



Full Length Article

 4π spectrometer of β -decay electrons with Si(Li)-detectors

I.E. Alekseev^b, S.V. Bakhlanov^a, N.V. Bazlov^{a,c}, E.A. Chmel^a, A.V. Derbin^{a,*}, I.S. Drachnev^a,
I.M. Kotina^a, M.S. Mikulich^a, V.N. Muratova^a, N.V. Niyazova^a, D.A. Semonov^a, M.V. Trushin^a,
E.V. Unzhakov^a

^a St. Petersburg Nuclear Physics Institute, National Research Center "Kurchatov Institute", Gatchina 188300, Russia

^b V. G. Khlopin Radium Institute, St. Petersburg 194021, Russia

^c St. Petersburg State University, St Petersburg 199034, Russia

ARTICLE INFO

Keywords:

Semiconductor detectors

Beta spectrometry

ABSTRACT

We present a description of the originally developed β -spectrometer consisting of two Si(Li)-detectors with sensitive area thickness above 8 mm and 4π -geometry. The full absorption spectrometer allows for direct measurements of β -spectra, disregarding the corrections to response function induced by the electron backscattering from the crystal surface. In case of β -spectra of transitions to the excited state of the daughter isotope additional $3''$ BGO-detector is used in order to detect the γ -quanta in coincidence with the pair of Si(Li)-spectrometers.

1. Introduction

A high precision knowledge of β -spectrum shape of particular isotopes is absolutely necessary for determination of the neutrino oscillation parameters in experiments with reactors and artificial neutrino sources. The positive outcome of the LSND experiment [1] obtained almost two decades ago, the calibration results of radio-chemical Ga-Ge solar neutrino detectors [2,3] and the recent calculations of reactor neutrino spectrum known as the "reactor anomaly" [4,5] have raised a question about existence of the sterile neutrino, which is mainly connected with neutrino mass state shifted from three known states by $\delta m_{14}^2 \sim 1$ eV and with effective mixing angle $\sin^2(2\theta_s) \sim 0.1$. In addition to the series of reactor and accelerator experiments looking for neutrino oscillations into the sterile state, there are projects employing artificial neutrino sources. The most popular electron neutrino source is ^{51}Ce isotope, proposed for use with various types of neutrino detectors and actually used for mentioned calibrations of SAGE [6] and Gallex/GNO [7] and BEST experiment [8].

Among the artificial sources of electron antineutrinos, ^{144}Ce - ^{144}Pr is the most promising one, which was planned for use with KamLand [9] and Borexino [10] detectors. Unfortunately, the most advanced project of Borexino SOX was canceled for several reasons, including the ones unrelated to the technical side of the project. One of the particular objectives to be solved in any experiment with ^{144}Ce - ^{144}Pr is the precision measurement of its β -spectrum, aimed to determine the intensity and shape of the antineutrino spectrum. This task is of the utmost importance, since calculated sensitivity of the experiment to the oscillation parameters δm_{14}^2 and $\sin^2(2\theta_s)$ can be achieved only as

long as the ratio between heat power and activity of the source and the expected rate of inverse β -decay are known with required precision ($\leq 1.5\%$ in case of Borexino SOX).

The measurements of ^{144}Ce - ^{144}Pr and ^{210}Bi β -spectra via the silicon semiconductor β -spectrometer in classic "target-detector" layout has been carried out previously in [11–13]. The isotope ^{210}Bi belongs to the natural radioactive decay chain of ^{238}U and as a product of radioactive gas ^{222}Rn resides inside or on the surface of almost all structural materials. The precise measurement of ^{210}Bi β -spectrum remains a crucial task for background modeling of modern neutrino detectors, as well as for the dark matter searches or other low-background experiments.

Current paper contains the description of custom made β -spectrometer with 4π -geometry based on Si(Li) semiconductor detectors. The designed spectrometer is capable of registering electron's full energy, thus solving the problem of crystal surface backscattering, whose probability can reach tens of percent, depending on the electron energy and incidence angle. The initial results of ^{144}Ce - ^{144}Pr and ^{210}Bi β -spectra measurements via the 4π β -spectrometer consisting pair of Si(Li) detectors were published in [14–17].

2. Experimental setup

Silicon Lithium (Si(Li) - lithium doped silicon) detectors were fabricated from a single-crystal p-type silicon with specific resistivity of 4 k Ω /cm and mean carrier lifetime of 800 μs , using a standard well-proven process, developed at Petersburg Nuclear Physics Institute NRC

* Corresponding author.

E-mail address: derbin_av@npni.nrcki.ru (A.V. Derbin).

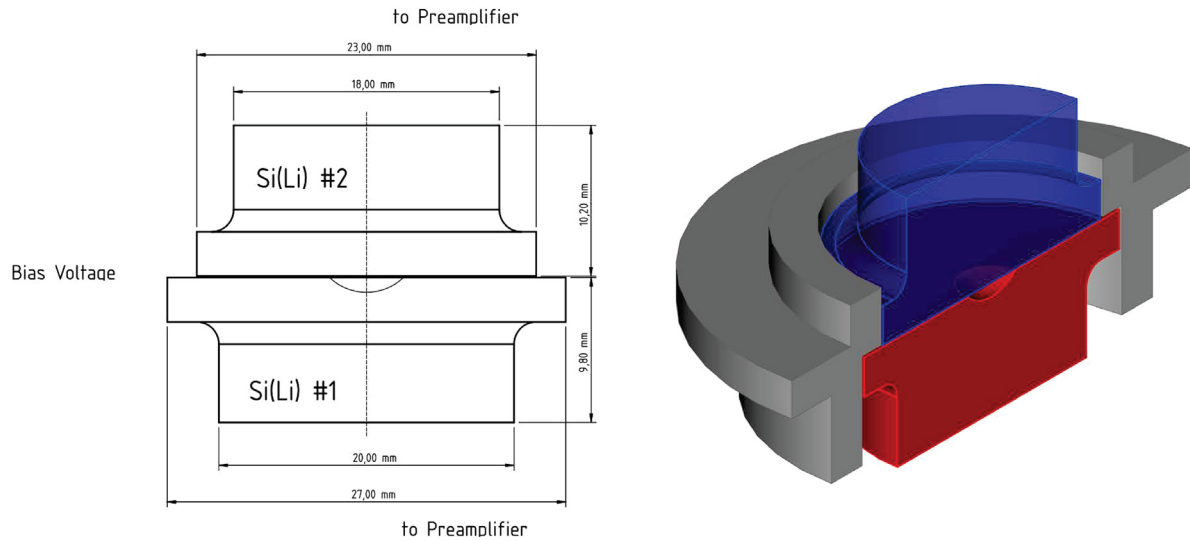


Fig. 1. Left: The layout of β -spectrometer with two planar Si(Li) detectors. Right: Vertical cross-section of spectrometer assembly with aluminum casing.

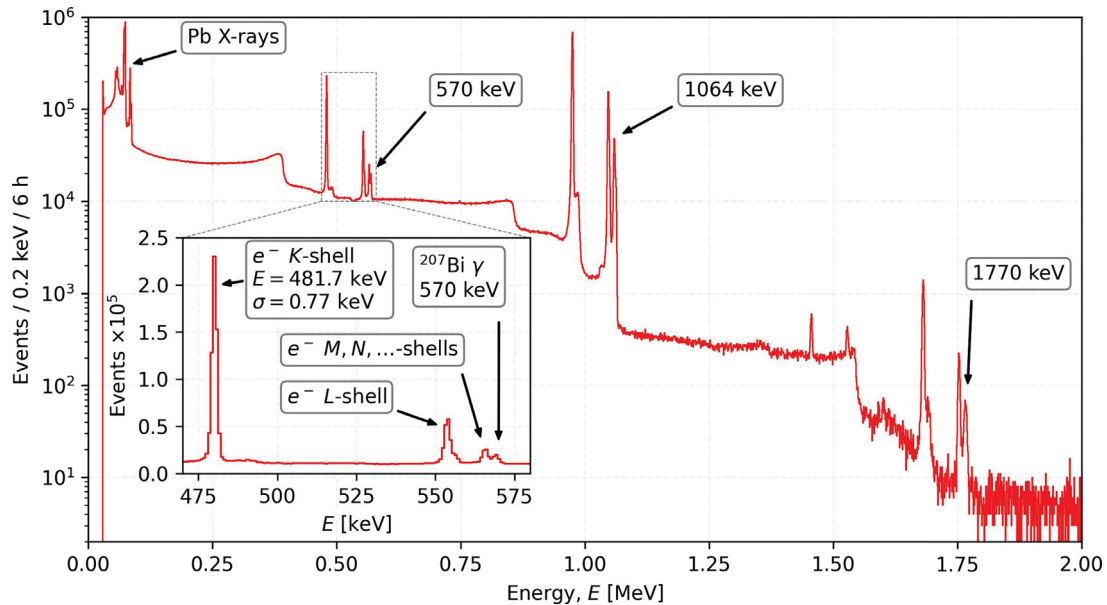


Fig. 2. The calibration spectra of the Si(Li) detector measured with ^{207}Bi source. The inset shows the electron peaks corresponding to internal conversion from K, L, M, and N shells of the 570 keV nuclear level.

KI. Detailed specifications for such detectors may be found in [11,12,18].

Two Si(Li) detectors with sensitive area thickness above 8 mm were custom-designed specifically for this experiment. Detector bulks were made in a “top hat” shape with outer diameters of 27 mm and 23 mm, sensitive area diameters of 20 mm and 18 mm, correspondingly. Both detectors had height of 9 mm. Different outer diameters were dictated by the dimensions of casing necessary for convenient face to face attachment of the detectors (see Fig. 1).

Performance of the manufactured detectors was tested in a separate vacuum cryostat, using gamma-rays (X-rays and nuclear lines) and electrons (conversion and Auger) produced by the ^{207}Bi source which was placed directly above the detector surface (see Fig. 2). The energy resolution of both detectors was found to be FWHM ≈ 2.0 keV for 482 keV electrons. The determined thickness of the dead layer, contributed by Pd and Au coatings and surface Si layer turned out to be ~ 500 nm in silicon equivalent. Upon traversing this depth, an electron with energy of 20 keV or 3 MeV would lose around 1 keV or 0.1 keV, correspondingly.

A small cavity was machined in the middle part of one of the detectors, with diameter of 5 mm and 1 mm deep. The investigated β -source (^{144}Ce , ^{210}Pb) was deposited inside this cavity, directly upon the golden coating of the planar Si(Li) detector. The second detector was placed, without any gap, on top of the cavity and the bias voltage was supplied to the shared n^+ -contact (Fig. 1).

The whole composition was placed inside the vacuum cryostat and cooled down to the liquid nitrogen temperature. The refrigeration is usually necessary for reduction of the detector reverse current and consequent improvement of the energy resolution. Both Si(Li) detectors had their own charge sensitive preamplifier with resistive feedback and cooled first field effect transistor (FET). Two separate sets of electronics were used for the signal processing: CAMAC and VME. CAMAC channel consisted of the BUI-3K amplifier and 12-bit successive approximation ADC with 4096 channels. The coincidence circuit was implemented at the ADC level via the conversion-blocking signals. The signals in VME channel were digitized by 14-bit digitizer module (CAEN V1725) with 8

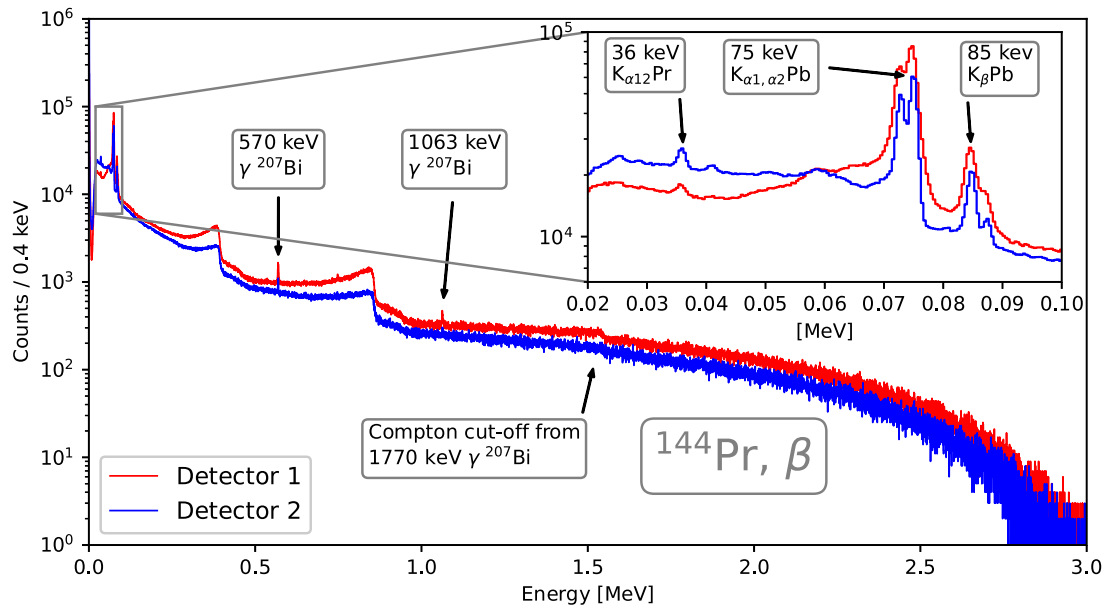


Fig. 3. The calibration spectra of the Si(Li) detectors measured with ^{207}Bi source outside the cryostat (s)pectrum of detector with cavity is represented by red line). The inset shows zoom-in of the low-energy region.

channels and 250 MHz sampling rate. Operation via two separate electronic sets allows for a comparison of coincidence selection efficiency and energy resolution between analogue and digital channels.

Coincidence circuit includes 3" BGO scintillation detector for selection of events of β -decay into the excited nuclear states. The choice of relatively small BGO-detector was driven by requirement for high γ -registration efficiency in case of low background of random coincidences. BGO-detector was placed at 25 mm distance from the shared surface of Si(Li) detectors (i. e. from the ^{144}Ce – ^{144}Pr source), providing 20% geometric efficiency. The data produced by registered events is represented as a series of time and amplitude signals from two Si(Li) and single BGO detectors. The entire assembly of Si(Li) and BGO detectors was surrounded by moderate layer of passive shielding ($\sim 30 \text{ g/cm}^2$) in order to reduce the natural radioactivity background.

The adopted (anti-)coincidence operation mode allows for the direct measurement of β -spectra, which does not require any complex corrections describing the electron backscattering from the surface of the detector. The deviation of response function from pure Gaussian is related mostly to the energy loss of the electron inside the source material and dead layer of the detector and also with escape of electron bremsstrahlung from the detector volume. For 1 MeV electrons the widths of the response function at 1/2, 1/10 and 1/40 of the height are 2 (2) keV, 5 (3.7) keV and 9 (4.6) keV, respectively. The value in brackets are expected for a Gaussian distribution and the broadening of the response function occurs on the left side of the Gaussian.

The fabrication of ultra thin homogeneous β -sources is a whole separate topic [13], far too complex to fit inside this article. We would like to note, though, that presence of low additional α -activity in the source helps to ensure the thickness and density homogeneity of the source.

The contribution of total radiative losses increases along with electron energy. In case of silicon, for 1 MeV and 3 MeV electrons they turn out to be 0.8% and 4.7%, correspondingly. Differential radiative loss dE/dx also rises accordingly from 1.5% to 4.7%. The correction that takes bremsstrahlung escape probability into account can be obtained through the numerical simulations with use of BGO coincidence spectrum.

3. Results

After installation of the Si(Li) detector assembly into the cryostat, the energy calibration was performed via external ^{207}Bi source that

was placed onto the cryostat beryllium window. While the calibration was performed with ^{144}Ce – ^{144}Pr source present, the spectrum clearly showed X-ray (75–78 keV) and γ -line (570 keV, 1063 keV) full absorption peaks, and also the prominent Compton scattering cutoff at 1547 keV from 1770 keV γ -line (see Fig. 3). These spectral features were used to calibrate both detectors.

The expected intensities of $K_{\alpha 1}$, $K_{\alpha 2}$, $K_{\beta 123}$ Pb peaks from external ^{207}Bi source were calculated for various thicknesses and fixed diameter of sensitive region. The comparison of measured X-ray intensity peaks (the inset in Fig. 3) against calculated ones allows to evaluate the thickness of detector's sensitive region. Thus, determined thicknesses for both detectors were found to be above 8.5 mm, providing the full absorption for electrons with energies up to 3.3 MeV, disregarding the backscattering cases. Coincidence spectrum of Si(Li) detectors with external ^{207}Bi source is given in Fig. 4. Slanted lines represent the total Compton cutoff energies of 570 keV, 1063 keV and 1779 keV γ -lines. Maximum electron energy in case of reverse scattering amounts to $E_C = 2E_\gamma^2/(2E_\gamma + m_e)$, yielding 394 keV, 857 keV and 1547 keV, respectively. The ranges of electrons with higher energies in silicon are 0.7 mm, 1.9 mm and 3.8 mm, respectively. The coincidences of signals from Si(Li) detectors are mostly caused by Compton electrons, traversing from upper detector into the bottom one. Rectangles in Fig. 4 denote the events when cascaded 1064 keV and 570 keV γ -quanta undergo Compton scattering in different detectors.

The decay scheme of the ^{144}Ce – ^{144}Pr nuclei are shown in Fig. 6. The ^{144}Ce nucleus undergoes three first-order forbidden nonunique beta-decays to the ground ($Q_\beta = 318.7 \text{ keV}$) and excited levels 1^- ($Q_\beta = 238.6 \text{ keV}$ and $Q_\beta = 185.2 \text{ keV}$) of the ^{144}Pr nucleus. Decays of the ^{144}Pr to the ground ($Q_\beta = 2997.5 \text{ keV}$) and first excited ($Q_\beta = 2301.0 \text{ keV}$) states of the ^{144}Nd nucleus correspond to first-order forbidden nonunique and unique transitions, respectively. Decay into the 1^- level with an energy of 2185 keV ($Q_\beta = 811.8 \text{ keV}$) is an allowed transition. The studied electron spectra produced by ^{144}Ce – ^{144}Pr β -decays registered by a single or both Si(Li) detectors are shown in Fig. 5. Comparing curves 1 and 3 one can find that the share of electrons backscattered by detector surface at 1 MeV energy amounted to 28%. This value decreases down to 20% as electron energy rises up to 2.5 MeV and is determined by the particular geometry of the source. It is worth noting that in case of backscattering the shape of registered energy spectrum (Fig. 5, curve 4) significantly varies from the actual electron energy spectrum (Fig. 5, curve 1). Full β -spectrum 1 obtained

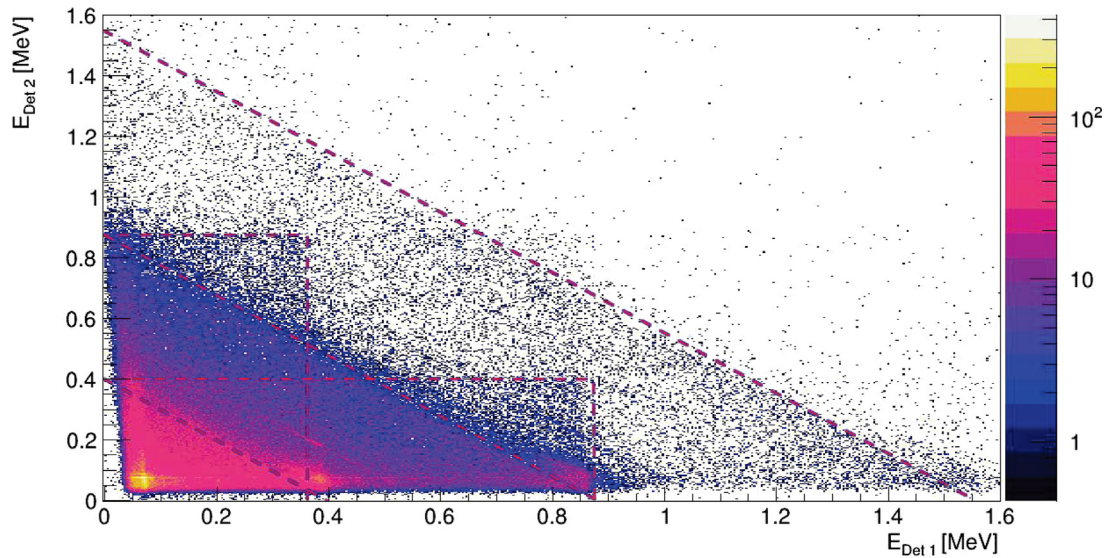


Fig. 4. The coincidence spectrum of two combined Si(Li) detectors measured with ^{207}Bi source. Slanted lines correspond to the Compton scattering of 570 keV, 1064 keV and 1770 keV γ -quanta. Rectangles denote events from the γ -cascade 1064 keV and 570 keV.

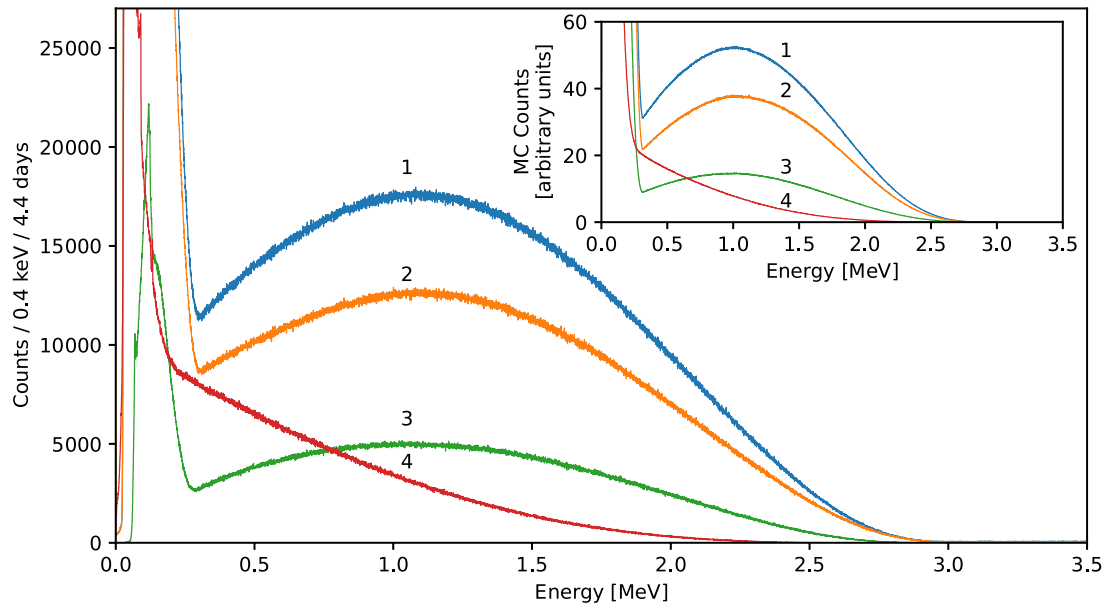


Fig. 5. The spectra of ^{144}Ce - ^{144}Pr source measured by 4π β -spectrometer: 1 – spectrum of total energy of all registered events, 2 – energy spectrum of single-site events, 3 – spectrum of total energy of multi-site events, 4 – single detector energy spectrum of multi-site events. The inset shows the spectra obtained by Monte-Carlo simulations.

as a sum of spectra 2 and 3, solves the problem of determining the response function with respect to electron backscattering.

Similar spectra calculated using GEANT4 simulations are shown in the inset in Fig. 5. One can see good agreement between the measured and calculated spectra, that indicates the correctness of the response function of the 4π -spectrometer.

Provided the electron spectrum was measured with almost Gaussian response function, the antineutrino spectrum can be obtained from the relation $Q_\beta = E_e + E_\nu$, here Q_β is the β -spectrum end-point energy, E_e and E_ν - energies of electron and antineutrino, correspondingly. In case of ^{144}Ce - ^{144}Pr source it is possible for neutrino energies to go below 2.7 MeV (difference between β -spectrum end-point energies of ^{144}Pr and ^{144}Ce). At energies below 300 keV the measured electron spectrum becomes a superposition of ^{144}Pr and ^{144}Ce β -spectra and the antineutrino spectrum must be determined using the theoretical corrections and shape factor parameters, obtained from the fitting of (0.3–3.0) MeV interval of ^{144}Pr β -spectrum.

The measurement of Si(Li) detector spectra in coincidence with signals from BGO detector allows for separation of β -spectra corresponding to transitions that produce daughter nuclei in the excited states. This appears to be important aspect of the measurements in case of ^{144}Pr isotope, since allowed $0^- \rightarrow 1^-$ transition from ground state 0^- of ^{144}Pr into 1^- 2186 keV level of ^{144}Nd has well defined shape and does not require introduction of shape factor for fitting. The agreement of the total measured spectrum shape to the shape of the allowed β -transition represents an important validity criterion for the measurements, response function and fitting procedure.

The 1^- 2186 keV nuclear level of ^{144}Nd can discharge directly into the ground state or through the intermediate 2^+ state, emitting 2186 keV (0.69%) or 1489 keV and 697 keV (0.28%) γ -quanta, as shown on the inset of Fig. 6. The same figure presents the total energy spectrum of events registered by BGO detector and the spectrum of coincidence with β -spectrometer events. The full spectrum contains

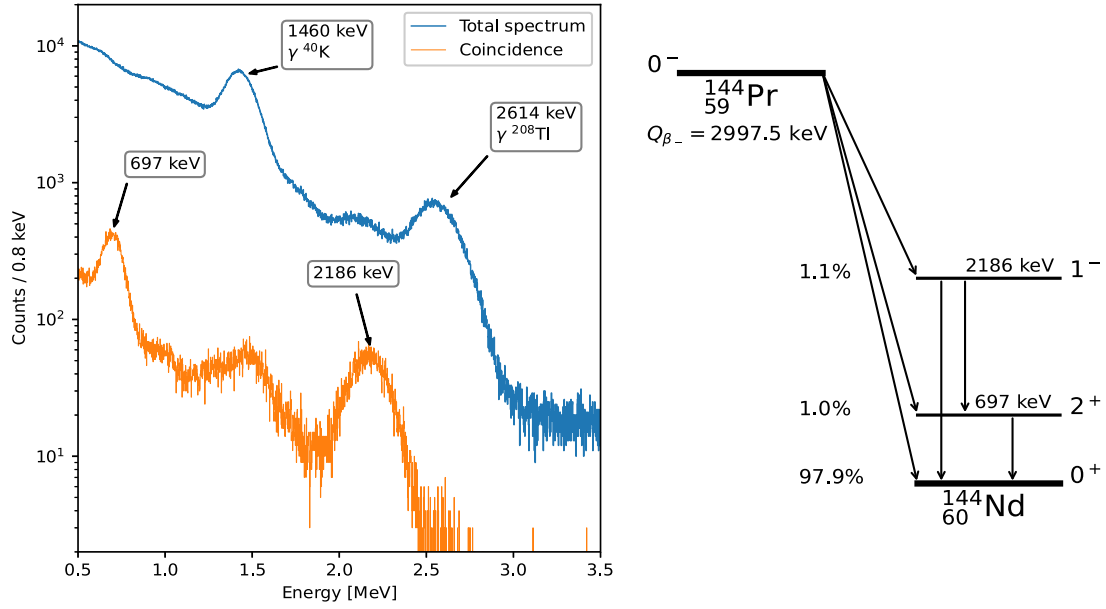


Fig. 6. Left: Spectrum of events acquired with BGO detector (total and in coincidence with Si(Li) spectrometer). Right: Decay scheme for ^{144}Pr β -decay.

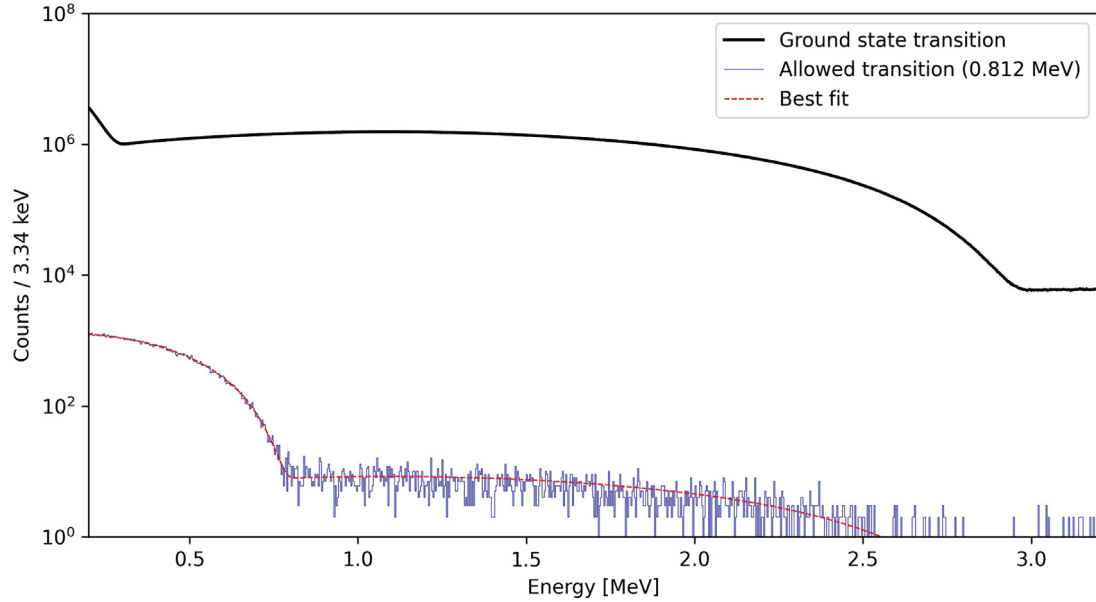


Fig. 7. The spectrum of allowed β -transition $^{144}\text{Pr}(0^-) \rightarrow ^{144}\text{Nd}(1^-)$ ($Q_\beta = 0.812$ MeV), measured in coincidence with BGO detector signal in comparison against the transition to ground state $^{144}\text{Nd}(0^+)$ ($Q_\beta = 3.0$ MeV). Fit result is shown by dashed red line.

prominent full absorption peaks of 1460 keV (^{40}K) and 2614 keV (^{208}Tl) γ -lines from the natural chain of ^{232}Th .

The coincidence spectrum (Fig. 6, curve 2) contains 697 keV and 2186 keV peaks, which correspond to the β -transitions into the excited states of ^{144}Nd nucleus. In order to select transitions to the 1^- state, we set the condition on the energy of γ -quantum registered by BGO detector to be above 1 MeV. This condition is fulfilled for the γ -quanta from the full absorption peak and part of the Compton scattering tail and allows for exclusion of transitions to 2^+ state followed by a single 697 keV γ -quantum. The energy resolution of the BGO detector allows to separate reliably the energies of 697 keV and 1 MeV.

The spectrum of Si(Li) detectors in coincidence with BGO signals that exceeded 1 MeV is given in Fig. 7. It consists of the β -spectrum of the allowed transition of $^{144}\text{Pr}(0^-)$ to the excited state of $^{144}\text{Nd}(1^-)$ and random coincidences. The spectrum shape is in good accordance with theoretical shape of the allowed β -transition with 812 keV endpoint,

thus confirming that the response function of the 4π β -spectrometer is indeed very similar to Gaussian. The same Fig. 7 shows the full spectrum, mainly attributed to the ground state transition $^{144}\text{Pr}(0^-) \rightarrow ^{144}\text{Nd}(0^+)$.

4. Conclusion

We presented the performance review of the newly developed spectrometer suited for the measurements of β -spectra with endpoint energies below 3 MeV. The spectrometer consists of two Si(Li) detectors with thickness of the sensitive layer above 8 mm and a BGO scintillation crystal for study of transitions to the excited states. The detector response function proved to be very similar to Gaussian and does not contain the term caused by the electron backscattering from the crystal surface. This feature allows for the direct measurement of electron

energy and, consequently, obtaining the electron antineutrino spectrum. In combination with scintillation BGO detector, the spectrometer can be employed for acquisition of spectra that correspond to the transitions to the excited states of the daughter nuclei. The designed spectrometer was successfully employed for measurements of β -spectra of ^{144}Ce - ^{144}Pr and ^{210}Bi sources [14–17].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request

Acknowledgments

This work has been carried out with support of Russian Foundation for Basic Research (project #20-02-00571) and Russian Science Foundation (projects #21-12-00063, #22-22-00017).

References

- [1] C. Athanassopoulos, L.B. Auerbach, R.L. Burman, D.O. Caldwell, E.D. Church, I. Cohen, J.B. Donahue, A. Fazely, F.J. Federspiel, G.T. Garvey, R.M. Gunasingha, R. Imlay, K. Johnston, H.J. Kim, W.C. Louis, R. Majkic, K. McIlhany, G.B. Mills, R.A. Reeder, V. Sandberg, D. Smith, I. Stancu, W. Strossman, R. Tayloe, G.J. VanDalen, W. Vernon, N. Wadia, J. Waltz, D.H. White, D. Works, Y. Xiao, S. Yellin, Results on $\nu_\mu \rightarrow \nu_e$ neutrino oscillations from the LSND experiment, *Phys. Rev. Lett.* **81** (1998) 1774–1777.
- [2] J.N. Abdurashitov, V.N. Gavrin, S.V. Girin, V.V. Gorbachev, T.V. Ibragimova, A.V. Kalikhov, N.G. Khairnasov, T.V. Knodel, V.N. Kornoukhov, I.N. Mirmov, A.A. Shikhin, E.P. Veretenkin, V.M. Vermul, V.E. Yants, G.T. Zatspin, Yu. S. Khomyakov, A.V. Zvonarev, T.J. Bowles, J.S. Nico, W.A. Teasdale, D.L. Wark, M.L. Cherry, V.N. Karaulov, V.L. Levitin, V.I. Maev, P.I. Nazarenko, V.S. Shkol'nik, N.V. Skorikov, B.T. Cleveland, T. Daily, R. Davis, K. Lande, C.K. Lee, P.S. Wildenhain, S.R. Elliott, J.F. Wilkerson, Measurement of the response of a gallium metal solar neutrino experiment to neutrinos from a ^{51}Cr source, *Phys. Rev. C* **59** (1999) 2246–2263.
- [3] W. Hampel, J. Handt, G. Heusser, J. Kiko, T. Kirsten, M. Laubenstein, E. Pernicka, W. Rau, M. Wojcik, Y. Zakharov, R.v. Ammon, K.H. Ebert, T. Fritsch, D. Heidt, E. Henrich, L. Stielglitz, F. Weirich, M. Balata, M. Sann, F.X. Hartmann, E. Bellotti, C. Cattadori, O. Cremonesi, N. Ferrari, E. Fiorini, L. Zanolini, M. Altmann, F.v. Feilitzsch, R. Mößbauer, S. Wänninger, G. Berthomieu, E. Schatzman, I. Carmi, I. Dostrovsky, C. Bacci, P. Belli, R. Bernabei, S. d'Angelo, L. Paoluzzi, M. Cribier, J. Rich, M. Spiro, C. Tao, D. Vignaud, J. Boger, R.L. Hahn, J.K. Rowley, R.W. Stoenner, J. Weneser, GALLEX solar neutrino observations: results for GALLEX IV, *Phys. Lett. B* **447** (1) (1999) 127–133.
- [4] G. Mention, M. Fechner, Th. Lasserre, Th. A. Mueller, D. Lhuillier, M. Cribier, A. Letourneau, Reactor antineutrino anomaly, *Phys. Rev. D* **83** (2011) 073006.
- [5] C. Giunti, Y.F. Li, C.A. Ternes, Z. Xin, Reactor antineutrino anomaly in light of recent flux model refinements, *Phys. Lett. B* **829** (2022) 137054.
- [6] SAGE Collaboration, J.N. Abdurashitov, V.N. Gavrin, S.V. Girin, V.V. Gorbachev, T.V. Ibragimova, A.V. Kalikhov, N.G. Khairnasov, T.V. Knodel, V.N. Kornoukhov, I.N. Mirmov, A.A. Shikhin, E.P. Veretenkin, V.M. Vermul, V.E. Yants, G.T. Zatspin, Yu.S. Khomyakov, A.V. Zvonarev, T.J. Bowles, J.S. Nico, W.A. Teasdale, D.L. Wark, M.L. Cherry, V.N. Karaulov, V.L. Levitin, V.I. Maev, P.I. Nazarenko, V.S. Shkol'nik, N.V. Skorikov, B.T. Cleveland, T. Daily, R. Davis, K. Lande Jr., C.K. Lee, P.S. Wildenhain, S.R. Elliott, J.F. Wilkerson, Measurement of the response of a gallium metal solar neutrino experiment to neutrinos from a ^{51}Cr source, *Phys. Rev. C* **59** (1999) 2246.
- [7] GALLEX Collaboration, W. Hampel, G. Heusser, J. Kiko, T. Kirsten, M. Laubenstein, E. Pernicka, W. Rau, U. Rönn, C. Schlosser, M. Wójcik, R. v. Ammon, K.H. Ebert, T. Fritsch, D. Heidt, E. Henrich, L. Stielglitz, F. Weirich, M. Balata, F.X. Hartmann, J. Weneser, Final results of the ^{51}Cr neutrino source experiments in GALLEX, *Phys. Lett. B* **420** (1–2) (1998) 114–127.
- [8] V.V. Barinov, S.N. Danshin, V.N. Gavrin, V.V. Gorbachev, D.S. Gorbunov, T.V. Ibragimova, Yu. P. Kozlova, L.V. Kravchuk, V.V. Kuzminov, B.K. Lubsandorzhiev, Yu. M. Malyskhin, I.N. Mirmov, A.A. Shikhin, E.P. Veretenkin, B.T. Cleveland, H. Ejiri, S.R. Elliott, I. Kim, R. Massarczyk, D. Frekers, W.C. Haxton, V.A. Matveev, G.V. Trubnikov, J.S. Nico, A.L. Petelin, V.A. Tarasov, A.I. Zvir, R.G.H. Robertson, D. Sinclair, J.F. Wilkerson, Search for electron-neutrino transitions to sterile states in the best experiment, *Phys. Rev. C* **105** (2022) 065502.
- [9] A. Gando, Y. Gando, S. Hayashida, H. Ikeda, K. Inoue, K. Ishidoshiro, H. Ishikawa, M. Koga, R. Matsuda, S. Matsuda, T. Mitsui, D. Motoki, K. Nakamura, Y. Oki, M. Otani, I. Shimizu, J. Shirai, F. Suekane, A. Suzuki, Y. Takemoto, K. Tamae, K. Ueshima, H. Watanabe, B.D. Xu, S. Yamada, Y. Yamauchi, H. Yoshida, M. Cribier, M. Durero, V. Fischer, J. Gaffiot, N. Jonquieres, A. Kouchner, T. Lasserre, D. Leterme, A. Letourneau, D. Lhuillier, G. Mention, G. Rampal, L. Scola, Ch. Veyssiere, M. Vivier, P. Yala, B.E. Berger, A. Kozlov, T. Banks, D. Dwyer, B.K. Fujikawa, K. Han, Yu. G. Kolomensky, Y. Mei, T. O'Donnell, P. Decowski, D.M. Markoff, S. Yoshida, V.N. Kornoukhov, T.V.M. Gelis, G.V. Tikhomirov, J.G. Learned, J. Maricic, S. Matsuno, R. Milincic, H.J. Karwowski, Y. Efremenko, A. Detwiler, S. Enomoto, CeLAND: search for a 4th light neutrino state with a 3 PBq ^{144}Ce - ^{144}Pr electron antineutrino generator in KamLAND, 2013.
- [10] G. Bellini, D. Bick, G. Bonfini, D. Bravo, B. Caccianiga, F. Calaprice, A. Caminata, P. Cavalcante, A. Chavarria, A. Chepurinov, D. D'Angelo, S. Davini, A. Derbin, A. Etenko, G. Fernandes, K. Fomenko, D. Franco, C. Galbiati, C. Ghiano, M. Göger-Neff, A. Goretti, C. Hagner, E. Hungerford, Aldo. Ianni, Andrea. Ianni, V. Kobychiev, D. Korabiev, G. Korga, D. Krasnický, D. Kryn, M. Laubenstein, J.M. Link, E. Litvinovich, F. Lombardi, P. Lombardi, L. Ludhova, G. Lukyanchenko, I. Machulin, S. Manecki, W. Maneschg, E. Meroni, M. Meyer, L. Miramonti, M. Misiaszek, P. Mosteiro, V. Muratova, L. Oberauer, M. Obolensky, F. Orlica, K. Otis, M. Pallavicini, E. Pantic, L. Papp, S. Perasso, A. Pocar, G. Ranucci, A. Razeto, A. Re, A. Romani, N. Rossi, R. Saldanha, C. Salvo, S. Schönert, D. Semenov, H. Simgen, M. Skorokhvatov, O. Smirnov, A. Sotnikov, S. Sukhotin, Y. Suvorov, R. Tartaglia, G. Testera, E. Unzhakov, R.B. Vogelaar, H. Wang, M. Wojcik, M. Wurm, O. Zaimidoroga, S. Zavatarelli, G. Zuzel, Sox: Short distance neutrino oscillations with borexino, *J. High Energy Phys.* **2013** (8) (2013) 38.
- [11] N.V. Bazlov, S.V. Bakhlanov, A.V. Derbin, I.S. Drachnev, V.K. Eremin, I.M. Kotina, V.N. Muratova, N.V. Pilipenko, D.A. Semenov, E.V. Unzhakov, E.A. Chmel, A beta spectrometer based on silicon detectors, *Instrum. Exp. Techn.* **61** (3) (2018) 323–327.
- [12] I.E. Alekseev, 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 ^{144}Ce - ^{144}Pr decays, *Nucl. Instrum. Methods Phys. Res. A* **890** (2018) 64–67.
- [13] 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, Precision measurement of the ^{210}Bi β spectrum, *Phys. Rev. C* **102** (2020) 064329.
- [14] S. Bakhlanov, A. Derbin, I. Drachnev, I. Kotina, I. Lomskaya, V. Muratova, N. Pilipenko, D. Semenov, E. Unzhakov, 4π Semiconductor beta-spectrometer for measurement of ^{144}Ce - ^{144}Pr spectra, *J. Phys. Conf. Ser.* **1390** (2019) 012117.
- [15] I.E. Alekseev, S.V. Bakhlanov, A.V. Derbin, I.S. Drachnev, I.M. Kotina, V.N. Muratova, N.V. Niyazova, D.A. Semenov, M.V. Trushin, E.V. Unzhakov, E.A. Chmel, A silicon 4π spectrometer of β -decay electrons with energies of up to 3 MeV, *Instrum. Exp. Techn.* **64** (2) (2021) 190–194.
- [16] I.E. Alekseev, S.V. Bakhlanov, A.V. Derbin, I.S. Drachnev, I.M. Kotina, I.S. Lomskaya, M.S. Mikulich, V.N. Muratova, N.V. Niyazova, D.A. Semenov, M.V. Trushin, E.V. Unzhakov, ^{144}Ce - ^{144}Pr Spectrum measurement with 4π semiconductor β -spectrometer, *J. Phys. Conf. Ser.* **2103** (1) (2021) 012141.
- [17] I.E. Alekseev, S.V. Bakhlanov, A.V. Derbin, I.S. Drachnev, I.M. Kotina, A.M. Kuzmichev, I.S. Lomskaya, M.S. Mikulich, V.N. Muratova, N.V. Niyazova, D.A. Semenov, M.V. Trushin, E.V. Unzhakov, New measurement of the β -spectrum of ^{210}Bi with a silicon 4π β -spectrometer, *J. Phys. Conf. Ser.* **2103** (1) (2021) 012144.
- [18] N.V. Bazlov, A.V. Derbin, I.S. Drachnev, G.E. Gicharevich, I.M. Kotina, O.I. Konkov, N.V. Pilipenko, E.A. Chmel, S.N. Abolmasov, E.I. Terukov, E.V. Unzhakov, Si(Li) detector with ultra-thin entrance window on the diffusive lithium side, *J. Phys. Conf. Ser.* **1400** (2019) 055056.