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Research Article

DETERMINATION OF THE COINCIDENCE SUMMING CORRECTION FACTOR IN THE MEASUREMENT OF THE EXPERIMENTAL EFFICIENCY OF SEMICONDUCTOR DETECTOR

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ABSTRACT

The detection efficiency of the semiconductor detector is an important factor, which directly impacts the experimental results of the instrumental neutron activation analysis. The efficiency curve was determined by the measurements of some standard sources including **^{137}Cs, ^{109}Cd, ^{133}Ba, ^{60}Co, ^{152}Eu**, **^{57}Co.** *However, for the multi-energy radioisotopes emitting more than two gammas, the coincidence summing effect appears when both gammas originating from a disintegration of an excited nucleus are detected within the resolving time of the detector. The coincidence effect is more significant at near source-detector distances and the measured efficiency is thus significantly different from the true value. In this paper, the coincidence effect has been determined at four positions and evaluated at two positions from the detector window as well. The activities of* ^{133}Ba *and* ^{60}Co *sources were determined at the positions H3 and H1 by using the corrected efficiency with the bias deviations were -3.9% and -4.2% for* ^{133}Ba. *Besides, the bias deviations obtained -3.4% and -0.3% for* ^{60}Co *source. This result was significantly better than the result which was determined by the experimental efficiency with the bias deviations of 5.7% and 12% for* ^{133}Ba *and -0.9% and 4.1% for* ^{60}Co.

Keywords: coincidence summing correction; detector efficiency; The Kafala method

1. Introduction

Instrumental neutron activation analysis (INAA) is a multi-element analysis technique with many advantages, especially with high accuracy results. INAA technique with k0-standardization is a power tool for multi-element analysis at a broad of trace element contents which requires the high correct of the efficiency value. Besides, the experimental measurement of the environmental sample requires techniques for the low-activity and large

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sample, which should be counted at the near geometry. However, this experiment raises a problem related to the coincidence summing effect that can be reduced by increasing sample-detector distance. The practical request of the low-activity source is infeasible at the far geometry. Therefore, there is a necessity for the coincidence summing effect correction at the near geometry. In the experiment, the efficiency values can be calculated using calibration via standard sources popularly used for efficiency determination including single and multi-energy standards such as ^{137}Cs, ^{109}Cd, and ^{133}Ba, ^{60}Co, ^{152}Eu, ^{57}Co respectively. For the single-energy standard emitters, the efficiency can be determined with high accuracy without correction, but for the multi-energy ones, the coincidence summing effect has to be taken into consideration. True coincidence summing effect occurs when isotopes simultaneously generate two or more cascading gammas in the resolving time of the gamma spectrometer, which can be illustrated for ^{60}Co in Figure 1. This effect is independent to the count rate, but it becomes more significant at near source-detector distances, i.e. it depends on the solid angle sustained by the detector. There was a probability that E1 and E2 acquired equal a summing pulse of the detector, which was expressed by Eq. (1.1) (with E1, E2 are gamma energies from a nuclide. For instance, E1=1173.2 keV and E2=1332.46 keV were two gamma rays emitted from ^{60}Co isotope).

$$N_{sp} = N_0 \varepsilon_1 \varepsilon_2 w(\theta) \quad (1.1)$$

Where N_0- is the disintegration rate of the source.

$\varepsilon_1, \varepsilon_2$ – full-energy peak efficiencies for E1 and E2, respectively.

$w(\theta)$- factor accounting for any angular correlation between the gamma rays.

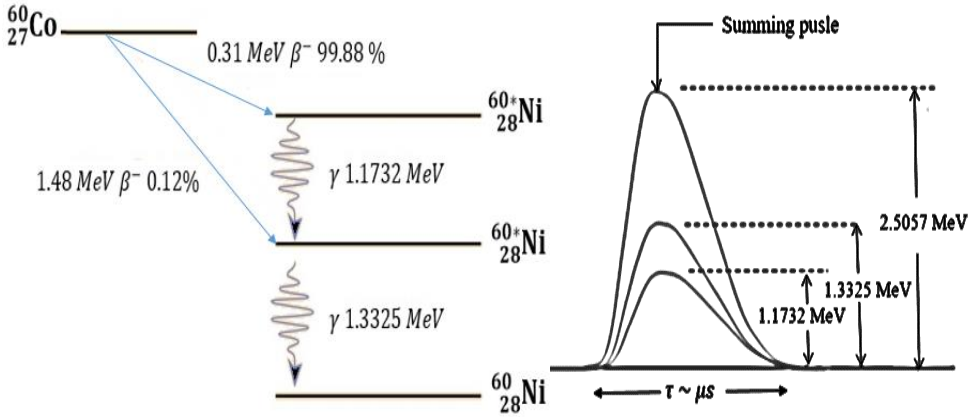

Fig 1. *Scheme of Co-60 decays with a two-step cascade*

The coincidence effect is normally corrected by some methods including the ratio peak-to-total (P/T) calibration method (Ababneh, 2015; Vidmar, 2007; Semkow, 1990), the transition probability matrix method (De Corte, 1992), and Kafala method (Kafala, 1995). The peak-to-total calibration method is a semi-empirical method which requires a set of the single-energy standard sources including ^{109}Cd, ^{137}Cs, ^{54}Mn, and ^{65}Zn which were used for determining the peak and total efficiency. The second step, the TRUECOINC software

(Sudár, 2002) having the ability of carrying out the coincidence summing correction is performed to obtain the coincidence summing factors corresponding to the concerned energy. Besides, the transition probability matrix method (De Corte, 1992) is a literature method that uses the decay data from the nuclear database for calculating the coincidence factors, and thus the calculation is complicated and required the computerization with complex matrixes. The Kafala method is a total experimental method, which allows the correction of the coincidence summing effect for radioactive isotopes without using its the cascade scheme. It requires radioactive standard sources measured at different distances from the detector window and is based on the ratio of a reference single gamma-ray energy to the ratio of cascade energies at the near and far geometry. The efficiency ratio of a gamma energy peak is a constant value at different distances. Therefore, the coincidence summing correction factors can be calculated via the efficiency ratio between near and far distances that are described in Figure 2.

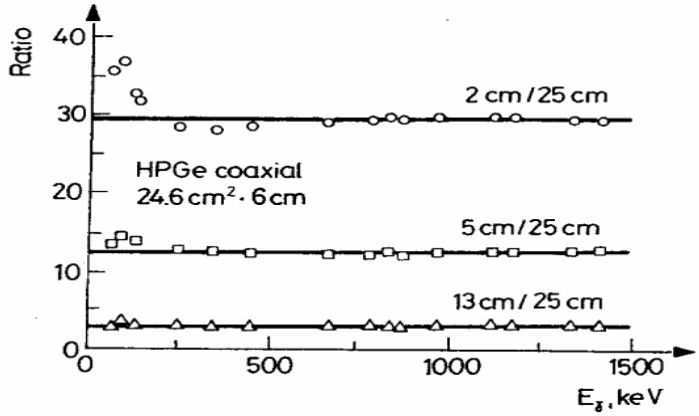

Fig 2. *The ratio between far and near geometry described by the Kafala method (Kafala, 1995)*

In the experiment, a radioactive standard source that emits a single gamma-ray and another source to correct the coincidence effect were measured at far and near distances corresponding to the detector window. The efficiency ratio at the far (R_f) and near (R_n) geometry is described as:

$$R_{f,n}=\left(\frac{\varepsilon_{\gamma,r}}{\varepsilon_{\gamma,s}}\right)_{f,n} \quad (1.2)$$

Wherein f, n indices corresponding to far and near geometry. $\varepsilon_{\gamma,r}$,$\varepsilon_{\gamma,s}$ are reference and source efficiency values. The efficiency was defined by Monthomery (1995).

$$\varepsilon_\gamma = \frac{N_p/t_c}{A.I_\gamma} \quad (1.3)$$

$$A=A_0\, e^{-ln2.\frac{t_d}{T_{1/2}}} \quad (1.4)$$

with A_0 and A are an initial activity that was certificated at the produced date by the manufacturer and a present activity (Eq. 1.4), respectively. N_p is the net area, t_c is the

counting time, I_γ is the absolute intensity of the concerned energy, t_d is the decay time, and $T_{1/2}$ is the half-life of a radioisotope.

The coincidence effect correction factor was defined by

$$C_f = \frac{R_n}{R_f} \quad (1.5)$$

C_f =1 when the coincidence was considered to be insignificant, $C_f \neq 1$ when the coincidence was considered to be significant.

In this experiment, the 661.66 keV energy gamma rays from ^{137}Cs source were only used for calculating the efficiency ratio between the near and far positions. Therefore, Eq. (1.2) can be simplified by:

$$R_{Cs} = \frac{\varepsilon_{\gamma,n}}{\varepsilon_{\gamma,f}} \quad (1.6)$$

The corrected efficiency was calculated by:

$$\varepsilon_{\gamma,c}(E) =. \varepsilon_{\gamma,f}(E). R_{Cs} \quad (1.7)$$

The coincidence summing effect correction factor in Eq. (1.5) can be rewritten by Eq. (1.8):

$$C_f = \frac{\varepsilon_{\gamma,c}(E)}{\varepsilon_{\gamma,exp}(E)} \quad (1.8)$$

To evaluate the accuracy of the coincidence summing correction factor, Eq. (1.9) was converted from Eqs. (1.3) and (1.4) for calculating the activity of the standard source at the certified date:

$$A_x = \frac{{N_p}/{t_c}}{\varepsilon_\gamma I_\gamma e^{-ln2.t_d/T_{1/2}}} \quad (1.9)$$

The relative uncertainty of the efficiency and activity obtained by the error propagation equation presented in Eqs. (1.10) and (1.11):

$$\delta_{\varepsilon_\gamma}(\%) = \sqrt{\delta I_\gamma{}^2 + \delta N_p{}^2 + \delta_{C_f}^2 + \delta_A{}^2} \quad (1.10)$$

$$\delta_{A_x}(\%) = \sqrt{\delta I_\gamma{}^2 + \delta N_p{}^2 + \delta_{\varepsilon_\gamma}{}^2} \quad (1.11)$$

Where δI_γ, δN_p, δ_A, and δ_{C_f} are the relative uncertainty of the intensity of gamma-ray-I_γ, the gamma peak area -N_p, source activity-A, and coincidence correction factor-C_f respectively.

2. Experiments

The gamma spectrometry system used in this experiment consists of connected devices as shown in Figure 3. The gamma detector GMX30190 with high purity germanium crystal, which has 1.9 keV energy resolution at 1332.5 keV of ^{60}Co and supplied by HV power supply 3106D, is connected to the amplifier 2026, integrated Easy MCA 8K and the computer with the Gamma Vision 6.01 software.

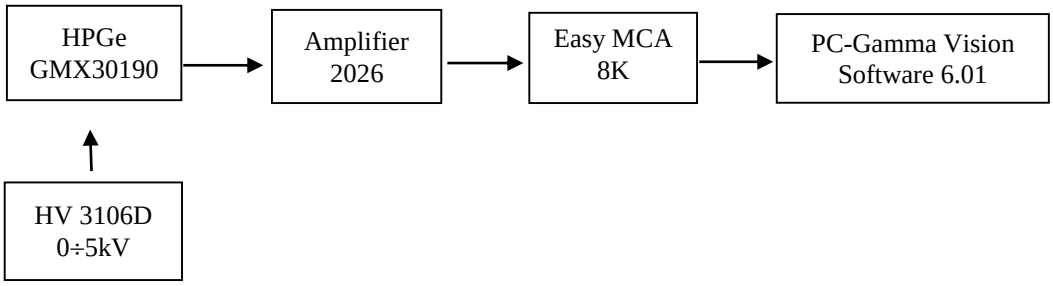

Fig 3. *Diagram of GMX30190 spectrometer system*

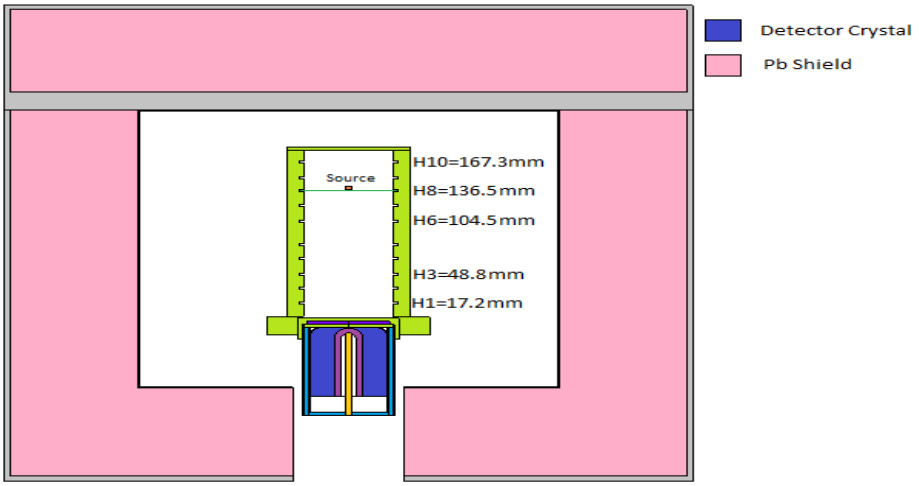

Fig 4. *Diagram of measurement geometry of GMX30190 detector*

The information of standard sources was listed in Table 1 with the relative uncertainty of activity was 3.2% (The uncertainty was released by the Manufacturer).

Table 1. *Parameters of two sets of the standard source used in the experimental procedure*

Isotope	Initial Activity(Bq)	Certificated date (dd/mm/yyyy)	Company
	No.1		
^{152}Eu	304.1	15/05/2002	An Ecker&Ziegler
^{133}Ba	37000	30/12/2014	U.S.NRC
^{109}Cd	37000	30/12/2014	U.S.NRC
^{137}Cs	9250	01/01/2015	U.S.NRC
^{57}Co	37000	30/12/2014	U.S.NRC
^{60}Co	37000	01/01/2015	U.S.NRC
	No. 2		
^{133}Ba	285.6	15/05/2002	An Ecker & Ziegler
^{137}Cs	259.0	15/05/2002	An Ecker & Ziegler
^{60}Co	367.0	15/05/2002	An Ecker & Ziegler

The No. 1 standard source was used for determining the experimental and corrected efficiency values and coincidence summing correction factors. Besides, the No. 2 standard source was utilized for evaluating the accuracy of the corrected efficiency.

The standard sources were measured at different geometries such as H1=17.2 mm, H3=48.8 mm, H6=104.5 mm, H8= 136.5 mm, and H10=167.3 mm by using a GMX30190

gamma spectrometer. The gamma spectra were processed to obtain the Net Area (N_p) of the concerned energy corresponds to the counting time (t_c). J.E. Cline has researched and concluded that the coincidence summing effect can be ignored with a source-detector distance of 100.0 mm (Cline, 1968). Therefore, the experimental measurements were carried out at H10=167.3mm can be used for calculating the reference efficiency values without correction. Then the efficiency curve was fitted by the least square method with a degree 5 polynomial function (G.L Molnar, 2002) to obtain the best efficiency curve with high accuracy at H10. The corrected and experimental efficiency were calculated for positions H8, H6, H3, and H1 by using Eqs. (1.3), (1.4), and (1.7). The coincidence summing correction factors were obtained by Eq. (1.8) and efficiency uncertainties obtained by using Eq. (1.10). The experimental value and relative uncertainty of the activity of the No. 2 standard source set were calculated by Eqs. (1.9) and (1.11) as well as compared with the certified activity in Table 1. The following section reports the results and discusses this experiment.

3. Results and discussion

Table 2. *The detail results were calculated at H8 and H6*

No.	Isotopes	Energy (keV)	$\varepsilon_\gamma *$ at H8 (experiment)	C_f at H8	ε_γ at H8 (corrected)	$\varepsilon_\gamma *$ at H6 (experiment)	C_f at H6	ε_γ at H6 (corrected)
1	^{133}Ba	81.00	5.869E-03	**0.976**	5.748E-03	8.246E-03	**0.993**	8.315E-03
2	^{109}Cd	88.00	6.291E-03	**0.995**	6.259E-03	9.274E-03	**0.978**	9.067E-03
3	^{57}Co	122.06	6.763E-03	**0.956**	6.471E-03	1.206E-02	**0.781**	9.445E-03
4	^{57}Co	136.47	6.443E-03	**0.943**	6.085E-03	1.131E-02	**0.783**	8.907E-03
5	^{133}Ba	276.40	3.127E-03	**1.019**	3.182E-03	4.539E-03	**1.053**	4.740E-03
6	^{133}Ba	302.85	2.888E-03	**1.014**	2.919E-03	4.204E-03	**1.046**	4.355E-03
7	^{133}Ba	356.01	2.508E-03	**1.014**	2.520E-03	3.700E-03	**1.001**	3.769E-03
8	^{133}Ba	383.85	2.386E-03	**1.000**	2.358E-03	3.580E-03	**0.971**	3.531E-03
9	^{137}Cs	661.66	1.491E-03	**1.000**	1.494E-03	2.238E-03	**1.000**	2.242E-03
10	^{60}Co	1173.20	9.571E-04	**0.968**	9.274E-04	1.417E-03	**0.981**	1.391E-03
11	^{60}Co	1332.50	8.562E-04	**0.987**	8.458E-04	1.277E-03	**0.993**	1.269E-03
12	^{152}Eu	344.29	2.650E-03	**0.958**	2.596E-03	3.859E-03	**1.017**	3.881E-03
13	^{152}Eu	443.89	1.964E-03	**1.047**	2.083E-03	2.891E-03	**1.099**	3.122E-03
14	^{152}Eu	778.92	1.274E-03	**1.022**	1.302E-03	1.883E-03	**1.038**	1.954E-03
15	^{152}Eu	867.38	1.143E-03	**1.041**	1.189E-03	1.765E-03	**1.012**	1.784E-03
16	^{152}Eu	964.11	1.067E-03	**1.019**	1.087E-03	1.607E-03	**1.016**	1.631E-03
17	^{152}Eu	1085.89	1.002E-03	**0.984**	9.858E-04	1.412E-03	**1.048**	1.478E-03
18	^{152}Eu	1112.08	9.426E-04	**1.026**	9.671E-04	1.400E-03	**1.036**	1.450E-03
19	^{152}Eu	1408.00	8.169E-04	**0.999**	8.165E-04	1.182E-03	**1.036**	1.225E-03

Where, $\varepsilon_\gamma *$, ε_γ are the efficiency values without and within the coincidence summing correction.

Table 3. *The detail results were calculated at H3 and H1*

No.	Isotopes	Energy (keV)	ε_γ * at H3 (experiment)	C_f at H3	ε_γ at H3 (corrected)	ε_γ * at H1 (experiment)	C_f at H1	ε_γ at H1 (corrected)
1	^{133}Ba	81.00	2.585E-02	**0.902**	2.456E-02	6.607E-02	**0.894**	5.909E-02
2	^{109}Cd	88.00	2.961E-02	**0.922**	2.729E-02	9.043E-02	**0.718**	6.490E-02
3	^{57}Co	122.06	3.403E-02	**0.804**	2.857E-02	9.464E-02	**0.718**	6.793E-02
4	^{57}Co	136.47	3.255E-02	**0.790**	2.662E-02	9.033E-02	**0.707**	6.387E-02
5	^{133}Ba	276.4	1.227E-02	**1.077**	1.320E-02	2.669E-02	**1.255**	3.349E-02
6	^{133}Ba	302.85	1.137E-02	**1.091**	1.210E-02	2.401E-02	**1.283**	3.080E-02
7	^{133}Ba	356.01	9.884E-03	**1.089**	1.045E-02	2.144E-02	**1.247**	2.673E-02
8	^{133}Ba	383.85	1.010E-02	**1.000**	9.788E-03	2.478E-02	**1.012**	2.508E-02
9	^{137}Cs	661.66	6.376E-03	**1.000**	6.213E-03	1.616E-02	**1.000**	1.616E-02
10	^{60}Co	1173.2	3.709E-03	**1.068**	3.786E-03	8.676E-03	**1.157**	1.004E-02
11	^{60}Co	1332.5	3.344E-03	**1.080**	3.468E-03	7.714E-03	**1.187**	9.154E-03
12	^{152}Eu	344.29	1.111E-02	**0.918**	1.076E-02	2.764E-02	**0.995**	2.750E-02
13	^{152}Eu	443.89	7.796E-03	**1.059**	8.663E-03	1.786E-02	**1.247**	2.227E-02
14	^{152}Eu	778.92	5.284E-03	**0.991**	5.389E-03	1.253E-02	**1.126**	1.411E-02
15	^{152}Eu	867.38	4.255E-03	**1.123**	4.897E-03	9.157E-03	**1.408**	1.289E-02
16	^{152}Eu	964.11	4.100E-03	**1.066**	4.459E-03	9.297E-03	**1.268**	1.178E-02
17	^{152}Eu	1085.89	3.960E-03	**1.064**	4.027E-03	9.352E-03	**1.142**	1.068E-02
18	^{152}Eu	1112.08	3.712E-03	**1.047**	3.949E-03	8.501E-03	**1.232**	1.047E-02
19	^{152}Eu	1408.00	3.137E-03	**1.045**	3.364E-03	6.806E-03	**1.299**	8.841E-03

The ratio between positions H10 and H8, H6, H3, H1 were expressed in Figure 4.

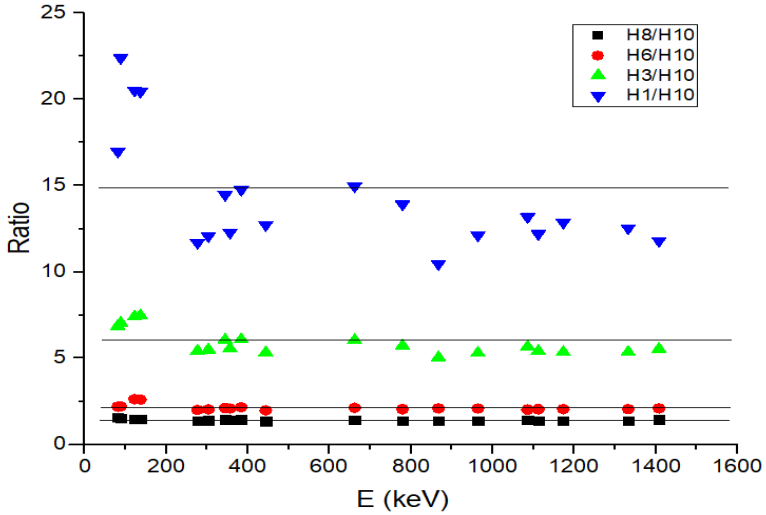

Fig 4. *The efficiency ratio between H10 and H8, H6, H3, H1*

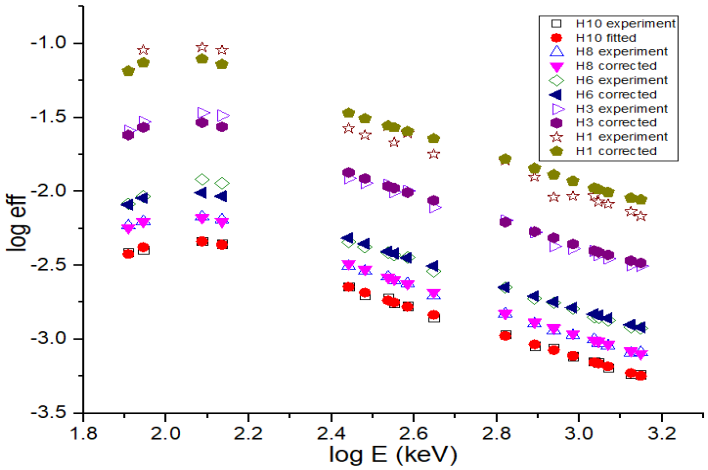

Fig 5. *The experimental and corrected efficiency values at H10, H8, H6, H3, and H1*

Table 4. *The activity values calculated for the No.2 standard sources by using the experimental efficiency values (without the coincidence summing effect correction)*

H3 Position					
No.	Isotope	Activity(Bq)	Uncertainty activity(Bq)	Certified activity(Bq)	Bias(%)
1	^{133}Ba	302.0	11.2	285.6	5.7
2	^{137}Cs	249.8	10.5	259	-3.6
3	^{60}Co	363.7	13.2	367	-0.9
H1 Position					
No.	Isotope	Activity (Bq)	Uncertainty activity(Bq)	Certified activity(Bq)	Bias(%)
1	^{133}Ba	320.0	12.4	285.6	12.0
2	^{137}Cs	253.0	11.0	259.0	-2.3
3	^{60}Co	382.0	14.1	367.0	4.1

Table 5. *The activity values calculated for the No.2 standard sources by using the corrected efficiency values (within the coincidence summing effect correction)*

H3 Position					
No.	Isotope	Activity(Bq)	Uncertainty activity(Bq)	Certified activity(Bq)	Bias(%)
1	^{133}Ba	274.3	10.2	285.6	-3.9
2	^{137}Cs	256.9	10.1	259.0	-0.8
3	^{60}Co	354.5	13.0	367.0	-3.4
H1 Position					
No.	Isotope	Activity (Bq)	Uncertainty activity(Bq)	Certified activity(Bq)	Bias(%)
1	^{133}Ba	273.6	10.6	285.6	-4.2
2	^{137}Cs	253.8	10.2	259.0	-2.0
3	^{60}Co	368.2	14.2	367.0	0.3

The results listed in Tables 2 and 3 pointed out that the coincidence effect tended to increase in the near positions. It was significantly higher at H1 and H3 positions than that at H6 and H8. Besides, the activities at H1 and H3 shown in Table 4 (without correction) were much more different than the activities revealed in Table 5 (within correction) and compared to certified activities in Table 1. The bias deviations of ^{133}Ba activities in Table 4 were 5.7% and 12.0% at H1 and H3, respectively, which accounted for -3.9% and -4.2% corresponding to H1 and H3 in Table 5. The corrected efficiency values at H1 and H3 were evaluated by using the No.2 standard source, the experimental activities were compared to certified activities in Table 5 showed that the results are in an agreement with the certified values. The bias deviations of activity results were in an acceptable range obtained -4.2%, -2.0 %, 0.3% and -3.9%, -0.8%, -3.4% at positions H3 and H1 corresponding to sources including ^{133}Ba, ^{137}Cs, and ^{60}Co.

4. Conclusion

In this paper, the results of efficiency correction by the Kafala approach demonstrated that the coincidence summing effect happened significantly at the near geometry, which can make a significant difference for experimental measurements. Therefore, the calibration procedure is necessary to determine the correct experimental efficiency for a gamma spectrometer. The Kafala approach is a simple and reliable method that can be applied for determining the coincidence summing correction factors with high accuracy, which is necessary for measuring the low-activity environmental sample at the near geometry as well as the activated sample in the INAA method. The bias deviation of the activity of ^{133}Ba source using the corrected efficiency was better than the one using the experimental efficiency. The bias deviations between the certified and measured activity of ^{133}Ba source were -3.9% at H3 = 48.8mm and -4.2% at H1 = 17.2 mm within correction, which accounted for 5.7% at H3 and 12% at H1 without correction.

❖ ***Conflict of Interest:*** *Authors have no conflict of interest to declare.*

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XÁC ĐỊNH HỆ SỐ HIỆU CHÍNH TRÙNG PHÙNG TRONG ĐO ĐẠC HIỆU SUẤT GHI THỰC NGHIỆM CỦA ĐẦU DÒ BÁN DẪN

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TÓM TẮT

Hiệu suất ghi của đầu dò bán dẫn là một đại lượng quan trọng ảnh hưởng đến kết quả thực nghiệm của phương pháp phân tích kích hoạt neutron dụng cụ. Đường cong hiệu suất ghi được xác định bằng phép đo đạc các nguồn chuẩn **^{37}Cs, ^{109}Cd, ^{133}Ba, ^{60}Co, ^{152}Eu**, **^{57}Co**. *Tuy nhiên, đối với các đồng vị phát ra từ hai tia gamma trở lên, hiệu ứng trùng phùng tổng xảy ra khi hai gamma có nguồn gốc từ một phân rã của hạt nhân kích thích được ghi nhận trong khoảng thời gian phân giải của đầu dò. Hiệu ứng trùng phùng tổng xảy ra đáng kể hơn tại các vị trí đo nguồn gần đầu dò, do đó giá trị hiệu suất đo đạc thực nghiệm sẽ sai khác đáng kể so với giá trị hiệu suất đúng. Trong bài báo này, hiệu ứng trùng phùng được nghiên cứu và tính toán tại bốn vị trí đo và được kiểm chứng tại hai vị trí đo của đầu dò bán dẫn. Hoạt độ của nguồn* ^{133}Ba *và* ^{60}Co *được xác định tại các vị trí H3 và H1 sử dụng giá trị hiệu suất đã hiệu chỉnh với độ lệch tương ứng là -3,9%, -4,2% đối với nguồn* ^{133}Ba *và độ lệch -3,4% và -0,3% đối với nguồn* ^{60}Co. *Kết quả nêu trên thì tốt hơn đáng kể kết quả được tính toán bằng giá trị hiệu suất thực nghiệm, các giá trị độ lệch lần lượt là 5,7%, 12,0% đối với* ^{133}Ba *và -0,9%, 4,1% đối với* ^{60}Co.

Từ khóa: hiệu chỉnh trùng phùng tổng; hiệu suất ghi; phương pháp Kafala