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Efficiency and coincidence benchmarking of Monte Carlo method using ^{152}Eu source

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Abstract

A real coaxial HPGe detector, and two lanthanide scintillation detectors have been modeled and characterized by means of Monte Carlo simulation, as part of a project to develop new techniques instrumentation to be used for the primary standardization of high intensity gamma source facilities. The simulation of ^{152}Eu spectra with MCNP 6.2 was used to characterize the detectors in full energy peak efficiency, and coincidence-summing corrections. The ^{152}Eu source, has a complex decay, one by electron conversion, and second beta decay (-β), and in return the spectrum of ^{152}Eu has a lot of peaks affected by the True Coincidence Summing, so any experimental or simulated data needs correction for this effect either during the simulations or after. For post processing of gamma-ray spectra, we used EFFTRAN and GESPECOR software for corrections factors for HPGe, $LaBr_3$(Ce), $LaCl_3$(Ce) detectors. This work also made a comparison on how the two software's will perform.

Keywords Gamma spectrometry · Monte-Carlo method · GESPECOR · MCNP · FITZPEAKS

Introduction

Two different materials detector type are being modeled, semiconductor (HPGe Coaxial P-type detector), and a scintillator one ($LaCl_3$(Ce), and $LaBr_3$(Ce)) in this work, these detectors and their setups are an important component of metrology system which will be used to standardize radionuclides and various new nuclear installations. There are new ways to look for performing primary standardizations of activity at the high energy gamma system at ELI-NP facility. This instrument will complement the existing measurement capability of the gamma system by providing a computational capability to aid in detection techniques and experimental situation. The scope of this work is the characterization of the gamma-ray detectors instrumentation by means of computational methods i.e. Monte Carlo (MC) and deterministic methods. This methodology is justified since it is widely recognized that the application of MC techniques to radiation detector modelling is important in understanding the complex physical interactions that take place, particularly those which cannot be measured directly [5, 6, 9, 12, 14, 25].

A secondary scope is the validation and verification of methods, software employed, gives valid data that can be applied to the radiation measurements techniques both at theoretical and practical level. The MC simulation provides an invaluable resource for the characterization and analysis of a radiation detector and supports the understanding of operating limitations. A MC simulation needs to be validated against experimental measurements in order to quantify the accuracy of the results qualitatively coming from it, in the present work is presented the validation for the MCNP simulation for HPGe detectors against experimental, for second type of detectors we assumed that the initial geometry for germanium detector without additional experimental data just the MC simulation [25]. Further on the coincidence-summing effects that alter the integral of the full energy peak (FEP), impacting the efficiency value and the derived activity is being corrected and compensated. Coincidence-summing arises when two or more γ-rays are emitted from a single decay and are detected at the same time. Moreover, other radiation such as -β particles and their bremsstrahlung, X-rays (from electron capture or internal conversion), and annihilation radiation from β + decay also can be in coincidence with the γ-rays. It has been demonstrated that MC simulations can provide a satisfactory correction for these

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effects [7, 10, 11]. In present work the aim is to model a fully functional detector in terms of, full energy peak efficiency with coincidence-summing correction. The candidate materials chosen are Ge (HPGe) semiconductor type present at Metrology Department, $LaBr_3(Ce)/LaCl_3(Ce)$ scintillation type present at ELI-NP facility, model of the HPGe detector-type is validated against experimental results, performed at the Department Radioisotopes Measurement and Ionizing Radiation Metrology of National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH). The simulation study provided a way to determine if or any required corrections and supply important information about the experimental conditions to be met in order to achieve optimal measurement efficiency and contribute to the data set credibility. Further to enhance the results we employ software used regularly for quantitative analysis in gamma-ray spectrometry analysis of spectra such as Fitzpeaks to provide the photopeak activity and later for correction of coincidence summing using EFFTRAN & GESPECOR 4.2 [2, 3, 8, 15, 16, 26, 31, 36].

Experimental

A ^{152}Eu source with an activity of 12.992 Bq has been measured experimentally at 5 cm from a HPGe coaxial detector preset in National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH). The details of the detectors used in both the experimental as well as the simulations are presented in the Methods section [13, 17, 18].

Methods

For the HPGe simulation (Fig. 1 gives the dimensions supplied by the manufacturer) we simulated a coaxial HPGe manufactured by ORTEC-AMETEK with a serial number S/N 47-TP22323A and model number GEM25P4 with a 25% relative efficiency available at (IFIN-HH). The crystal detector dead layers have been supplied by the manufacturer ORTEC. Based on these characteristics and the crystals dimensions we build the virtual detector in MCNP, GESPECOR and EFFTRAN. Figure 1 shows the manufacturer dimensions of our crystal detector [17, 18, 41, 42].

For the scintillation simulation we employed a general cylindrical shaped type detectors similar to those found in metrology laboratories.

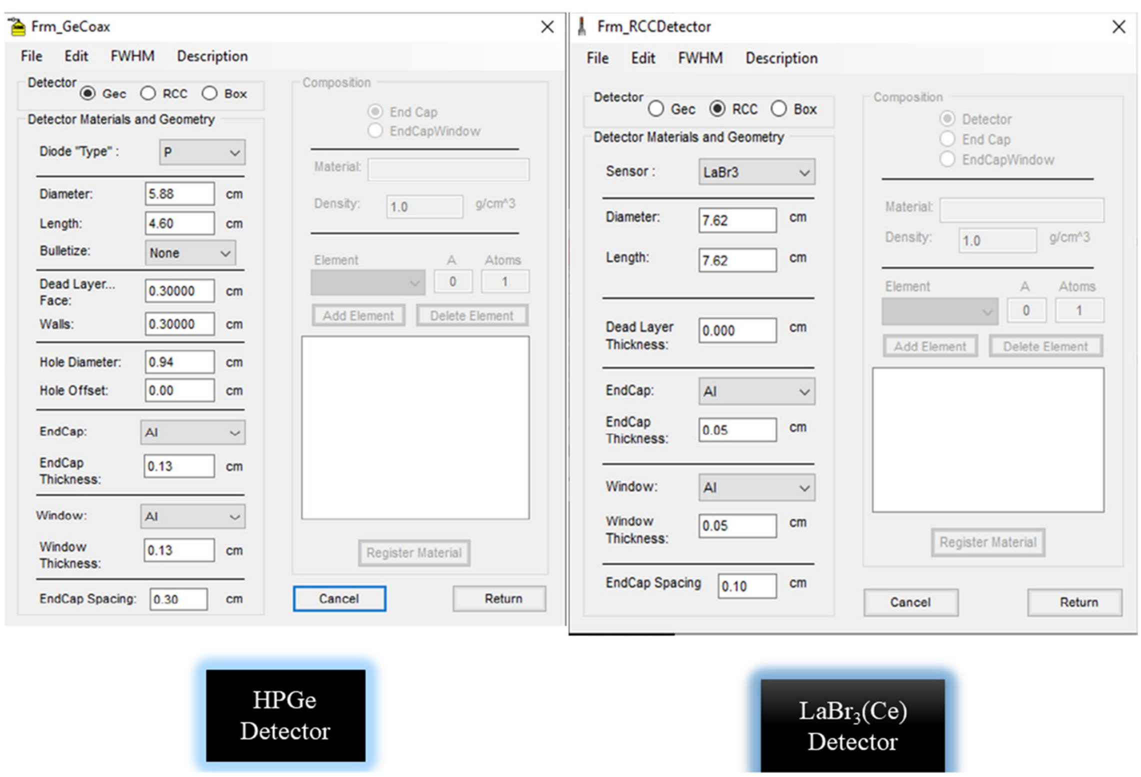

Fig. 1 Detectors characteristics supplied by manufacturer

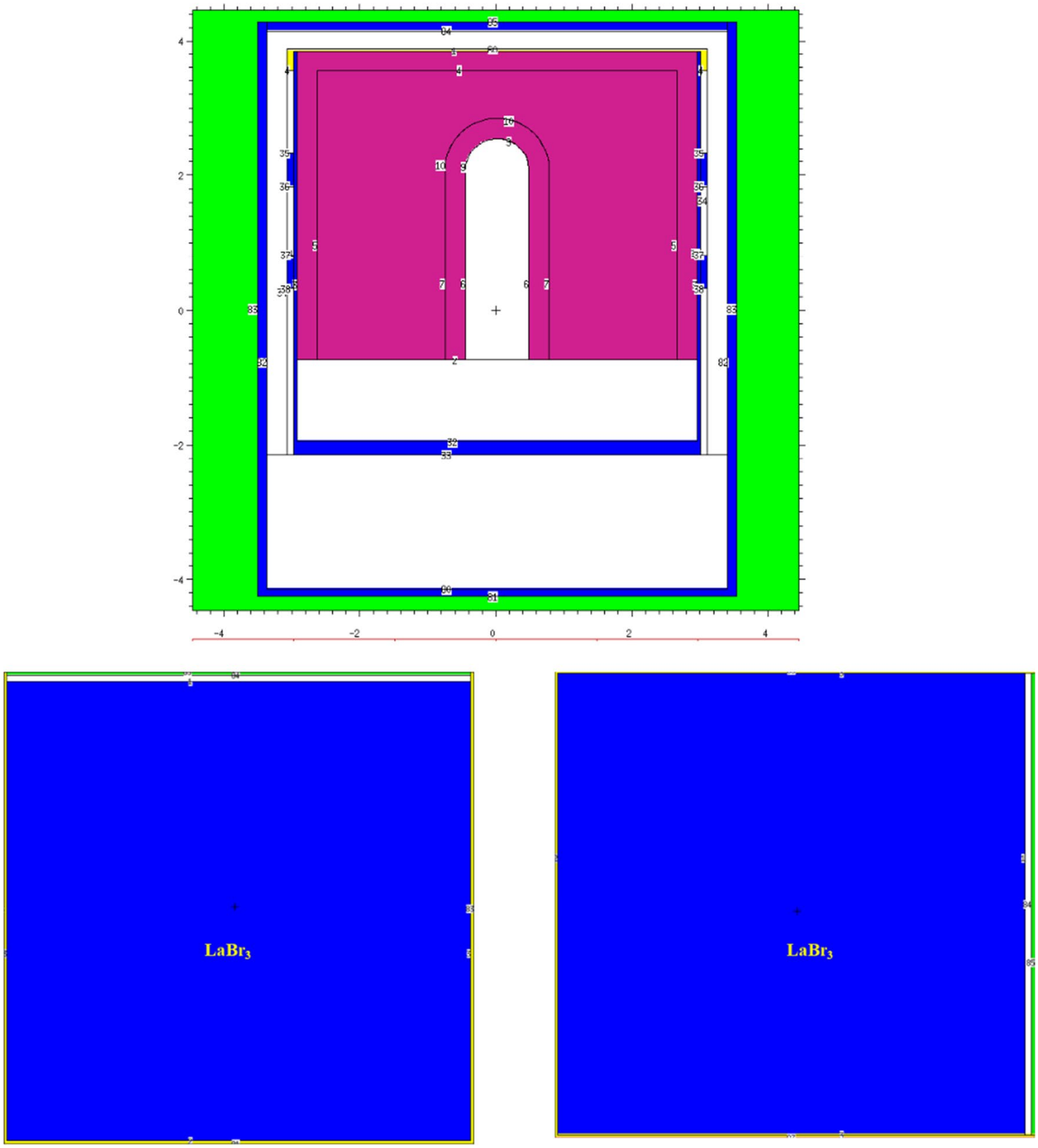

Fig. 2 HPGe, $LaBr_3$(Ce) detector

Scintillation detectors type $LaBr_3$(Ce) and $LaCl_3$(Ce) are being less complex in construction as the material designed for radiation interaction is homogenous and of a single type either $LaBr_3$(Ce) or $LaCl_3$(Ce). The users should be warned that MCNP defines the material characteristics for these two types of detectors as $LaBr_3$ or $LaCl_3$ in material cards and no Cerium is present. Material doping is still a work in progress for the MCNP developing team. Figure 2 presents the scintillation detector in a similar manner previously for HPGe detector, for saving space and not to be too repetitive only one of the scintillation detector figure is used, a similar approach but with $LaCl_3$(Ce) material is used for the third detector [19, 22].

Short details about the employed softwares, starting with SUPERSynth interface for MCNP 6.2, Fitzpeaks for efficiency calculations and spectral analysis, and coincidence correction software employed on the analyzed ^{152}Eu

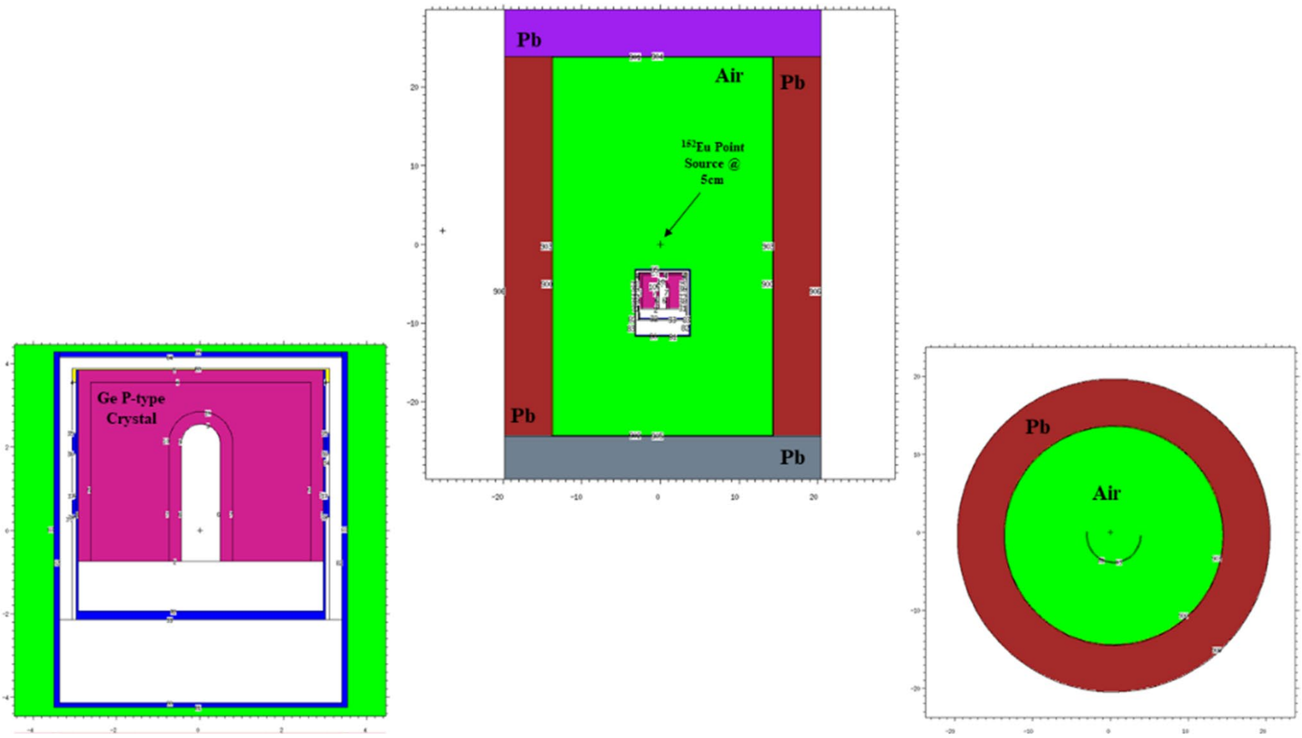

Fig. 3 Shows the detectors setup used with the Lead shield around

photopeaks [24]. The best way to model the response of any detector is by using a standardized source like ^{152}Eu which was selected and alongside a real-life detector [13]. Figure 3 shows side views of HPGe detector using MCNP plotter window (left hand side), and the geometry construction of the detector in MCNP (right hand side) [1, 23].

SUPERSynth is an easy-to-use interface to build up the MCNP input card, thus reducing the time spend of user to generate the input file for running. The menu is easy to use and self-explanatory and most users with advanced experience or little experience in running MCNP simulations will find it very useful in gamma-ray spectrometry

Table 1 Characteristics of ^{152}Eu source (transitions, decay mode, etc.) [35]

Nr.Crt	Transitions	Decay Mode	Energy (keV)	Intensity(100 γ-rays)	Half-Life	Activity Bq	
1	1,0 (Sm)	EC	121.8	61.50	13.52 years	Laboratory Source	Simulated Source
2	2,1 (Sm)	EC	244.7	8.37		12,992	12,992
3	1,0 (Gd)	BETA (-β)	344.3	27.65			
4	5,2 (Sm) 13,9 (Sm)	EC	444.0	2.82			
5	7,1 (Gd)	BETA (-β)	778.9	12.99			
6	10,2 (Sm)	EC	867.4	4.25			
7	9,1 (Sm)	EC	964.1	14.54			
8	9,0 (Sm)	EC	1085.8	10.15			
9	10,1 (Sm)	EC	1112.1	18.98			
10	14,1 (Gd)	BETA (-β)	1299.1	1.63			
11	13,1 (Sm)	EC	1408.0	20.86			
12	14,1 (Sm)	EC	1457.6	0.49			
13	16,1 (Sm)	EC	1528.1	0.28			

Table 2 Data for experimental source of ^{152}Eu @ 5 cm

HPGe

Nr. Crt	Activity (Bq)	Energy	Peak Area Counts	Uncertainty	GESPECOR Correction Factors	EFFTRAN Correction Factors	Probability %	Probability per 100 gamma-rays	Uncertainity Probability (%)	Uncertainity Probability	Live Time (s)	Efficiency	Efficiency (%)	Inc. ef. (%)	Inc. ef
1	12,992	121.8	9.22E+04	0.6	1.0858	1.0751	0.284100	28.4100	0.0012	0.120	1000	0.02498	2.49752	0.42246	0.00011
2	12,992	244.7	1.68E+04	1.4	1.1167	1.1103	0.075500	7.5500	0.0003	0.030	1000	0.01714	1.71354	0.39751	0.00007
3	12,992	344.3	4.53E+04	0.8	1.0538	1.0255	0.265900	26.5900	0.0150	1.500	1000	0.01312	1.31165	5.64122	0.00074
4	12,992	444.0	4.23E+03	2.9	1.1020	1.0969	0.028000	2.8000	0.0003	0.027	1000	0.01163	1.16250	0.96675	0.00011
5	12,992	778.9	1.02E+04	1.8	1.0728	1.0377	0.129700	12.9700	0.0009	0.090	1000	0.00604	0.60384	0.69418	0.00004
6	12,992	867.4	2.98E+03	3.7	1.1293	1.1250	0.042430	4.2430	0.0003	0.029	1000	0.00541	0.54130	0.69468	0.00004
7	12,992	964.1	9.73E+03	1.8	1.0425	1.0822	0.145000	14.5000	0.0009	0.090	1000	0.00517	0.51665	0.62101	0.00003
8	12,992	1085.8	6.30E+03	2.3	0.9709	1.0089	0.101300	10.1300	0.0009	0.090	1000	0.00479	0.47860	0.88923	0.00004
9	12,992	1112.1	8.09E+03	2	1.0291	1.0685	0.134100	13.4100	0.0008	0.080	1000	0.00464	0.46436	0.59713	0.00003
10	12,992	1299.2	7.78E+02	7.1	1.0731	1.0380	0.016330	1.6330	0.0003	0.029	1000	0.00367	0.36685	1.99648	0.00007
11	12,992	1408.0	1.00E+04	1.7	1.0408	1.0740	0.208500	20.8500	0.0007	0.070	1000	0.00370	0.36961	0.33625	0.00001
12	12,992	1457.6	2.72E+02	10.6	0.8838	0.9930	0.004980	0.4980	0.0001	0.006	1000	0.00421	0.42094	4.07427	0.00017
13	12,992	1528.1	2.53E+02	11	0.9805	1.0507	0.002810	0.2810	0.0001	0.006	1000	0.00694	0.69424	4.83692	0.00034

Table 3 Simulated Data for ^{152}Eu @ 5 cm

Nr. Crt	Activity (Bq)	Energy	Measured	Error	Fitted	Error	Peak Area Counts	Uncertainty	GESPECOR Correction Factors	EFFTRAN Correction Factors	Probability %	Probability per 100 gamma-rays	Uncertainity Probability (%)	Uncertainity Probability	Live Time (s)	Efficiency	Efficiency (%)	Inc. ef. (%)	Inc. ef
HPGe																			
1	12,992	121.8	2.1536	1.1	2.1540	0.5	1.50E+07	0.1	1.0858	1.0751	0.284100	28.4100	0.0012	0.120	200,000	0.02033	2.03290	0.42246	0.00009
2	12,992	244.7	1.7757	1.1	1.7755	0.5	3.28E+06	0.1	1.1167	1.1103	0.075500	7.5500	0.0003	0.030	200,000	0.01674	1.67408	0.39743	0.00007
3	12,992	344.3	1.2930	1.1	1.2928	1.1	8.44E+06	0.1	1.0538	1.0255	0.265900	26.5900	0.0150	1.500	200,000	0.01221	1.22131	5.64122	0.00069
4	12,992	444.0	1.0096	1.1	1.0095	1.1	7.75E+05	0.3	1.1020	1.0969	0.028000	2.8000	0.0003	0.027	200,000	0.01065	1.06511	0.96432	0.00010
5	12,992	778.9	0.6047	1.1	0.7467	1.1	1.93E+06	0.2	1.0728	1.0377	0.129700	12.9700	0.0009	0.090	200,000	0.00572	0.57158	0.69395	0.00004
6	12,992	867.4	0.5559	1.2	0.3774	1.2	5.75E+05	0.4	1.1293	1.1250	0.042430	4.2430	0.0003	0.029	200,000	0.00522	0.52185	0.68352	0.00004
7	12,992	964.1	0.5072	1.1	0.2529	1.1	1.82E+06	0.2	1.0425	1.0822	0.145000	14.5000	0.0009	0.090	200,000	0.00484	0.48375	0.62074	0.00003
8	12,992	1085.8	0.4587	1.1	0.2335	1.1	1.14E+06	0.2	0.9709	1.0089	0.101300	10.1300	0.0009	0.090	200,000	0.00434	0.43356	0.88848	0.00004
9	12,992	1112.1	0.4542	1.1	0.2421	1.1	1.51E+06	0.2	1.0291	1.0685	0.134100	13.4100	0.0008	0.080	200,000	0.00434	0.43353	0.59662	0.00003
10	12,992	1299.2	0.3878	1.3	0.4935	1.3	1.55E+05	0.6	1.0731	1.0380	0.016330	1.6330	0.0003	0.029	200,000	0.00365	0.36499	1.77589	0.00006
11	12,992	1408.0	0.3683	1.1	0.3688	1.1	1.89E+06	0.1	1.0408	1.0740	0.208500	20.8500	0.0007	0.070	200,000	0.00348	0.34808	0.33582	0.00001
12	12,992	1457.6	0.3563	1.4	0.3570	1.4	4.38E+04	1.0	0.8838	0.9930	0.004980	0.4980	0.0001	0.006	200,000	0.00338	0.33811	1.20485	0.00004
13	12,992	1528.1	0.3567	1.5	0.3558	1.5	2.37E+04	1.3	0.9805	1.0507	0.002810	0.2810	0.0001	0.006	200,000	0.00324	0.32393	2.13525	0.00007
$LaBr_3$(Ce)																			
1	12,992	121.8	9.25090	1.1	9.19300	1.1	6.45E+07	0.1	N/A	2.242	0.284100	28.4100	0.0012	0.120	200,000	0.08731	8.73131	0.42246	0.00037
2	12,992	244.7	6.98340	1.1	6.51750	1.1	1.29E+07	0.1	N/A	3.110	0.075500	7.5500	0.0003	0.030	200,000	0.06583	6.58276	0.39743	0.00026
3	12,992	344.3	5.61670	1.1	5.40330	1.1	3.67E+07	0.1	N/A	1.356	0.265900	26.5900	0.0150	1.500	200,000	0.05305	5.30471	5.64122	0.00299
4	12,992	444.0	4.56270	1.1	4.64060	1.1	3.50E+06	0.3	N/A	2.721	0.028000	2.8000	0.0003	0.027	200,000	0.04813	4.81313	0.96432	0.00046
5	12,992	778.9	2.94050	1.1	3.15350	1.1	9.37E+06	0.2	N/A	1.643	0.129700	12.9700	0.0009	0.090	200,000	0.02779	2.77924	0.69395	0.00019
6	12,992	867.4	2.69170	1.3	2.90160	1.3	2.79E+06	0.6	N/A	3.730	0.042430	4.2430	0.0003	0.029	200,000	0.02527	2.52671	0.68352	0.00017
7	12,992	964.1	2.37190	1.1	2.66490	1.1	8.52E+06	0.2	N/A	2.222	0.145000	14.5000	0.0009	0.090	200,000	0.02262	2.26190	0.62074	0.00014
8	12,992	1085.8	2.74680	1.1	2.41160	1.1	6.83E+06	0.2	N/A	1.152	0.101300	10.1300	0.0009	0.090	200,000	0.02596	2.59618	0.88848	0.00023
9	12,992	1112.1	2.41510	1.1	2.36240	1.1	8.03E+06	0.2	N/A	1.897	0.134100	13.4100	0.0008	0.080	200,000	0.02305	2.30475	0.59662	0.00014
10	12,992	1299.2	2.14930	1.3	2.05640	1.3	8.58E+05	0.2	N/A	1.640	0.016330	1.6330	0.0003	0.029	200,000	0.02023	2.02270	1.77589	0.00036
11	12,992	1408.0	1.86430	1.1	1.90760	1.1	9.55E+06	0.1	N/A	2.012	0.208500	20.8500	0.0007	0.070	200,000	0.01762	1.76203	0.33582	0.00006
12	12,992	1457.6	1.82890	1.2	1.84570	1.2	2.25E+05	0.5	N/A	0.953	0.004980	0.4980	0.0001	0.006	200,000	0.01736	1.73554	1.20484	0.00021
13	12,992	1528.1	1.80590	1.3	1.76320	1.3	1.20E+05	0.6	N/A	1.423	0.002810	0.2810	0.0001	0.006	200,000	0.01640	1.64007	2.13525	0.00035
$LaCl_3$(Ce)																			
1	12,992	121.8	9.10580	1.1	9.01860	1.1	6.34E+07	0.1	N/A	2.242	0.284100	28.4100	0.0012	0.120	200,000	0.08594	8.59422	0.42246	0.00036
2	12,992	244.7	7.17060	1.1	7.12000	1.1	1.33E+07	0.1	N/A	3.110	0.075500	7.5500	0.0003	0.030	200,000	0.06759	6.75913	0.39743	0.00027
3	12,992	344.3	5.84390	1.1	6.01070	1.1	3.81E+07	0.1	N/A	1.356	0.265900	26.5900	0.0150	1.500	200,000	0.05519	5.51921	5.64122	0.00311
4	12,992	444.0	4.80810	1.1	5.17760	1.1	3.69E+06	0.2	N/A	2.721	0.028000	2.8000	0.0003	0.027	200,000	0.05072	5.07194	0.96432	0.00049
5	12,992	778.9	3.12580	1.1	3.47060	1.1	9.96E+06	0.2	N/A	1.643	0.129700	12.9700	0.0009	0.090	200,000	0.02954	2.95434	0.69395	0.00021
6	12,992	867.4	2.86550	1.3	3.17940	1.3	2.97E+06	0.5	N/A	3.730	0.042430	4.2430	0.0003	0.029	200,000	0.02690	2.68979	0.68352	0.00018
7	12,992	964.1	2.55400	1.1	2.90710	1.1	9.18E+06	0.2	N/A	2.222	0.145000	14.5000	0.0009	0.090	200,000	0.02436	2.43556	0.62074	0.00015
8	12,992	1085.8	2.94310	1.1	2.61760	1.1	7.32E+06	0.2	N/A	1.152	0.101300	10.1300	0.0009	0.090	200,000	0.02782	2.78173	0.88848	0.00025

Table 3 (continued)

Nr. Crt	Activity (Bq)	Energy	Measured	Error	Fitted	Error	Peak Area Counts	Uncertainty	GESPECOR Correction Factors	EFFTRAN Correction Factors	Probability %	Probability per 100 gamma-rays	Uncertainty Probability (%)	Uncertainty Probability	Live Time (s)	Efficiency	Efficiency (%)	Inc. ef. (%)	Inc. ef
9	12,992	1112.1	2.58420	1.1	2.56170	1.1	8.59E+06	0.2	N/A	1.897	0.134100	13.4100	0.0008	0.080	200,000	0.02466	2.46615	0.59662	0.00015
10	12,992	1299.2	2.30960	1.1	2.21620	1.1	9.22E+05	0.7	N/A	1.640	0.016330	1.6330	0.0003	0.029	200,000	0.02174	2.17358	1.77589	0.00039
11	12,992	1408.0	2.01740	1.1	2.05010	1.1	1.03E+07	0.1	N/A	2.012	0.208500	20.8500	0.0007	0.070	200,000	0.01907	1.90673	0.33582	0.00006
12	12,992	1457.6	1.97980	1.2	1.98130	1.2	2.43E+05	0.5	N/A	0.953	0.004980	0.4980	0.0001	0.006	200,000	0.01879	1.87874	1.20484	0.00023
13	12,992	1528.1	1.95960	1.3	1.89000	1.3	1.30E+05	0.6	N/A	1.423	0.002810	0.2810	0.0001	0.006	200,000	0.01780	1.77963	2.13525	0.00038

works. Used in generating our data was MCNP 6.2, mode P for photons with Doppler Broadening and Gaussian Energy Broadening (GEB) terms active. Computer time was ~ 2262.47 min (135,748.2 s).

After the MCNP finished successfully the output was converted to ORTEC spe file format which was read with Fitzpeaks. Fitzpeaks is a gamma- ray analysis software used in both experimental and simulated data. We employed Fitzpeaks to get the photopeaks areas and the efficiencies per photopeaks of the spectrum.

Germanium Spectrum Correction (GESPECOR) is software that employs Monte Carlo method for getting the correction factor for coincidence gamma- ray spectrometry. GESPECOR can be applied to coaxial and well-type HPGe or to Ge (Li) detectors and to various types of sources, including point, cylindrical, and spherical sources or Marinelli beakers.

EFFTRAN is a Monte Carlo efficiency transfer code, recently was updated with a deterministic code for coincidence correction factor calculation. The approach is aimed at the analysis of extended samples measured on p-type HPGe detectors in environmental gamma-ray spectrometry and was verified against the results of a state-of-the-art full Monte Carlo code [4, 28, 33, 39, 40].

The applied MC method from GESPCOR 4.2 and EFFTRAN deterministic method for benchmarking between the two-software coincidence correction is being used for HPGe detector. Experimentally the full energy peak efficiency ε is given by the equation:

$$\varepsilon = \frac{N_{\mathbf{meas}}}{A \bullet I_{\gamma} \bullet LT_{\mathbf{meas}}} \quad (1)$$

N_{meas} is the measured counts, A is the known activity of the source in becquerels, I_{γ} is the γ-emission intensity and LT_{meas} is the live-time of measurement in seconds.

Table 1 Presents the decay peaks of the ^{152}Eu, intensity, transitions, and decay mode.

We selected a widely used and relevant geometry and distance source- detector, a 5 cm distance from the source emitter and the detectors have been employed, this is a typical distance in most calibrations, simulations, and experiments performed in the literature.

Figure 3 gives detail picture of the setup of the present work using HPGe detector but similar position has been employed for scintillation detectors, we can see the lead shield detector and the source at 5 cm place on top of detectors.

No absorber has been used, electronics, the counting parameters (gain, channels number, live time), the gain was set 1, channel number was selected to a typical experimental acquisition of 4096 channels, and a live time of 200.000 s. the shielding used around the setup was a 5 cm thickness

Table 4 Simulated Data for ^{152}Eu @ 10cm

Nr.Crt	Activity (Bq)	Energy	Measured	Error	Fitted	Error	Peak Area Counts	Uncertainty	GESPECOR Correction Factors	EFFTRAN Correction Factors	Probability %	Probability per 100 gamma-rays	Uncertainity Probability (%)	Uncertainity Probability	Live Time (s)	Efficiency	Efficiency (%)	Inc. ef. (%)	Inc. ef
HPGe																			
1	12,992	121.8	0.7272	1.1	0.7272	1.1	5.07E+06	0.1	N/A	1.017	0.284100	28.4100	0.0012	0.120	200,000	0.00686	0.68641	0.42246	0.00003
2	12,992	244.7	0.6262	1.1	0.6262	1.1	1.16E+06	0.2	N/A	1.024	0.075500	7.5500	0.0003	0.030	200,000	0.00590	0.59038	0.39743	0.00002
3	12,992	344.3	0.4616	1.1	0.4616	1.1	3.01E+06	0.1	N/A	1.009	0.265900	26.5900	0.0150	1.500	200,000	0.00436	0.43600	5.64122	0.00025
4	12,992	444.0	0.3631	1.2	0.3631	1.2	2.79E+05	0.4	N/A	1.021	0.028000	2.8000	0.0003	0.027	200,000	0.00383	0.38305	0.96432	0.00004
5	12,992	778.9	0.2193	1.1	0.2193	1.1	6.99E+05	0.2	N/A	1.012	0.129700	12.9700	0.0009	0.090	200,000	0.00207	0.20732	0.69395	0.00001
6	12,992	867.4	0.2012	1.3	0.2012	1.3	2.08E+05	0.5	N/A	1.027	0.042430	4.2430	0.0003	0.029	200,000	0.00189	0.18889	0.68352	0.00001
7	12,992	964.1	0.1841	1.1	0.1841	1.1	6.62E+05	0.2	N/A	1.015	0.145000	14.5000	0.0009	0.090	200,000	0.00176	0.17561	0.62074	0.00001
8	12,992	1085.8	0.1673	1.1	0.1673	1.1	4.16E+05	0.3	N/A	0.997	0.101300	10.1300	0.0009	0.090	200,000	0.00158	0.15815	0.88848	0.00001
9	12,992	1112.1	0.1661	1.1	0.1661	1.1	5.52E+05	0.2	N/A	1.011	0.134100	13.4100	0.0008	0.080	200,000	0.00159	0.15854	0.59662	0.00001
10	12,992	1299.2	0.1417	1.4	0.1417	1.4	5.66E+04	0.8	N/A	1.012	0.016330	1.6330	0.0003	0.029	200,000	0.00133	0.13335	1.77589	0.00002
11	12,992	1408.0	0.1344	1.1	0.1344	1.1	6.88E+05	0.2	N/A	1.013	0.208500	20.8500	0.0007	0.070	200,000	0.00127	0.12704	0.33582	0.00000
12	12,992	1457.6	0.1306	1.7	0.1306	1.7	1.60E+04	1.3	N/A	0.987	0.004980	0.4980	0.0001	0.006	200,000	0.00124	0.12393	1.20487	0.00001
13	12,992	1528.1	0.1311	1.1	0.1311	1.1	8.70E+03	1.8	N/A	1.006	0.002810	0.2810	0.0001	0.006	200,000	0.00119	0.11909	2.13535	0.00003
$LaBr_3$(Ce)																			
1	12,992	121.8	3.06980	1.1	3.05370	1.1	2.14E+07	0.1	N/A	1.013	0.284100	28.4100	0.0012	0.120	200,000	0.02897	2.89743	0.42246	0.00012
2	12,992	244.7	2.47870	1.1	2.38430	1.1	4.58E+06	0.1	N/A	1.019	0.075500	7.5500	0.0003	0.030	200,000	0.02337	2.33664	0.39743	0.00009
3	12,992	344.3	2.03120	1.1	2.02400	1.1	1.33E+07	0.1	N/A	1.008	0.265900	26.5900	0.0150	1.500	200,000	0.01918	1.91847	5.64122	0.00108
4	12,992	444.0	1.67800	1.2	1.75470	1.2	1.29E+06	0.4	N/A	1.017	0.028000	2.8000	0.0003	0.027	200,000	0.01770	1.77018	0.96432	0.00017
5	12,992	778.9	2.20840	2.8	1.65470	2.8	3.45E+06	0.3	N/A	1.012	0.129700	12.9700	0.0009	0.090	200,000	0.01023	1.02302	0.69395	0.00007
6	12,992	867.4	1.08230	1.1	1.19380	1.1	1.10E+06	0.5	N/A	1.023	0.042430	4.2430	0.0003	0.029	200,000	0.00993	0.99338	0.68352	0.00007
7	12,992	964.1	1.05820	1.3	1.09610	1.3	3.30E+06	0.2	N/A	1.010	0.145000	14.5000	0.0009	0.090	200,000	0.00876	0.87582	0.62074	0.00005
8	12,992	1085.8	0.91840	1.1	1.00390	1.1	2.49E+06	0.2	N/A	0.993	0.101300	10.1300	0.0009	0.090	200,000	0.00947	0.94701	0.88848	0.00008
9	12,992	1112.1	1.00190	1.1	0.90510	1.1	2.92E+06	0.2	N/A	1.005	0.134100	13.4100	0.0008	0.080	200,000	0.00837	0.83683	0.59662	0.00005
10	12,992	1299.2	0.87690	1.1	0.88590	1.1	2.47E+05	0.9	N/A	1.012	0.016330	1.6330	0.0003	0.029	200,000	0.00581	0.58147	1.77589	0.00010
11	12,992	1408.0	0.71240	1.1	0.70890	1.1	3.65E+06	0.1	N/A	1.008	0.208500	20.8500	0.0007	0.070	200,000	0.00673	0.67337	0.33582	0.00002
12	12,992	1457.6	0.67250	1.6	0.68490	1.6	8.26E+04	1.2	N/A	0.972	0.004980	0.4980	0.0001	0.006	200,000	0.00638	0.63821	1.20484	0.00008
13	12,992	1528.1	0.70450	2.1	0.65290	2.1	4.67E+04	1.8	N/A	0.996	0.002810	0.2810	0.0001	0.006	200,000	0.00640	0.63984	2.13525	0.00014
$LaCl_3$(Ce)																			
1	12,992	121.8	3.0194	1.1	2.9809	1.1	2.10E+07	0.1	N/A	1.013	0.284100	28.4100	0.0012	0.120	200,000	0.02850	2.84975	0.42246	0.00012
2	12,992	244.7	2.1901	1.1	2.1901	1.1	4.58E+06	0.1	N/A	1.019	0.075500	7.5500	0.0003	0.030	200,000	0.02336	2.33587	0.39743	0.00009
3	12,992	344.3	2.0966	1.1	2.0479	1.1	1.37E+07	0.1	N/A	1.008	0.265900	26.5900	0.0150	1.500	200,000	0.01980	1.98013	5.64122	0.00112
4	12,992	444.0	1.7602	1.2	1.8053	1.2	1.35E+06	0.4	N/A	1.017	0.028000	2.8000	0.0003	0.027	200,000	0.01857	1.85677	0.96432	0.00018
5	12,992	778.9	1.1729	1.1	1.2718	1.1	3.74E+06	0.2	N/A	1.012	0.129700	12.9700	0.0009	0.090	200,000	0.01109	1.10853	0.69395	0.00008
6	12,992	867.4	1.1156	1.3	1.1739	1.3	1.15E+06	0.5	N/A	1.023	0.042430	4.2430	0.0003	0.029	200,000	0.01047	1.04716	0.68352	0.00007
7	12,992	964.1	0.9741	1.1	1.0801	1.1	3.50E+06	0.2	N/A	1.010	0.145000	14.5000	0.0009	0.090	200,000	0.00929	0.92893	0.62074	0.00006

Table 4 (continued)

Nr.Crt	Activity (Bq)	Energy	Measured	Error	Fitted	Error	Peak Area Counts	Uncertainty	GESPECOR Correction Factors	EFFTRAN Correction Factors	Probability %	Probability per 100 gamma-rays	Uncertainty Probability (%)	Uncertainty Probability	Live Time (s)	Efficiency	Efficiency (%)	Inc. ef. (%)	Inc. ef
8	12,992	1085.8	1.0781	1.1	0.9779	1.1	2.68E+06	0.2	N/A	0.993	0.101300	10.1300	0.0009	0.090	200,000	0.01019	1.01897	0.88848	0.00009
9	12,992	1112.1	0.9402	1.1	0.9579	1.1	3.13E+06	0.2	N/A	1.005	0.134100	13.4100	0.0008	0.080	200,000	0.00897	0.89718	0.59662	0.00005
10	12,992	1299.2	0.7738	1.1	0.7697	1.1	2.76E+05	0.8	N/A	1.012	0.016330	1.6330	0.0003	0.029	200,000	0.00650	0.64979	1.77589	0.00012
11	12,992	1408.0	0.7738	1.1	0.7697	1.1	3.96E+06	0.1	N/A	1.008	0.208500	20.8500	0.0007	0.070	200,000	0.00731	0.73139	0.33582	0.00002
12	12,992	1457.6	0.7565	1.4	0.7438	1.4	9.29E+04	0.8	N/A	0.972	0.004980	0.4980	0.0001	0.006	200,000	0.00718	0.71789	1.20484	0.00009
13	12,992	1528.1	0.7374	1.7	0.7091	1.7	4.89E+04	1.2	N/A	0.996	0.002810	0.2810	0.0001	0.006	200,000	0.00670	0.66963	2.13525	0.00014

shield made of lead with 0.1 mm thickness copper layers covering the ceiling, walls, floor of the shield.

Results and discussion

In the present work, results of ^{152}Eu source at 5 cm from the detection setup is being presented. Experimentally it has been employed a source with an activity of 12.992 Bq at 5 cm from the detector, while the MCNP simulation used 4 sets of data (5 cm, 10 cm, 20 cm, 30 cm). The input development has been done with the help of SUPERSynth interface for MCNP all the details of geometry, source definition, detectors characteristics, electronics, environment, furthermore all the results have been simulated with MCNP 6.2 version. The results were processed, by calculating the efficiency separately and with the aid of Fitzpeaks 3.90 and we obtained a comparison of detectors efficiencies, further we employed two different software for gamma coincidence predictions for benchmarking and comparison reasons on experimental and on the HPGe, $LaBr_3$(Ce) and $LaCl_3$(Ce) detector simulation, GESPECOR 4.2 (licensed to IFIN-HH), EFFTRAN from European Commission (Dr. Tim Vidmar) [3, 15, 16, 31, 36]. GESPECOR correction is being used for the laboratory spectra with 12.992 as well as the simulated ones taken, as a comparison for our work. ^{152}Eu, the lines overlap on both software's which provide good agreement of the value of data in this work.

We have obtained data on efficiency of the detectors of HPGe, $LaBr_3$(Ce), $LaCl_3$(Ce). Further ahead tables with correction factors used. A single experimental data set was taken with HPGe detector from the Spectrometric laboratory from (IFIN-HH) with the source placed at 5 cm. Four different sets at four different distances from the detectors have been simulated plus a laboratory measurement have been chosen for this work so to establish the efficacy of the softwares and methods employed in the current work. $LaBr_3$(Ce) and $LaCl_3$(Ce) where observed in a similar process and both have close if not identical data sets. The efficiency curve has been fitted with a decay function which fits the data sets in good agreement and some points overlap perfectly.

Table 2 Contains data for the experimental source with selected 13 photopeaks, data contained are energy, initial photopeaks area, correction factors from EFFTRAN/GESPECOR, and the error in percentages. Table 3 @5 cm, Table 4 @10 cm, Table 5 @20 cm, Table 6 @30 cm, data for all 3 type detectors [27, 29, 30, 32, 34, 37, 38].

Figures 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, present the efficiency curves obtained. Figure 4 presents the curves for experimental and MC simulations so the readers will have a better view of differences obtained from experiments compared with simulations.

Table 5 Simulated Data for ^{152}Eu @ 20cm

Nr.Crt	Activity (Bq)	Energy	Meas-ured	Error	Fitted	Error	Peak Area Counts	Uncer-tainty	GESPE-COR Cor-rection Factors	EFFTRAN Correction Factors	Probabil-ity %	Prob-ability per 100 gamma-rays	Uncer-tainity Probabil-ity (%)	Uncer-tainity Prob-ability	Live Time (s)	Effi-ciency	Effi-ciency (%)	Inc. ef. (%)	Inc. ef
HPGe																			
1	12,992	121.8	0.21060	1.1	0.21059	1.1	1.47E+06	1.1	N/A	1.005	0.284100	28.4100	0.0012	0.120	200,000	0.00199	0.19877	0.42246	0.00001
2	12,992	244.7	0.18800	1.2	0.18800	1.2	3.48E+05	1.3	N/A	1.007	0.075500	7.5500	0.0003	0.030	200,000	0.00177	0.17725	0.39743	0.00001
3	12,992	344.3	0.14050	1.1	0.14050	1.1	9.17E+05	1.2	N/A	1.003	0.265900	26.5900	0.0150	1.500	200,000	0.00133	0.13271	5.64122	0.00007
4	12,992	444.0	0.11130	1.3	0.11130	1.3	8.54E+04	1.7	N/A	1.006	0.028000	2.8000	0.0003	0.027	200,000	0.00117	0.11740	0.96432	0.00001
5	12,992	778.9	0.06793	1.1	0.06793	1.1	2.16E+05	1.4	N/A	1.004	0.129700	12.9700	0.0009	0.090	200,000	0.00064	0.06421	0.69395	0.00000
6	12,992	867.4	0.06248	1.4	0.06248	1.4	6.47E+04	1.8	N/A	1.008	0.042430	4.2430	0.0003	0.029	200,000	0.00059	0.05866	0.68353	0.00000
7	12,992	964.1	0.05672	1.1	0.05672	1.1	2.04E+05	1.4	N/A	1.004	0.145000	14.5000	0.0009	0.090	200,000	0.00054	0.05410	0.62074	0.00000
8	12,992	1085.8	0.05171	1.2	0.05171	1.2	1.29E+05	1.5	N/A	0.999	0.101300	10.1300	0.0009	0.090	200,000	0.00049	0.04888	0.88848	0.00000
9	12,992	1112.1	0.04103	1.2	0.04103	1.2	1.72E+05	1.5	N/A	1.003	0.134100	13.4100	0.0008	0.080	200,000	0.00049	0.04923	0.59662	0.00000
10	12,992	1299.2	0.04456	1.8	0.04456	1.8	1.78E+04	1.4	N/A	1.004	0.016330	1.6330	0.0003	0.029	200,000	0.00042	0.04194	1.77591	0.00001
11	12,992	1408.0	0.04171	1.1	0.04171	1.1	2.14E+05	1.4	N/A	1.004	0.208500	20.8500	0.0007	0.070	200,000	0.00039	0.03943	0.33582	0.00000
12	12,992	1457.6	0.04098	1.6	0.04098	1.6	5.03E+03	1.3	N/A	0.996	0.004980	0.4980	0.0001	0.006	200,000	0.00039	0.03890	1.20512	0.00000
13	12,992	1528.1	0.03917	1.4	0.03917	1.4	2.60E+03	1.2	N/A	1.001	0.002810	0.2810	0.0001	0.006	200,000	0.00036	0.03558	2.13574	0.00001
$LaBr_3$(Ce)																			
1	12,992	121.8	0.85490	1.1	0.8529	1.1	5.96E+06	1.1	N/A	1.004	0.284100	28.4100	0.0012	0.120	200,000	0.00807	0.80694	0.42246	0.00003
2	12,992	244.7	0.58920	1.2	0.6584	1.2	1.32E+06	1.2	N/A	1.006	0.075500	7.5500	0.0003	0.030	200,000	0.00672	0.67229	0.39743	0.00003
3	12,992	344.3	0.61500	1.1	0.6141	1.1	4.01E+06	1.1	N/A	1.003	0.265900	26.5900	0.0150	1.500	200,000	0.00581	0.58091	5.64122	0.00033
4	12,992	444.0	0.51800	1.3	0.5374	1.3	3.98E+05	1.8	N/A	1.005	0.028000	2.8000	0.0003	0.027	200,000	0.00546	0.54642	0.96432	0.00005
5	12,992	778.9	0.36280	1.4	0.3358	1.4	1.09E+06	1.3	N/A	1.004	0.129700	12.9700	0.0009	0.090	200,000	0.00323	0.32251	0.69395	0.00002
6	12,992	867.4	0.32110	1.4	0.3439	1.4	3.32E+05	1.8	N/A	1.007	0.042430	4.2430	0.0003	0.029	200,000	0.00301	0.30147	0.68352	0.00002
7	12,992	964.1	0.28940	1.1	0.3166	1.1	1.04E+06	1.3	N/A	1.003	0.145000	14.5000	0.0009	0.090	200,000	0.00276	0.27603	0.62074	0.00002
8	12,992	1085.8	0.31990	1.2	0.2873	1.2	7.96E+05	1.3	N/A	0.998	0.101300	10.1300	0.0009	0.090	200,000	0.00302	0.30234	0.88848	0.00003
9	12,992	1112.1	0.28130	1.1	0.2817	1.1	9.35E+05	1.3	N/A	1.001	0.134100	13.4100	0.0008	0.080	200,000	0.00268	0.26848	0.59662	0.00002
10	12,992	1299.2	0.25220	1.6	0.2463	1.6	1.01E+05	1.3	N/A	1.004	0.016330	1.6330	0.0003	0.029	200,000	0.00237	0.23739	1.77589	0.00004
11	12,992	1408.0	0.22920	1.1	0.2292	1.1	1.17E+06	1.2	N/A	1.002	0.208500	20.8500	0.0007	0.070	200,000	0.00217	0.21668	0.33582	0.00001
12	12,992	1457.6	0.21640	1.5	0.2221	1.5	2.66E+04	1.3	N/A	0.991	0.004980	0.4980	0.0001	0.006	200,000	0.00205	0.20533	1.20485	0.00002
13	12,992	1528.1	0.21500	1.8	0.2126	1.8	1.43E+04	1.6	N/A	0.999	0.002810	0.2810	0.0001	0.006	200,000	0.00195	0.19526	2.13527	0.00004
$LaCl_3$(Ce)																			
1	12,992	121.8	0.8400	1.1	0.83900	1.1	5.85E+06	1.1	N/A	1.004	0.284100	28.4100	0.0012	0.120	200,000	0.00793	0.79275	0.42246	0.00003
2	12,992	244.7	0.8930	1.1	0.71890	1.1	1.33E+06	1.2	N/A	1.006	0.075500	7.5500	0.0003	0.030	200,000	0.00680	0.67974	0.39743	0.00003
3	12,992	344.3	0.6469	1.1	0.64960	1.1	4.22E+06	1.2	N/A	1.003	0.265900	26.5900	0.0150	1.500	200,000	0.00611	0.61093	5.64122	0.00034
4	12,992	444.0	0.5420	1.3	0.56960	1.3	4.16E+05	1.7	N/A	1.005	0.028000	2.8000	0.0003	0.027	200,000	0.00572	0.57175	0.96432	0.00006
5	12,992	778.9	0.4942	1.8	0.41900	1.8	1.15E+06	1.3	N/A	1.004	0.129700	12.9700	0.0009	0.090	200,000	0.00341	0.34073	0.69395	0.00002
6	12,992	867.4	0.3443	1.5	0.36560	1.5	3.56E+05	1.9	N/A	1.007	0.042430	4.2430	0.0003	0.029	200,000	0.00323	0.32322	0.68352	0.00002
7	12,992	964.1	0.3088	1.1	0.33730	1.1	1.11E+06	1.3	N/A	1.003	0.145000	14.5000	0.0009	0.090	200,000	0.00294	0.29443	0.62074	0.00002
8	12,992	1085.8	0.3440	1.2	0.30720	1.2	8.56E+05	1.3	N/A	0.998	0.101300	10.1300	0.0009	0.090	200,000	0.00325	0.32517	0.88848	0.00003

Table 5 (continued)

Nr.Crt	Activity (Bq)	Energy	Measured	Error	Fitted	Error	Peak Area Counts	Uncertainty	GESPECOR Correction Factors	EFFTRAN Correction Factors	Probability %	Probability per 100 gamma-rays	Uncertainty Probability (%)	Uncertainty Probability	Live Time (s)	Efficiency	Efficiency (%)	Inc. ef. (%)	Inc. ef
9	12,992	1112.1	0.3013	1.1	0.30140	1.1	1.00E+06	1.3	N/A	1.001	0.134100	13.4100	0.0008	0.080	200,000	0.00288	0.28756	0.59662	0.00002
10	12,992	1299.2	0.2719	1.5	0.26550	1.5	1.09E+05	1.2	N/A	1.004	0.016330	1.6330	0.0003	0.029	200,000	0.00256	0.25585	1.77589	0.00005
11	12,992	1408.0	0.2475	1.1	0.24820	1.1	1.27E+06	1.2	N/A	1.002	0.208500	20.8500	0.0007	0.070	200,000	0.00234	0.23388	0.33582	0.00001
12	12,992	1457.6	0.2318	1.7	0.24100	1.7	2.85E+04	1.4	N/A	0.991	0.004980	0.4980	0.0001	0.006	200,000	0.00220	0.21991	1.20485	0.00003
13	12,992	1528.1	0.2313	1.2	0.23150	1.2	1.53E+04	1.4	N/A	0.999	0.002810	0.2810	0.0001	0.006	200,000	0.00210	0.21009	2.13526	0.00004

The efficiency was calculated and computed with the aid of Fitzpeaks Gamma Analysis and Calibration software, it was performed directly on the spectrum generated from MCNP. The analysis is performed automatically by peak searching, activity of the source, and then a calibration curve in efficiency is obtained from the data set. The results and correction data are in line with the published benchmarked data on correction factors codes. Data in the graphs is being fitted with a decay function. There have been no large discrepancies between measured from the spectras obtained from MCNP. The efficiency of the Scintillation is higher than the HPGe as expected [24].

Conclusions

The results show that the simulated data performs well and can in some cases substitute the laboratory manual work, and could be used for further training of people in gamma spectrometry metrology, or development of new methods and techniques in gamma-ray metrology.

Both the experimental measurements and simulated data sets are in good agreement and have been performed in accordance with the known and established gamma-ray spectrometry way, which gave a good proposition to benchmark software and methods for coincidence problem and efficiency.

Fitzpeaks software previously used for peak fittings here we employed very well in getting the efficiency of the detector from spectra either measured using a live laboratory source (in our case the 12.992 Bq ^{152}Eu source) or the ones that have been generated/simulated with the aid of Monte Carlo method (MCNP). Fitzpeaks software which deals with both theoretically generated MCNP data and also experimental obtained spectra can be an extremely useful tool in aiding the laboratory in performing new measurements on a different radionuclide saving time in measuring the efficiency of the detector and getting the photopeak areas.

The downside is the need for computational power, the higher the activity and the more complex the decay of the radionuclides employed will further add to the computation time.

MCNP with the aid of SUPERSynth interface is of a real help to a gamma- ray spectrometrist, it saves precious time and removes the errors in making the input files, the downside for SUPERSynth interface is lack of multiple detectors at the same time, at the moment a single detector can be added to the simulation, so for adding a second detector would be a complex task. The experiment performed here in ^{152}Eu is in good agreement with the available data published. The result obtained here are with the ENDF VII.1 version [4, 43].

Table 6 Simulated Data for ^{152}Eu @ 30cm

Nr. Crt	Activity (Bq)	Energy	Measured	Error	Fitted	Error	Peak Area Counts	Uncertainty	GESPECOR Correction Factors	EFFTRAN Correction Factors	Probability %	Probability per 100 gamma-rays	Uncertainity Probability (%)	Uncertainity Probability	Live Time (s)	Efficiency	Efficiency (%)	Inc. ef. (%)	Inc. ef
HPGe																			
1	12,992	121.8	0.09797	1.1	0.09797	1.1	6.83E+05	1.2	N/A	1.002	0.284100	28.4100	0.0012	0.120	200,000	0.00092	0.09248	0.42246	0.00000
2	12,992	244.7	0.08912	1.2	0.08912	1.2	1.65E+05	1.5	N/A	1.003	0.075500	7.5500	0.0003	0.030	200,000	0.00084	0.08403	0.39743	0.00000
3	12,992	344.3	0.06680	1.1	0.06680	1.1	4.36E+05	1.3	N/A	1.001	0.265900	26.5900	0.0150	1.500	200,000	0.00063	0.06310	5.64122	0.00004
4	12,992	444.0	0.05325	1.5	0.05325	1.5	4.09E+04	1.0	N/A	1.003	0.028000	2.8000	0.0003	0.027	200,000	0.00056	0.05618	0.96432	0.00001
5	12,992	778.9	0.03252	1.2	0.03252	1.2	1.04E+05	1.6	N/A	1.002	0.129700	12.9700	0.0009	0.090	200,000	0.00031	0.03074	0.69395	0.00000
6	12,992	867.4	0.02976	1.7	0.02976	1.7	3.08E+04	1.2	N/A	1.004	0.042430	4.2430	0.0003	0.029	200,000	0.00028	0.02794	0.68353	0.00000
7	12,992	964.1	0.02717	1.2	0.02717	1.2	9.76E+04	1.6	N/A	1.002	0.145000	14.5000	0.0009	0.090	200,000	0.00026	0.02591	0.62074	0.00000
8	12,992	1085.8	0.02479	1.3	0.02479	1.3	6.17E+04	1.7	N/A	1.000	0.101300	10.1300	0.0009	0.090	200,000	0.00023	0.02343	0.88849	0.00000
9	12,992	1112.1	0.02476	1.3	0.02476	1.3	8.24E+04	1.6	N/A	1.001	0.134100	13.4100	0.0008	0.080	200,000	0.00024	0.02364	0.59662	0.00000
10	12,992	1299.2	0.02169	1.5	0.02169	1.5	8.66E+03	1.2	N/A	1.002	0.016330	1.6330	0.0003	0.029	200,000	0.00020	0.02042	1.77594	0.00000
11	12,992	1408.0	0.01995	1.2	0.01995	1.2	1.02E+05	1.5	N/A	1.002	0.208500	20.8500	0.0007	0.070	200,000	0.00019	0.01886	0.33582	0.00000
12	12,992	1457.6	0.01982	1.5	0.01982	1.5	2.43E+03	1.3	N/A	0.998	0.004980	0.4980	0.0001	0.006	200,000	0.00019	0.01881	1.20603	0.00000
13	12,992	1528.1	0.01936	1.7	0.01936	1.7	1.28E+03	1.6	N/A	1.001	0.002810	0.2810	0.0001	0.006	200,000	0.00018	0.01759	2.13888	0.00000
$LaBr_3$(Ce)																			
1	12,992	121.8	0.38960	1.1	0.3898	1.1	2.72E+06	1.1	N/A	1.002	0.284100	28.4100	0.0012	0.120	200,000	0.00368	0.36778	0.42246	0.00002
2	12,992	244.7	0.16520	1.3	0.3112	1.3	6.14E+05	1.4	N/A	1.003	0.075500	7.5500	0.0003	0.030	200,000	0.00313	0.31272	0.39743	0.00001
3	12,992	344.3	0.29780	1.1	0.2901	1.1	1.94E+06	1.3	N/A	1.001	0.265900	26.5900	0.0150	1.500	200,000	0.00281	0.28128	5.64122	0.00016
4	12,992	444.0	0.24080	1.5	0.2534	1.5	1.85E+05	1.1	N/A	1.002	0.028000	2.8000	0.0003	0.027	200,000	0.00254	0.25399	0.96432	0.00002
5	12,992	778.9	0.16490	1.2	0.1757	1.2	5.25E+05	1.5	N/A	1.002	0.129700	12.9700	0.0009	0.090	200,000	0.00156	0.15586	0.69395	0.00001
6	12,992	867.4	0.16270	1.6	0.1623	1.6	1.68E+05	1.2	N/A	1.003	0.042430	4.2430	0.0003	0.029	200,000	0.00153	0.15275	0.68352	0.00001
7	12,992	964.1	0.14240	1.2	0.1498	1.2	5.12E+05	1.5	N/A	1.001	0.145000	14.5000	0.0009	0.090	200,000	0.00136	0.13576	0.62074	0.00001
8	12,992	1085.8	0.15540	1.2	0.1365	1.2	3.87E+05	1.5	N/A	0.999	0.101300	10.1300	0.0009	0.090	200,000	0.00147	0.14692	0.88848	0.00001
9	12,992	1112.1	0.13640	1.2	0.1339	1.2	4.54E+05	1.4	N/A	1.001	0.134100	13.4100	0.0008	0.080	200,000	0.00130	0.13018	0.59662	0.00001
10	12,992	1299.2	0.09305	1.5	0.1181	1.5	3.72E+04	1.2	N/A	1.002	0.016330	1.6330	0.0003	0.029	200,000	0.00088	0.08758	1.77589	0.00002
11	12,992	1408.0	0.11140	1.1	0.1104	1.1	5.71E+05	1.2	N/A	1.001	0.208500	20.8500	0.0007	0.070	200,000	0.00105	0.10534	0.33582	0.00000
12	12,992	1457.6	0.10240	1.2	0.1073	1.2	1.26E+04	1.3	N/A	0.996	0.004980	0.4980	0.0001	0.006	200,000	0.00097	0.09715	1.20489	0.00001
13	12,992	1528.1	0.10370	1.8	0.1031	1.8	6.87E+03	1.7	N/A	0.999	0.002810	0.2810	0.0001	0.006	200,000	0.00094	0.09414	2.13539	0.00002
$LaCl_3$(Ce)																			
1	12,992	121.8	0.38260	1.1	0.38310	1.1	2.67E+06	1.1	N/A	1.002	0.284100	28.4100	0.0012	0.120	200,000	0.00361	0.36112	0.42246	0.00002
2	12,992	244.7	0.31150	1.3	0.32040	1.3	6.19E+05	1.4	N/A	1.003	0.075500	7.5500	0.0003	0.030	200,000	0.00316	0.31570	0.39743	0.00001
3	12,992	344.3	0.30390	1.1	0.29950	1.1	1.98E+06	1.2	N/A	1.001	0.265900	26.5900	0.0150	1.500	200,000	0.00287	0.28704	5.64122	0.00016
4	12,992	444.0	0.25150	1.5	0.26260	1.5	1.93E+05	1.1	N/A	1.002	0.028000	2.8000	0.0003	0.027	200,000	0.00265	0.26530	0.96432	0.00003
5	12,992	778.9	0.17570	1.2	0.18520	1.2	5.60E+05	1.4	N/A	1.002	0.129700	12.9700	0.0009	0.090	200,000	0.00166	0.16610	0.69395	0.00001
6	12,992	867.4	0.17120	1.5	0.17210	1.5	1.77E+05	1.1	N/A	1.003	0.042430	4.2430	0.0003	0.029	200,000	0.00161	0.16067	0.68352	0.00001
7	12,992	964.1	0.15180	1.2	0.16000	1.2	5.45E+05	1.4	N/A	1.001	0.145000	14.5000	0.0009	0.090	200,000	0.00145	0.14475	0.62074	0.00001
8	12,992	1085.8	0.16700	1.2	0.14730	1.2	4.15E+05	1.4	N/A	0.999	0.101300	10.1300	0.0009	0.090	200,000	0.00158	0.15779	0.88848	0.00001

Table 6 (continued)

Nr. Crt	Activity (Bq)	Energy	Measured	Error	Fitted	Error	Peak Area Counts	Uncertainty	GESPECOR Correction Factors	EFFTRAN Correction Factors	Probability %	Probability per 100 gamma-rays	Uncertainty Probability (%)	Uncertainty Probability	Live Time (s)	Efficiency	Efficiency (%)	Inc. ef. (%)	Inc. ef
9	12,992	1112.1	0.14610	1.2	0.14490	1.2	4.86E+05	1.4	N/A	1.001	0.134100	13.4100	0.0008	0.080	200,000	0.00139	0.13940	0.59662	0.00001
10	12,992	1299.2	0.13200	1.1	0.12990	1.1	5.27E+04	1.9	N/A	1.002	0.016330	1.6330	0.0003	0.029	200,000	0.00124	0.12425	1.77589	0.00002
11	12,992	1408.0	0.12040	1.1	0.12280	1.1	6.16E+05	1.2	N/A	1.001	0.208500	20.8500	0.0007	0.070	200,000	0.00114	0.11376	0.33582	0.00000
12	12,992	1457.6	0.11210	1.2	0.11990	1.2	1.38E+04	1.3	N/A	0.996	0.004980	0.4980	0.0001	0.006	200,000	0.00106	0.10639	1.20488	0.00001
13	12,992	1528.1	0.11280	1.0	0.11600	1.0	7.48E+03	1.8	N/A	0.999	0.002810	0.2810	0.0001	0.006	200,000	0.00102	0.10245	2.13538	0.00002

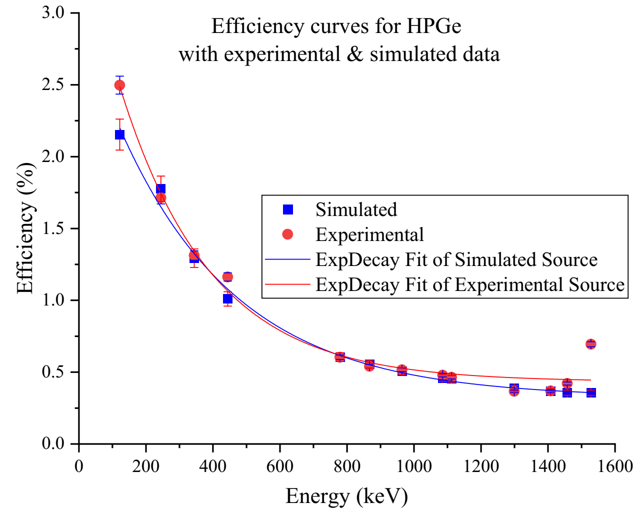

Fig. 4 Efficiencies (%) of experimental source and simulated ^{152}Eu @ 5 cm

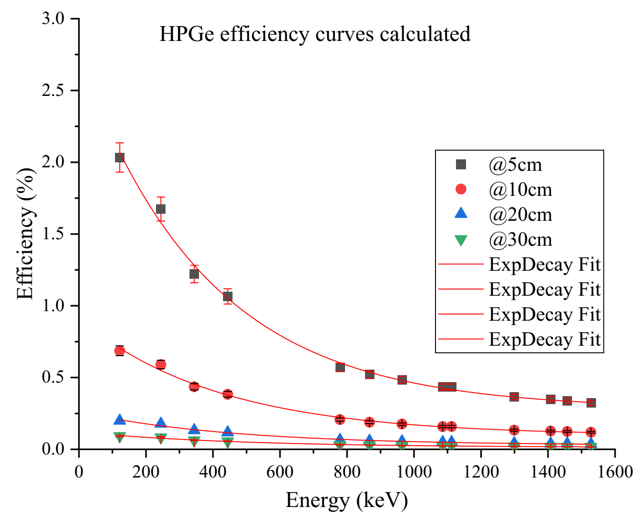

Fig. 5 Shows efficiencies *calculated* based on data from spectra at various distances

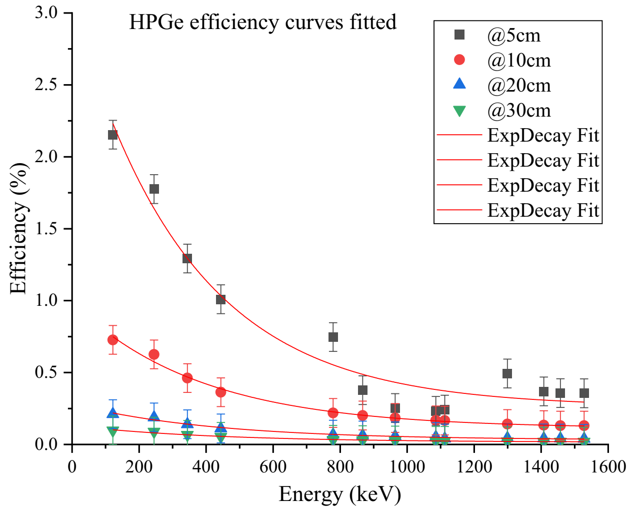

Fig. 6 Shows efficiencies *fitted* based on data from spectra at various distances

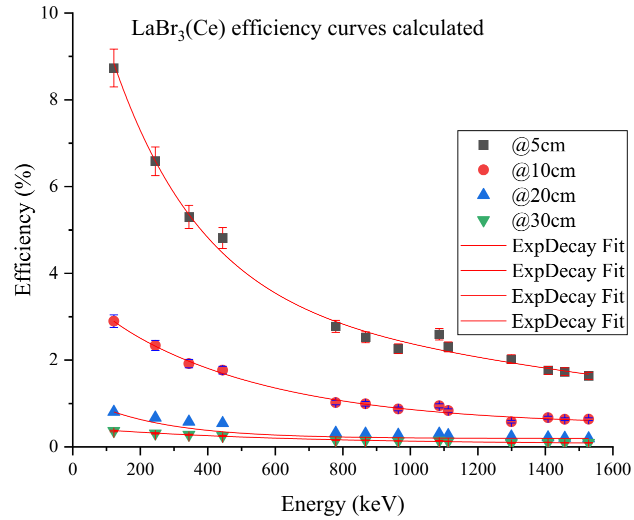

Fig. 8 Shows efficiencies *calculated* based on data from spectra at various distances

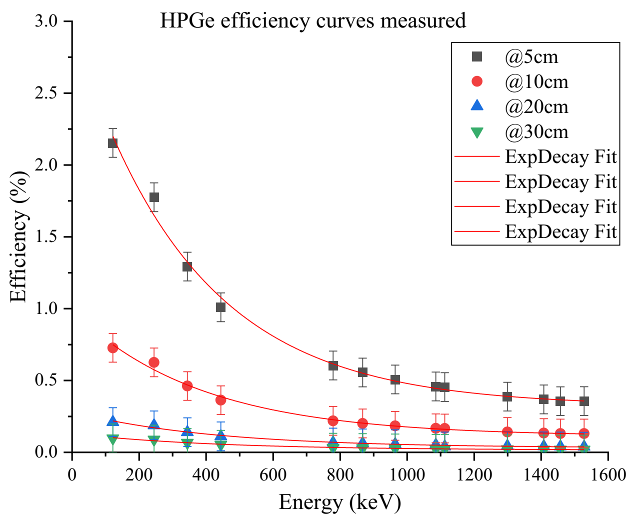

Fig. 7 Shows efficiencies *measured* based on data from spectra at various distances

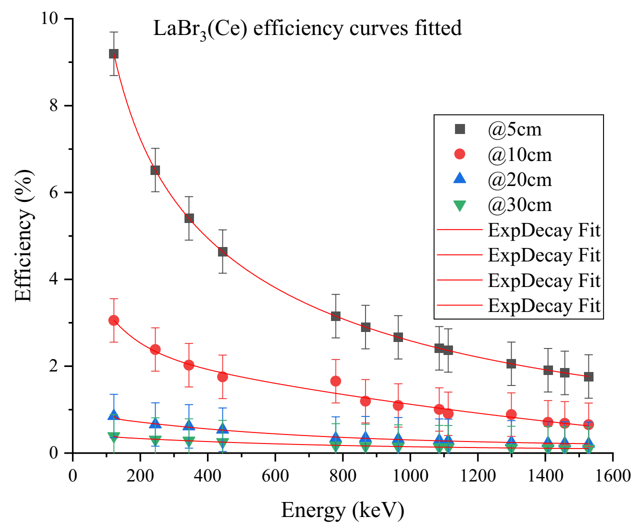

Fig. 9 Shows efficiencies *fitted* based on data from spectra at various distances

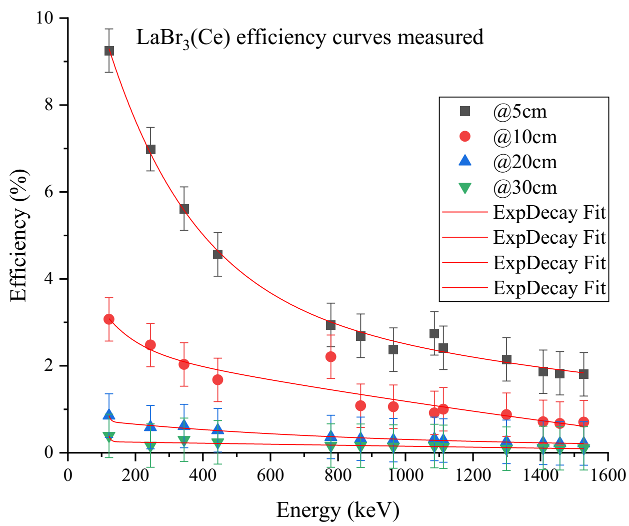

Fig. 10 Shows efficiencies *measured* based on data from spectra at various distances

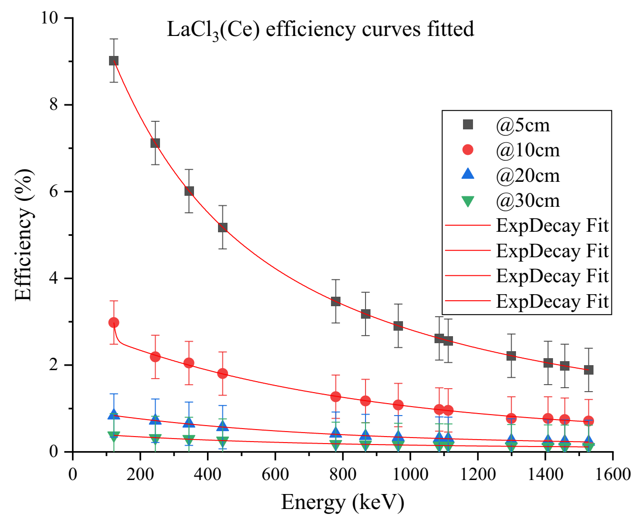

Fig. 12 Shows efficiencies *fitted* based on data from spectra at various distances

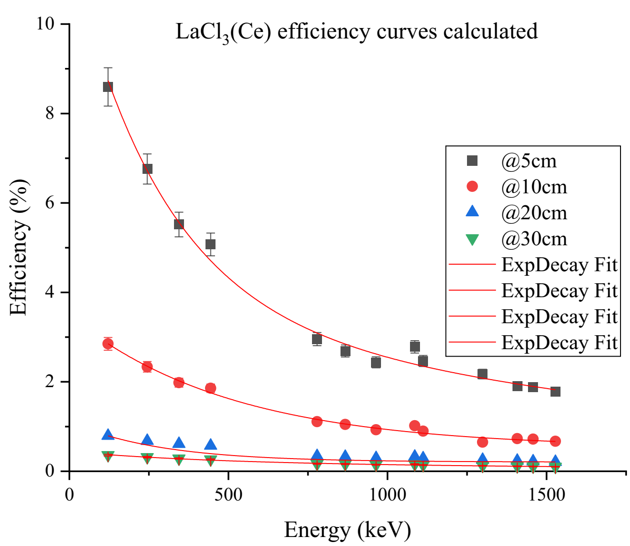

Fig. 11 Shows efficiencies *calculated* based on data from spectra at various distances

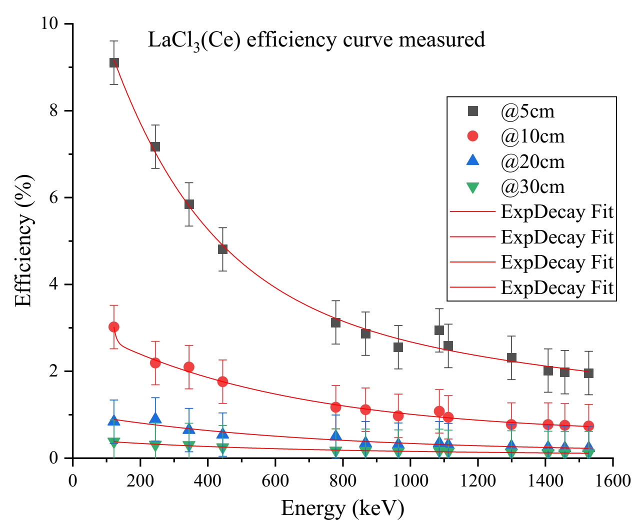

Fig. 13 Shows efficiencies *measured* based on data from spectra at various distances

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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