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Validation of Full Energy Peak Efficiency Calibration of HPGe Gamma-Ray Spectrometer Using Empirical Efficiency Curve Transfer

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Abstract: Full energy peak efficiency (FEPE) calibration is a necessity for a prices radioactivity measurement using gamma-ray spectrometry. There are different approaches for FEPE calibration such as experimental, empirical and Monte Carlo methods. The aim of this work is to shed more light on the FEPE calibration approach associated with an empirical efficiency curve transfer method using ^{226}Ra point source and KCl salt. The concept of relative FEPE were applied using relative intensity and fundamental parameter methods. The empirical FEPE curve transfer method is a relatively easy and inexpensive that overcomes some obstacles due to the lack of suitable standard calibration sources.

Keywords: gamma-ray spectrometry; efficiency calibration; ^{226}Ra point source; KCI.

1 Introduction

The activity concentration of any radionuclides can be calculated from the gamma-ray spectrum using the following equation [1, 2];

$$A_i = \frac{\mathrm{C}\ (\mathbf{E_i})}{\varepsilon\ (\mathrm{E}) \times \mathrm{I}\ (\mathbf{E_i})} \tag{1}$$

$$\varepsilon\ (\mathrm{E}) = \frac{\mathrm{C}\ (\mathbf{E_i})}{A_i \times \mathrm{I}\ (\mathbf{E_i})} \tag{2}$$

Where,

- ε (E) is the absolute photopeak efficiency at energy E.
- C (E_i) is the net count rate (counts/sec, cps) of the photopeak at energy E of radionuclide i.
- A_i is the activity concentration of certain radionuclide i, Bq.
- I (E_i) is the absolute intensity percentage of gamma-ray transition at energy E of radionuclide i.

The aim of this work is to validate a simple, an easy and inexpensive FEPE calibration method for HPGe gamma-ray spectrometer using ^{226}Ra point source with different gamma-ray transitions, KCl salt and an empirical efficiency Curve transfer technique.

2 Experimental Works

2.1 Gamma ray Spectrometer

Two extended range Hyper Pure Germanium (HPGe) detectors (Canberra Model GX4018) of about 47 % relative efficiency and 1.8 keV FWHM (energy resolution) at 1332 keV gamma-ray energy line of ^{60}Co were used simultaneously. They were associated with preamplifier model 2002CSL, amplifier model 2025, 16 k digital multichannel analyzer multiport II and Genie-2000 gamma-ray spectrometry software. The detectors are mounted on a vertical cryostat model 7935SL with liquid nitrogen Dewar and surrounded by a 10 cm lead shield, which is internally layered by a copper sheet. The energy calibration of the spectrometers was performed using ^{137}Cs and ^{60}Co point sources. Then it was reconfirmed using the multiple energy lines of ^{226}Ra (^{214}Pb-^{214}Bi) point source, using the most intense gamma-ray energy lines such as 186.58 (3.6%), 351.9 (35.6%), 609.3 (45.5%), 1120.3 (14.9%), 1764.5 (15.3%) and 2204.21 (4.9%) keV.

Radium-226 point source was measured in coaxial position and 25 cm away from the top surface of the detector. Potassium chloride solutions of different concentrations (4, 8 and 16 g per 100 ml sample) were prepared transferred to

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150 ml capacity polyethylene container where each gram of KCl contains 16.28 Bq of ^{40}K (1% of K contains 313 Bq of ^{40}K) [3]. Each sample was measured using HPGe gamma-ray using the gamma-ray transition at 1460.4 keV to calculate the absolute efficiency (ε) and the normalization factor- NF (Bq/cps) [4].

2.2 Empirical Efficiency Curve Transfer Method

The empirical efficiency curve transfer method was applied using the concept of the relative efficiency for ^{226}Ra (^{214}Pb-^{214}Bi) gamma-ray transition energy using point source to achieve the source-detector optimum (good) geometry condition of gamma-ray spectrometric measurements [5]. The relative efficiency curve was calculated using two concepts related to fundamental parameter method [6] and to the relative intensity (photopeak area) of the different gamma-ray transitions of ^{214}Pb-^{214}Bi to 609 keV photopeak [7]. Both concept will be briefly described in the following paragraphs.

I- Fundamental Parameter Method (FPM);

Secular equilibrium of natural radionuclides series such as ^{238}U and ^{232}Th series could be confirmed using the activity ratios between series radionuclides using the fundamental parameter method (FPM) and the relative efficiency (ε_R) concept that given by equation (3);

$$\textbf{Realtive Efficiency}, \mathrm{RE}\ (\mathbf{E}, \boldsymbol{i}) = \frac{\textbf{net count rate in the photopeak } (\mathbf{E_i}), (\mathbf{cps})}{\textbf{Absolute intensity } (\mathbf{E_i}), (\%)} \quad (3)$$

The details of the FPM were described by Eberle et al. (1978) where the activity ratio of series radionuclides such as ^{234}Th, ^{234m}Pa, ^{226}Ra, ^{214}Pb and ^{214}Bi within ^{238}U series can be given by equation (4);

$$\frac{\mathbf{A_i}}{\mathbf{A_j}} = \frac{\mathbf{C}\ (\mathbf{E_i})}{\mathbf{C}\ (\mathbf{E_j})} \cdot \frac{\boldsymbol{\varepsilon}(\mathbf{E_j})}{\boldsymbol{\varepsilon}(\mathbf{E_i})} \cdot \frac{\mathbf{I}\ (\mathbf{E_j})}{\mathbf{I}(\mathbf{E_i})} \quad (4)$$

$$\frac{\boldsymbol{\varepsilon}(\mathbf{E_j})}{\boldsymbol{\varepsilon}(\mathbf{E_i})} = \frac{\mathbf{RE}\ (\mathbf{E_j})}{\mathbf{RE}(\mathbf{E_i})}$$

$$\therefore \frac{\mathbf{A_i}}{\mathbf{A_j}} = \frac{\mathbf{C}\ (\mathbf{E_i})}{\mathbf{C}\ (\mathbf{E_j})} \cdot \frac{\mathbf{RE}(\mathbf{E_j})}{\mathbf{RE}\ (\mathbf{E_i})} \cdot \frac{\mathbf{I}\ (\mathbf{E_j})}{\mathbf{I}(\mathbf{E_i})} \quad (5)$$

Where;

$\frac{\mathbf{A_i}}{\mathbf{A_j}}$	the activity ratio of radionuclides i and j with the gamma-ray transition E_i and E_j
$\frac{\mathbf{C}\ (\mathbf{E_i})}{\mathbf{C}\ (\mathbf{E_j})}$	the net count rate (cps) ratio of photopeak of the gamma-ray transition E_i and E_j
$\frac{\mathbf{RE}(\mathbf{E_j})}{\mathbf{RE}\ (\mathbf{E_i})}$	the relative efficiency ratio of the gamma-ray transition E_j and E_i
$\frac{\mathbf{I}\ (\mathbf{E_j})}{\mathbf{I}(\mathbf{E_i})}$	the absolute intensity ratio of the gamma-ray transition E_j and E_i

I- The Relative Intensity Concept;

The relative efficiency (ε_R) of different gamma-ray transitions of ^{214}Pb-^{214}Bi, Table-1, were calculated using the following equations;

$$\boldsymbol{Calculated\ reltaive\ intenisty}, \boldsymbol{CRI}(\boldsymbol{E_i}) = \frac{\textbf{net count in the photopeak } (\mathbf{E}_{\boldsymbol{i}})}{\textbf{net count in the photopeak } (\mathbf{609}\ \boldsymbol{keV})} \quad (6)$$

$$\textbf{Realtive Efficiency}, \mathbf{RE}\ (\mathbf{E_i}) = \frac{\boldsymbol{Calculated\ RI}(\mathbf{E_i})}{\boldsymbol{Reference\ RI}\ (\mathbf{E_i})} \quad (7)$$

Where

Reference RI (E_i) for Pb-214-Bi-214 is given in table 1 [8, 9, 10]

Most intense energy transition photopeaks of ^{214}Pb-^{214}Bi, Table-1, achieved counting errors between <0.1% and 0.2%. Then, ε_R of the different gamma-ray transitions were calculated using equation (6), and were used to generate RE's polynomial fitting curves of 4th or 5th degree, figure 1.

II-*Efficiency Curve Transfer from Point to Bulk Geometry*

The absolute efficiency curve as a function of gamma-ray transition energy can be build up through an empirical efficiency curve transfer concept. Using the net count rate (C) of ^{40}K photopeak at 1460.4 keV, the calculated relative efficiency from the polynomial fitting equation, Fig 1, ^{40}K activity concentration and the absolute efficiency (equation 2), The equation (4) could be modified to

$$\boldsymbol{NF}(\boldsymbol{E_i}) = \frac{\mathbf{A_i}}{\mathbf{C}\ (\mathbf{E_i})} = \frac{\mathbf{A_{K-40}}}{\mathbf{C}\ (\mathbf{1460\ keV})} \cdot \frac{\mathbf{RE}\ (\mathbf{1460\ keV})}{\mathbf{RE}\ (\mathbf{E_i})} \cdot \frac{\mathbf{I}\ (\mathbf{1460\ keV})}{\mathbf{I}(\mathbf{E_i})} \quad (7)$$

Where

NF (E_i) is the ratio of activity (Bq) to net count rate (cps) and called normalization factor for radionuclide i at photopeak energy E_i, Bq/cps .

From equation (1),

$$NF(E_i) = \frac{A_i}{C\,(E_i)} = \frac{1}{\varepsilon_i\,.\ I(E_i)} \quad (8)$$

$$\varepsilon\,(E) = \frac{1}{NF(E_i)\,.\,I\,(E_i)} \quad (9)$$

The details on the sources of uncertainty and their calculation were given in the previous work [11].

3 Results and Discussion

The relative efficiency as a function of energy was calculated using equations 3 & 6, and shown in figure 1. The absolute efficiency values were calculated using equation 9 that are given in Table 2. Using the fitting equation of the absolute efficiency curve, the absolute efficiency value for any gamma-ray transition could be calculated.

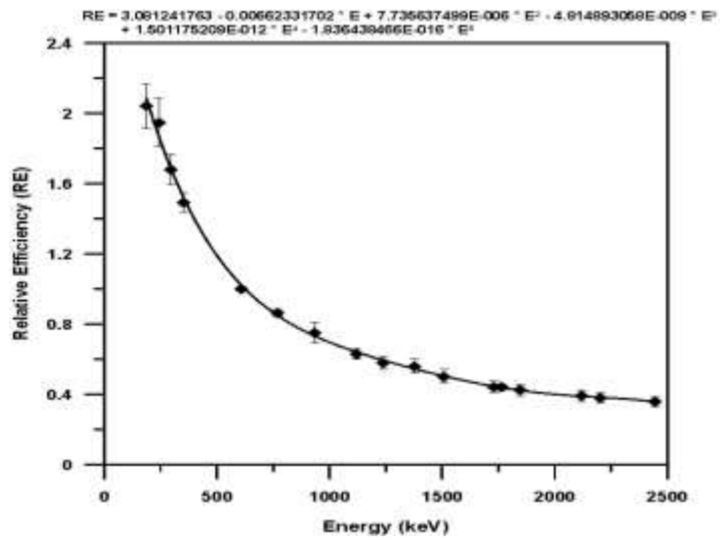
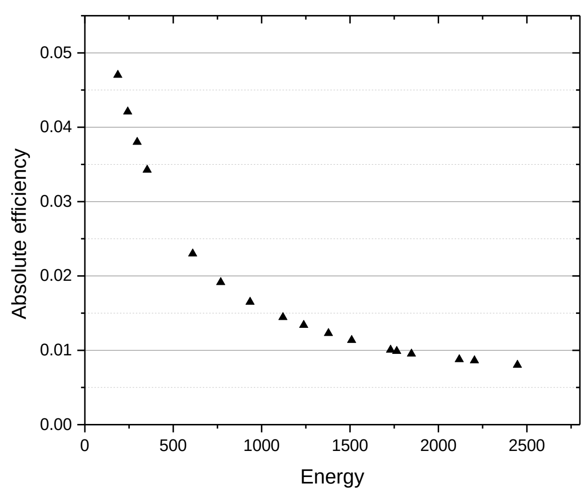


Fig. 1: The relative efficiency curve as a function of energy (keV) for the different gamma-ray transitions of ^{214}Pb-^{214}Bi (242-2447 keV)



[log(Eff) = -3.890e-005*E - 2.246e+000 + 6.685e+002/E - 2.277e+005/E^2 + 3.944e+007/E^3 - 2.653e+009/E^4]

Fig.2: The absolute full energy peak efficiency curve as a function the photopeak energy using an empirical efficiency curve transfer method.

Table 1: Selective gamma-ray transmission of ^{214}Pb-^{214}Bi and their absolute (AI) and relative intensity (RI) percentages [8, 9, and 10].

Ser.	Radionuclide	Energy (keV)	AI %	*RI %
1	Pb-214	242.00	7.43	16.53
2	Pb-214	295.22	18.414	42.52
3	Pb-214	351.93	35.6	81.29
4	Bi-214	609.31	45.49	100
5	Bi-214	768.36	4.892	10.64
6	Bi-214	934.06	3.10	6.54
7	Bi-214	1120.29	14.91	33.52
8	Bi-214	1238.11	5.831	13.25
9	Bi-214	1377.67	3.968	8.66
10	Bi-214	1509.23	2.128	4.77
11	Bi-214	1729.6	2.844	6.56
12	Bi-214	1764.49	15.31	34.91
13	Bi-214	1847.42	2.025	4.59
14	Bi-214	2118.55	1.158	2.51
15	Bi-214	2204.21	4.913	10.66
16	Bi-214	2447.86	1.548	3.28

Table 2: Calculated relative efficiency, normalization factor – NF (Bq/count per second) and the absolute efficiency using an empirical efficiency curve transfer method.

		Energy keV	I %	Relative Efficiency	Error	Relative Efficiency*	Error	Normalization Factor	Absolute Efficiency
1	Ra-226	186.58	0.03555	2.041	0.128	2.085	0.130	598.1976	0.047024
2	Pb-214	242.4	0.0743	1.947	0.138	1.867	0.133	319.7234	0.042096
3	Pb-214	295.89	0.18414	1.678	0.088	1.685	0.088	142.9136	0.038
4	Pb-214	352.34	0.356	1.492	0.056	1.519	0.057	81.98046	0.034264
5	Bi-214	609.71	0.4549	1.000	0.005	1.019	0.005	95.63865	0.022985
6	Bi-214	768.59	0.04892	0.864	0.019	0.849	0.018	1067.956	0.019141
7	Bi-214	934.4	0.031	0.749	0.058	0.732	0.057	1954.608	0.016504
8	Bi-214	1120.46	0.1491	0.630	0.030	0.640	0.031	464.4087	0.014442
9	Bi-214	1238.2	0.05831	0.578	0.037	0.594	0.038	1280.639	0.013392
10	Bi-214	1377.64	0.03968	0.560	0.040	0.545	0.039	2050.729	0.012289
11	Bi-214	1509.08	0.02128	0.501	0.039	0.504	0.039	4137.707	0.011357
12	Bi-214	1729.45	0.02844	0.442	0.032	0.446	0.032	3498.045	0.010052
13	Bi-214	1764.31	0.1531	0.440	0.020	0.438	0.020	661.0225	0.009881
14	Bi-214	1847.26	0.02025	0.423	0.033	0.422	0.033	5187.162	0.00952
15	Bi-214	2118.16	0.0114	0.392	0.033	0.389	0.032	9998.449	0.008773
16	Bi-214	2203.61	0.04913	0.380	0.027	0.383	0.028	2357.929	0.008632
17	Bi-214	2446.99	0.01548	0.356	0.027	0.356	0.026	8048.567	0.008026

*Relative efficiency calculated using the polynomial fitting equation

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