JOINT INSTITUTE FOR NUCLEAR RESEARCH

Frank Laboratory of Neutron Physics

# FINAL REPORT ON THE SUMMER STUDENT PROGRAM

## Characterization of "TANGRA"-setup Multi-detector Gamma-ray Spectrometer "Romashka"

**Supervisors:**
Dr. Yu.N. Kopatch
Dr. I.N. Ruskov
**Technical assistance:**
MSc. D.N. Grozdanov
**Student:**
Nikita Fedorov, Russia
Lomonosov Moscow State University

**Participation period:**
June 10 - July 21

Dubna 2016

# Contents

## Abstract

An experimental setup TANGRA (TAgged Neutron and Gamma RAys) for studying of neutron-induced nuclear reactions was created in the Joint Institute of Nuclear Research (JINR) Frank Laboratory of Neutron Physics (FLNP) [1]. It consists of: a neutron generator ING-27, an array of 22 NaI(Tl) gamma-ray detectors, which allows one to study the angular and energy distributions of gamma quanta emitted from a target. These distributions provide important information for applied and fundamental physics research. The main characteristics of the detector system, such as time- and energy- resolution, as well as, the efficiency of registration have to be established via a calibration procedure. Determination of the detector system parameters and their influence to the experimental results are discussed.

# 1 Introduction

The Tagged Neutrons Method (TNM) is widely used in science. The main idea of this approach is quite simple: the neutrons are produced in a D-T fusion-fission reaction:

$$\mathrm{D} + \mathrm{T} \rightarrow \alpha + n + 17.6\mathrm{MeV} \tag{1}$$

The products of this reaction, the alpha particle and the neutron, fly in opposite directions; the alpha-particle can be simply detected and its direction can be determined, therefore the direction of the neutron can be established, too. If the neutron interacts with the target nucleus it can excite it in an inelastic scattering process in which the nucleus emits gamma-rays. The ordinary time interval between the neutron scattering and the emission of gamma quanta is very short, therefore the space coordinates of interaction point can be estimated. The information about the energy of the emitted gamma-rays allows to determine the elemental and isotopic composition of the target, the coordinates of the interaction points give information about the space distributions of particular elements in the sample.

The construction of the experimental setup allows one to study the angle distribution of gamma quanta, a very important characteristic of inelastic scattering process, which provides information about the nature of the neutron-nucleus interaction and allows to determine its mechanism (a reaction through compound nucleus or via direct reaction). This aspect is discussed in detail in [2] and some initial information is presented in the Appendix C.

# 2 Tangra setup

The TANGRA-setup consists of a portable neutron generator (ING-27)[3] for producing a continuous beam of 14.1 MeV neutrons, a compact neutron-gamma shielding-collimator assembly and an array of NaI (Tl), BGO, Stilbene (or Plastic) detectors for gamma-ray and neutron spectroscopy in variable configurations. The current configuration utilizes 22 hexagonal NaI(Tl) scintillation probes, produced by Amcrys®. A 32 channel multi-parametric digital data acquisition system (DAQ) is used for analog signal processing.

## 2.1 ING-27 characteristics

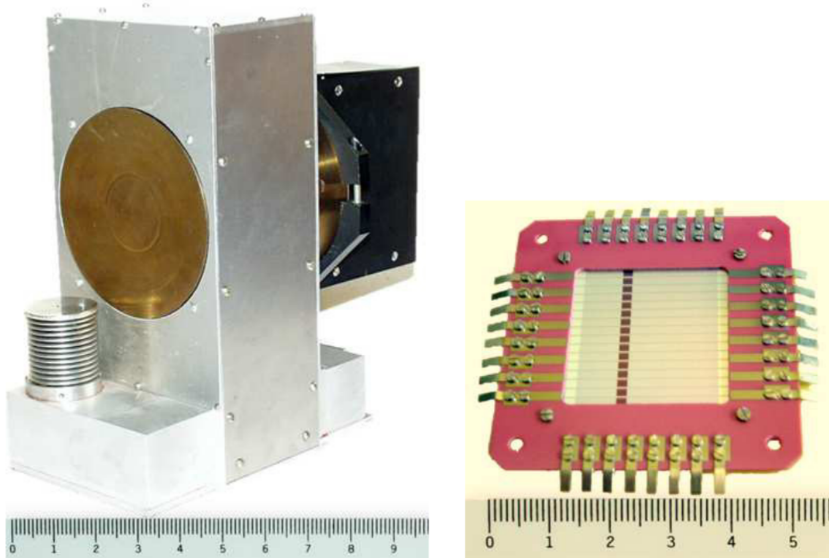

Figure 1: Neutron generator ING-27 (left); 64-pixel Si $\alpha$-particle detector (right)

The ING-27 is a computer-controlled portable neutron generator, based on a sealed ( $^2H$ + $^3H$) gas-filled neutron tube with a built-in 64-pixel silicon (Si) $\alpha$-particle detector, which was developed at All-Russia Research Institute of Automatics in Moscow (VNIIA, 2014). For example, it is used for detection and identification of explosives and other hazardous materials, searching the diamonds in kimberlite, etc., using associated particle imaging (API) methods. The ING-27 provides a continuous neutron flux with an intensity of about $5 \times 10^7$ n/s.

The $\alpha$-detector incorporated into the ING-27 (Fig.1, right side) consists of 8 mutually perpendicular Si strips on each side, mounted on a plastic frame and forming a $8 \times 8$ matrix of $4 \times 4$ mm 2 pixels. The total sensitive area of the 64-element $\alpha$-detector is $32 \times 32$ mm$^2$ [4]. It is located in 62 mm away from the centre of the TiT-target. The front-end electronics, which consists of 16 pre-amplifiers, is mounted on the back side of the neutron generator.

## 2.2 Neutron-gamma detector system

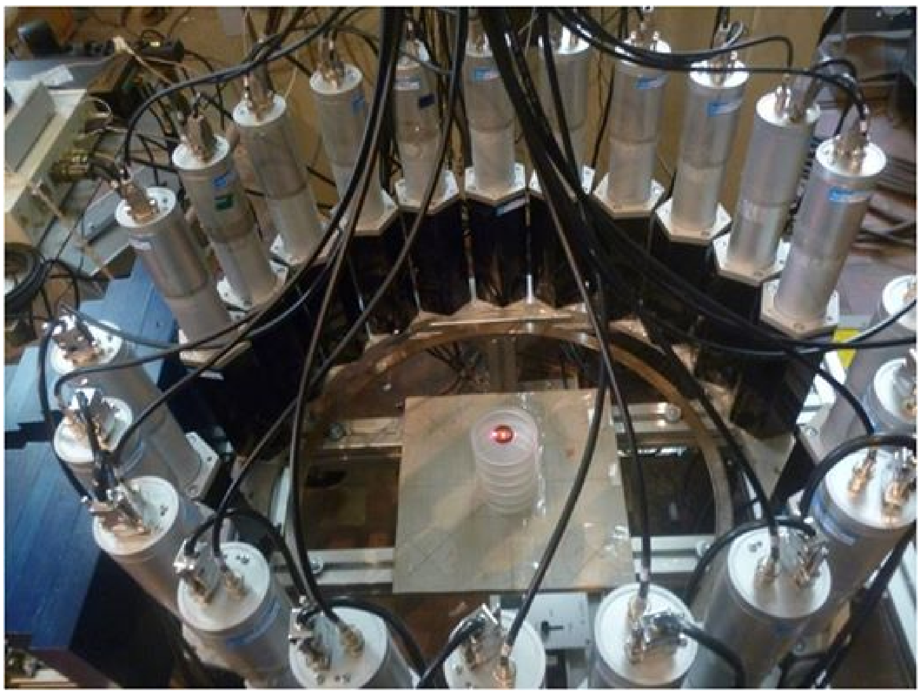

Figure 2: ROMASHKA detector array with the calibration source

The radiation detection system of the TANGRA setup, so-called "ROMASHKA"[5],[6] is presented in Fig. 2. It consists of 22 NaI(Tl) scintillator detectors placed around the target. Such setup gives the possibility to measure the multiplicity, energy and angular anisotropy of the emitted gamma rays. The data acquisition system ADCM executes analog-to-digital converting and digital signal processing. It is a 32-channel signal digitizer constructively designed as two boards with the size of a standard PCI card, giving the possibility to install it in a PCI slot of a personal computer and to work under its control, exchanging the information via its

PCI bus. The signals from all detectors are recorded simultaneously in digitized form and are stored on the hard disk of a personal computer for further off-line analysis by ROOT ADCM software. The subsequent processing of the stored data is performed by ROOT-based program ROMANA, which sorts the recorded pulses by their time and amplitude, forms histograms (so called amplitude spectra) and writes results in .root files. Determination of the parameters of the gamma-detector system is discussed in the next section.

# 3 Gamma detector's characteristics

The accurate determination of the parameters of the detector system is very important for the future research. Recently TANGRA has been equipped with a new ING-27 neutron generator and transported to other experimental hall. That is why the calibration procedure for calculation the efficiency and the energy resolution of Romashka's detectors has been repeated. A computer program for determination of the detector system parameters was written and used.

## 3.1 Energy calibration

The calibration of the detector system was done first and foremost because in this procedure a relation between amplitude channels and corresponding gamma-ray energies is established and a calibration curve is obtained. A set of reference sources of gamma-rays with well-known energies are needed for this procedure. We used certified point-type gamma-sources of $^{60}$Co, $^{137}$Cs and $^{133}$Ba for calibration, their parameters are presented in the Table 1:

Table 1: Parameters of reference gamma-sources

| Nucleus | Half-Life, years | Initial Activity(Bq) | Energy keV | Yield (%) | Date of measurement (DD/MM/YY) |
|---|---|---|---|---|---|
| $^{60}$Co | 5.271 | 105300 | 1173.228 3<br>1332.492 4 | 99.85 % 3<br>99.9826 % 6 | 01/10/2014 |
| $^{137}$Cs | 30.08 | 110000 | 661.657 3 | 85.10 % 20 | 01/10/2014 |
| $^{133}$Ba | 10.551 11 | 58900 | 356.0129 7 | 62.05 % | 01/10/2014 |

The calibration procedure for NaI(Tl) detectors is quite simple, because the relation between the gamma-ray energies and the amplitude channels is a linear. Therefore, this process can be described in the following simple algorithm:

1. to find the peaks in the measured spectra
2. to compare them with the reference gamma-rays energies
3. to approximate the obtained experimental points by a predefined function

The analysis of peaks in step 1 should be discussed in detail: the photo-peak in the measured spectra must be found first, after that it must be approximated by some curve (ordinary it is a sum of Gaussian function (Eq.2) and background approximation) An example of the photo-peak approximation is presented in the Fig. 3

$$f(E) = \frac{S}{\sigma\sqrt{2\pi}} e^{-\frac{(E-E_0)^2}{2\sigma^2}} \tag{2}$$

The peak parameters can be extracted from the approximation, namely, from the fitting coefficients of the Gaussian function: $S$ corresponds to the photo-peak area, $E_0$–to photo-peak position and $\sigma$–to photo-peak width. In order to speed-up the least-square fitting procedure, the initial "guess" parameters of fitting function should be set correctly. Figure 4 presents an example of calibration curve. The fitting function parameters error-bars of this approximation are reasonably small.

## 3.2 Efficiency of gamma-quanta registration

Before looking at this matter in detail, it should first be established what we mean by "efficiency". It can be defined in a number of ways. In gamma spectrometry, the intention is to relate the photo-peak area in the spectrum to the amount of radioactivity it represents. For this we need the absolute full energy peak efficiency. This relates the photo-peak area, at a particular energy, to the number of gamma-rays emitted by the source and must depends upon the source-detector configuration.

The absolute total efficiency relates the number of counts detected in the whole spectrum to the number of gamma rays emitted by the source.

The intrinsic efficiency (full energy peak or total) relates the counts in the spectrum to the number of gamma rays incident on the detector. This efficiency is a basic parameter of the detector and is independent of the source/detector geometry.

The absolute full energy peak efficiency is most important parameter for practical applications, because it should be used for calculation of the radioactive source

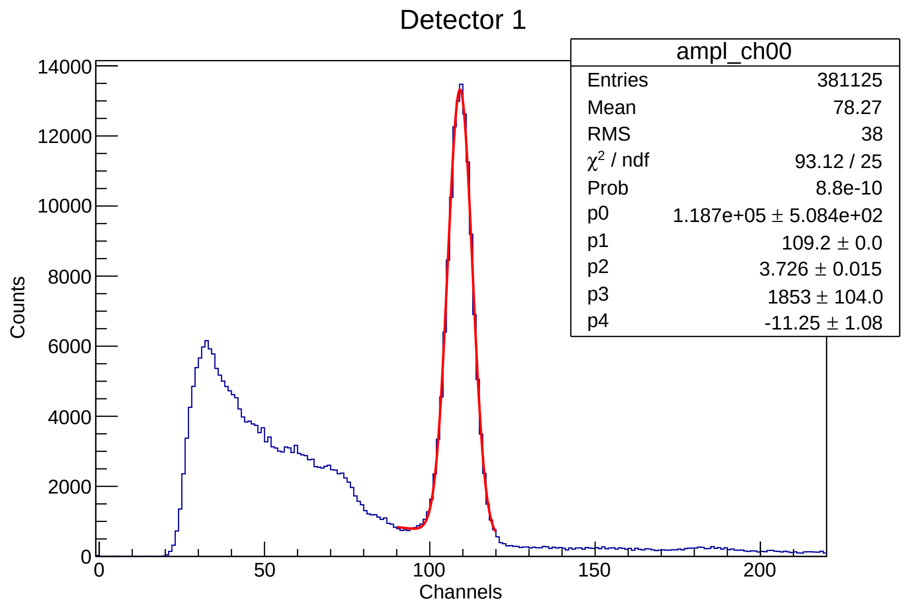


Figure 3: Approximation of the measured amplitude spectra of gamma rays from $^{137}$Cs, recorded by detector 1. The fit function is $\frac{p_0}{p_2\sqrt{2\pi}}e^{-\frac{(E-p_1)^2}{2p_1^2}} + p_3 + p_4E$

current activity. This parameter can be defined as

$$\varepsilon = \frac{S}{N_\gamma} \tag{3}$$

where $S$ is the area under the photo-peak, which can be obtained from the approximation parameters, $N_\gamma$ is the number of the emitted gamma quanta from the radioactive source and it can be obtained from Eq. 4:

$$N_\gamma = \frac{A_0 e^{-\lambda t}(1 - e^{-\lambda \Delta t})\gamma}{\lambda} \tag{4}$$

where $A_0$–is the initial activity, $t$–is the time between the dates of the radioactive source specification and the current measurement, $\gamma$–is an intensity of the gamma line (probability of decay with emission of a gamma quantum with this energy). Eq. 3 can be rewritten as:

$$\varepsilon = \frac{S \log 2}{A_0 T_{1/2} 2^{-\frac{t}{T_{1/2}}}(1 - 2^{-\frac{\Delta t}{T_{1/2}}})\gamma} \tag{5}$$

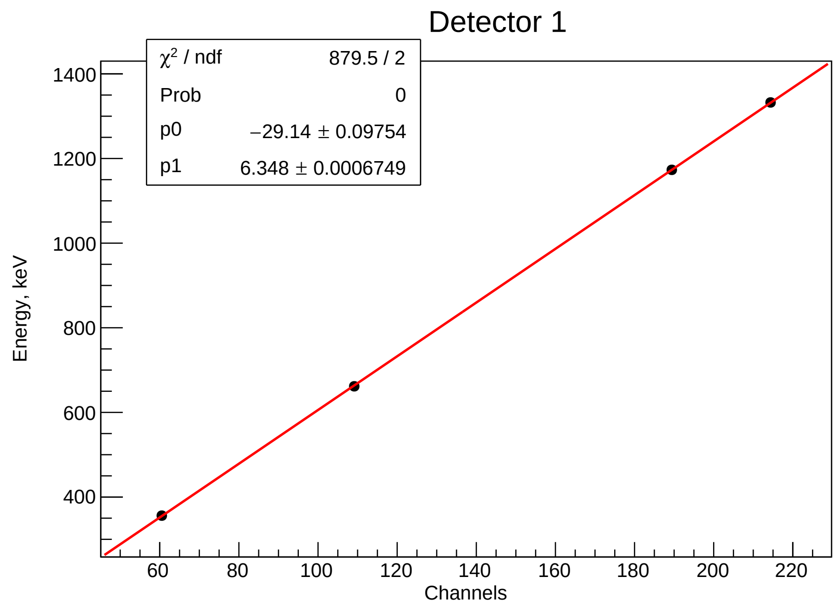


Figure 4: Calibration curve for detector 1.

In case of $T_{1/2} \gg \Delta t$ Eq. 5 turns into

$$\varepsilon = \frac{S}{A_0 \Delta t 2^{-\frac{t}{T_{1/2}}} \gamma} \tag{6}$$

The total uncertainty of the efficiency has to be taken into account. It can be estimated by the general formula:

$$\sigma\left(f(x_1 ... x_n)\right) = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i} \sigma(x_i)\right)^2} \tag{7}$$

The main sources of the uncertainties are $\sigma(S)$ and $\sigma(A_0)$. So, the final expression for the total uncertainty is expressed by the formula:

$$\sigma(\varepsilon) = \sqrt{\left(\frac{\varepsilon}{S}\sigma(S)\right)^2 + \left(\frac{\varepsilon}{A_0}\sigma(A_0)\right)^2} \tag{8}$$

An example of the experimentally determined efficiency is shown in the Fig. 5.

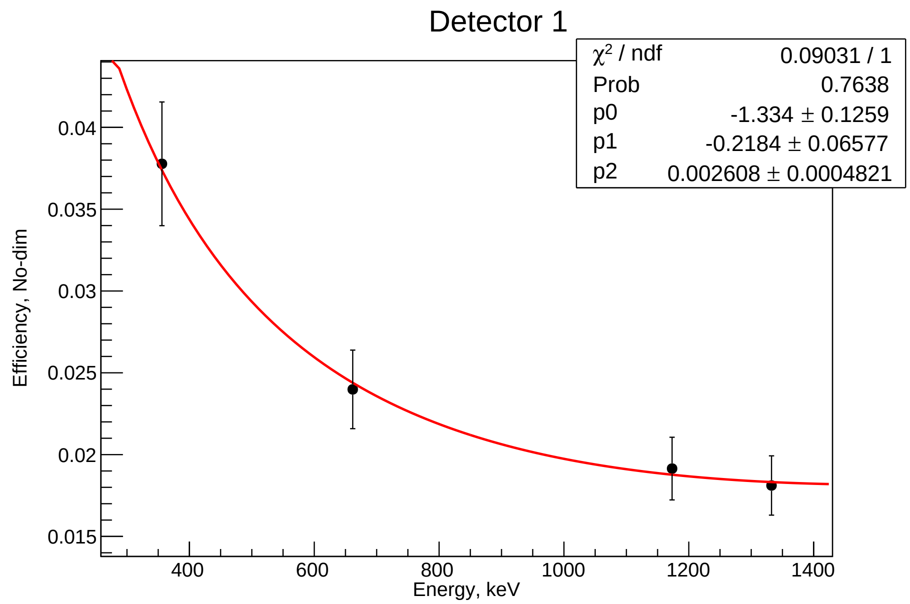


Figure 5: Efficiency of the detector 1. The approximation function is $p_0 + \exp(p_1 \log(E)) + \exp(p_2 \log^2(E))$.

It can be seen in Fig. 5 that absolute full energy peak efficiency decreases with increasing energy. The reason of this effect is the change of probability of photon interaction with detector's media. The dependence the of linear attenuation coefficient (i.e. the probability of gamma quanta absorption per unit of path-length) is presented in the Fig. 6:

The analytical calculation of the detector efficiency is very complex procedure, because there are many of effects in photon interaction with detector's media, that should be taken into account. The main principals of it are discussed in ref.[8]. In practice, the most widely used ways to obtain the absolute full energy peak efficiency are Monte-Carlo simulation and the experimental data model function fitting.

## 3.3 Gamma-detector energy resolution

The next important parameter of gamma detector is its energy resolution. In an "ideal" experiment, every gamma-quantum of the same energy detected would give rise to a count in the same channel of the gamma-ray spectrometer. Clearly, they do not. The peaks are spread over several channels, with preponderance at a central

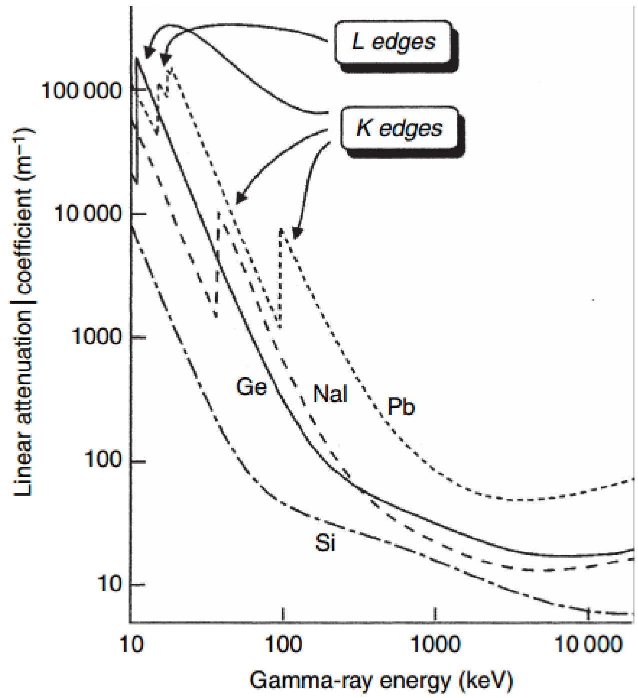


Figure 6: Attenuation coefficient as a function of gamma-ray energy [7]

point, which can be identified by the gamma-ray energy. The reason is, that there are some uncertainties within the detection and measurement processes that, cause nominally identical events to end up as counts in different spectrometer channels.

There are several sources of peak width widening:

1. $\omega_1$–is the uncertainty in the gamma-ray energy–the intrinsic width, can be determined from the Heisenberg Uncertainty Principle $\Delta E \Delta t \geq \hbar$. The influence on the resulting width is minimal.

2. $\omega_2$–is the uncertainty in the intensity of the scintillation.

3. $\omega_3$–is the uncertainty of the light-to-electrical pulse transformation in the photomultiplier tube;

4. $\omega_4$–is the uncertainty introduced by the electronic noise during the pulse formation and processing.

The total uncertainty in the energy measured by the spectrometer will be:

$$\omega = \omega_1 + \omega_2 + \omega_3 + \omega_4 \tag{9}$$

The terms 2-4 in Eq. 9 represent the statistical processes, which are expected to have a Gaussian distribution. So, the photo-peak can be approximated by a Gaussian function.

The energy resolution can be determined by the expression:

$$R = \frac{FWHM}{E} \tag{10}$$

where $FWHM$ is the peak Full Width at Half Maximum height, which can be calculated by the formula:

$$FWHM = \sqrt{8 \log 2}\sigma \tag{11}$$

The energy resolution uncertainty can be calculated by the formula below:

$$\sigma(R) = \sqrt{\left(\frac{R}{\sigma}\sigma(\sigma)\right)^2 + \left(\frac{R}{E}\sigma(E)\right)^2} \tag{12}$$

where $\sigma(\sigma)$ is the uncertainty of $\sigma$ as defined in Eq. 2. An example of the experimentally determined energy resolution is presented in Fig. 7

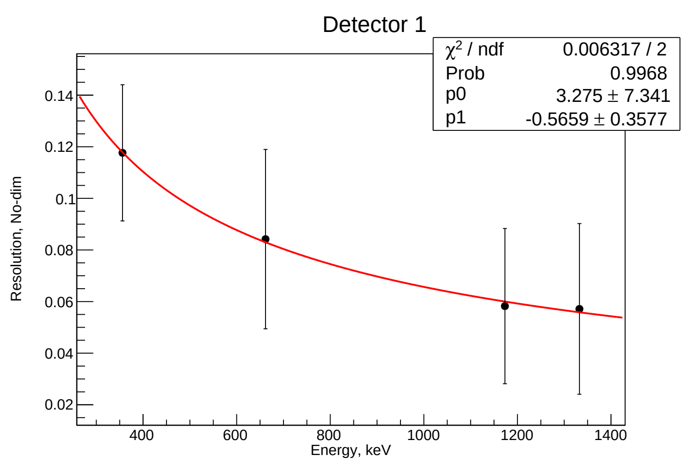


Figure 7: Experimentally obtained resolution. The fit function is $p_0 E^{p_1}$

# 4 Computer program "Calibration". The algorithm

Determination of the detector array parameters is a complex and computationally intensive task. A program for determining the parameters of the detector system was written in the frame of Summer Student Practice. The algorithm and main features of this program are discussed further in this section.

First of all, for analysis of the experimental data some initial information (such as amplitude spectra, characteristics of used gamma radiation sources, date of their certification, duration of the measurement). The amplitude spectra are stored in **.root** files, parameters of the calibration gamma-sources are written in the "parameters.txt" file. The **.root** files are generated by the "ROMANA" C++ program, which creates the amplitude spectra from the initial files containing the recorded pulses. The file "parameters.txt" is filled by the user.

The file with histograms is read by standard ROOT functions, and a library "par_io.h" is used for parsing the "parameters.txt". The parameters of gamma source should be predefined by keywords. A list of keywords and an example of the file "parameters.txt" are shown in the Appendix A.

After successful load of the input data, the initial information is placed to the **input_data** object, which contains all the predefined data. This class contains also the function, which calculates the number of the emitted gamma quanta from the source and its uncertainty.

Other parameters, which are important for further calculations, are obtained from the fitting of a function to the measured spectra. The fit function and its initial parameters should be set in "parameters.txt" file by the user. If there are no peaks in the predefined interval, the program can find the nearest peak automatically. The fit procedure is executing by the function "FitSpectra()", the results are assigned as a part of the **input_data** object.

After fitting the histogram, a calibration procedure should be executed. In this program it is done by the "calibration_det_array()" function, which is a member of **out_data** class, using the method described in the subsection3.1.

The functions "efficiency_det_array()" and "resolution_det_array()" calculate the efficiency and the resolution, respectively, using the methods described in subsections 3.2 and 3.3. Also, in these functions the peaks parameters ($\sigma$ and $S$) must be recalculated from "channel" units to 'energy" ones using the next formulas:

$$\sigma_E = k\sigma_{ch};\ \sigma(\sigma_E) = \sqrt{(k\sigma(\sigma_{ch}))^2 + (\sigma_{ch}\sigma(k))^2} \tag{13}$$

and

$$S_E = \frac{S_{ch}\sigma_E}{\sigma_{ch}} = S_{ch}k;\ \sigma(S_E) = \sqrt{\left(\frac{S_E}{S_{ch}}\sigma(S_{ch})\right)^2 + \left(\frac{S_E}{k}\sigma(k)\right)^2} \tag{14}$$

These formulas can be simply obtained from the fact that the distance between two points in the "energy" scale and "channel" scale is $E_2 - E_1 = k(Ch_2 - Ch_1)$ and the fact that the peak height is constant i.e. $h_{ch} = h_E \rightarrow \frac{S_{ch}}{\sqrt{2\pi}\sigma_{ch}} = \frac{S_E}{\sqrt{2\pi}\sigma_E}$.

The results of calculations (the fitting functions parameters, the photopeak efficiency and energy resolution) are saved in ASCII files, while the figures–in .pdf files. The resulting data are discussed below.

# 5 Results

The obtained results are presented in this section. In Figs. 8 and 9 the efficiency and the resolution of each detector are presented. It can be seen that the efficiency and the resolution of all the detectors are similar, but not the same. These differences should be taken into account in the data handling process. Also, the comparison between the parameters obtained by different detectors provides additional information about the proper functioning of the lab equipment and/or data processing software.

Table 2: Absolute full energy peak efficiency

| Energy | Detector # | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| 1332.49keV | $\varepsilon$ | 0.0181 | 0.0176 | 0.0183 | 0.0192 | 0.0183 | 0.0193 |
| | $\sigma(\varepsilon)$ | 0.0018 | 0.0018 | 0.0018 | 0.0019 | 0.0018 | 0.0019 |
| 1173.23keV | $\varepsilon$ | 0.0191 | 0.0187 | 0.0197 | 0.0210 | 0.0194 | 0.0210 |
| | $\sigma(\varepsilon)$ | 0.0019 | 0.0019 | 0.0020 | 0.0021 | 0.0019 | 0.0021 |
| 661.657keV | $\varepsilon$ | 0.0240 | 0.0246 | 0.0263 | 0.0266 | 0.0257 | 0.0267 |
| | $\sigma(\varepsilon)$ | 0.0024 | 0.0025 | 0.0026 | 0.0027 | 0.0026 | 0.0027 |
| 356.005keV | $\varepsilon$ | 0.0378 | 0.0376 | 0.0401 | 0.0406 | 0.0395 | 0.0405 |
| | $\sigma(\varepsilon)$ | 0.0038 | 0.0038 | 0.0040 | 0.0041 | 0.0040 | 0.0041 |

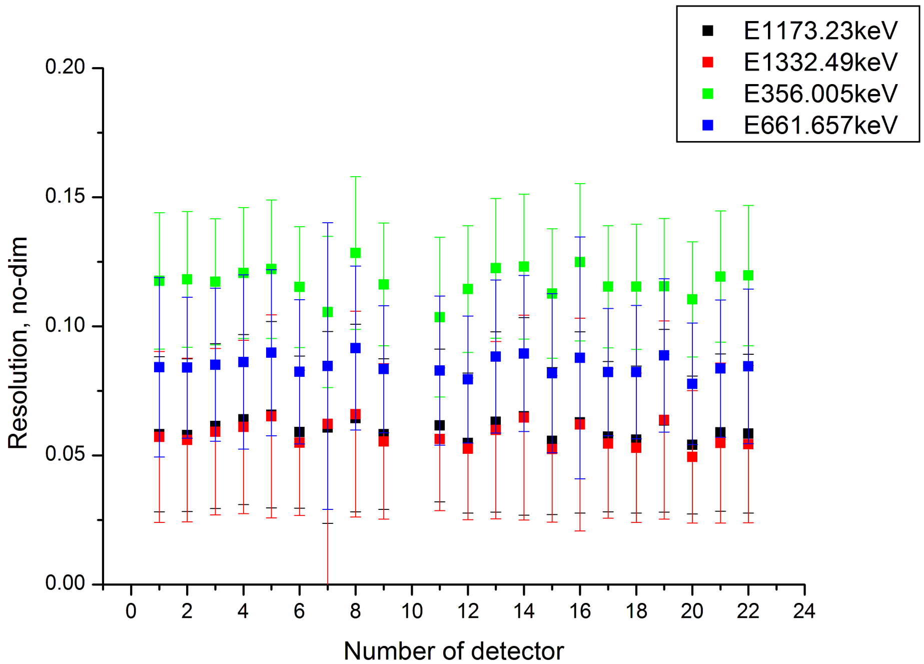


Figure 8: Experimentally obtained detector efficiency. Detector # 10 was not used

Table 3: Detector energy resolution

| Energy | Detector # | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| 1332.49keV | $R$ | 0.057 | 0.056 | 0.059 | 0.061 | 0.065 | 0.055 |
| | $\sigma(R)$ | 0.033 | 0.032 | 0.032 | 0.034 | 0.039 | 0.028 |
| 1173.23keV | $R$ | 0.058 | 0.058 | 0.061 | 0.064 | 0.066 | 0.059 |
| | $\sigma(R)$ | 0.030 | 0.030 | 0.032 | 0.033 | 0.036 | 0.029 |
| 661.657keV | $R$ | 0.084 | 0.084 | 0.085 | 0.086 | 0.090 | 0.082 |
| | $\sigma(R)$ | 0.035 | 0.027 | 0.030 | 0.034 | 0.032 | 0.028 |
| 356.005keV | $R$ | 0.118 | 0.118 | 0.117 | 0.121 | 0.122 | 0.115 |
| | $\sigma(R)$ | 0.026 | 0.026 | 0.024 | 0.025 | 0.027 | 0.023 |

# Conclusion

A computer ROOT script program for determining the characteristics of the "ROMASHKA" setup has been written and used for obtaining the main parameters of gamma-ray detectors, such as: "amplitude-to-energy" calibration curve, absolute

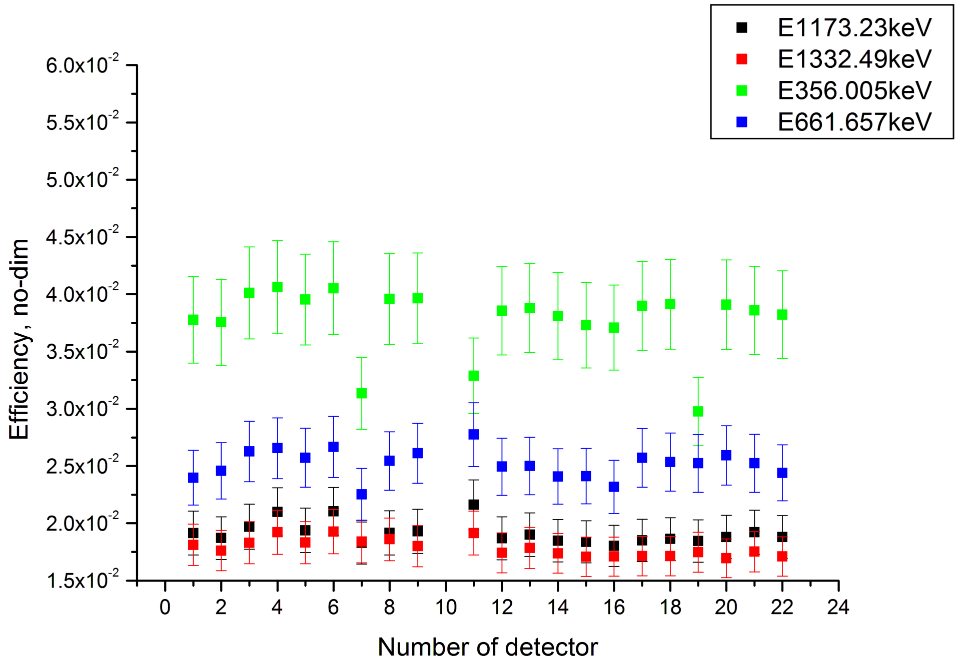


Figure 9: Experimentally obtained detector resolution. Detector # 10 was not used

full energy peak efficiency and energy resolution. They have been calculated from the experimental data for four different energies of gamma quanta. The results obtained coincide with previous calculations [9] within the margin of total errors. So, the created computer program can be used for calibration of the "ROMASHKA" multi-detector gamma-spectrometer.

# Acknowledgments

I have to express out appreciation to my scientific supervisors, Dr. Yu.N. Kopatch and Dr. I.N. Ruskov for their patience, motivation, and immense knowledge. I am also immensely grateful to MSc. D.N. Grozdanov for his invaluable assistance in performing of this work.

Also, I would like to thank the University Center of the Joint Institute for Nuclear Research and the Management of the Frank Laboratory for Neutron Physics for the financial support of my summer practice and the excellent working atmosphere during all my stay in Dubna.

# Appendix A. "parameters.txt"

Keywords:

1. **#** a comment sign (string beginning from this symbol will be ignored).
2. **Source**: (string) A name of radioactive source. Used for designation of output files.
3. **Path**: (string) Path to the .root file.
4. **MeasurementDate**: Date of reference sources certification.
5. **ExperimentDate**: Date of experiment.
6. **Activity** and **ActivityErr**: (float) The radiation source activity on the date of certification and its error.
7. **ExperimentTime**: (float) Duration of the measurement (in seconds).
8. **HalfLife**: (float) Radioactive isotope decay half-life.
9. **ApproxFunction**: (string) Photopeak fit function for measured spectra.
10. **Limits**: (float),(float) Margins of fit (in channels).
11. **ParametersArray**: (int,/ float[]) Number of the parameters and their initial values (at the next string).
12. **NumberOfPeaksInApproximation**: (int) Number of peaks in the fit function.
13. **PeaksAreaIndexes**: (int,/ int[]) Number of *important* peaks and indexes corresponding to the peaks' areas (i.e. $S$).
14. **PeaksMiddleIndexes**: (int[]) Indexes corresponding to the middle of peaks (i.e. $E_0$).
15. **PeaksEnergies** and **PeaksEnergiesErr**: (float[], float[]) Reference energies and their errors.
16. **Gamma**: (float[]) Intensities of the gamma lines.
17. **AutomaticPeakSearch**: (yes/no) A flag for automatic peak search.
18. **End**: End of source description.

## An example of "parameters.txt"

```
#File for Co-60
Source
Co-60
Path
/home/tangra/root/run02_Co60_100mm.root
MeasurementDate
01/10/2014
ExperimentDate
21/06/2016
Activity
105300
ActivityErr
10 %
ExperimentTime
719
HalfLife
5.271
ApproxFunction
gausn(0)+gausn(3)+pol1(6)
Limits
150 240
ParametersArray
9
90000 180 5 90000 220 5 0 0 0
NumberOfPeaksInApproximation
2
PeaksAreaIndexes
2
0 3
PeaksMiddleIndexes
1 4
PeaksEnergies
1173.228 1332.494
PeaksEnergiesErr
0.001 0.001
Gamma
```

```
100 100
AutomaticPeakSearch
yes
End
```

# Appendix B. Calibration parameters

Table 4: Calibration parameters

| $p_0$,keV | $p_1$keV/Ch | $\sigma(p_0)$ | $\sigma(p_1)$ |
|---|---|---|---|
| -29.1434 | 6.34788 | 0.097542 | 0.000675 |
| -27.8858 | 6.53112 | 0.098543 | 0.000703 |
| -27.3266 | 6.80868 | 0.101249 | 0.000774 |
| -29.5145 | 6.95256 | 0.106606 | 0.000816 |
| -26.6802 | 6.76674 | 0.111154 | 0.000855 |
| -27.1142 | 6.86219 | 0.096725 | 0.000724 |
| -25.4721 | 5.99024 | 0.106529 | 0.000696 |
| -30.4801 | 6.72353 | 0.116964 | 0.000869 |
| -35.5671 | 6.69591 | 0.094498 | 0.000706 |
| -30.4478 | 7.93172 | 0.146445 | 0.001453 |
| -26.725 | 6.97551 | 0.103661 | 0.000771 |
| -26.9132 | 6.42621 | 0.08786 | 0.000624 |
| -23.636 | 6.68762 | 0.109557 | 0.000805 |
| -22.8921 | 6.50692 | 0.108412 | 0.000808 |
| -23.623 | 6.3109 | 0.090881 | 0.000633 |
| -22.3478 | 6.23646 | 0.109036 | 0.000753 |
| -30.0261 | 6.62756 | 0.093603 | 0.000693 |
| -26.7588 | 6.48937 | 0.092297 | 0.000666 |
| -21.478 | 6.63 | 0.107999 | 0.000816 |
| -27.9728 | 6.75675 | 0.089682 | 0.000669 |
| -37.0555 | 6.84149 | 0.104314 | 0.000769 |

# Appendix C. Angular distribution of gamma quanta

The angular distribution of gamma quanta provides an important information about the properties of a decayed excited state. It can be described using the angular momentum algebra[10]:

$$W = \sum_{\alpha\alpha' JJ' kq} \rho^f_{kq}(\alpha J, \alpha' J')\varepsilon^*_{kq}(\alpha J, \alpha' J') \tag{15}$$

In this formula $\varepsilon^*_{kq}(pL, p'L')$ is a gamma detector efficiency tensor and $\rho^f_{kq}(\alpha J)$ is the statistical tensor of the decaying system, which depends on the momentums of decaying system and its intrinsic structure. The physics notation of the efficiency tensor is the "state", in which the detector "see" the system. The formula (15) can be expanded, using some initial information about the decay. For a considered system, in which a gamma decay takes place, $\rho^f_{kq}(\alpha J)$ can be represented as a combination of statistical tensors of the nucleus in excited state and the photon, as follows (16)

$$\begin{aligned} W_{\alpha_f J_f} = \sum_{pp'LL'kq} (-1)^{L'+J+J_f+k} \begin{Bmatrix} J & L' & J_f \\ L & J & k \end{Bmatrix} \varepsilon^*_{kq}(pL, p'L')\rho_{kq}(\alpha J)\times \\ \times \langle \alpha_f J_f, pL : J||H_{int}||\alpha J\rangle \langle \alpha_f J_f, p'L' : J||H_{int}||\alpha J\rangle^* \end{aligned} \tag{16}$$

In this formula $\rho_{kq}(\alpha J)$ is the statistical tensor for the excited state of nucleus and $H_{int}$ is the operator, describing the interaction between the nucleus and the electromagnetic field. The information about the excitation process is contained in $\rho_{kq}(\alpha J)$, as shown in Eq. 17:

$$\rho_{kq}(\alpha j, \alpha' j') = \frac{1}{\sqrt{2j+1}\sqrt{2j'+1}} \sum_{\beta,\beta'} \langle \alpha j||T||\beta j\rangle \langle \alpha' j'||T||\beta' j'\rangle^* \rho^i_{kq}(\alpha j, \alpha' j'). \tag{17}$$

The statistical tensor of the initial state $\rho^i_{kq}(\alpha j, \alpha' j')$, in the case of absence of polarization, can be simply determined as:

$$\rho_{k=0,q=0}(j, j') = \frac{1}{\sqrt{2j+1}} \tag{18}$$

where the matrix elements $\langle \alpha' j'||T||\beta' j'\rangle$ should be calculated theoretically.

The angular distribution of $\gamma$-rays, produced in the inelastic scattering of neutrons is an interesting object of an experimental research.

One of the first experiments, which was performed in the frame of the project TANGRA[11], is the measurement of the angular distribution of the gamma quanta, produced in the reaction of inelastic scattering of 14.1 MeV neutrons on carbon nuclei. Similar experiments were done in the past [12],[13],[14]. Their results are presented in the Fig. 10. It can be seen, that results obtained differ each other. Therefore, further experimental investigations should be done.

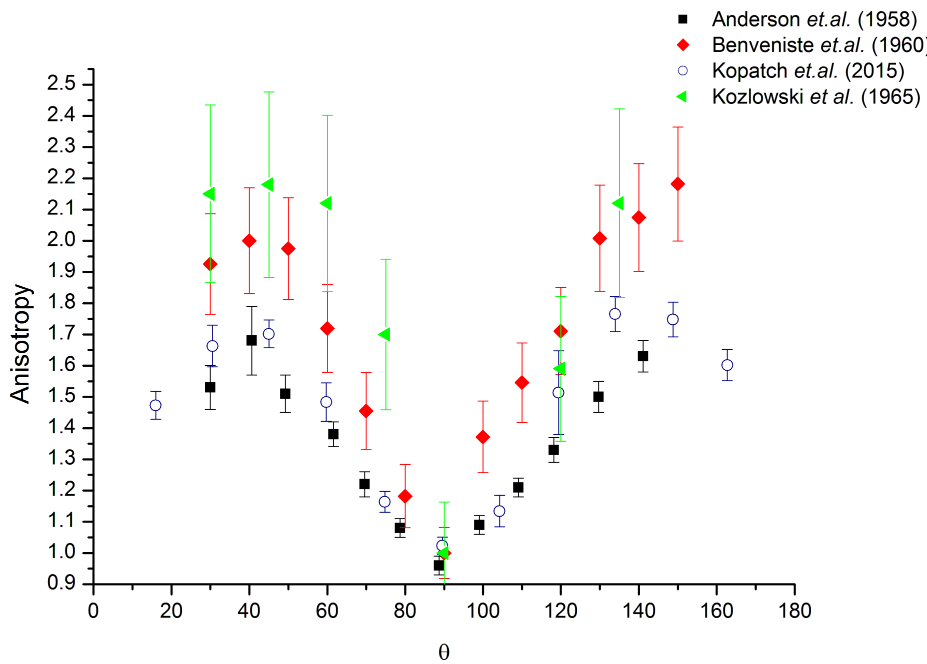


Figure 10: Angular anisotropy obtained from experiments [12],[13],[14] and [11]

# References

[1] I.N. Ruskov, Yu.N. Kopatch, V.M. Bystritsky *et al.,* TANGRA-Setup for the Investigation of Nuclear Fission induced by 14.1 MeV neutrons. Physics Procedia, 64 (2015) 163-170

[2] B. A. Benetskii and I. M. Frank, Angular correlation between gamma rays and 14-MeV neutrons, JETP, 17, 1963, 309-313.

[3] Neutron generators for analysis of substances and materials. ING-27 gas-filled neutron tube based neutron generator of VNIIA, http://www.vniia.ru/eng/ng/docs/ing_element_eng.pdf.

[4] Bystritsky V.M., Zamyatin, N.I., Zubarev, *et al.,* Stationary setup for identifying explosives using the tagged neutron method. Physics of Particles and Nuclei Letters 10, (2013), 442-446. http://ntech.jinr.ru/img/papers/PHPL442.pdf.

[5] Skoy, V.R., Kopatch Yu.N., Ruskov I., A versatile multi-detector gamma-ray spectrometry system for investigation of neutron induced reactions. 21st International Seminar on Interaction of Neutrons with Nuclei, ISINN-21, 20-25 May 2013, Alushta, Ukraine, pp. 242-248.

[6] D.N. Grozdanov, A.O. Zontikov, Optimization of "Romashka" setup for investigation of $(n, n'\gamma)$-reactions with tagged neutrons method, ISINN-23 proceedings: http:isinn.jinr.rupast-isinnsisinn-23program.html

[7] Gordon R. Gilmore, Practical Gamma-ray Spectrometry. John Wiley & Sons Ltd, Chichester (UK), 2008

[8] B.S. Ishkhanov, I.M. Kapitonov, E.I. Kabin. "Particles and nuclei. Experiment", Max Press, Moscow, 2013. (in Russian)

[9] Serikova N.A. Energy Calibration of the Multi-detector System "Romashka" OF "TANGRA"-setup. A Final report on the JINR summer student program. Dubna, 2016

[10] V.V. Balashov, A.N. Grum-Grzhimailo, N.M. Kabachnik. Polarisation and Correlation Phenomena in Atomic Collisions. Kluwer Academic/Plenum Publishers, New York (USA), 2000.

[11] Yu.N. Kopatch, V.M. Bystritsky, D.N. Grozdanov *et.al.* Angular correlation of gamma-rays in the inelastic scattering of 14.1 MeV neutrons on Carbon. ISINN-23 proceedings 2016.

[12] J. D. Anderson, C. C. Gardner, J. W. McClure *et. al.* Inelastic scattering of 14-MeV neutrons from Carbon and Beryllium, Phys. Rev., 111 (1958) 572-574.

[13] J. Benveniste, A.C. Mitchell, C.D. Schrader *et al.,* Gamma rays from the interaction of 14-MeV neutrons with beryllium. Nucl. Phys. 19 (1960) 52-61

[14] T.Kozlowski, W.Kusch, J.Wojtkowska. Angular distribution of gamma rays from inelastic scattering of 14.1 MeV neutrons on C-12 and O-16. Inst.Badan Jadr.(Nucl.Res.),Swierk+Warsaw,Repts, No.661 (1965)