JOINT INSTITUTE FOR NUCLEAR RESEARCH
Frank Laboratory of Neutron Physics

FINAL REPORT ON THE
SUMMER STUDENT PROGRAM

ENERGY CALIBRATION OF THE MULTI-DETECTOR SYSTEM “ROMASHKA” OF “TANGRA”-SETUP

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ABSTRACT

At the Joint Institute for Nuclear Research (JINR) Frank Laboratory of Neutron Physics (FLNP) a new multi-detector gamma-ray spectrometry system was constructed. It consists of 22 hexagonal NaI(Tl) detectors, which can be arranged in different configurations depending on the requirements of the experiment. In combination with, for example, a multi-section parallel-plate gas-ionization chamber as a fission fragment detector, positioned in the center of the system, it is possible, also, to investigate the neutron-induced capture and fission reactions on a number of heavy isotopes, important for fundamental and applied neutron and nuclear physics.

INTRODUCTION

The experimental investigations of the 14.1 MeV neutron induced nuclear reactions, (n, n), (n, n'γ), (n, 2n), (n, f) and (n, γf), on a number of important for neutron-nuclear physics nuclei are the first priority scientific research in the frame of the new project TANGRA (Tagged Neutrons & Gamma Rays) [1, 5], which has been recently started at Frank Laboratory of Neutron Physics (FLNP) of the Joint Institute for Nuclear Research (JINR) in Dubna, Russia.

The objective of this work is to conduct a series of experiments on the measurement of gamma-ray background in the laboratory, the energy calibration of multi-detector system, using the certified reference materials (^{137}Cs, ^{60}Co, ^{133}Ba), processing the accumulated data and analysis of the results, including the calculation of the efficiency of registration and energy resolution of NaI(Tl) detectors.

The work tasks included a) the study of the characteristics of devices and detectors of the experimental setup "Tangra" b) data acquisition and analysis with ADCM, ROMANA, CERN ROOT software and c) determination of the characteristics of NaI(Tl) gamma-ray detectors.

EXPERIMENTAL SETUP «ROMASHKA»

This setup is a constituent part of the project «TANGRA» [5] based on the “tagged” neutron method (TNM). The TNM, for example, is used also in inspection of cargo containers for the purpose of detection of concealed high explosive (HE) [2]. The given method is based on determination of the direction of “tagged” neutron movement by registration of the associated alpha-particle.

As a source of 14.1 MeV neutrons, an All-Russia Research Institute of Automatics (VNIIA) portable neutron generator ING-27 (Fig. 1, left) is used [1-4].

The 14.1 MeV neutrons are produced in D-T fusion-fission reaction:

$$D + T \to \alpha + n,\ Q = 17.59\ MeV \qquad (1)$$

The incorporated in ING-27 vacuum chamber 64-pixel α-sensor permits to “tag” and count every neutron, because the both reaction products are irradiated nearly collinear in opposite directions.

The main characteristics of ING-27 are given in the **Appendix**.

For detection of the inelastic scattered neutrons and gamma-rays, a multi-detector system of “Romashka” type (Fig. 1) was commissioned [1, 3].

Such type of measurements generally faced the problem of suppressing the neutron background produced by neutrons that penetrate directly from the source into the scintillation detectors that are used to detect secondary nuclear radiation (neutrons and gamma-quanta). It is important that the passive shielding of the scintillation detectors from the direct impact on them of neutrons from the source be optimized.

A position-sensitive multi-pixel alpha-detector is measuring the time and coordinate of the associated alpha-particle, thus enabling one to specify the angle and time of neutron escape (“tag”). Gamma-detectors detect gamma-quanta produced from the interaction of “tagged” neutrons with the sample’s nuclei.

The signal processing and data collecting with “Romashka” was done by a computerized 32-channel digital readout system, utilizing two ADCM16-LTC (16-channel/14-bit/100MHz) ADC-boards from AFI Electronics© [1, 3, 4].

The signals from all the detectors are recorded simultaneously in digitized form and are stored in list-mode on the hard disk of a personal computer for further off-line analysis.

The coincidence of alpha-particles with gamma-quanta signals provides selection of those gamma-quanta, which correspond to object under investigation. Computer processes the obtained data and sends information on elemental composition of the sample to the terminal.

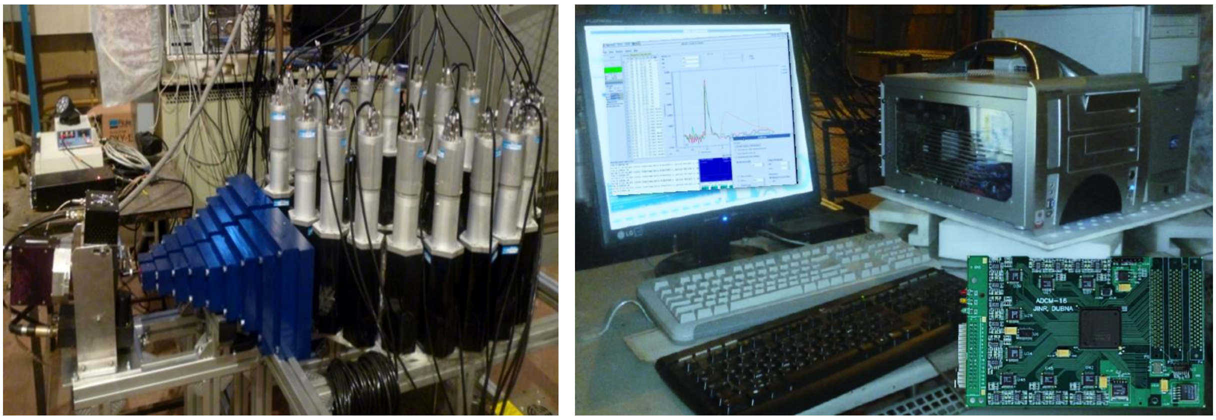

Fig. 1. Portable neutron generator ING-27 and “Romashka” base setup of 22 NaI(Tl) scintillation gamma-ray detectors (left). MCA ADCM data acquisition system (right).

This work is devoted to determination of the parameters of the response function of the installation “Romashka”, consisting of 22 NaI(Tl) scintillation detectors (Amcrys-H), which are used in experiments, dedicated to measure the angular distribution of gamma-rays from the inelastic neutron scattering of 14.1 MeV on light nuclei.

Two main characteristics of NaI(Tl) detector chains, energy- resolution and efficiency, were investigated experimentally.

MEASURING CONDITIONS AND EXPERIMENTAL RESULTS

Measuring conditions

The energy calibration of NaI(Tl) gamma-ray detectors, determination of their efficiency and measurement of the radiation background in two locations of “Romaska” setup, IREN experimental hall and Building #117, were done following a common and well established procedure. For this purpose, certified point-type gamma-sources of ^{137}Cs, ^{60}Co, ^{133}Ba were used. They were positioned one-by-one in the geometrical center of “Romashka” and their activity measured (Fig. 2). The time of data acquisition depened on the current activities of the gamma-ray sources and was chosen as long as to have a characteristic gamma-ray photopeak uncertainty of no more than 1%.

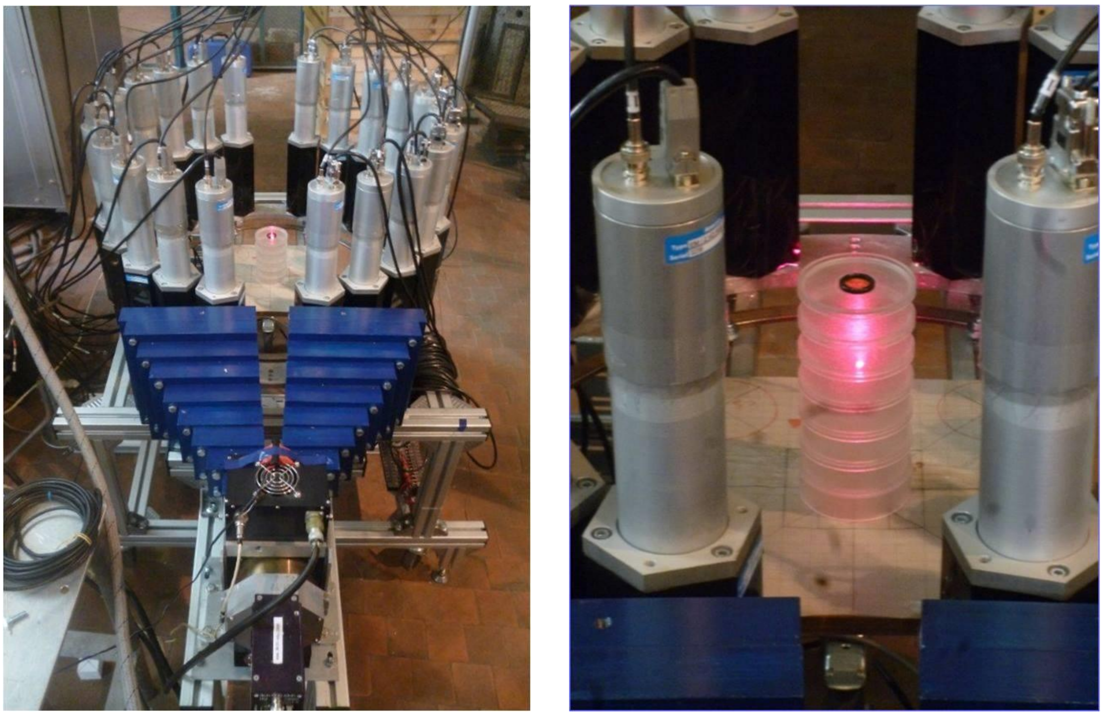

Fig. 2. The “source-detectors” geometry (left). The calibration point-type gamma-sources of ^{137}Cs, ^{60}Co, ^{133}Ba, situated at the geometrical center of “Romashka” (right).

Experimental data analysis and results

Two time-separated runs were done and the results compared, namely:

nRun 1 – in IREN experimental hall (Date of measurement: 16.10.2015)

nRun 2 – in Building #117 (Date of measurement: 23.06.2016)

In the both of them, the energy calibration and determination of the efficiency of NaI(Tl) gamma-ray detectors were done by means of 3 certified reference gamma-ray sources of ^{133}Ba, ^{137}Cs, ^{60}Co. Their main characteristics are listed in Table 2.

Table 2 – Isotopes' main characteristics

Source	**Activity (Bq)**	**Half-life (y)**	**Date of measurement**
^{133}Ba	58900	10.5407	01/10/2014
^{137}Cs	110000	30.1711	01/10/2014
^{60}Co	105300	5.2712	01/10/2014

The signals from the 22 detectors were digitized one-by-one and stored in *.dat-file on the computer hard-disk in list-mode (one-after-another) by ADCM software for further off-line processing. The list-mode data files were analyzed by ROMANA home-made program and the time- and amplitude- 2d-histograms were stored in a *.root file. Gauss and Line functions, used to describe the form of the amplitude spectra key-gamma-lines and the background under them, were least-square fitted to the experimental data-points by means of ROOT scripts. The resulting curves from the both runs, for one of the detectors, are shown in Fig. 3. The parameters of the Gaussian fit-functions were used to make an “amplitude channel/gamma-ray energy”-calibration of every gamma-spectrometry chain.

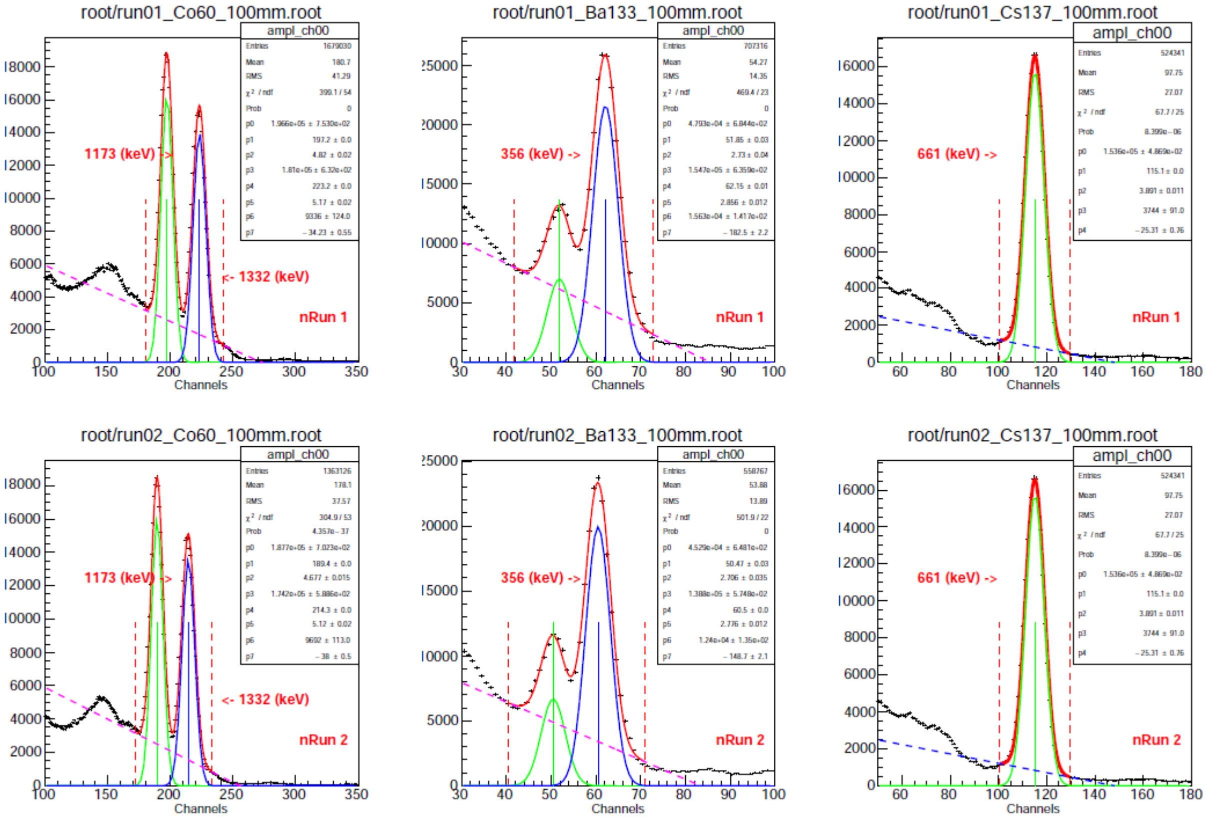

Fig. 3 The amplitude spectra obtained in the both runs with ^{60}Co, ^{133}Ba and ^{137}Cs. Gauss and linear functions were least-square fitted to the amplitude spectra full-energy peak data points.

In order to assess the possible amplitude (energy) drift of the system, the channel number (position) of each calibration Gauss-peak was recorded for each calibration along with the standard deviation of the peak fit-function, as reported by the software. The range of the drift was then calculated. In order to relate the drift in channel number to errors in energy, an average calibration curve was calculated by taking the average channel number for each full-energy peak used and fitting it with a second-degree polynomial. This allows to determine the changes in calculated energies based upon the calibration curve. The experimentally obtained energies versus the reference ones are shown in Fig. 4.

As an example, in Fig. 5 are shown the energy spectra of the radiation background curve (black) in “nRun 1”- experiment for all the three calibration gamma-ray sources before (green) and after subtracting the background gamma-ray contribution (red) as measured with NaI(Tl) gamma-ray detector #1.

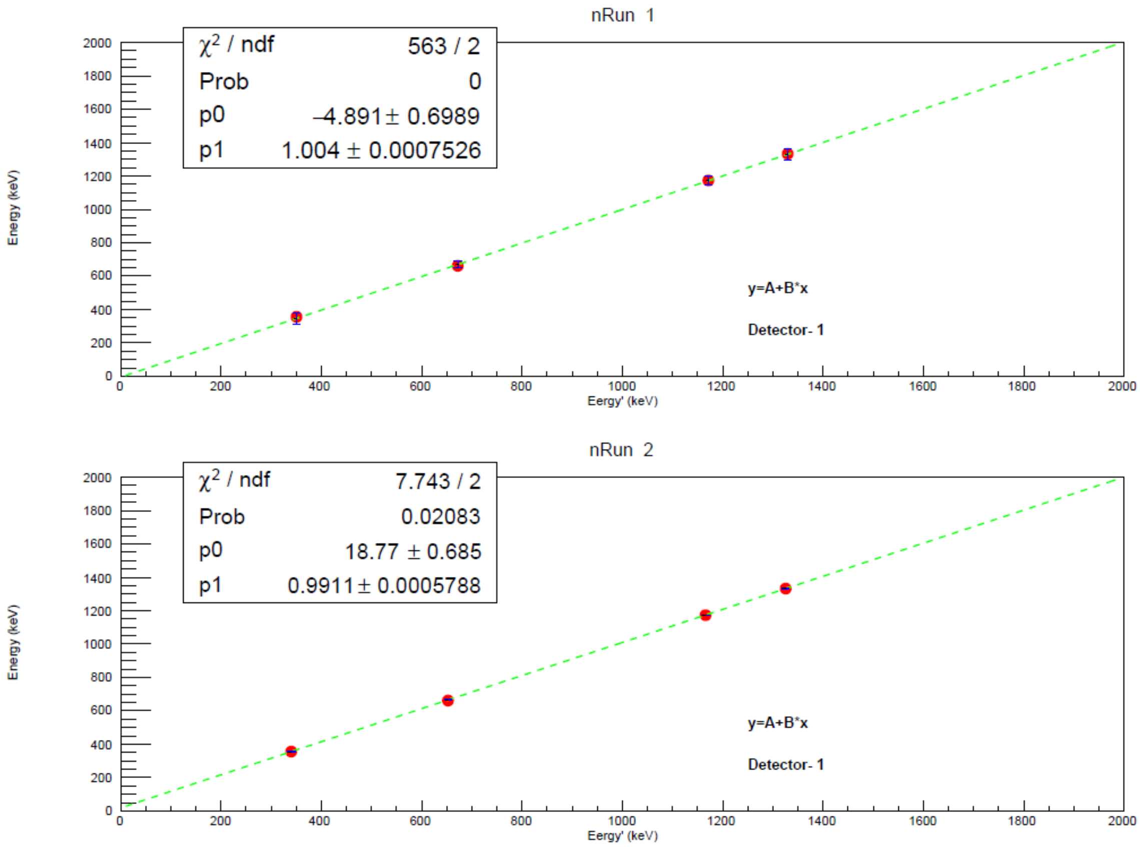

Fig. 4 The experimentally obtained energies versus the reference ones.

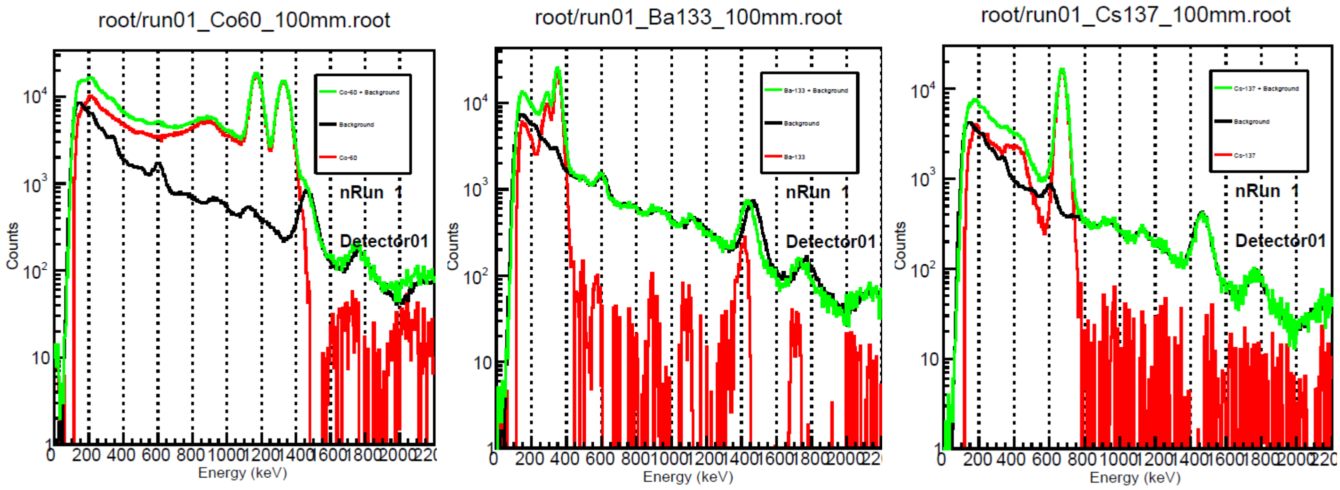

Fig. 5 Total (green), Background (black) and Net (red) γ-ray energy spectra for NaI(Tl) det. #1.

The energy resolution

The energy resolution of the detector probe was obtained from the full-width at one-half of the maximum height (FWHM) of a single photo-peak using the following equation:

$$R = \frac{FWHM}{E_0}.100,\% \tag{2}$$

Here R is energy resolution and E_0 is the related energy. It will provide the separation for two adjacent energy peaks which will lead to the identification of different isotopes in the spectrum. The measured energy resolutions of the NaI(Tl) detector as a function of gamma-ray energy is displayed in Figs. 6.1 and 6.2.

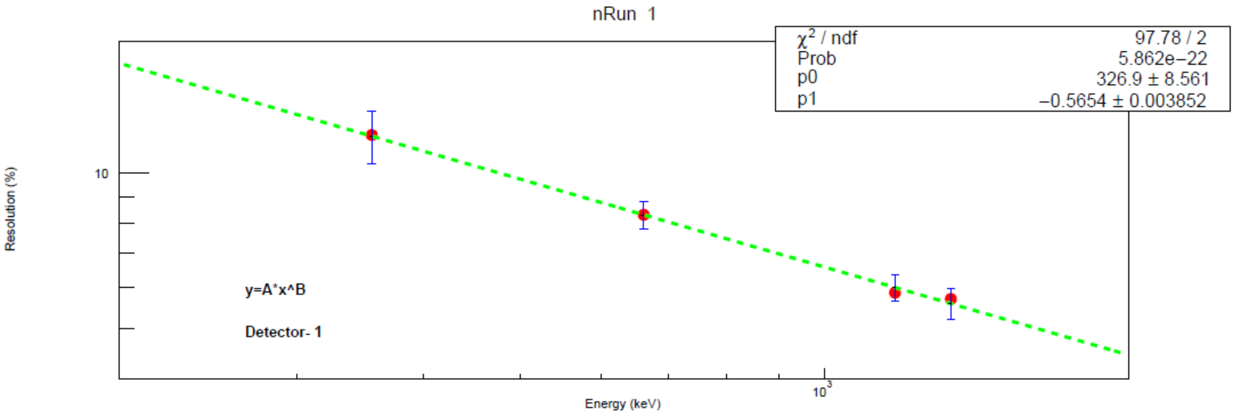

Fig. 6.1 The energy resolution in nRun 1

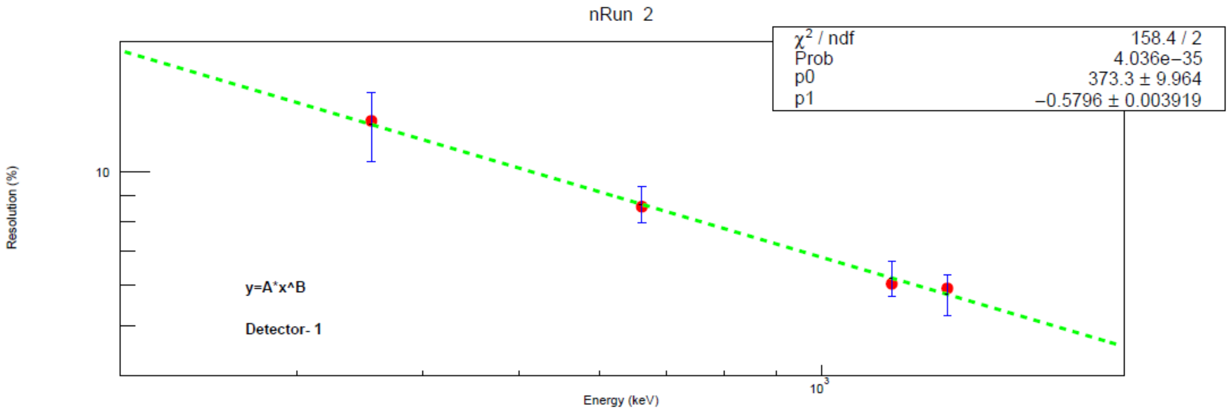

Fig. 6.2 The energy resolution in nRun 2

From these figures it is seen that the energy-resolution of the NaI(Tl) detector is decreasing with increasing the gamma-ray energy. The difference between them can be explained by the statistical nature of the radioactive decay and the introduction of some systematical uncertainties due to technological differences between the detectors (as size, material composition and characteristics) and the photomultipliers. But, the obtained by the two experimental setups, gamma-energy resolution values of the key gamma-ray lines, agreed with the factory certified ones in the limits of the obtained experimental error-bars.

The experimental photo-efficiency

NaI(Tl) scintillation probe is one of the most widely used gamma-ray detector in the field of elemental analysis of materials and its performance directly depends on the knowledge of the detection efficiency. The detection efficiency is a measure of the percentage of radiation that a given detector detects from the overall yield emitted from the source. It can vary with the volume and shape of the detector material, absorption cross-section in the material, attenuation layers in front of the detector, the distance and position from the source to the detector. The absolute efficiency of the detector is defined as the ratio of the number of counts recorded by the detector N for time Δt, to the number of gamma-rays A.η(E) with energy E, emitted (in all directions) from the source with an activity A (Bq).

The experimentally measured full-energy peak efficiency (FEPE) values, as a function of the gamma-ray energy E, for the hexagonal NaI(Tl) detector, when using radioactive point-type sources for their calibration, are determined by the following equation:

$$\varepsilon(E) = \frac{\lambda N(\mathrm{E},\Delta t)}{A e^{-\lambda t}\left(1 - e^{-\lambda \Delta t}\right)\eta(E)} \qquad (3)$$

where: λ – is the decay constant (in seconds), N(E, Δt) – is the total counts under the full gamma-ray energy E peak, measure for a time interval of Δt (in seconds), η(E) – is the emission probability of gamma-rays with energy E (number of gamma-rays/decay), A – is the radionuclide reference activity (in Bq), t – is the time interval (in seconds) between the date of the isotope certification and the start of the measurement (the decay correction). The overall (total) uncertainty for the full-energy peak efficiency Δε is given by the following equation:

$$\Delta\varepsilon = \varepsilon.\sqrt{\left(\frac{\partial\varepsilon}{\partial A}\Delta A\right)^2 + \left(\frac{\partial\varepsilon}{\partial\eta}\Delta\eta\right)^2 + \left(\frac{\partial\varepsilon}{\partial N}\Delta N\right)^2} \qquad (4)$$

where: ΔA, Δη and ΔN are the uncertainties associated with the quantities A, η(E) and N(E), respectively, assuming that the only correction made is those for the source activity decay.

Table 3 – the experimentally obtained photo-efficiency

nRun	∑N, imp	**^{133}Ba (356 keV)**				Δt (s)	A (Bq)
		Photopeak area, N	ΔN	**ε (%)**	**Δε (%)**		
1	340073	937930	4367	**3.87**	**0.39**	714	54689
2	306825	842070	3837	**3.70**	**0.37**	719	52575

nRun	∑N, imp	**^{137}Cs (662 keV)**				Δt (s)	A (Bq)
		Photopeak area, N	ΔN	**ε (%)**	**Δε (%)**		
1	313127	936665	3087	**2.50**	**0.25**	410	107402
2	254975	711540	2650	**2.26**	**0.23**	349	105720

nRun	∑N, imp	**^{60}Co (1173 keV)**				Δt (s)	A (Bq)
		Photopeak area, N	ΔN	**ε (%)**	**Δε (%)**		
1	1257089	1175323	4302	**1.56**	**0.16**	821	91902
2	1103739	1124945	4219	**1.86**	**0.19**	719	83901

nRun	∑N, imp	**^{60}Co (1332 keV)**				Δt (s)	A (Bq)
		Photopeak area, N	ΔN	**ε (%)**	**Δε (%)**		
1	1257089	1133213	3862	**1.50**	**0.15**	821	91902
2	1103739	1076763	3681	**1.78**	**0.16**	719	83901

The detection efficiency of the NaI(Tl) detector was obtained using Eq. 3 for each gamma-ray energy emitted by the ^{133}Ba, ^{60}Co, and ^{137}Cs isotopes. The obtained results are displayed as a function of gamma-ray energy in Fig. 7. Many analytical functions can be used to describe the efficiency dependence on the energy. The solid line represents a second degree polynomial fit that gives a good description of the correlation between the efficiency values and the gamma-ray energies (Fig. 7).

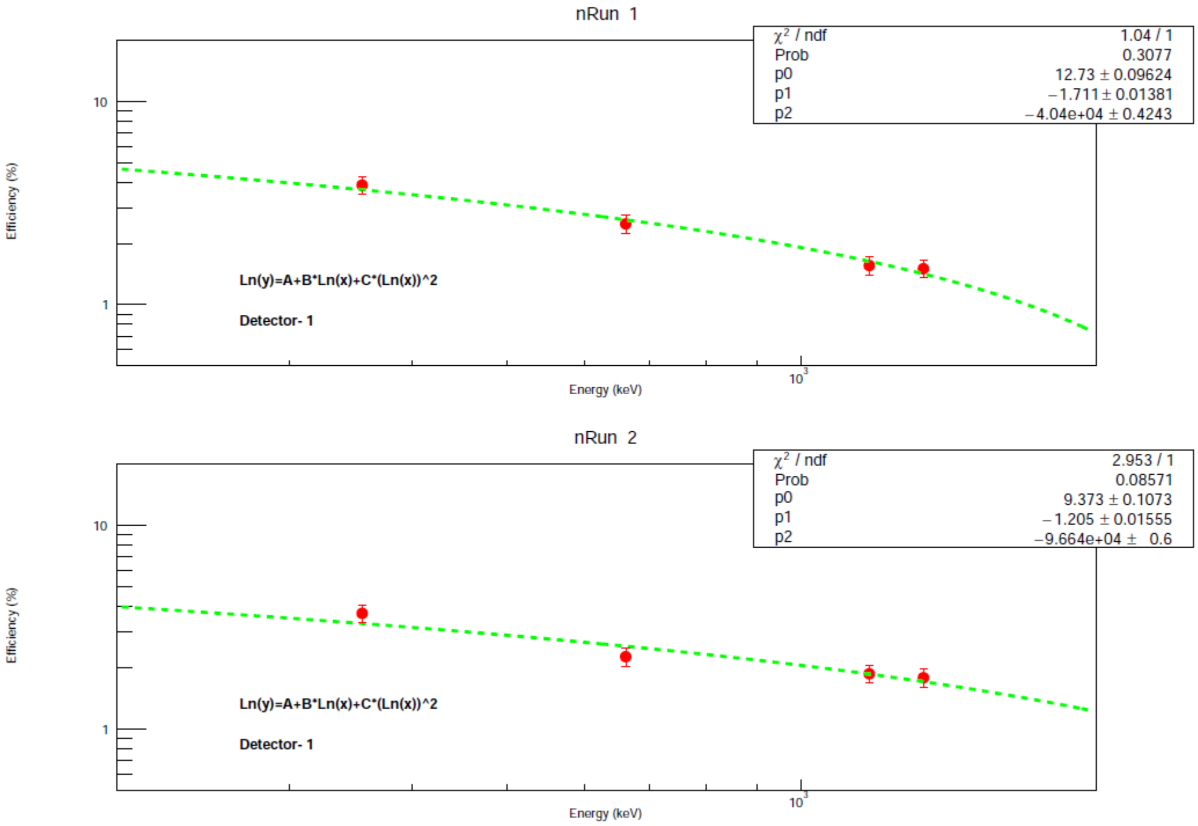

Fig. 7 The detection efficiency of a NaI(Tl) detector as a function of gamma-ray energy.

In Fig. 8 are plotted the NaI(Tl) total efficiencies obtained before (in IREN experimental hall) and after recommissioning of the “Romashka” setup at a present location in Building #117. As can be seen, they agree (defer) in the limits of their total uncertainties.

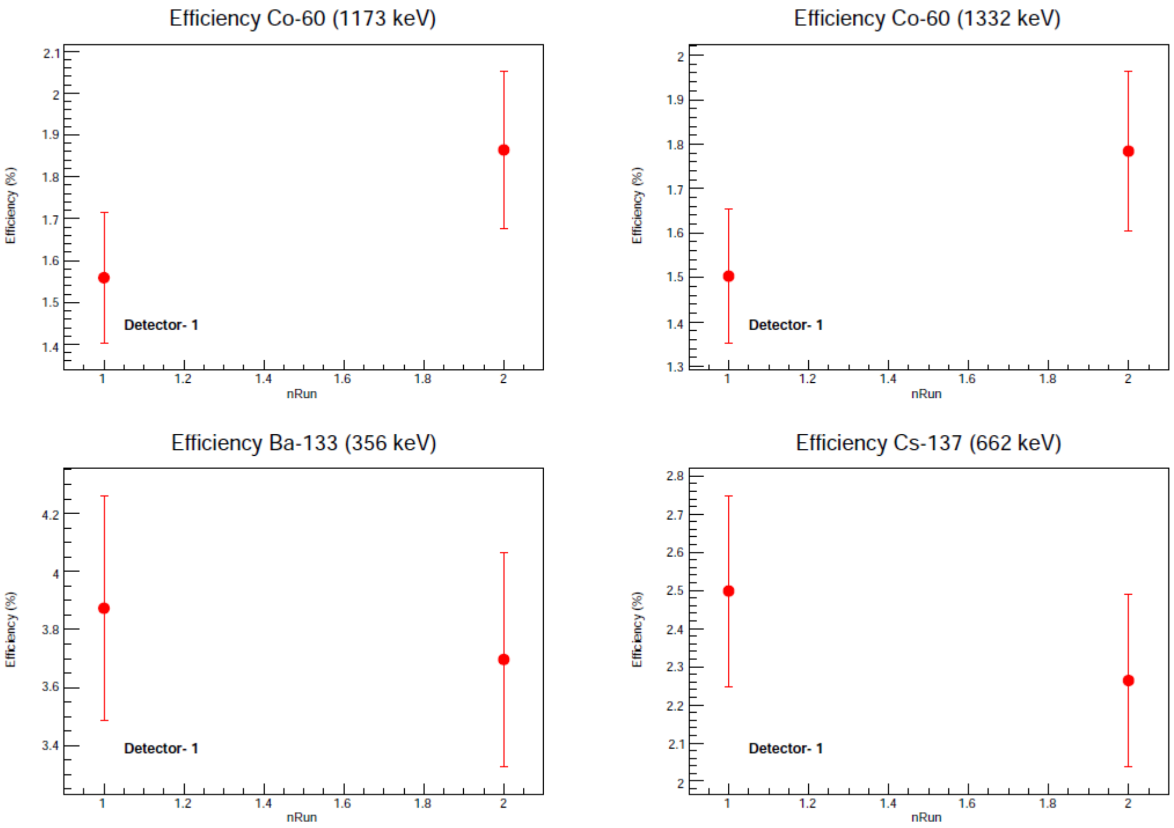

Fig. 8. The efficiencies of a Na(Tl) detector as determined from the data obtained in two runs.

CONCLUSION

The main properties of NaI(Tl) gamma-ray detectors: efficiency of registration, energy calibration and energy resolution have been measured for four different gamma-ray energies. By analyzing the results from the energy calibration over an extended period of time, this work demonstrates a method for better understanding the energy calibration drifts in “Romashka” setup. This information can be used for the assessment of “Romashka” setup precision in long-term measurements.

For multi-detector systems of the examined type, the regular energy calibration is needed to ensure the obtaining of high-quality data.

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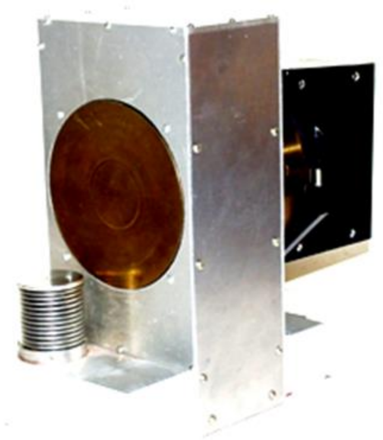
APPENDIX



The ING-27 neutron generator is a new generation computer-controlled portable neutron generators, based on a sealed (^{2}H + ^{3}H) gas-filled neutron tube with a built-in 64-pixel silicon α-particle detector, which was developed at All-Russia Research Institute of Automatics in Moscow (VNIIA, 2014). It is used for remote detection and identification of explosives and other hazardous materials, diamonds in kimberlite, etc., using associated particle imaging (API or MTN) methods. The ING-27 provides a continuous neutron flux with an intensity of about 5 × 107 n/s. A compact shielding-collimator assembly made from iron (Fe), borated polyethylene (BPE) and lead (Pb) is used to shape the neutron beam on target and to protect the neutron and γ-ray detectors. Some characteristics of the generator, e.g. neutron fluxes, operation mode and lifetime, are summarized in Table 1.

Table 1 – ING-27 main operating characteristics

Characteristics	**Value**
Maximum power consumption	40 W
Maximal intensity	~$5 \cdot 10^7$ c^{-1}
Neutron energy	14.1 MэВ
Neutron radiation mode	steady-state
Power supply	200±5 V
Dimensions	130x279x227 mm
Operation time	~800 hours
Detector of α-particles	64-pixel position sensitive silicon detector
Operation temperature	10-45° C