Determination of the Shape and Dimensions of the Sensitive Volume for Solid State Detectors Using Monte Carlo Computer Technique

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Abstract

In this research the active volume for a number of solid-state detectors of the type of high-purity germanium (HPGe) crystal was evaluated with different radii and depths using scanning method for diagonal (front) and lateral (side). It has been used for this purpose Monte-Carlo efficiency program after its development by adding a subroutine-program for its (subroutine scanning).Also a program has been written to calculate the stopping power and range for incident charged particle on the detector, in order to determine the exact sufficient energy to stop it inside the detector material. The calculations of our results of efficiency were compared with the results of published efficiency and the comparison is very good in terms of improving the values for practical from the calculated results in other ways.

Keywords: Efficiency, Active Volume (Side and Front), High-Purity Germanium (HPGe) Detector, Scanning, Solid-State Detectors and Monte-Carlo Method

تحديد ألشكل والأبعاد للحجم ألفعال لكواشف ألحالة ألصلبة بإستعمال تقنية مونتِ كارلو

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الخلاصة

في هذا البحث تم تخمين الحجم الفعال لعدد من كواشف الحالة الصلبة من نوع بلورة الجرمانيوم عالي النقاوةHigh–Purity Germanium (HPGe) Crystal مختلفة انصاف الاقطار وابعاد بطريقة المسح القطري والجانبي (Front and Side).وقد استخدم لهذا الغرض تطوير برنامج محاكاة مونتِ كارلو لحساب الكفاءة بعد تطويرة بإضافة برنامج فرعي له (Subroutine Scanning).وكذلك تم كتابة برنامج لحساب قدرة الإيقاف والمدى للجسيمة المشحونة الساقطة على الكاشف لغرض تحديد الطاقة الدقيقة الكافية لإيقافها داخل مادة الكاشف.حيث قورنت حسابات الكفاءة الجديدة مع لكفاءة المنشورة وكانت المقارنة جيدة جداً من حيث تحسين القيم بالنسبة للعملي من النتائج ألمحسوبة بطرق أخرى.

Introduction

The field of nuclear physics has been completely revoutionalized with the development of semiconductor radiation detectors. A semiconductor radiation detector which is called a solid state detector such as Ge (Li), Si (Li), is simply a reverse biased p-n junction (diode) where radiations produce electron-hole pairs in the depletion region. There pairs are collected by the electric field applied and thus the detector gives an electric pulse and the amplitude of which is proportional to the energy of the ionizing radiation [1]. An energetic charged particle through a semiconductortransfers its

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energy to the bound electrons in the valence band electrons, the vast majority of which are. Sufficient energy may be transferred to them allowing them to move into the conduction band. This results in the formation of an electron-hole pair. In semiconductor detectors, an electric field is present throughout the active volume, i.e. the volume of the detector, where incident radiations are detected. The subsequent drift of the electrons and holes towards electrodes on the surface of the semiconductor material generates a current pulse [2].

High purity Germanium (HPGe) detectors with the advancement of semiconductor technology became possible to get germanium of very high purity, i.e. about (1 atom) of impurity for about (10^{13} to 10^{14} atoms) of germanium because of this high purity, it has become possible to fabricate thick detectors without lithium compensation. These germanium detectors are commonly referred to as High Purity Germanium (HPGe) detectors. The biggest advantage of this is that the (HPGe) detectors can be maintained or stored at room temperature. There is no lithium in these detectors. However, (HPGe) detectors like Ge (Li) or Si (Li) detectors must be operated at liquid nitrogen temperature. Keeping the detector at liquid nitrogen temperature reduces the background electrical noise that may be generated in the detector due to thermal energy. The energy resolution of this detector is high if it compare with Na (Ti). These detectors are also commonly available with active volume of (5 to 100 cc) [3].

It is necessary to obtain a theoretical (simulated) and measured efficiency of these detectors before using them for any measuring activity or other nuclear experiment. Efficiency can be regarded as absolute or intrinsic efficiency, depending on the purpose of the measurement. The intrinsic efficiency depends not only on energy of photons but also on the geometry configuration of the system and active volume of the detector.

Semiconductor detectors offer many advantages over scintillation or gas –filled detectors. Some of these are:

1. Excellent energy resolution.
2. Linear response over wide-energy range of incident radiation.
3. Generally compact and are of small size.
4. Fast detectors.
5. Can be fabricated in a wide range of sensitive depth and geometry [4].

Walford and Doust (1969) made the variation of active volume and full peak efficiency of Ge (Li) detectors. It was found that only high resolution detectors had the expected high efficiencies [5]. But In (2005) Boson et al. scanned the detector along its side and front with collimated ^{241}Am and ^{152}Eu sources to check its response. It was found that the active volume of the detector appears to be somewhat smaller than its physical dimensions [6]. Then Rehman et al. (2010) determined the total efficiency of cylindrical scintillation gamma-ray detectors using a novel; primary interaction based on Monte Carlo algorithm .A similar behavior was observed when the radius of the detector was increased from 1-20 cm, while keeping the length of the detector fixed at 7.62 cm for various values of disk sources radii and gamma-ray energy [7].

So that it was decided to check the active volume of the High Purity Germanium (HPGe) detector since any deviation from the nominal active volume would affect the solid angle and /or upper energy limit of detectable charged particle [8].

Monte Carlo Simulation Efficiency Program:

The term simulation refers to the formation modeling (Dynamic Process). This model is used to study the composition of that process. The model may include an equation, or many equations describing this process. In some problems, the studied process involves some random properties. The computer software that simulates such operations use random number generator, which is a subroutine-program, produces a random number selected between (0-1). The program consists of the main program with a number of sub-programs each serves a certain purpose as needed during the run of the program [9]. It is very important to determine the active volume, so for this purpose a program has been developed by adding subroutine-program (subroutine scanning) in order to calculate the active volume besides the efficiency with new diameter and length of the (HPGe) detector or another detector.

Description of Program:

The program is designed mainly for the (geometric arrangement) detector with a point source closer to being bulleted on the axis of the detector [9] as shows in figure-1.

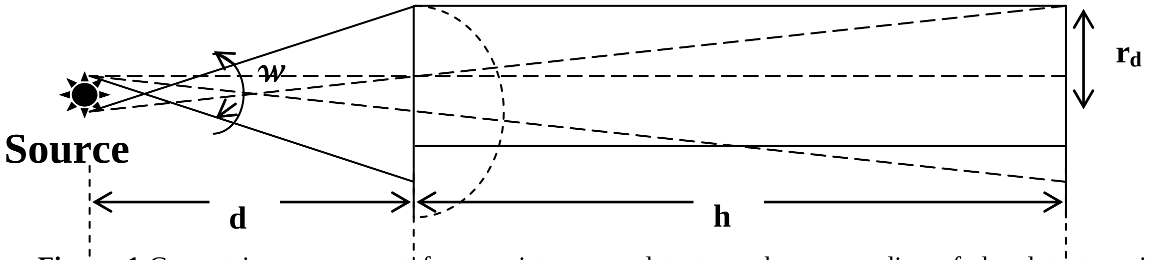

Figure 1-Geometric arrangement for a point source-detector, where r_d: radius of the detector window, h: detector length, d: distance between the detector and the source and w: solid angle [9].

The distance (d) may change to take different values depending on the circumstances of the experiment. Since the detector has a cylindrical symmetry there is no need to produce gamma rays at all levels, it is appropriate to take into account the level shown in figure-1, where the photon is emitted from the point source of random selection within the size of the source and in a random direction within the domain containing the detector [9] as shown in figure-2.

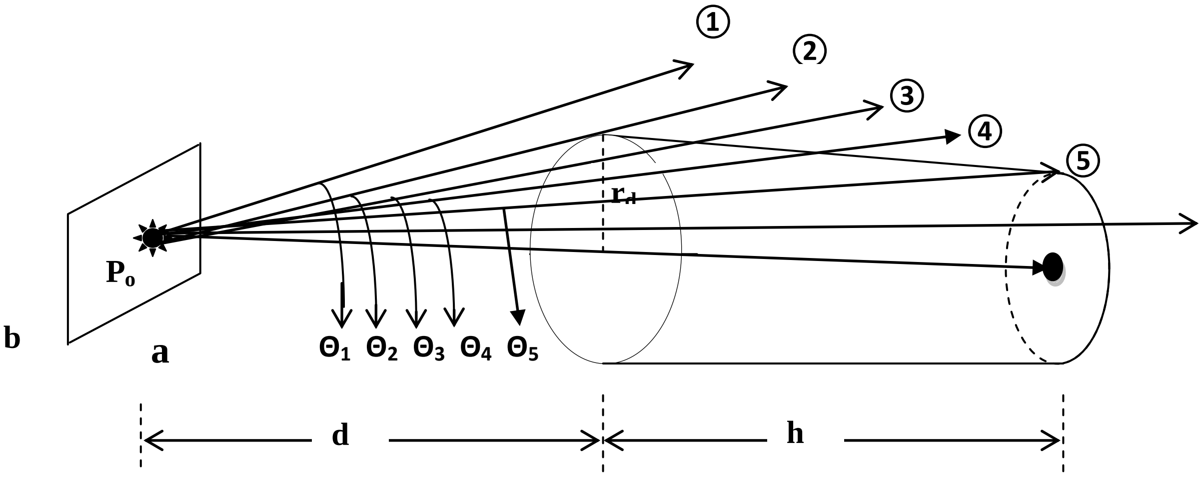

Figure 2-Point of emission and direction of photons from the source to detector [9].

The length and the attenuation of the photon along its path in the source itself was neglected, because it was considered as a point source (where the value of a and b (The dimensions of the radioactive source in the x and y axis respectively) was considered equal to 0.001 cm or less). In addition to that, any attenuation for the energy of the emitted photon from the source was also neglected before the photon collides with the detector window because the air was considered as the only medium between the source and the detector, besides neglecting the attenuation of the detector window because it is very thin. Due to the similarity in the source, the photons must be distributed in spherical section as shown in the dotted curve figure-1. Thus only gamma photons emitted within the solid angle (w) will have a real opportunity to be counted [9].

Stopping Power and Range Program:

In order to calculate the stopping power and range for charged particles (proton), target (Germanium ($^{72}_{32}Ge$)) and energy range (0-200 MeV) a program in FORTRAN language (77-90) has been written separately. This program helps us to know how much energy is needed in order to stop the charged particles inside the detector.

The stopping power of a substance is the energy lost by the particle per unit path in the substance [1].

$$S = -\frac{dE}{dx} = \frac{z^2 e^4}{4\pi \epsilon_\circ^2 m_\circ \upsilon^2} nZ \ln\left(\frac{2m_\circ \upsilon^2}{\bar{I}}\right) \text{.........................} \quad (1)$$

The range of a charged particle is given by the equation [1]:

$$\overline{\mathrm{R}}=\int_0^{\overline{\mathrm{R}}} \mathrm{dx}=\int_0^{\mathrm{T}}\left(-\frac{\mathrm{dT}}{\mathrm{dx}}\right)^{-1} \mathrm{dT} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

$$T=\frac{1}{2} m_P \upsilon^2,\ \mathrm{dT}=m_P \upsilon \mathrm{d}\upsilon \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

$$\mathrm{R}= 4\pi\epsilon_\circ^2 \frac{\mathrm{m}_\circ}{\mathrm{e}^4\ \mathrm{N_a}} \frac{\mathrm{A}}{\rho \mathrm{Z}} \frac{m_P}{\mathrm{z}} \int_0^{\mathrm{v}_\circ} \frac{\upsilon^3}{\ln\left(\frac{2\mathrm{m}_\circ\upsilon^2}{\bar{\mathrm{I}}}\right)} \mathrm{d}\upsilon \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4)}$$

where $\mathrm{n} = \frac{\rho \times N_a}{A}$

Integration of a function using Simpson's rule gives [1]:

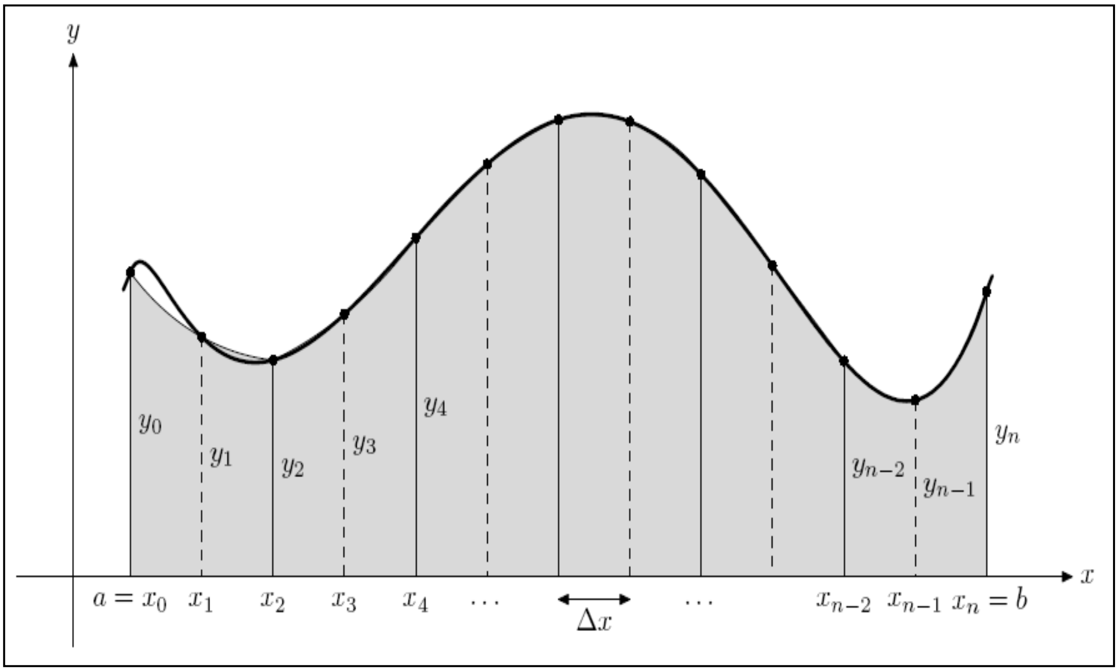

Figure 3-The explanation derivation of Simpson rule formula [1].

$$\int_a^b \mathrm{f(x)dx} \approx \mathrm{S}_1 \approx \frac{1}{3}\mathrm{h}\,(\mathrm{y}_\circ + 4\mathrm{y}_1 + 2\mathrm{y}_2 + 4\mathrm{y}_3 + \cdots + 2\mathrm{y}_{\mathrm{n}-2} + 4\mathrm{y}_{\mathrm{n}-1} + \mathrm{y}_\mathrm{n}).$$

The number n is even, where a = 0 and b = υ

$\mathrm{Y}_\circ$ = f (a)

$\mathrm{Y_n}$ = f (b)

$\mathrm{Y}_a = 0$

$$\mathrm{Y_b} = \frac{(\mathrm{h}\times\mathrm{n})^3}{\ln\left(\frac{2\mathrm{m}(\mathrm{h}\times\mathrm{n})^2}{\bar{\mathrm{I}}}\right)}$$

$$\mathrm{Y} = \frac{(\mathrm{h})^3}{\ln\left(\frac{2\mathrm{m}(\mathrm{h})^2}{\bar{\mathrm{I}}}\right)}$$

SY = SY+Y

Hence

$$\mathrm{R}= \left(\left(\left(\frac{1}{3} \times \mathrm{h} \times (\mathrm{Y_a} + \mathrm{SY} + \mathrm{Y_b})\right)\right) \times 4\pi\epsilon_\circ \frac{\mathrm{m}}{\mathrm{e}^4\ \mathrm{N_a}} \frac{\mathrm{A}}{\rho\mathrm{Z}} \frac{\mathrm{M}}{\mathrm{z}^2}\right) \times 10^3) \text{ mm} \ldots\ldots\ldots\ldots\ldots\ldots \text{(1-5)}$$

Results and Discussion:

Monte-Carlo simulation efficiency program in FORTRAN language (77-90) has been developed to calculate the active volume (side and front) for the solid-state detectors (HPGe). For this purpose has been written subroutine program to work scanning. Then plot the data which has been obtained from studied researches then entered these data in the program at distance between source to detector (d=2cm), number of photons emitted from the source (N_T =1000000) and also worked on these data scanning and then plot these data. After that determined the new diameter (front) and length (side) for the studied detector by Full Width at Half Maximum (FWHM). In order to draw solid line which pass through the data points it has to do fitting and choose the degree of polynomial curve it depends on the values of ($R^2 \approx 1.0$). Where the diameter and length of the detector from the reference [10] respectively (D = 55 mm and L = 60 mm (161MeV)) but the active diameter and length of our results (D = 48 mm and L = 52 mm (149MeV)) less than the reference. This mean that the energy of charged particle (proton) should have incident energy less than or equal (149MeV) to be absorbed completely inside the detector as shown in table-3 for example, otherwise the charged particle escapes from the detector. So will not give corrected information. Then plot the results as shown in table-1 and figure-4 and figure-5.

Table 1-The results of the scanning of the position (cm) for HPGe detector**.**

Count Rate (Our Results)	Position (Side(cm))	Count Rate (Our Results)	Position (Front(cm))
17	0.1	18	0.1
55	0.2	56	0.2
111	0.3	112	0.3
204	0.4	203	0.4
303	0.5	304	0.5
381	0.6	380	0.6
434	0.7	434	0.7
485	0.8	486	0.8
537	0.9	541	0.9
557	1	561	1
567	1.1	566	1.1
574	1.2	570	1.2
580	1.3	575	1.3
585	1.4	578	1.4
590	1.5	580	1.5
596	1.6	585	1.6
603	1.7	590	1.7
606	1.8	593	1.8
608	1.9	595	1.9
609	2	598	2
611	2.1	600	2.1
613	2.2	604	2.2
615	2.3	605	2.3
618	2.4	604	2.4
619	2.5	605	2.5
621	2.6	607	2.6
623	2.7	608	2.7
625	2.8	606	2.8
626	2.9	605	2.9
624	3	601	3
622	3.1	599	3.1
620	3.2	596	3.2
618	3.3	594	3.3
615	3.4	591	3.4
612	3.5	585	3.5
610	3.6	581	3.6
608	3.7	579	3.7
605	3.8	577	3.8

603	3.9	575	3.9
600	4	573	4
597	4.1	572	4.1
595	4.2	570	4.2
591	4.3	569	4.3
587	4.4	568	4.4
584	4.5	566	4.5
578	4.6	550	4.6
572	4.7	540	4.7
567	4.8	487	4.8
562	4.9	435	4.9
559	5	382	5
551	5.1	305	5.1
523	5.2	204	5.2
481	5.3	113	5.3
429	5.4	55	5.4
378	5.5	19	5.5
309	5.6		
205	5.7		
118	5.8		
63	5.9		
22	6		

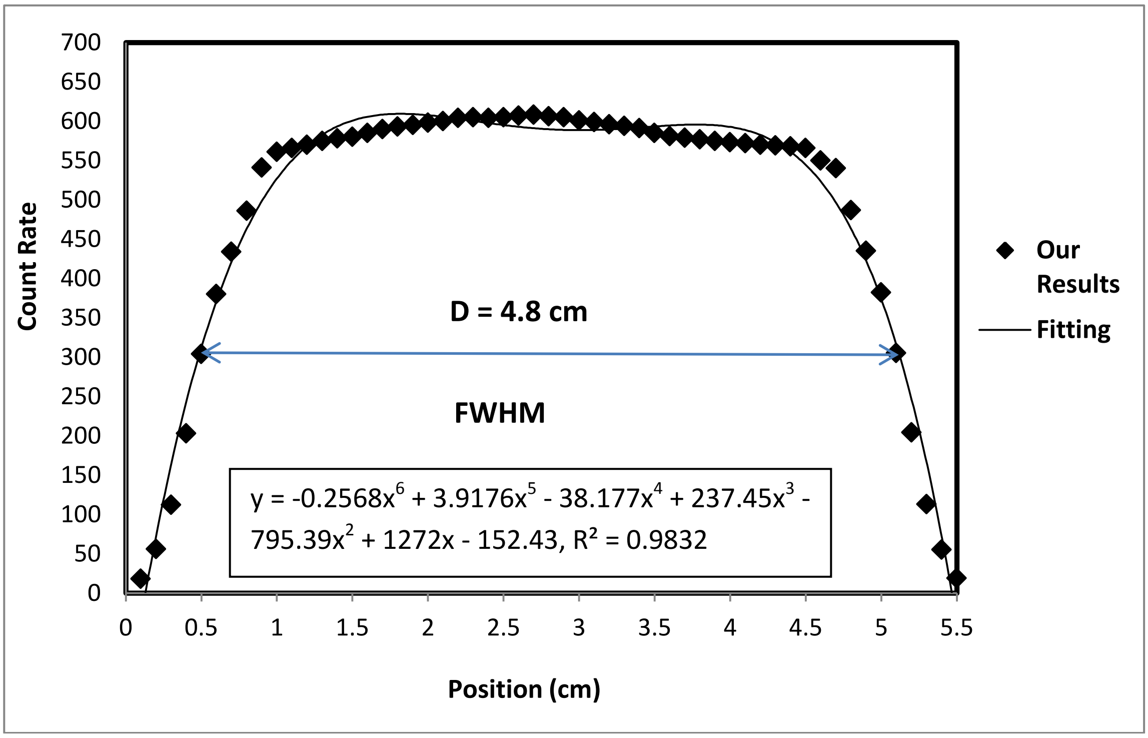

Figure 4-Variation of the count rate of the HPGe detector as a function of position [front (diameter (cm))] of the detector.

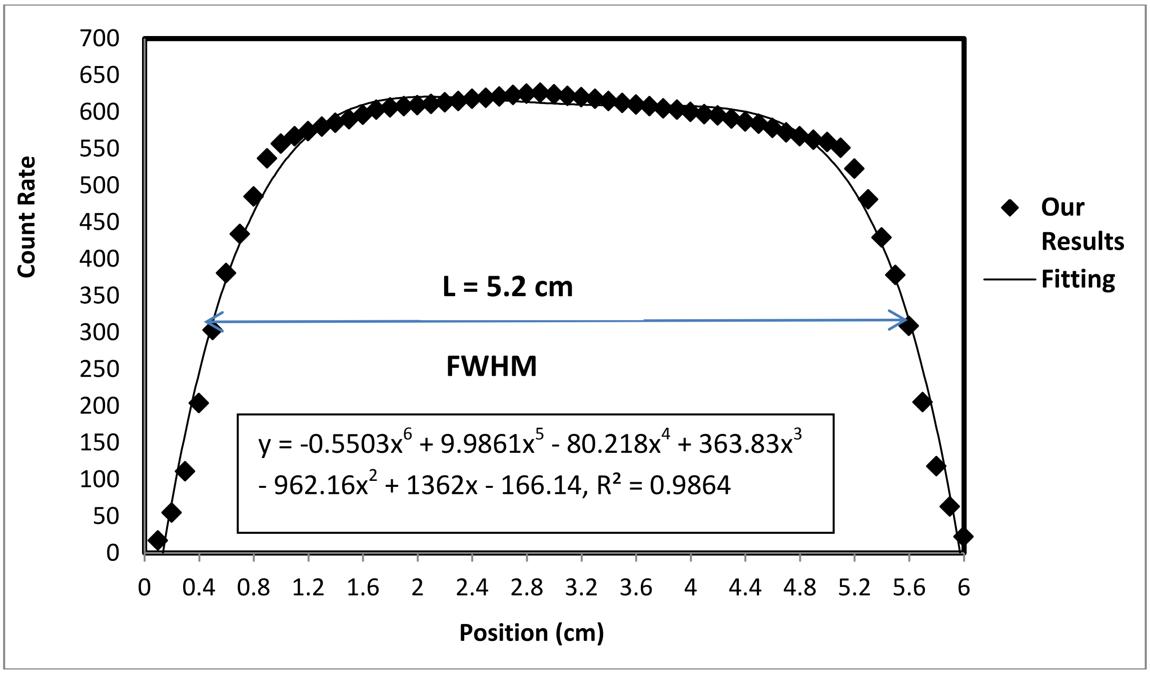

Figure 5-Variation of the count rate of the HPGe detector as a function of position [side (length (cm))] of the detector.

Monte Carlo simulation efficiency program in FORTRAN language (77-90) was used to calculate the efficiency for the solid state detectors (HPGe) at distance between source to detector (d=10 cm), number of photons emitted from the source (N_T =1000000) for dimensions (radius (Rd), length (L)) of the detector for the reference and our results. Found the results of efficiency of our results (with scanning) closer to the results of efficiency experimental from results of the efficiency reference (without scanning) as shown in table-2 and figure-6.

Table 2-Comparison the efficiency of the HPGe detector before and after changes dimensions (Rd, L) at distance (10 cm), with addition the mean squared error .

Energy (keV)	**FEPE(Absolute)**		
	Efficiency Experimental [10]	**Efficiency Reference (Before Change)(Rd=2.75cm, L=6cm) [10]**	**Efficiency Our Results (After Change) (Rd=2.4cm, L=5.2cm)**
60	0.055	0.04	0.043
100	0.048	0.038	0.037
150	0.04	0.031	0.033
380	0.021	0.011	0.015
650	0.015	0.0082	0.0088
750	0.014	0.0076	0.008
1150	0.01	0.0077	0.0079
1200	0.0095	0.009	0.0088
1332	0.009	0.0085	0.0082

Mean Squared Error of Efficiency Our Results and Experimental	**Mean Squared Error of Efficiency Reference and Experimental [10]**
0.000144	0.000225
0.000121	0.0001
0.000049	0.000081
0.000036	0.0001
0.00003844	0.00004624
0.000036	0.00004096
0.00000441	0.00000529
4.9E-07	0.00000025
6.4E-07	2.5E-07
Average of Mean Squared Error =4.77756E-05	**Average of Mean Squared Error =6.65544E-05**

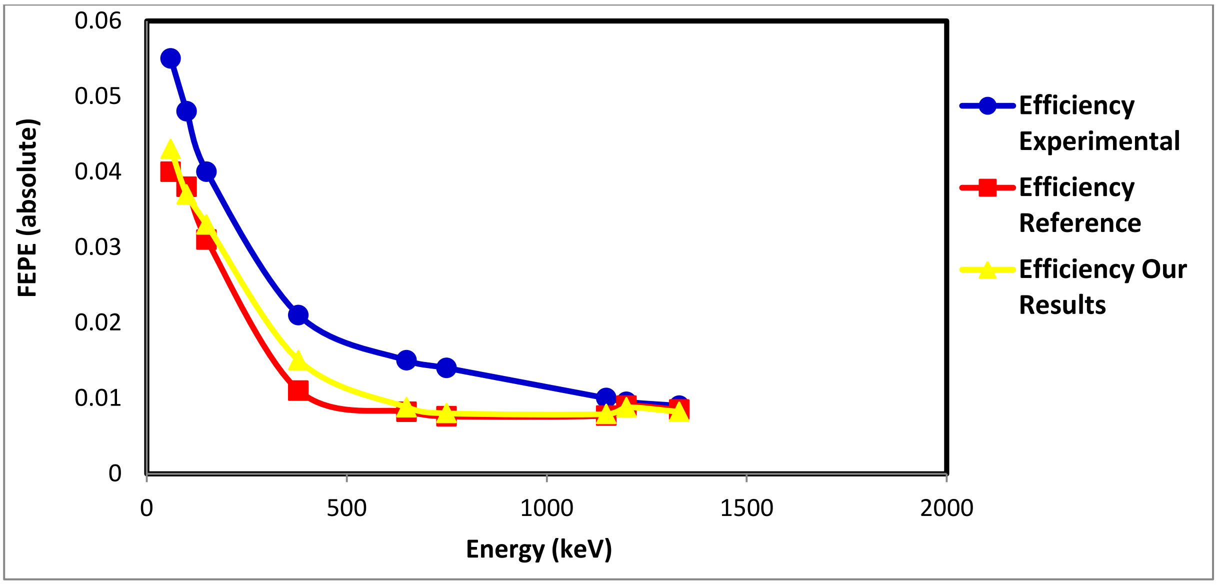

Figure 6-Variation of the full energy peak efficiency (absolute) as a function of the energy (keV).

In order to calculate the stopping power and range for charged particles a program in FORTRAN language (77-90) has been written separately. This program helps us to calculate how much energy is needed to stop charged particle inside the detector and to plot the results of the program (Proton, Germanium (${}^{72}_{32}Ge$)) as shown in figure-7. It can be seen that the stopping power of charged particles is inversely proportional to the energy and directly proportional to the atomic number for charged particle and target material, While the range is directly proportional to the energy and inversely proportional to the atomic number for charged particle and target material.

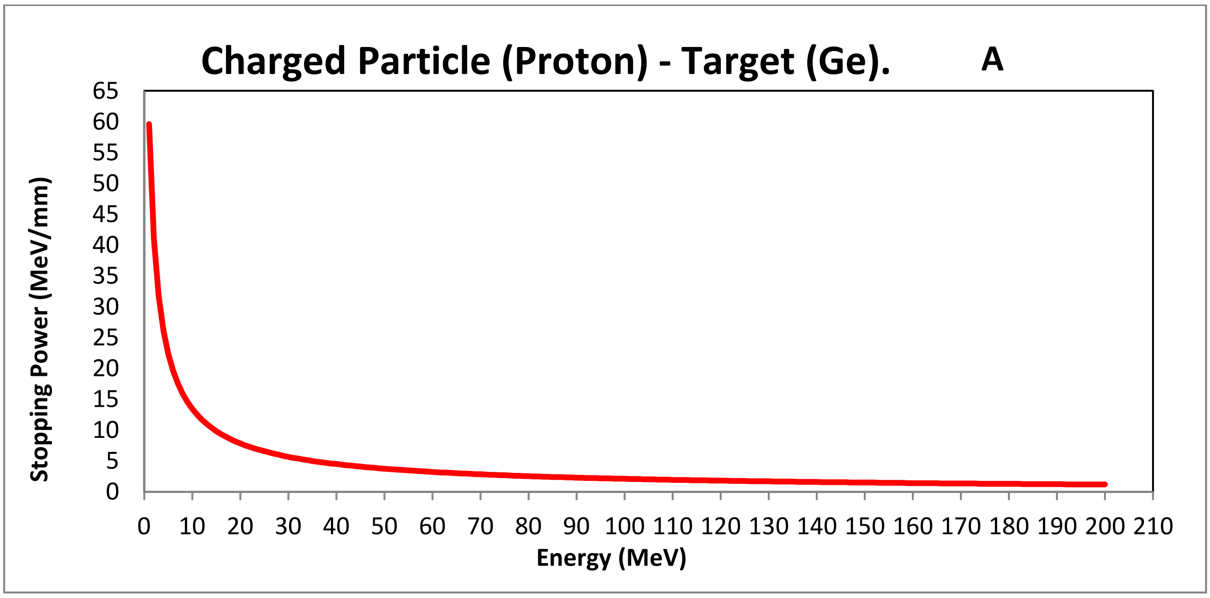

Figure 7A-Variation of the stopping power (MeV/mm) as a function of the energy (MeV) for the charged particle (Proton) and target (Germanium (${}^{72}_{32}Ge$)).

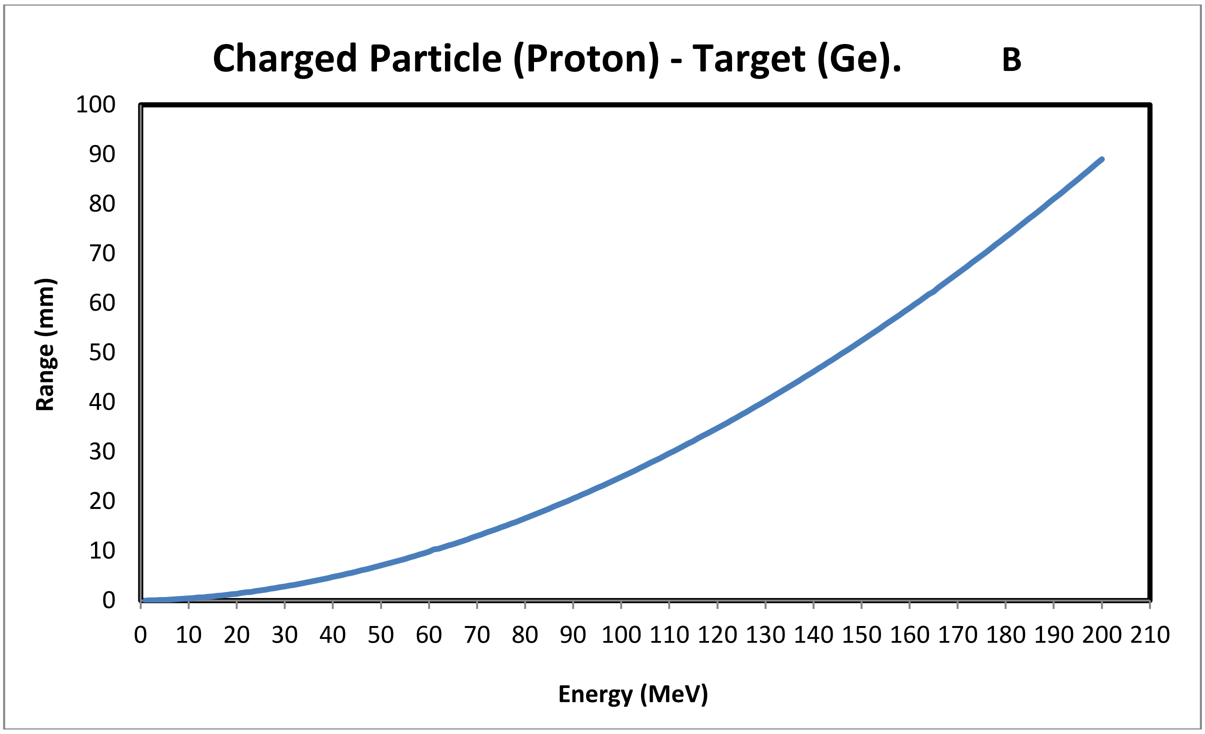

Figure 7B-Variation of the range (mm) as a function of the energy (MeV) for the charged particle (Proton) and target (Germanium ($^{72}_{32}Ge$)).

By stopping power and range calculation we can determine the sufficient energy for charged particles to stop them inside the (HPGe) crystal as shown in table-3.

Table 3-The energy deposits of charged particles in the detector as a function of crystal length

Energy (MeV)	Crystal Length New (mm)	Energy (MeV)	Crystal Length Old (mm)	Charged Particle
149	52	161	60 [10]	**Proton**
204	52	221	60 [10]	**Deuteron**
596	52	644	60 [10]	**Alpha Particle**

and type of charged particle for our results.

Conclusions:

The active volume for different detector crystals was evaluated by using Monte-Carlo efficiency program that has been developed. This computation method allows simple and easy dimensions calculation for all detectors studies. The conclusions of this work are:

1. The calculations of our results of the efficiency for new diameter and length is better from the results of the efficiency of studied researches because the results of efficiency of our results (with scanning) closer to the results of efficiency experimental from results of the efficiency of studied researches (without scanning).

2. The determination of the energy deposits of the charged particles in order to stop them inside the detector crystal.

3. Improve the efficiency results comparing with other methods.

4. The method can be also applied to other type of detectors such as (NaI and Si (Li)).

5. The possibility of determination the active volume in terms of radius and length accurately.

6. Provide Monte Carlo method independently for each radiant source on the other when you perform calculations to group of radioactive sources at once, and thus subject to the same geometric factor unlike practical measurements where will affect volumes of radioactive sources to the geometric factor to measurement system.

7. Back deviation in the values of calculations, largely, to error rate in measurement attenuation coefficient while contributing statistical side to Monte Carlo method a relatively small proportion.

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