A Silicon Detector Based Beta-spectrometer

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Abstract. Here we present the specifications of the newly developed beta-spectrometer based on thick full absorption Si(Li) detector. The spectrometer was designed for precision measurements of various beta-spectra, namely for the beta-spectrum shape study of $^{144}\text{Pr}$, which is considered to be one of the most promising anti-neutrino source for sterile neutrino searches.

1. Introduction

Precision measurements of beta-spectra have always been and are still playing an important role in several fundamental physical problems predominantly in neutrino physics. It was the continuous shape of beta-decay spectrum, that has driven W. Pauli towards the neutrino hypothesis. The initial beta-spectrum measurements for the purpose of determining the neutrino mass were carried out by G. Hanna and B. Pontecorvo [1] via gas counter that registered electrons produced by decays of tritium added into the detector volume.

Magnetic and electrostatic spectrometers possess the superior energy resolution, but at the same time such devices appear to be very complex and large-scale installments. Since the electron free path at 3 MeV (which is, basically, the maximum beta-transition energy for long-living isotopes) does not exceed 2 g/cm$^3$, solid state scintillation and ionization detectors were effectively employed for detection of electrons [2, 3]. The main drawback of solid state scintillators is their relatively poor energy resolution, which stands at approximately 10% at 1 MeV. In case of semiconductor detectors there is a significant probability of back-scattering from the detector surface that depends on the detector material. The most widespread silicon-based semiconductors have the backscattering probability of the order of 10% for 100 keV electrons at normal incidence [4]. In case of electron energies above 1 MeV and high Z detector materials, it also becomes important to take the bremsstrahlung into account.

The considered Si(Li) spectrometer was developed for precision measurement of $^{144}\text{Ce}-^{144}\text{Pr}$ beta-spectrum in order to determine the antineutrino energy spectrum. The $^{144}\text{Ce}-^{144}\text{Pr}$ antineutrino source will be used for experimental sterile neutrino searches by Borexino SOX collaboration [5].
2. Experimental setup

The photo of the experimental setup based on full absorption Si(Li) detector is shown in figure 1. The sensitive region of the Si(Li) detector fabricated at NRC KI PNPI has a diameter about 15 mm and a thickness of 6.5 mm. These dimensions ensure effective absorption of electrons with energies up to 3 MeV. The detector was equipped with a tungsten collimator with a diameter of 14 mm and a thickness of 2 mm. The negative bias voltage of 1 kV was applied directly to the gold coating of the detector. The energy resolution determined for 59.6 keV gamma-line of $^{241}$Am turned out to be FWHM = 900 eV.

The entire setup was placed inside the vacuum cryostat and cooled down to the liquid nitrogen temperature. The detector was equipped with charge-sensitive preamplifier with resistive feedback and cooled field-effect transistor. As noted above, the spectrometer was designed with intent of measuring the beta-spectrum of $^{144}$Pr in the energy range of (0 − 3) MeV. In order to perform measurements in such a broad dynamic range, the Si(Li) detector was equipped with two separate spectrometric channels, each with spectrometric amplifier and 14-bit analogue-to-digital converter set up as a standalone module. Channel settings were adjusted to register events within (0.01 − 0.5) MeV and (0.05 − 6.0) MeV energy intervals. The choice of the upper energy limit at 6 MeV was conditioned by our intention to monitor the possible alpha-activity of the sample under investigation. A dedicated DAQ control software allows one to acquire and record two 16000-channel spectra from the Si(Li) detector.

3. Results

In order to determine the main characteristics of the spectrometer we used a $^{207}$Bi source, providing gamma-rays, X-rays and conversion and Auger electrons. The $^{207}$Bi spectrum, measured with the Si(Li) detector, is shown in figure 2(a) for the intervals (0.01 − 2.0) MeV and (450 − 580) keV, respectively. The $^{207}$Bi source with an activity of $10^4$ Bq was placed inside the vacuum cryostat at a distance of 14 mm from the Si(Li) detector surface. Three of the most intense $^{207}$Bi gamma-lines have energies of 569.7 keV, 1063.7 keV and 1770.2 keV and are emitted with probabilities of 0.977, 0.745 and 0.069 per single $^{207}$Bi decay, respectively. The corresponding peaks of conversion electrons form K-, L- and M-shells are clearly visible.
in the spectrum in figure 2(a). The electron energy resolution determined via 480 keV line is FWHM = 1.8 keV.

The low-energy part of the spectrum was used to evaluate the thickness of non-sensitive layer on the surface of Si(Li) detector. This area contains a set of peaks corresponding to Pb X-rays from $K^-$ and $L$-series and Auger electrons. The observed position of 56.94 keV Auger peak ($e_{KL,L_2}$) appeared to be 56.22 keV. Inclusive of the golden coating thickness of (500 Å), the measured 59 keV electron energy loss of 720 eV corresponds to 4700 Å of non-sensitive layer.

The energy spectrum of the $^{144}$Ce-$^{144}$Pr source, measured with the Si(Li) detector during 10 days, is shown in figure 2(b). The total spectrum contains gamma- and electron peaks. The spectrum contains characteristic X-ray lines of Np at 13.9 keV, 17.8 keV and 20.8 keV, produced by trace amounts of alpha-decaying $^{241}$Am contained in the $^{144}$Ce source. The peaks at 59.6 keV, 80.1 keV and 133.5 keV are related to the gamma-transitions of $^{237}$Np and $^{144}$Pr nuclei. The most intense peaks at 35.8 keV and 41 keV correspond to $K_{\alpha_1,\alpha_2}$- and $K_{\beta}$-lines of Pr X-rays. The spectrum of electrons from beta-decay of $^{144}$Ce-$^{144}$Pr consists of also conversion and Auger electrons from 133.5 keV gamma-transition. After the main measurements were completed the thin silicon detector was mounted and $\gamma$- and X-rays activity was measured by Si(Li)-detector in anti-coincidence with thin Si-detector. Inclusion of this spectrum into the analysis allows us to account for overall gamma- and X-ray contribution.

The differential energy spectrum of electrons in $\beta-$decay is described as:
\[ N(W)dW \sim pW(W - W_0)^2 \cdot F(Z,W) \cdot H(W) \cdot L_0(Z,W) \cdot C_{A,V}(Z,W) \cdot S(Z,W) \cdot G(Z,W) \cdot B(W), \]

where \( W \) and \( p \) are total energy and momentum of electron and \( F(W,Z) \) is Fermi function. Additionally, the following correction factors have to be taken into account: finite size of the nucleus correction for electromagnetic \( L_0(Z,W) \) and weak \( C_{A,V}(Z,W) \) interaction; screening corrections of the nuclear charge by electrons \( S(Z,W) \); radiative corrections \( G(Z,W) \) and weak magnetism correction \( B(W) \). The antineutrino spectrum can be calculated after the parameters of shape factor \( H(W) \) will be extracted from the analysis of experimental spectrum.

4. Conclusion
The beta-spectrometer with of 6.5 mm thick full absorption Si(Li)-detector has been developed. The spectrometer can be used for precision measurements of the beta-spectrum shapes of various radioactive nuclei, in particular to measure the beta-spectra of \(^{144}\)Pr, which is the most promising antineutrino source for searching for neutrino oscillations to a sterile state.

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References
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