NATIONAL RESEARCH CENTER
"KURCHATOV INSTITUTE"

Petersburg Nuclear Physics Institute
named by B.P. Konstantinov

ЯДРО 2025

The precision measurement of the electron anti-neutrino spectrum in beta-decay of ^{144}Ce- ^{144}Pr nuclei

A.V. Derbin, I .S. Drachnev, I.M. Kotina, I.S. Lomskaya, V.N. Muratova, N.V. Niyazova, D.A. Semenov, M.V. Trushin, E.V. Unzhakov

Jul 03, 2025

Motivations for the measurement

- Situation with hypothetic sterile neutrino
- Advantages of ^{144}Pr antineutrino source
- Previous knowledge of the spectral shape for ^{144}Pr

Beta-spectrometry of ^{144}Ce – ^{144}Pr

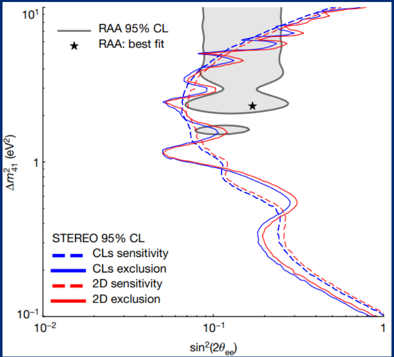
- Description of a beta-spectrum
- Target-detector spectrometer
- 4π semiconductor spectrometer

The neutrino spectrum

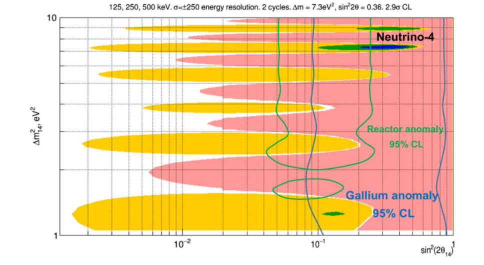
- evaluated neutrino spectrum
- The spectrum interpolation
- Estimate of the final precision

Conclusions

Situation with hypothetic sterile neutrino

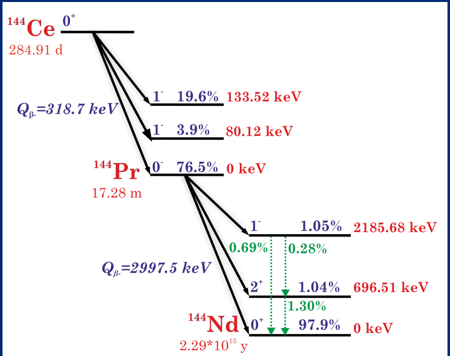


The STEREO experiment sets new limits on sterile neutrino parameters



Same time the Neutrino-4 and BEST experiments suggest existence of sterile neutrino with parameters in the excluded region. This conflict has to be resolved, perfectly with another type of experiment, e.g. radiochemical!

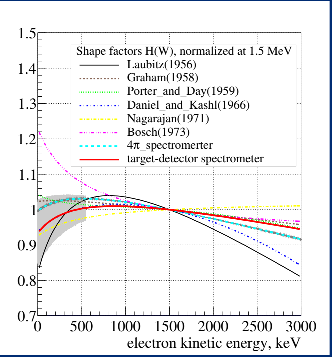
Properties of ^{144}Pr antineutrino source



Decay scheme of ^{144}Ce – ^{144}Pr

- The antineutrino could be identified by its signature in hydrogen-containing detectors
- The GS transition in ^{144}Pr has the endpoint energy of 3 MeV, whilst the IBD cross section grows with neutrino energy.
- The halflife of ^{144}Ce is 285 days, that suits the technical issues of a possible experiment

^{144}Pr beta-spectrum measurements before our study



Shape-factor of ^{144}Pr GS tranition according to various studies

The shape factor of the GS transition for ^{144}Pr was previously quite undefined. That was a reason for significant systematic uncertainties of a perspective sterile neutrino experiment.
e.g. as for a planned Borexino-SOX experiment the estimate of spectrum-related systematic uncertainty was estimated as large as 5 %

Description of a beta-spectrum

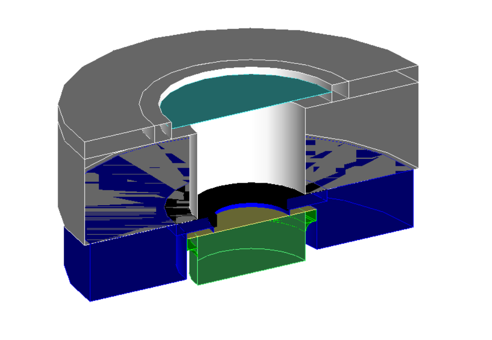
A generic Beta-spectrum could be descibed as

$$S(W) = PW(W - W_0)^2 F(W,Z) H(W,Z),$$

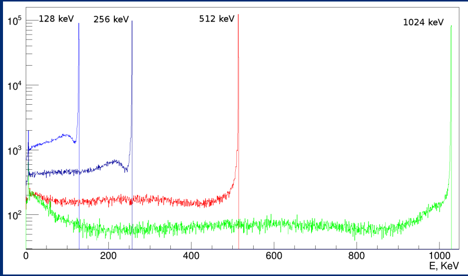
Where

- $PW(W - W_0)^2$- phase space
- H(W,Z) - nuclear shape factor, the subject of our experimental study; We use an empiric model after Laubitz (1956): $H(W) = 1 + P_1 W + P_2 W^{-1}$
- $F(W,Z) = F_0(Z,W) L_0(Z,W) C(Z,W) S(Z,W) G_\beta(Z,W)(1 - \delta_{WM} W)$. - Fermi function with corrections
  - $F_0(Z,W)$ - function for point nucleus
  - $L_0(Z,W)$ - electromagnetic finite size correction
  - $C(Z,W)$ - weak finite size correction
  - $S(Z,W)$ - screening correction
  - $G_\beta(Z,W)$ - radiative correction
  - $(1 - \delta_{WM} W)$ - weak magnetism correction

Target-detector spectrometer construction

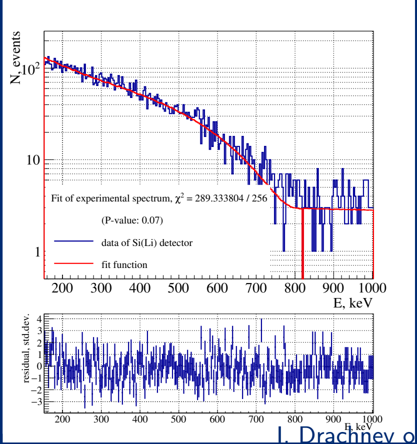


The spectometer construction



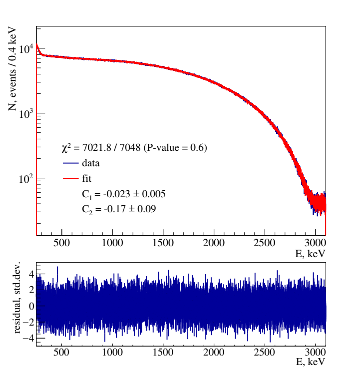
The spectrometer response. one should note a significant fraction of backscattered electrons

Target-detector spectrometer allowed beta-spectrum fit



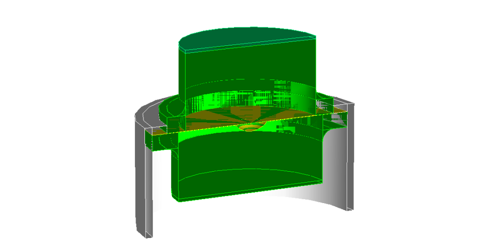
- The quality of the response function was tested with allowed transition fit
- The allowed transition events were selected through coincidences with gamma-line 2185 keV detected with a high-efficiency 2.5 kg BGO scintillator
- The evaluated shape factor shows statistical agreement with unity expected for an allowed transition

Target-detector spectrometer beta-spectrum fit

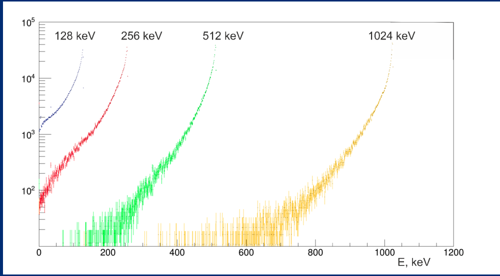


- The data were collected for 2048 hours
- Due to low activity of the source (aged source) the background was excluded bu division the dataset into two equal parts and fitting the first part with the second one summed with the beta-spectrum
- The beta-spectrum was described as a convolution of the theoretical beta-spectrum and MC response.
- The shape of the beta-spectrum could be also used for sterile neutrino mixing search, see poster 181 on Jul 2, 2025

4π semiconductor spectrometer construction

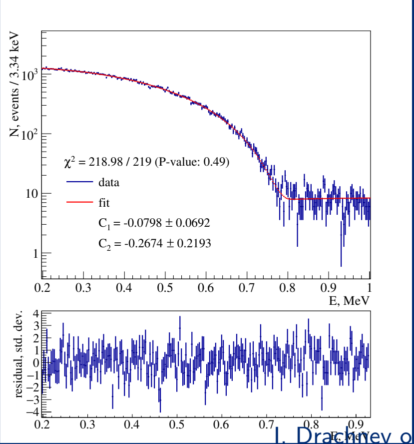


The spectometer construction



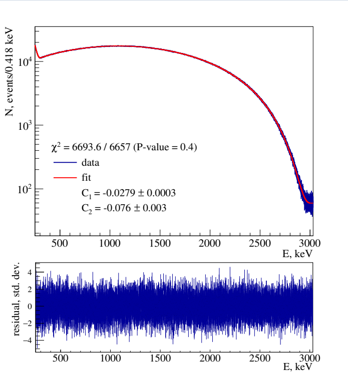
The spectrometer response. The response is almost a gaussian function. We used an exponential with a cutoff as an analytical model.

4π spectrometer allowed beta-spectrum fit



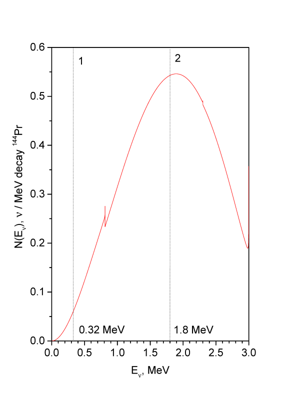
- The quality of the response function was tested with allowed transition fit
- The allowed transition events were selected through coincidences with gamma-line 2185 keV detected with a high-efficiency 2.5 kg BGO scintillator
- The evaluated shape factor shows statistical agreement with unity expected for an allowed transition

4π spectrometer beta-spectrum fit



- The data were collected for 78 hours
- The detector response was described as an exponential with a cutoff equalized by the RMS with the MC simulation with an additional parabolic freedom.
- The beta-spectrum was described as a convolution of the theoretical beta-spectrum and MC response.

Evaluated neutrino spectrum



- The neutrino spectrum could be evaluated for each beta-transition
- The statistical uncertainty could be evaluated with toy Mote-Carlo method: the shape factor parameters are played according to the fit results, i.e. uncertainties and correlation coefficient
- The sources of systematic uncertainties are:
  - Model variation for the screening correction to the F(W,Z)
  - Uncertainty of the GS transition endpoint energy

The spectrum interpolation

For neutrino energies E above the unique forbidden transition endpoint of 2.301 MeV, the spectrum is interpolated as follows:

$$N(E)_{(2.3)\mathrm{MeV}} = a_1 + a_2 E + a_3 E^2 + a_4 E^3 + \\ + a_5 E^4 + \exp(a_6 + a_7 E^2) + \exp(a_8 + a_9 E^3).$$

Between the inverse beta decay threshold of 1.806 MeV and 2.301 MeV, we also include a transition to the excited level of $0^- \to 2^+$ in ^{144}Nd, adding an additional component $N(E)_{(2.3)\mathrm{MeV}}$:

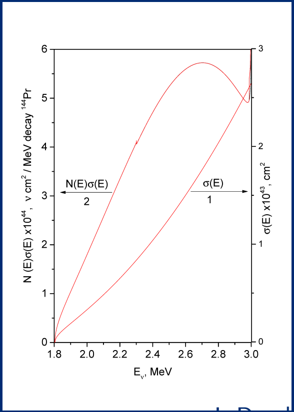
$$N(E)_{(1.8)\mathrm{MeV}} = N(E)_{(2.3)\mathrm{MeV}} + a_{10} + a_{11} E + \\ + a_{12} E^2 + a_{13} E^3$$

- The neutrino spectrum is fitted with following parameters:

a_1	1.12×10^{-2}	a_8	$-8.19 \times 10^{+2}$
a_2	-1.79×10^{-5}	a_9	3.01×10^{-8}
a_3	1.14×10^{-8}	a_{10}	-6.29×10^{-3}
a_4	-3.21×10^{-12}	a_{11}	8.21×10^{-6}
a_5	3.30×10^{-16}	a_{12}	-3.57×10^{-9}
a_6	$-1.52 \times 10^{+2}$	a_{13}	5.19×10^{-13}
a_7	1.56×10^{-5}		

- For neutrino energies greater than 1.8 MeV, the dicreapancy of interpolated and directly evaluated spectra integrals was found to be as low as 0.4 %

Estimate of the final precision



- The precision of the measurement could be treated through the integral of the spectrum above the IBD threshold on hydrogen. The value is $(0.50192 \pm 0.00006_{stat} \pm 0.00065_{syst})$ so the statistic precision of this value is as low as 0.01 %.
- One could evaluate the experimental IBD neutrino count rate, that is $\sigma_{144Pr} = (4.7448 \pm 0.0006_{stat} \pm 0.012_{syst}) \times 10^{-44}$ cm^2 per one decay of $^{144}\mathrm{Pr}$ nucleus.
- It is important to note that the systematic uncertainty coming from the cross section is not considered here

Conclusions

- The neutrino spectrum of ^{144}Pr was evaluated with high precision
- The measurement was performed with two different spectrometers with statistical agreement of the result
- Both spectrometers analysis procedures were tested on allowed transition in ^{144}Pr and have shown statistical agreement of the evaluated shape factor with unity
- The precision of the expected count rate for a sterile neutrino experiment is now limited by the calorimetry quality and the IBD cross section calculation
- The final paper is already on arXiv:2506.03716 and is sent to PRD.

Thank you for your attention