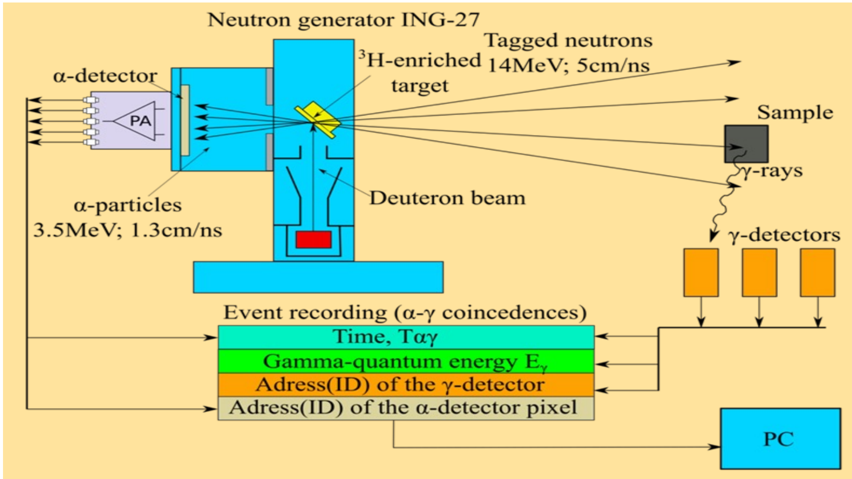
Project TANGRA

TAgged Neutrons & Gamma-Rays

"Measurement of Relative Efficiency of HPGe and $LaBr_3$ detector using ^{60}Co, ^{152}Eu, ^{228}Th and $^{35}Cl(n, \gamma)^{36}Cl$"



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Contents

Introduction

- Information about neutron-nuclear interaction is extremely important for both fundamental and applied physics.
- The study of neutron-nuclear processes also allows learning more about the properties of nuclear forces and the structure of nuclei.
- To fulfill the demand of energy of our modern society, we need different types of energy production sources like solar, wind, hydro, fission, fusion reactors.
- Between them the most effective sources of clean energy still are the nuclear power plants. (Need to solve the utilization of the burned fuel and radioactive wastes from Generation-I- III nuclear power reactors).
- To develop the Generation-IV fast neutron reactors, we need to have a good and reliable libraries of information about the characteristics of different type of fast neutron induced reactions (elastic and nonelastic neutron scattering, fission, etc.)
- Accurate soil carbon field mapping can benefit modern agricultural practices. For creating such maps, soil carbon measurements using neutron-gamma analysis were developed and applied as a better alternative to traditional chemical analysis.
- Main advantage of the tagged neutron method is possibility to detect diamond inside the kimberlite stone without crushing in grinding rolls.
- In the case of fast neutron induced nuclear reaction many possibilities (channels) are possible (open), i.e. (n, xnγ), (n, p), (n, α), (n, f), depends on the energy of the neutrons and the mass of the nuclei, and the use of multidetector systems is preferable.

Introduction

Our (n, xγ) reactions using TNM for accurate Data:

- The TANGRA project (TAGGED NEUTRONS & GAMMA RAYS) is being implemented at JINR with the participation of Russian and foreign institutes
- Eliminate discrepancies between available experimental and evaluated data.
- For some nuclei/gamma transitions the gamma-ray anisotropy hasn't been measured at all.
- Investigate possible differences between neutron and proton scattering.
- Angular anisotropy of the emitted gamma-rays has to be taken into account if the tagged neutron method is used for elemental analysis.
- Investigation of reactions (n,2n\`), (n,n\`) using the tagged neutron method

Available data on (n,xγ) reactions is not accurate:

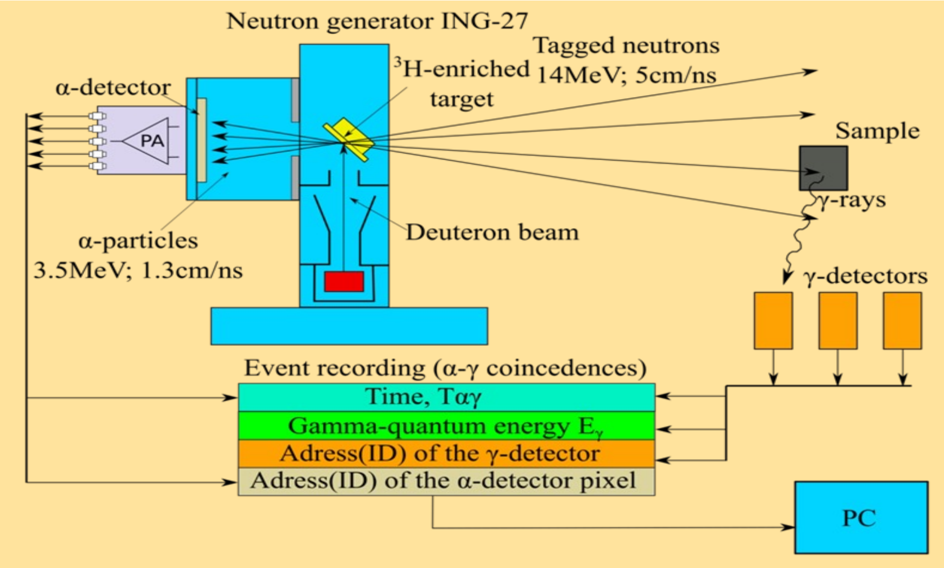
- Poor cross-section accuracy (up to several times discrepancy)
- Angular distributions for low-intense γ-transitions have not been measured before.

Aim of this Work

- ❖ Possible upgrade of the setup with $LaBr_3(Ce)$ and HPGe γ-detectors to measure angular distributions.
- ❖ To measure cross-section value of (n,xγ) reaction accurately, we need calibrate our LaBr3(Ce) and HPGe γ-detectors.
- ❖ **We have analyzed the photo-peak efficiencies of HPGe and $LaBr_3(Ce)$ using ^{60}Co, ^{152}Eu and ^{228}Th.**
- ❖ **We have measured the relative photo-peak efficiency using $^{35}Cl(n, \gamma)^{36}Cl$ reactions.**
- ❖ **We have compared our data with Geant4 and found good agreement between our data.**
- ❖ **We have added the covariance matrix analysis in our calculation.**

Tagged Neutrons Method – TNM

d + t → ^{4}He (3.5MeV) + n (14.1MeV)



Main components:

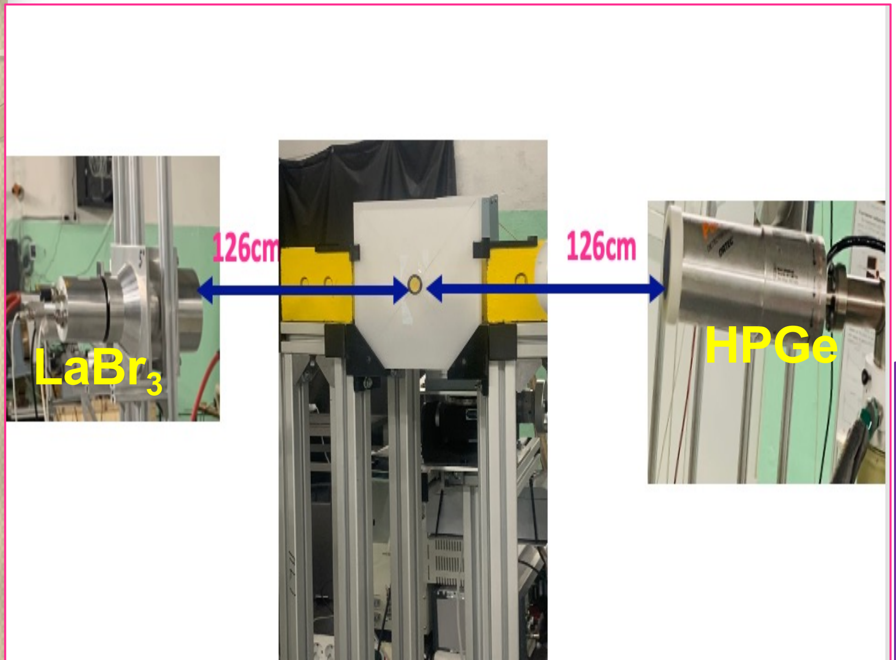
1. Neutron generator with a position sensitive detector of α-particles
2. Shielding
3. Detectors of γ-rays / neutrons
4. Sample

Main advantages of the method:

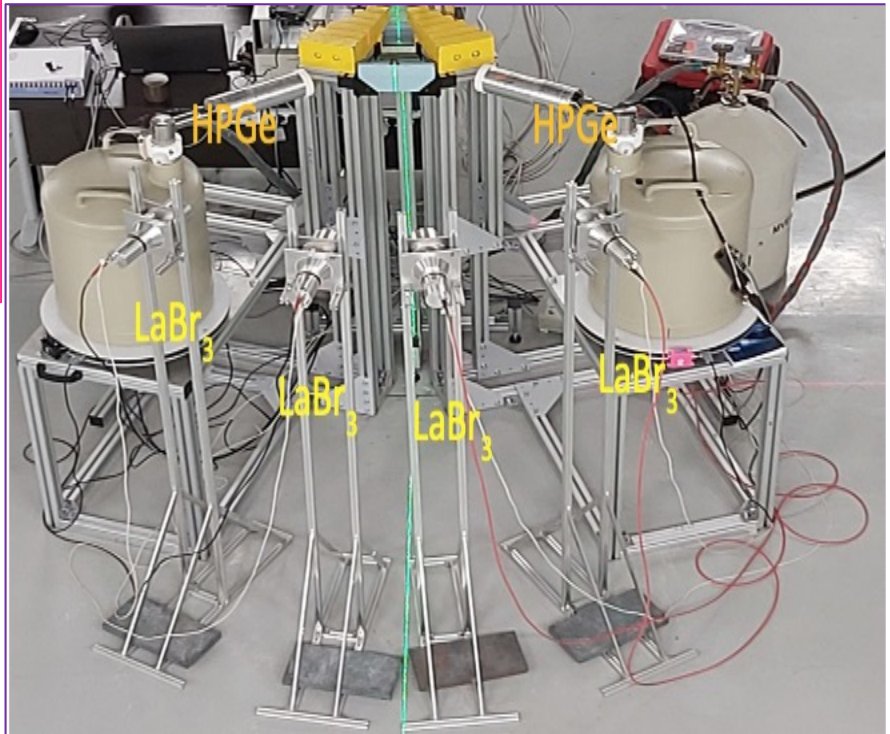
- Precise determination of the number of neutrons hitting the target: each neutron is "tagged" by the α-detector
- Information about space and time location of the interaction of the neutron with a target (X,Y-coordinates are given by the pixels of the α-detector; Z,t-coordinates are defined by the time-of-flight)
- Due to the selection of a small space-time volume of interaction (voxel) the contribution of background is significantly reduced
- The method allows to identify different elements and substances using their characteristic gamma-rays

Studying of Characteristics of HPGe and $LaBr_3$ Detectors

We have performed the Characteristics Srudies of HPGe and LaBr3 gamma-rays detectors.



Possible upgrade of the setup with $LaBr_3$(Ce) γ-detectors to measure angular distributions.



Characteristics of Gamma-Sources

Radioactive Source	Activity (kBq)	Half-Life (Years)	Daughter Nucleus	Energy (keV)	Emission Probability [%]
^{60}Co	96	5.2712	^{60}Ni	1173.23	99.85
			^{60}Ni	1332.49	99.99
^{152}Eu	108	13.54	^{152}Sm	121.7817	28.58
				244.6975	7.583
				344.2785	26.50
				411.1163	2.234
				443.965	2.821
				778.904	12.942
				867.378	4.245
				964.079	14.605
				1085.869	10.207
				1112.074	13.644
				1408.006	21.005
^{228}Th	106	1.9131	^{212}Pb	238.63	43.63
			^{208}Pb	510.74	8.08
			^{208}Pb	583.19	30.54
			^{212}Pb	727.33	6.65
			^{208}Pb	860.53	4.84
			^{212}Pb	1620.74	1.51
			^{208}Pb	2614.51	35.84

Characteristics of Gamma-Sources

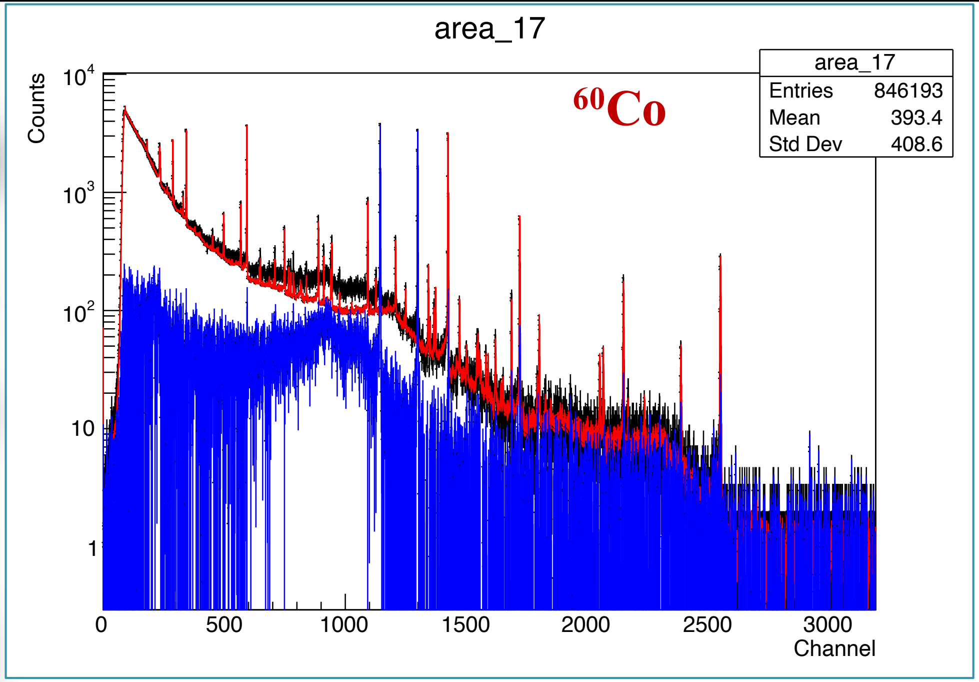
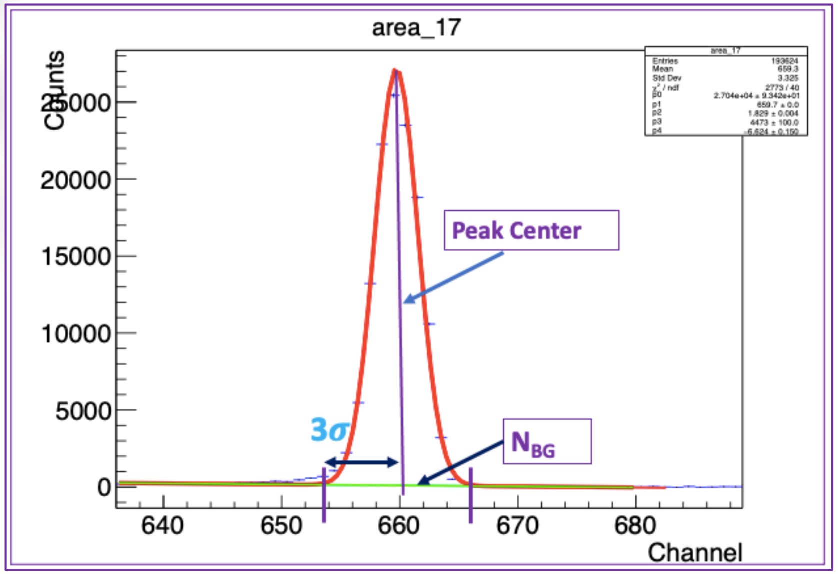


Figure shows the Gamma ray spectrum of all the radioactive sources ^{60}Co (Black line shows the Raw data, Red Line shows the Background data and Blue line shows the Data without Background),



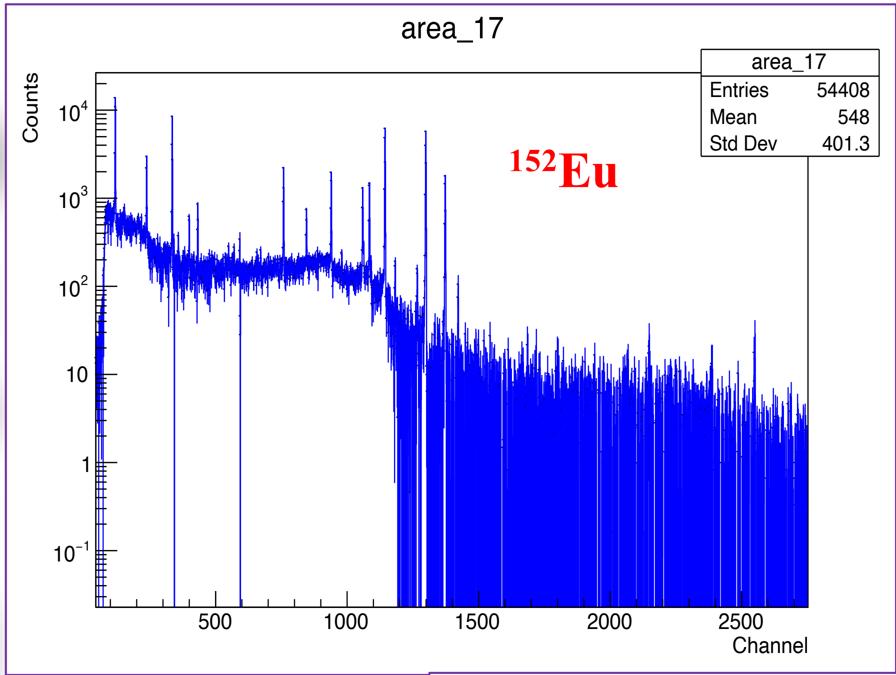
The number of counts of photo peak can be calculated from the below equation:

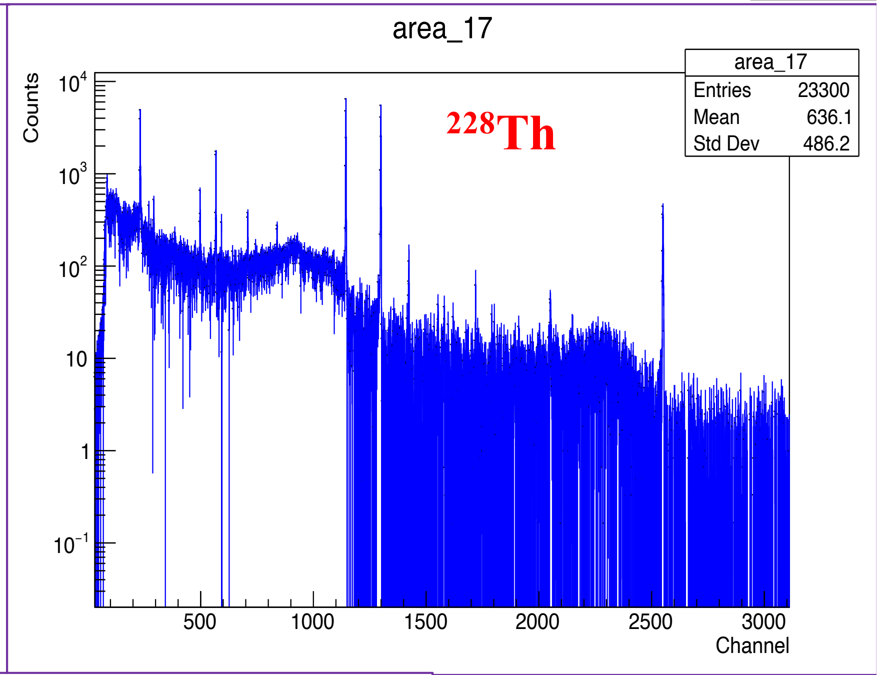
$$N = N_{Raw} - N_{BG}$$

Where N_{Raw} is the raw data and N_{BG} is the background data.

Figure shows the fitting peaks to count the number of events in the photo-peak.

Gamma-ray Spectrum of ^{152}Eu, ^{228}Th and ^{35}Cl(n, γ)^{36}Cl





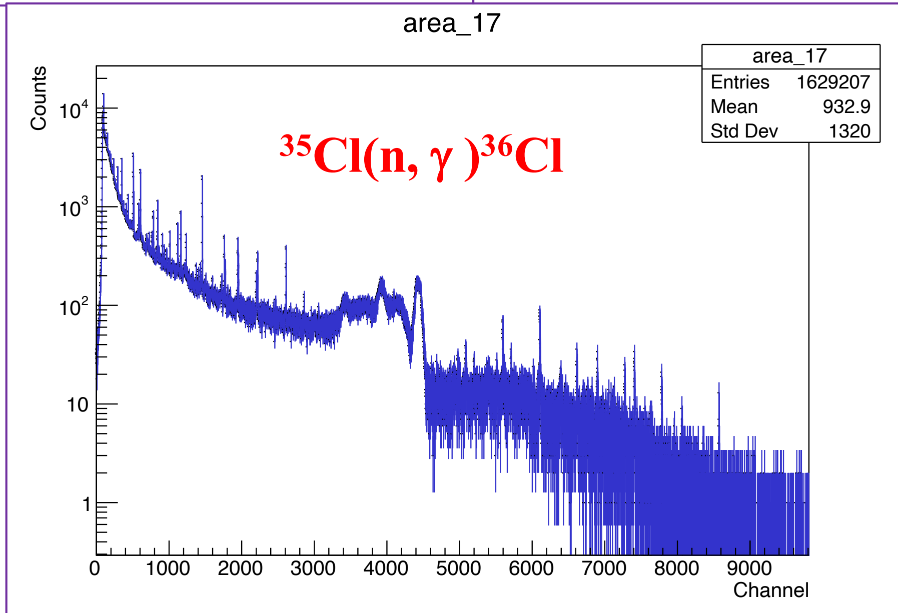


Photo-peak Efficiency

Absolute efficiency can be defined as

$$\epsilon_{abs} = \frac{\textit{number of pulses recorded}}{\textit{number of radiation quanta emitted by source}}$$

Photo-peak efficiency,

$$\epsilon_{exp} = \frac{N}{AI_y T_m} \times 100\%$$

Where,

A= Activity of the Radioactive Source.

N=Number of Counts of the Photo-peak.

I_Y= Emission Probability

T_m= Measuring time.

Error in Photo-peak Efficiency,

$$\delta\epsilon_{exp} = \epsilon_{exp}\sqrt{(\frac{\delta N}{N})^2 + (\frac{\delta A}{A})^2 + (\frac{\delta I_Y}{I_Y})^2 + (\frac{\delta T_m}{T_m})^2}$$

Photo-peak Efficiency

^{60}Co		
Energy (keV)	Efficiency (%)	Error
1173	0.00413526	3.59097E-05
1332	0.003833126	3.2463E-05

^{228}Th		
Energy (keV)	Efficiency (%)	Error
238	0.01264	0.000197
509	0.00714	0.000127
582	0.00694	8.57E-05
726	0.00634	1.00E-04
859	0.00458	7.06E-05
1620	0.00331	6.16E-05
2614	0.00234	1.97E-05

^{152}Eu		
Energy (keV)	Efficiency (%)	Error
121	0.014735546	0.000234135
244	0.011367401	0.000174988
344	0.009137874	1.19E-04
411	0.009230878	0.000228039
443	0.008603681	0.000190345
778	0.005391136	1.01E-04
867	0.005276983	6.77E-05
964	0.004644203	4.68E-05
1085	0.004245793	4.34E-05
1112	0.00402167	3.90E-05
1408	0.003361192	2.86E-05

Covariance Analysis

- The covariance (correlation) analysis is a mathematical tool that calculates the best estimate of the uncertainty as well as cross-correlations between measured quantities.

Photo-peak Efficiency

$$\epsilon_{exp} = \frac{N}{A I_y T_m}$$

- There are several sources of uncertainty in the calibration process, which propagate as the uncertainty in the detector's efficiency. This is basically from N, Iγ, A. As a result, the detector's efficiency can be expressed as a function of three attributes,

$$\varepsilon = f(N, I\gamma, A)$$

If the measurements of a particular attribute are made independently, then the corresponding micro–correlation matrix is a unit matrix.

Covariance Matrix Analysis

Let x1, x2, x3 represent the three attributes, namely, γ-ray abundance, γ-ray peak counts, source activity of the radio nuclide respectively.

If Δx_r is the uncertainty in x_r which is used in measuring efficiency ε_i then the partial uncertainty in ε_i due to the attribute x_r is given by

$$e_{ir} = \frac{\partial \epsilon_i}{\partial x_r} \Delta x_r, \qquad i = 1, 2, 3, 4 \ldots .11 \ (for\ 152 - Eu)$$

The covariance matrix for these i-th (11 for Eu-152) measurements is given by

$$(V_\epsilon)_{ij} = \sum_{r=1}^{W} S_{ijr} e_{ir} e_{jr}$$

where S_{ijr} is the micro–correlation between e_{ir} and e_{jr} due to the r-th attribute.

With this information of micro–correlations and partial uncertainties, we generate covariance matrix for efficiencies with Complete information of uncertainties. Infact the total uncertainties in measured efficiencies are given by

$$(\sigma_\epsilon)_i = \sqrt{(V_\epsilon)_{ij}}$$

Covariance Matrix Analysis

The efficiency calibration of the HPGe detector using the single source of ^{60}Co for the 2 characteristic gamma energies resulting in the 2×2 covariance matrix of efficiencies.

Partial Uncertainties due to Attribute for ^{60}Co

Energy (KeV)	Efficiency	$R_1 = \Delta C$	$R_2 = \Delta I_y$	$R_3 = \Delta A$
1173	0.00414±0.00004	4.45874E-05	1.2443E-06	6.21221E-05
1332	0.00383±0.00003	4.28675E-05	7.6678E-07	5.75026E-05

Covariance Matrix of ^{60}Co

Energy (KeV)	Efficiency	Covariance Matrix	
1173	0.00414±7.6477E−05	5.84874E-09	
1332	0.00383±7.1727E−05	3.57218E-09	5.14476E-09

Covariance Matrix Analysis

The efficiency calibration of the HPGe detector using the single source of ^{152}Eu for the 11 characteristic gamma energies resulting in the 11×11 covariance matrix of efficiencies.

Energy (Kev)	Efficiency	Partial Uncertainties due to Attribute for ^{152}Eu			Total Uncertainty(Δε)
		R1(ΔN)	R2(ΔIy)	R3(ΔA)	
121	0.01474±0.00023	8.98753E-05	3.09354E-05	0.000221033	0.000240604
244	0.011367±0.00017	0.000153242	5.99626E-05	0.000170511	0.000236965
344	0.009138±0.00012	7.34998E-05	6.89651E-05	0.000137068	0.000170135
411	0.009231±0.00023	0.000254434	0.000537159	0.000138463	0.000610286
443	0.008604±0.00019	0.000218593	0.000426982	0.000129055	0.000496741
778	0.00539±0.000101	8.07817E-05	3.33301E-05	8.0867E-05	0.000119063
867	0.00528±0.000068	0.000139556	3.72932E-05	7.91547E-05	0.000164718
964	0.00464±0.000047	7.05748E-05	2.22591E-05	6.9663E-05	0.000101633
1085	0.00425±0.000043	8.04793E-05	2.06709E-05	6.36869E-05	0.000104691
1112	0.004022±0.000009	6.79754E-05	2.35944E-05	6.03427E-05	9.39074E-05
1408	0.003361±0.000029	5.00634E-05	1.44017E-05	5.04179E-05	7.24963E-05

Covariance matrix for Efficiency of detector for ^{152}Eu

Energy keV	Efficiency	Covariance matrix of Efficiency of HPGe detector for ^{222}Th										
121	0.01474±0.00024	5.78902E-08										
244	0.011367±0.00024	3.76886E-08	5.61526E-08									
344	0.009138±0.00017	3.02966E-08	2.33716E-08	2.8946E-08								
411	0.009231±0.00061	3.06049E-08	2.36095E-08	1.89788E-08	3.72448E-07							
443	0.008604±0.00050	2.85254E-08	2.20053E-08	1.76893E-08	1.78693E-08	2.46752E-07						
778	0.00539±0.00012	1.78743E-08	1.37887E-08	1.10843E-08	1.11971E-08	1.04363E-08	1.41761E-08					
867	0.00528±0.00016	1.74958E-08	1.34967E-08	1.08496E-08	1.096E-08	1.02153E-08	6.401E-09	2.71321E-08				
964	0.00464±0.000101	1.53978E-08	1.18783E-08	9.54857E-09	9.64575E-09	8.99036E-09	5.63344E-09	5.51415E-09	1.03292E-08			
1085	0.00425±0.000105	1.40769E-08	1.08593E-08	8.72944E-09	8.81828E-09	8.21911E-09	5.15017E-09	5.04112E-09	4.43662E-09	1.09602E-08		
1112	0.004022±0.000094	1.33377E-08	1.02891E-08	8.27105E-09	8.35523E-09	7.78753E-09	4.87973E-09	4.77641E-09	4.20365E-09	3.84304E-09	8.81859E-09	
1408	0.003361±0.000073	1.1144E-08	8.59681E-09	6.91068E-09	6.98101E-09	6.50668E-09	4.07714E-09	3.99081E-09	3.51226E-09	3.21096E-09	3.04235E-09	5.25572E-09

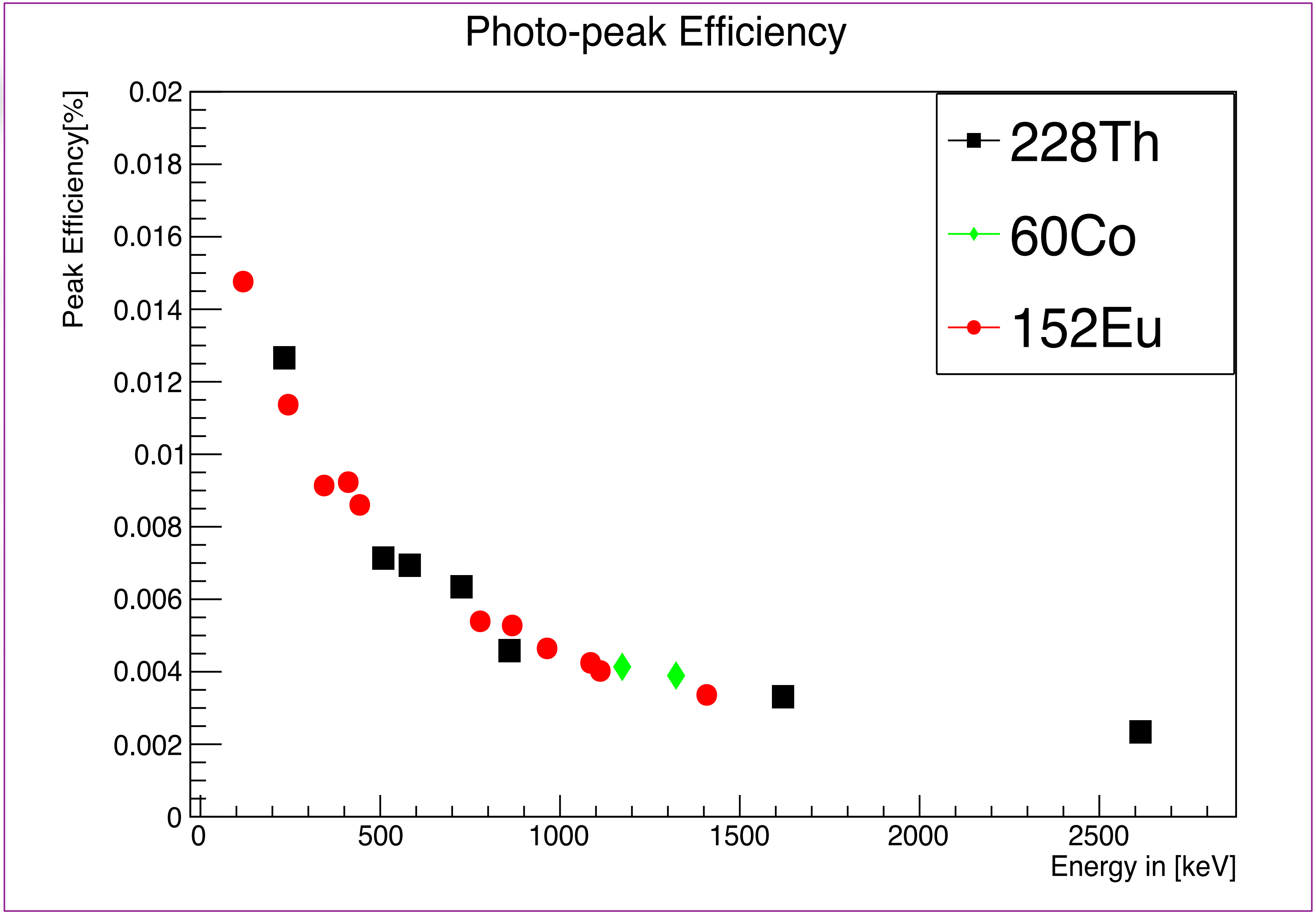
Co-relation matrix for Efficiency of detector for ^{228}Th

Energy (KeV)	Efficiency	Partial Uncertainties due to Attribute for ^{228}Th			Total Uncertainty ($\Delta\varepsilon$)
		$R_1 = \Delta C$	$R_2 = \Delta I_y$	$R_3 = \Delta A_0$	
238	0.01264±0.0002	0.000124146	8.694E-05	0.000769595	0.000784
509	0.00714±0.00013	0.0002167	0.00020309	0.000434551	0.000524
582	0.00694±0.000086	0.000109923	1.8176E-05	0.000422628	0.000436
726	0.00634±0.000010	0.000225227	4.7692E-05	0.000386343	0.000446
859	0.00458±0.0000071	0.000224373	3.7865E-05	0.000279059	0.000352
1620	0.00331±0.0000062	0.000341553	2.1936E-05	0.000201745	0.000389
2614	0.00234±0.0000020	5.89427E-05	1.6332E-05	0.000142606	0.000155

Covariance Matrix Analysis

Energy	Efficiency	Covariance matrix of Efficiency of detector for ^{222}Th						
238	0.0122646±0.000784	6.14355E-07						
509	0.0069252±0.000524	3.34428E-07	2.74323E-07					
582	0.0067352±0.000436	3.25252E-07	1.83653E-07	1.9033E-07				
726	0.0061569±0.000446	2.97328E-07	1.67886E-07	1.63279E-07	1.9933E-07			
859	0.0044472±0.000352	2.14762E-07	1.21265E-07	1.17938E-07	1.07812E-07	1.24158E-07		
1620	0.003215±0.000389	1.55262E-07	8.76685E-08	8.52631E-08	7.79428E-08	5.62988E-08	1.51094E-07	
2614	0.0022726±0.000155	1.09749E-07	6.19696E-08	6.02693E-08	5.50948E-08	3.97955E-08	2.877E-08	2.38766E-08

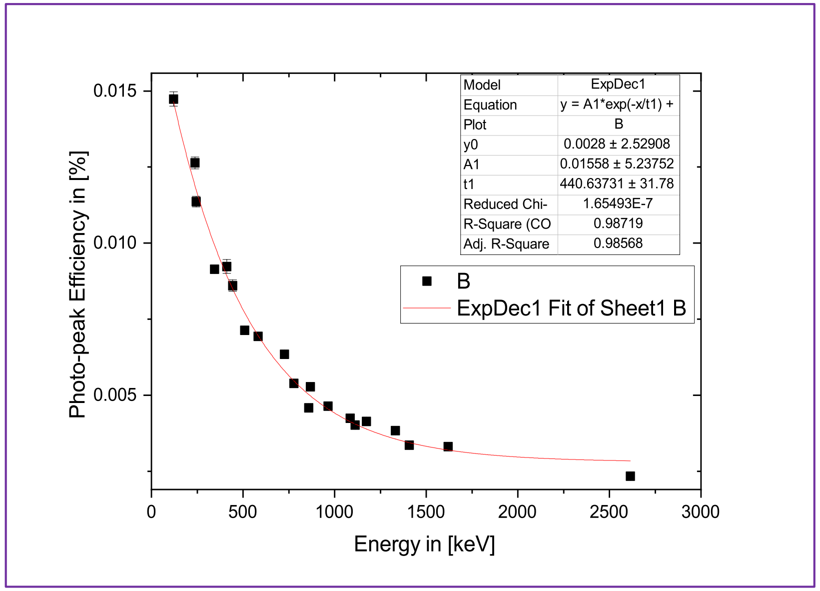
Photo-peak Efficiency



Relative Photo-peak Efficiency $^{35}Cl(n, \gamma)^{36}Cl$

N be the number of events of the Photo-peak, N_{norm} be the normalization of the number of events of the photo-peaks.

$$N_{norm} = \frac{N}{N_{max}} \times 100\%$$



Ratio,

$$R = \frac{N_{norm}}{I_R}$$

Where,

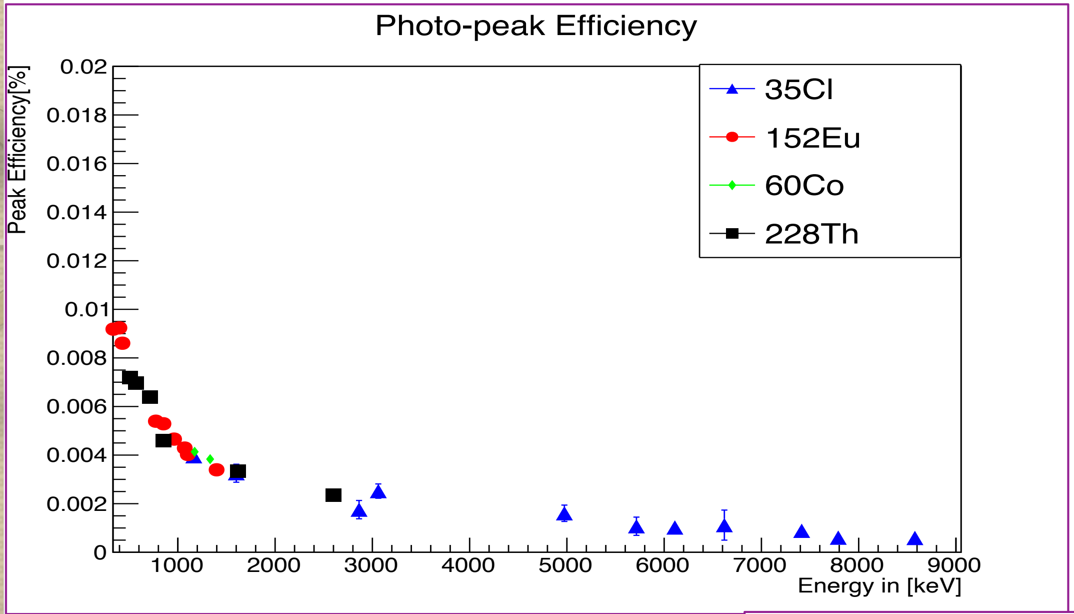
I_R =Relative Intensity.

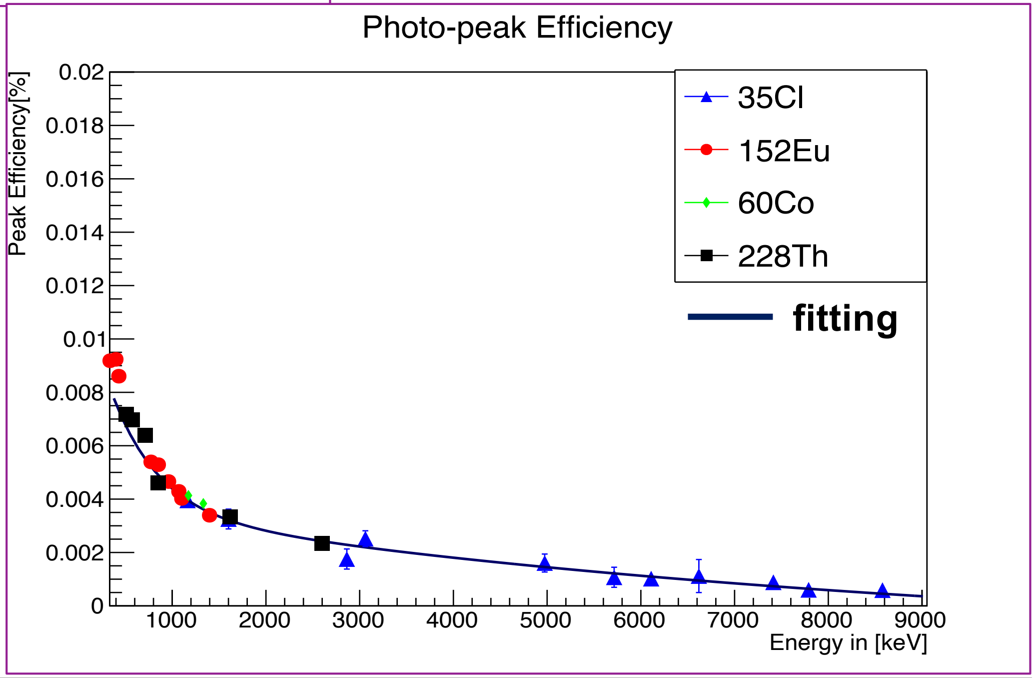
Relative Efficiency,

$$\epsilon_{Rel} = R \times \epsilon_{Const(fitting)}$$

Where, $\epsilon_{Const(fitting)}$ is the constant term from fitting the photo-peak efficiency curve using 60Co, 152Eu and 228Th.

Relative Photo-peak Efficiency $^{35}Cl(n, \gamma)^{36}$





Monte Carlo Simulation: Geant4

- ❖ Geant4 (short for "Geometry and Tracking 4"), a software toolkit for the MC simulation of particle movement through matter .
- ❖ It is a top tool for simulating particle-matter collisions in a variety of contexts.

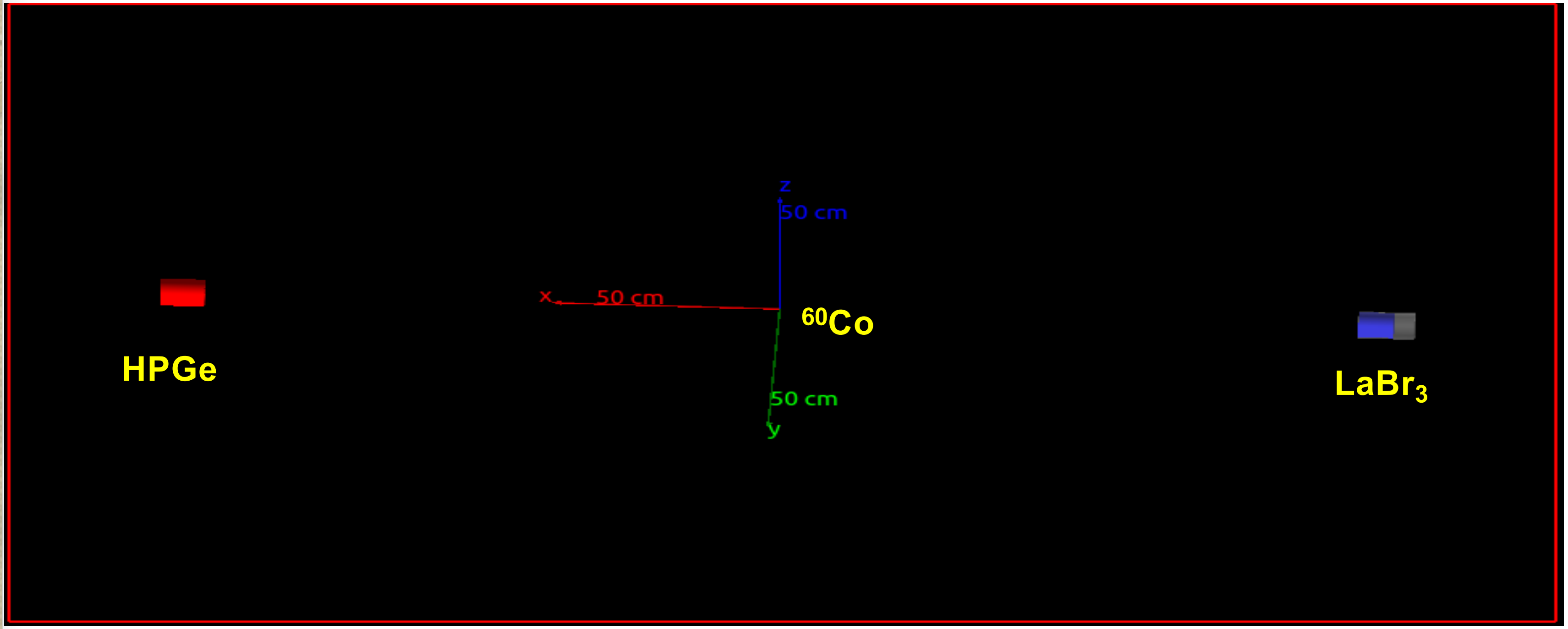


Photo-peak efficiency of Geant4,

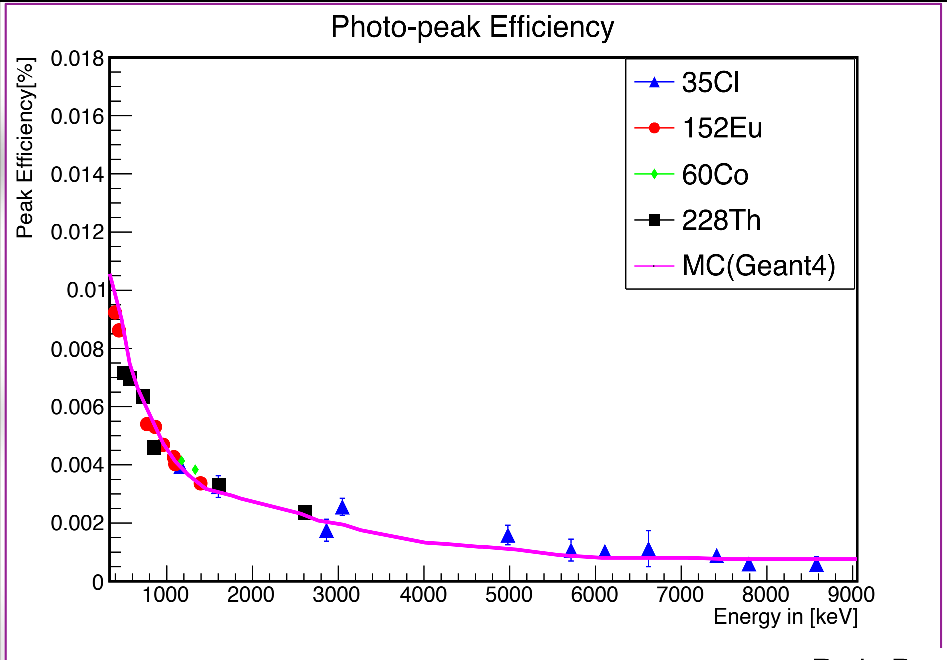
$$\epsilon_{MC} = \frac{N_{De}}{N_{Ge}} \times 100\%$$

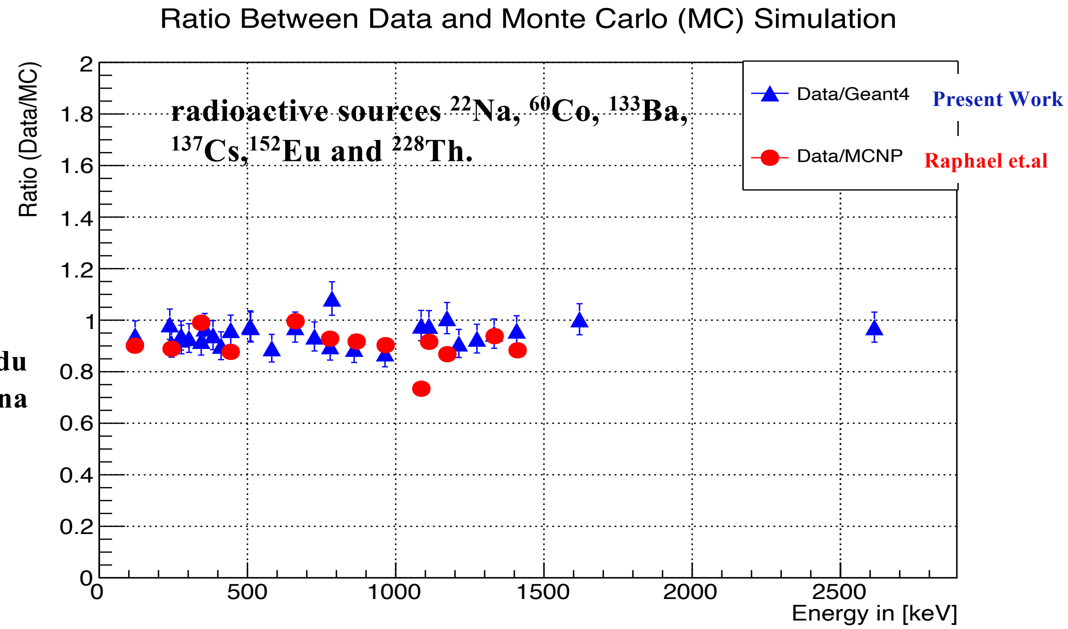
Where,

N_{De}= Number of gamma-rays detected by the detector.

N_{Ge}=Number of gamma-rays generated by the Geant4.

Relative Photo-peak Efficiency





Reference:

Raphael_MCNP:<https://www.npl.washington.edu/majorana/sites/sand.npl.washington.edu.majorana/files/documents/theses/DamonThesis.pdf>.

Intrinsic Photo-peak Efficiency

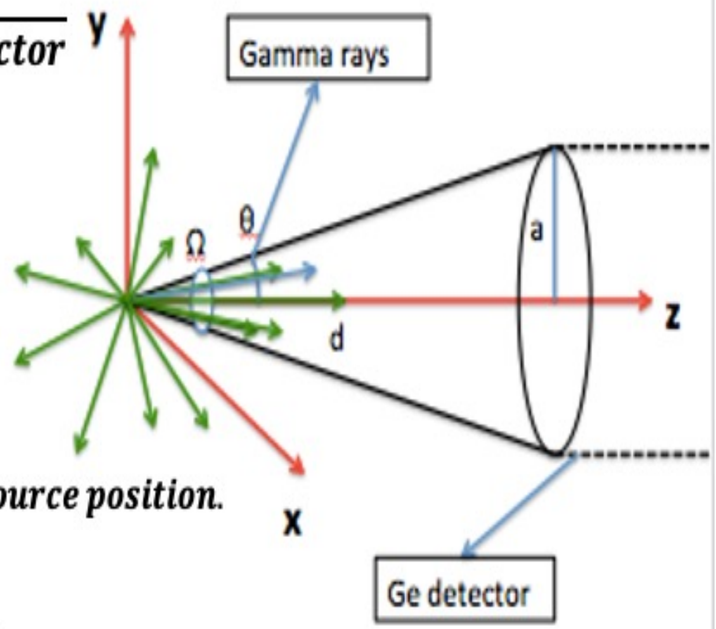
The Instrinsic Photo-peak Efficiency

$$\epsilon_{int} = \frac{\text{Number of pulses recorded}}{\text{Number of radiation quanta incident on detector}}$$

$$\epsilon_{int} = \frac{\epsilon_{abs}}{\eta}$$

Where,

η *is the Geometric Efficiency* $\qquad \eta = \frac{\Omega}{4\pi}$



Ω is the Solid angle of the detector seen from the actual source position.

Solid angle of the circular shape detector

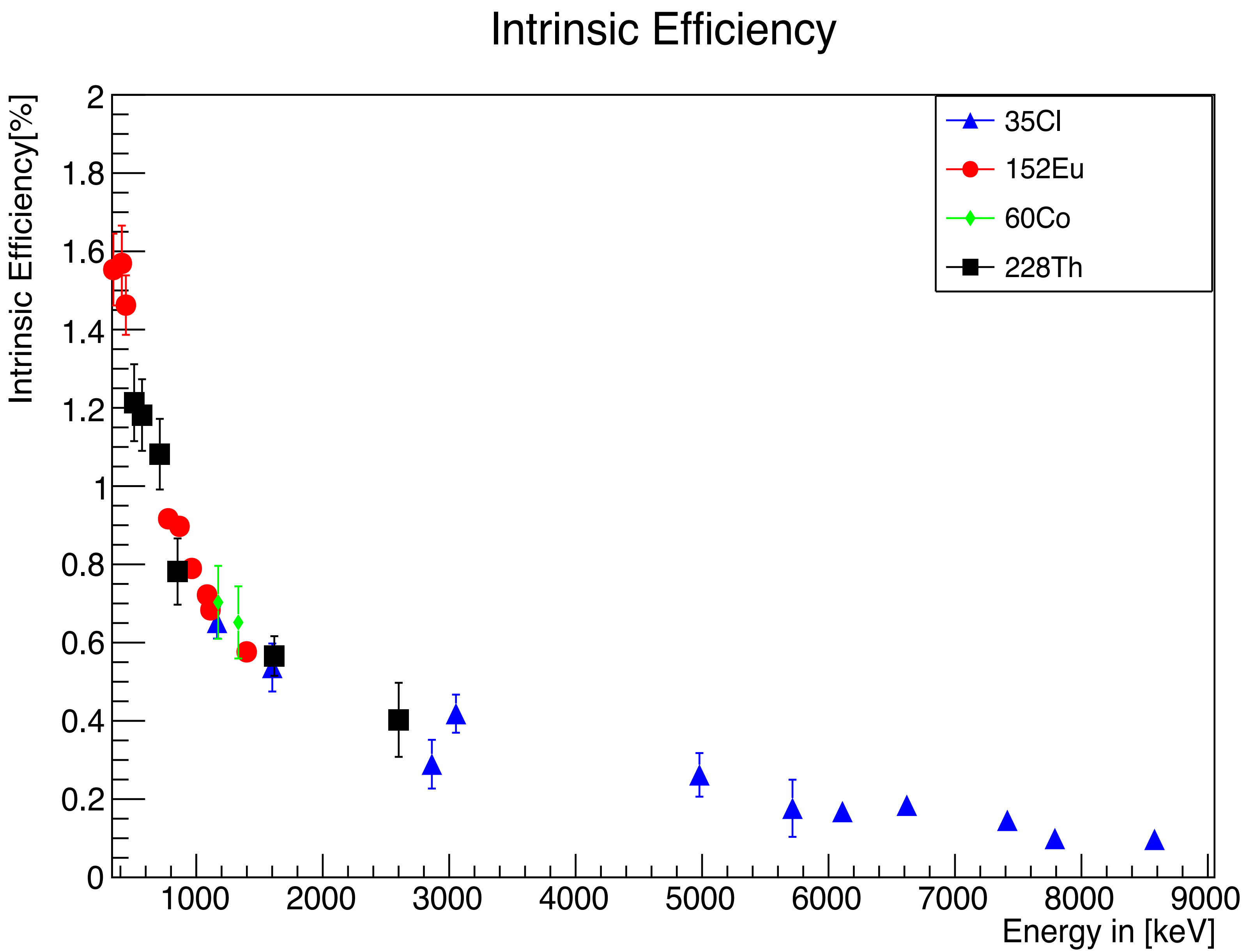
$$\Omega = 2\pi\left(1 - \frac{d}{\sqrt{d^2+a^2}}\right)$$

Where,

d is the source-detector distance.

a is the detector radius.

Intrinsic Photo-peak Efficiency



Conclusion

- The primary goal of the TANGRA project at the Frank Laboratory of Neutron Physics (FLNP) of the Joint Institute for Nuclear Research (JINR) in Dubna, Russia, is to conduct comprehensive studies on the inelastic scattering of 14.1 MeV neutrons on atomic nuclei using the tagged neutron method (TMN).
- As part of this ongoing research program, we measured the relative photo-peak efficiencies of the HPGe and LaBr3 detectors within a newly constructed experimental facility.
- We have calculated the relative efficiency and Intrinsic efficiency of HPGe detector using the standard gamma-ray point sources including ^{60}Co, ^{152}Eu, and ^{228}Th, as well as the ^{35}Cl(n,γ)^{36}Cl reaction.
- The simulations demonstrated very good agreement between the results obtained from Monte Carlo calculations and the experimental data.
- The findings of our research may prove useful for processing and analyzing data obtained during experiments within the TANGRA project, as well as for scientists utilizing HPGe and $LaBr_3$ detectors for gamma-ray spectroscopy.

Thank You for Your Attention