Precision measurement of $^{144}Ce - {}^{144}Pr$ β-spectra with 4π geometry Si(Li)-detectors

I. E. Alekseev, S. V. Bakhlanov, 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

Petersburg Nuclear Physics Institute, NRC Kurchatov Institute

НАЦИОНАЛЬНЫЙ ИССЛЕДОВАТЕЛЬСКИЙ ЦЕНТР «КУРЧАТОВСКИЙ ИНСТИТУТ»
Петербургский институт ядерной физики им. Б. П. Константинова

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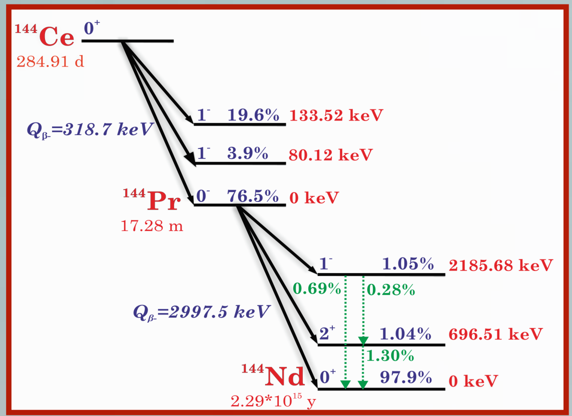
Abstract

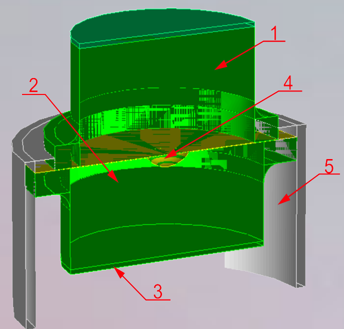
The artificial source of antineutrinos ^{144}Ce-^{144}Pr is one of the most promising for the experiments on the search for neutrino oscillation to the sterile state. We produced the new semiconductor beta-spectrometer with a sensitive region thickness of more than 8 mm and with response function close to Gaussian for electrons with an energy less than 3 MeV. As a result precise beta spectra of ^{144}Ce-^{144}Pr were measured. The measured form-factor parameters are: $C(W) = 1 + (-0.011 \pm 0.002) \cdot W + (-0.016 \pm 0.013)/W$. This result was used in simulation of different scintillator detector geometries with the Monte-Carlo methods and GEANT4 for searching the sensitivity for sterile neutrinos with ^{144}Ce-^{144}Pr antineutrino source.

^{144}Ce-^{144}Pr decay scheme

The scheme shows the most intensive beta-transitions in ^{144}Ce and ^{144}Pr. This transitions make a contribution in the measured spectrum. One should notice that, all gamma-transitions with energy exceeding 1459 keV are accompanied with an allowed beta-transition to 1- exited state in ^{144}Pr with 2185 keV of excitation energy.



Semi-conductor beta-spectrometer



The beta-spectrometer prototype scheme with 4π geometry
1 - Upper Si(Li) detector;
2 - Bottom Si(Li) detector;
3 - Diffusive lithium insensitive layer;
4 - Cavity produced in the detector covered with dried drop ^{144}Ce-^{144}Pr source;
5 - Detectors support structure;

The ^{144}Ce-^{144}Pr spectrum measurement was carried out via two planar semi-conductor Si(Li) detectors. These detectors thickness were 8.9 and 9.2 mm. The whole setup was placed into vacuum cryostat and cooled down to liquid nitrogen temperature. The scintillator detector, based on BGO crystal, was placed on the top of the cryostat and used in coincidence scheme for discrimination of transitions to the excited states of ^{144}Vd.

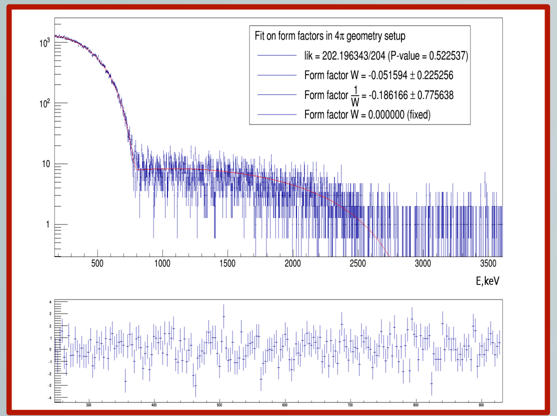
Beta-spectrum describing

The theoretical description of a beta-spectrum has as suggested by E. Fermi in 1930s, factorised it as

$$N(W) = F(W,Z)PW(W-W_0)^2C(W)$$

where $PW(W-W_0)^2$ - phase factor;
$F(W,Z)$ - Fermi function, responsible for the electromagnetic interaction between electron and atom;
$C(W)$ - the form-factor responsible for the nuclear exchange interactions of the transition. Is expected to be unity for allowed spectra.

The beta-spectrum measurement results



The coincidence with 1489 and 2185 keV gamma-lines in BGO detector allows to obtain the spectrum of electrons with an a priori well-known allowed transition $0^+ \to 1^-$.
The spectral fit of the allowed beta-transition $0^+ \to 1^-$ for ^{144}Ce-^{144}Pr shows that the form-factor parameters are consistent with zero and thus the fitting procedure is well-established

The experimental nuclear form-factor was taken in an empiric form as

$$C(W) = 1 + A \cdot W + \frac{B}{W}$$

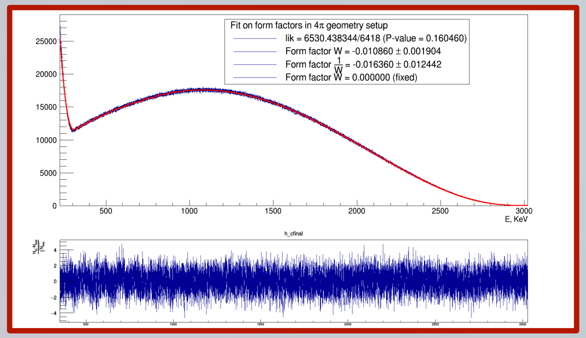
The response accounting is consist of spectrum fit with likelihood function

$$F(E) = \int N(W)R(E,W),$$

where $R(E,W)$ - the spectrometer response for electron with full energy W;
A simplified analytical function was used:

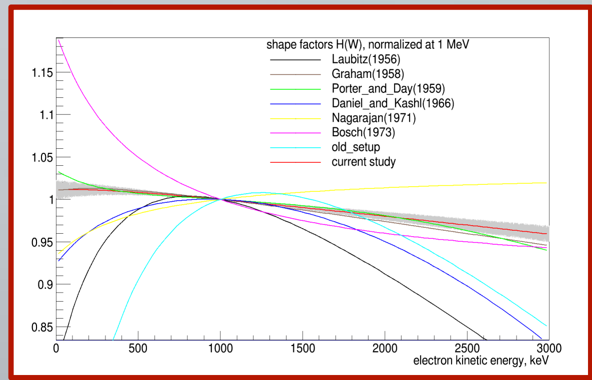
$$R(E,W) = A(W) \cdot exp(B(W) + B_0(W)E) \cdot \theta(E-W)$$

The parameters A(W) and B(W) were established through equalisation of the variance with a MC simulation and fixing the detection efficiency to unity. An Extra parabolic freedom for B(W) was given to compensate for the MC simulation lack of precision.

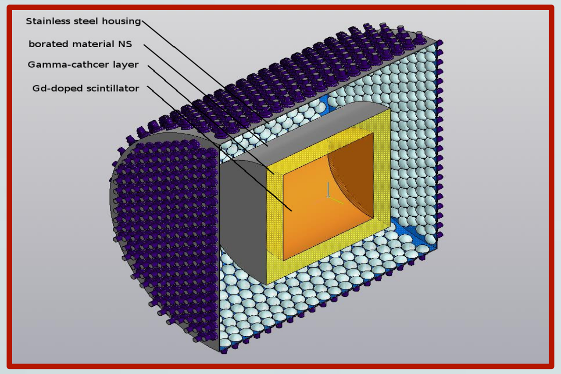


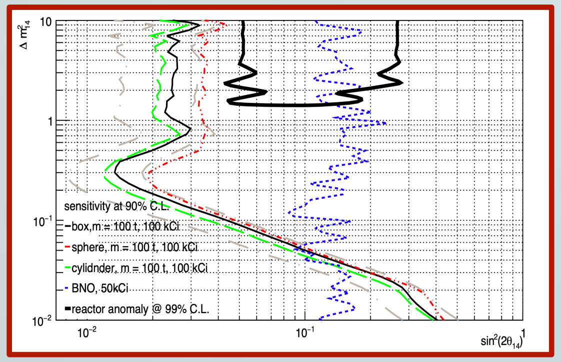
The spectral shape for allowed beta-transition $0^+ \to 1^-$ for ^{144}Ce-^{144}Pr. The fit shows statistical agreement of the fit model and experimental spectrum.

The form-factors for first forbidden beta-transition $0^+ \to 0^-$ for ^{144}Ce-^{144}Pr in comparison with the results of the previous investigations. It should be noticed, that the analysis result with an empiric model is in the good agreement with theoretically expected shape for an axial-vector transition[3].



The sterile neutrino search simulation





The Monte-Carlo methods and GEANT4 software framework have been applied for a scintillation detector modelling. This model is of cylindric al geometry with linear size of sensitive region circa 3.3 m of radius and 3.3 m of height for the scintillator (pseudocumene) providing the volume of 100 t.
The shell of inner sensitive region is made from radiochemically pure acryl and is fitted with a shell of the external gamma-catcher with ^{157}Gd.
The detector has a water neutron shield with boric acid with concentration in 15 g/l and the thickness of 1400 mm.
2186 12" PMTs located inside the detector water tank could provide coverage as large as 83.6%.

The sensitivity curves for the different geometries of the detectors for a sensitivity study at 90% C.L. with ^{144}Ce-^{144}Pr source with 100 kCi activity and exposure time of 1.5 year. It was found out that the linear detector sizes relevant with scintillator volume of 100 t combined with 100 kCi source provide enough sensitivity to fully cover reactor neutrino anomaly region.

References

[1] S. Bakhlanov, A. Derbin, I. Drachnev, I. Kotina, I. Lomskaia, V. Muratova, N. Pilipenko, D. Semenov, E. Unzhakov, 4pi semiconductor beta-spectrometer for measurement of 144Ce-144Pr spectra, Journal of Physics: Conference Series 1390 (2019) 012117
[2] Derbin A.V., Bakhlanov S.V, Drachnev I.S., Filipov I.P., Lukyanchenko L.A., Machulin I.N., Muratova V.N., Pilipenko N.V., Semenov D.A, Unzhakov E.V., Measurement of 144 Pr beta-spectrum with Si(Li) detectors for the purpose of determining the spectrum of electron antineutrinos, arXiv:1711.06985
[3]A.V. Derbin, I.S. Drachnev, I.S. Lomskaya, V.N. Muratova, N.V. Pilipenko, D.A. Semenov, E.V. Unzhakov, Monte-Carlo sensitivity study for sterile neutrino search with 144Ce–144Pr source and liquid scintillation detectors of various geometries, arXiv:1905.06670
[4] E. J. Konopinski and G. E. Uhlenbeck. On the Fermi theory of β-radioactivity. II. The "forbidden" doi:spectra.Phys. Rev., 60:308–320, Aug 1941.10.1103/PhysRev.60.308.
[5] I.E. Alexeev, S.V. Bakhlanov, N.V. Bazlov, E.A. Chmel, A.V. Derbin, I.S. Drachnev, I.M. Kotina, V.N. Muratova, N.V. Pilipenko, D.A. Semyonov, E.V. Unzhakov, V.K. Yeremin, Beta-spectrometer with Si-detectors for the study of 144Ce–144Pr decays, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 890, 2018, Pages 64-67, ISSN 0168-9002, https://doi.org/10.1016/j.nima.2018.02.031.