New measurement of the $\beta$-spectrum of $^{210}$Bi with a silicon $4\pi\beta$-spectrometer

I E Alekseev$^1$, S V Bakhlanov$^2$, A V Derbin$^2$, I S Drachnev$^2$, I M Kotina$^2$, A M Kuzmichev$^2$, I S Lomskaya$^2$, M S Mikulich$^2$, V N Muratova$^2$, N V Niyazova$^2$, D A Semenov$^2$, M V Trushin$^2$ and E V Unzhakov$^2$

$^1$V.G. Khlopin Radium Institute, St. Petersburg 194021, Russia
$^2$Petersburg Nuclear Physics Institute, Gatchina 188350, Russia
National Research Center “Kurchatov Institute”

Corresponding author’s e-mail: niyazova_nv@pnpi.nrcki.ru

Abstract. The shape of $^{210}$Bi $\beta$-spectrum was measured using a spectrometer based on Si(Li) detectors with a $4\pi$ geometry. Full absorption spectrometer allows for a direct measurement of the $\beta$-spectra without using the electron backscattering corrections for the response function. The measured value of nuclear shape factor $C(W)=1+(-0.4378\pm0.0072)W+(0.0526\pm0.0021)W^2$ is in agreement with the results of previous studies.

1. Introduction
Today the interest to precise measurements of $\beta$-spectra is associated with the search of effects beyond the Standard Model (SM) in the low energy region. This paper presents the first results of measurements of $^{210}$Bi $\beta$-electron spectrum performed using the spectrometer based on Si(Li) detectors with a $4\pi$ geometry [1]. The $^{210}$Bi isotope as a decay product of the $^{222}$Rn radioactive gas from the $^{238}$U-family of natural radioactivity is present inside or on the surface of almost all structural materials of low-background installations. Accurate knowledge of $^{210}$Bi $\beta$- spectrum is needed for background modeling of modern detectors of neutrinos and dark matter particles. In particular, the shape of $^{210}$Bi spectrum is very similar to the recoil electron spectrum, which is produced by the scattering of solar CNO-neutrinos. Therefore, in order to isolate the CNO-neutrino signal, it is necessary to determine the shape of $\beta$-spectrum with sufficient accuracy [2].

The measurements of $^{210}$Bi $\beta$-spectrum using a silicon semiconductor $\beta$-spectrometer in the classical “target - detector” layout were carried out earlier in [3]. This article presents the first results of measurements with a custom-designed semiconductor $\beta$-spectrometer based on Si(Li) detectors with a $4\pi$ geometry. The spectrometer records the total energy of an electron and solves the problem of the electron backscattering from the crystal surface, the probability of which can reach tens of percent depending on the electron energy and the angle of incidence.

2. Experimental setup
The carrierless $^{210}$Pb source was specially prepared for this experiment and started a chain of decays, the particles of which was detected in the experiment:
\[ ^{210}\text{Pb}(\beta, T_{1/2} = 22\text{ y}) \rightarrow ^{210}\text{Bi}(\beta, T_{1/2} = 5\text{ d}) \rightarrow ^{210}\text{Po}(\alpha, T_{1/2} = 138\text{ d}) \] (1)

The endpoint energies of \(^{210}\text{Pb}\) and \(^{210}\text{Bi}\) \(\beta\)-spectra are 64 keV and 1162 keV, respectively. The energy of \(^{210}\text{Po}\) \(\alpha\)-particles is 5304 keV.

In order to carry out the measurements we used the pair of Si(Li) detectors with a diameter of 16 mm and thickness of 6 mm, which ensured the full absorption of electrons up to energies of 2 MeV. The source was deposited into a small concavity, ground in the center of one of the detectors; the second one was attached on top of the first one, providing a 4\(\pi\) geometry. A bias voltage was applied to the resulting common n\(^+\)-contact (Figure 1).

![Figure 1. Layout of the 4\(\pi\) \(\beta\)-spectrometer with two Si(Li) detectors. PA - preamplifier, HV – bias voltage. The \(^{210}\text{Bi}\) source is deposited on the surface of the concavity.](image)

Compound Si(Li) detectors was installed into the vacuum cryostat and cooled down to the liquid nitrogen temperature. The energy resolution of the detectors was determined beforehand from the line of \(^{207}\text{Bi}\) conversion electrons with energy of 480 keV, is 2.0 keV (FWHM) [4]. The electronics included a multichannel 14-bit ADC with a sampling rate of 250 MHz and made possible the selection of (anti) coincident events from both detectors.

The full absorption spectrometer can be used for direct measurement of \(\beta\)-spectra, which does not require considering the corrections for response function included by electron backscattering from the crystal surface.

### 3. Experimental results

After installation of the Si(Li) detectors into the cryostat, the energy calibration was performed with the help of \(^{207}\text{Bi}\) source, mounted on a beryllium window of a vacuum cryostat. Although the \(^{210}\text{Bi}\) source has already been present during the calibration, the measured spectrum clearly shows full absorption peaks of X-ray (75 – 85 keV) and \(\gamma\)-lines (570 keV, 1063 keV), as well as sharp edges of Compton scattering. These features of the spectrum were used for the energy calibration of the detectors.

The Figure 2 shows the energy spectra of electrons and \(\alpha\)-particles, produced by the decay chain of \(^{210}\text{Pb}\) and registered by one and both Si(Li) detectors. The events recorded by both detectors in a 100 ns time window were considered coincident. The total registered energy spectrum (curve 1) is the sum of the single event spectra from each of the detectors and the total energy spectrum of events, recorded by two detectors in coincidence (curve 3). Additionally, Figure 2 shows the energy spectrum of a single-detector (curve 2) and coincident (curve 4) events of one of the Si(Li) detector (with the concavity). One can see that in case of given experimental geometry the probability of ~500 keV electron reflection from the crystal surface is ~30%.

It should be noted that the registered energy spectrum in the case electron reflection from the surface (line 4), is fundamentally different from the spectrum of actual electron energy. The total \(\beta\)-spectrum is
the sum of the spectra 2 and 3, thus solving the response function problem, associated with the backscattering of electrons from the detector surface.

![Figure 2](image-url)

**Figure 2.** The experimental spectra measured by 4π β-spectrometer. 1 – total registered energy spectrum; 2 and 4 – spectra of single-detector, recorded in anticoincidence and coincidence, respectively; 3 – spectrum of events recorded by two detectors.

4. Analysis

The electron energy spectrum $S(W)$, emitted in β-decay is parameterized as

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

(2)

where P and T are the momentum and energy of electron, W is the total electron energy, $W_0$ is the endpoint energy of β-spectrum, $F(W,Z)$ is the Fermi function, which takes into account the electromagnetic interaction of the outgoing electron with the nucleus and atomic shell, $C(W)$ is the nuclear shape-factor that takes into account intranuclear interactions for a given transition.

Fermi function $F(W,Z)$ was calculated with consideration of several corrections including the screening effect, the finite size of the nucleus and radiative QED corrections [3]. The shape factor of the first forbidden non-unique transition was parameterized by a polynomial of the second degree as in [5,3]:

$$C(W) = 1 + C_1W + C_2W^2.$$  

(3)

To compare the experimental spectrum with the theoretical shape, the $S(W)$ function was convolved with the detector response function $R(W, W')$. The detector response function $R(W, W')$ was presented as a convolution of a Gaussian function with an exponential “tail”, which describes small energy losses in the target and non-sensitive layers of the detectors. The fit result is shown in Figure 3. The parameters of the nuclear shape factor were determined $C_1 = -0.4378 \pm 0.0072$ and $C_2 = 0.0526 \pm 0.0021$. These values are in agreement with our previous results $C_1 = -0.4470 \pm 0.0013$ and $C_2 = 0.0552 \pm 0.0004$, which were determined in the experiment with the “target - detector” layout [3]. Due to the significantly lower analyzed statistics in comparison with [3] the parameters $C_1$ and $C_2$ were determined with lesser accuracy.
Figure 3. The results of fitting the measured spectrum (blue curve) to the theoretical curve (red curve). The bottom graph shows the difference between the experimental spectrum and the theoretical curve in standard deviation units.

5. Conclusion
The electron spectrum produced by β-decay of $^{210}$Bi was measured using the new 4π-spectrometer, consisting of two Si(Li) detectors. The spectrometer response function is close to the Gaussian and does not contain a low-energy part associated with backscattering of electrons from the crystal surface. The determined values of the nuclear shape factor parameters $C_1 = -0.4378 \pm 0.0072$ and $C_2 = 0.0526 \pm 0.0021$ are in agreement with the results of the previous measurements [3,5,6].

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