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Detection of Ionizing Radiation: Practical Training for Students of Military Technology

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Abstract
This paper shows how to use an ionizing radiation detector for practical training for students of the Department of Mathematics and Physics, Faculty of Military Technology, University of Defence. The Department of Mathematics and Physics educates future officers in technical fields, as well as civilian experts for the national security system and the defence industry. Teaching takes place in the form of lectures, theoretical exercises, and laboratory sessions. In this document, we present how students learn to apply theoretical knowledge in practice using laboratory tasks. The laboratory tasks deal with high purity germanium detectors (HPGe), which are usually used in gamma spectrometry set-ups to identify radionuclides and determine their activities in a sample.

KEY WORDS: *education, radiation, high purity germanium, laboratory experience, radiation standards*.

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1. Introduction

High-purity germanium (HPGe) detectors are widely used worldwide for gamma-ray spectroscopy because of their excellent energy resolution, which enables precise identification of radionuclides and detailed analysis of gamma spectra. Since their first development, HPGe detectors have played a major role in fundamental nuclear and radiation research and remain among the most accurate instruments for high-resolution gamma-ray measurements [1]. In addition to laboratory applications, these detectors are increasingly important in military and security fields, particularly in radiation monitoring, nuclear material identification, CBRN defence, and emergency response to radiological incidents.

HPGe detectors are semiconductor diodes with a P-I-N structure, where the intrinsic (I) region is highly sensitive to ionizing radiation, especially X-rays and gamma rays. Under reverse bias, an electric field is established across the depleted region. When incident photons interact with the germanium crystal, electron-hole pairs are generated within the depleted volume and are collected by the electric field at the P and N electrodes. The resulting charge, proportional to the deposited photon energy, is converted into a voltage pulse by a charge-sensitive preamplifier [2, 3]. This signal can then be processed to determine the energy of incoming radiation with very high precision. Due to the relatively low band gap of germanium, HPGe detectors require cooling to suppress thermal generation of charge carriers and reduce leakage current, which would otherwise significantly degrade energy resolution. Liquid nitrogen at 77 K is most commonly used for cooling. The detector is typically housed in a vacuum cryostat connected to or inserted into a liquid nitrogen Dewar vessel. This configuration not only ensures thermal stability but also protects the detector from moisture and contamination.

Modern HPGe detectors are manufactured from highly purified germanium crystals, often reaching impurity concentrations as low as one impurity atom per approximately 10^{10} germanium atoms. Such purity is achieved using advanced metallurgical techniques, particularly zone refining. Only a limited number of specialized laboratories worldwide are capable of producing germanium crystals of sufficient purity and size for commercial detector fabrication. Although the principle of manufacturing an HPGe detector is relatively straightforward, practical implementation is technologically demanding. The germanium crystal must be carefully shaped, equipped with optimized electrical contacts, mounted in a cryostat ensuring excellent thermal contact with the cooling system while minimizing microphonic noise, and connected to the first stage of the preamplifier, which is often located inside the cryostat [4].

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After a sufficient vacuum is established inside the cryostat and the detector assembly is cooled in liquid nitrogen, the detector characteristics can be evaluated. One of the most important parameters is energy resolution, which strongly influences the detector's commercial value. For example, a detector with an energy resolution of approximately 1.68 keV is considered high quality and commands a significantly higher price than a detector with a resolution of 2.2 keV, which may be valued at roughly half the cost. Although detector development is based on solid physical principles, successful fabrication depends largely on precise manufacturing, advanced technological processes, and careful quality control. Several types of germanium detectors have been developed, differing in geometry and structural design, including p-type germanium detectors, n-type germanium detectors, planar germanium detectors, and low-energy germanium detectors [5, 6].

The conventional coaxial HPGe detector is typically fabricated from p-type germanium and is widely used in gamma-ray spectroscopy. It is suitable for an energy range extending from approximately 100 keV to several MeV. At lower energies, detection efficiency is limited by attenuation of low-energy gamma rays in the cryostat wall and detector housing. At higher energies, some gamma rays may pass through the detector volume without depositing their full energy, which reduces full-energy peak efficiency. Accurate determination of detection efficiency across a broad energy range is essential, particularly for radiopurity studies performed in specific measurement geometries. Detector efficiency is influenced by several factors, including detector volume, crystal size and type, source geometry, source-to-detector distance, interaction cross-sections, and the thickness of the detector dead layer [5, 6]. An increase in dead-layer thickness reduces detector efficiency both through gamma attenuation before photons reach the active region and by decreasing the effective active detector volume [7].

For measurements of low-activity environmental or radiological samples, geometries that maximize counting efficiency are preferred. In such cases, sample containers positioned close to the detector, such as Marinelli beakers or cylindrical geometries adapted to detector dimensions, are commonly used to improve detection sensitivity [8]. In military applications, HPGe detectors are valuable for the detection and identification of radioactive isotopes in unknown radiation fields, border security screening, verification of nuclear materials, and forensic analysis after radiological or nuclear events. Their superior spectral resolution allows reliable discrimination between naturally occurring radioactive materials, industrial sources, and special nuclear materials, which is essential for operational decision-making and protection of military personnel in environments with potential radiological threats.

2. Experimental Details

In this study, all the results were achieved by using high-resolution gamma ray spectroscopy technique with a high-purity germanium (HPGe) detector. The HPGe detector, with its built-in preamplifier, is operated with a high voltage power supply at approximately 3.3 kV for p-n type, respectively. The output signal was connected to a spectroscopy amplifier, followed by a multi-channel analyzer (MCA). The shaping time was adjusted to 8 and 6 μs for p-type. The curves of 2π and 4πgeometry measurement, density and comparison between point and bulk source were achieved by using p-type 100% at 4.5 kV with adjusted shaping time 19 μs. Finally, the spectra of all point and standard sources were analyzed using computer GENIE 2000 software for system.

The detectors are calibrated by developing efficiency curves for different source geometries and various source-to-detector distances. When necessary, these efficiency curves are verified using previously calibrated ^{60}Co and ^{137}Cs point sources with Eckert & Ziegler, it seen in Table 1. This calibration procedure is applicable to radionuclides emitting gamma rays with energies between 35 keV and 3.5 MeV and activities ranging from 1 kBq to 10 MBq. The nominal relative uncertainty ranges from 0.8% to 2% (corresponding to 1 standard deviation).

Efficiency curves for the HPGe detectors are developed for point sources (solids), 5 mL ampoules (liquids), Marinelli beakers, plastic vials (of various volumes), and other gamma-ray emitting sources, covering the energy range 14 keV < E < 3.6 MeV. The ambient background around the p-n type HPGe detector was reduced using Pb shielding and cooling detector [9, 10].

The most common medium for detector cooling is liquid nitrogen, however, recent advances in electrical cooling systems have made electrically refrigerated cryostats a viable alternative for many detector applications.
In liquid nitrogen (LN^2) cooled detectors, the detector element (and in some cases preamplifier components), are housed in a clean vacuum chamber which is attached to or inserted in a LN^2 Dewar (see Fig. 1 as an illustration of our used configuration). The detector is in thermal contact with the liquid nitrogen which cools it to around 77°C. At these temperatures, reverse leakage currents are in the range of 10^{-9} to 10^{-12} amperes.

2.1. Energy Calibration

In gamma-ray spectroscopy using high-purity germanium detectors, accurate energy calibration is essential for correct identification and quantitative analysis of radionuclides. The raw detector output is recorded as a spectrum in which detected events are assigned to digital channels according to pulse amplitude. Since channel numbers do not directly correspond to physical energy values, the pulse-height scale must be calibrated in terms of absolute gamma-ray energy. Energy calibration establishes a mathematical relationship, typically linear or polynomial, between channel number and photon energy. This is achieved by measuring reference calibration sources containing radionuclides with well-known gamma-ray energies, such as ^{137}Cs, ^{60}Co, see Table 1. The positions of characteristic full-energy peaks are

identified in the measured spectrum, and their corresponding channel numbers are assigned to known energies. A fitting procedure is then used to determine calibration coefficients describing the channel-to-energy conversion. For many measurement systems, a linear calibration function is sufficient over a limited energy range. However, for wider spectral ranges or high-precision applications, polynomial calibration may be required to compensate for small nonlinearities in detector electronics and signal processing. Calibration points distributed across the entire spectrum improve accuracy and reduce interpolation errors when determining unknown peak energies.

Once calibration is completed, the energy of any detected peak can be determined with high precision, enabling reliable isotope identification and spectral interpretation. Regular recalibration is recommended, as small changes in detector operating conditions, electronics drift, or temperature variations may cause peak shifts over time. In military, environmental, and nuclear security applications, accurate energy calibration is particularly important because precise radionuclide identification is required for radiation monitoring, nuclear material detection, contamination assessment, and emergency response to radiological incidents. Reliable calibration therefore represents a fundamental prerequisite for all subsequent gamma-spectrum analysis.

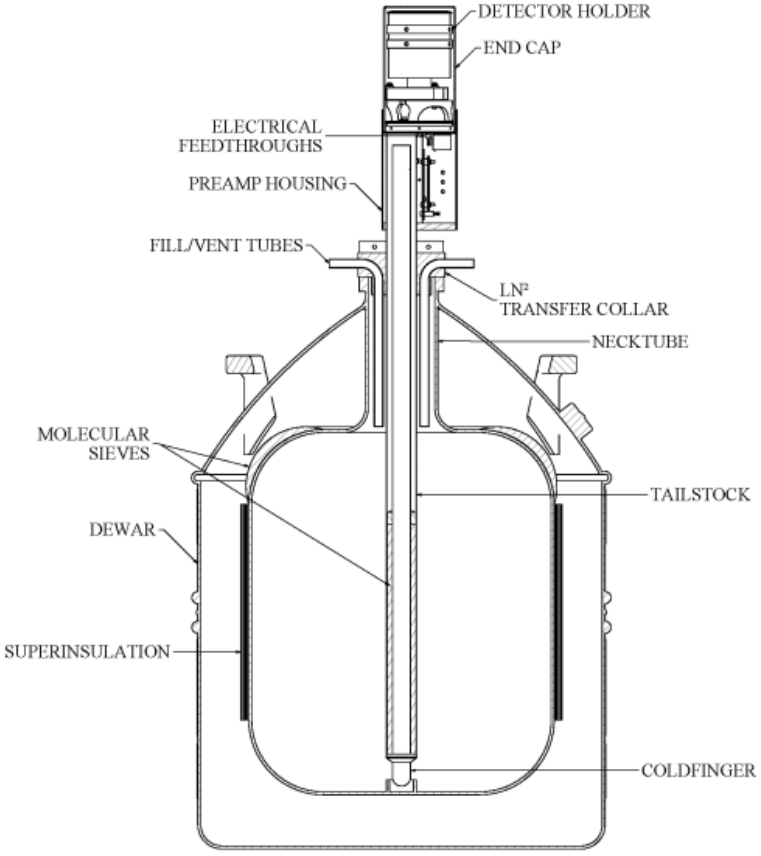

Fig. 1. Schematic Diagram of HPGe detector [7].

Table 1: Calibration data of standards ^{137}Cs and ^{60}Co.

Source	Activity (kBq) 2022.09.22	Channel	Exact energy (keV)
^{137}Cs	267 (32)	843	663.09
^{60}Co	214,5 (24)	1568	1176.64
^{60}Co	214,5 (24)	1793	1336.60

2.2. Efficiency Calibration

Detector efficiency is a key parameter in gamma-ray spectroscopy, as it determines the probability that emitted radiation will be successfully detected and recorded. Detector efficiencies are commonly classified as absolute, intrinsic, and relative efficiencies. Absolute efficiency is defined as the ratio between the total number of photons detected by the system and the total number of photons emitted by the radioactive source. This parameter reflects not only the detector performance itself but also measurement geometry, source-to-detector distance, and attenuation effects. Intrinsic efficiency describes the performance of the detector material alone and is defined as the ratio of detected photons to the number of photons incident on the detector surface. Unlike absolute efficiency, intrinsic

efficiency excludes geometrical factors and characterizes the detector's inherent ability to convert incoming radiation into measurable signals. Both absolute and intrinsic efficiencies can also be expressed as full-energy peak efficiency, which considers only photons that deposit their complete energy in the detector and therefore contribute to the full-energy peak of the measured spectrum. This quantity is particularly important for quantitative gamma-ray analysis, as radionuclide activity calculations are generally based on full-energy peak areas.

In practice, HPGe detector performance is often specified using relative efficiency, which compares the detector's full-energy peak efficiency to that of a standard 3 × 3 inch sodium iodide NaI(Tl) detector under defined measurement conditions, typically for the 1332.5 keV gamma line of ^{60}Co at a fixed distance. Relative efficiency provides a convenient standardized parameter for comparing detector performance across different detector models and manufacturers. Accurate efficiency calibration is essential for activity determination, radionuclide quantification, environmental monitoring, and nuclear security applications, where reliable conversion of measured count rates into physical source activities is required.

3. Results

A set of standard and unknown samples was analysed. In the first stage, liquid samples were measured in Marinelli beakers. The measured activities of ^{137}Cs for individual samples are presented in Figure 2 A, B, C. The activity concentrations ranged from 20 to 60 Bq. Sample A exhibited an activity of 20 Bq, sample B 40 Bq, and sample C 60 Bq. In all measured samples, ^{137}Cs was clearly identified at channel 848, corresponding to a gamma-ray energy of 663 keV. The progressive increase in ^{137}Cs activity is illustrated in Figure 2 A, B, C. The ambient background radiation of the p–n type HPGe detector was minimized using lead (Pb) shielding and continuous cooling with liquid nitrogen. In addition to ^{137}Cs, other naturally occurring radionuclides, including isotopes of Pb, Na, and K, were also detected. A comprehensive summary of the identified radionuclides is provided in Table 2. Some peaks from the background spectrum are not visible in the measured sample spectrum because their contribution is negligible compared to the activity of the radionuclide in the sample.

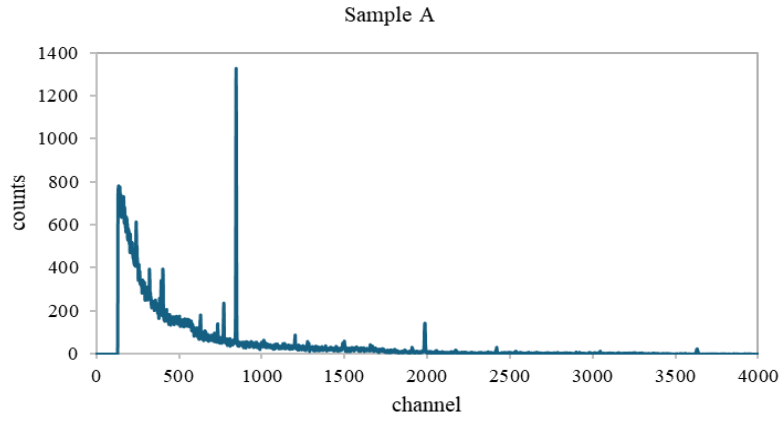

Fig. 2 A: Marinelli beakers with ^{137}Cs

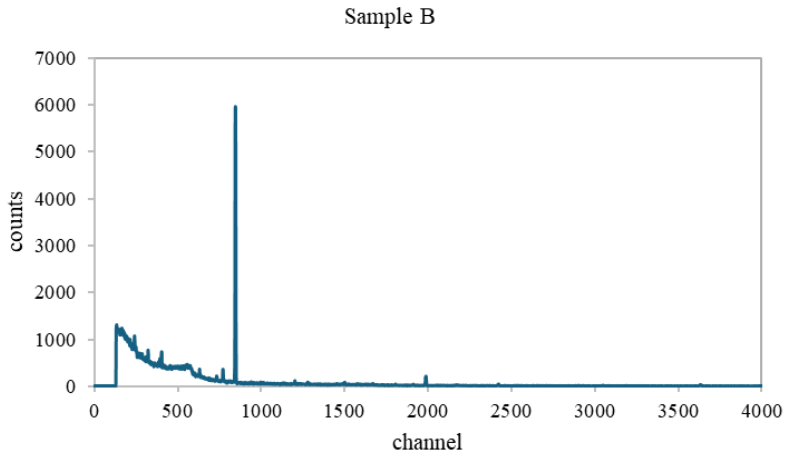

Fig. 2 B: Marinelli beakers with ^{137}Cs

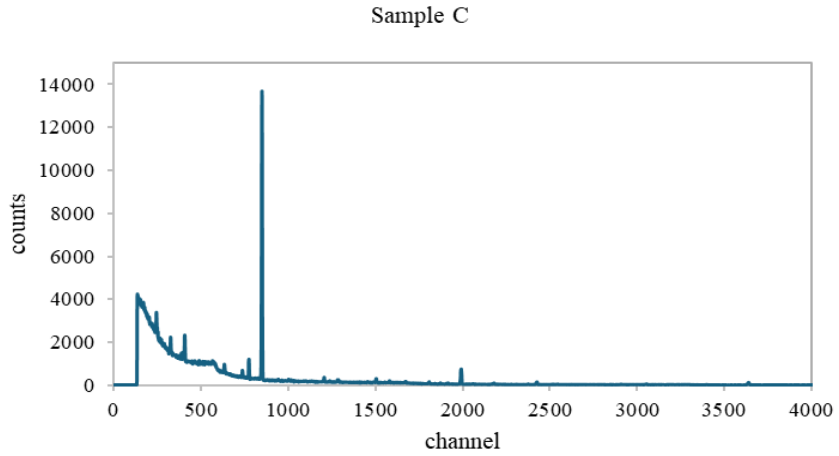

Fig. 2 C: Marinelli beakers with ^{137}Cs

Table 2: The list of identified radiations isotopes in Marinelli beakers identification by NIST [4].

Background			**Marinelli sample**		
isotope	channel	energy (keV)	isotope	channel	energy (keV)
U	133	160.42	Pb	243	238.63
U	243	237.51	Pb	324	294.19
Pb	324	294.19	Pb	405	351.51
Pb	405	351.51	Na	633	511.58
Na	632	511.04	Cs	848	663.23
Bi	772	609.94	K	1989	1466.24
K	1989	1464.99	Bi	2423	1771.65
Bi	2423	1769.87	Th	3635	2622.57
Bi	3047	2210.70			
Th	3635	2622.13			

The analysed samples, including an old watch, a mineral specimen, and a uranium-containing decorative sample ("uranium flower"), exhibited the presence of multiple radionuclides. The identified radionuclides, together with their corresponding channel numbers and gamma-ray energies, are summarized in Table 3.

The old watch originates from a period when radium-based luminescent materials were commonly used. Consequently, radionuclides associated with ^{226}Radium and its decay products were detected. The presence of these radionuclides confirms the historical use of radium in luminescent coatings.

The mineral sample consists of uranium-bearing material originating from the Bohemian-Moravian Highlands and is associated with remnants of historical geological exploration and small-scale uranium deposits. A notable locality is situated near the village of Strhaře, north of Tišnov, where evidence of past uranium ore exploration and mining activities is still present.

Both samples exhibit very similar gamma-ray spectral characteristics, with several identical radionuclides identified. The principal radionuclides detected in both samples are listed in Table 3. Figures 3 and 4 show the gamma-ray spectra acquired using an HPGe detector and processed with the software SpectraLine, which enables radionuclide identification based on gamma-ray energies and allows conversion between channel number and calibrated energy scale.

The obtained gamma-ray spectra exhibit multiple photopeaks corresponding to radionuclides from the uranium and thorium decay series, as well as naturally occurring ^{40}Potassium. Prominent peaks were observed at 352 keV (^{214}Pb), 609 keV and 1764 keV (^{214}Bi), 1460 keV (^{40}K), and 2614 keV (^{208}Tl). These radionuclides are associated with the decay chains of ^{238}Uranium, ^{226}Radium, and ^{232}Thorium under conditions of secular equilibrium. Overall, the measured spectra confirm the presence of naturally occurring radionuclides and decay products typical of uranium- and thorium-bearing materials, as well as anthropogenic radionuclides associated with historical applications.

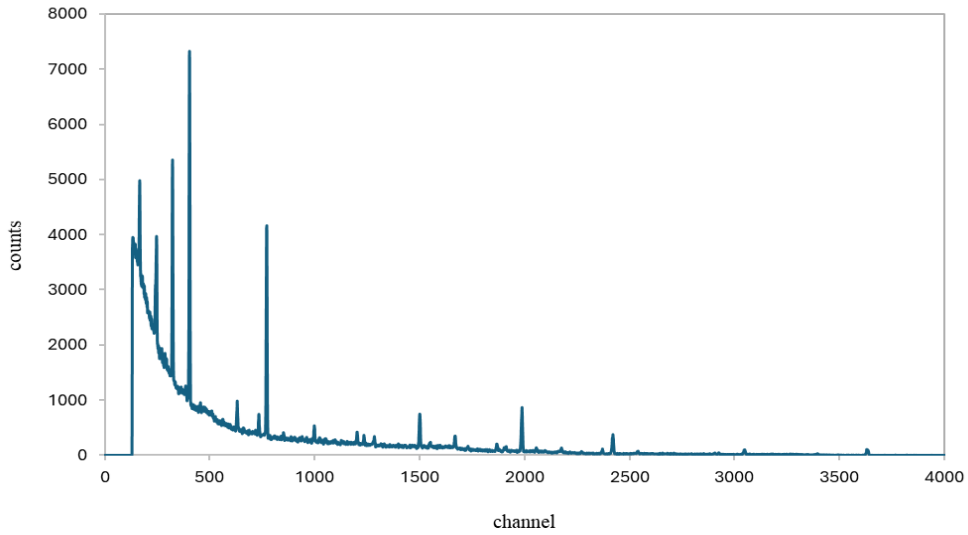

Fig. 3. Uran flower

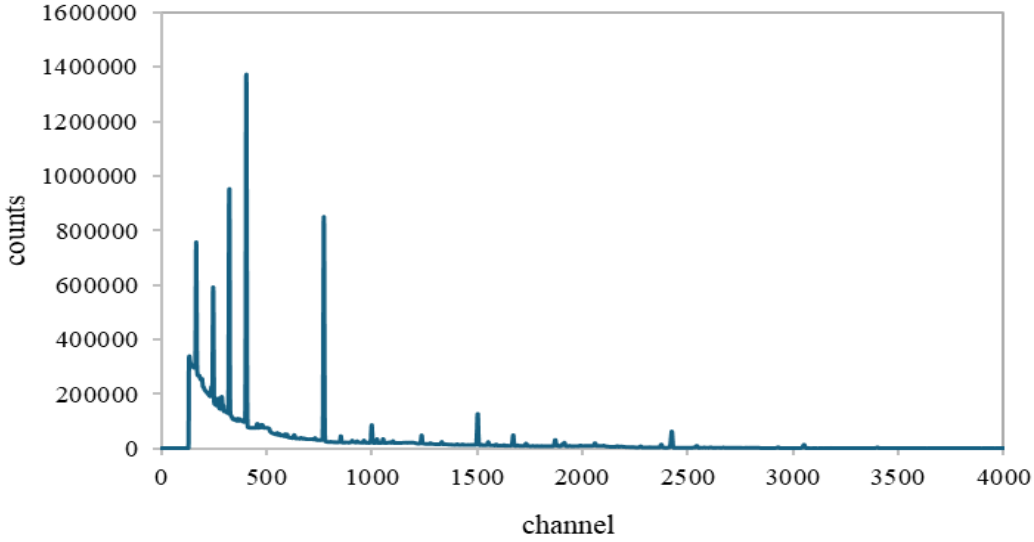

Fig. 4. Old watch

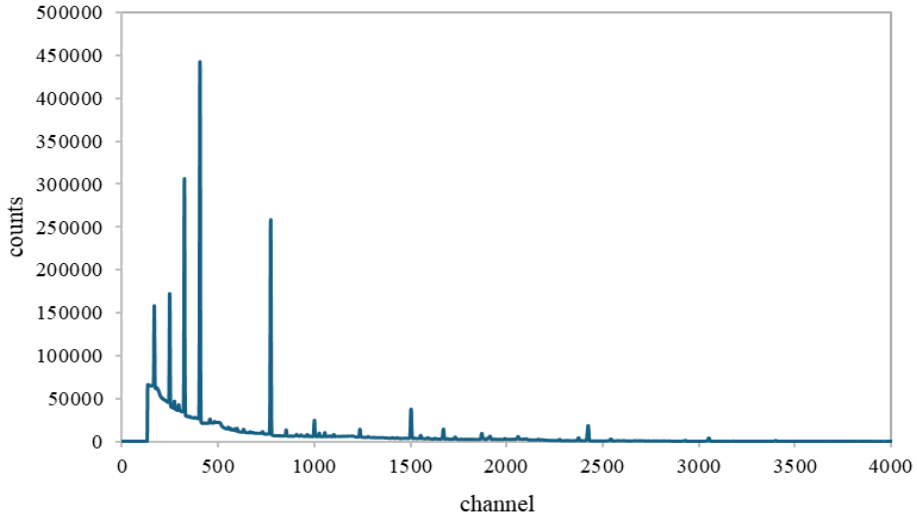

Fig. 5. Stone from Strhaře location

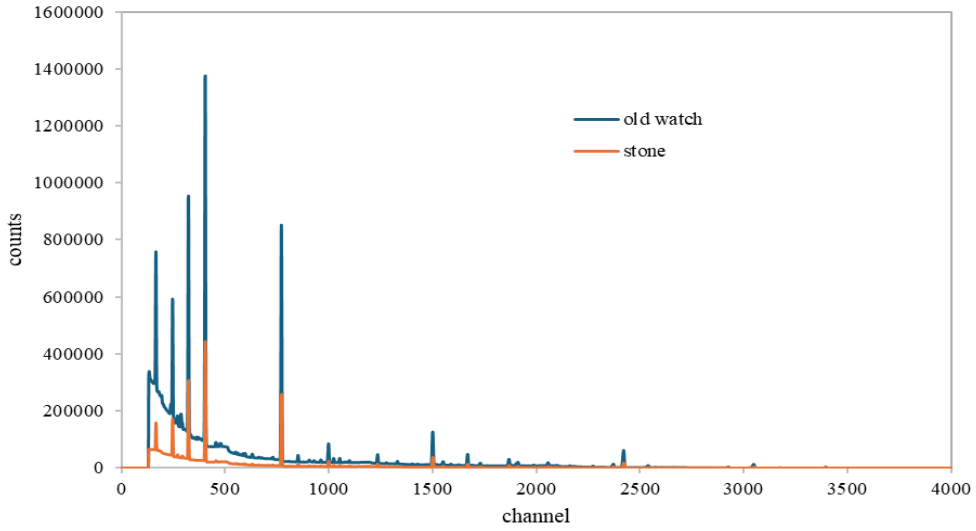

Fig. 6. Comparison of the spectrum of an old watch and a stone

Table 3: The list of identified radiations isotopes in Marinelli beakers identification by NIST [4].

Uran flower			**Old watch**			**Stone**		
Isotope	channel	energy (keV)	isotope	channel	energy (keV)	isotope	channel	energy (keV)
U	133	160.46	U	133	160.45	U	133	160.42
Th	168	184.39	Th	168	184.9	Th	168	184.44
U	324	294.75	Pb	248	241.30	Pb	248	241.24
Pb	405	351.71	Ra	325	294.94	U	324	294.86
Na	632	511.15	Pb	406	351.96	Pb	406	351.96
Bi	772	609.99	Na	633	511.61	Na	633	511.24
Bi	1500	1122.80	Bi	773	610.90	Bi	772	609.51
K	1988	1465.38	Cs	854	667.22	Cs	853	666.67
Bi	2421	1770.01	U	1001	770.56	U	999	770.16
Th	3631	2621.78	Po	1053	808.60	Po	1052	808.21
			Pa	1237	937.14	Pa	1235	936.39
			Bi	1504	1124.51	Bi	1502	1123.86
			Bi	1554	1159.57	Bi	1553	1159.10
			Bi	1672	1242.90	Bi	1670	1242.23
			Na	1733	1285.95	Na	1731	1285.32
			Na	1871	1383.35	Na	1870	1382.65
			K	1914	1413.93	K	1913	1413.27
			Ac	2059	1516.13	Ac	2058	1515.07
			Bi	2425	1772.70	Bi	2424	1771.64
			Tc	2543	1856.00	Tc	2542	1854.98
			Bi	3052	2214.54	Bi	3051	2213.33

4. Conclusions

This laboratory experiment provides a practical demonstration of the fundamental principles of ionizing radiation (IR) detection, including the interaction of IR with matter, calibration procedures using standard radiation sources, and the identification of unknown samples. The method represents an effective training tool for students, enabling independent work and the analysis of self-provided samples such as food, liquids, or solid materials (e.g., stones).

The characterization and performance assessment of the p–n type high-purity germanium (HPGe) detector confirm that the system operates reliably and is suitable for environmental radioactivity studies as well as for the identification and analysis of unknown samples.

In this study, measurements of various liquid samples were carried out using Marinelli beakers, along with solid samples such as stones and other materials. The analyzed samples exhibited contamination by radionuclides, with varying activities of Cs^{137} detected in the liquid samples.

Comparable gamma-ray spectra were obtained for uranium glass, an old watch, and selected stone samples. The measured spectra exhibit multiple photopeaks corresponding to radionuclides from the uranium and thorium decay series, as well as naturally occurring ^{40}Potassium. Prominent peaks were observed at 352 keV (^{214}Pb), 609 keV and 1764 keV (^{214}Bi), 1460 keV (^{40}K), and 2614 keV (^{208}Tl). These radionuclides are associated with the decay chains of ^{238}U, ^{226}Ra, and ^{232}Th under conditions of secular equilibrium.

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