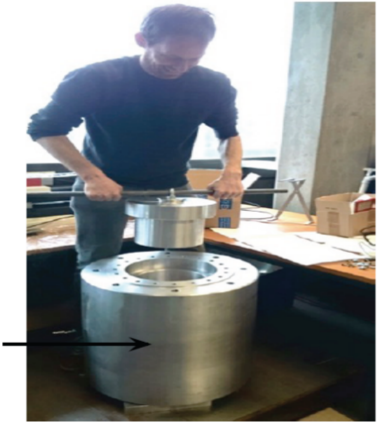
***Rate + Shape***

1. *Improved sensitivity compared to shape only*
2. *Sensitive to dm² > 5 eV²*
3. *Precise measurements of heat dissipation and power to activity conversion are needed.*
4. *Systematic errors are important for energy and spatial reconstructions and the effectiveness of the IBD reaction*

*Many tasks has been done during preparing the project. Mention only 2 points that can be used in the future – passive shielding an calorimeters.*

# Tungsten container

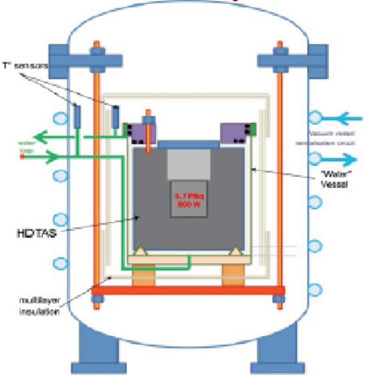


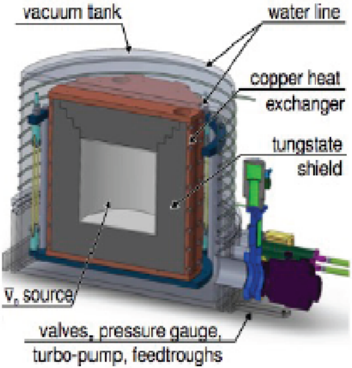
*The largest tungsten compound shielding in the world. The cylinder is 60 cm high and 60 cm in diameter. Thickness is 19 cm. Weight is 2.3 tons. The dimensions are determined by 144Pr gamma-line with an energy of 2.185 keV (BR = 0.7%), which must be suppressed $10^{12}$ times and by the size of the hole (1 m) under Borexino. The expected temperature inside is 500 ° C, on the surface 80 ° C.*

# Two calorimeters

**CEA- Sacley**




**TUM / Genova**




*Expected 216 W / $10^{15}$ Bq or 800 W at the beginning of measurements. The flow and temperature of the water at the inlet and outlet will be measured. Pdt = CdMdT + Leak. The challenge is to minimize heat leakage. Thermal conductivity (bridges). Convection (vacuum). Radiation (screens). Thermal power measurements with accuracy <0.5%. Transfer into activity A = P / <E> (average energy release per decay). High requirements for third-party γ- and α-activity.*

# Tasks of PNPI group

- Measurements $^{144}$Ce – $^{144}$Pr beta-spectrum for the purpose of determinating the antineutrino spectrum
  - Target-detector scheme
  - 4-$\pi$ detector scheme
  - Corrections to the shape of $^{144}$Ce – $^{144}$Pr beta spectrum
- MC simulations of the experiment
  - Sensitivity to oscillation parameters:
    - vs different LS detectors forms
    - vs Energy resolution
    - vs Detector mass
  - Backgrounds – neutrons ($^{244}$Cm) and natural radioactivity
  - Prompt and delay spectra
  - Other reactions for study

# Measurement of $^{144}Ce - {}^{144}Pr$ beta-spectra for the purpose of $\tilde{\nu}_e$ spectrum determination.

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# Decay schemes of $^{144}$Ce – $^{144}$Pr

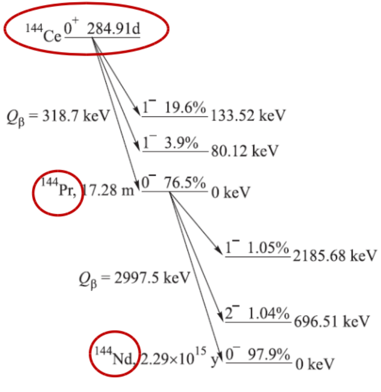



**Fig. 1.** Scheme of the $^{144}$Ce → $^{144}$Pr → $^{144}$Nd decays.

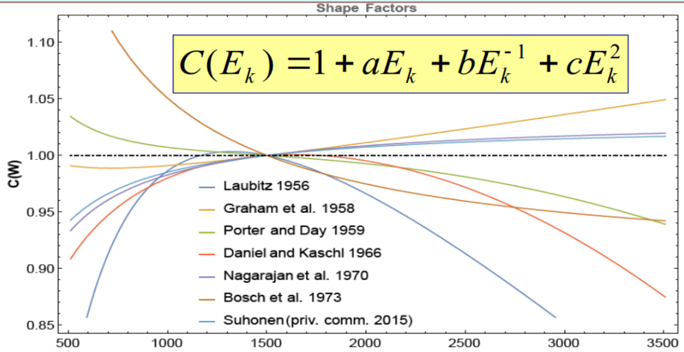
$^{144}$Ce – fission fragment,
5% in spent fuel
$E_0$ = 3.0 MeV, τ = 411 days
**7.5 кW/MCi,** 300 g/MCi
**3 PBq - 0.6 kW**
Mayak

| $Q_\beta$ $^{144}$Ce | $Q_\beta$ $^{144}$Pr | γ $^{144}$Ce | γ $^{144}$Pr |
|---|---|---|---|
| 318.7(76.5%) | 2997.5(97.9 %) | 133.5(11.1%) | 696.5(1.3%) |
| 185.2(19.6%) | 2301.0(1.04 %) | 80.1(1.36%) | 2185.7(0.69 %) |
| 238.6(3.9%) | 811.8(1.05%) | 41.0(0.26%) | 1489.1(0.28 %) |

*The $^{144}$Ce nucleus undergoes three nonunique first-order forbidden beta transitions to the ground and excited levels of the $^{144}$Pr nucleus. Decays of the $^{144}$Pr nucleus to the ground and first excited states of the $^{144}$Nd nucleus correspond to nonunique and unique first-order forbidden transitions, respectively. Decay into the 1–level with an energy of 2185 keV is an allowed transition.*

# Previous measurements of $^{144}Ce - {}^{144}Pr$ $\beta$-spectra

$$S(E_e, E_0, m_\nu) \propto P_e E_e (E_0 - E_e)^2 F(E_e, Z) C(E_k)$$

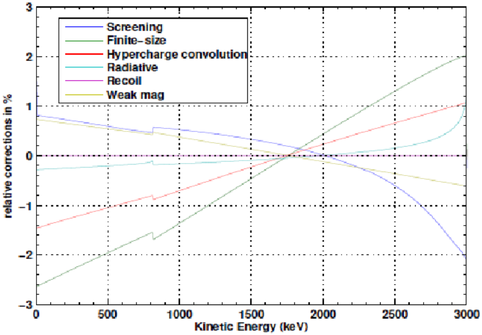



*Several measurements of the beta spectrum of $^{144}Pr$ have been performed since 1956. The measurement results are not very consistent with each other. The approximation of 144Pr b-spectra require a shape factor. The figure shows the shape factor measured by several authors. They are normalized such that they are equal to 1 at 1.5 MeV. One can see that difference can reach 25%. It is important that the shape of the spectrum affects the average energy value, the determination of source activity and the expected rate of inverse beta-decay.*

# Corrections to the Fermi function of $^{144}Ce - {}^{144}Pr$

arXiv:1312.0896v2 13 Apr 2014

$$N(E)dp = Kp^2(E-E_0)^2F(Z,E)\ L_0(E,Z)\ C(E,Z)\ R(E,M)\ G(E,Z)\ S(Z,E)\ B(E,Z)dp;$$




$L_0(E,Z)$ and $C(E,Z)$ - finite size and mass of the nucleus for e.m. and weak interactions

$R(E,M)$ - recoil effect on the phase space factor

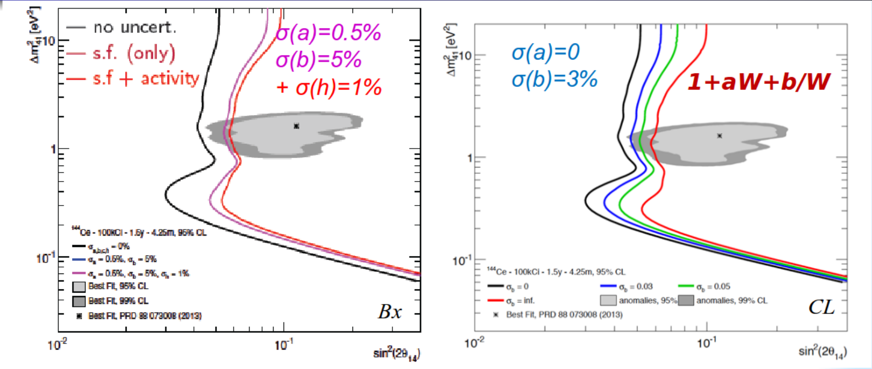
$G(E,Z)$ - radiative corrections

$S(Z,E)$ - screening of beta particle by atomic electrons

$B(E,Z)$ - weak magnetism correction

*Fermi spectrum needs to be corrected for various atomic and nucleus effects. All corrective terms have the structure 1+δ(E,Z,M). These terms represent up to a few percent correction to the Fermi spectrum. Figure compares the relative weights of each corrections. The* $^{144}$*Pr spectrum exhibits two discontinuities at 800 keV and 2300 keV, which are the end point energies of the branches with intensities of 1% .*

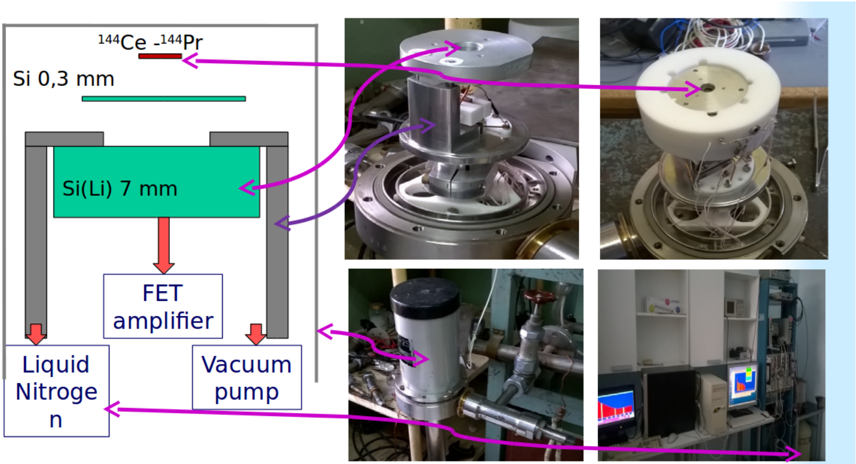
# Impact of $^{144}$Pr Shape Factor uncertainty on $\Delta m^2$ and $sin^2(2\theta_{14})$




*The shape factor for nonunique first order forbidden transition 1 + a W + b / W have to be measured with accuracy better than 2-3%*

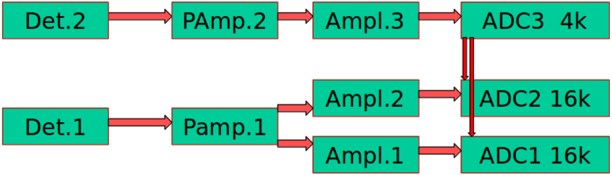
*The shape of 144Pr beta-spectrum has a significant effect on the precision of determining of oscillation parameters for sterile neutrino. Precision measurements of 144Pr beta spectra are needed to achieve high (<1%) accuracy for the coefficient linking thermal power and activity, and for the expected rate of IBD reaction.*

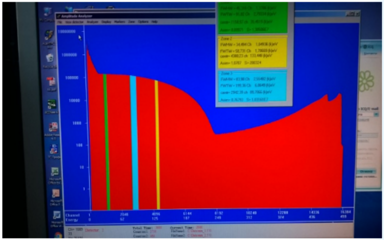
# Beta-spectrometer with Si-detectors




*At first stage, we used the target-detector circuit. The $^{144}$Ce source 6 mm in diameter with an activity 7 kBq was deposited on the 20 μm mylar film by an evaporation. The thickness of the sources was less then 1 mg /cm$^2$. The detector had a diameter of 16 mm and a thickness of 7 mm. The thickness of the insensitive layer did not exceed 4700 A.*

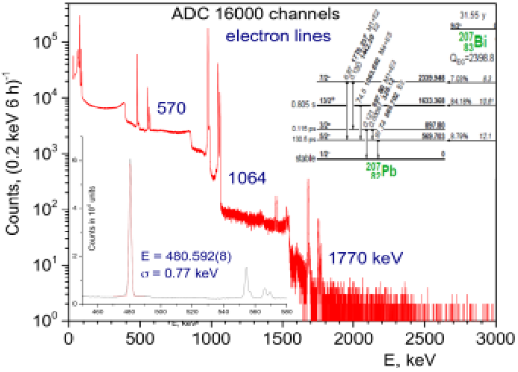
# Electronics and DAQ system

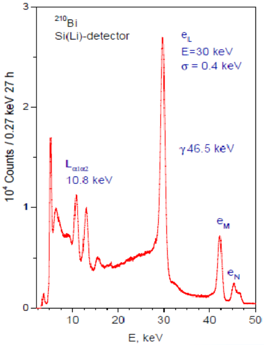


*The Si(Li)-detector has two spectrometric channels: a preamplifier with resistive feedback, an amplifier with a time constant 2 μs and 14-bit (16 000 channels) ADC. Fist ADC measures the spectrum up to 0.5 MeV energy and the second one – up to 6 MeV. The low threshold of detected energy is 5 keV. The energy resolution measured with γ lines of $^{241}$Am is FWHM= 1.1 keV. Two 16k ch spectra were stored in the computer memory.*

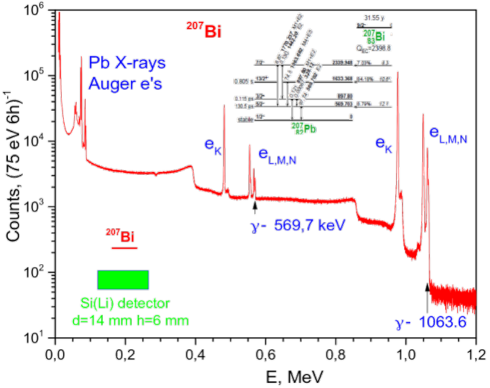
# Si(Li) detector response function

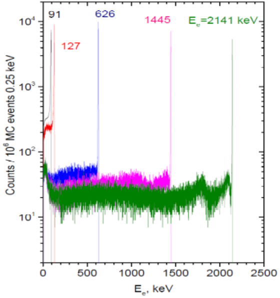



*The spectrum of $^{207}$Bi source measured with the Si(Li) detector in energy range of (0.01–3.0) MeV. The corresponding peaks of the conversion electrons form K-, L- and M-shells are clearly visible in the spectrum. The electron energy resolution determined via 480 keV line is 0.8 keV. The right figure show the electron peaks corresponding to internal conversion of 46.5 keV nuclear level of $^{210}$Bi.*

# $^{207}$Bi spectrum in the 0 – 1200 keV range

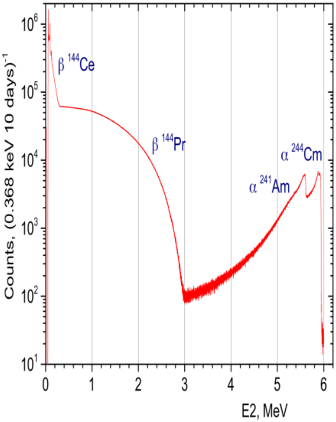


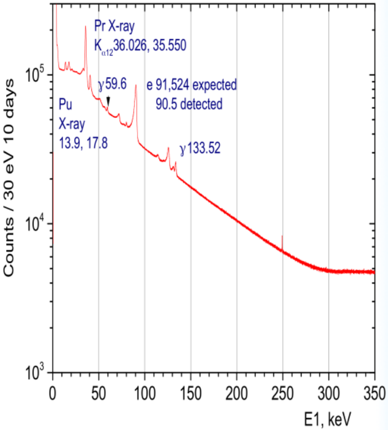




*Monte-Carlo simulation of monochromatic 91 – 2141 keV electrons*

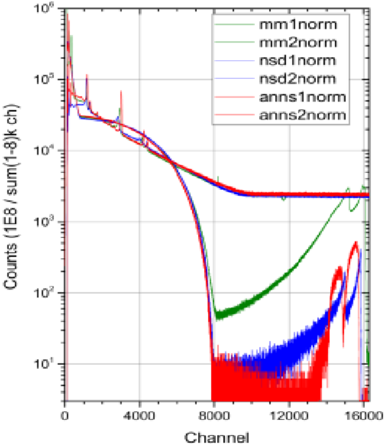
*The reliability of restoring the neutrino spectrum depends on how well the response function of the detector is known. To study the responce function the measured spectrum of $^{207}$Bi was compared with Monte Carlo simulation with Geant 4. Two main effects - backscattering and bremsstrahlung - lead to the appearance of the tail and to the deviation of the response function from the Gaussian shape.*

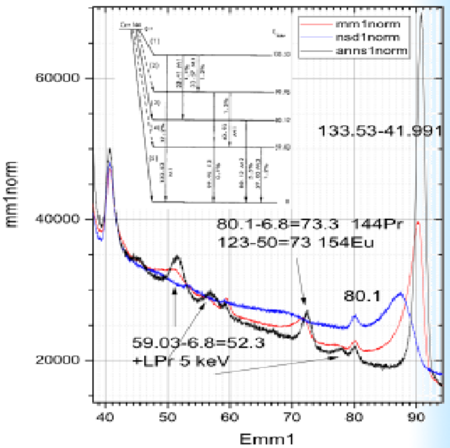
# $^{144}Ce$ – $^{144}Pr$ beta-spectra



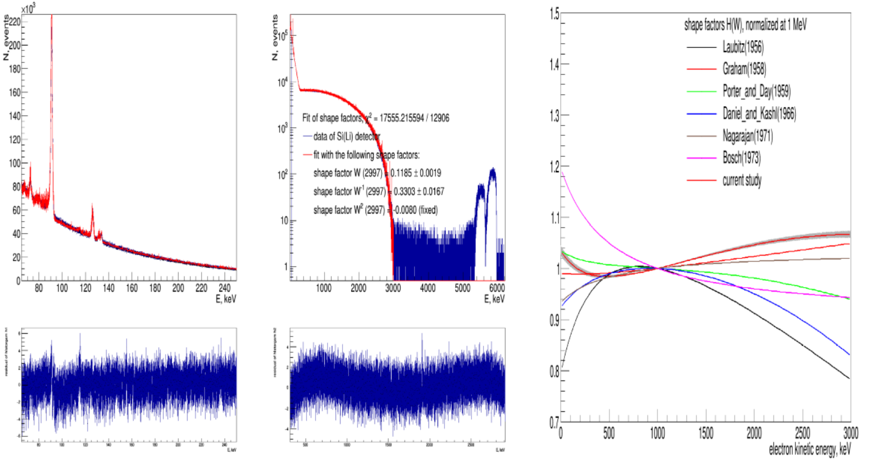
# Response functions in "target-detector" scheme



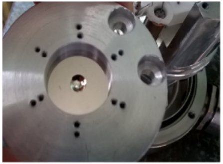

*The response functions of the beta spectrometer for a- and b-particle in the "target-detector" scheme depends on the method of preparation of the target. On the left is the response for alpha particles, on the right - for low energy electrons. The real problem is backscattering of electrons.*

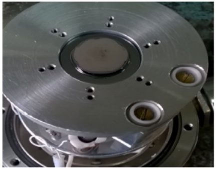
# Fit results and shape factor for "target-detector" scheme




*A complex response function for electrons requires the use of three parameters in the shape factor to fit with an acceptable chi square.*

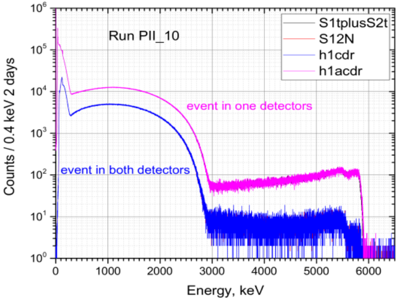
# 4-$\pi$ beta-spectrometer

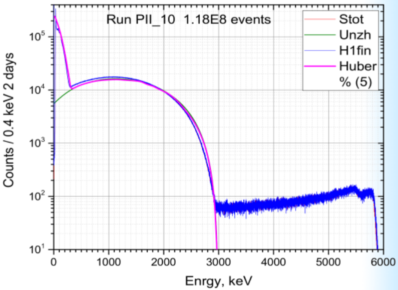


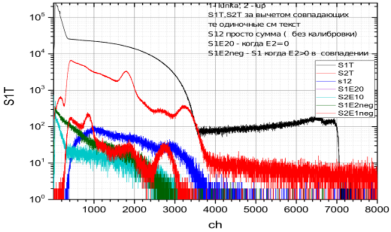


*To solve the problem of backscattering 4pi-spectrometer was produced. Spectrometer register backscattering electrons and the RF is close to Gaussian. In center of detector small hole was polished into which 144Ce-144Pr source is applied. The detector with the hole is covered by the upper detector. In order to study transitions to excited states of daughter nuclei an additional 4 inches BGO detector was included in the coincidence with silicon detectors.*

# Spectra of Si(Li) and BGO in coincidence – anticoincidence

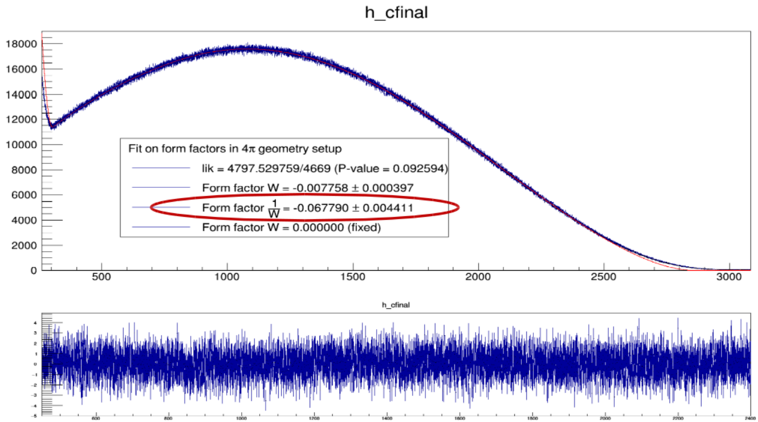


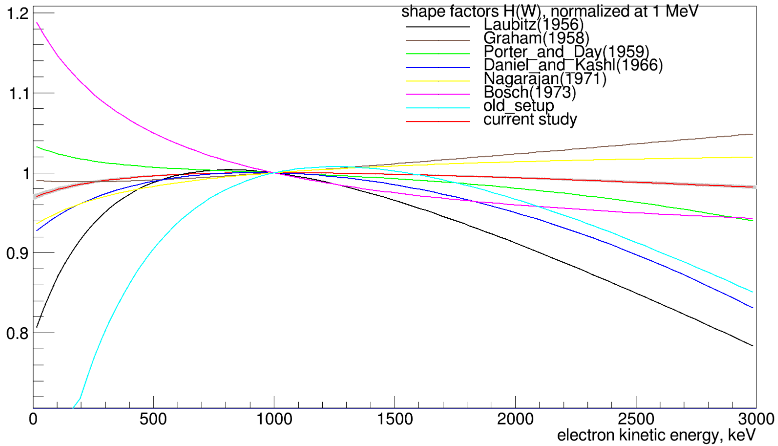

*4-pi spectrometer with Gaussian response function practically solves the problem of the neutrino spectrum, for Ee > 320 keV, Ev = 3 MeV - Ee. Of course, 1% branching ratios for transitions to the exited states have be taken into account. To extract the 144Pr spectra below 320 keV one have to calculate corrections and shape factors for 144Pr and 144Ce.*

# Preliminary fit results for $1.6 \times 10^8$ statistics




*The task of measuring the beta spectra of 144Pr nuclei for Ee > 320 keV and, accordingly, the spectrum of electronic antineutrinos, with an accuracy of 1% in the value of parameter b at (1/W) has been practically fulfilled. The tasks to be performed are the accurate accounting of bremsstrahlung, refinement of corrections and comparison with results of other experiments and results obtained with the target-detector scheme.*

# Shape factor 1 - (0.007±0.004)W - (0.068±0.004)$W^{-1}$



# MC study: introduction

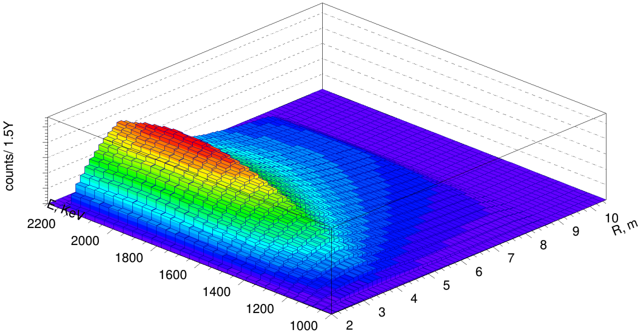
The study is devoted to production of a procedure allowing to estimate sensitivity of a dedicated detector for sterile neutrino search with a $^{144}Ce - ^{144}Pr$ source. The study includes estimates of various background effects, resolutions and source quality and their affection on final sensitivity to sterile neutrino mixing parameters. Uncertainties caused by $^{144}Ce - ^{144}Pr$ will be accounted in future studies.

# Sensitivity study approach

The sensitivity study includes the stages of

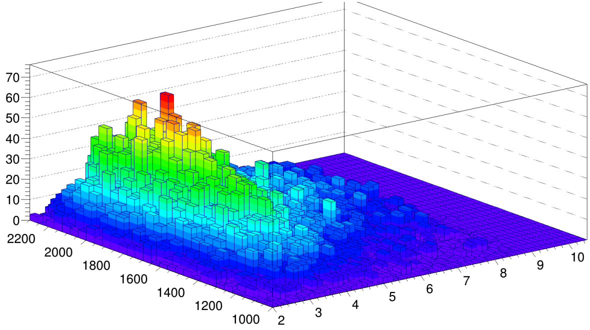
- Two-stage MC simulation: neutrino simulation and inverse beta-decay products energy deposit
- Implementation of 1000 real statistics datasets, where the total datasets is used as a reference
- $\chi^2$-based study of the sensitivity to sterile neutrino mixing for each dataset
- construction of averaged sensitivity contours and statistical jitter scale

# Spectrum of positron signal




Spectrum in 100t cylindrical detector with 100 MCi source
1.5 years (2 m from source), 20 M events

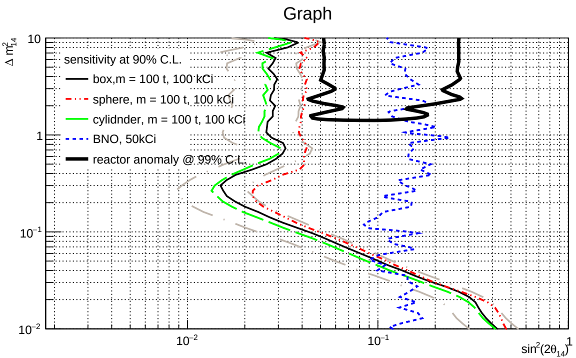
# Spectrum of positron signal




Spectrum in 100t cylindrical detector with 100 kCi source 1.5 years (2 m from source), 20 k events

# Geometry selection

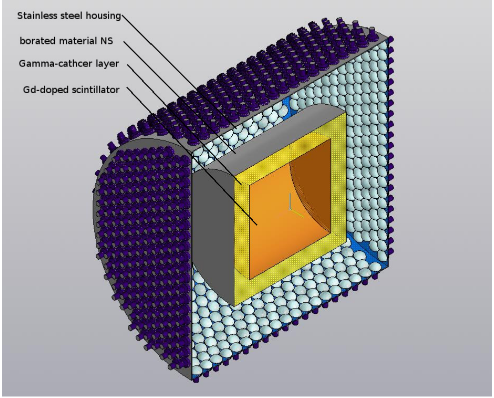
The study was performed for 4 kinds of detector geometry




Energy resolution of 5% at 1 MeV, 15 cm of positional resolution. Neutron shield of 2 m.

Dashed lines show statistical jitter scale for cylindrical geometry

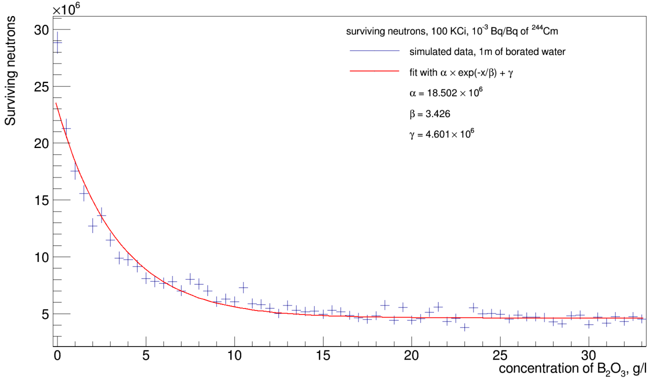
# what it may look like ("pushed" setup)




Total number of 12" PMTs is 2186. Coverage of 83.6 %, with QE of 0.4 and LY of $10^4$ $MeV^{-1}$ giving 2000 p.e. at 1 MeV Positioning of the source not considered yet and will probably decrease the coverage.

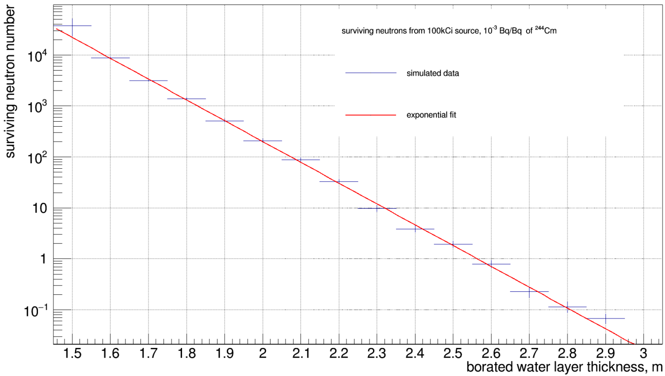
# neutron background

Neutron shield effectiveness was calculated for 1m layer of borated water (with $B_2O_3$ dissolved). The simulation was considering real geometry and Watt fission spectrum.



# neutron background

Neutron shield minimal thickness is around 2m, could be reduced to 1.5 m in case of $10^{-5}$ g/g of $^{244}$Cm contamination



# accidental coincidence contribution

Natural radioactivity from internal sources

| Elements | Radioactivity in ROI (sphere r=1m), Bq | | Number of random coincidence for full exposure | |
|---|---|---|---|---|
| | Acrilyc | Scintillator | Acrilyc | Scintillator |
| $^{40}K$ | 0.25 | - | 1 | - |
| $^{238}U$ | 0.09 | $4.11\times10^{-7}$ | 0.36 | $1.64\times10^{-6}$ |
| $^{232}Th$ | 0.06 | $1.34\times10^{-10}$ | 0.24 | $5.36\times10^{-10}$ |

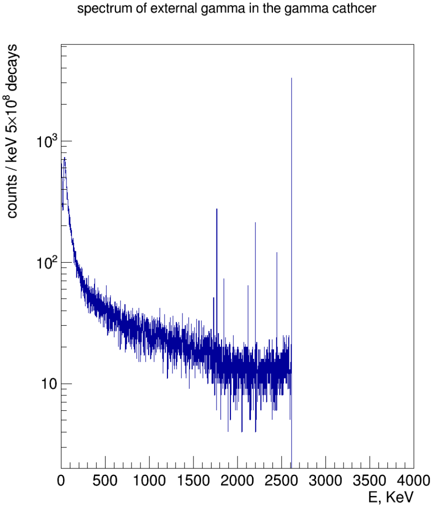
Radioactivity in solid materials

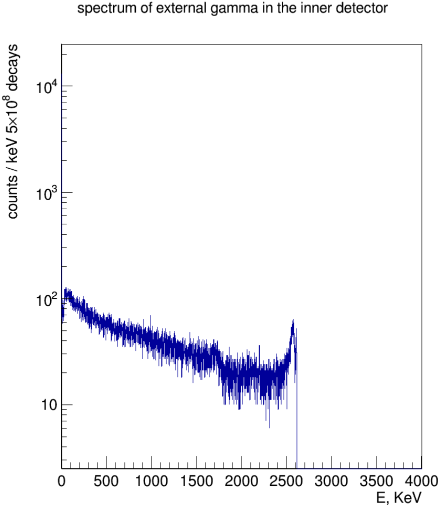
| Elements | Concentration, g/g | | | Mass of the detector components, kg | | |
|---|---|---|---|---|---|---|
| | Acrilyc | Steel | Scintillator | Acrilyc (max. in ROI) | Steel | Scintillator |
| $^{40}K$ | $1.3\times10^{-11}$ | $10^{-9}$ | - | 75 | 16418 | 3309 |
| $^{238}U$ | $0.1\times10^{-9}$ | $10^{-8}$ | $10^{-17}$ | | | |
| $^{232}Th$ | $0.2\times10^{-9}$ | $10^{-8}$ | $10^{-20}$ | | | |

External Gamma-backgrounds

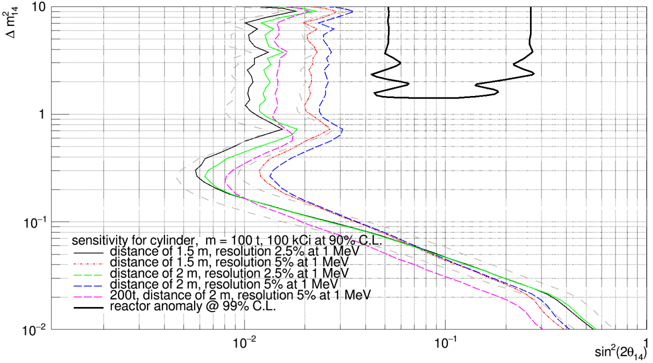
| Components | | Contamination | Activity, Bq | Count rate in the ROI, $s^{-1}$ | Expected RC |
|---|---|---|---|---|---|
| Steel | $^{40}K$ | $1.3\times10^{-11}$g/g | 82 | 0.02 | 0.08 |
| | $^{238}U$ | $0.1\times10^{-9}$g/g | 2946 | 0.59 | 2.36 |
| | $^{232}Th$ | $0.2\times10^{-9}$g/g | 964 | 0.19 | 0.76 |
| PMT | $^{40}K$ | 7.5 $\mu g$/PMT | 4351 | 0.87 | 3.48 |
| | $^{238}U$ | 112 $\mu g$/PMT | 3045 | 0.61 | 2.44 |
| | $^{232}Th$ | 50 $\mu g$/PMT | 445 | 0.09 | 0.36 |

# External gamma-background spectra



# influence of the source placement, detector resolution and mass




Comparison shown for cylindrical geometry.

Dashed lines show statistical jitter for the case of 2 m and 100 t shield with 2.5% resolution at 1 MeV

# conclusions

- A package allowing estimation setup sensitivity to sterile neutrino oscillation parameters is implemented
- Neutron background estimation was performed and could provide optimal size of neutron shielding
- Natural radioactivity backgrounds could be estimated to be low enough to be statistically insignificant at the current stage

Thank You for Your attention