Precise Gamma-ray Spectrum Stabilization Using Full Spectral Information

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Abstract

One of the most important steps in recording, processing and analyzing gamma-ray spectra is stabilizing. Baseline shifts and gain changes of any origin including environmental condition, high voltage instability and amplifying not only cause drifts in gamma-ray spectrum, but also allow the spectrum to be noticeably distorted. In this work, a stabilization method based on full gamma-ray spectrum shape consideration is introduced for online as well as offline stabilizing of gamma-ray spectra. The method relies on sequentially comparing spectra measured during time windows starting from the first time window to the last, and finding the optimum shift for each time window using an artificial intelligence method so that the difference between the general shapes of the spectra is minimized. By utilizing spectra measured during shorter acquisition times and stabilizing them, a stable spectrum can be obtained for the longer acquisition time without the need to determine the detection system parameters, peak positions, or perform energy calibration. Subsequently, a sequence of stabilized spectra converging to the total stabilized spectrum is created. The proposed method has been applied to stabilize and analyze 14 MeV neutron induced prompt gamma-ray (PG) spectra of various samples measured using a 3×3 inch NaI detector. Additionally, the method has been used to stabilize the recorded spectra of

^{152}Eu and ^{60}Co gamma-ray point sources. The proposed method has efficiently stabilized all gamma-ray spectra, resulting in a significant improvement of the analysis results.

Keywords: Gamma-ray Spectroscopy, Spectrum drift, Stabilizing, Prompt gamma spectrum analysis, Artificial intelligence, Machine learning

Introduction

Stabilizing gamma-ray spectra is extremely crucial for both identification and quantification purposes, especially when the gamma-ray detector is a scintillator (Knoll, 2000). Without stabilizing, a gamma-ray spectrum is usually distorted during long-duration measurements due to baseline shifts and changes in the overall gain of the spectrometer (Waard, 1955; Dixon, 1963; Dudley and Scarpatetti, 1964). The distortion which appears as a drift, changing full width at half maximum of peaks and even changing the intensity of peaks may be caused by either amplification effects or ADC non-linearity effects of the spectrometer system (Metwally and Gardner, 2004; Wang et al., 2021). The spectrum drift, in particular, has been reported and discussed in different applications including Prompt Gamma (PG) neutron activation analysis (Metwally and Gardner, 2004; Zhong et al., 2018), analysis of environmental samples (Prietoa et al., 2020; Liu et al., 2022), radioisotope identification (Burr and Hamada, 2009; Alamaniotis and Jevremovic, 2015), etc. Many methods have been developed for online and offline stabilizing of gamma-ray spectra which work mainly based on controlling of a reference peak (Knoll, 2000). Among them a well-known method for online stabilizing is to fix the position of a well-resolved intense peak in the gamma-ray spectrum (Knoll, 2000). Fixing the position of a peak is typically done by monitoring the counts in two windows, one to the left and one to the right of the peak. The counts in the windows are compared to ensure that they are equal. If they are not equal, a feedback signal is sent to the amplification section to adjust the gain of the amplifier in the

appropriate direction and make them equal. The peak should be both well-resolved and intense, and it could be a peak that is inherently related to the measured sample or NORM (Naturally Occurring Radioactive Material) isotopes, an incorporated alpha emitter, or an isotope that has been intentionally inserted into the measuring system. Some developed offline methods also work based on fixing a well-resolved peak in a predefined channel (Casanovas, 2012) and continuously calibrating the detection system for correcting the different gains (Wang et al., 2021). In both cases there is a need for good counting statistics to first find the position of the peaks and then fix a peak position or energy calibration of the system. In many applications, it is not possible to find a well-resolved intense photopeak for stabilization, and introducing an external source to the detection system can heavily interfere with the main spectrum being analyzed, thereby changing the analysis results.

This work presents a new method to stabilize a spectrum measured over a long time period by utilizing the full gamma-ray spectral information from shorter time windows. An intended spectrum is sequentially stabilized using heuristic adaptive mutation based Particle Swarm Optimization (PSO) (Eberhart and Kennedy, 1995; Wang et al., 2013; Shahabinejad and Sohrabpour, 2017; Shahabinejad and Vosoughi, 2018) method from shorter time windows converging to a long-term measured spectrum. Since the method uses full spectrum information, every peak and part of the spectrum can contribute to stabilization, thereby enhancing the method's effectiveness. The proposed method is tested using various scenarios, containing gamma-ray spectra of point sources, and the analysis of fast neutron-induced PG spectra measured with a NaI detector.

Material and methods

Several measured spectra are used to validate the proposed method for stabilizing the gamma-ray spectra in this work. We first present our experimental setup and then describe the developed method in detail.

- **Experimental setup**

Figure 1 shows the implemented set-up for measuring neutron induced PG spectra of different samples. The neutron source is a Thermo Electron API-120 neutron generator, into which an associated alpha particles detector has been incorporated. The alpha detector is a 0.5 cm thick YAP (Yttrium Aluminum Perovskite):Ce crystal, with one side coated with a 1 mg/cm^2 layer of metallic Ag shield to protect it from elastically scattered deuterons and produced electrons. Additionally, the alpha detector has been located at an angle of 90^0 with respect to the incoming deuteron beam. The neutron generator produces 14.16 MeV neutrons by ^{3}H(d,n)^{4}He nuclear reaction. A number of these neutrons interact with the sample, the center of which is located 25 cm away from the tritium target and 15 cm away from the front surface of the 3"x 3" NaI detector, as shown in panel (a) of Figure 1. The sample container has dimensions of 10 cm × 10 cm × 10 cm, into which different samples are placed to measure the PG spectra. As illustrated in panel (b) of Figure 1, in order to register only those PG events that are in coincidence with alpha particles, the fast anode output from the gamma detector is guided through the CFD (Constant Fraction Discriminator) to the start of the TAC (Time-to-Amplitude Converter), while the fast output from the alpha detector is guided through the CFD and delay line to the TAC stop. The attenuated TAC output triggers the ADC (Analogue to Digital Convertor), which then records the amplified signals from the gamma detector in channel 1, as depicted in Figure 1 (b). The Nu DAQ Card PCI-9812/10 (AD Link Technology Inc., Taiwan) is utilized in this work as a flash ADC, and the data acquisition and storage are controlled by software installed on a personal

computer (PC). The modules used in this work are standard Ortec models, including the dual spectroscopy amplifier model 855, CFD model 2126, and TAC model 567.

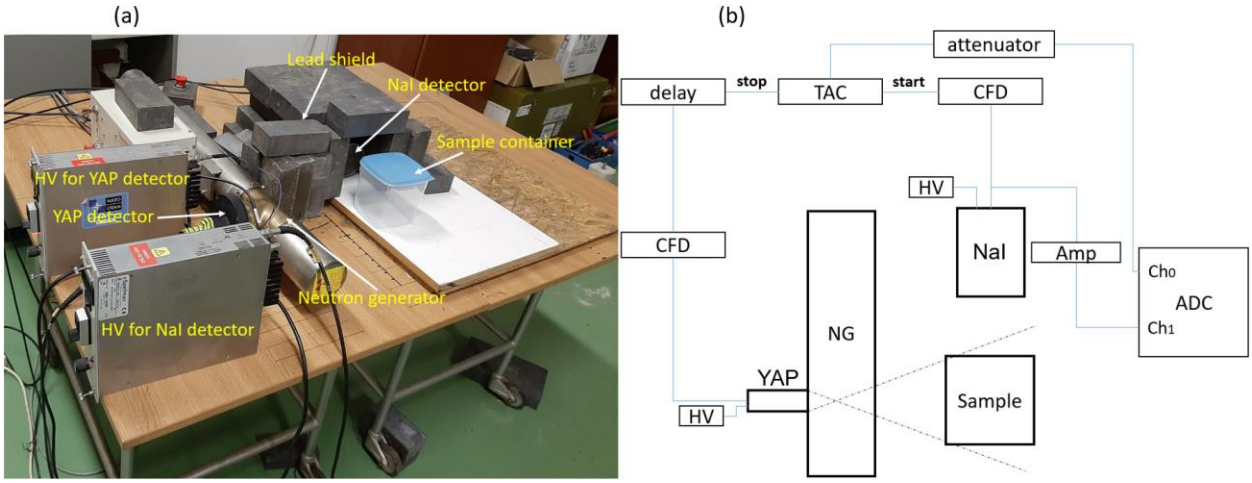

Figure 1: (a) Experimental setup and (b) schematic representation of the coincidence detection system circuit for measuring neutron induced PG spectra of different samples. In panel (b), abbreviations stand for: TAC (Time to Amplitude Convertor), CFD (Constant Fraction Discriminator, Amp (spectroscopy Amplifier) and ADC (Analogue to Digital Convertor)).

The PG spectra induced by fast neutrons are measured for five different samples and background in coincidence with alpha detector signals. The samples included Graphite (1.68 g/cm^3), Water (1 g/cm^3), Quartz sand (1.73 g/cm^3), Melamine (1.03 g/cm^3), and a mixed sample (1.29 g/cm^3) whose composition is presented in Table 1. The measurement time for each sample is approximately 2 hours, which is equivalent to registering 1.957×10^8 signals from the alpha detector and a neutron flux of around ~2×10^7 n/s in 4π. It is worth mentioning that the sample container is taken into account when measuring background radiation.

Table 1: The elemental composition of the mixed sample.

Compound	Weight fraction
Graphite	0.1473
Quartz sand	0.4806
Melamine	0.3721
Water	0

Figure 2 shows the measured total PG spectrum of graphite recorded in NaI detector, along with the TAC pulse height spectrum of coincidence events. The selected coincidence window for accepting the registered PG spectra and rejecting others has also been specified in the Figure 2 (b). In this work, the TAC range is set 200 ns, resulting in a coincidence window of 13.5 ns. It has previously been proven that the background radiation is effectively eliminated by coincidence counting of PG when using an associated alpha particle neutron generator (Obhodas et al., 2016). In other words, the produced neutrons are electronically collimated by detecting coincidences between alpha particles and gamma rays emitted from the inelastic scattering of 14 MeV neutrons. Figure 3 shows the PG spectrum of graphite for a coincidence window presented in Figure 2, measured over two hours, along with spectra for the first and last 10 minutes of the measurement. As can be seen in Figure 3, there is a relatively significant drift between the first and last 10 minutes of the two-hour-long measured PG spectrum of graphite in our work. The method presented in the next subsection will address this discrepancy.

In order to check the method with standard point sources, some experiments are conducted using ^{60}Co (0.3 kBq) and ^{152}Eu (22.1 kBq) radioactive point sources. The point sources are placed on the detector axis, 10 cm away from its front surface to record their spectra in different measurement times. To simulate the drift in gamma-ray spectra using point sources, the spectra are measured for different amplifier gains. The methods used to create the drifted spectrum and the stabilization process of drifted spectrum will be discussed in detail in the results section.

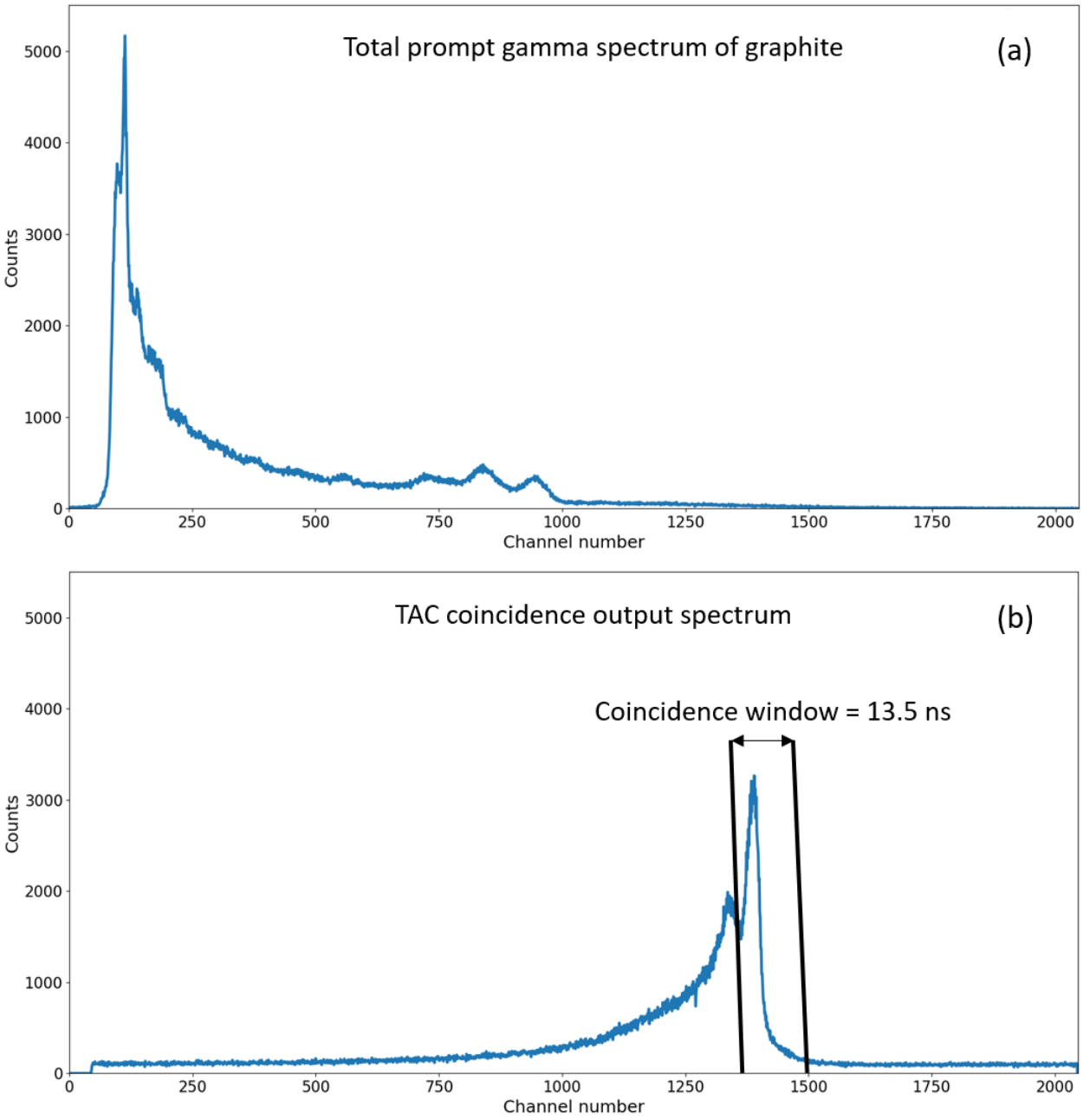

Figure 2: (a) Total PG spectrum of graphite measured with NaI detector, and (b) TAC pulse height spectrum of coincidence events. The TAC range is 200 ns.

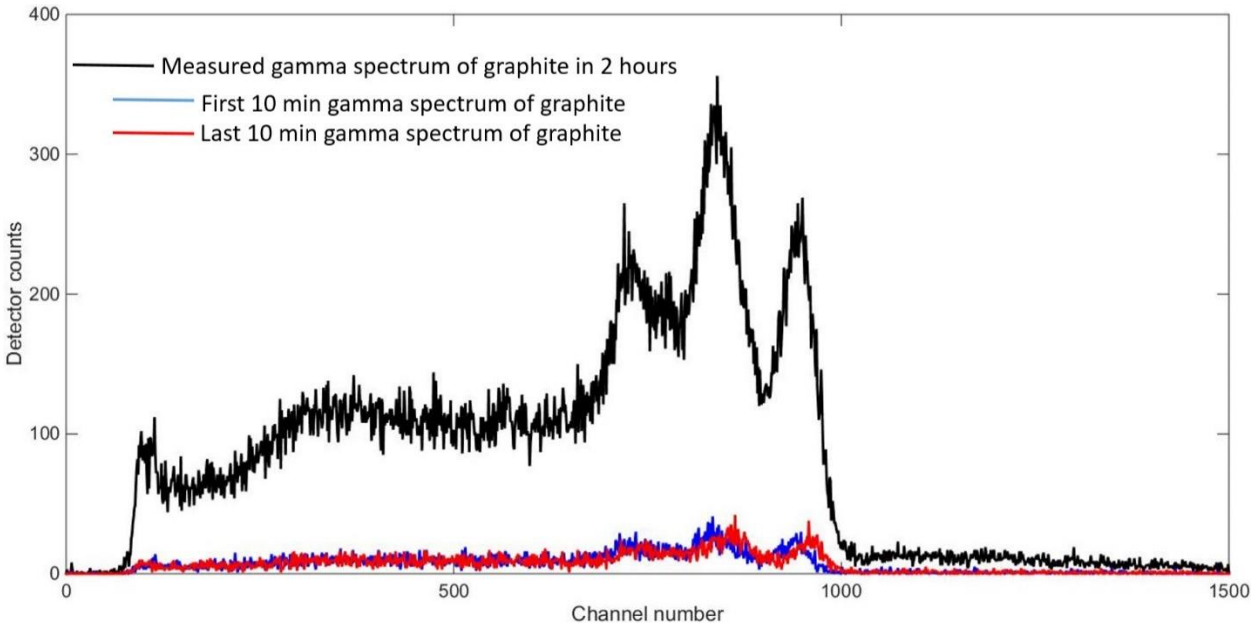

Figure 3: PG spectrum of graphite measured over two hours, along with spectra for the first and last 10 minutes of the measurement.

- **The proposed stabilizing method**

In gamma-ray spectroscopy, the theoretical deposited energy (E) of a gamma-ray could be correlated with the channel number (Ch) of an MCA through a linear relationship, as presented in Equation 1 (Knoll, 2000);

$$E = \mathrm{a}_0 + \mathrm{a}_1 \times Ch \qquad (1)$$

Where a_0 and a_1 coefficients are the zero offset and spectrum gain, respectively. Spectrum drift changes the channel number associated with a specific gamma line, resulting in changes to the a_0 and a_1 coefficients. By considering (s) and (d) superscripts to represent stabilized and drifted spectra, and utilizing Equation (1), we obtain:

$$1 = \frac{\mathrm{a}_0{}^{(d)} + \mathrm{a}_1{}^{(d)} \times Ch^{(d)}}{\mathrm{a}_0{}^{(s)} + \mathrm{a}_1{}^{(s)} \times Ch^{(s)}} \qquad (2)$$

By rearranging the relationship 2, we get to the relationship 3 below:

$$Ch^{(s)} = \frac{(\mathrm{a_0}^{(d)} - \mathrm{a_0}^{(s)}) + \mathrm{a_1}^{(d)} \times Ch^{(d)}}{\mathrm{a_1}^{(s)}} \qquad (3)$$

Considering the $\frac{(\mathrm{a_0}^{(d)} - \mathrm{a_0}^{(s)})}{\mathrm{a_1}^{(s)}} = \alpha$, and $\frac{\mathrm{a_1}^{(d)}}{\mathrm{a_1}^{(s)}} = \beta$, Equation 3 reduces to Equation 4;

$$Ch^{(s)} = \alpha + \beta \times Ch^{(d)} \qquad (4)$$

Therefore, the channel numbers of a stabilized spectrum ($Ch^{(s)}$) could be obtained by rebinning the channels of the drifted spectrum ($Ch^{(d)}$) through the determination of the α and β parameters. The contribution of the α parameter has been considered negligible in all previous studies of stabilizing methods based on a reference peak. To correct the counts of the drifted spectrum, Wang et al. (Wang et al., 2021) have applied the system transformation theory of random signals to transfer the recorded spectra from channel domain to energy domain. According to this theory, the theoretical detector counts in each energy ($N(E)$) could be obtained from the recorded count of corresponding channel in the MCA ($N(Ch)$), through Equation 5;

$$N(E) = \frac{N(Ch)}{dE/dCh} \qquad (5)$$

By combining equations (1) and (5), one may obtain the relations between the detector counts of stabilized and drifted spectra as given below:

$$N^{(s)}\left(Ch^{(s)}\right) = \frac{1}{\beta} \times N^{(d)}\left(Ch^{(d)}\right) \qquad (6)$$

The β parameter in Equation 6 is the same as the one in Equation 4. Hence, by disregarding the α parameter in Equation 4, the stabilization of gamma-ray spectra can be accomplished efficiently by determining the exact value of the β parameter.

The adaptive mutation based PSO introduced, developed and verified in other work (Wang et al., 2013; Shahabinejad and Sohrabpour, 2017; Shahabinejad and Vosoughi, 2018; Shahabinejad and Vosoughi, 2019), is used for finding the β parameter in this work. PSO (Eberhart and Kennedy, 1995) is a well-known artificial intelligence method that mimics social behaviors found in nature in order to address complex mathematical optimization problems (Shahabinejad and Sohrabpour, 2017). Similar to other evolutionary algorithms, PSO is a search algorithm that operates on a population-based model. It begins by creating an initial set of individuals (i.e. solution candidates), referred to as particles, which are randomly dispersed throughout the search space (Eberhart and Kennedy, 1995). A particle in PSO represents a potential solution for a search problem involving multiple dimensions. It possesses both a position (referred to as the β parameter in this study) and a velocity. The set of potential solutions moves through the search space by employing standard dynamics to explore a global optimum for a cost function. PSO guides potential solutions towards the global optimum by remembering the best position discovered by all potential solutions and the best positions discovered by each individual potential solution during the search process. The velocity v_i and the position β_i of the ith potential solution are updated in t+1 iteration according to Equations (7) and (8), respectively (Eberhart and Kennedy, 1995; Shahabinejad and Sohrabpour, 2017):

$$v_i(t+1) = w.v_i(t) + c_1.r_1.(pbest_i(t) - \beta_i(t)) + c_2.r_2.(gbest(t) - \beta_i(t)), \quad (7)$$

$$\beta_i(t+1) = \beta_i(t) + v_i(t+1) \quad (8)$$

Where, acceleration constants c_1, c_2 and inertia weight, w, are predefined parameters set by the user. Additionally, r_1 and r_2 represent the uniformly generated random numbers between 0 and 1. The previous best position of the ith potential solution is denoted by $pbest_i$, and the global best potential solution discovered by all potential solutions so far is referred to as $gbest$.

To achieve gamma-ray spectrum stabilization in this study, PSO aims to identify a global optimum for the single objective optimization problem presented below.

$$\underset{\beta}{\text{Minimize}} \left\{ \frac{1}{n} \| \boldsymbol{N}^{(ref)} - \boldsymbol{N}^{(s)} \|_1 \right\} \qquad (9)$$
$$\text{w.r.t.} \qquad 0.8 \le \beta \le 1.2$$

Where, $\boldsymbol{N}^{(ref)}$ vector could be, for instance, the spectrum recorded during the first 10 minutes of a long-term measurement and $\boldsymbol{N}^{(s)}$ is the stabilized version of a drifted gamma-ray spectrum in each iteration of the algorithm, updated with the new value of β, according to the relations 4 and 6. The most promising aspect of $\boldsymbol{N}^{(ref)}$ is that it can be updated based on upcoming measurements and utilized for all future measurements. An example case of updating $\boldsymbol{N}^{(ref)}$ will be provided in results section. A relatively wide range was considered for randomly initializing the β parameter in this work, specifically a range of 0.8 to 1.2. This range represents a potential 20% drift in the gamma-ray spectrum, which is a considerable value. In Equation 9, $\|.\|_1$ refers to the sum of the absolute values of the elements in a vector and n is the length of the vector. It has to be noted that the first channels near the thresholds are deleted for calculating the cost function during the stabilization process, as shifting the spectra makes large errors in this area.

Our work also employs the adaptive mutation based PSO, which has been introduced and utilized by researchers (Wang et al., 2013; Shahabinejad and Sohrabpour, 2017; Shahabinejad and Vosoughi, 2018). This method addresses the issue in basic PSO where potential solutions get stuck in local optima due to the small values of the second and third terms of equation 7 as increasing number of generations. The method involves applying mutations to *gbest* and $pbest_i$, if they do not show improvement over a predefined number of updates.

In the development of the gamma-ray spectrum analysis algorithm using PSO, a chaotic inertia

weight is employed, wherein a chaotic mapping is applied to set the inertia weight coefficient (Shahabinejad and Sohrabpour, 2017; Feng et al., 2007). The developed algorithm uses a swarm size of 20, with c_1 and c_2 values of 2.0 each. Finally, the final β value is obtained by selecting the best solution with the lowest cost among five independent runs of the algorithm.

The developed code has been executed on a 2.6 GHz Intel Core i7 PC. Each run of the developed code takes less than 10 seconds to perform different stabilizations in this work.

Results and discussion

To verify the ability of the algorithm in finding optimal β value discussed earlier, the measured spectra of ^{152}Eu and ^{60}Co point sources are first stabilized under three different scenarios. In the first scenario, the spectrum of ^{152}Eu source is measured using three different fine gains of amplifier (3.8, 4.0 and 4.4) for 200 seconds each, as shown in Figure 4. The spectrum that corresponds to the gain of 4.0 is considered the reference spectrum ($\boldsymbol{N}^{(ref)}$ in Equation 9), and it is checked how well the algorithm can stabilize the drifted spectra to match the reference. The resulting β values are 1.0418 and 0.9195, respectively, and the stabilized spectra are compared to the reference spectrum in Figure 5.

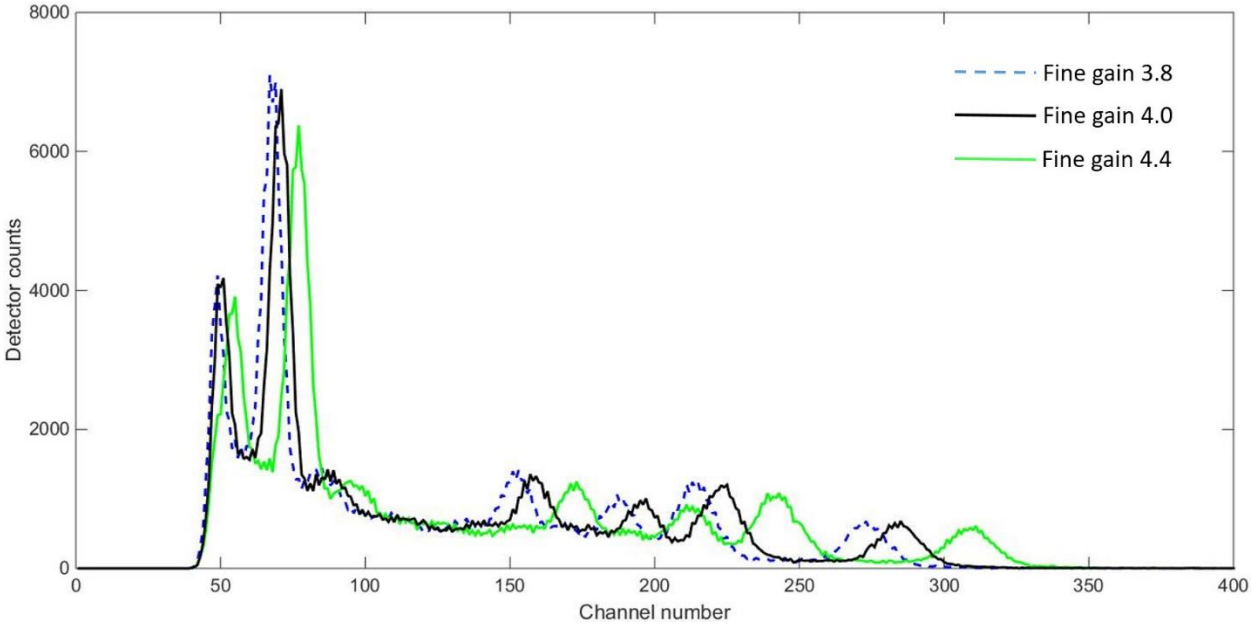

Figure 4: Measured spectra of ^{152}Eu point source with different gains. The spectrum related to gain 4.0 is considered as reference spectrum and others as drifted spectra.

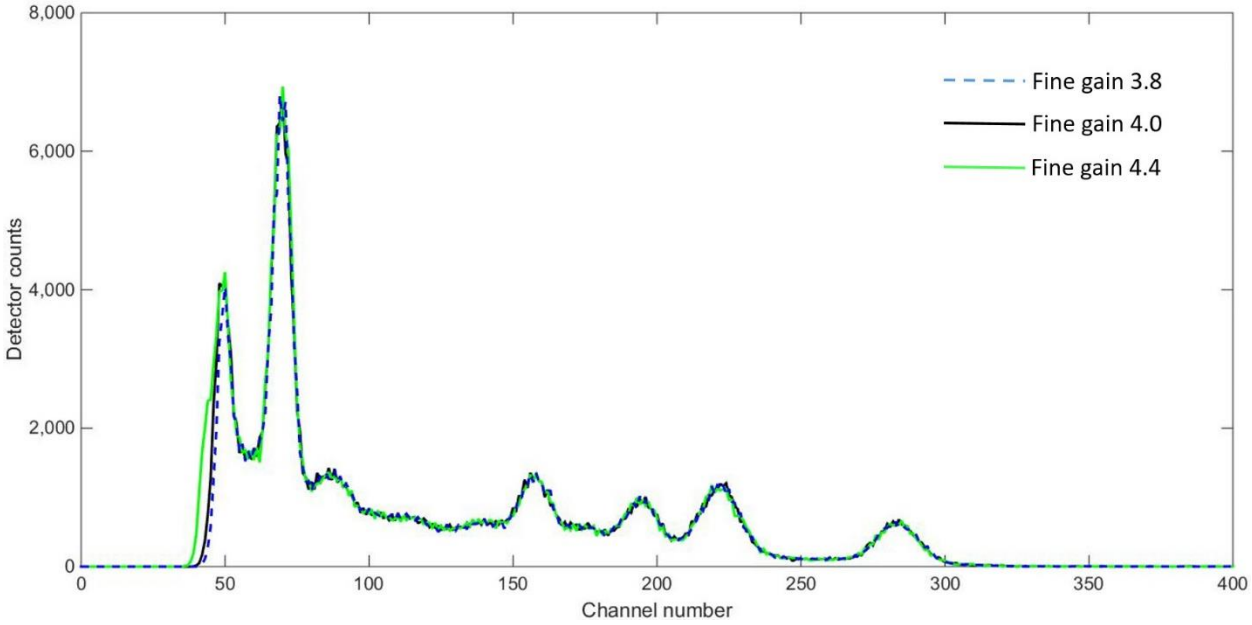

Figure 5: The stabilized spectra of ^{152}Eu for different gains (drifts) presented in Figure 4.

The integrated counts under major peaks are the same for different gains in the stabilized spectra. As can be seen in Figure 5, the proposed method is precise in correcting the drift except for near threshold value, which is inevitable due to the shift in spectra. In fact, the algorithm does not

consider channels below 60 when calculating the cost function.

The second scenario presents a real-world example of common gamma-ray spectroscopy, where the spectrum of ^{152}Eu is measured for 200 seconds, using a gain of 4.0 and the same experimental setup, four days after the initial measurement. Figure 6 compares the obtained spectrum to the reference spectrum from the first day (shown in Figure 5 with Fine gain 4.0) and the stabilized spectrum. As seen in Figure 6, the reference spectrum from day 1 has been successfully applied to stabilize the spectrum from another day.

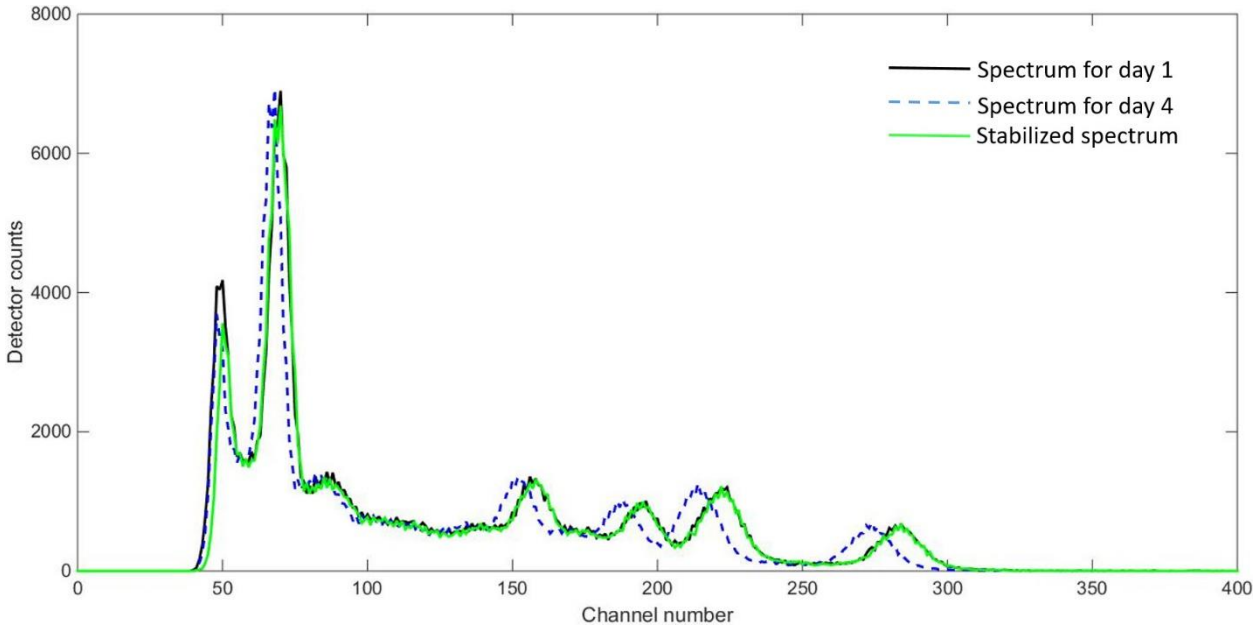

Figure 6: The measured spectra of ^{152}Eu in two different days with the same setup along with the stabilized spectrum.

In the third scenario of testing the algorithm using point sources, which is the main concept of this work for spectrum stabilization, the ^{60}Co spectrum is measured for 200 seconds with and without drift. To simulate real drift in long-term measured spectra, the 200 seconds are divided into ten 20-second measurements. Similar to real long-term measurements, where there is usually no drift in the first time windows, the fine gain of amplifier does not change in the first five time

windows considered in this work. After that, the gain is gradually changed. The gains considered for 10 measurements are 4.0, 4.0, 4.0, 4.0, 4.0, 4.1, 4.2, 4.3, 4.4, and 4.5. The total 200-second drifted spectrum is the sum of the spectra obtained using these gains. Figure 7 shows the recorded ^{60}Co spectrum in the first (gain 4.0), eighth (gain 4.3), and tenth (gain 4.5) time windows. As can be seen in Figure 7, the spectra obtained in 20-second time windows are highly variant and have poor statistics.

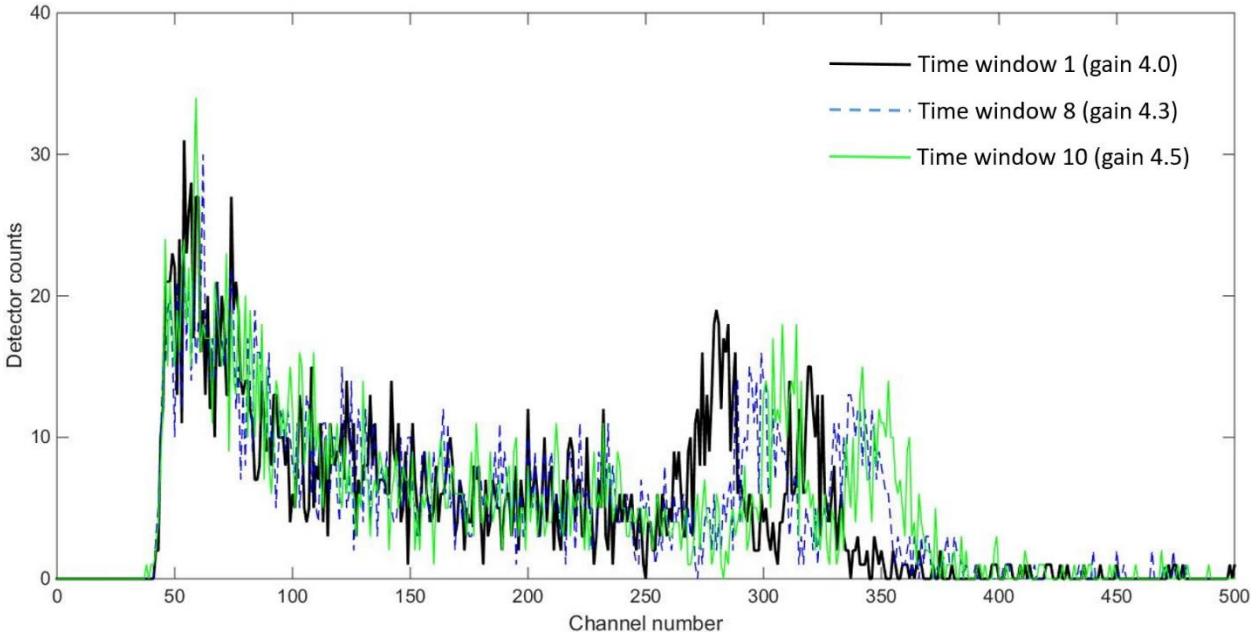

Figure 7: Measured spectra of ^{60}Co point source in different time windows.

The algorithm considers the spectrum from the first time window as $\boldsymbol{N}^{(ref)}$ and stabilizes the second time window with respect to it. The sum of the stabilized spectra is a 40-second-long measured spectrum without any drift. Then, the mean of the two stabilized spectra is considered as the new updated $\boldsymbol{N}^{(ref)}$ and the spectrum from the third time window is stabilized. In this work, the $\boldsymbol{N}^{(ref)}$ is updated if the calculated β value falls within a 0.02 margin of error from 1; otherwise, it remains unchanged. The stabilized spectrum is added to the previous stabilized ones to create a 60-second-long measured spectrum. This process continues until the final time window. The

obtained β values are 0.9982, 1.0047, 1.0048, 1.0046, 0.9777, 0.9634, 0.9379, 0.9254, and 0.9201 for the second to tenth time windows, respectively. The interesting point is that since all the spectra from the first five time windows are obtained with the same gain, the first four obtained β values are approximately 1. The final stabilized spectrum, compared to the drifted spectrum and the 200-second long measured spectrum with gain 4.0, has been depicted in Figure 8.

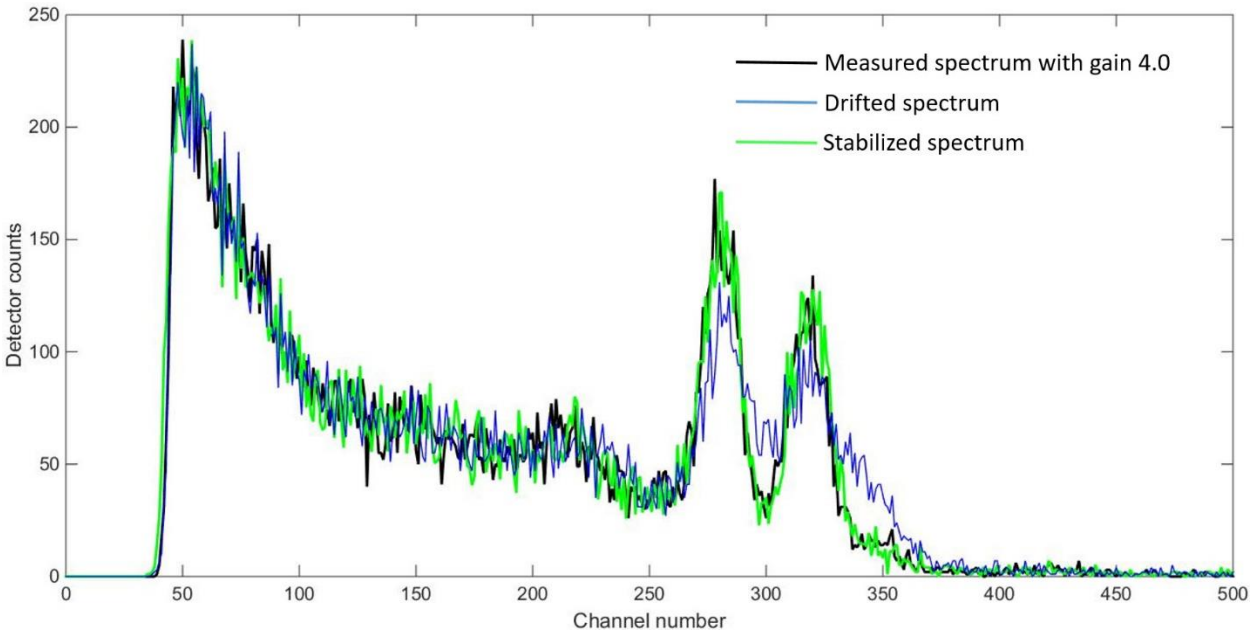

Figure 8: The measured spectrum of ^{60}Co in 200 seconds with and without drift along with the stabilized one.

As evident from figure 8, the method presented in this work has efficiently stabilized a highly distorted gamma-ray spectrum. The capability of this method to stabilize spectra in small time windows makes it particularly suitable for real-time online stabilization of gamma-ray spectra. However, it is important to note that achieving online stabilization of gamma-ray spectra requires the implementation of a feedback algorithm control which is not discussed in this work.

The verified method is applied to stabilize 2 hour-long measured PG spectra of samples in 10 min time windows. Figure 9 shows the stabilized spectra of graphite and mixed samples

compared to their raw measured spectra. While one may consider the drifts in Figure 8 to be negligible, they can result in significant errors when analyzing gamma-ray spectra using the least-squares method. To demonstrate this, the stabilized and drifted PG spectra of mixed sample are analyzed using library least square method (Obhodas et al., 2016). Library least square method is a technique to identify and quantify the radioactive isotopes present in a sample based on their emitted gamma-ray energies. This method involves comparing the measured gamma-ray spectrum from the sample to a library or database of known gamma-ray spectra associated with specific isotopes. The method employs a least squares optimization approach to find the best-fit combination of isotopes that can reproduce the measured spectrum. In this work, the library spectra consist of the PG spectra of graphite, water, quartz sand, and melamine compounds. Table 2 presents the calculated weight fractions (W.F.) and corresponding standard deviations (S.D.), along with their absolute errors in comparison to the real weight fractions of Table 1.

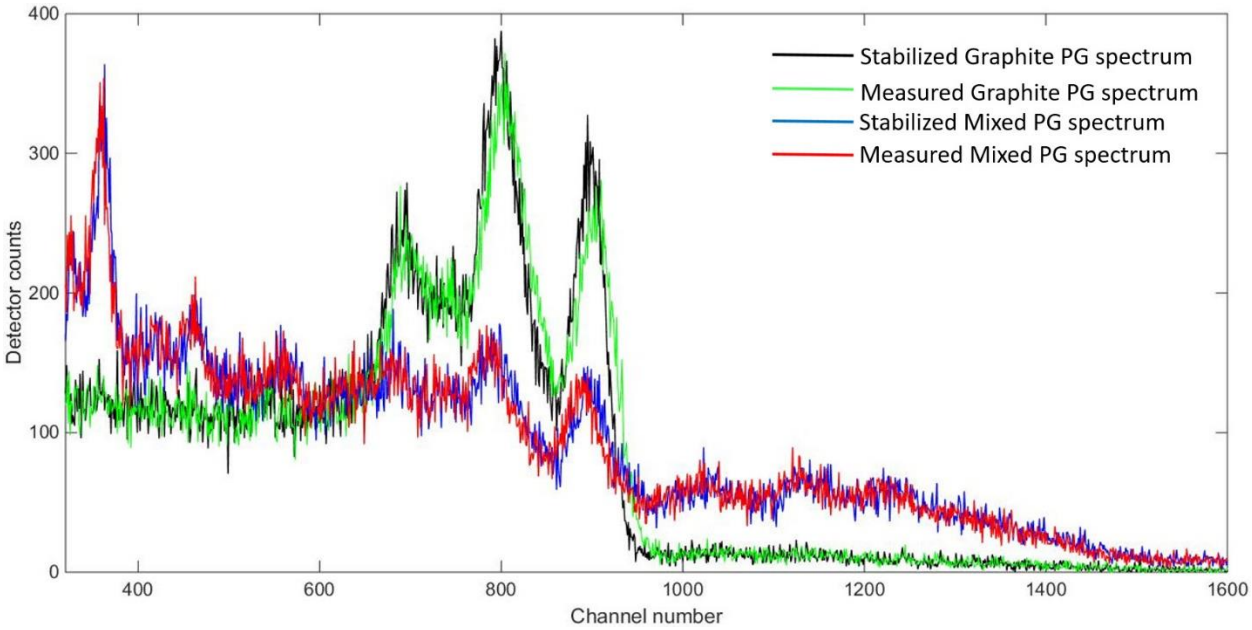

Figure 9: The stabilized and measured raw PG spectra of Graphite and Mixed sample whose composition presented in Table 1.

Table 2: Library least square analysis results of stabilized and raw measured PG spectra

Analysis results						
	Stabilized spectra			Raw measured spectra		
Compound	W.F.	S.D.	Error (%)	W.F.	S.D.	Error (%)
Graphite	0.1234	0.0103	16.2	0.0797	0.0119	45.9
Water	-0.0437	0.0149	-	-0.0448	0.0151	-
Sand	0.5127	0.0056	6.7	0.5015	0.0060	4.3
Melamine	0.3455	0.0113	7.2	0.4235	0.0119	14.3

In addition to promising results for radioisotopes presented earlier, Table 2 shows that the presented method can be utilized for improving the analysis results in gamma-ray spectroscopy.

Conclusion

A new method based on the general shape of gamma-ray spectrum was introduced for stabilizing gamma-ray spectra. The method exploits particle swarm optimization, which belongs to the realm of the artificial intelligence and machine learning, to find a β parameter in search space for correcting the drift in different gamma-ray spectra of radioisotopes and prompt gamma-ray neutron activation analysis.

The proposed method has the following advantages:

- Even in low statistics, the algorithm can efficiently stabilize the spectra by considering the general shape of the spectrum for stabilization, in contrast to common methods that use specified peaks and continuous calibration of the detection system.
- Algorithm can stabilize the spectra, even spectra recorded in different days or different amplification gains, by considering a sub-measured spectrum as the reference stable spectrum and shifting other spectra to match it.
- Since the proposed method does not change any parameters of the detection system and

works separately with the registered discrete gamma spectrum of MCA in predefined time windows, it can be applied in both analogue and digital spectroscopy for real time stabilizing or offline stabilizing.

- The proposed method can be also applied to all type of gamma-ray detectors as it utilizes the measured spectra in lower time regions to stabilize the long-measured spectra of the same detector.

Acknowledgments

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References:

Alamaniotis, M., and Jevremovic, T., 2015. Hybrid Fuzzy-Genetic Approach Integrating Peak Identification and Spectrum Fitting for Complex Gamma-Ray Spectra Analysis, IEEE transactions on nuclear science, 62, 1262.

Burr, T. and Hamada, M., 2009. Radio-isotope identification algorithms for NaI spectra, Algorithms, 2, 339–360.

Casanovas, R., Morant, J.J. and Salvadó, M., 2012. Temperature peak-shift correction methods for NaI(Tl) and LaBr3(Ce) gamma-ray spectrum stabilization, Radiation Measurements, 47, 588-595.

Dixon, I., 1963. Stabilisation of a gamma-ray spectrometer, Nuclear instruments and methods, 25, 26-28.

Dudley, R.A. and Scarpatetti, R., 1964. Stabilization of a gamma scintillation spectrometer

against zero and gain drifts, Nuclear instruments and methods, 25, 297-313.

Eberhart, R., and Kennedy, J., 1995. A new optimizer using particle swarm theory, In Proceedings of the Sixth International Symposium on Micro Machine and Human Science, 39-43.

Feng, Y., Teng, G.F., Wang, A.X., Yao, Y.M., 2007. Chaotic Inertia Weight in Particle Swarm Optimization, Second International Conference on Innovative Computing, Information and Control, IEEE, 475.

Knoll, G.F., 2000. Radiation Detection and Measurement, John Wiley & Sons, New York.

Liu, C., Benotto, M., Ungar, K., and Chen, J., 2022. Environmental monitoring and external exposure to natural radiation in Canada, Journal of Environmental Radioactivity, 243, 106811.

Metwally, W.A. and Gardner, R.P., 2004. Stabilization of prompt gamma-ray neutron activation analysis (PGNAA) spectra from NaI detectors, Nuclear Instruments and Methods in Physics Research A, 525, 518–521.

Obhodas, J., Sudac, D., and Valkovic, V., 2016. Development of the Quality Assurance/Quality Control Procedures for a Neutron Interrogation System, IEEE Transactions on Nuclear Science, 63, 1544.

Prieto, E., Jabaloyas, E., Casanovas, R., Rovira, C., Salvadó, M., 2020. Set up of a gamma spectrometry mobile unit equipped with LaBr3(Ce) detectors for radioactivity monitoring, Radiation Physics and Chemistry, 168, 108600.

Shahabinejad, H. and Sohrabpour, M., 2017. A novel neutron energy spectrum unfolding code

using particle swarm optimization, Radiat. Phys. Chem., 136, 9-16.

Shahabinejad, H. and Vosoughi, N., 2018. Analysis of complex gamma-ray spectra using particle swarm optimization, Nucl. Instrum. Methods Phys. Res. A, 911, 123-130.

Shahabinejad, H. and Vosoughi, N., 2019. SGSD: A novel Sequential Gamma-ray Spectrum Deconvolution algorithm, Annals of Nuclear Energy, 132, 369-380.

Waard, H. de, 1955. Stabilizing scintillation spectrometers with counting-rate-difference feedback, Nucleonics, 13, 36.

Wang, C. , Zhang, Q., Sun, Y., Liu, J., Zhou, Y., Zhang, M., 2021. A new numerical correction method for gamma spectra based on the system transformation theory of random signals, Applied Radiation and Isotopes, 172, 109671.

Wang, H., Wang, W., Wu, Z., 2013. Particle swarm optimization with adaptive mutation for multimodal optimization, Applied Mathematics and Computation 221, 296–305.

Zhong, X., Chen, L., Wang, B., and Jin, G., 2018. A spectrometer with baseline correction and fast pulse pile-up rejection for prompt gamma neutron activation analysis technology, Review of scientific instruments, 89, 123504.