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Design, Construction and Performance Evaluation of a HPGe Detector Shield

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***Abstract*—**A multilayer passive shield composed of low-activity lead (Pb), copper (Cu), tin (Sn) and iron (Fe) was designed and manufactured for a coaxial HPGe detector placed at a surface laboratory for reducing background radiation and radiation dose to the personnel. The performance of the shield was evaluated and efficiency curves of the detector were plotted by using of various standard sources in different distances. Monte Carlo simulations and a set of TLD chips were used for dose estimation in two distances of 20 and 40 cm. The results show that the shield reduced background spectrum and the personnel dose more than 95%.

***Keywords*—**HPGe shield, background count, personnel dose, efficiency curve.

I. INTRODUCTION

NOWADAYS, radioactivity measurements are frequently performed in order to evaluate radionuclidic purity of radiopharmaceuticals, radioactive samples and handle environmental radioactive background, etc. One of the most common and powerful tools for these purposes is a high-purity germanium (HPGe) detector based gamma spectrometry due to its high sensitivity and energy resolution, especially for low-level activity materials. Since as compared to various detectors like NaI(Tl), HPGe detectors often have lower full energy peak efficiency and for any given radionuclide, the detection limit decreases by improving detectors detection efficiency and decreasing background level; in low-level gamma-ray spectrometry measurements, the background of detectors is a very significant and often critical parameter. Therefore, at many laboratories, effort for detection efficiency improvement of HPGe based gamma spectrometers is of much interest [1].

The main background sources are: environmental gamma radiation, radioactivity in the construction material of the detector, radioimpurities in the shield, Radon in air, cosmic rays [2]-[6]. The first three sources can be reduced significantly using a suitable passive shielding made of very low-activity lead and by a careful selection of materials surrounding the crystal. The radon component can be reduced by inserting either nitrogen gas or clean air into the detector chamber in order to create a positive pressure and further minimize radon intrusion from outside. Thus, the cosmic-ray component dominates the remaining background. Cosmic rays induce a background in a germanium detector arising from the interactions of nucleons and muons with materials surrounding the detector. The muons penetrate the lead shield producing a background in the detector [2]. This component can be reduced by installing the germanium detect or in an underground laboratory [2], [7]-[10]. However, building and operating an underground laboratory is expensive and inconvenient if no ultralow levels have to be met [2], [11]-[15].

In this work, in order to reduce background radiation and radiation dose to the personnel in the time of spectrometry procedures, a multilayer shield composed of lead (Pb), copper (Cu), tin (Sn) and iron (Fe) was designed and manufactured for a HPGe gamma spectrometer. The operation of the shield was evaluated by comparing background counting before and after shield installation. At last, efficiency curves of the detector were plotted by putting of various standard sources in different distances.

II. MATERIALS AND METHODS

A. Spectroscopy System Specification

Spectroscopy system in our surface laboratory is a coaxial p-type HPGe detector made by Canbera Co. (Model GC1020-7500SL). The germanium crystal has a relative efficiency of 10% and a volume of 62.7 cm^3. This system is applied for quality control of radiopharmaceuticals and determination of radionuclidic and radiochemical purity evaluation. The system generally used for quantitative and qualitative study of any radioactive samples such as environmental samples.

B. Shielding Material Determination

Since the highest source energy applied in our laboratory was 1.5 MeV, with a little caution, 2 MeV energy was selected as a base for shielding calculations. In order to specific chemical, mechanical and shielding properties and K-shell energies of Pb, Sn and Cu (88.005, 29.2 and 8.979 keV, respectively [16]), they were selected as the best shielding materials in this range of energy. Due to photoelectric interaction and produced characteristic X-rays in the materials, this arrangement can reduce the X-rays energies from 88.005 to 8.979 keV. Since Pb is a high poisonous, soft and malleable metal, this condition is not appropriate for laboratory environment and workers. Therefore, Pb was covered by a thin iron layer.

C. Determination of the Materials Thickness Using Analytical Formula

Pb, as the most common material for shielding of gamma and X-rays, is a heavy metal; therefore, the accurate

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calculation of its thickness is very important. First, utilizing of $I = I_0 e^{-\mu x}$ and selection of different values for I/I_0, the related thickness values were obtained.

Considering of the calculated values, the most suitable thickness for Pb was for I/I_0=5%. But this thickness can attenuate parallel gamma rays. For attenuating unparalleled and scattered beams, build up factor (B) was added to the $I = I_0 e^{-\mu x}$ formula where I, is transmitted intensity; I_0, primary intensity; μ, attenuation coefficient; x, material thickness. Build up factor for x=5.74 ($\mu_{pb} = 0.522$ cm^{-1}) is 2.17. By using of $I = BI_0e^{-\mu x}$ formula, where B is build-up factor, the least thickness of the materials for 95% attenuating of the photons reached from the previous layer was calculated. For Pb, by considering $\mu_{pb} = 0.522cm^{-1}at\ 2\ MeV$, the thickness for attenuating 95% of total radiation was calculated 7.5 cm. For Sn and Cu (with attenuation coefficient of $\mu_{Sn} = 18.184\ cm^{-1}$ and $\mu_{Cu} = 97.84\ cm^{-1}$ in 88 keV and 29.5 keV, respectively), the proper thickness for shielding were calculated 0.16 and 0.03 cm, respectively.

D. Monte Carlo Simulation

By development of computational power, Monte Carlo simulations of detector systems have increasingly become an alternative or complement to experimental efficiency calibrations and shielding design [6], [17].

In this study, Monte Carlo simulation was performed by means of MCNP4C code. MCNP is a Monte Carlo radiation transport code used for modeling of transport and interaction of radiation with matter. It utilizes the nuclear cross section libraries and physics models for particle interactions and gives the required quantity with certain error [18], [19].

The shield body was simulated in cylindrical geometry with four layers. The results of the simulation showed that, in the studied range of energy, internal diameter of the multilayer cylinder doesn't have any effect on HPGe detector counting. The most important parameters in determining of internal diameter are: easy availability to the shield inside for putting and taking the samples, the weight of the shield and the cost. Considering of detector tube diameter (7.5 cm) and the parameters mentioned above, the most suitable dimension for internal diameter was considered 20 cm. The door of the shield was also simulated with 4 layers in cylindrical shape (Fig. 1).

F6 tally was used to calculate and optimize dose in a simulated spherical human body equivalent phantom. Sufficient particle histories were run which resulted in a statistical uncertainty of less than 1% for all cases.

E. SolidWorks Software Simulation

In order to have a better accuracy in designing of the shield geometry, the shield was simulated using SolidWorks software in details. According to the various thicknesses of the layers and shield dimension, shield body including the peripheral surface and lower part of the cylinder in separated part was designed in SolidWork software environment (using Assembly environment).

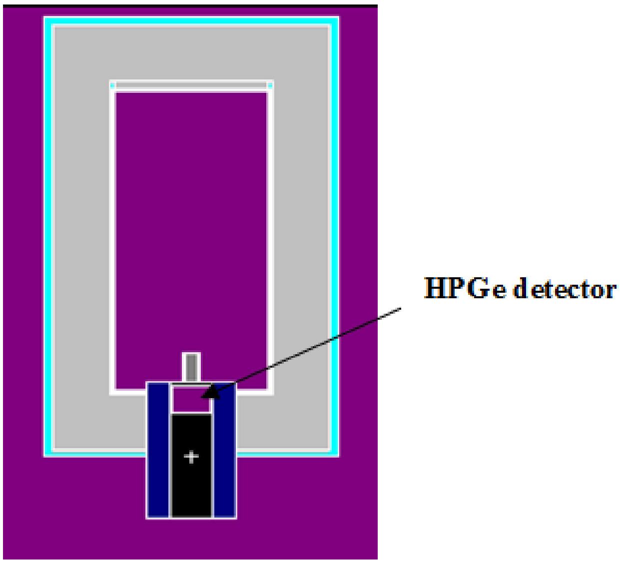

Fig. 1 Simulated shield geometry including the HPGe detector

The door of the shield was also simulated in the Assembly environment. In order to prevent penetrating or escaping the photons in the contact of door and body of the shield, a stair was designed for snapping up the door and body. Considering of the high weigh of the shield (approximately 100 kg) and the need for opening and closing the door, the lifting system of the door is designed as follows. In the first step, the lifting value of the door (considering to the stair height) was calculated. In the next step, a tonsil was designed to create this height difference. For transferring of the tonsil movement to the door, a shaft in suitable staddle was used. For preventing corrosion and damaging to the shaft, the staddle was constructed by brass. In order to transfer force to the tonsil, a lever with a moving arm was added. Fig. 2 shows a schematic geometry of the shield by means of this software.

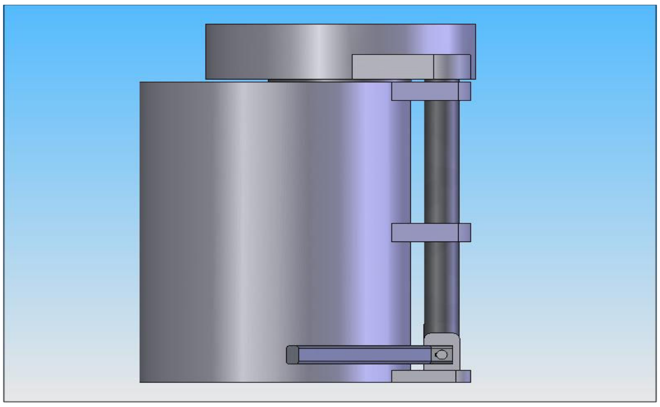

Fig. 2 Shield designed by Solidworks software

F. Shield Manufacturing

Considering MCNP4C and SolidWorks software simulations and technical notes for the construction, the shield was manufactured. Since Pb was the main part of the shield, in the first step, this metal was melted and then casted for body and door of the shield. A hollow iron in cylindrical shape as an external cover for Pb was constructed with definite thickness and diameter. In the next step, a Cu sheet with the definite dimension and thickness was rolled and smoothed. In the case of Sn, because of lack of sheets with a definite thickness, after melting the pure Sn, they converted to ingots and then by heating were deposited on the external Cu layer. By putting this cylinder into the Pb cylinder and fixing it in its place, the body of the shield was prepared.

G. Testing of the Shield

After construction, the shield was installed on the detector and the effect of the manufactured shield on background radiation and personnel dose reduction were tested.

H. Background Radiation Measurement with and without Shield

In the first condition, background radiation in our lab was measured by HPGe detector in the absence of the shield and any radioactive samples for different times (short and long times). In order to investigate the effect of manufactured shield on the background radiation, background was measured in the presence of the shield for different times.

I. Personnel Dose Measurement with and without Shield

Two plexiglass planes with the dimension of 45 × 45 × 3 mm^3 including a set of TLD chips were used for dose estimation in two distances of 20 and 40 cm. TLDs were irradiated in presence and absence the shield with ^{60}Co source at 48 hours (Fig. 3). The geometry was simulated by MCNP4C code and the results were compared with the measured data.

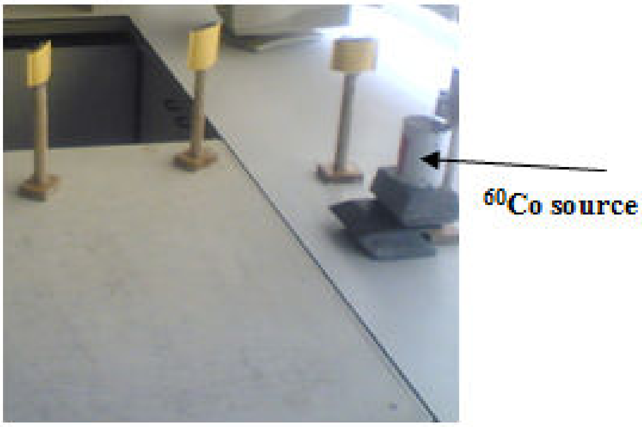

Fig. 3 Experimental set-up for dose measurements

J. Efficiency Curves Plotting

Efficiency calibration was performed by means of ^{152}Eu, ^{60}Co, ^{133}Ba, ^{137}Cs and ^{22}Na standard sources, in presence of the shield at different geometries. For this purpose, standard sources were prepared according to the required geometry and were located in given distances from the detector. Efficiency was calculated by using (1) [20] for point and liquid sources in the distances of 0, 10, 20 and 30 cm.

$$Eff = \frac{Area}{t_{real} \times Br \times Activity} \quad (1)$$

where, Area, t_{real}, Br and Activity are area under the peak, total counting time, branching ratio and standard source activity, respectively.

III. Results and Discussions

A. Background Radiation Measurement with and without Shield

The results for background radiation measurement with and without shield were compared in Fig. 4. As expected, background spectrum was significantly reduced (more than 95% percent). This is due to attenuating and absorbing in different photon energies (especially in low energies) by various layers of the shield.

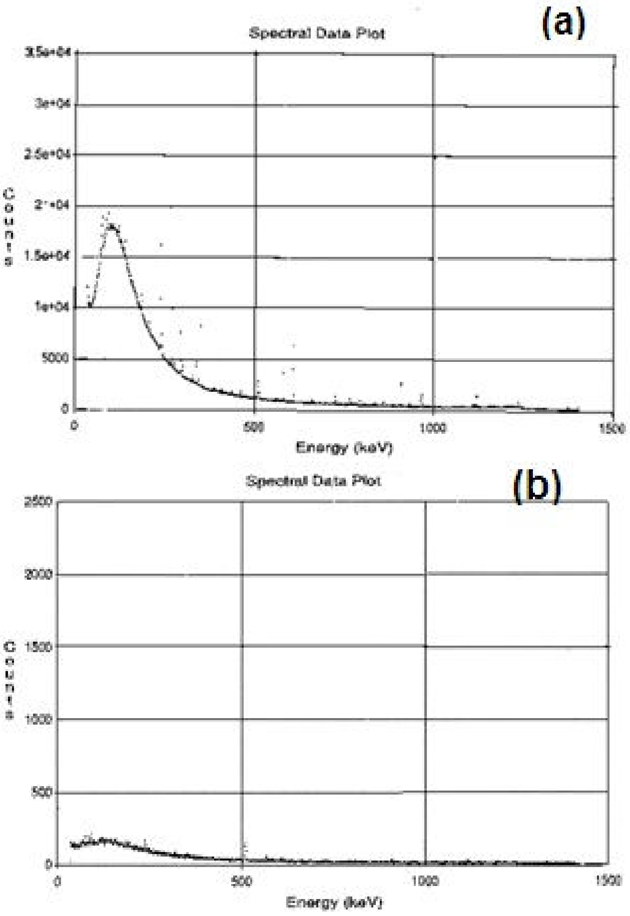

Fig. 4 Background radiation measurement without (a) and with (b) Shield for 24 h Counting Times

B. Personnel Dose Measurement with and without Shield

The results obtained from simulated and experimental data for personnel dose assessment in the distances of 20 and 40 cm have been shown in Table I. The calculated results have an acceptable agreement with the experimental data in all cases. Experimental data indicate that the shield is able to reduce the dose more than 95% in different conditions for ^{60}Co source energies. Therefore, HPGe personnel dose can be considerably reduced.

C. Efficiency Curves Plotting

Efficiency curves were plotted for point and liquid standard sources at different distances (Figs. 5 and 6). As expected, the curves show that by increasing the photon energy or the distance between source and detector, the efficiency of the detector reduces. Also, there is no significant difference between measured efficiency in the distance of 20 and 30 cm especially in high energies (more than 500 keV). The considerable difference among detector efficiencies in different distances at lower energies is due to more possibility of photoelectric effect in this range of energies which cause full energy peak in the process of gamma spectrometry.

TABLE I
A COMPARISON BETWEEN CALCULATED AND MEASURED DOSE RATE IN DIFFERENT CONDITIONS AT 20 AND 40 CM DISTANCES FROM ^{60}CO SOURCE

Situation, distance	Experiment	MCNP simulation	Difference (%)
Without shield, 20 cm	297.2	312.71	4.96
Without shield, 40 cm	75.6	79.42	4.81
With shield, 20 cm	3.96	4.16	4.81
With shield, 40 cm	1.19	1.09	8.4

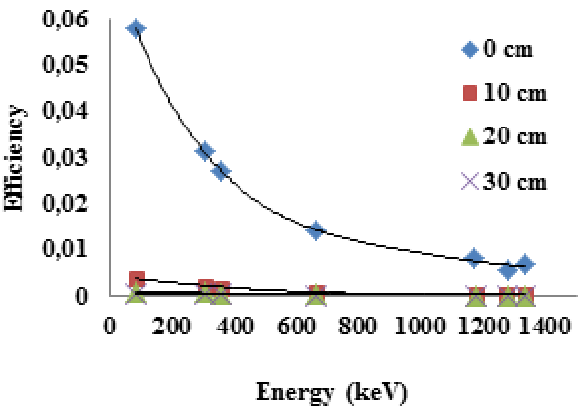

Fig. 5 Efficiency Curves Plotted by Using of ^{22}Na, ^{133}Ba, ^{60}Co and ^{137}Cs Point Standard Sources at Different Distances after Shield Installation

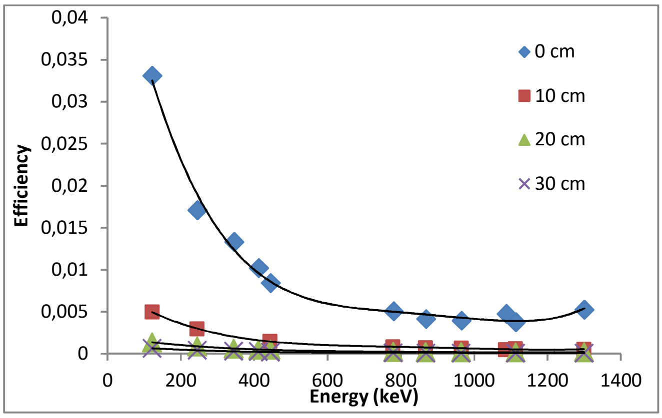

Fig. 6 Efficiency Curves Plotted by Using of 152Eu Liquid Source at Different Distances after Shield Installation

IV. CONCLUSION

In this work, in order to reduce background radiation and radiation dose to the personnel, a multilayer shield composed of Pb, Cu, Sn and Fe was designed and manufactured for a HPGe gamma spectrometer. The effectiveness of the shield was evaluated by comparing background counting and personnel dose before and after shield installation. At last, efficiency curves of the detector were plotted by means of various standard sources at different distances. The shield can reduce background spectrum and personnel dose for ^{60}Co energies more than 90 and 98 percent respectively. The shield can increase the analyze accuracy of the standard and low level activity samples. Also, the shield can considerably decrease the personnel dose. As expected, the efficiency of the detector decreases with increasing of energy or distance of the sources.

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