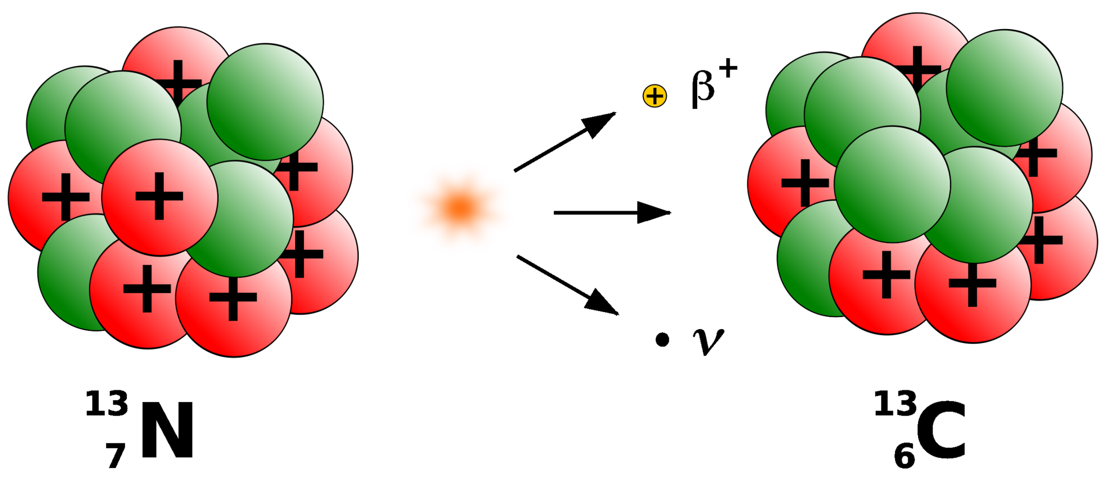
Precision measurement of ^{144}Ce – ^{144}Pr beta-spectrum

Ilia Drachnev, Alexander Debin, Igor Alexeev, Sergey Bakhlanov, Irina Kotina, Irina Lomskaya, Valentina Muratova, Nelly Niyazova, Maxim Trushin, Ekaterina Chmel'
NRC «Kurchatov Institute» – PNPI, Gatchina, Russia

Abstract

Beta-decay is a specific decay process that undergoes a reaction with thee-particle product composition that results in continuous spectral shape of electrons or positrons. Precision beta-spectra measurement always had a great importance in some fundamental physics problems including neutrino physics, e.g. a ^{144}Ce – ^{144}Pr source is one of the most suitable to search for neutrino oscillation into sterile state for sterile neutrino mass around 1 eV. Since the range of electron at the energy of 3 MeV (which is basically the maximum energy of a beta-transition for the long-lived nuclei) does not exceed 2 g/cm^2, electron registration could be effectively performed with solid state scintillators and semiconductors. A strong probability of backscattering from detector surface is present in case of semiconductor detectors and is dependent upon the detector material. One possible way of solving this issue is a precise simulation of the spectrometer response function that is quite promising as it could be used in a very simple target-detector setup. Another solution to this problem is usage of 4π geometry [1], that fully covers the radioactive source and is able to register the backscattered electrons. In this work we present the results of ^{144}Ce – ^{144}Pr spectrum measurement performed with two setups of both types and controlled with the shape of an allowed $0^- - 1^-$ transition in ^{144}Pr, having precision that was substantially increased with respect to the previous studies of these beta-spectra. We have obtained parameter values for the parameterized transition shape factor that is compared with the other experiments and could be used for electron antineutrino spectrum definition.

Beta-decays



Generally, a beta-decay shape could be expressed as

$$S(W) = PW(W - W_0)^2 \times F(W,Z) \times C(W,Z),$$

where $PW(W - W_0)^2$ - phase space, $F(W,Z)$ - Fermi-function, $C(W,Z)$ - nuclear form-factor.
Beta-transitions are classified as:

- allowed:
  $\Delta\pi = +1, \Delta I = 0, 1$
  In the most cases for allowed transitions S(W,Z) = 1
- forbidden:
  $\Delta\pi = -1, \Delta I = 0, 1$ - first forbidden
  $\Delta\pi = -1, \Delta I = 2$ - first forbidden unique
  $\Delta\pi = +1, \Delta I = 2$ - second forbidden etc.

As for forbidden decays S(W) is different from unity, sometimes substantially. This value needs to be defined experimentally.

Beta-spectrometers

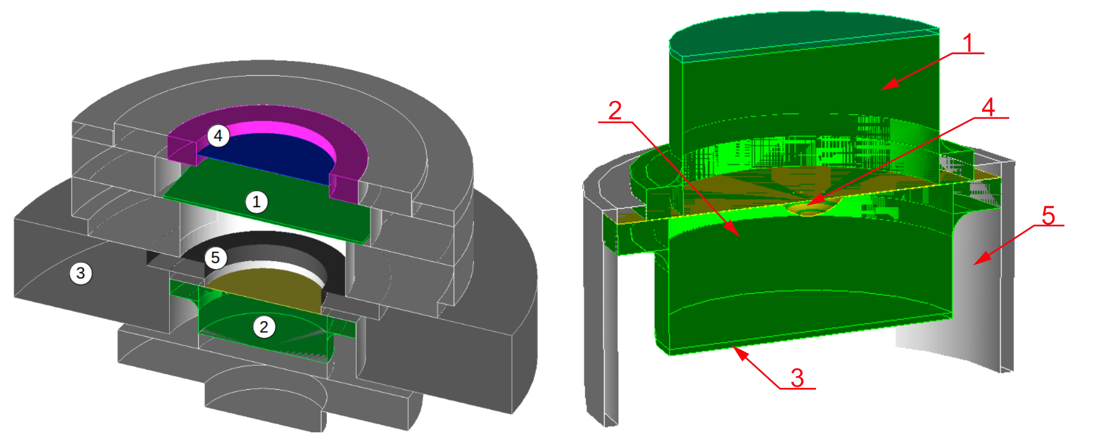
Beta-spectra could be measured with various spectrometer types:

- Magnetic and electrostatic spectrometers – precise, but bulk and expensive devices with difficult-to-control systematics related with their complexity
- Crystallite and organic scintillators – Compact and easy-to-use setups having quite bad resolution and difficult to control systematics related with quenching effect and Čerenkov light emission
- Cryohenic, bolometric spectrometers – Devices the apply to a limited number of nuclides
- semiconductor spectrometers – Compact and easy-to-use devices, having basically an only problem: difficulties in the spectrometer response definition as they work only with external source positioning

References

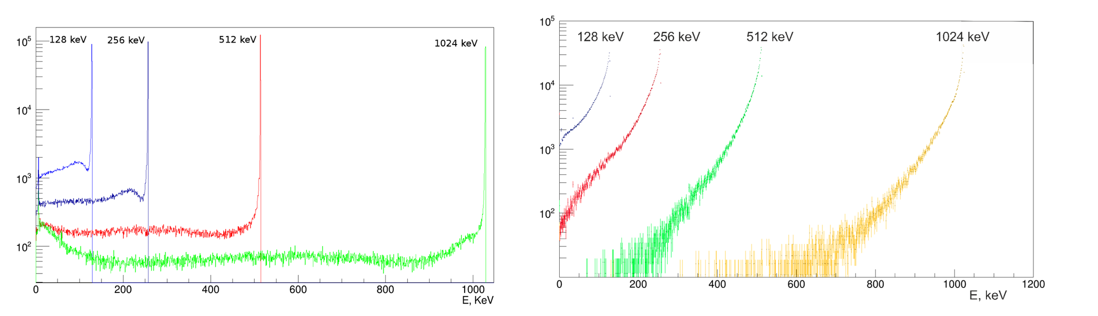
[1] A Silicon 4π Spectrometer of β-Decay Electrons with Energies of up to 3 MeV,IE Alekseev, SV Bakhlanov, AV Derbin, IS Drachnev, IM Kotina, VN Muratova, NV Niyazova, DA Semenov, MV Trushin, EV Unzhakov, EA Chmel, Instruments and Experimental Techniques 64 (2), 190-194
[2] Precision measurement of the ^{210}Bi $\beta-$spectrum, E Alekseev, SV Bakhlanov, AV Derbin, IS Drachnev, IM Kotina, IS Lomskaya, VN Muratova, NV Niyazova, DA Semenov, MV Trushin, EV Unzhakov, Physical Review C 102 (6), 064329

Construction of Si(Li) - spectrometers



Left figure: target-detector spectrometer. Right figure: spectrometer with 4π geometry.
The 4π spectrometer uses the source in form of a dried drop, located in a cavity made on the surface of the lower detector that makes it single-use, but such geometry makes the response function much easier to describe and less disturbing the spectral shape as the backscratching from one of the detectors is registered by the other one. This experimental technique is used for the first time.

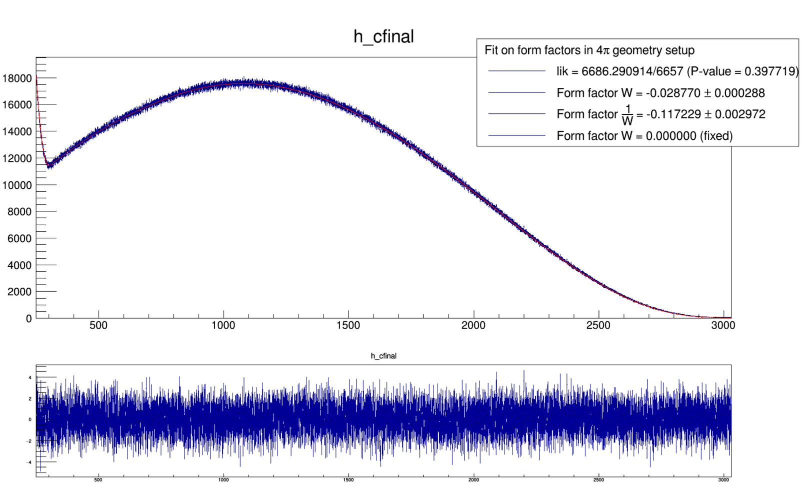
Spectrometer response

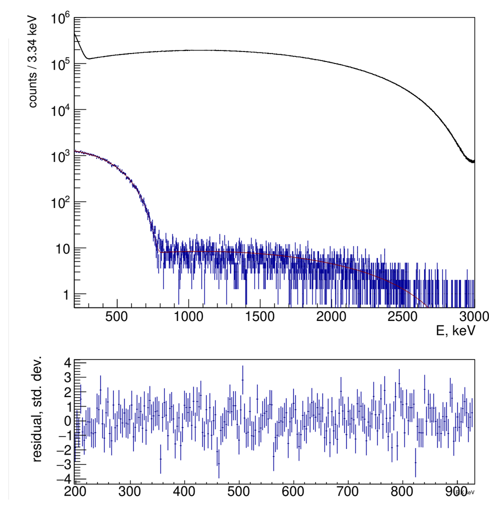


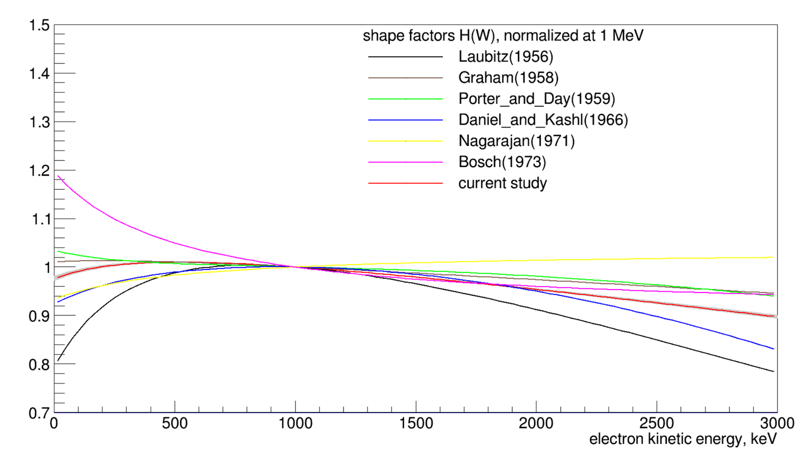
Left figure - response of the "target-detector" spectrometer. Right figure - 4π-spectrometer response. The response functions were calculated with GEANT4.10.6 package with enabled G4EmStandardPhysics_option4 electromagnetic physics model. The final fit of the $4\text{-}\pi$ spectrometer spectrum was performed with analytic response description as $e^{A(T_e)E+B(T_e)} \times \theta(E - T_e)$ equalized with the simulation results by variance with extra parabolic freedom given to this value. Such model allows to account for nonuniform insensitive parts of the source and detectors

$4\text{-}\pi$ spectrometer data analysis

The experimental spectra were fitted with the function $F(E) = \int S(W)R(E,W)dW$ where R(W, E) is the spectrometer response function.



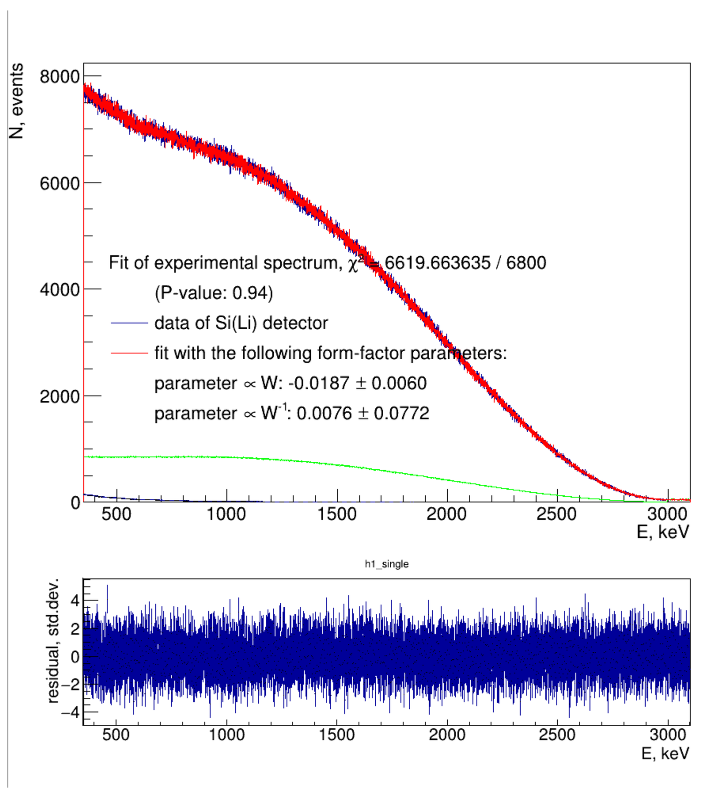


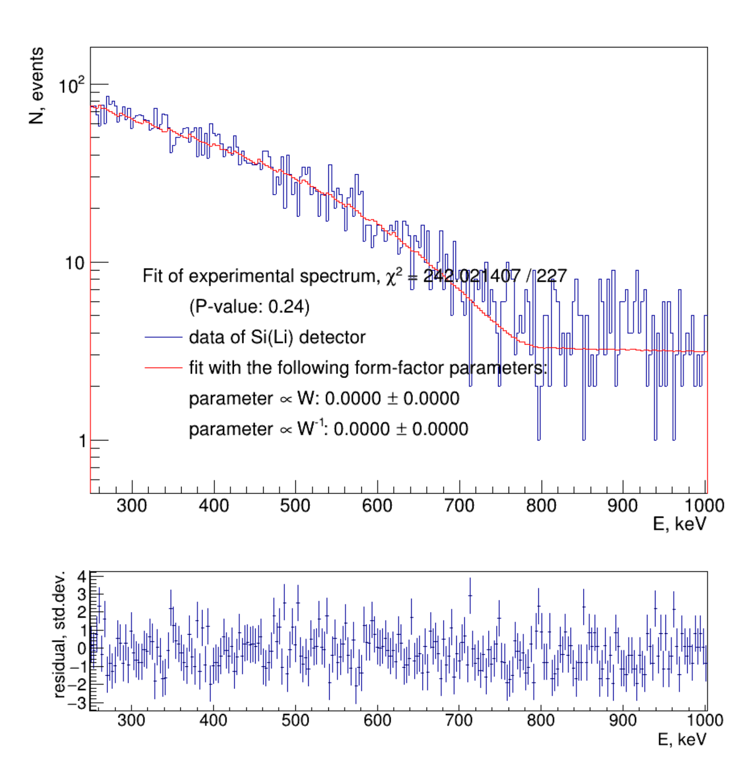


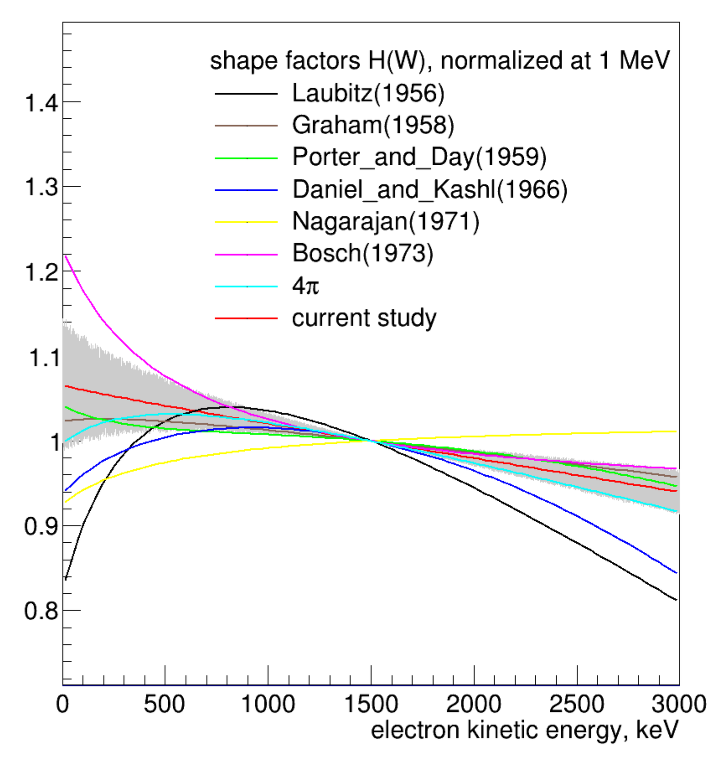
left figure - the spectral fit of the ^{144}Ce-^{144}Pr beta-spectrum.
Middle figure - spectral fit of the ^{144}Pr allowed $0^- - 1^-$ transition in ^{144}Pr that was obtained by fast coincidence scheme with a BGO scintillation detector registering the gamma-radiation that follows this transition. The measured spectral shape agrees with unity form-factor expected for allowed transitions
The right figure shows the form-factor C(W) in comparison with the previous investigations

"Target-detector" data analysis

The experimental spectra were fitted with the function $F(E) = \int S(W)R(E,W)dW$.







Left figure - fit of the "target-detector" spectrometer beta-spectrum
Central figure - fit of allowed $0^- - 1^-$ transition in ^{144}Pr
Right figure - comparison of the final form-factors
The experiment was complicated by weakness of the source (caused by its age) that made it necessary to divide the data into two parts with the same exposure and fit the difference (green line on the left figure) that corresponds to ^{144}Ce that decayed during the experiment (over 5400 hours). The background was still present after this procedure, was identified as ^{154}Eu and accounted for.
Still, the result of this experiment agrees with the 4π spectrometer and confirms it, although it has worse precision

Acknowledgements

The study was performed under support of Russian Science Foundation (projects № 21-12-00063 and № 17-12-01009)