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k_0-IAEA DETERMINATION OF FULL ENERGY PEAK EFFICIENCY FOR A HIGH PURITY GERMANIUM DETECTOR

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ABSTRACT

The k_0-IAEA software was used to determine full peak energy efficiency of a High Purity Germanium (HPGe) co-axial detector within the energy range of 121.8 2204.5keV and geometries of 17cm, 15cm and 2cm. The experimentally (direct technique) determination of the efficiency of the co-axial detector was within the energy range of 59.54 2204.5keV. Plotted ratios of the k_0-IAEA derived efficiency over the k_0-fitted FEPE values showed slight oscillations at certain energies attributed to the characteristics of the detector while the results of the ratio of k_0-IAEA FEPE measurement over the experimentally derived efficiency obtained yielded inconsequential oscillations at certain energy around the unity mark. These deviations of 0.1 to 6% for the three geometries measured from the k_0-IAEA experimental data agreed to the accurate and large acceptance of the software for analysis.

KEY WORDS: k_0-IAEA software, full energy peak efficiency, HPGe detector, standard sources

The International Atomic Energy Agency (IAEA) via technical cooperation and coordinated research projects (CRP), expert services, and fellowship awards developed a nondestructive, multi-element determination method with a high degree of accuracy and reliability called the k_0-IAEA program software. In recent years, the k_0 program was developed at various NAA laboratories using different approaches. This method is now well established in the nuclear analytical community all over the world.

Manufacturer of detectors usually quote efficiency values relative to that of a 3x3 in (76x76 mm) NaI(Tl) scintillation crystal, for the 1332.5keV gamma ray emitted by a ^{60}Co point source placed at a distance of 25.0 cm from the detector end cap (ANSI/IEEE, 1996). In some gamma ray spectroscopic applications, 25.0 cm geometry have little importance since most analytical conditions require detector efficiency at various photon energies and source geometries (Ewa et al.,2002). Thus, one may wish for the experimental technique of determining efficiency at specific geometries using radioactive sources with specific geometries using radioactive source with specific activities and gamma emission probabilities. Since this method could yield good results with little uncertainties, it has some limitations that may propagate errors in the final determination of the full energy peak efficiency, arising from the following:

i. Inconsistency of photon emission probabilities used by different researcher

ii. Specification of source date/time not précised, may affect measurement accuracy and

iii. Employ many different sources to cover the low, intermediate, and high energy regions, which may lead to the existence of energy gaps, thereby creating large uncertainty through fitted curves (interpolations).

It is against these limitations that the application of the k_0-IAEA program becomes progressively desirable. Besides, the k_0-IAEA simulation program affords unique opportunity of investigating the interaction of photons with the sensitive detector volume excluding the effect of the cryostat since detectors are usually sealed from the factory by the manufacturers. This sealing procedure could be very useful in analyzing poor performances if the reference

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(theoretical) efficiency curves for the detector are established. However, users of the k_0-IAEA program may encounter some modeling problems due to;

a) Insufficiency of accurate detector and cryostat parameters from manufacturers, which in turn affects the geometry of the model and

b) Complexities on computerization, restricting its accuracy to the end-users understanding of the program.

Therefore, in this paper, the k_0-IAEA program was used in calculating the full energy peak efficiency for a HPGe detector within 121 2204 keV energy range. The results were compared with data obtained via experimental determination using standard point sources within the range 59.54-2204keV.

THEORY

In principle, the photopeak efficiencies, the peak-to-total relation and the number of disintegrations can be obtained by nonlinear least squares methods, where the chi-square, χ_r^2 -value of the measured photopeak areas as compared to the computed areas is minimized by the definition expressed mathematically (Blaauw, 1993) as;

$$\chi_r^2 = \frac{\dfrac{\sum_i \left({}_m p_{a_i} - {}_c p_{a_i} \right)^2}{\sigma_i^2}}{N_{obs} - \left(N_{emi} + 3 \right)} \qquad ...1$$

where $N_{obs} - N_{emi} > 3$ and ${}_c p_{a_i}$ = computed peak areas

${}_m p_{a_i}$ = measured peak areas

σ = uncertainty of the measured peak area

N_{obs} = observed peak counts

N_{emi} = emitted photon energies

An estimation of the number of disintegrations during the measurement is readily available from which the number of the measured areas of "true" photopeaks and the gamma-ray abundances, the peak efficiencies are estimated.

The peak-to-total ratio of detector efficiencies can be approximated by a linear curve on a log-log scale for n-type detectors (Blaauw; 1993). Thus, only the parameters; decay constant and emission probability may be needed to cover all total efficiencies. Estimate of the peak-to-total parameters are taken from a separate measurement of the Ge detector, or by setting the peak-to-total ratio to unity for all photon energies at the beginning of the computation.

EXPERIMENTAL

*k*0-IAEA Simulation Technique

A coaxial HPGe detector (ORTEC ©) of crystal length 76.3 mm, diameter 58.8 mm, relative efficiency of 30%, and resolution of 1.95 keV for ^{60}Co gamma ray at 1332.5keV was used for the investigation. Two standard sources were used, the single energy peak source ^{137}Cs for peak-to-total ratio evaluation and the multi-energy peak ^{152}Eu point source for Full Energy Peak Efficiency (FEPE) measurements. The spectra reduction performed by *k*0-IAEA simulation software for these two sources measured at 17cm, 15cm and 2cm, from the detector end-cap. The measurements, were obtained from the MAESTRO emulation software manufactured by the EG & G ORTEC Company®. This emulation software is very well compatible with the ADCAM Multi-Channel Analyzer (MCA) card used.

In the evaluation of the FEPE of the coaxial germanium detector, the permanent database of the *k0*-IAEA software was first edited and the detector's dimensions; crystal diameter 58.8 mm, crystal length 76.3 mm, end cap to crystal 3 mm, aluminum absorbing layers 1.27 mm, inactive Germanium layer 0.7 mm, and the top cover diameter 72.4 mm were entered. The certificates of the point sources of ^{152}Eu and ^{137}Cs were entered as shown in Table 1 below.

Table 1: Certificate entered in the permanent database

Radionuclide	Activity (Bq)	Uncertainty (%)	Date	Time
^{152}Eu	38000	1.10	15/July/20 04	12:00 PM
^{137}Cs	38400	1.10	15/July/20 04	12:00 PM

The two samples were measured at three different geometries of 17cm, 15 cm, and 2cm long enough so that the peak statistics in each main peak of each radionuclide were better than 0.5%. The single-radionuclide source ^{137}Cs was measured at geometry of 17cm only for p/t curve estimation. The mixed peaks (energies) source ^{152}Eu was measured at the three listed distances of 17cm, 15 cm and 2cm from the detector end cap. The series data base of samples was opened to contain only these two samples and the spectrum files in the series folder were stored with the Edit/Series database command.

To prevent convergence problems, the values of the parameters; decay constant, gamma ray abundance were checked and the peak efficiencies were kept from changing by more than 50% in a single iteration. They were kept positive and less than unity. The total efficiencies were kept larger than the peak efficiencies, but again less than unity.

Standard Sources

Validation of the k_0-IAEA simulation software FEPE results was accomplished experimentally by placing standard sources at distances 17cm, 15cm and 2cm along the co-axial detector axis. A set of four sealed radionuclides (^{241}Am, ^{137}Cs, ^{226}Ra and ^{152}Eu) whose photon energies covered the range under investigation was used for the direct measurements. These are the three photon-emission geometries simulated in the k_0-IAEA model. After accumulating sufficient counts by an MCA for each of the sources, the MAESTRO emulation software program was used to evaluate the net full energy peak (background subtracted) counts for each photon of interest. The ORTEC Model 257P amplifier time-constant was set to 6 micro-seconds, ensuring optimum detector performance as specified by manufacturer.

The activity for each source were normalized to the measurement date before obtaining the full energy peak efficiency through the calculation of the net peak count rate per photon emission rate, using the emission probability of Erdmann and Soyka, (1979).

RESULTS

The detector FEPE (Fig. 1) varies as a function of Energy of the incident photon and interactions at the sensitive volume. Each curve of the direct FEPE measurements consists of three parts;

i. A low energy region below 100 keV which is almost linear

ii. Followed by a curve above the 100 keV energy region and

iii. A linear component as the energy approaches 1000 keV and beyond

Full Energy Peak Efficiency curves have its highest value around 100 keV and the shape does not depend on the distance of the photon source from the detector end-cap. The energy (E_γ) dependence for the photons in the photo-electric absorption cross section (τ) of the absorbing material dependent upon Z is given by the expression

$$\tau \alpha \frac{Z^n}{E_\gamma^{3.5}} \qquad ...2$$

Where 'n' is normally between 4 and 5 depending on the absorber material (Debertin and Helmer, 1988). This dependence on Z explains the choice of high-Z materials such as lead with Z = 82 for shielding used in this study. The Ge materials with Z=32 indicates that the incident photons (E_γ) will deposit almost all its energies within the range of (59.54-200 KeV) with the absorption probability within the range (0.645-0.009).

All the FEPE data sets had a common turning point around 122keV (Fig.1) where the efficiency is close to its maximum value. The departure of the *k*0-IAEA curve from the trend exhibited by the experimentally determined data confirms the fact that low energy photons are not included in *k*0-IAEA program and is highly attenuated by the Al end-cap material of the detector cryostat. At higher energy (beyond 200keV), simulated model agreed very well with the experimental data. This region shows a near linear response in the log-log plot of the FEPE versus energy (Fig. 1).

The fitted values over the experimental data were obtained using the semi-empirical least square fit-function described by the general equation;

$$\log(\varepsilon) = \sum_{j=0}^{n} a_j \left(\log E / E_0\right)^j \qquad ...3$$

Where ε is the FEPE, a_j are constants and set at 1 keV, thereby making the quantity E (photon energy in keV). The semi-empirical functions with their corresponding fit constants were evaluated for the energy range of 50-200 keV, and between 200 keV-1408 keV for the three geometries (17cm, 15cm, and 2cm) to take into account the inadequacies of using only single polynomial for the whole energy range of the curve as shown in Table 2.

Table 2 : Fit constants data evaluated for the various energy range

Constants	**Energy $\mu_1$17cm**	**Energy $\mu_2$17cm**	**Energy $\mu_1$15cm**	**Energy $\mu_2$15cm**	**Energy μ_1 2cm**	**Energy $\mu_2$2cm**
a_0	-181.18	-29.75	-192.19	-26.75	-191.79	-27.75
a_1	100.36	11.43	99.84	12.94	100.36	11.43
a_2	-17.20	-2.44	-18.20	-1.94	-19.70	-2.44
a_3	1.09	0.13	1.17	0.13	1.09	0.13
Regression	0.88	0.90	0.98	0.99	0.98	0.99

where μ1=50-200keV and μ2=200-1408keV

The minimum -value of the match for 52Eu between the measured and the computed for all three geometries was 0.9 for 15 cm. The individual values for each peak are shown in Tables 3-5. In these tables, the relative precision of the measured photopeak areas, the ratio between measured and computed areas and the z-value of this ratio, computed from equation 4 are shown.

$$z = \frac{\left({}_m p_a - {}_c p_a\right)}{\sigma} \qquad \text{...4}$$

One notices some large z values in these tables especially for the photopeak with the energy 964.11 keV at distance 2cm. The 244.69 keV discrepancy reported by Debertin et al., (1976) may indicate that some property of the decay scheme of 52Eu remains as yet unknown, alongside with other low emission probabilities and low z-values were neglected.

The results (Table 3-6) showed that the ratios of the *k*0-IAEA and fitted efficiency versus energy (keV) were very stable at unit value since ratio-values fluctuate between 1-0.7 for all three geometries. However, from Figs. 2-4, the ratios of the *k*0-IAEA and experimental efficiency versus energy (keV) were not very stable at unit mark but rather, exhibited oscillations at some energy with successive maxima and minima. It was noted by Debertin and Helmer ,(1988) that oscillations are characteristic of large and medium size Ge-detectors. However, Owens (1989) in using such a ratio, observed that this oscillations account for the fractional deviations between the measured and fitted values.

CONCLUSION

This work agreed with findings of other workers in the field (Kamboj and Kahn ,1994; Laborie et al*.,* 2000; Ewa et al*.,* 2002; Ludington and Helmer*,* 2000; Wainio et al*.,* 1966 and Owens ,1989), that FEPE curves follow a systematic pattern of increase of HPGe detector efficiency from a low energy region of 59.54 keV, followed by an optimum peak of efficiency value which further decreases as the energy increases. The *k*0-IAEA software fully agreed between the regions of 121 keV - 1408 keV since we

Table 3: Experimental and k_0-IAEA data obtained at 17cm

Energy (keV)	**k_0-IAEA efficiencies**	**χ_r^2-value**	**Experimental efficiency**	**Uncertainty in efficiencies**	**k_0-Fitted efficiencies**	**k_0-Ratio**	**k_0-z-score**	**peak/total**
59.5	AS	AS	4.65E-04	AS	AS	AS	AS	AS
121.78	3.00E-03	1.3	2.99E-03	2.78E-04	3.00E-03	1	0	7.92E-01
344.29	2.11E-03	1.3	2.00E-03	1.79E-04	2.07E-03	1.019	0.2	3.55E-01
351.9	AS	AS	1.85E-03	AS	AS	AS	AS	AS
778.92	1.25E-03	1.3	1.12E-03	1.02E-04	1.14E-03	1.097	1.1	1.89E-01
964.11	1.15E-03	1.3	1.03E-03	9.55E-05	9.95E-04	1.153	1.6	1.60E-01
1112.07	9.24E-04	1.3	8.84E-04	6.67E-05	9.11E-04	1.014	0.2	1.43E-01
1408	7.74E-04	1.3	7.12E-04	4.97E-05	7.94E-04	0.976	-0.4	1.20E-01

Table 4: Experimental and k_0 -IAEA data obtained at 15cm

Energy (keV)	k_0-IAEA efficiencies	χ_r^2- value	Experimental efficiency	Uncertainty In efficiencies	k_0-Fitted efficiencies	k_0-Ratio	k_0-z-score	peak/total values
59.5	AS	AS	6.16E-04	AS	AS	AS	AS	AS
121.78	3.75E-03	0.9	3.68E-03	1.46E-04	3.75E-03	1	0	7.92E-01
344.29	2.50E-03	0.9	2.58E-03	8.08E-05	2.39E-03	1.046	1.3	3.55E-01
351.9	AS	AS	2.44E-03	AS	AS	AS	AS	AS
778.92	1.44E-03	0.9	1.51E-03	4.77E-05	1.43E-03	1.002	0.1	1.89E-01
964.11	1.29E-03	0.9	1.27E-03	4.41E-05	1.26E-03	1.024	0.7	1.60E-01
112.07	1.13E-03	0.9	1.11E-03	3.98E-05	1.16E-03	0.973	-0.8	1.43E-01
1408	9.64E-04	0.9	9.87E-04	3.22E-05	1.01E-03	0.958	-1.3	1.20E-01

Table 5: Experimental and k_0-IAEA data obtained at 2cm

Energy (keV)	k_0-IAEA efficiencies	χ_r^2- value	Experimental efficiency	Uncertainty In efficiencies	k_0-Fitted efficiencies	k_0-Ratio	k_0-z-score	peak/total values
59.5	AS	AS	77E-03	AS	AS	AS	AS	AS
121.78	3.93E-02	6.9	3.93E-02	1.21E-03	3.93E-02	1.001	0	7.92E-01
344.29	2.30E-02	6.9	2.10E-02	1.31E-03	2.02E-02	1.141	2.2	3.55E-01
351.9	AS	AS	2.13E-02	AS	AS	AS	AS	AS
778.92	1.12E-02	6.9	1.12E-02	8.41E-04	9.88E-03	1.13	1.5	1.89E-01
964.11	1.01E-02	6.9	9.01E-03	3.28E-04	8.47E-03	1.197	5.1	1.60E-01
1112.07	8.95E-03	6.9	7.95E-03	2.86E-04	8.49E-03	1.054	1.6	1.43E-01
1408	8.22E-03	6.9	6.92E-03	2.94E-04	1.12E-02	0.732	10.2	1.20E-01

where AS = absence

Table 6: Ratio data for k_0 -IAEA and experimental efficiency

Energy keV	The ratio of k_0-IAEA FEPE to direct FEPE		
	at 17cm	at 15cm	at 2cm
121.78	1.041738531	1.028291621	0.941475827
344.29	1.055251369	1.016686069	1.014285714
778.92	1.039396479	1.027170311	0.964285714
964.11	1.019417476	1.016548463	0.997780244
1112.07	1.044353926	1.018935978	0.998742138
1408	1.08988764	0.978822576	0.969653179

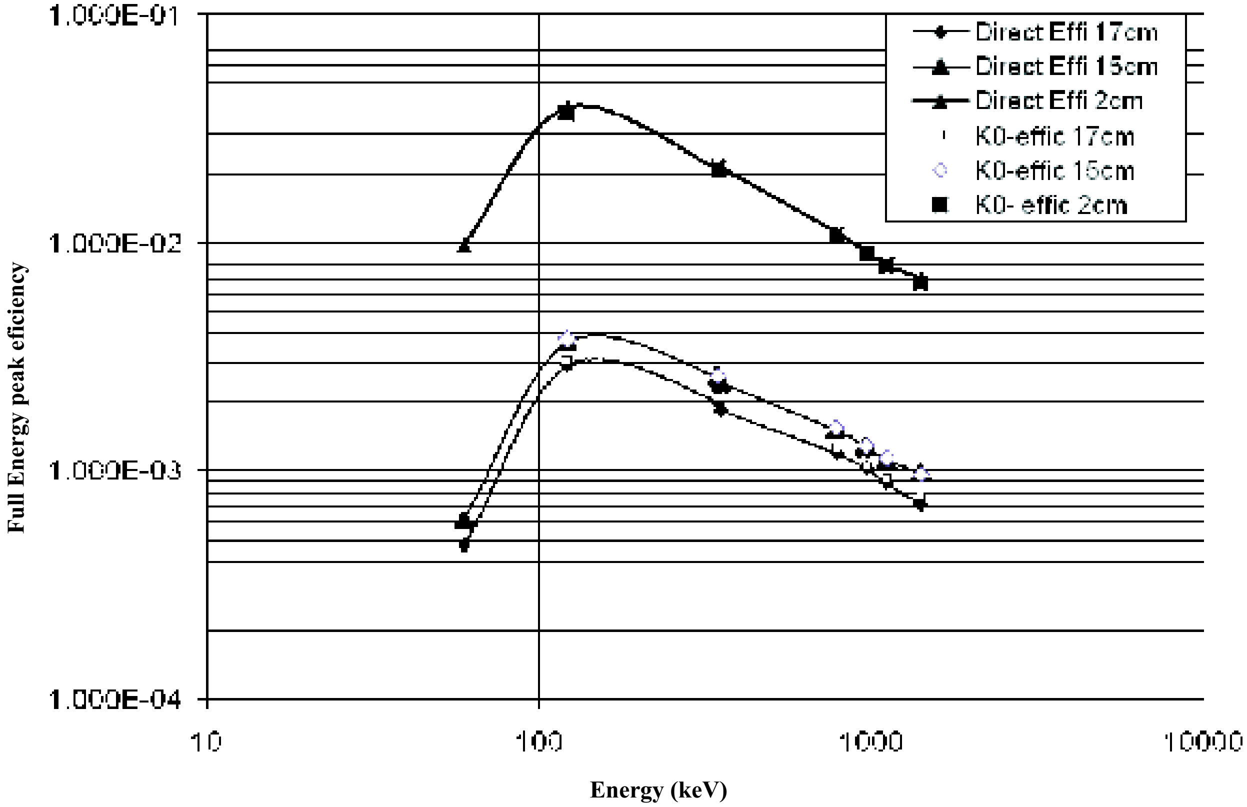

Fig. 1: k_0-IAEA and Experimental FEPE curves comparison at 17cm, 15cm and 2cm

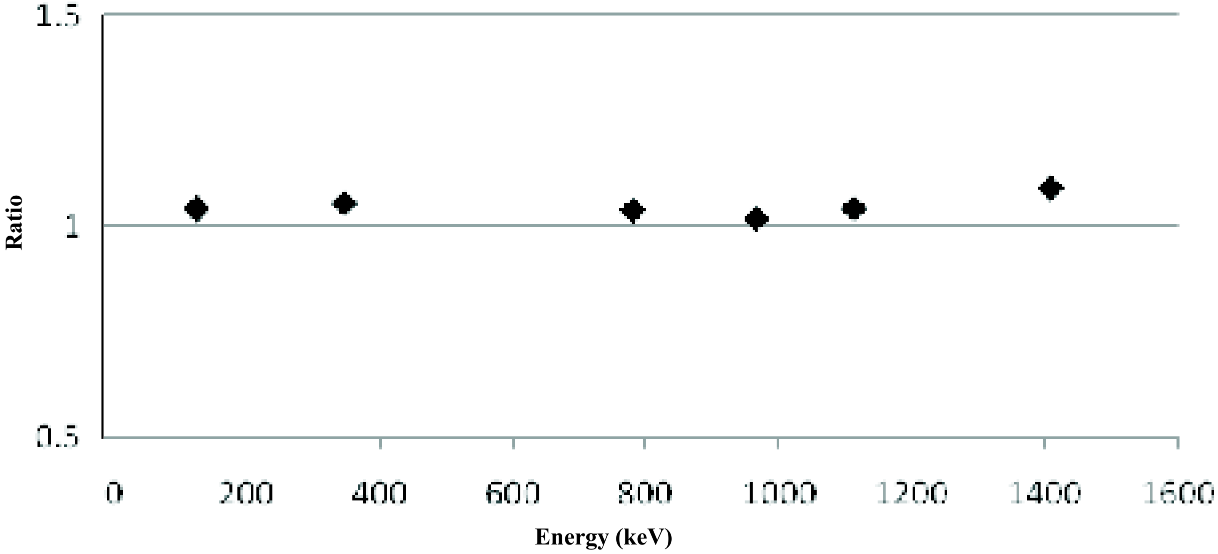

Fig. 2: Ratio of k_0-IAEA and Direct FEPE Measurement at 17cm

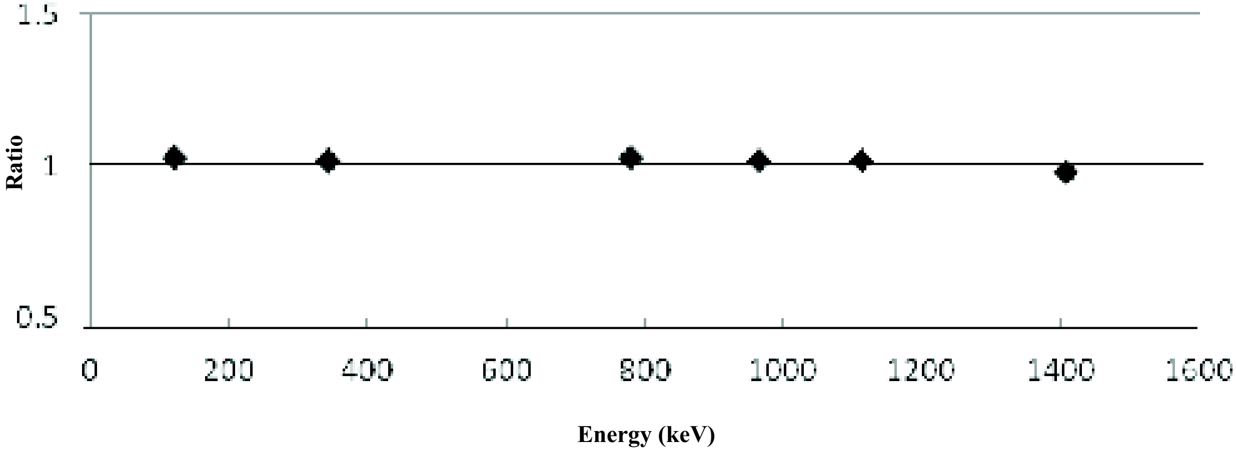

Fig. 3: Ratio of k_0-IAEA to Direct FEPE Measurements at 15cm

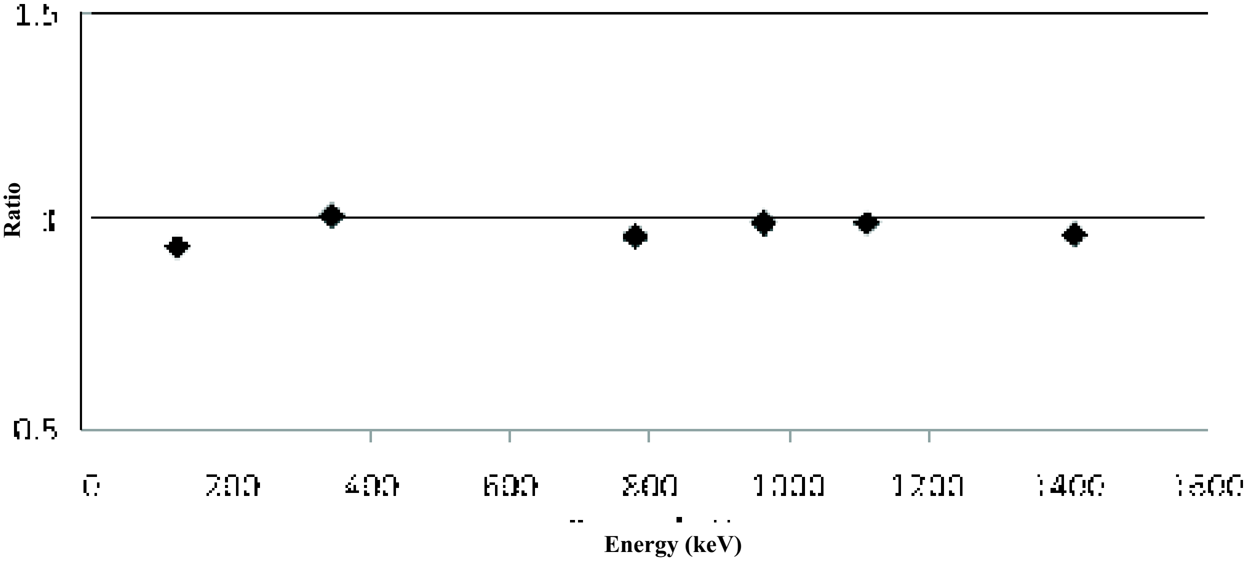

Fig. 4: Ratio of k_0-IAEA to Direct FEPE Measurements at 2 cm

observed slight oscillations and deviations of 0.1 to 6.01 % for the three geometries at certain energies attributed to the characteristics of the detector.

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REFERENCES

ANSI/IEEE.,1996. IEEE Standard Test Procedures for Germanium Gamma-Ray Detectors*,* ANSI/IEEE Std. Inst. of Elect. And Electronics Engineers. Inc., New York, USA:325.

Blaauw, M.,1993. The use of sources emitting coincident γ-rays for determination of absolute efficiency curves of highly efficient Ge detectors. Nuclear Instruments and Methods in Physics Research, A **332** : 493-500.

Debertin K and Helmer R.G. 1988.Gamma-and X-Ray Spectrometry with Semiconductor Detectors. Elsevier Science Publishers B.V.,North-Holland.

Debertin K., Schötzig U., Walz K.F. and Wein H.M., 1976. Efficiency Calibration of Semiconductor Spectrometers-Techniques and Accuracies. Journal of Proceedings, ERDA X-Ray Symp. Ann .Arbor. MI : 59-62.

Erdtmann G. and Soyka W., 1979. The -Rays of the Radionuclides. Tables for Applied-Ray Spectrometry. Verlag Chemie, Weinheim, New York,**7**: 1-236.

Ewa I.O.B., Bodizs D., Czifrus S., Balla M. and Molnar, Z ,2002. Germanium Detector Efficiency for a marinelli Beaker Source-Goemetry using the Monte Carlo Method. Journal of Trace and Microprobe Techniques, **20** (2) :161-170.

Kamboj S. and Kahn B., 1994. Intrinsic efficiency calibration of a large germanium detector. Radioact. Radiochem, **5** (2): 46- 56.

Laborie, J.M., Le Petit G., Abt D. and Girard M., 2000. Monte Carlo calculation of the efficiency calibration curve and coincidence-summing corrections in low level gamma-ray spectrometry using well-type HPGe detectors. Appl. Rad. Isot., **53** :57- 62.

Ludington M. A. and Helmer R. G., 2000. High accuracy measurements and Monte Carlo calculation of relative efficiency curve of an HPGe detector from 433 to 2754 keV. Nucl. Instr. Meth., A **446** (3): 506-521.

Owens, A.,1989. A comparison of empirical and semi empirical efficiency calculations for Ge detectors. Nucl. Instr. Meth., A **274**:297- 304.

Wainio K.M. and Knoll G.F., 1966. Calculated Gamma-Ray Response Characteristics of Semi-Conductor Detectors. Nucl. Instr. Meth., **44**: 213-223.