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MONTE CARLO SIMULATION OF GEOMETRICAL PARAMETERS AFFECTING THE EFFICIENCIES OF SOME SCINTILLATION AND SEMICONDUCTOR GAMMA-RAY DETECTORS

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Abstract

A computer simulation program based Monte Carlo approach has been designed and written to be as viable tool to test the performance and calculate more than one type of efficiency for some scintillation (NaI(Tl), PbWO4, CWO, TlBr and BGO) and semiconductor (CdTe, HPGe, InP and Si) gamma rays detectors with punctiform virtual radioactive sources. This computer program of Monte Carlo workable, flexibly, to follow step by step the scenario of a certain number of photons, begining from their generation in the radioactive-source, up to them probable to be absorbed within the active volume of detector or them possible to escape apart from. The program has a modular structure to mimic a broad range for the choice of suitable geometries for practical applied. Dependence of the intrinsic efficiency for mentioned detectors on the ratio between a distance of radioactive source-on-the front face of detector over radius of detector (D_{sd}/R_d) was exhibited and discussed. The CWO and BGO detectors showed a higher efficiency than other detectors, which make them a widely desirable candidate to supersede NaI(Tl) detectors for high-energy of γ-detection. The superior of absorption of detector type of CdTe, compared with such of BaF2, HPGe and NaI detectors is very attractive feature in applications concern efficiency at high values of γ-rays energy. The standard error between the present calculations and other results from previously reported literature were found to be, generally, less than 3% at all energy regions.

Keywords**:** scintillation semiconductor detectors, total efficiency, Monte Carlo Method.

1. Introduction:

Gamma detection techniques play an important role in field of gamma-rays spectroscopy applied in nuclear physics, medical radiography [1], neutron activation analysis [2], well logging [3], and study of cosmic rays [4]. In year of 1948, NaI(Tl) scintillation crystals begin to use and provide better conditions for γ-rays detection [5]. Ever after, scintillation detectors was expand to many of other inorganic crystals [e.g. CsI(TI), $Bi_4Ge_3O_{12}$(BGO), $CdWO_4$(CWO)] and organic- based liquids and plastics.

In the onset of the 1960's, germanium and silicon semi-conductor crystals drifted with lithium, Ge(Li) and Si(Li) respectively, and later high purity (intrinsic) germanium (HPGe) worked qualitative leap in the nuclear fields because high energy resolution of them. At onset of 1970's, Cadmium Telluride detector (CdTe) was considered promising as a semi-conductor material for applications of hard X-rays and γ-rays detection. In the year of 1990's, the noticeable improve in the technique of manufacture a high quality single crystal of CdTe and the emersion of Cadmium Zinc Telluride (CdZnTe) as a detector has, significantly, changed the situations of high resolution of detectors that worked at room

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temperature [6] and thus is particularly suited for field measurements. Cryogenic detectors [7] are the latest generation for technology of detectors and are under development in many of concerned laboratories. It characterize with a high energy resolution which make it able to register phonons of the thermal ruins for the ionizing event [1].

Detector efficiencies as a function of, mainly, energy can be obtained either experimen-tal, empirical, semi-empirical or by modeling approaches i.e. (analytical and Monte Carlo approaches) [8-26]. One main reason for following Monte Carlo simulation is that, in many practicle cases, it is difficult to prepare calibrated radioactive-sources providing the whole pertinent energy range, also, these sources are clearly restricted as concerns their dimensions and compositions. While, by Monte Carlo method, one can copy, flexibly, any experimental physical circumstance, whatever how complicated.

This work describes and evaluates, by Monte Carlo Simulation, the total (absolute and intrinsic) and geometrical efficiencies of some scintillation (NaI(Tl), CdWO4, BaF_2 and BGO) and semiconductor (HPGe, and CdTe/CdZnTe) detectors with punctiform sources for a vast range of gamma-radiations. The short computation time is one of the clear advantages with this approach. Other advantage is the flexibility of putting various setup-related parameters, whether a physical or geometrical parameters, as input variables into the computer algorithm. These parameters are controlable such as source-to-detector distance, source dimension, radius and hieght of detector, attenuation coefficients of a particular detector material related to γ-radiation and etc. This facility makes this approach quite versatile and can be applied to whatever detection setup.

2. Simulation procedure:

The present Monte Carlo computer program permits to go after, step by step, of a pre-fixed number of photons whereby a certain scenario, begining from them generation in the radio-active source, up to them probaible as absosred, full or partial, wthin the active volume of detector or them escape apart from. The program has a modular structure, to mimic a vast range of prospected geometry, in practical fields, to be choice.

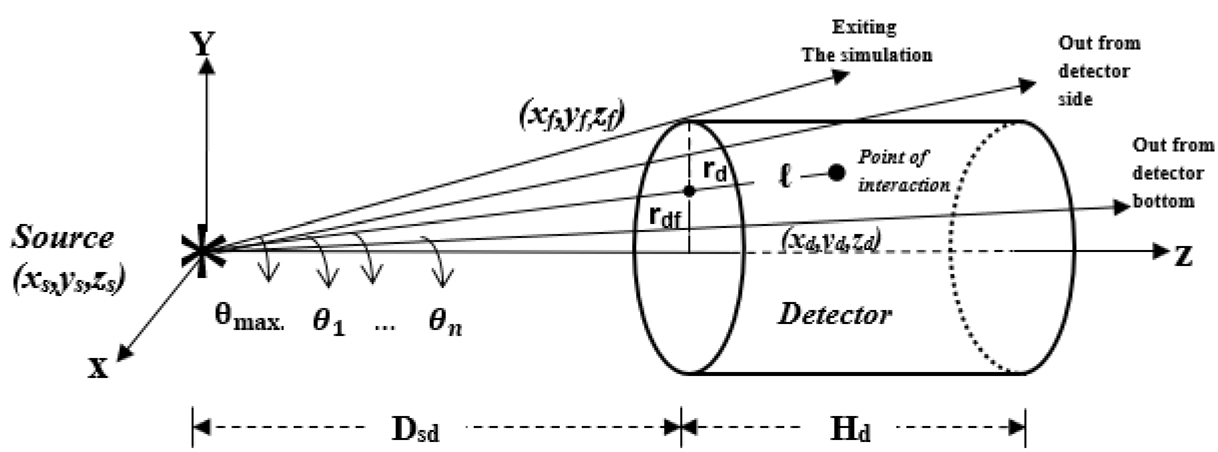

Fig.1 Configuration of the simulated geometrical.

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isotropic punctiform source - cylindrical detector system are shown in Fig.1, its supposed the presence of a punctiform source which placed at a particular position, merely, sights the front bace of a cylindrical detector. In the Fig.1, the Z-axis is the symmetry axis of the setup (with orientation from the positin of source to the detector) and the XY plane is tangent to the source at its point far from the position of detector itself. This simulation neglected the interactions of photons within the materials of source and own container. also, its neglected the scattered photons from the shield and other surrounding materials concern the detector.

To begining the program, the input information as physical and geometrical data must be read in, such as: identity of detector, the geometrical characteristics and positional variables of the source-detector setup. The photons are commonly supposed to be isotropically emitted, with a normal (Gaussian) distribution of energy. Therewith, the program arranges, with easily possible, to mimic discriminatory-emission directions and more complexity of the energy distributions.

Depending on the type of detector crystal, viz, difference an attenuation coefficients or the probabilities of the interaction between the gamma ray and this crystal. The different followed steps of the program, to simulate the story of each photon, have been, briefly, formed as follows:

Step A:generate two random numbers r_1 and r_2 using a Linear Congruential Random Number Generation (LCRNG) sequence.

Step B: based on stepA, (x_s,y_s,z_s) is a random point of emission and trajectory direction of the emitted photon from the volume of virtual radioactive source towards the front face of the detector, as described in fig. 1. Or else the program continue with the next step.

Step C: (x_f,y_f,z_f) is the point of interception with the plane that contains the front face of the detector as a result of photon way out path from the source is extended up to. If this point is outside the dimension of this face, then increasing a particular counter is done (this number concern the estimation of the solid angle). Therefore, the program begins again from *step A*. while, if the photon steps inside the detector, the 'virtual' path-lenghth l_d is estimated (l_d is the distance which the photon would travels inside active volume of the detector untill it interacts).

Step D: Estimate the probaible interaction point which the photon really undergoes. firstly, up to 50 MeV of γ-rays energy, suitable particular polynomial expressions of the pertinent attenuation coefficients as a function of the γ-rays energy have been acquired. it is reproduce to output data of Xcom program [27]. The whole energy range has been interpolated, in respect of minimize the computing time. These expressions are contribute to estimate the point (x_d,y_d,z_d) which indicates whether or not a photon interacts inside the active volume of detector concerning with the path l_d. In the rejection case, increasing a particular counter is done and re-implemetation of the program with followed photon begin from *step A*.

The efficiency indicates to the percentage of radiation that a particular detector detects from the aggregate output that is emitted from the radioactive source within a solid angle of ordinarily 4π. More one of paramrters that evaluates efficiency of the detector, such as: the volume and shape of the active medium of the detector, the dimension of the radioactive-source, the absorption or attenuation coefficients in the active medium, the position and distance from the source to the front face of detector. The efficiency curves for the particular detector was estimated using the equations, as follow, for each energy of γ-rays that emit by the calibration sources:[28]

$$\text{absolute total efficiency: } abs.\,\varepsilon_t = \frac{\text{Number of registered photons}}{\text{Number of photons that emit by the source}}$$

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$$\text{Intrinsic total efficiency: } int.\,\varepsilon_t = \frac{\text{Number of registered photons}}{\text{Number of impinging photons}}$$

The ratio of the number of gamma rays reaching the detector by the number of emitted gamma rays from the source, called geometric efficiency $\varepsilon_g(E)$, is estimated by: [29]

$$\text{geometrical efficiency: } \varepsilon_g = \frac{\text{Number of impinging photons}}{\text{Number of photons that emit by the source}}$$

3. Results and Discussion:

In this simulation, various total detection efficiencies of different scintillation and semiconductor detectors for different energy photons incoming from punctiform source was simulated and estimated by employing Monte Carlo technique using a Compaq Visual Fortran version 6.6 package under windows in a personal computer (PC). A computer program has been designed and written to execution these simulations. Since, it can be applied for various dimensions and types of γ-rays detectors by controlling the input variables.

At nearby distances, for a well statistical distribution, 10^5 photons was followed. The error rate on value of the total efficiency was found to be ± 0.0012 from iteration of the determinations for a particular value of energy as shown in fig.2.

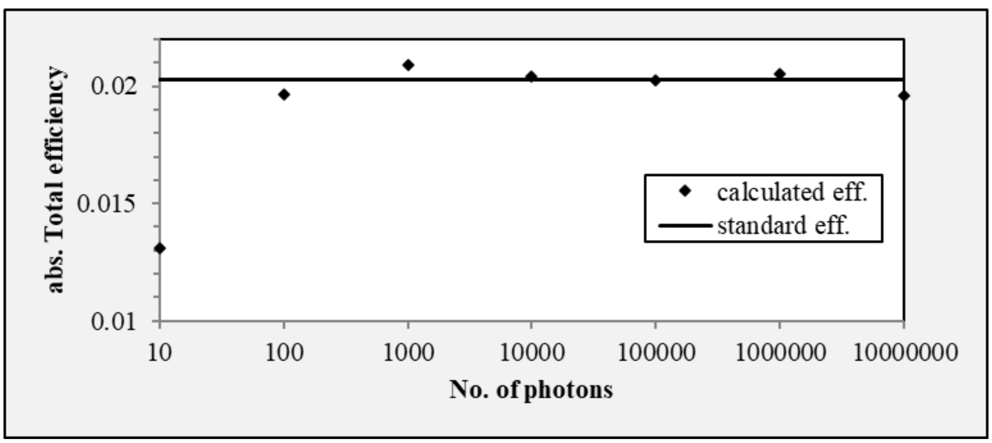

Fig.2.The statistical influence of the value of efficiency versus the number of emitted photons from source.

Firstly, for testing the success of the written program, different types of total efficiency values determined for a 3″×3″ and 2″×2″ NaI(Tl) detectors for different source-to-front face detector distances as given in the Tables (1 to 5), respectively. These results, clearly, are consistent with other results from previously reported literature. Then, our program is practical and adaptable for such kind of calculations.

Table1.The values of absolute total efficiency for 3″×3″ of NaI(Tl) detector for axial punctiform source at D_{sd}=0.001 cm.

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D_{sd} (cm)	E_i (MeV)	Absolute Total Efficiency						mean of st.err.%
		present work	ref.30 (2016)	ref.24 (2007)	ref.12 (1972)	ref.31 (1961)	ref.19 (1958)	
0.001	0.662	0.36828	0.3618	0.3646	0.367	0.37	0.362	1.06
	1.332	0.29367	0.3011	0.2930	0.296	0.302	0.293	1.32
	2.620	0.24216	0.2491	0.2476	0.249	0.25	0.248	2.72

Table2.The values of absolute total efficiency for 3″×3″ of NaI(Tl) detector for axial punctiform source at D_{sd}=0.5 cm.

D_{sd} (cm)	E (Mev)	Absolute Total Efficiency				St.Er.%
		present work	ref.24 (2007)	ref.14 (1977)	ref.16 (1964)	
0.5	0.080	0.433053	0.43330	0.435	0.435	0.06
	0.212	0.40167	0.40130	0.404	0.403	-0.09
	1.100	0.23092	0.22810	0.229	0.228	-1.24

Table3.The values of absolute total efficiency for 3″×3″ of NaI(Tl) detector for axial punctiform source at D_{sd}=10 cm.

D_{sd} (cm)	E (Mev)	Absolute Total Efficiency							mean st.err.%
		present work	ref.25 (2010)	ref.24 (2007)	ref.14 (1977)	ref.13 (1974)	ref.12 (1972)	ref.16 (1964)	
10	0.320	0.025056	0.02520	0.0249	0.0251	0.025	-	0.0247	0.57
	0.662	0.02042	0.02030	0.0202	0.0201	0.019	0.0183	0.0198	-0.57
	1.330	0.01653	0.01650	0.0164	0.0165	0.0164	0.0168	0.0162	-0.17
	2.620	0.01380	0.01415	0.0140	-	-	0.0132	-	2.46
	2.750	0.01365	0.01400	0.0139	-	0.0141	-	-	2.53

Table4.Intrinsic total efficiency values for a 3″×3″ of NaI(Tl) with a axial punctiform source at D_{sd}=20 and 30 cm.

E (Mev)	Intrinsic Total Efficiency								mean st.err. %	mean st.err. %
	D_{sd}=20 cm				D_{sd}=30 cm					
	present work	ref.32 (1981) *	ref.32 (1981) **	ref.33 (1983)	present work	ref.32 (1981) *	ref.32 (1981) **	ref.33 (1983)		
0.514	0.755	0.784	0.746	0.76	0.799	-	-	-	3.70	-
0.662	0.7121	0.720	0.700	0.72	0.76	0.78	0.739	0.77	1.09	3.40
0.835	0.6718	0.695	0.669	0.67	0.72	0.76	0.707	0.72	3.33	5.52
* Experimental values, ** Calculated values										

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Table5.Total (absolute and intrinsic) and geometric efficiency values of a 2"×2" NaI(Tl) detector for γ-rays emitted from point sources with several energies.

E_i (MeV)	D_{sd} (cm)	efficiency					
		abs. ε_t		int. ε_t		ε_g	
		present work	ref. 29 (2018)	present work	ref. 29 (2018)	present work	ref. 29 (2018)
0.15	0.001	0.498695	0.4988	0.997405	0.9980	0.499992	0.4998
	5	0.047543	0.0476	0.876347	0.8805	0.054251	0.0541
	10	0.014195	0.0141	0.920984	0.9233	0.015412	0.0153
	15	0.006595	0.0065	0.942804	0.9451	0.006995	0.0069
0.2	0.001	0.48352	0.4842	0.967052	0.9688	0.499994	0.4998
	5	0.043244	0.0435	0.797274	0.7999	0.054239	0.0544
	10	0.013335	0.0133	0.865248	0.8656	0.015412	0.0154
	15	0.006299	0.0064	0.899944	0.904	0.006999	0.0071
0.3	0.001	0.419021	0.4192	0.838053	0.8387	0.499994	0.4998
	5	0.036109	0.0363	0.666106	0.6673	0.05421	0.0543
	10	0.011636	0.0117	0.755162	0.753	0.015408	0.0155
	15	0.005628	0.0056	0.803198	0.8056	0.007007	0.007
0.4	0.001	0.366309	0.3658	0.732633	0.7318	0.49999	0.4998
	5	0.031555	0.0315	0.582427	0.5816	0.054178	0.0542
	10	0.010372	0.0104	0.673185	0.6747	0.015408	0.0154
	15	0.005069	0.0051	0.723036	0.7228	0.00701	0.007
0.5	0.001	0.331323	0.3318	0.662657	0.6639	0.499992	0.4998
	5	0.028585	0.0285	0.527669	0.529	0.054172	0.0539
	10	0.009484	0.0096	0.615879	0.6158	0.0154	0.0156
	15	0.004672	0.0046	0.665927	0.6638	0.007015	0.0069
0.6	0.001	0.309168	0.3074	0.618346	0.615	0.499991	0.4998
	5	0.026681	0.0267	0.49243	0.4908	0.054183	0.0543
	10	0.008921	0.0088	0.579225	0.5747	0.015402	0.0153
	15	0.004402	0.0044	0.627302	0.627	0.007017	0.0071
0.661	0.001	0.297591	0.294	0.595194	0.5882	0.499989	0.4998
	5	0.025733	0.0255	0.474803	0.4699	0.054198	0.0542
	10	0.008635	0.0086	0.560837	0.555	0.015397	0.0155
	15	0.004267	0.0042	0.607872	0.5995	0.00702	0.007
0.8	0.001	0.276811	0.2738	0.553633	0.5477	0.499991	0.4998
	5	0.023954	0.0238	0.442234	0.4384	0.054165	0.0542
	10	0.008077	0.0081	0.524639	0.5189	0.015395	0.0155
	15	0.004009	0.004	0.57103	0.5662	0.007021	0.0070
1	0.001	0.253606	0.2509	0.507219	0.5019	0.499993	0.4998
	5	0.022032	0.0219	0.406449	0.4024	0.054207	0.0544
	10	0.007451	0.0074	0.484003	0.4793	0.015395	0.0154
	15	0.003707	0.0037	0.528026	0.5219	0.00702	0.0070
1.332	0.001	0.22487	0.2295	0.449749	0.4591	0.49999	0.4998
	5	0.019649	0.02	0.362514	0.3693	0.054202	0.0543
	10	0.006677	0.0067	0.43369	0.4415	0.015397	0.0153
	15	0.003321	0.0033	0.472954	0.4803	0.007022	0.007
2	0.001	0.186172	0.1964	0.372353	0.393	0.499987	0.4998
	5	0.016349	0.0174	0.301692	0.3189	0.05419	0.0545
	10	0.005585	0.0059	0.362749	0.3829	0.015396	0.0154
	15	0.0028	0.0029	0.398575	0.4174	0.007024	0.007
3	0.001	0.176902	0.1793	0.353812	0.3587	0.49999	0.4998
	5	0.015542	0.0157	0.286595	0.2905	0.054231	0.0542
	10	0.00533	0.0054	0.346285	0.3514	0.015393	0.0153
	15	0.00267	0.0027	0.380234	0.3843	0.007023	0.007

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The intrinsic total efficiency of $CdWO_4$, BGO, BaF_2, CdTe, HPGe and NaI(Tl) detector, as exhibit in Fig.3, indicates to the total counts (that can be expected, experimentaly, in the channel or energy integrated spectrum).

From fig.3 appear, obviously, the materials that were less dense or have a lower atomic number has less total efficiency.

Also, the efficiency of a particular detector was high at low energy (absorption coefficients are considerably high) and decreases when it was the energy increases (decline in the absorption coefficients). Where, at below 100 keV, the photoelectric effect is dominant. Therefore, The CWO detector has a high probability of γ-radiation detection. Also as shown in Fig.4, all γ-rays energies is comprehension because a much higher probability of absorbing.

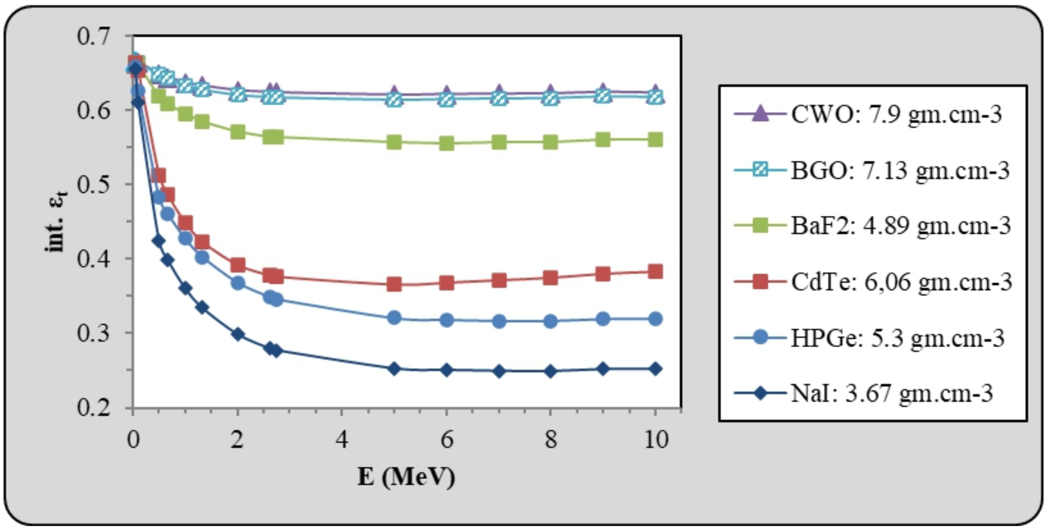

Fig.3. The intrinsic total efficiency of various detectors with 3″× 3″ dimensions (for same geometrical parameters).

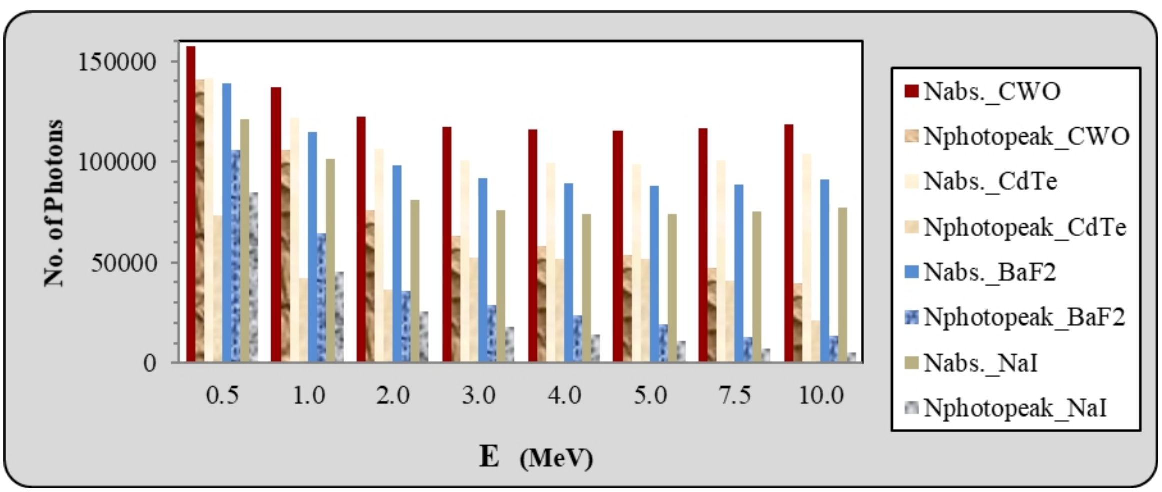

Fig.4. Comparison of high full absorption probability of photons for CWO detector with different type detectors.

for low-energy γ- / X- ray detection, the small dimensions of the CdTe detector necessitates its use for applications, when monitoring is necessary in a limited space. as well, the high absorption of cadmium telluride (CdTe) comparable with that of BaF_2, HPGe, NaI and CsI, is very attractive feature for competitor γ-rays detector. Especially, when increasing the dimensions (particularly, the thickness) of the CdTe detector to improve the efficiency for high energy gamma-rays, as shown in fig.4 and before that in fig3.

To helpful the researchers whose work experimentally, for how source-to-detector distance selection in their measurements, our simulation results have been presented for wide range of distances (i.e. smaller, around equal or bigger than the detector radius) at extend rang of gamma ray energies as was showed in above tables and figures 5&6.

So, let's review the results by other procedure as describe in below figures. Total intrinsic efficiency int.ε_t was graphed versus to the ratio of the source-to-front face of detector distance per radius of the detector (D_{sd}/R_d). Note that, in these figures, the intrinsic efficiency has a minimum around $D_{sd}/R_d \approx$ (0.7-0.8) which is high agreement with MCNP code calculations [28] at extended range of gamma-rays energy, as exhibit in figs.(5 and 6) for 3″× 3″ NaI detector.

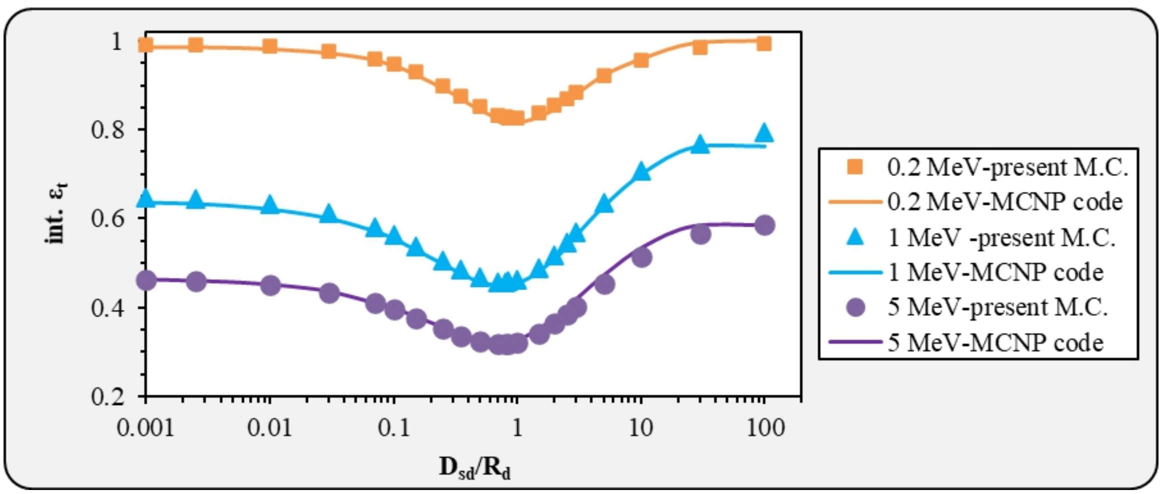

Fig.5. Intrinsic efficiency for 3″×3″ type of NaI(Tl) detector as a function of the ratio D_{sd}/R_d for γ- rays energies of 0.2, 1, and 5 MeV comparison with MCNP code [28].

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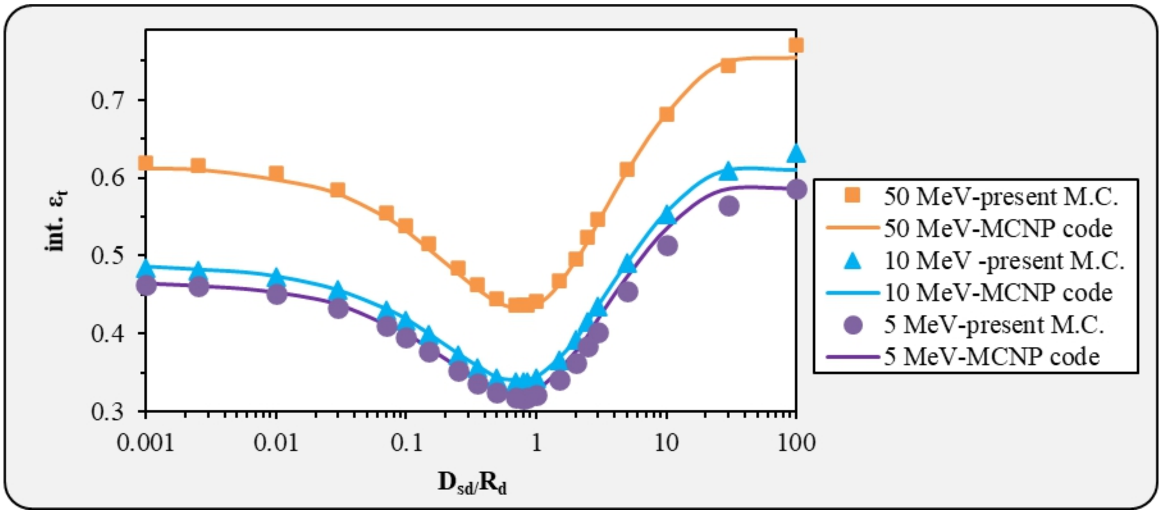

Fig.6. Intrinsic efficiency for 3″×3″ type of NaI(Tl) detector as a function of the ratio D_{sd}/R_d for γ- rays energies of 5, 10, and 50 MeV comparison with MCNP code [28].

As well, for other geometries, the behaviour of curves in fig.7 and them in figs.(5 and 6) was identical. Also, the bottom of well of these curves which represent the value of source-to-front face of detector distance relative to particular radius of detector was around (0.7-0.8).

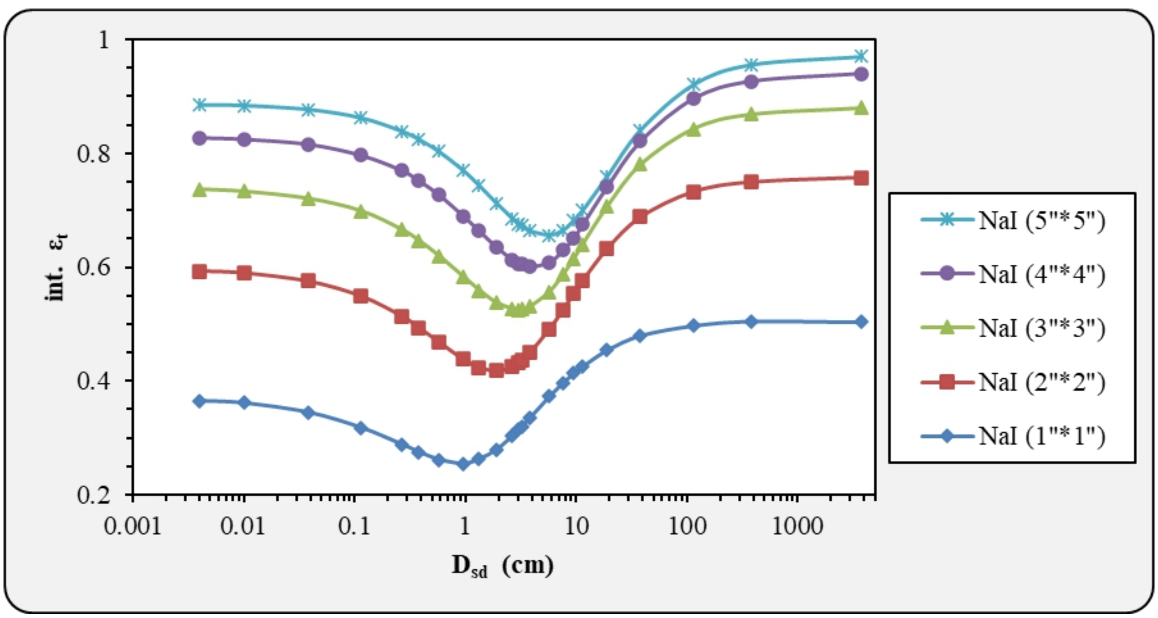

Fig.7. Intrinsic efficiency of various volume detectors as a function of D_{sd} at 662 keV gamma rays.

Variation of int.$\varepsilon_{t.}$ values, in mentioned figuires, were due to variation of mean chord as a function of geometric parameter (i.e. D_{sd}, R_d and H_d) and attenuation coefficient or mean free path values which correlate with probability of γ-rays interaction whose shown in fig.8 and fig.9 or fig.10 respectively.

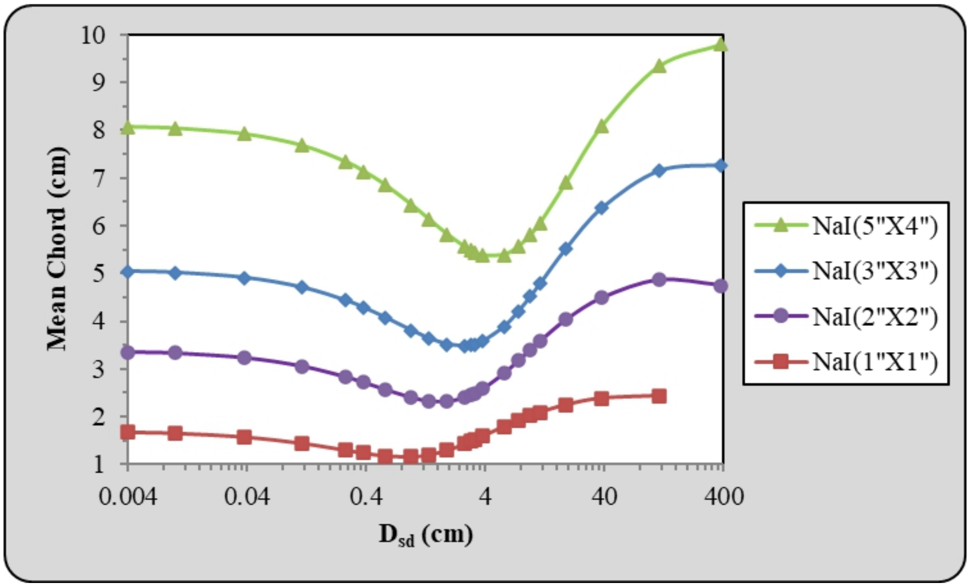

Fig.8. Mean chord of various volumes of NaI detector as a function of D_{sd} at 662 keV gamma rays.

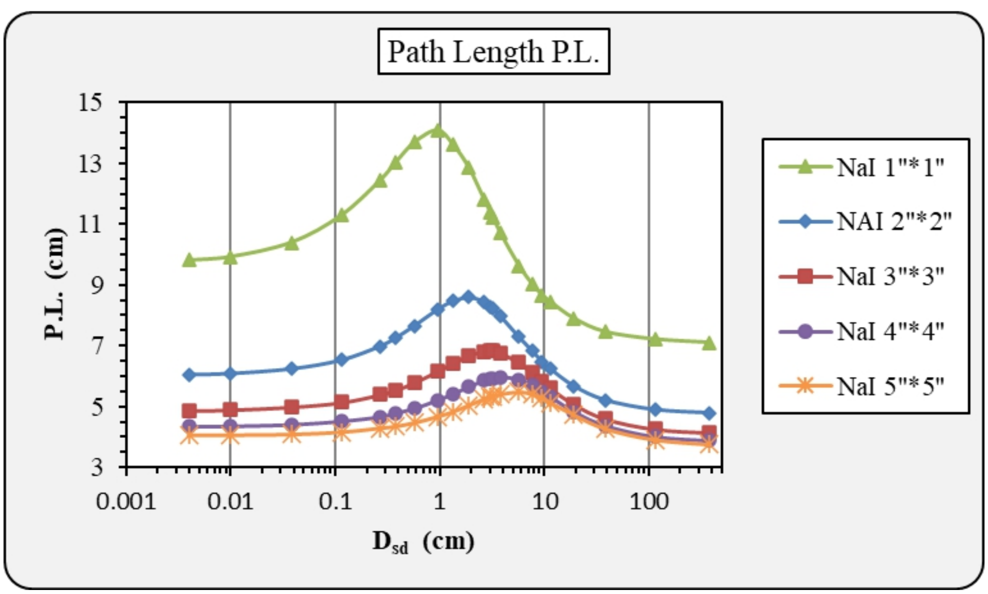

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Fig.9. mean free path length of various volume NaI detectors as a function of D_{sd} at 662 keV gamma rays.

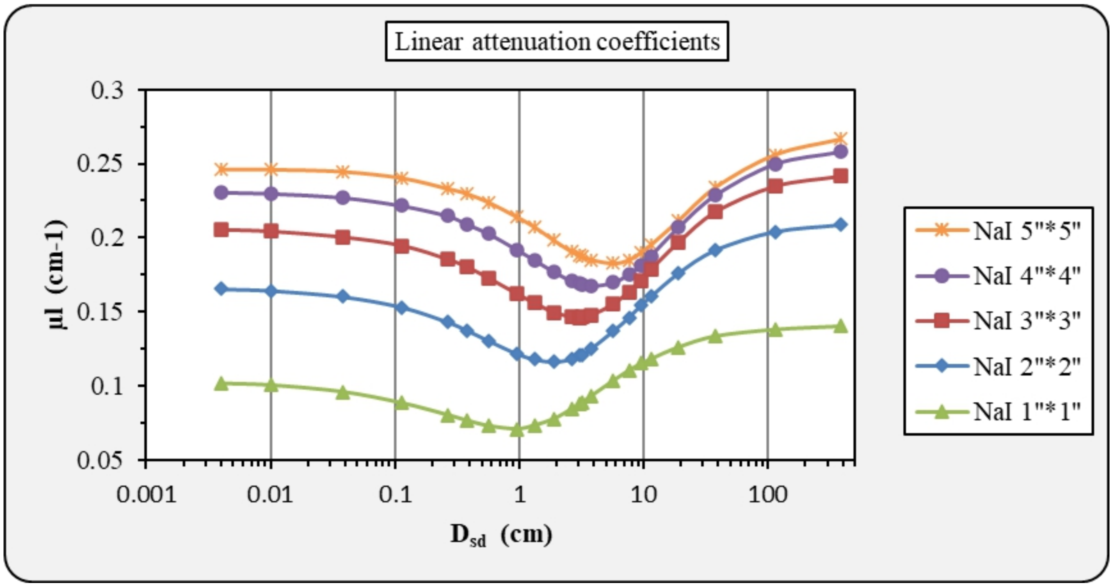

Fig.10. linear attenuation coefficients of various volume for NaI detectors as a function of D_{sd} at 662 keV gamma rays.

To generalization, the present monte carlo simulation carried out for vary types of semi-conductor and scintilation detectors. Since, source-to-front face of detector distance, detector dimensions and energy of γ-rays dependent linear attenuation coefficients, as an input data, are all controllable. The yield results for scintilation PbWO4, CWO, TlBr and BGO also NaI detectors and semiconductor CdTe, HPGe, InP and Si detectors and plastic NE102A detectors shown in fig.11 were identical with them of mentioned NaI detector. As for figs.(12-14) which that corelated with the justifications of behaviour for exhibited data in fig.11 were macthing of them for mentiond NaI detector too.

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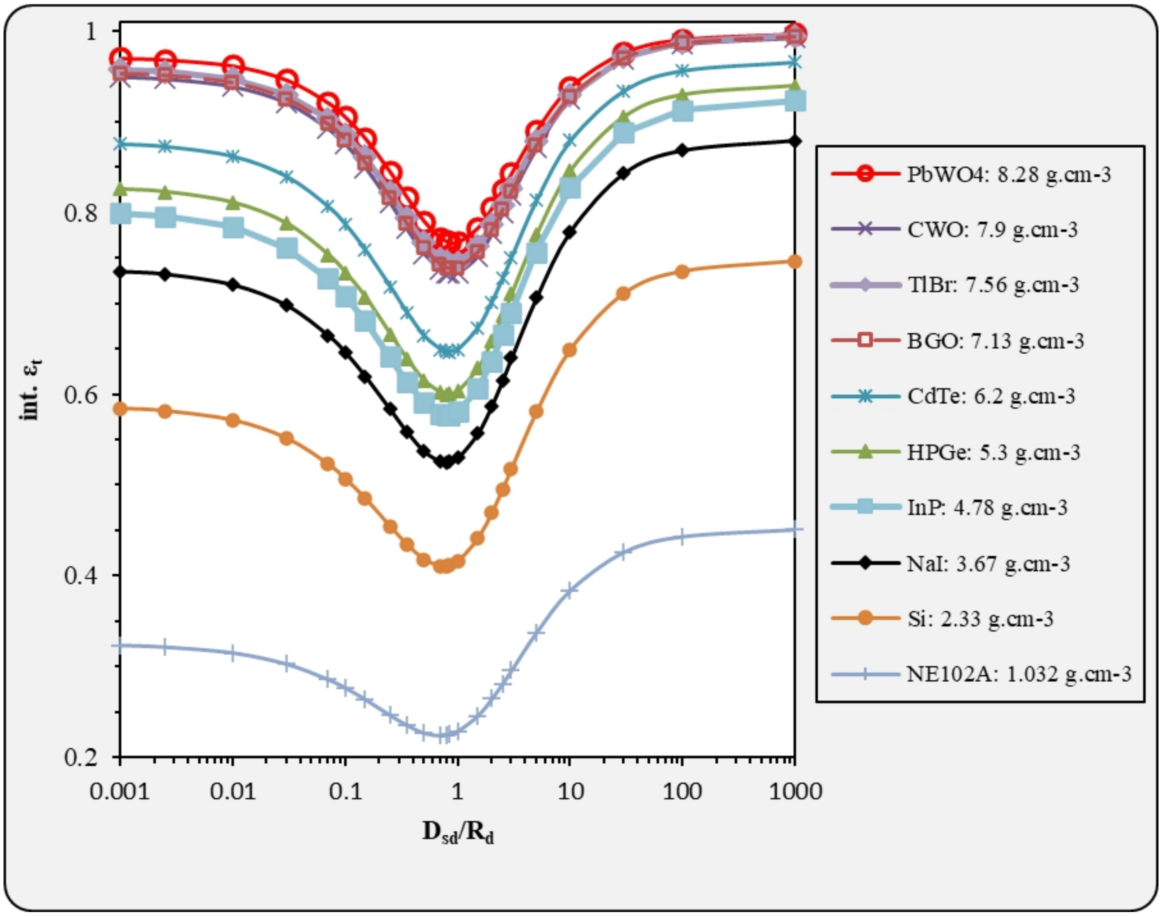

Fig.11. Intrinsic efficiency of various type 3″×3″ detectors as a function of D_{sd}/R_d at 662 keV gamma rays.

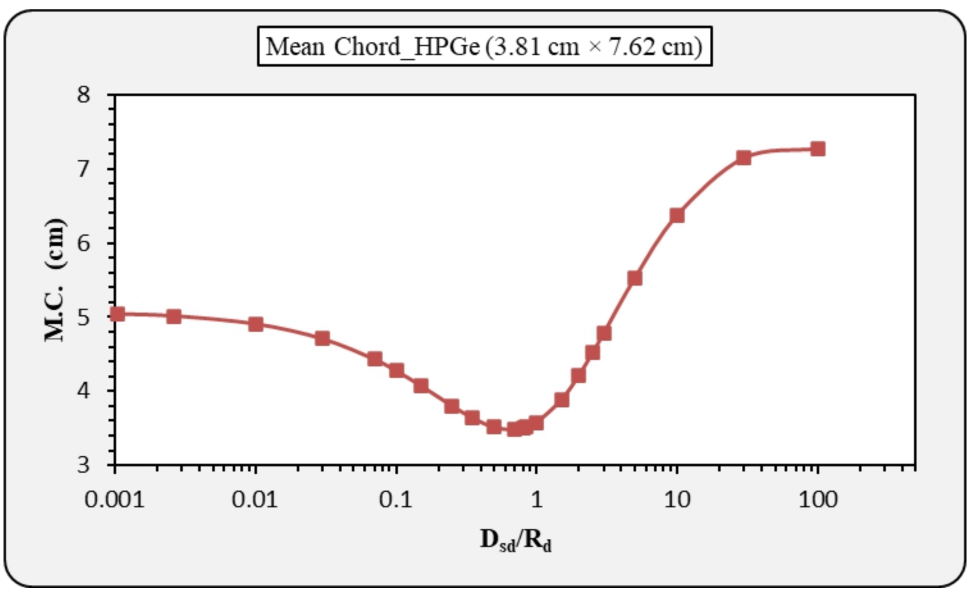

Fig.12. Mean chord of HPGe detector as a function of D_{sd}/R_d at 662 keV gamma rays.

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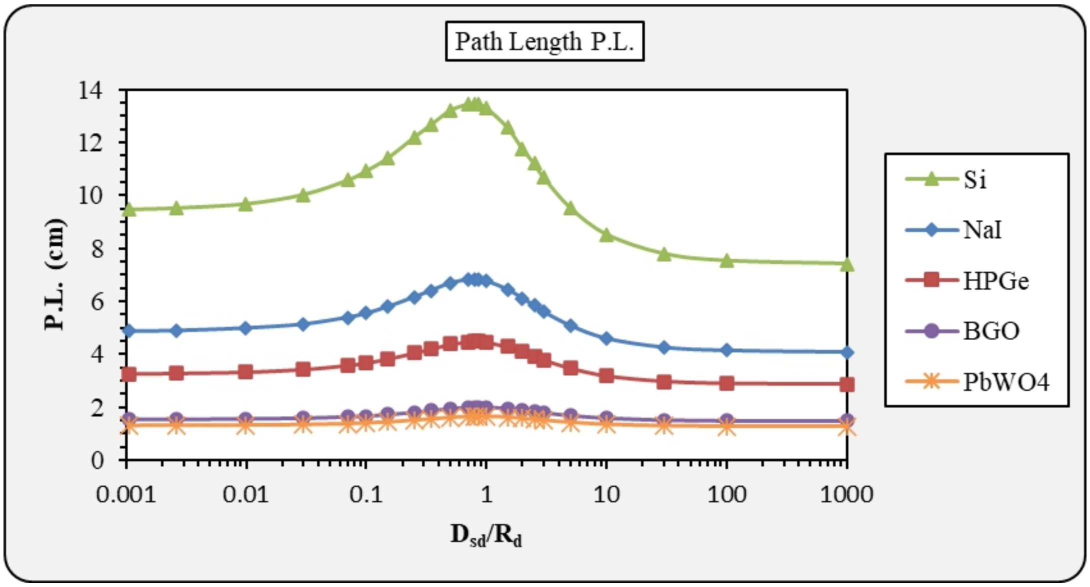

Fig.13. mean free path length of various detectors as a function of D_{sd}/R_d at 662 keV gamma rays.

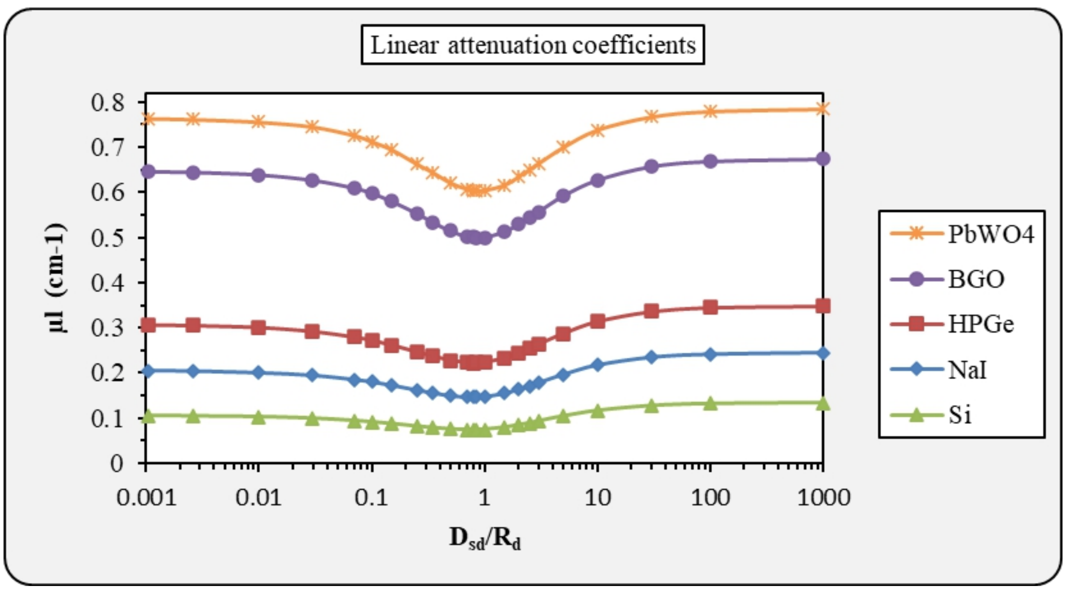

Fig.14. linear attenuation coefficients of various detectors as a function of D_{sd}/R_d at 662 keV gamma rays.

4. Conclusions:

In this paper various types of total efficiency and the change in the intrinsic efficiency of some scintillation and semiconductor detectors with the source-detector distance or its ratio to detector radius (D_{sd}/R_s) were simulated and calculated at wide range of γ-rays energy using Monte Carlo approach, then:

1. The present work provides us with useful tool for efficiency calculations and constitutes a good procedure for the reliable computations instead of the routine of laboratory or exprimental

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measurements. Therefore, one can economize time by averting the calibration of experimental setup for every particular geometry.
2. Variation of intrinsic efficiency versus D_{sd}/R_d can be clear up using mean chord path length of the photons in the active medium of detector and the mean interaction path-length of the photons.
3. Safely from radiation hazards and in less time, the present simulation is helping the experimenter to achieve the best geometry of setup.
4. The results can be functioned in gamma spectroscopy and determination the activity of radioactive sources.
5. The high values of efficiency for detectors type of CWO and BGO makes them a quite rival versus NaI(Tl) detector, especially, for high gamma - energy detection.
6. The superior of absorption of detector type of CdTe, compared with such of BaF_2, HPGe and NaI detectors is very attractive feature in applications concern efficiency at high values of γ-rays energy.

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