144Ce - 144Pr spectrum measurement with 4π semiconductor β-spectrometer

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Abstract. Precision β-spectra measurement always had a great importance in some fundamental physics problems including neutrino physics. Magnetic and electrostatic spectrometers have high resolution, but at the same time usage of such kinds of equipment involves the size and cost issues. Since electron mean free path at the energy of 3 MeV (which is basically the maximum energy of a β-transition for the long-lived nuclei) does not exceed 2 g/cm², electron registration could be effectively performed with the 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. Such problem can be solved with 4π geometry detector development, which fully covers the radioactive source and is able to register the backscattered electrons. In this work we present the newly developed technology of 4π geometry β-spectrometer based on two semiconductor detectors. This spectrometer was used for measurement of the 144Ce - 144Pr spectrum, that is the perspective anti-neutrino source due to endpoint energy at 3 MeV and can be used for the sterile neutrino search experiments. The form-factor parameters that were obtained are: $C(W) = 1 + (-0.02877 ± 0.00029)W + (-0.11722 ± 0.00297)W^{-1}$. The measurement accuracy was sufficiently enhanced with respect to the previous results.

1. Introduction

The moment of the beginning of β-spectrometry problems might be considered when Pauli discovered neutrino and its description as a particle which snatches away some energy in the β-decay in 1930. Shortly thereafter the theory allowing to explain β-spectra was introduced by E.Fermi, but notwithstanding a clear success as several problems for some cases still remained. The β-spectra theoretical description could be performed for an electron spectrum as:

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

where W and P are total energy and momenta of the electron, $F(W, Z)$ - Fermi-function, responsible for the electromagnetic interaction between electron and atom and $C(W)$ is the form-factor responsible for the nuclear exchange in the transition. The form-factor $C(W)$ is expected to be unity for allowed transition spectra.

It was found out that the parity quantum number conservation law is being violated and there were determined two variations of weak interactions that contribute: vector one that is analytical...
Figure 1. Decay scheme of $^{144}$Ce. The scheme shows the most intensive $\beta$-transitions of $^{144}$Ce and $^{144}$Pr that contribute to the detected spectrum. One should notice that all the $\gamma$-transitions with energy exceeding 696 keV follow an allowed $\beta$-transition to the $1^-$ excited state of $^{144}$Pr with excitation energy of 2185 keV.

were evaluated using the C(W) for $^{144}$Ce-$^{144}$Pr decay which has a complex scheme and with endpoint energy of 2997.44 keV. $^{144}$Ce-$^{144}$Pr is one of the most energetic long-lived $\beta$-sources while inverse $\beta$-decay cross section scales as the square of anti-neutrino energy that makes it a quite promising source for sterile neutrino search experiments.

2. Experimental setup

The $\beta$-decay experimental studies are performed via different $\beta$-spectrometer types, and the final accuracy depends on the type of spectrometer. Usually magnetic spectrometers provide good energy resolution. But such spectrometers have large sizes and high cost, that hampers to accommodate them in the laboratory. If the nuclei has high endpoint energy, another approach to $\beta$-spectrometry is scintillator detector usage. But due to the problem of poor energy resolution and difficult-to-control systematics...
Figure 2. Principal scheme of the $\beta$-spectrometer with $4\pi$ geometry: 1 - upper Si(Li) detector, 3 - lower Si(Li) detector, 2 - a drilled cavity with the $^{144}$Ce - $^{144}$Pr $\beta$-source in form of dried solution on the cavity surface. PA - preamplifiers; HV - offset voltage.

cauased by quenching and Čerenkov radiation application of such detector kind has serious restrictions.

Semiconductor detectors are some sort of a compromise and being broad application inasmuch as they have possibility to work with short-living and low-energy sources. Although in spite of plenty benefits semiconductor detectors are restricted to planar or coaxial construction shapes and have issues of entrance window thickness as well. Detector chemical compound and source location also limit manufacturing and usage. The only approach to this problem solution is an external source but there are backscattering from the crystal surface and bremsstrahlung radiation escape factors [1].

In this work, considering all limitations, we propose a compact and reliable $\beta$-spectrometer effective for accurate $\beta$-spectrometry at high kinetic energy.

The $^{144}$Ce - $^{144}$Pr measurement was held via two Si(Li) semiconductor detectors [2]. Since in $^{144}$Pr nuclei transition $0^- \rightarrow 0^+$ endpoint energy is just slightly lower than 3 MeV and systematic errors minimization requires detector thickness exceeding electron free path that is 7.78 mm in silicon, the detectors were produced with thicknesses of 8.9 and 9.2 mm and top-hat shape. The outer diameters were 27 and 23 mm respectively, with 20 mm and 18 mm of sensitive region diameter. The bottom detector center was fitted with a cavity that has the diameter of 5 mm and depth of 1 mm drilled in the gold contact surface and the dried drop $^{144}$Ce source was located there. The upper detector was overlaid on the gold surface of bottom detector directly and high voltage was supplied onto the common $n^+$-contact, see Figure 2.

The setup included preamplifiers with the field effect transistors located inside the vacuum cryostate and cooled down to the liquid nitrogen temperature in order to decrease the detector current and enhance the energy resolution. Also a BGO scintillator crystal was located on the top of the setup for the $\gamma$-signals detection in coincidence with the signals from the semiconductor detectors. The signals from the preamplifiers were digitized by the 14bit CAEN v1725 parallel type ADC. Three shaping types CR-RC, CR-2RC, and triangle type have been used in order to obtain the optimal temporal reference and signal-to-noise ratio in comparison to standard quasi-gaussian CR-nRC shaping. The data were collected for 2.3 days.

3. Data analysis
The spectrometer response function was derived with Monte-Carlo method with the GEANT4.10.4 [3] simulation package. Inasmuch as low-energy physics requires especially accurate calculations of the electromagnetic part, the package G4EmStandardPhysics option4 was chosen. Detectors geometry was measured precisely as well as the sensitive volumes that might be different from the detector thickness due to a diffusive lithium layer presence. The
Figure 3. Spectral fit of the total energy spectrum for $^{144}$Ce - $^{144}$Pr. The fit shows satisfactory statistical agreement of the theoretical description with the spectrometer data as well as high sensitivity to the form-factor parameters.

The final fitting procedure was evaluated with maximum likelihood approach. As for the nuclear form-factor option the response spectrometer function was required, that is albeit approximative with delta-function due to the detector construction features, but differs because of electron transit through the insensitive detector and source layers. The entrance window thickness was analysed via $^{207}$Bi $\gamma$ and conversion electron peaks as well as via $^{244}$Cm and $^{241}$Am alpha peaks modeling that provides good precision.

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

$$C(W) = 1 + A \cdot W + B \cdot W^{-1},$$

The response function is convoluted with the spectrum and used for fitting the data by maximum likelihood method:

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

where $R(E,W)$ is the spectrometer response for electron with total energy $W$. A simplified analytical response function was used:

$$R(E,W) = A(W) \times exp(B(W) + B_0(W)) \times \Theta(W - E),$$

where $A(W)$ was taken as MC-derived registration efficiency and $B_0(W)$ - with interpolation by fourth degree polynomial over MC simulation results for variance and equalization of the response function variance, $B(W)$ - was used to introduce additional free parameters for variance as $B(W) = 1 + B_1 + B_2 \cdot W^2$. As a result of the spectral fit, we have obtained the form factor of the $0^- \rightarrow 0^+$ transition as $C(W) = 1 + (-0.02877 \pm 0.00028)W + (-0.11722 \pm 0.00297)W^{-1}$. The precision of this measurement is significantly improved with respect to the previous studies [4], [5]. Also our result was compared with earlier investigation results and one should be noticed...
Figure 4. The evaluated form-factors of the first-forbidden $\beta$-transition $0^+ \rightarrow 0^-$ for $^{144}\text{Ce} - ^{144}\text{Pr}$ (red line) in comparison with the results of earlier measurements. The grey area shows the uncertainties for 1 standard deviation.

that it is in a good agreement with theoretical predictions for an axial-vector transition shape. The results comparison is presented on Figure 4.

4. Conclusion
The $\beta$-spectrometer based on Si(Li) semiconductor detectors with $4\pi$ geometry was developed. The setup demonstrates a good energy resolution and makes it possible to perform $\beta$-spectrometry for nuclei with high endpoint energy, such as $^{144}\text{Pr}$. The $^{144}\text{Ce} - ^{144}\text{Pr}$ measurement results is $C(W) = 1 + (-0.02877 \pm 0.00028)W + (-0.11722 \pm 0.00297)W^{-1}$ and shows good statistical agreement of the theoretical model with experimental data.

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