



JOINT INSTITUTE FOR NUCLEAR RESEARCH
V. P. Dzhelepov Laboratory of Nuclear Problems

FINAL REPORT ON THE START PROGRAMME

*Development of prototype neutrino detector
(COFE technology)*

Supervisor:

Dr. Mark Vladislavovich
Shirchenko

Student:

Artyom Shishin, Russia
Novosibirsk State Technical
University

Participation period:

February 15 – April 11,
Winter Session 2026

Dubna, 2026

Contents

Abstract.....	3
Introduction	4
Project goals.....	6
Experimental.....	7
Results and discussion.....	8
Initial Tuning of Spectra	8
Spectral analysis.....	9
Investigation of the BaF₂ crystal using a germanium detector	10
Conclusion.....	13
References	14
Acknowledgments.....	15

Abstract

This report presents results of a prototype neutrino detector study developed within the COFE technology at the Dzhelepov Laboratory of Nuclear Problems, JINR. The detector consists of a composite scintillation medium: BaF₂ crystallites, glycerol as a hydrogen-containing target for inverse beta decay, GdF₃ for neutron capture, and wavelength-shifting fibers for light collection. The main objectives included tuning the readout chain, processing cosmic radiation spectra, and evaluating the radioactive purity of the BaF₂ crystal using an HPGe spectrometer.

Spectral tuning positioned the main muon peak between QDC channels 56 and 60. Comparative analysis of edge and central channels revealed no significant edge effects in the horizontal assemblies, whereas an edge effect was observed in the vertical assemblies (channel 16 – edge, channel 20 – central). HPGe spectroscopy identified γ -lines from the uranium series (²¹⁴Bi, ²¹⁴Pb, ²²⁶Ra) and thorium series (²⁰⁸Tl, ²²⁸Ac, ²¹²Pb). Peaks corresponding to K _{α} and K _{β} X-ray emission of barium were also observed.

Introduction

Antineutrino detection represents an advanced field in experimental particle physics. It enables a wide range of applications, from fundamental studies of neutrino properties to the monitoring of nuclear reactor power. Electron antineutrinos ($\bar{\nu}_e$) are produced in large quantities via β -decay of fission products of nuclear fuel. Their energy spectrum and intensity directly depend on the fuel composition and reactor power.

For their detection, the inverse beta decay reaction is commonly employed:



However, this process is associated with significant technical challenges. Neutrinos interact with matter extremely weakly, with interaction cross sections ranging from 10^{-34} to 10^{-43} cm². Consequently, their detection requires detectors with enormous mass and volumes of tens of tons, which also entails substantial costs.

Considerable progress in the field of reactor antineutrino detection has been achieved by a number of experimental projects. One notable example is the Cowan–Reines experiment conducted in the 1950s, which provided the first experimental proof of the existence of the neutrino. The experiment employed a liquid scintillator detector based on cadmium chloride (CdCl₂), placed near the Savannah River nuclear reactor. It also introduced the use of time coincidence between the positron and neutron signals [1].

The Daya Bay experiment is one of the most successful projects in this field. Using eight identical liquid scintillator detectors placed at different distances from the reactor core, the experiment achieved high-precision measurements of neutrino oscillation parameters. The detectors utilized a liquid scintillator based on linear alkylbenzene (LAB) with the addition of

2,5-diphenyloxazole (PPO) and 1,4-bis(5-phenyl-2-oxazolyl)benzene (bis-MSB) for scintillation light collection, as well as gadolinium to enhance neutron detection efficiency. Each detector features a three-level structure: an inner region containing the liquid scintillator, an intermediate gamma-ray shielding layer, and an outer muon veto system. This complex design ensures efficient background suppression but requires large detector volumes and massive passive shielding [2].

The DANSS (Detector of the Reactor Antineutrino based on Solid Scintillator) experiment demonstrates an alternative approach to neutrino detection. The detector consists of 2,500 plastic scintillator plates with a total mass of approximately one ton, assembled into 50 layers, with wavelength-shifting fibers placed between the plates for light collection. Thanks to its compact design and mobility — the detector can be repositioned vertically — it achieves a high signal-to-background ratio without the need for massive shielding [3].

Despite the successes of these projects, they share a common drawback: the necessity of using large volumes of scintillator material and, with the exception of DANSS, massive passive shielding. This creates a demand for the development of a compact detector with relatively small dimensions and reduced cost. A detector meeting these requirements has been developed at the Laboratory of Nuclear Problems at JINR using the COFE (Chemical Optical Fluoride Engineering) technology [4].

Project goals

The main objective of the project is to test a new detector based on COFE technology, which, owing to its design features and detection methodology, could operate without massive shielding. Additional advantages include its compactness, high gamma-ray detection efficiency, neutron detection capability, fast timing resolution, and scalability.

Since the detector is currently at the prototype stage, it is necessary to test its response to cosmic radiation and perform energy calibration. Accordingly, the objectives of this work were as follows:

1. Connecting all photomultiplier tube channels;
2. Tuning the spectra according to the amplitude of the strongest signal;
3. Processing cosmic radiation spectra;
4. Investigation of the BaF₂ crystal using a germanium detector.

Experimental

The detector active volume is contained in a Teflon cube with dimensions of 20×20×20 cm (figure 1) [4].

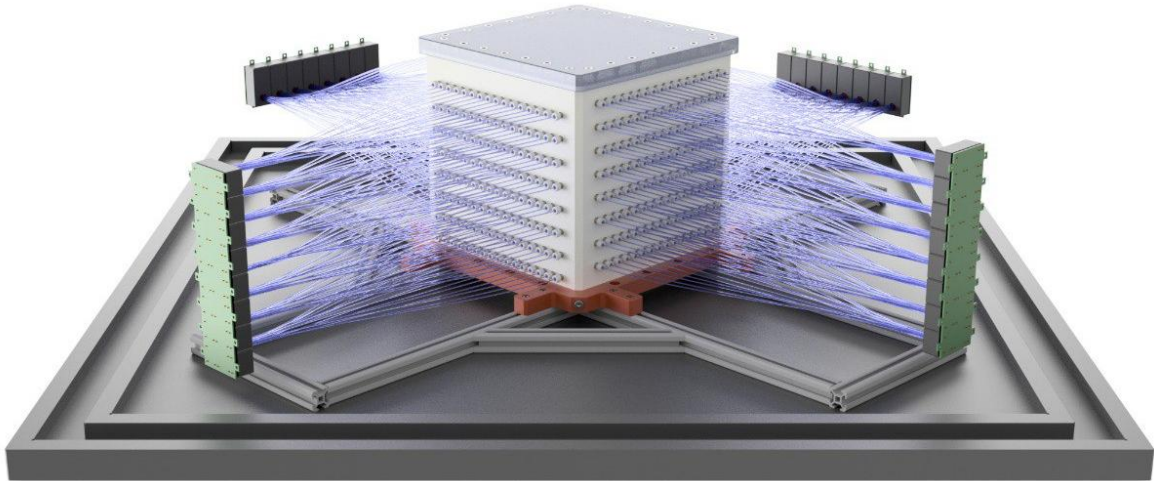


Figure 1 – 3D model of the detector prototype [4]

Barium fluoride (BaF_2) crystals in the form of small crystallites are used as the scintillation material. This material was selected due to its high density (4.89 g/cm^3) and high atomic number.

Glycerol serves as the hydrogen-containing medium for the inverse beta decay reaction and fills the space between the barium fluoride crystals. Glycerol was chosen because its refractive index (1.47) is close to that of BaF_2 (1.49).

Gadolinium fluoride (GdF_3) is used for neutron capture, comprising 0.6% by weight of the total detecting medium.

Light collection is achieved using Kuraray B-2 wavelength-shifting (WLS) fibers, which are assembled in a holder.

Results and discussion

Initial Tuning of Spectra

Calibration is illustrated using the spectrum of Channel 4 as an example. The spectrum is shown in Figure 2.

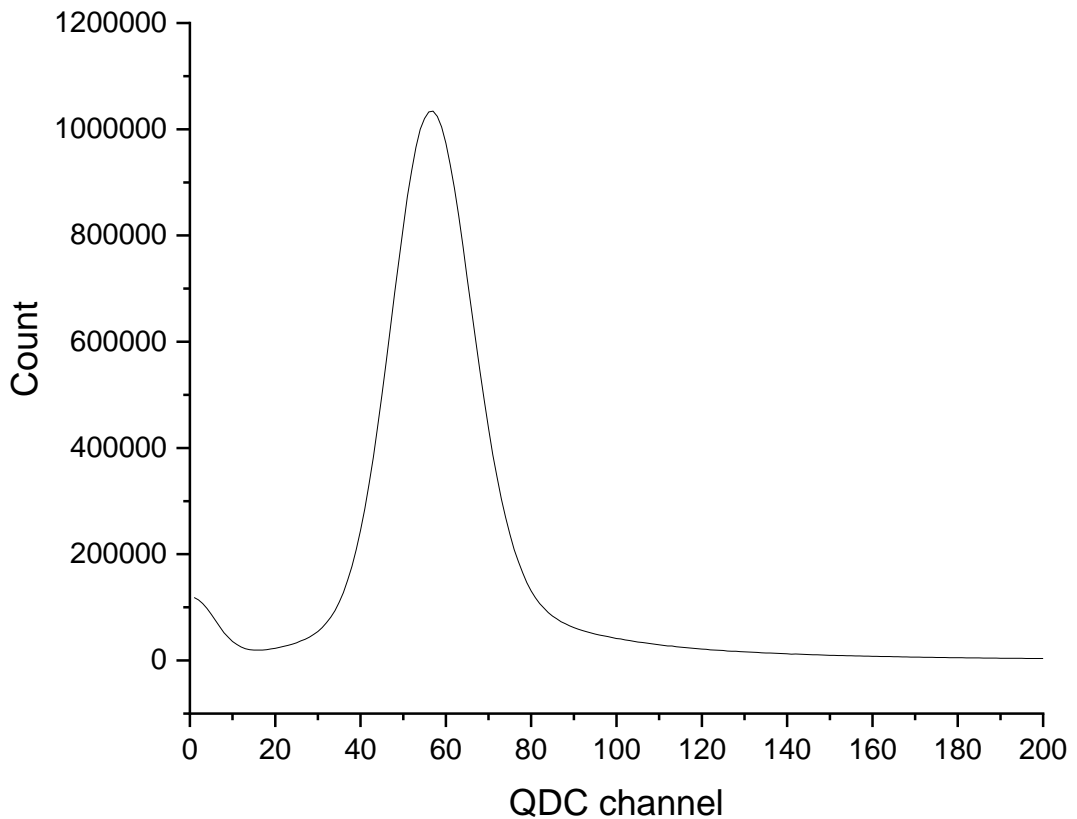


Figure 2 – Spectrum of Channel 4

A distinct peak is clearly visible in the spectrum, with its center located at approximately channel 60.

The tuning of the spectra was performed using OriginPro software. The precise position of the peak was determined using the Peak Analyzer tool. The peak was fitted using a Gaussian function. By adjusting the voltage on each channel, the position of the spectrum was corrected so that the main peak fell within the range of 56–60 channels for all major channels. The results are presented in Table 1.

Table 1 – Position of the main peak for all channels

Channel	0	1	2	3	4	5
Peak Pos.	59,7	56,4	58,3	61,8	57,0	57,0
Channel	6	7	16	17	18	19
Peak Pos.	59,6	57,1	57,2	58,5	58,8	58,3
Channel	20	21	22	23	24	25
Peak Pos.	57,7	56,9	57,3	56,8	56,8	59,9
Channel	26	27	28	29	30	31
Peak Pos.	59,0	59,8	59,5	59,7	58,9	57,1

Spectral analysis

Signal processing is performed using channels arranged either horizontally or vertically on different sides of the detector (Figure 3).

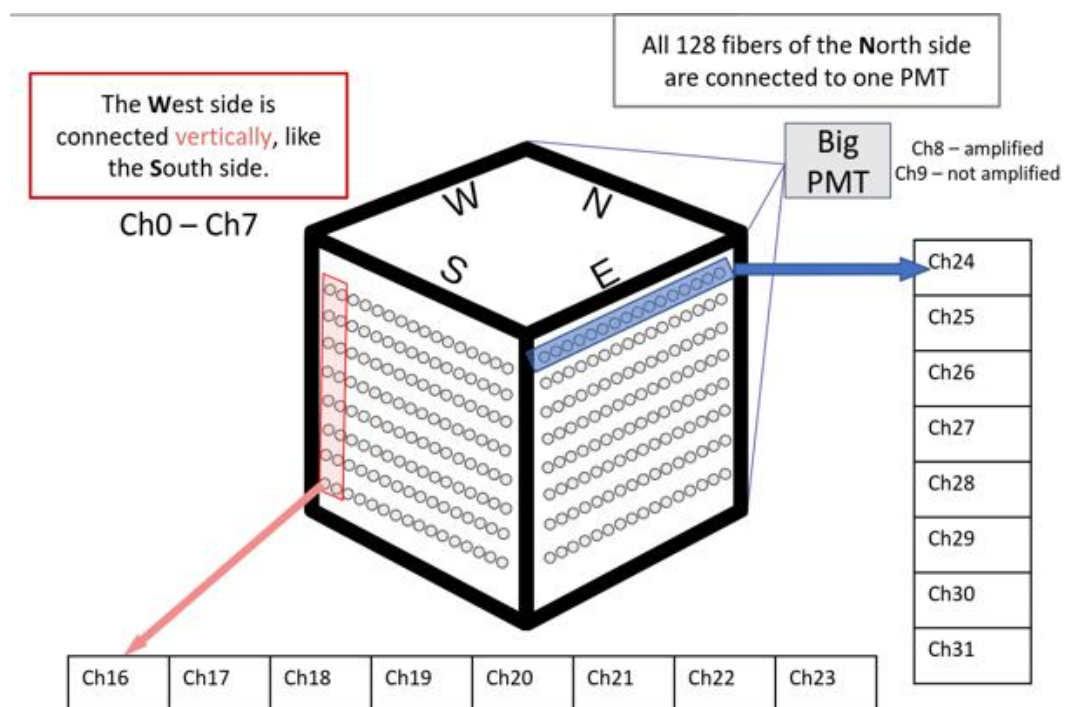


Figure 3 – Signal processing

A comparison was made between the channels connected to the outermost rows of the optical fibers and the channels collecting light from the fibers located in the center of the cube. The results are presented in Figure 4.

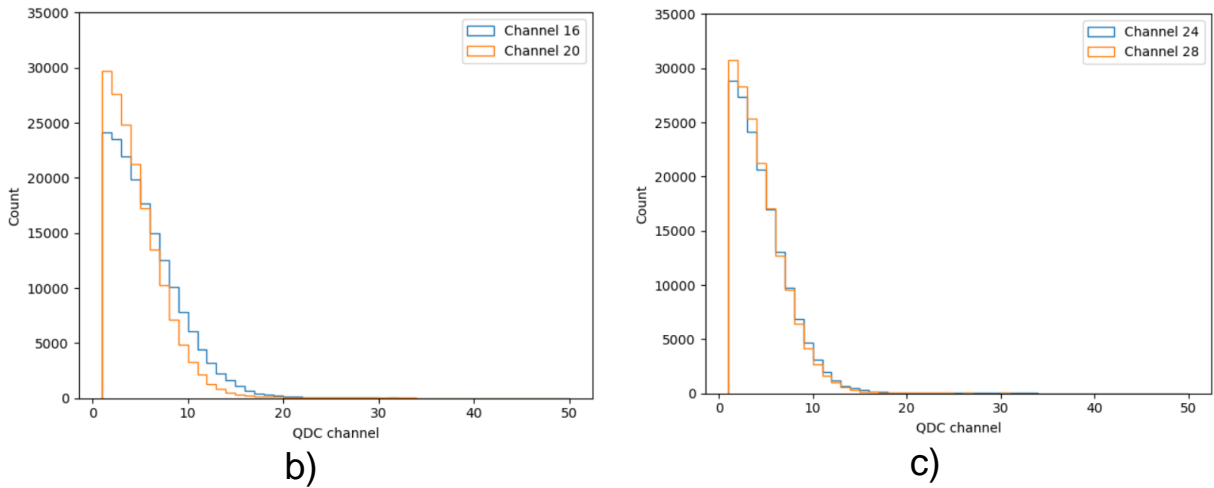


Figure 4 – Comparison of the edge and central channels from different sides

It can be observed that in the horizontal assemblies, the comparison of the muon peaks at the edge and central PMTs showed no significant difference. In contrast, for the vertical assemblies, an edge effect can be observed (channel 16 — edge, channel 20 — central).

Investigation of the BaF₂ crystal using a germanium detector

In order to study the impurity content in the BaF₂ crystal, measurements were performed using a high-purity germanium (HPGe) detector. The energy calibration was performed using calibration coefficients stored in the spectrum files. The calibration is linear and is described by the following equation:

$$E(\text{keV}) = a + b \cdot Ch, \quad (2)$$

where Ch is the channel number; $a = 0.2019$ keV; $b = 0.04154$ keV/channel.

The spectrum without background subtraction is shown in Figure 6.

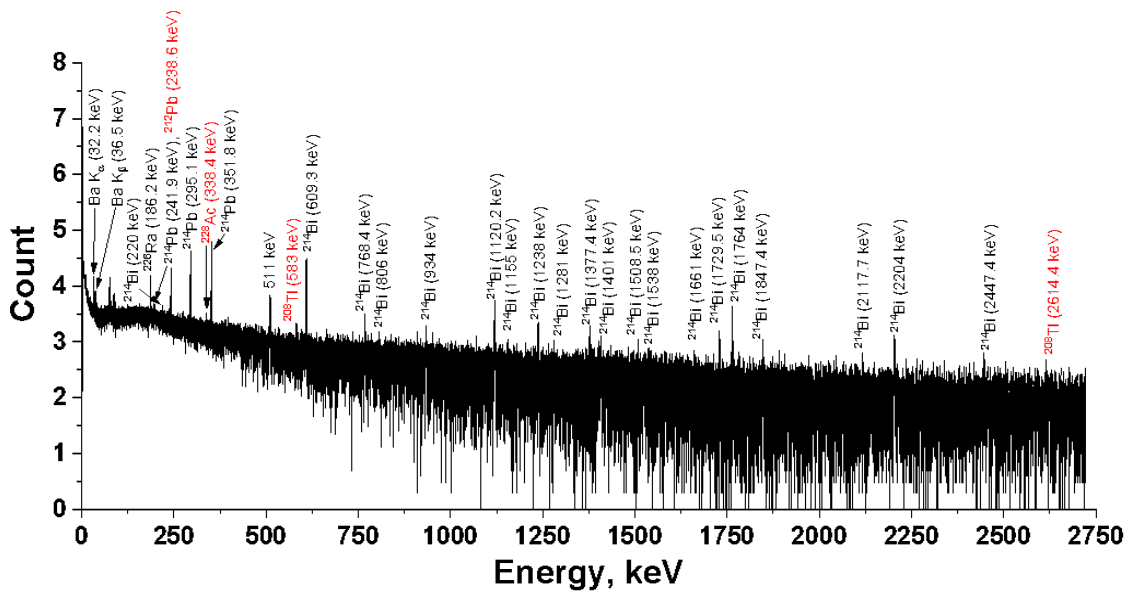


Figure 6 – Spectrum of the BaF₂ crystal without background subtraction

As a result of the analysis, γ -lines belonging to the uranium series (^{238}U) were identified: ^{214}Bi , ^{214}Pb , ^{226}Ra [5]. γ -lines corresponding to the thorium series (^{232}Th) were also found: ^{208}Tl , ^{228}Ac , ^{212}Pb [5]. In the low-energy region of the spectrum, peaks corresponding to the K_{α} and K_{β} characteristic X-ray emission of barium were registered.

The spectrum after background subtraction is shown in Figure 7.

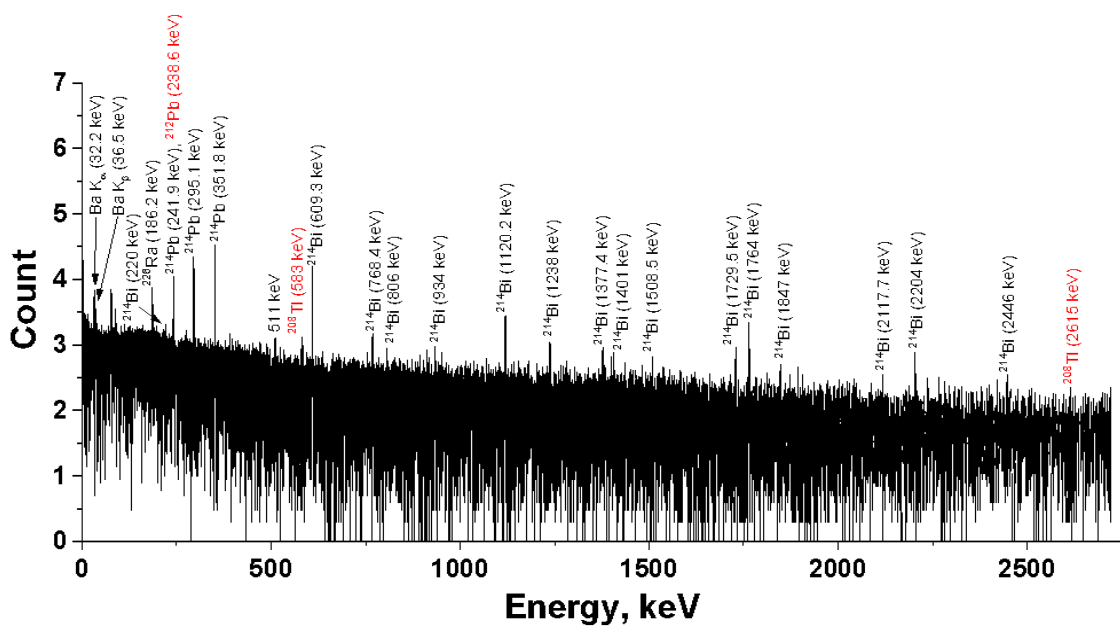


Figure 7 - Spectrum of the BaF₂ crystal after background subtraction

The HPGe measurements revealed the presence of natural radioactive impurities in the BaF₂ crystal. Gamma-lines belonging to the uranium series (²¹⁴Bi, ²¹⁴Pb, ²²⁶Ra) and the thorium series (²⁰⁸Tl, ²²⁸Ac, ²¹²Pb) were identified. Therefore, the contribution of these intrinsic impurities should be taken into account in future experiments.

Conclusion

In this work, the prototype of a compact antineutrino detector based on COFE technology was tested. As a result, the following tasks were successfully accomplished:

1. All available channels of the detector were successfully connected and read out.

2. The spectra were calibrated using the amplitude of the strongest signal as a reference. For each channel, the voltage was adjusted so that the main muon peak fell within the range of channels 56–60, ensuring a consistent energy response across the entire detector.

3. Cosmic radiation spectra were successfully recorded and analyzed. For the horizontal assemblies, no significant edge effects were observed when comparing edge and central channels, confirming uniform light collection. However, for the vertical assemblies, an edge effect was observed (channel 16 – edge, channel 20 – central).

4. HPGe spectroscopy revealed γ -lines belonging to the uranium series (^{214}Bi , ^{214}Pb , ^{226}Ra) and the thorium series (^{208}Tl , ^{228}Ac , ^{212}Pb), indicating the presence of natural radioactive impurities in the Ba_2 crystal. In the low-energy region, peaks corresponding to K_α and K_β characteristic X-ray emission of barium were also observed. These findings should be taken into account in future experiments.

References

1. Cowan C.L., Reines F., Harrison F.B., Kruse H.W., McGuire A.D. Detection of the Free Neutrino: A Confirmation // Science. 1956. V. 124. № 3212. P. 103–104.
2. Cao J., Luk K-B. An overview of the Daya Bay reactor neutrino experiment // Nuclear Physics B. 2016. V. 908. P. 62-73.
3. Alekseev I., Belov V., Brudanin V. et al. DANSS: Detector of the reactor AntiNeutrino based on Solid Scintillator // JINST. 2016. V. 11. P. 11011.
4. Filosofov D.V., Antokhina K.V., Belov V.V. et al. Development of barium and strontium fluoride multi-composite scintillation detection systems for neutrino experiments: COFE technology (Chemical Optical Fluoride Engineering) // JINST. 2025. V. 20. P. 08008.
5. IAEA Nuclear Data Section, Actinide Decay Data Library (DDL), International Atomic Energy Agency, Vienna, 2026. URL: https://nds.iaea.org/act_ddl/

Acknowledgments

I would like to express my deepest gratitude to my supervisor, Mark Vladislavovich Shirchenko, for giving me the opportunity to participate in the START programme and for introducing me to the field of neutrino physics and detector technologies. His valuable advice, support, friendliness, and working together with him made this internship unforgettable and truly wonderful.

I am also greatly thankful to my colleagues, Antokhina K.V., Belov V.V., and Kazartsev S.V., for their invaluable help during my stay at the laboratory. They patiently explained the experimental setup, assisted with data acquisition and processing, and shared their experience and knowledge. Their friendly guidance and active involvement in this work made my learning experience both productive and enjoyable.