JOINT INSTITUTE FOR NUCLEAR RESEARCH
Dzelepov Laboratory of Nuclear Problems

FINAL REPORT ON THE SUMMER STUDENT PROGRAM

Study of germanium spectrometer and front-end electronics.

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Introduction.

One of the projects of the Dzelepov Laboratory of Nuclear Problems of JINR is the GERDA experiment [1]. The experiment is designed to search for neutrinoless double beta (0vββ) decay of ^{76}Ge. GERDA operates with bare germanium semiconductor detectors (enriched in ^{76}Ge) directly immersed in liquid argon (LAr). First phase of the experiment (GERDA Phase I) started in 2010 and has been completed in 2013. The very low background level $10^{-2} counts/keV \cdot kg \cdot yr$ has been reached. The 0vββ decay of ^{76}Ge has not been observed and the new limit on the half-life > 2.1 x 10^{25}yr (90% C.L.), corresponding to the limit on the effective neutrino mass < 0.2 – 0.4 eV has been set.

In 2014-2015 years the upgrade of GERDA experiment to the second phase has been performed. It required a significant change of the hardware. In GERDA Phase II detector mass is doubled compared with Phase I and the background level is reduced by one order of magnitude. The latter is achieved by using of cleaner materials and the superior pulse shape analysis of BEGe detectors. In Phase II the LAr is instrumented to readout liquid argon scintillations for vetoing background events.

In the final configuration 7 strings with BEGe and coaxial detectors made from ^{76}Ge (about 40 kg of ^{76}Ge in total) as well as 3 detectors made from natural Ge have been integrated in the setup and GERDA Phase II data taking has been started successfully in December 2015.

At the GERDA collaboration meeting in June 2016 data accumulated during first 5 months were unblinded for analysis. No events in the region of interest has been found. The background index in GERDA Phase II has been improved to $10^{-3} counts/(keV\ kg\ yr)$ and the new limit on the 0vββ decay half-life > 5.3 x 10^{25} yr has been derived. Phase II data taking will be continued until 2019 in order to reach the exposure of 100 kg x years aiming to achieve the sensitivity > 10^{26} yr.

At the same time the R&D work on the next generation ton-scale ^{76}Ge experiment LEGEND is ongoing. The goal of this ambitious project is to reduce the background up to $10^{-4}\ counts/(keV\ kg\ yr)$ which would ultimately improve the sensitivity to 10^{28} yr, required to cover the inverted neutrino mass hierarchy region. LEGEND project as well as GERDA will have two phases. The first one (LEGEND-200) with 200 kg of HPGe detectors made from ^{76}Ge is going to be performed in the modified GERDA setup.

The core of abovementioned experiments are low background high purity germanium (HPGe) detectors. Such a detector made from enriched ^{76}Ge which has been used in one of the past experiments – IGEX [2], I was studying during the practice period.

Germanium γ-spectrometer.

The gamma radiation HPGe detector is a semiconductor diode with a p-n junction, often made in a coaxial (cylindrical) geometry in order to increase the volume of the sensitive region. This geometry helps to significantly improve the detection efficiency in comparison with a detector in planar geometry. The efficiency of γ-ray detection also strongly depends on the material of the detector. The most common materials for semiconductor detector production are silicon and germanium. Detectors made from germanium are usually used to detect γ-rays.

The choice of germanium as material for detector manufacturing is caused by the fact that the cross section γ-interaction depends on the atomic number Z. Thus the photoelectric effect cross section is proportional to ~ Z^5, the cross section of the Compton effect is ~ Z, and the cross section for the formation of electron-positron pairs is ~ Z^2. The larger value of Z for germanium (Z(Ge)=32, and Z(Si)=14) determines the choice of this material for γ–ray detector production.

The technology of manufacturing HPGe detectors in coaxial geometry is as follows. In a *p*-type germanium crystal a cylindrical hole is drilled. A p^+-Ge layer is created by implanting boron ions on the surface of this hole. On the outer surface, lithium diffusion is carried out to form the n^+-Ge layer. The working volume of the detector is the entire cylinder. Such a design allows detecting the charge carriers formed in a depleted region when ionizing radiation passes through. If energy E is released in this region, then E / ω carrier pairs are formed, where ω is the energy required to form one pair of free charge carriers (for germanium this value is equal to 2.8 eV). In order to collect the whole charge, it is necessary that the charge collection time in the electric field applied to the p-n junction is significantly smaller than the lifetime of the non-equilibrium charge carriers. By this reason the bias voltage is usually chosen rather high (> 1000 V).

Electron-hole pair's movement in the electric field is equivalent to a current pulse flowing through the capacitance of the p-n junction. As a result, a charge is formed on this capacitance and its value is proportional to the energy absorbed by the detector.

Detectors based on ultrapure germanium are characterized by low reverse current and high energy resolution. Unlike silicon semiconductor detectors, HPGe detectors must be operated at a liquid nitrogen temperature. This is due to the fact that the width of the band gap Eg of germanium is smaller than of silicon (0.66 eV for germanium and 1.09 eV for silicon). So the probability of thermal generation of minority charge carriers ($\sim e^{-Eg/(kT)}$) in germanium is substantially higher, and at room temperature the leakage current is too high.

Fig. 1 shows the typical HPGe detector in vacuum cryostat. The detector is mounted in the holder usually made from Cu or Al who is attached to a copper rod. The other end of the rod (so-called coldfinger) is placed in a dewar with liquid nitrogen. Before cooling down the cryostat has to be pumped.

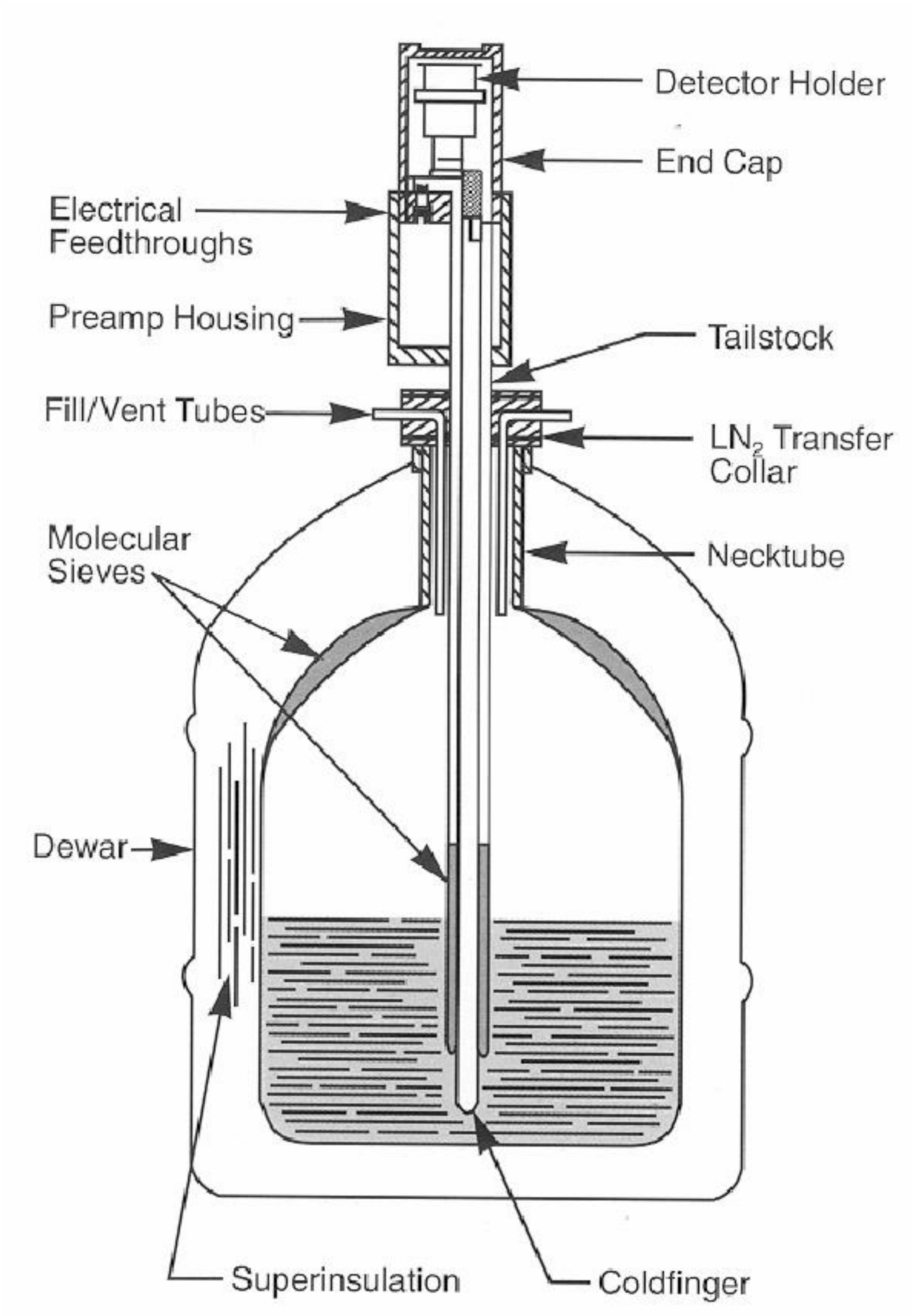

Fig. 1. HPGe detector in a cryostat

The scheme of typical germanium γ-ray spectrometer is presented on Fig. 2. The charge-sensitive preamplifier is designed to convert the amount of charge collected at the input to the voltage amplitude. To avoid signal loss and to reduce the effect of pick-up noise, the preamplifier is placed in close proximity to the detector. Moreover, the head stage of the preamplifier (field effect transistor and feedback circuit) is usually mounted directly on the detector holder and also cooled to liquid nitrogen temperature. Typical spectrometric complex (Fig. 2) allows recording the amplitude distributions of signals from HPGe detector, calibrating the spectrometer, determining the energies of the γ-lines, identifying the emitting isotopes, determining the activity of the sources, etc. The complex includes: a detection unit, which consists of HPGe detector and preamplifier together with high voltage filter; a spectrometric section (main amplifier and ADC), a high-voltage power supply for the detector; a low-voltage power supply; computer and software that allows to control the spectrometer, store and present experimental data in graphical and numerical form, perform mathematical processing of data, including energy and efficiency calibration, identify isotopes and calculate their activity.

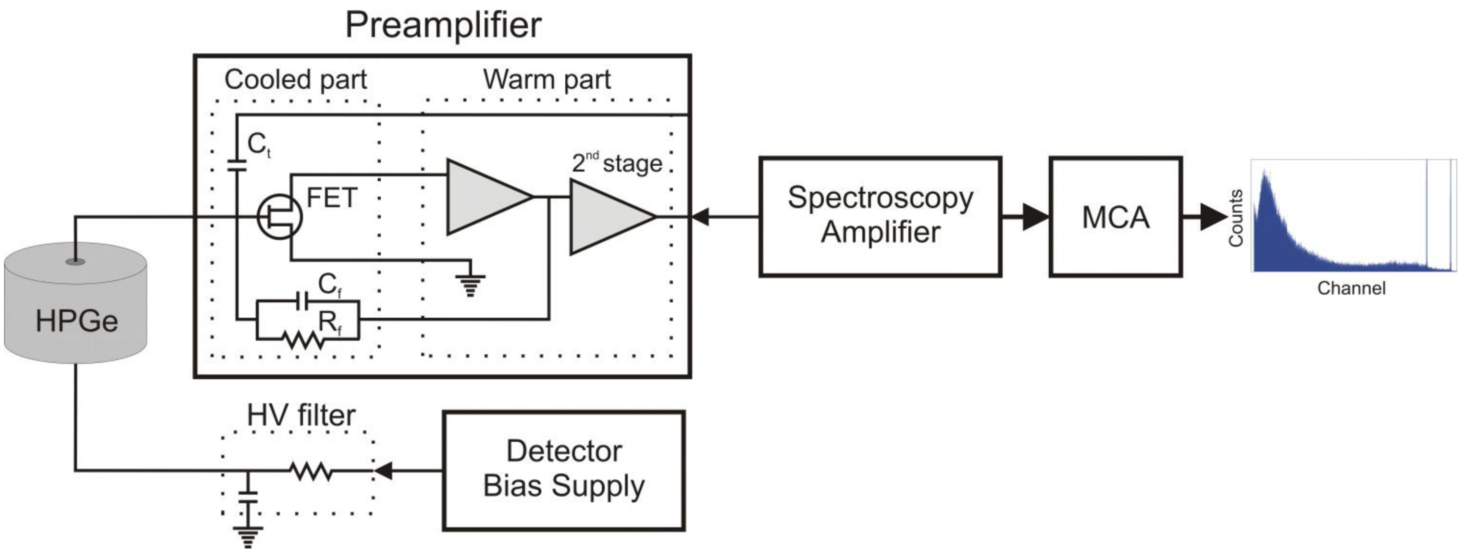

Fig.2. A typical spectrometric complex.

Practical part.

Disassembly of non-working low-background HPGe detector made from enriched ^{76}Ge (model OXFORD Ge-76 SPECIAL) occurred in a clean room (Fig.3).

Fig. 3.

Since it was no signal from the detector, it was assumed that the first cooled stage was broken. After opening of the cryostat and removing the copper cap, the FET characteristics were checked. It turned out that the field effect transistor burned (Fig.4).

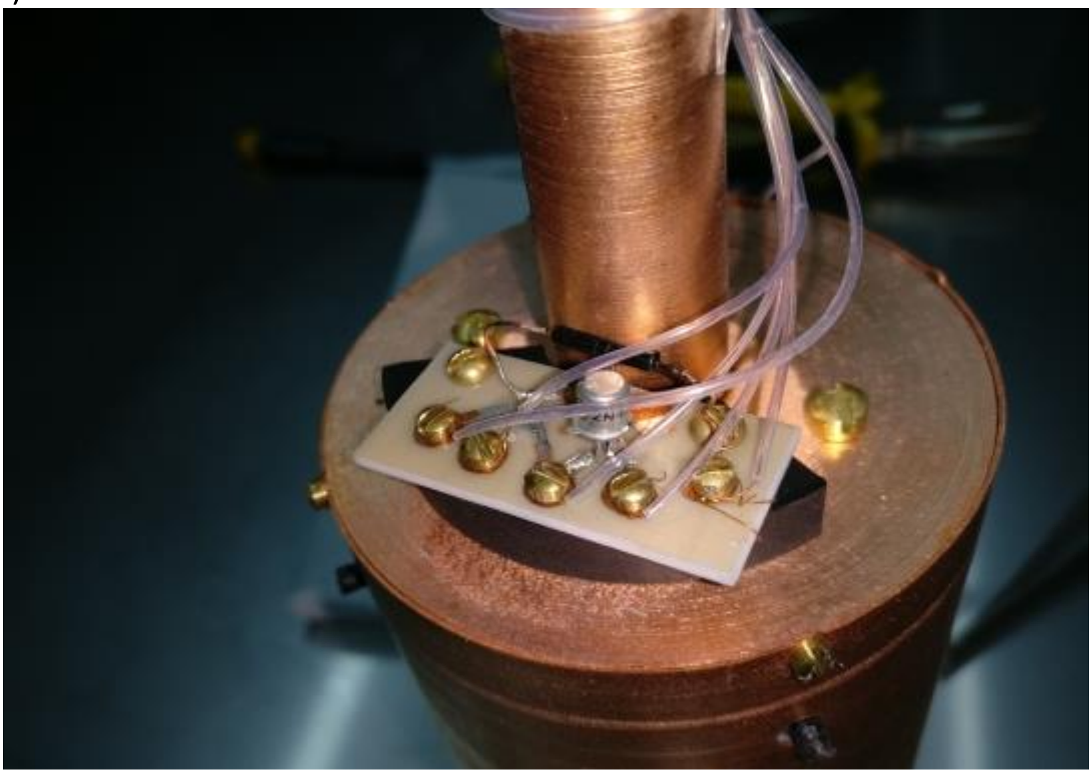

Fig.4.

The entire first stage has been replaced by another one (Fig.5 and Fig.6). The working low background first stage was taken from the cryostat of one of the IGEX detectors, which are now being used in the GERDA experiment.

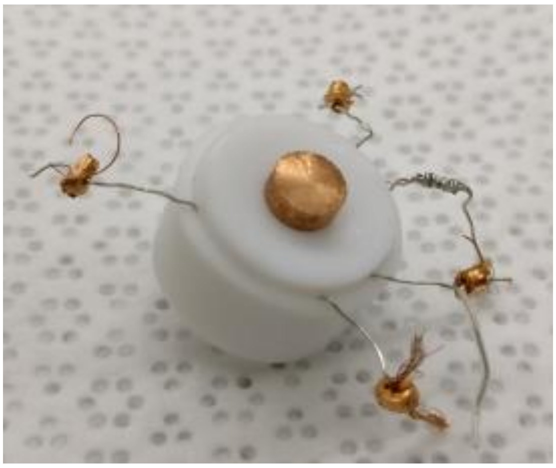

Fig.5.

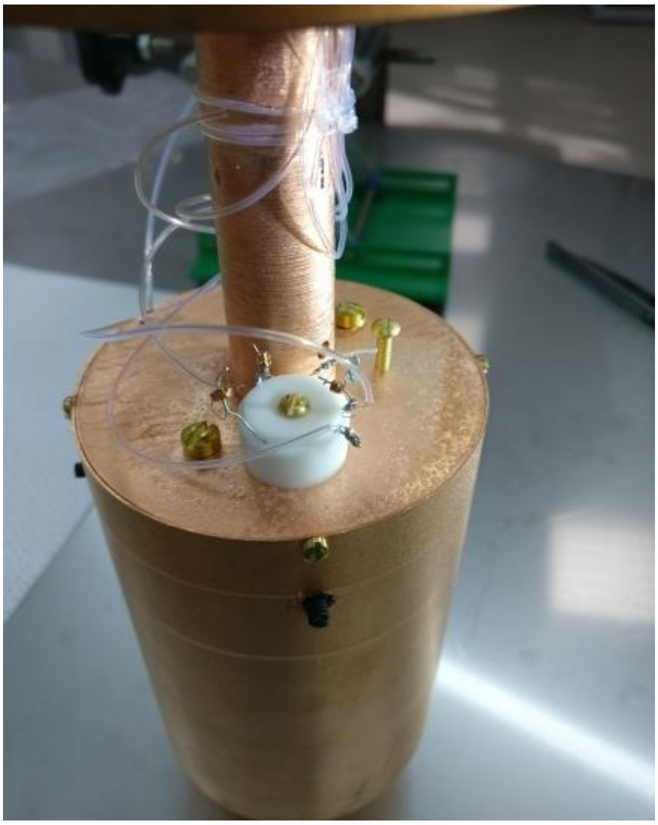

Fig.6.

The cryostat was pumped out with heating for about three hours in order to improve the surface leakage current of the detector. Then the cryostat was immersed into liquid nitrogen (Fig.7) to cool down the detector to operating temperature.

Fig.7.

After 24 hours (time required to cool down the detector) a high voltage was increased in few hundred volts steps.

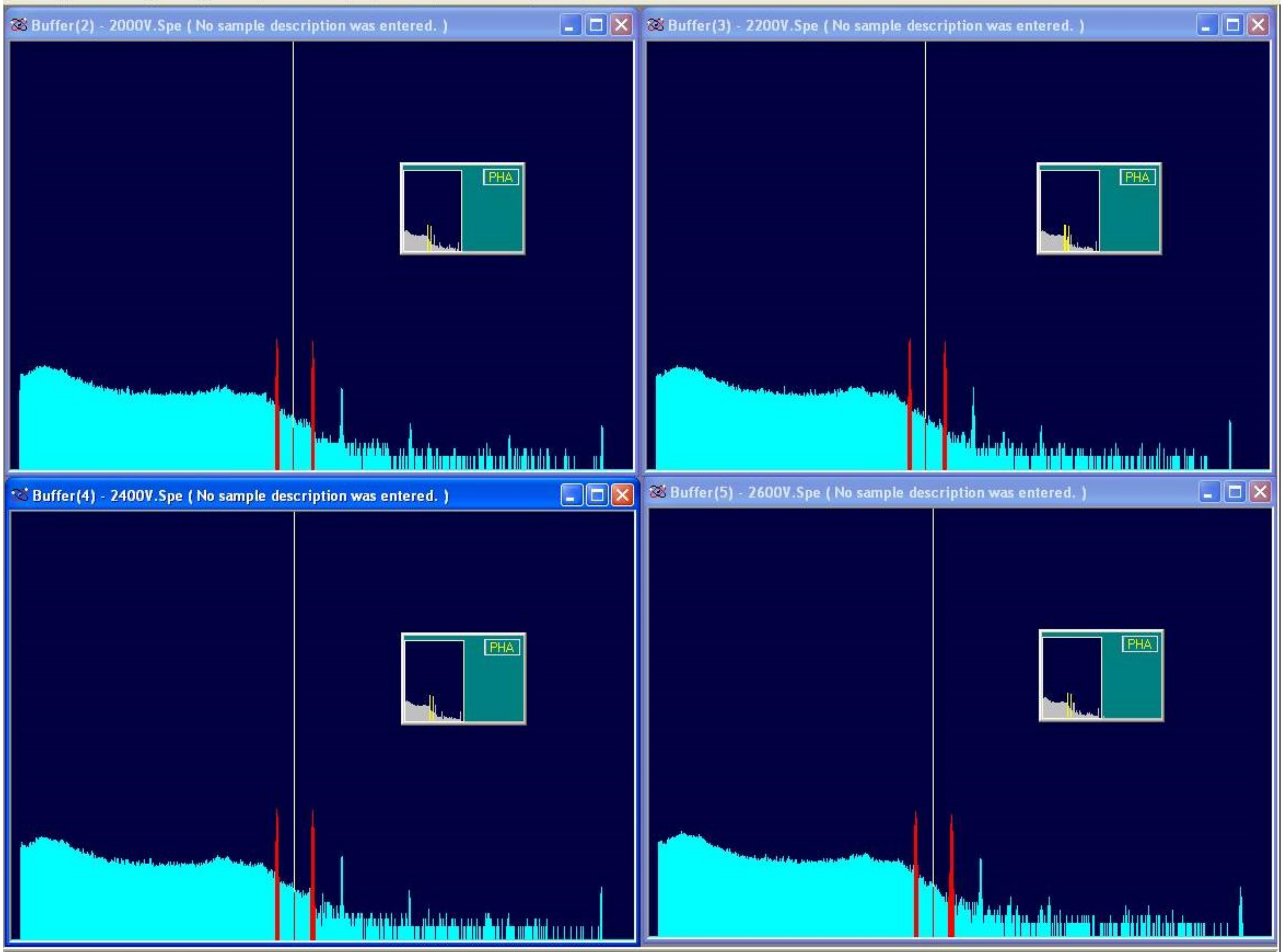

Fig.8.

In order to check the performance of the detector the ^{60}Co source was used. The number of counts in the 1.3 MeV peak, its amplitude and energy resolution (FWHM – full width of half maximum) were estimated (Fig. 8). The dependence of the characteristics on the bias voltage is given in the table. All measurements were made with 3 μs shaping time of the spectrometric amplifier. The data collection time was 600 s.

High Voltage (V)	Amplitude (Chn)	Number of counts under peak	FWHM (keV)
2000	1928	4662±93	3.98
2200	1960	5293±76	4.51
2400	1982	5684±99	4.53
2600	1989	5539±99	6.35

From this table the depletion voltage of the detector can be estimated. In this case it’s about 2400V, since only above this value the signal amplitude and count rate under the peak is not changing anymore. Typically, the operating voltage should exceed the depletion voltage by several hundred volts to improve charge collection. In the actual case at such voltages the detector energy resolution deteriorates drastically because of increase of the leakage current. It was not possible to achieve the operational voltage recommended by the manufacturer (3000 V). The leakage current became too high and the preamplifier was saturated. Thus, it seems that additional long-term annealing of the detector is needed. Perhaps this will lead to a reduction in the leakage current and, accordingly, an improvement in the spectrometric characteristics of the detector. However the detector can be used as a spectrometric device at 2400V since it’s fully depleted.

Conclusion.

During the summer student program at JINR I have been acquainted with a unique experiment GERDA which is aiming to search for neutrinoless double beta decay of ^{76}Ge. This is one of many projects of the JINR Laboratory of Nuclear Problems.

I got knowledge in the field of the design and operation of low-background semiconductor detectors. The knowledge was fixed in practice. We managed to partially restore the performance of a low-background semiconductor detector made from enriched germanium which will be used at Baksan Neutrino Observatory (BNO) of the INR RAS for screening measurements.

Acknowledgements.

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1. «The GERDA experiment for the search of 0νββ decay in Ge-76». In: *Eur. Phys. J. C 73 (2013) 2330*. http://link.springer.com/article/10.1140%2Fepjc%2Fs10052-013-2330-0
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