EXPERIMENTAL VERIFICATION OF GAMMA-EFFICIENCY CALCULATIONS FOR SCINTILLATION DETECTORS IN ANGLE 4 SOFTWARE

by

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Scientific paper
DOI: 10.2298/NTRP1501035T

ANGLE software for semiconductor detector efficiency calculations – long existing and widely accepted tool in quantitative gamma spectrometry – has been recently extended to scintillation NaI detectors. The extension features in the latest edition (ANGLE 4) and it is briefly outlined. Discretization of reference efficiency curve, meaning possibility of using ANGLE 4 for particular gamma energies without constructing the complete reference efficiency curve, is particularly emphasized. This yields both in enhanced practicality and higher accuracy, while reducing the potential for systematic errors. The present work is primarily focussed on experimental verification of ANGLE 4 for NaI detectors. Two detectors (2 2 and 3 3 inches) were employed in the experiment. Commercially calibrated gamma sources (in the forms of quasi point and cylinder) and homemade solutions (diluted from calibrated ones) were measured at various distances from the detector(s), ranging 0 cm to 50 cm. Energy range observed was 59 keV to 1408 keV. Versatility of counting conditions, in terms of detectors and sources used, gamma energies observed, source detector separations, *etc*., was aimed at creating as large experimental evidence as possible for verification purposes. Experimentally obtained efficiencies are compared with those calculated by ANGLE 4. Very good agreement is obtained – well within the experimental uncertainties – thus proving the reliability of the software.

Key words: gamma spectrometry, scintillation detector, efficiency calculation, ANGLE software, experimental verification

INTRODUCTION

ANGLE software for semiconductor detector gamma efficiency calculations in its various forms has been in use for more than 20 years now [1-3]. It is generally regarded as a sophisticated/advanced tool in quantitative gamma spectrometry – nowadays routinely exploited in hundreds of gamma spectrometry based laboratories worldwide, including the most prominent ones [4]. ANGLE allows accurate determination of the activities of gamma spectroscopic samples for which no replicate standard exists, in terms of geometry and matrix. A semi empirical efficiency transfer (ET) approach is employed, combining advantages of both absolute (Monte Carlo) and relative (traceable source based) methods to determine the sample activity by gamma spectrometry [2, 5-15] – in this way the practical limitations of relative methods are reduced, while the potential for systematic errors in the absolute ones is minimized.

The physical model behind ET is the concept of the effective solid angle ($\overline{\Omega}$) – a compound parameter, calculated upon the input data on geometrical, physical, and chemical (composition) characteristics of (1) the source (incl. its container vessel), (2) the detector (incl. crystal housing and endcap), and (3) counting arrangement (incl. intercepting layers between the latter two) [1, 12, 16-18].

The program is broadly applicable (practically to all most common situations encountered in gamma-spectrometry practice), *e. g*., in nuclear industry, environmen-

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tal monitoring, radioactivity control, food safety, medicine, radioactive waste management, safety/security/safeguards, scientific research (*e. g.*, neutron activation analysis, nuclear data standardization, reactor physics), education and training, *etc.* [19-26]. Point, disc, cylindrical or Marinelli samples, small or large, of any matrix composition, measured on coaxial, planar or well type detectors, HPGe or Ge(Li) – and now NaI – can be accommodated. No standards are required, but a start up reference efficiency curve (REC) must be obtained, generally as a onetime calibration procedure. Time and effort put into obtaining a reliable REC is largely paid off in subsequent ANGLE utilization, through the simplicity, speed and productivity in obtaining analytical results – leading to improved laboratory performance.

ANGLE is thus characterized by its (1) wide range of applicability, (2) high accuracy, (3) ease of use, (4) flexibility in respect to input parameters and output data, (5) short computation times, (6) easy communication with another software, (7) suitability for teaching/training purposes, (8) potential for accommodating – into its architecture – other efficiency calculation methods of semi empirical or absolute (Monte Carlo) types, and (9) possibility of expanding its current scope of applicability to further/particular user's needs and/or fields of interest. A key aspect and difference from other approaches, which greatly enhances practicality, is the fact that no factory characterization of the detector response is required – any detector may be accommodated as long as some basic knowledge concerning its construction is available (which is normally the case – detector manufacturers do supply relevant data sheets).

Besides the decades of practical utilization, accuracy of the software is successfully tested in an IAEA organized gamma spectrometry software intercomparison exercise [10] – ANGLE scored 0.65% average deviation from the exercise mean (for $E_\gamma > 20$ keV energies). ANGLE is available from the developers, while commercially distributed by AMETEK/ORTEC, USA as well [4, 27].

NEW VERSION OF ANGLE AND EXTENSION TO SCINTILLATION DETECTORS

Details about ANGLE software principles, including theoretical background and application to various types of semiconductor detectors, as well as the description of the software, are elaborated in detail elsewhere [1, 4, 12, 16-18, 27]. New version, ANGLE 4, is about to be released [4]. As compared to previous version, ANGLE 3, the new version brings many new

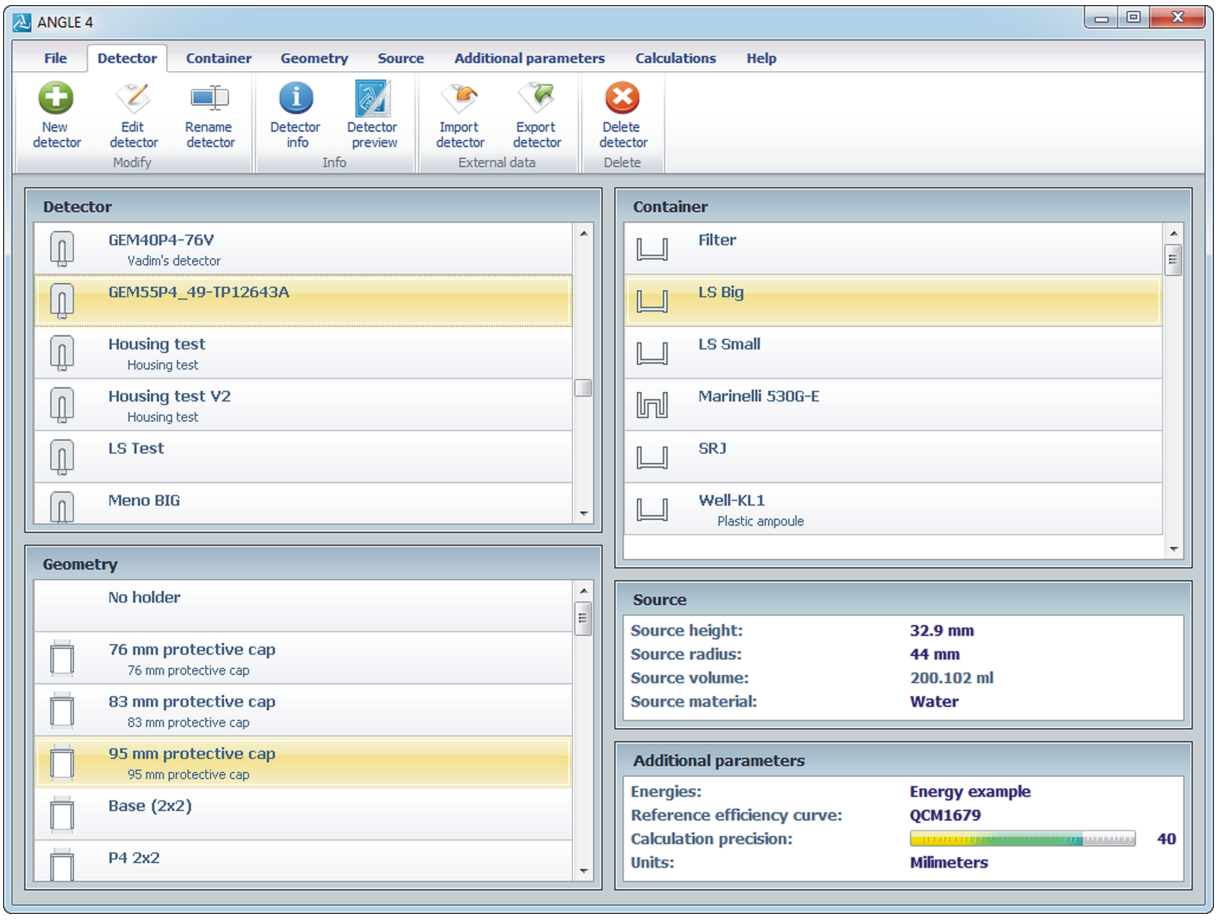

Figure 1. ANGLE 4 main screen

features, among which (1) support for scintillation NaI detectors (both cylindrical and well type), (2) new XML based file format which allows easy manipulation of both input and output files by a third party software, and thus, (3) automation and complex analyses, (4) scaled graphical preview of input and output parameters, which can be exported to bitmap or vector file formats, (5) multilanguage support, (6) additional input parameters for detectors, (7) user interface improvements, (8) discrete reference efficiencies, *etc*. ANGLE 4 main screen is shown in fig. 1.

The option of NaI detectors was considered from the very beginning of ANGLE development. It was believed, however, that the concept of advanced software for semiconductor detectors does not allow for scintillation ones, regarding (wrongly) the latter as inadequate and obsolete. Nevertheless, in house version of ANGLE which supports NaI detectors exists since 2002 and was successfully tested in geochronology research [24].

The idea of creating a separate, much less elaborate software (for NaI detectors only) was another possibility, but that was deemed a sort of trivial and oversimplified ANGLE variation to exist on its own. It came eventually as a result of ANGLE users' feedback and growing interest, that this option should be incorporated within the new version of ANGLE – as it is now the case in ANGLE 4. The fact that NaI detectors do not belong to semiconductor family is largely overshadowed by the attributes they have in common and/or complement each other.

The use of NaI detectors for gamma spectrometry is steadily increasing, despite their apparent drawbacks (most of all the poor resolution) as compared to semiconductor ones (HPGe in particular) which made NaI look like a historical relict 30 years ago. However, in many fields of application, only a few targeted radionuclides are being measured (most notably Cs-137 in environmental monitoring), often on "industrial scale", *i. e.*, for huge number of samples of similar origin (*e. g*., food, soil, air filters, construction materials, consumables, *etc*.). An order of magnitude lower price, simple maintenance and high efficiency (short counting times) then come decisively in NaI favour – when laboratory performance and output are paramount.

Applicability of ANGLE concept to NaI detectors is straightforward, especially for those already familiar with ANGLE architecture. This comes as a consequence of apparent fundamental similarity between the two types of detectors, HPGe and NaI. Of course, ANGLE 4 accounts for NaI as gamma ray absorbing material which gives rise to impulses/count in a gamma spectrum. The use of REC – as onetime calibration – which is typical for ANGLE, is still recommended. Care must be taken, however, that not so many experimental calibration points can be obtained within the gamma energy region of interest (*e. g*. 50 keV to 2000 keV), due to the fact these have to be separated by considerable margins (in gamma energies) to avoid overlapping of the peaks. This is particularly valid when REC is obtained from a single multi gamma source, but can be avoided using several single gamma sources measured successively/separately.

Concerning reference calibration, *i. e*. REC, there is a very important advantage that ANGLE 4 offers. Namely, given the nature of NaI measurements, it went in most cases about measuring only one nuclide at a time, even just one energy (*e. g*., 661.6 keV of Cs-137). In such case, ANGLE 4 allows REC to be considered as separate/single points (thus not as a curve interpolated between experimental calibration points). Let us call it "REC discretization". One or more discrete points can be chosen/used for particular gamma energy (or energies) of interest.

Apparently REC discretization makes ANGLE application not only extremely simple, but also more accurate. It can fairly be said this is quasi relative approach to quantitative gamma spectrometry on its best – preserving most of the accuracy of relative method, yet allowing for unlimited flexibility in sample type, matrix, size, its container characteristics and other intercepting layers, counting arrangement, *etc.* Two most common types of NaI detectors are available in ANGLE 4: standard (with cylindrical crystal as the active body) and well type (a hole is drilled in the crystal to enable placement of small sources, in order to maximize the efficiency). Detector data input is organized in the same way as for semiconductor detectors. User oriented and error correcting graphical interface is instructive and self explanatory (fig. 2). Much less detector parameters are required, as compared with semiconductor detectors, due to simplicity of NaI detector construction. Some new detector parameters are introduced, specific for this detector type, such as reflecting layer, optical coupling and photomultiplier tubes.

EXPERIMENTAL

Experimental verification of ANGLE 4 software for NaI detectors was effectuated at Prof. Younis S. Selim Laboratory for Radiation Physics, Physics Department, Faculty of Science, Alexandria University (Alexandria, Egypt). For the sake of verification, the laboratory was supplied with the pre release version of ANGLE 4. Two NaI detectors with cylindrical crystals, 2 2 and 3 3 inches were used in the experiments. All the details about the detectors are listed in tab. 1; some of the parameters (concerning the optical coupling and photomultiplier tube) were irrelevant for efficiency calculations performed by ANGLE 4.

The first set of activity standards in the form of point sources was used for calibration of gamma spectrometers. Radioactive substance itself is a very thin,

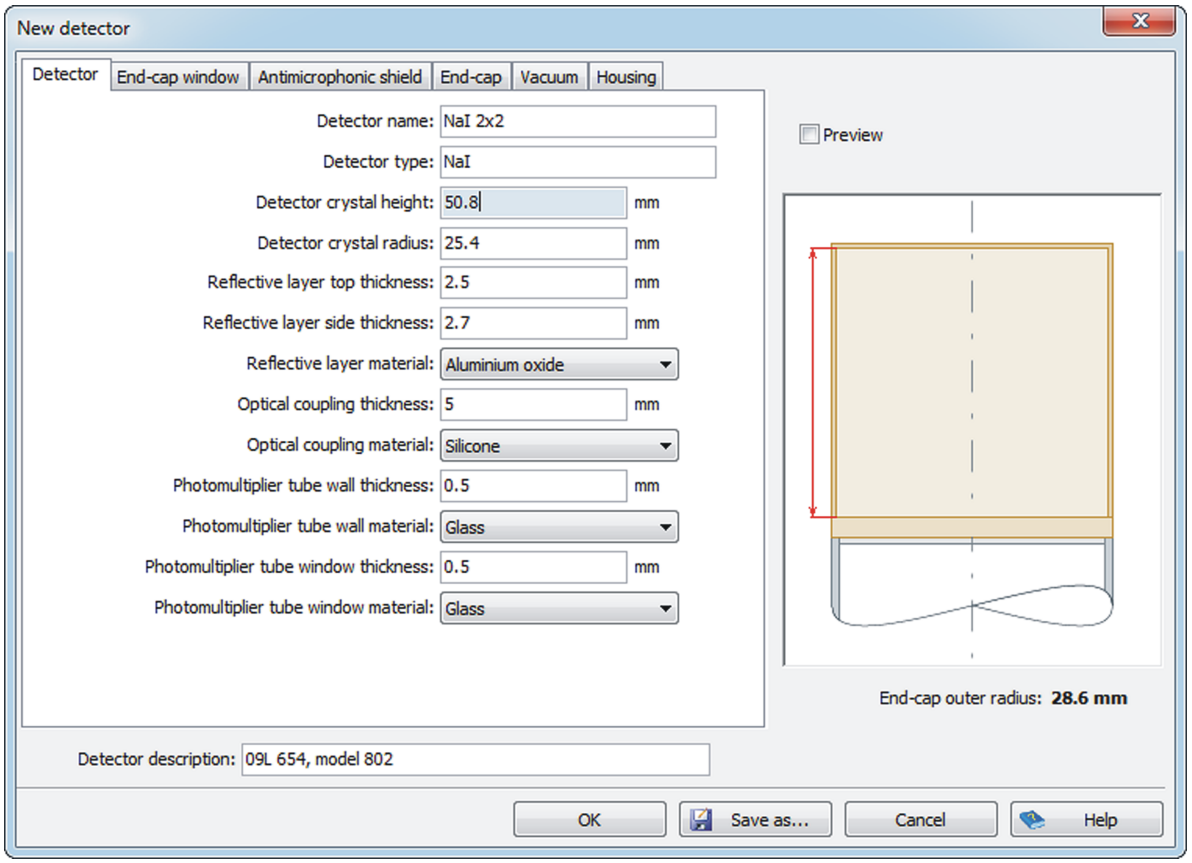

Figure 2. Data input dialog for cylindrical NaI detector

Table 1. Characteristics of NaI detectors used in the experiments

Item	Detector 3 3	Detector 2 2
Manufacturer	Canberra	
Serial number	09L 652	09L 654
Detector model	802	
Type	Cylindrical	
Mounting	Vertical	
Resolution (FWHM) at 661 keV	8.5%	7.5%
Cathode to anode voltage	+800 V DC	+900 V DC
Dynode to dynode	+80 V DC	
Cathode to dynode	+150 V DC	
Tube base	Model 2007	
Shaping mode	Gaussian	
Detector type	NaI(Tl)	
Crystal diameter [mm]	76.2	50.8
Crystal length [mm]	76.2	50.8
Top cover thickness [mm]	Al (0.5)	
Side cover thickness [mm]	Al (0.5)	
Reflector – oxide [mm]	2.5	
Weight [kg]	1.8	0.77
Outer diameter [mm]	80.9	57.2
Outer length [mm]	79.4	53.9
Crystal volume [cm^3]	347.49	102.96

compact grained layer, applied to a small circular area (5 mm in diameter, *i. e.*, "quasi point"), in the middle of the source, between two polyethylene foils and each having a mass per unit area of 21.3 1.8 mg/cm^2. By heating under pressure, the two foils were welded together over the whole area, so that they are leak proof. To facilitate handling, the foil 26 mm in diameter is mounted in a circular aluminum ring (outer diameter 30 mm and height 3 mm), from which it can easily be removed if and when required. These point sources (^{241}Am, ^{137}Cs, ^{133}Ba, ^{60}Co, and ^{152}Eu) were purchased from the Physikalisch Technische Bundesanstalt (PTB) in Braunschweig and Berlin, which is national institute for science and technology and the highest technical authority of Germany in the field of metrology and certain sectors of safety engineering. The certificates showing the activities of the sources and corresponding uncertainties are listed in tab. 2. The data sheet stating the values of half life photon energies and photon emission probabilities per decay for all radionuclides used in the calibration process is given in tab. 3.

The second set of activity standards was homemade volumetric from standard solution. The details of the preparation are listed in tab. 4. Polypropylene 500 ml vial was filled with 200 ml, 300 ml, and 400 ml of ^{152}Eu aqueous solution of known activity.

Table 2. PTB point sources' activities and their uncertainties

PTB – Nuclide	Activity [kBq]	Reference date	Uncertainty [kBq]
^{241}Am	259.0	June 1, 2009	2.6
^{133}Ba	275.3		2.8
^{152}Eu	290.0		4.0
^{137}Cs	385.0		4.0
^{60}Co	212.1		1.5

Table 3. Half-lives, photon energies and photon emission probabilities per decay for the radionuclides used in this work

PTB – Nuclide	Energy [keV]	Emission probability [%]	Half life [d]
^{241}Am	59.52	35.9	157861.05
^{133}Ba	80.99	34.1	3847.91
^{152}Eu	121.78	28.4	4943.29
	244.69	7.49	
	344.28	26.6	
	778.95	12.96	
	964.13	14.0	
	1408.01	20.87	
^{137}Cs	661.66	85.21	11004.98
^{60}Co	1173.23	99.9	1925.31
	1332.50	99.982	

Table 4. Properties of volumetric radioactive sources used in the measurements

Items	^{152}Eu solution sources description (homemade)		
Volume [ml]	200	300	400
Activity [kBq]	5		
Uncertainty [%]	1.98		
Reference date	January 1, 2010		
Vial manufacturer	Nalgene		
Vial material	Polypropylene		

The preparation method of the homemade sources was based on the original (PTB) aqueous source activity and its properties which are known [total activity 202 4 kBq at Jan. 1, 2010, with a total weight 1000.41 g) – simply dividing the solution activity by the total mass of the solution, the activity for each gram will be known from the specific activity law

$$a \quad \frac{A}{m} \tag{1}$$

where a [Bqg^{-1}] is the specific activity, A [Bq] – the activity, and m [g] – the mass of the material. So, to prepare the source with the needed activity one just calculates how many grams to take from the parent solution. In the present work, in order to prepare various volumes of solutions with the activity of 5 kBq, each time we took 25 g from the parent solution and completed the rest of the vials by the carrier solution; carrier solution was prepared from 0.1 M HCl in aqueous form.

Measurements were carried out to obtain statistically significant main peaks in the spectra; spectra are recorded and processed by winTMCA32 software made by ICx Technologies. Measured spectrum was saved as spectrum ORTEC files which can be opened by ISO 9001 Genie 2000 data acquisition and analysis software made by Canberra where the peak analysis is accomplished. Acquisition time is set high enough to get the number of counts to be at least (or more than) 10,000, which makes the statistical uncertainties less than 1%. The spectra were analyzed with the program using its automatic peak search and peak area calculations, along with the changes in the peak fit using the interactive peak fit interface, when necessary to reduce the residuals and error in the peak area values. The peak areas, the live time, the run time and the start time for each spectrum are entered in the spreadsheets that are used to perform the calculations necessary to generate the experimental efficiency curves [28-40]. Some representative spectra, including all sources and both detectors, can be found at a dedicated web page accompanying this paper [41].

The experimental full energy peak efficiency at energy E, for a given set of measuring conditions can be computed by the equation

$$\varepsilon(E) \quad \frac{N(E)}{TA_{\mathrm{S}}P(E)}C_{\mathrm{i}} \tag{2}$$

where $N(E)$ is the number of counts in the full energy peak, T [s] – the measuring time, $P(E)$ – the photon emission probability at energy E, A_{S} – the radionuclide activity, and C_{i} – the correction factor due to dead time and radionuclide decay. In these measurements of the low activity sources, the dead time had been always less than 2%, so the corresponding factor was obtained simply by using ADC live time. The decay correction, C_{d}, for the calibrating source from the reference time to the run time is given by

$$C_{\mathrm{d}} \quad \mathrm{e}^{\lambda\Delta T} \tag{3}$$

where λ is the decay constant and ΔT – the time interval over which the source decays corresponding to the run time. The uncertainty in the experimental full energy peak efficiency, σ_ε, is given by [40]

$$\sigma_\varepsilon \quad \varepsilon\sqrt{\left(\frac{\partial\varepsilon}{\partial A}\right)^2\sigma_A^2 \quad \left(\frac{\partial\varepsilon}{\partial P}\right)^2\sigma_P^2 \quad \left(\frac{\partial\varepsilon}{\partial N}\right)^2\sigma_N^2} \tag{4}$$

where σ_A, σ_P, and σ_N, are the uncertainties associated with the quantities A_{S}, $P(E)$, and $N(E)$, respectively, assuming that the only correction made is due to the source activity decay.

While measuring volumetric sources, a thick plexiglas cover was placed directly on the detector entrance window as an absorber, so as to avoid the effect of β- and X-rays and to protect detector endcaps. Therefore, no correction was needed for X-gamma coincidences, since in most cases the accompanying X-rays were soft enough to be absorbed completely before entering the detector. In addition, angular correlation effects were negligible for low source to detector distances.

As to γ-γ true coincidence summing (TCS), no corrections were deemed to be made neither. It is apparent that for point sources the summing is negligible – the closest counting position (P4) is more than 20 cm from the detector top. For voluminous sources it is not negligible, but it is fair to estimate that it does not exceed a few percent, neither. Namely, all three voluminous sources had the diameter (11.15 cm) much larger than that of the detector(s) (5.08 cm to 7.62 cm). Together with source height (2.145 cm to 4.183 cm), this makes a few cm effective distance from the detector. In addition, voluminous sources were measured at 0.8 cm from the detector top (including container bottom thickness of 2.03 mm, container foot height of 2.00 mm, and source support thickness of 3.36 mm to 3.63 mm). When comparing with literature values for Eu-152 correction factors (all six significant γ-lines, but mostly prominent for 122 keV), we came to the conclusion that this effect could not produce more than 5% systematic error. This is within experimental uncertainty budget (2% on factory calibration of the solution, a few percent on homemade dilution, and another few percent on counting statistics). Last but not least, ANGLE software – based upon efficiency transfer (ET) principle – inherently tends to reduce systematic errors of this type, due to similarity of counting arrangements (partial error cancelling); this is especially valid when counting arrangements are similar (*e. g.*, comparing voluminous sources among themselves).

In order to prevent dead time and pile up effects, source activities were kept below a few kBq for each radionuclide. High count rates were, hence, avoided when measuring at close distances; however, this implicated long counting times at higher distances [37]. The experiments were set so as to extract maximum information possible for ANGLE 4 software validation for NaI detectors. Sources were positioned coaxially with detector when measured. All the details about the source to detector configurations for using point and volumetric radioactive sources are listed in tab. 5, while figs. 3 and 4 show schematic diagrams of NaI detectors with an isotropic radiating point and volumetric sources, respectively.

Table 5. Relevant data for the detectors, radioactive sources and counting geometries used in the experiment

	Item	Detector 2 2 [mm]	Detector 3 3 [mm]
Detector dimensions	D_d (detector diameter)	50.80	76.20
	D_l (detector height)	50.80	76.20
	EC_{th} (end cap thickness)	0.50	0.50
	R_{th1} (face reflector layer thickness)	2.50	2.50
	R_{th2} (side reflector layer thickness)	2.70	1.85
Plexiglas holder dimensions	A	7.08	12.16
	B	13.09	16.57
	C	22.61	36.99
	D	3.36	3.63
	E	4.42	6.83
	F	35.06	22.82
	G	4.13	4.65
	H	31.28	46.73
	I	42.14	34.98
	J	149.92	160.09
	K	135.75	135.75
	L	27.31	27.31
	M	81.00	81.00
	N	9.85	9.85
	O	2.38	2.38
Point sources height	P	1.50	1.50
	P4	204.15	204.42
	P5	254.34	254.61
	P6	305.10	305.37
	P7	355.63	355.90
	P8	405.73	406.00
	P9	456.39	456.66
	P10	506.90	507.17
Volumetric sources dimensions	S_d (source diameter)	111.50 mm	
	S_h (source height)	21.45/31.59/41.83 mm	
	W_{th} (wall thickness)	2.03	
	B_{th} (bottom thickness)	2.03	
	F_{th} (foot height)	2.00	
	Source volume	200/300/400 ml	

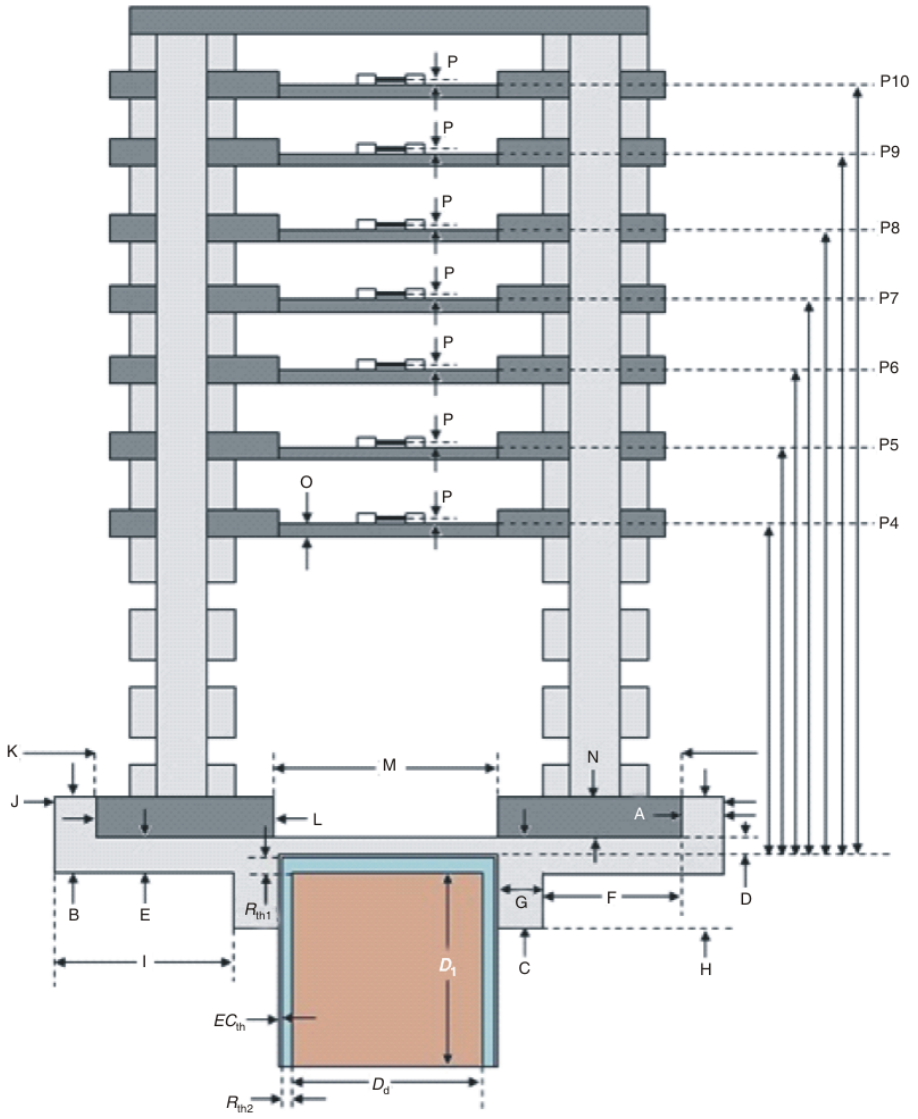

Figure 3. Schematic diagram of NaI detectors using isotropic radiating point sources measured from position P4 up to position P10

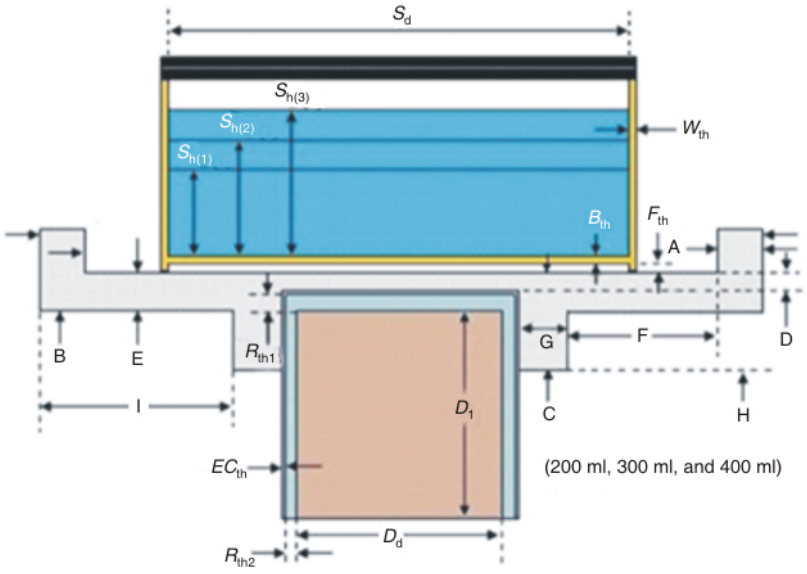

Figure 4. Schematic diagram of NaI detectors using volumetric sources measured on the top of the holders; angular correlation effects can be neglected for low source to detector distances

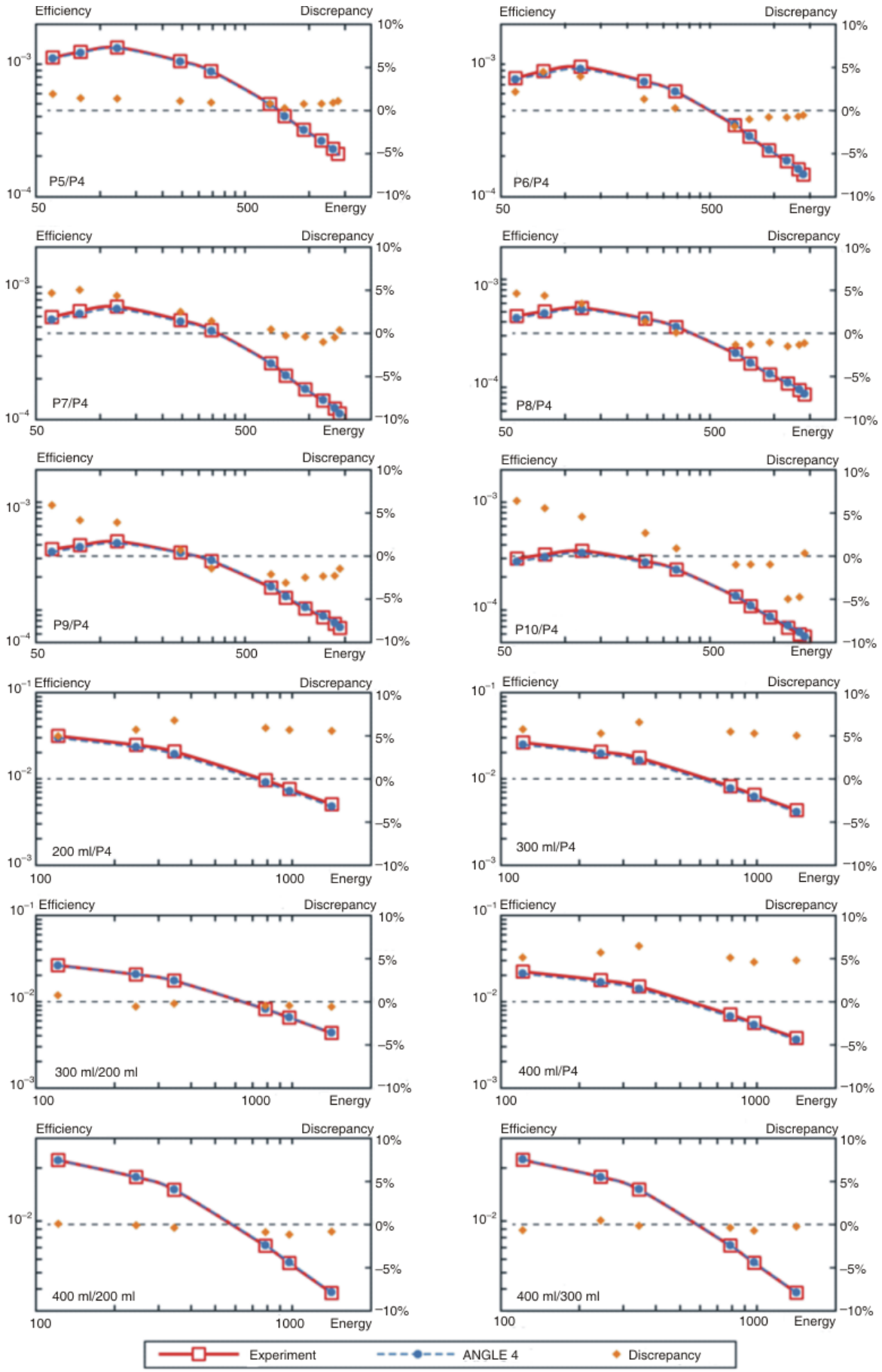

Figure 5. ANGLE 4 calculation *vs*. experiment for 2 2 inch detector and various counting arrangements

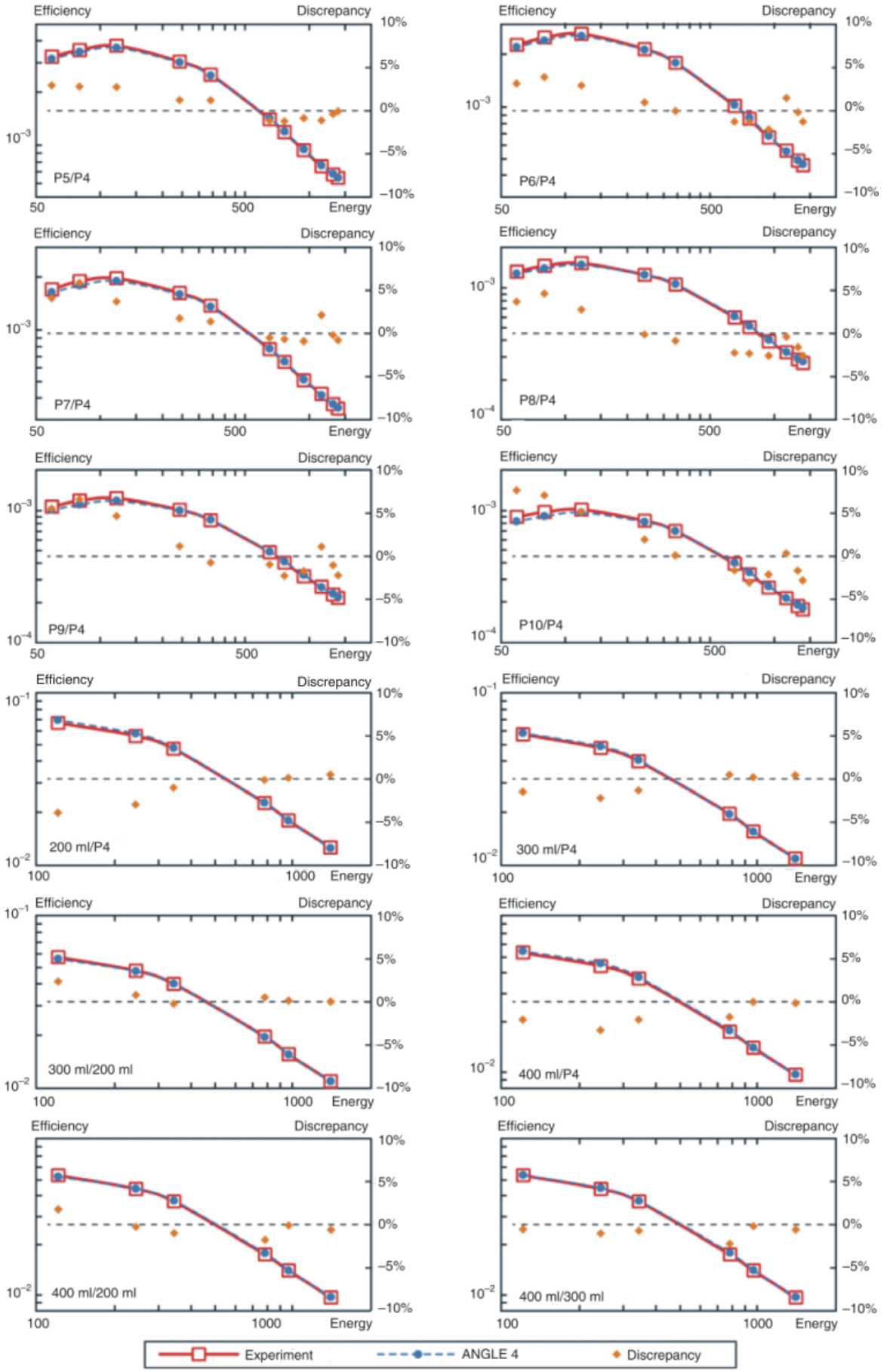

Figure 6. ANGLE 4 calculation *vs*. experiment for 3 × 3 inch detector and various counting arrangements

Table 6. Comparison between experimental and calculated (by ANGLE 4) detection efficiencies – summary

Source/reference source	Energy range [keV]	Number of energies	Detector 2 2		Detector 3 × 3	
			Average arithmetic discrepancy	Average absolute discrepancy	Average arithmetic discrepancy	Average absolute discrepancy
P5/P4	59.53-1408.01	11	1.01%	1.01%	0.50%	1.44%
P6/P4	59.53-1408.01	11	0.62%	1.62%	0.51%	1.72%
P7/P4	59.53-1408.01	11	1.53%	1.91%	1.40%	2.01%
P8/P4	59.53-1408.01	11	0.56%	1.96%	–0.19%	2.19%
P9/P4	59.53-1408.01	11	–0.03%	2.71%	0.87%	2.57%
P10/P4	59.53-1408.01	11	0.73%	3.01%	0.94%	3.06%
200 ml/P4	121.78-1408.01	6	5.78%	5.78%	–1.30%	1.48%
300 ml/P4	121.78-1408.01	6	5.59%	5.59%	–0.69%	1.03%
300 ml/200 ml	121.78-1408.01	6	–0.24%	0.49%	0.56%	0.66%
400 ml/P4	121.78-1408.01	6	5.32%	5.32%	–1.61%	1.61%
400 ml/200 ml	121.78-1408.01	6	–0.52%	0.55%	–0.36%	0.95%
400 ml/300 ml	121.78-1408.01	6	–0.28%	0.44%	–0.92%	0.92%
Mean			1.67%	2.53%	–0.03%	1.64%

CALCULATIONS AND RESULTS

Detection efficiencies are calculated using ANGLE 4 software. Various sources are tried as reference (calibration) ones, from which the detection efficiencies are calculated for the unknown sources – actually calibrated ones as well, thus with known activities.

Very good agreement is obtained between experimentally determined and calculated (using ANGLE 4) detection efficiencies for NaI detectors. The agreement is apparently within experimental uncertainties. There is no indication of bias or systematic errors.

Results for each detector and counting arrangement are given in figs. 5 and 6 (for 2 2 and 3 3 inches detectors, respectively). Summarized results are presented in tab. 6. Details can be found in the form of extensive Excel file, which is available for downloading [41].

CONCLUSIONS

Experimental verification of ANGLE 4 software for NaI detectors proved the reliability of the software. As a matter of fact, this was expected with pretty much confidence, since the core software performs much more complex task of the same type – efficiency calculations for semiconductor detectors, the latter being extensively tested during more than twenty years of practical application in gamma-spectrometry labs all around.

From the other side, this work also proved the reliability of both experimental set-up and procedure applied. These are intended to be further used in testing and validating new upgrades of ANGLE software – within scientific collaboration between the universities of Alexandria and of Montenegro.

AUTHOR CONTRIBUTIONS

ANGLE 4 software extension to NaI detectors was developed by A. D. Dlabac. Experimental part of the verification work was carried out by A. A. Thabet and M. S. Badawi. All authors took part in planning the work and in discussions during all phases of its elaboration. The manuscript was conceived and written by S. I. Jovanović, M. S. Badawi, A. M. El Khatib, and M. I. Abbas. A. D. Dlabac performed data elaboration and the graphical representation of results.

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Received on February 1, 2015
Accepted on March 18, 2015

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ЕКСПЕРИМЕНТАЛНА ПРОВЕРА СОФТВЕРА ANGLE 4 У ДЕЛУ ПРОРАЧУНА ЕФИКАСНОСТИ СЦИНТИЛАЦИОНИХ ДЕТЕКТОРА ГАМА ЗРАЧЕЊА

Софтвер ANGLE за прорачун ефикасности полупроводничких детектора гама зрачења, широко распростањен и одавно у употреби, недавно је надграђен за коришћење код сцинтилационих NaI детектора. Ова опција фигурише у последњој верзији ANGLE 4 и у раду је укратко приказана. Посебно је наглашена тзв. "дискретизација" криве референтне ефикасности, што отвара могућност употребе софтвера ANGLE 4 на појединачним гама-енергијама, тј. без претходног одређивања референтне криве. Ово доприноси не само бољој употребљивости и већој поузданости методе и софтвера, него и смањује могућности за систематске грешке. Рад је првенствено усмерен на експерименталну проверу софтвера ANGLE 4 код NaI детектора. Коришћена су два детектора различитих карактеристика (2 2 и 3 3 инча). Комерцијални калибрисани гама-извори (тачкасти и цилиндрични) и раствори припремљени у сопственој изради (разблаживањем калибрисаних раствора), мерени су на различитим растојањима од детектора, у опсегу 0-50 cm. Посматран је енергетски опсег 59-1408 keV. Ова разноврсност услова мерења која се тиче детектора, извора, растојања извор-детектор, разматраних гама-енергија и другог, имала је за циљ да обезбеди што ширу експерименталну основу за проверу методе и софтвера. Експериментално добијене ефикасности упоређиване су са оним добијеним прорачуном помоћу ANGLE 4. Постигнута је веома добра сагласност – увек у границама мерне несигурности – чиме је потврђена поузданост софтвера за коришћења у NaI квантитативној гама-спектрометрији.

Кључне речи: гама-спектрометрија, сцинтилациони детектор, прорачун ефикасности, софтвер ANGLE, експериментална провера