Determination of Performance Specifications of Gamma Spectrometry Systems in Universiti Teknologi Malaysia

ABUBAKAR USMAN

A dissertation submitted in partial fulfilment of the
requirements for the award of the degree of
Master of Science

Faculty of Science
Universiti Teknologi Malaysia

OCTOBER, 2019

DEDICATION

This thesis is dedicated to my father, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time.

ACKNOWLEDGEMENT

Thank Almighty Allah, the Omnipotent, Omnipresent, and Omniscient, He who spare my life to accomplished this work. May the peace and blessings of Allah (S.W.T) be upon the noble prophet Muhammad (S.A.W), the members of his family, his companions and all those who proceed on his path.

First and Foremost, I would like to offer my deepest gratitude to my supervisor, Dr. Norehan Binti Mohd Nor for her advice, patient, encouragement, guidance, constant support and quick response from initial to final level which enable me to develop an understanding of this research.

I wish to appreciate my gratitude to the University of Teknologi Malaysia at large for having conducive learning atmosphere. I wish also, to acknowledge the support of Technical staff at the physics department, UTM.

Notwithstanding, my sincerest gratitude goes to Sokoto State University (SSU) and Tertiary Education Trust Fund (TETFUND) for offering financially support for my study. I’m greatly indebted and appreciate to my parent (Alh. Abubakar K/Rini and Modibbo Atika Saidu) for their fervent prayer, courage and support. Finally, thank goes to my friends and entire family that made this journey more delightful.

ABSTRACT

High purity germanium (HPGe) detector received a research attention in radiation measurement area. It is the most distinguished radiation measurement instrument and have excellent energy resolution. Their demands are kept on increasing with modernization in industries. Typically, good working performance of the system is totally depending on warranted specifications offered by its manufacturer. This study aims to determine the working condition and compare the performances of two gamma-ray spectrometry (GS1 and GS2) in nuclear laboratory, UTM. The GS1 consist of n-type closed end coaxial HPGe detector and GS2 consist of p-type closed end coaxial HPGe detector. The specification such as resolution, peak-to-Compton ratio, peak shapes and relative efficiency are measured using American National Standard Institute and Institute for Electrical and Electronic Engineers ANSI/IEEE 325-1996 standard procedure in order to have the same meaning with the manufacturers. Perfect Gaussian peaks, counting efficiency and time measurement were also determined. The result obtained from the specification test, shows the measured values fall within the recommended limit. GS1 found to have high resolution 1.9 keV as compared with GS2 with 1.69 keV, while GS2 shows higher counting efficiency detection and peak-to-Compton ratio. Also, the skew factor checked in both GS1 and GS2 is found to be 1.0 which presented well defined Gaussian peaks. Dead time effect found to be decreased with the increased in gamma-ray energy in both detectors. It concluded that based on the results, the performance of the two coaxial HPGe detectors in nuclear laboratories UTM are in good working condition. The significance of this study is to ensure that the detectors are keep control and monitoring for future use. This will improve the efficacy potential performance of these two gamma ray spectrometry systems.

ABSTRAK

Pengesan hiper-tulen germanium (HPGe) mendapat perhatian di dalam bidang penyelidikan yang melibatkan pengukuran radiasi. Ia adalah alat pengukuran radiasi yang paling terkenal dan mempunyai peleraian tenaga yang sangat baik. Permintaan terhadap alat ini terus meningkat dengan pemodenan dalam industri. Biasanya, prestasi kerja bagi sistem yang baik bergantung sepenuhnya kepada spesifikasi yang ditawarkan oleh pengilang. Kajian ini bertujuan untuk menentukan keadaan kerja dan membandingkan prestasi dua spektrometri sinar gama (GS1 dan GS2) di makmal Nuklear, UTM. GS1 terdiri daripada pengesan HPGe sepaksi hujung tertutup jenis-n dan GS2 terdiri daripada pengesan HPGe sepaksi hujung tertutup jenis-p. Spesifikasi seperti peleraian, nisbah puncak-ke-Compton, bentuk puncak dan kecekapan relatif diukur menggunakan prosedur ujian piawaian American National Standard Institute dan piawaian institut untuk kejuruteraan Elektrik dan Elektronic ANSI/IEEE 325-1996 supaya ia selaras dengan prosedur ujian yang dilakukan oleh pengilang. Puncak Gaussian sempurna, kecekapan pembilang dan ukuran masa juga ditentukan. Hasil yang diperolehi dari ujian spesifikasi, menunjukkan nilai diukur telah jatuh dalam had yang disyorkan. GS1 didapati mempunyai peleraian tinggi iaitu 1.9 keV berbanding dengan GS2 dengan 1.69 keV, manakala GS2 menunjukkan mempunyai pengesanan kecekapan pembilang dan nisbah puncak-ke-Compton yang lebih tinggi. Selain itu, faktor pencongan yang diperiksa dalam kedua-dua GS1 dan GS2 didapati mempunyai nilai 1.0 yang menunjukkan puncak gaussian sempurna. Kesan masa mati didapati berkurangan dengan peningkatan tenaga sinar gama dalam kedua-dua pengesan. Kesimpulannya, berdasarkan hasil kajian, prestasi kedua-dua pengesan HPGe sepaksi di makmal Nuklear, UTM berada dalam keadaan baik. Kepentigan Kajian ini adalah untuk memastikan bahawa pengesan depat dikawal dan dipantau untuk kegunnan masa depan. Hal ini akan meningkatkan prestasi keberkesanan kedua-dua sistem spektrometri sinar gama ini.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ADC	-	Analog Digital Converter
ANSI/IEEE	-	American National Standard Institute/ Institute for Electrical and Electronic Engineers
CCA	-	Compton Continuum Correction Area
CERT	-	Centre for Energy Research Training
CIAE	-	China Institute of Atomic Energy
DSP	-	Digital Signal Processing
FoM	-	Figure of Merit
FWHM	-	Full Width Half Maximum
FWTM	-	Full Width Tenth Maximum
FWFM	-	Full Width Fifty Maximum
GS1	-	Gamma Spectrometry in Block C
GS2	-	Gamma Spectrometry in T05
HPGe	-	High Purity Germanium Detector
HVS	-	High Voltage Source
IAEA	-	International Atomic Energy Agency
IUPAC	-	International Union Pure and Applied Chemistry
LabSOC	-	Laboratory Source less Object Calibration
LT	-	Live Time
MCA	-	Multichannel Analyzer
MDA	-	Minimum Detectable Activity
NASA	-	National Aeronautics and Space Administration
NORM	-	Naturally Occurring Radioactive Materials
NaI	-	Sodium Iodide
NIST	-	National Institute of Standards Technology
P/C	-	Peak-to-Compton Ratio
PC	-	Personal Computer
QA	-	Quality Assurance
ROI	-	Region of Interest
RT	-	Real Time

UTM	-	Universiti Teknologi Malaysia
US.NRC	-	United State National Research Council
WHO	-	World Health Organization

LIST OF SYMBOLS

λ	-	Decay constant
e	-	Euler's constant
t	-	Time taken
$t_{1/2}$	-	Half life
E_{γ}	-	Gamma-ray energy
E_b	-	Binding energy
E_e	-	Recoil energy
E_{γ^1}	-	Scattering gamma-ray
h	-	Plank's constant
θ	-	Scattering angle
m_o	-	Rest mass
C	-	Speed of light
λ_i	-	Initial photon wavelength
λ_f	-	Reflected photon wavelength
n^+	-	Lithium contact
p^+	-	Ion implantation contact
$N._{\gamma}$	-	Number of detected gamma-ray
S_i	-	Silicon
μ	-	Linear coefficient
$B_r(\gamma)$	-	Branch ratio
ε_{abs}	-	Absolute efficiency
ε_{intrs}	-	Intrinsic efficiency
ε_{rel}	-	Relative efficiency
A	-	Activity
d	-	Source detector distance
Ω	-	Solid angle
R	-	Radius of the detector crystal
Δ	-	Resolution
τ	-	Dead time

Z	-	Atomic number
$S_{0.1}$	-	Ratio of tenth maximum
$S_{0.2}$	-	Ratio of fifty maximum
σ	-	Standard deviation
$K(\gamma)$	-	Decay correction
L_D	-	Detection limit
L_c	-	Critical level
M^*	-	Measured parameter
M^{**}	-	Calculated parameter using interpolation method
W^*	-	Warranted value certified by the manufacturer

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of the Problem

High purity germanium (HPGe) detectors are the most popular tool for gamma-ray spectrometry because of their excellent high energy resolution than scintillation detectors. Typically, it is less in effective atomic number as compared to sodium iodide (NaI). HPGe is significantly higher expansive than NaI. Therefore, must be considered for a specific application in laboratory. A typical analog gamma-ray spectrometry system consists of a detector shielding with heavy cylindrical container (mainly leads) to minimise possible ambient background radiation (e.g., cosmic muons, building materials and ceiling), germanium crystal, national institute of standards technology (NIST) traceable standard source. High voltage supplied, electronics signal processing chamber such as preamplifier, amplifier, oscilloscope, multichannel analyzer (MCA), computer system and gamma automatic software for analysis. Liquid nitrogen cooling system must provide, typically 77 K to reduce leakage current result from high bias voltage.

When monoenergetic gamma ray interacts with the crystal detector on sensitive region. It ionised with germanium atoms and this will create electron-hole pairs production within a few microseconds. This electrons and holes drift in opposite direction under the influence of high electric field to electrodes ($p^+$and n^+ contacts) and constitute a current. Once optimized by the preamplifier, output signal will be observed (Knoll, 2010).

Conservatives estimate that over 200,000 gamma-ray spectrometers are in use at various research institutions and modern industrial laboratories throughout the world (Reguigui, 2014). Because of the technical nature of this technique required by sudden increase in leakage current. This still remaining a major challenge encountered today, for scientists and engineers. It is believable that ANSI/IEEE-325, 1996 standard test procedure becomes a unique procedure in which both user and manufacturer agreed, especially on what parameters should be measure and how to measure it. Both are specified in the standard, in order to have a valid record of measurement for future reference. The parameter specifications such as resolution, peak-to-Compton ratio and relative efficiency, yield a better indication of good working gamma-ray spectrometry. The main focus of HPGe detector is to covert gamma ray into electrical pulse which can be used suitable signal processing to achieve a desirable application. Despite the importance of these specifications few work have been published by examining some specific parameters stated in ANSI/IEEE std 325, 1996 (Mei-wo, 2014; Jinga and Jonah, 2015; Meena et al., 2017; Shouop et al., 2017).

1.2 Statement of Problem

In semiconductor detectors, HPGe detector become the most widely used as a tool diverse in nuclear applications such as nuclear waste in industries and medical field. Therefore, it is very necessary to verify gamma spectrometry system by calibrating the stability of its parameters over period of time. This is to ensure good working performance of the detector or otherwise, such specifications specified by manufacturers will eventually no longer be accurate to predict the efficacy of the detector.

The common problem associate with gamma ray spectrometry detectors is incomplete charge collection (charge trapping centre) during interactions of gamma rays with matter. This will cause loss of counts and led worse energy resolution in photo peak. Therefore, it is important to measure the resolution and peak shape to ensure the shape of the peak is perfectly Gaussian. Other common problem associate with gamma-ray spectrometry detector is high dislocation in the crystal due to natural background radiation. This problem will increase the leakage current and reduce the sensitivity of the working detector (Wang et al., 2015). The lengthy period taken by leakage current in gamma-ray spectrometry will also contribute to detector damaged (Gilmore, 1996).

Variation in temperature which is followed by warm up the detector will contribute to the effect of electrical noise by preamplifier. Likewise, electrical cooling with constant temperature should be monitored between cool fingertip and detector crystal otherwise may destroy potential energy resolution of the gamma ray spectrometry (Looker, Amman and Vetter, 2015).

HPGe detector should be protected from to natural background radiation which can damage the detector and generate less count rate signal. Naturally occurring radionuclides such as potassium (^{40}K) contributes immensely to the formation of long tail in the test peaks (Islam et al., 2018). In addition, presence of contamination on the surface of the detector due to leakage of water vapor and other impurity gases around the detector especially, radon progeny (e.g. ^{214}Bi) is the most common cause of failure to germanium detector over long period of time (Sharifi et al., 2015). Therefore there is a need to require a proper periodic measurement to ensure detector are safe from background radiation or otherwise, these will produce much greater efficiency loss at low energy (Institute, 1997).

The utilization and prolonged working of two gamma spectrometry system in Nuclear Physics laboratories at Universiti Teknologi Malaysia, causing one to questioning its performance. The problems that associated with resolution and efficiency of the detector (performance of gamma spectrometry system) can be identify and solved by verifying the specifications against the warranted value certified by the respective manufacturers during installation and commission. Therefore, the aims of this study are to investigates the potential performance of the two closed end coaxial gamma spectrometry against its warranted specifications issued by the manufacturer. Furthermore, it will validate a record for future reference.

In this research to achieve the higher quality potential performance and proper control of gamma spectrometry system in our laboratories, its resolution, efficiency and dead time parameters should be measure to standard.

1.3 Objectives of Research

The main objective is to verify the specifications parameters resolution, peak shapes, peak-to-Compton ratio and relative efficiency using ANSI N42-1991/IEEE 325-1996 standard test procedure to ensure good working condition of the systems. The specific objectives are:

i. To measure energy resolution, skew factor, Compton correction peak area and counting error associated with the test peak.

ii. To measure variation counting efficiency with different gamma ray's energy and dead time with energy resolution.

iii. To compare and validate the potential performance specifications for two HPGe detectors against the warranted value certified by the manufacturer during installation.

1.4 Scope of the Study

The scope of this research is limited to measure and correlate potential performance of two enclosed coaxial germanium detectors in UTM. The working performance of the detectors were investigated using ANSI/IEEE 325-1996 standards test procedure. The test procedure was carried out using traceable standard point source. This will enhance a full confidence by the researchers on reliability of the working gamma spectrometers in our laboratories.

This present study was performed using standard point source in line with 1332.5 keV ^{60}Co photo peak placed axially 25 cm from endcap of the detector, in order to eliminate possible coincidence loss cascade of gamma ray's energy. The two available gamma ray n- type closed end coaxial Canberra Model 2002CSL, (USA) product located at Block *C* named as gamma spectroscopy one, (GS1) and p-type closed end coaxial Ortec Model GME25-76-LB-C, USA product located at T05 named as gamma spectroscopy two, (GS2) was used, in Nuclear Physics laboratories, UTM. Measurement was carried out using two automatic acquisition software (Gennie 2000 & Gamma Vision) and manually by using peak height or linear interpolation method, so that possible reliable data could be measured.

1.5 Significance of the Study

Gamma spectrometry is very essential tool that allow identification and quantification of gamma emitting radionuclides in a variety of matrices (e.g. soil, water & air). It allows several emitted photons to be detected and displays information on the spectrum line. Background radiation is varying periodically might have damaged crystal detector and yield poor resolution. Therefore, it's very crucial to keep controlled and monitoring the gamma spectrometer for future use.

In practical, energy calibration usually conducted before sampling by evaluating relationship between energy deposited and channel number of the peak. Once the calibration is performed, then, it is easy to find energy of unknown source. However, efficiency calibration is to measure the activity of a quantify radionuclides of a spectrum. That is relationship between number of counts and disintegration rate. While, in the other hand the present study is specifically regards to manufacturer periodic test namely resolution, peak shape, relative efficiency and peak-to-Compton ratio. This will determine the potential condition of gamma spectrometry system.

The significance of this study is to provide base line data or information on gamma-ray spectrometers in UTM**.** This database is useful to acquire knowledge and understanding the working principle of the two coaxial closed end detectors in perspective of promoting research and improving gamma-ray spectrometry facilities in our laboratories.

1.6 Thesis Plan

The work presented in this thesis describes a specifications parameters conditions of the two-working gamma-ray spectrometer based on ANSI/IEEE 135-1996 standard procedure. The intent was to suggest the best procedure for verifying gamma-ray spectrometry for nuclear and environmental monitoring. Chapter 1 described the background of the problem that gives emphasis on the behaviour of HPGe detector, problem statement, objectives of the research, scope of study and significant of the study was presented. Chapter 2 deals with literature review of the present research which includes gamma ray interactions and absorption in matter, semiconductor detectors, HPGe detectors, common type of geometries used in our laboratories, major specifications parameter for verifying the good working condition of HPGe detectors against the warranted values specified by the manufacturers was discussed. Chapter 3 focuses on experimental methodology using a suitable geometry described by ANSI/IEEE 325-1996 standard procedure, linear interpolation method for calculating resolution manually, and others mandatory test recommended by the standard was applied. Chapter 4 concerns the most important part of the research, where the result of our findings was discussed. Chapter 5 presents the conclusion and the future perspectives.

REFERENCES

Agnello, M., Botta, E., Bressani, T., Bruschi, M., Bufalino, S., Napoli, De. M., Feliciello, A., Fontana, A., Giacobbe, B., Lavezzi, L.,Raciti, G., Rapisarda, E., Rotondi, A., Sbarra, C., Sfienti, C. and Zoccoli, A. (2009) 'Study of the performance of HPGe detectors operating in very high magnetic fields', *Nuclear Instruments and Methods in Physics Research Section A*, 606(3), 560–568.

Akkurt, I., Gunoglu, K. and Arda, S. S. (2014) 'Detection Efficiency of NaI (Tl) Detector in 511 – 1332 keV Energy Range', *Science and Technology of Nuclear Installations*, 2014(1), 6–11.

Chakraborty, A. K., Shariff, M. A., Latif, S. A., Rashid, M. A. and Khandaker, M. U. (2019) 'Efficiency Calibration of γ -ray Detector for Extended Sources', *Pramana - Journal of Physics*, 92(4), 1–5.

Chechev, V. and Kuzmenko, N. (2004) *Table of radionuclides*. France: Gib-Sur-Yvette Cedex.

Chham, E., Pinero, G. F., Bardouni, E. T., Ferr-Garcia A. M., Azhara, M., Benaalilou, K., Krikiz, M., Elyaakoubi, H., Bakkali, E. J and Kaddour, M. (2015) 'Monte Carlo analysis of the influence of germanium dead layer thickness on the HPGe gamma detector experimental efficiency measured by use of extended sources', *Applied Radiation and Isotopes*. 95, 30–35.

Chinnaesakki, S., Bara, S.V., Sartandel, J. S., Tripathi, M. R. and Puranik, D. V. (2012) 'Performance of HPGe gamma spectrometry system for the measurement of low level radioactivity', *Journal of Radioanalytical and Nuclear Chemistry*, 294(1), pp. 143–147.

Cooper, R. J., Amman, M. and Vetter, K. (2018) 'High Resolution Gamma-ray Spectroscopy at High Count Rates with a Prototype High Purity Germanium detector', *Nuclear Instruments and Methods in Physics Research Section A*, 886, pp. 1–6.

Currie, L. A. (1968) 'Limits for Qualitative Detection and Quantitative Determination: Application to Radiochemistry', *Analytical Chemistry*, 40(3), pp. 586–593.

Demir, D., Eroğlu, M. and Turşucu, A. (2013) 'Studying of characteristics of the HPGe Detector for Radioactivity Measurements', *Journal of Instrumentation*, 8(10), P10027–P10027.

Drahansky, M., Paridah, M.T., Moradbak, A., Mohamed, A.Z., Owolabi, F., Abdulwahab, T., Asniza, M. and Abdul Khalid, S. H.P. (2016) 'Gamma-Ray Spectrometry and the Investigation of Environmental and Food Samples', *Intech open science*, 13.

Gilmore, G. R. (1996) *Practical gamma-ray spectrometry*: 2nd edition. Warrington, UK: John Wiley & Sons Ltd.

Gilmore, G. R. (2008) *Practical Gamma-Ray Spectrometry:2nd edition*. Warrington, UK: John Wiley & Sons Ltd.

Glidish, G.L. and Burinsky, D. (2008) *Resolution in Mass Spectroscopy*. 2nd edition, *Research Triagle Park, NC*.

Grigorescu, E. L., Cristina, R., Anamaria. S., Maria. L. A., Ivan, C. and Tanase, G. (2002) 'Standardization of ^{152}Eu', *Applied Radiation and Isotopes*, 56(1–2), 435–439.

Gudelis, A., Gorina, I., Butkus, P. and Nedveckaite, T. (2014) 'A long-term performance evaluation of the gamma-ray activity measurement laboratory in CPST, Lithuania', *Applied Radiation and Isotopes*, 87, 439–442.

Hossain, I., Sharip, N. and Viswanathan, k. (2012) 'Efficiency and resolution of HPGe and NaI(Tl) detectors using gamma-ray spectroscopy', *Scientific Research and Essays*, 7(1), 86–89.

Institute, A. national standard (1997) *IEEE Standard Test Procedures for Germanium Gamma-Ray Detectors*. New York, USA: Institute of Electrical and Electronics Engineers, Inc.

Islam, M. N., Akhter, H., Begum, M., Mawla, Y. and Kamal, M. (2018) 'Study of a Laboratory-based Gamma Spectrometry for Food and Environmental Samples', *International Journal of Advanced Engineering, Management and Science (IJAEM*, 4(1), 2454–1311.

Iwagami, S., Onda, Y., Tsujimura, M., Hada, M. and Pun, I. (2017) 'Vertical distribution and temporal dynamics of dissolved ^{137}Cs concentrations in soil water after the Fukushima Dai-ichi Nuclear Power Plant accident', *Environmental Pollution*. 230, 1090–1098.

Jinga, R. L. and Jonah, S. A. (2015) ‘Calibration of the High Purity Germanium Gamma-Ray Spectrometer in CERT ’, *Modern Istrumentation*, 4, 11–17.

Karabıdak, S. M. (2017) ‘Dead Time in the Gamma-Ray Spectrometry’, *New Insights on Gamma Rays*. InTech, 1, 13.

Keyser, R. M. Webster, N. A., Belbot, M. D. and Twomey, T R. (2011) ‘A Figure of Merit for Comparing the Performance of Different Radiation Identification and Detection Systems Used in Illicit Trafficking Control’, *Innm*, 1–9.

Khandaker, M. U. (2011) ‘High purity germanium detector in gamma-ray spectrometry’, *Internatinal journal of fundamental physical science*, 1(2), pp. 42–46.

Khandaker, M. U., Jojo, P. J. and Kassim, H. A. (2012) ‘Determination of Primordial Radionuclides in Natural Samples Using HPGe Gamma-Ray Spectrometry’, *APCBEE Procedia*. Mayeen Uddin Khandaker, 1, 187–192.

Knoll, G. (2010) *Radiation Detection and Measurement*. 4th edition. USA: John Wiley & Sons, Inc.

Koskinas, M. F., Yamazaki, IM., Bessa, A. C.M., Caldas, L. V. E. and Dias, M. S. (2010) ‘Comparative measurements in dose calibrators and a gamma-ray spectrometer’, *Applied Radiation and Isotopes*. 68(4–5), 589–591.

Krishnan, N., Anilkumar, S., Verma, A. and Singh, R. (2017) ‘Assessment of the inactive dead layer thickness of old high-purity germanium detector: A study by Monte Carlo simulations and experimental verification’, *Radiation Protection and Environment*, 40(2), 69.

Li, L., Alexander, Q. and Van der Ende, B. (2016) ‘A Method for Coincidence Summing Compensation of Simulation Results Using MCNP on ^{60}Co Volume Source’, *CNL Nuclear Review*, 1–5

Lioliou, G. and Barnett, A. M. (2015) ‘Electronic Noise in Charge Sensitive Preamplifiers for X-ray Spectroscopy and the Benefits of a SiC input JFET’, *Nuclear Instruments and Methods in Physics Research, Section A:* 801, 63–72.

Looker, Q., Amman, M. and Vetter, K. (2015) ‘Leakage current in high-purity germanium detectors with amorphous semiconductor contacts’, *Nuclear Instruments and Methods in Physics Research, Section A*, 777, 138–147..

Meena, D., Gupta, S K., Palsania, H. S., Jakhar, N. and Chejara, N. (2017)‘Optimization of Gamma Spectroscopy Setup for Am-Be based

PGNAA Setup', *International Journal of Engineering Science Invention*, 6(12), 13–20.

Mei-wo, Y. (2014) 'Determination Performance of Gamma Spectrometry Co-axial HPGe Detector in Radiochemistry and Enviroment Group, Nuclear Malaysia', *Siminar R&D*. 14–16.

Nahar, A., Asaduzzaman, K., Islam, M. M. Rahman, M. M. and Begum, M. (2018) 'Assessment of natural radioactivity in rice and their associated population dose estimation', *Radiation Effects and Defects in Solids*, 173(11–12), 1105–1114.

Quang, N. (2011) 'Nuclear Instruments and Methods in Physics Research A Dead-layer thickness effect for gamma spectra measured in an HPGe p-type detector', *Nuclear Inst. and Methods in Physics Research, A*, 641(1),. 101–104.

Reguigui, N. (2014) *Gamma Ray Spectrometry Practical Information*,Tunis, Tunisia: Center National des science et Technology Nuclearies

Rizwan, U., Garnsworthy, A. B., Andreoiu, C., Ball, G. C., Chester, A., Domingo, T., Dunlop, R., Hackman, G., Rand, E. T., Smith, J. K., Starosta, K., Svensson, C. E. Voss, P. and Williams, J. (2016) 'Characteristics of Griffen high-purity germanium clover detectors', *Nuclear Instruments and Methods in Physics Research, Section A*, 820, 126–131.

Saat, A., Hamzah, Z. and Fariz, M. (2010) 'Experimental Determination of the HPGe Spectrometer Efficiency Calibration Curves for Various Sample Geometry for Gamma Energy from 50 keV to 2000 keV Experimental Determination of the HPGe Spectrometer Efficiency Calibration Curves for Various Sample Geo, *AIP Conference Proceeding*, 1250, 39.

Sayed, M., Abdel-Rahman, M. and El-Mongy, S. (2018) 'Study of Some Parameters Affecting Efficiency of HpGe Detectors for Accurate Radionuclides Analysis', *The International Conference on Chemical and Environmental Engineering*, 9(6), 371–388.

Sharifi, M., Mirzaii, M., Bolourinovin, F., Yousefnia, H. and Akbari, M. (2015) 'Design Construction and Performance Evaluation of a HPGe Detector Shield', *International Journal of Physical and Mathematical Sciences*, 9(9), 539–543.

Shouop, G. J., Penabei, S., Ndontchueng, M M., Chene, G., Mekontso, E., Jilbert N., Ebongue, A N., Ousmanou, M. and David, S. (2017) 'Methods Precision measurement of radioactivity in gamma-rays spectrometry using two HPGe detectors (BEGe-6530 and GC0818-7600SL models) comparison techniques ', *MethodsX*, 4, . 42–54.

Smith, T. and Kearfott, K. J. (2018) 'Practical Considerations for Gamma Ray Spectroscopy with NaI(Tl): A Tutorial', *Health Physics*, 114(1), 94–106.

Stancu, E., Costache, C. and Sima, O. (2015) 'Monte carlo simulation of p-type HPGe detectors – The dead layer problem', *Romanian Reports in Physics*, 67(2), 465–473.

Stinneth, J. (2017) 'Basics of Gamma Ray Detection(National Nuclear Securiry Administration)'. USA: *Internatinal Nuclear Safequards*, 1–46.

Thi, T., Loan, H., Ba, V. N., Huu, T., Thy, N., Thi, H., Hong, Y., Huy, N.,and Quang*et*, N. (2017) 'Determination of the dead-layer thickness for both p- and n-type HPGe detectors using the two-line method', *Journal of Radioanalytical and Nuclear Chemistry*, 315 (2), 1–8.

Usman, S. and Patil, A. (2018) 'Radiation detector deadtime and pile up: A review of the status of science', *Nuclear Engineering and Technology*. 50(7), 1006–1016.

Wang, G., Amman, M., Mei, H., Mei, D., Irmscher, K., Guan, Y. and Yang, Gang. (2015) 'High purity germanium crystal growth at the University of South Dakota', *Journal of Physics: Conference Series*, 606(1), 1–9.

Wójcik-Gargula, A., Racz, G., Dworak, D. and Królas, W. (2019) 'Characterization of the coaxial n-type HPGE detector for activity measurements of ITER materials irradiated in JEt', *Acta Physica Polonica B*, 50(3), 719–726.

Yang, B. L., Zhou, Qiang., Zhang, Jing., Yao, S.M., Li, Z. S., Li, W. H. and Tuo, F. (2019) 'Performances of different efficiency calibration methods of high-purity-germanium gamma-ray spectrometry in an inter-comparison exercise', *Nuclear Science and Techniques*, 30(3), 1–6.

Zahn, G. S., Genezini, F. A., Ticianelli, R. B. and Saiki, M. (2017) 'Long-term performance assessment of HPGE detectors used in the neutron activation analysis laboratory of IPEN-CNEN/SP (Brazil)', *Applied Radiation and Isotopes*., 125, 108–112.