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ORIGINAL PAPER

Performance of NaI(Tl) detector for gamma-ray spectroscopy

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Abstract: Radiation measurement is vital in radiation physics as its possible hazardous effect on human health should be known. Although radiation may be measured using different kinds of detector types, the NaI(Tl) crystal is one of the most commonly used detector types. This is due to its advantages such as low cost, resistance to thermal effects, and weather conditions. In the use of a gamma spectrometer system, the performance of the detector system is very important in order to determine absolute radiation values as the variation of measurement may affect health due to the radiation. In this work, the performance of $3'' \times 3''$ NaI(Tl) detector has been determined by obtaining some parameters such as response function, resolution, energy spectrum, the figure of merit. Those parameters have been measured using ^{22}Na, ^{137}Cs, and ^{60}Co radioactive sources. The system was also modeled by using FLUKA code.

Keywords: Gamma spectrometer; NaI(Tl) detector; FLUKA; Radioactive Source

1. Introduction

Nowadays, the radiation and related studies have been very popular for scienticists as it has been started to be used in many different fields such as medical hospital, energy power plants, agriculture, environmental issues, etc. In all fields, the radiation measurement is an important issue as it is needed to be known exact values of radiation, due to its possible especially health effects. For gamma-ray measurement, there are different types detector system and NaI(Tl) scintillation detectors are one of the most widely used detector types for many years. This is because of its low cost, resistant to thermal effects and weather conditions (especially when compared to HPGe detectors) and do not need extra cooling devices. Its high detection efficiency [1] is also an advantage in comparison with HPGe type. On the other hand HPGe type detector has higher resolution. The high absorption efficiency of NaI(Tl) detector is due to the presence of Tl (Thallium, $Z = 53$) element in its structure, and so a high photopeak to Compton ratio [2] makes it also prefable detector type. In the detection process of a gamma rays with NaI(Tl) detector, the physical interactions of gamma rays with the crystal of the detector are well-known. Those interactions are mainly photoelectric effect, Compton scattering and pair production. On the other hand in order to use any NaI(Tl) detector for gamma ray measurement, it is important to know its some parameters such as response function, energy resolution and their relation with the experimental setup conditions such as geometry, gamma ray energies as well as source distance to detector. Those can be obtained by experimental way but this is valid only for limited range due to the experimental conditions. On the other hand, calculation using Monte Carlo codes are available to obtain many different parameters without any energy or experimental setup limitation. The simulation tool of **FLU**ktruierende **KA**skade (FLUKA) is one the tool which is a general purpose tool for calculations of particle transport and interactions with matter, covering an extended range of applications spanning from proton and electron accelerator shielding to target design, calorimetry, activation, dosimetry, detector design, Accelerator Driven Systems, cosmic rays, neutrino physics, radiotherapy, etc.. There are many features of FLUKA, probably not found in any other Monte Carlo program, as its double capability to be used in a biased mode as well as a fully analog code. That means that while it can be used to predict fluctuations, signal coincidences, and other correlated events, a wide choice of statistical techniques is also available to

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*Corresponding author, E-mail: iskenderakkurt@sdu.edu.tr investigate punch through or other rare events in connection with attenuations by many orders of magnitude [3, 4].

A large set of works have been published using the FLUKA and the other Monte Carlo codes. Some of those works are about modeling of 3″ × 3″ NaI(Tl) scintillation detector [1, 5–12], some of them are about measurements done for this purposes [13–16] and also some of them are related to radiation-dosimetric applications [17–32]. The works done on this subjects are related to detector capabilities, in detector applications and also are related to specific detector characteristics.

In this study, some parameters such as energy resolution, response function of a 3″ × 3″ NaI(Tl) scintillation detector were measured and the results were compared with the FLUKA simulation code (fluka2011-2 × respin) for 551, 662,1173,1275 and 1332 keV gama-rays energies. The variation of some parameters with the source distance to detector were also investigated.

The quality parameters of gamma spectrometers are important for gamma-ray measurement and it should be determined in this kind of measurement. So obtaining these factors will contribute to measurement quality and it will be an important proper gamma measurement system. This study will be one of the few ones in this field. Thus, it will be a valuable contribution to the literature background.

2. Experimental details

2.1. Radioactive sources and gamma spectrometer system

Some parameters of the gamma spectrometer consists of a 3″ × 3″ NaI(Tl) detector have been measured in this study. The gamma spectrometer system has a counting electronic system (high voltage, preamplifier, amplifier 16,384-channel Multichannel Analyses (MCA)), and a PC (where software was installed) to record data. The pulses of signals from detector were analyzed by MCA using Maestro software provided by ORTEC and analyzed spectrum were recorded on a PC. The schematic view of the system is shown in Fig. 1. In order to reduce the background radiation level for the system, the detector is surrounded using lead shielding material on all sides as shown in Fig. 2. Three different radioactive sources, namely ^{22}Na, ^{137}Cs, and ^{60}Co were used and gamma rays of 511, 662, 1173, 1275, 1332 keV energies obtained from those sources. In Table 1, the properties of those sources have been tabulated.

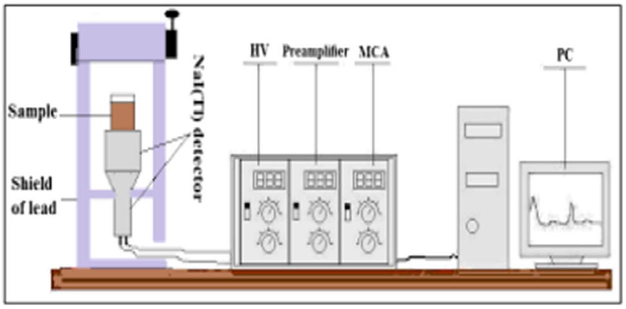

Fig. 1 Schematic view of the gamma spectrometer system

2.2. FLUKA modeling

The simulation of the gamma spectrometer system contains NaI(Tl) detector was done using FLUKA code [2, 3] which should be modeled with the best possible accuracy because of variations of the detector crystal and surrounding materials. The detector physical data and crystal dimension and other properties is illustrated in Fig. 3. The geometry of FLUKA simulation should be exactly to the experimental setup condition such as the physical volume, the mother volume, and sensitive volume. Those were implemented in the description accordingly using FLUKA version of fluka2011-2 × respin done by following routines as describe in FLUKA user manual [3].

Figure 3 shows practical geometry put side and pack shielding and covered all by lead shielding to illumination background radiation.

In the experimental spectra, the data has a Gaussian distribution shape for the energy lines. However, the FLUKA code does not simulate physical effects leading to the broadening of the spectrum, but it uses a fitting technique to take into account the resolution of the real detector, measured experimentally, and provided in the input file of this code. Thus, for more realistic results obtained by simulation, it is necessary to consider the spectrum resolution by applying a Gaussian function. The technique consists of using a “USRBDX” card and calculating the Full Width at Half Maximum (FWHM) of the peak.

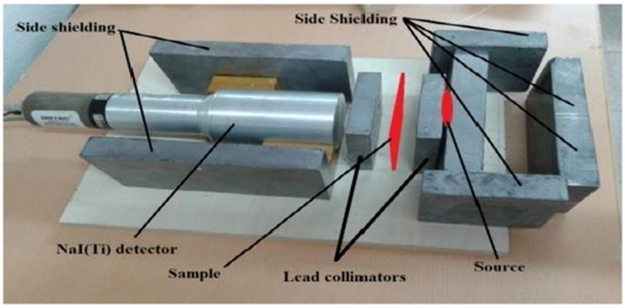

Fig. 2 The experimental setup used in gamma ray measurement by NaI(Tl) detector

Table 1 The properties of the radioactive sources

Source	Half-live (year)	Energy (keV)	Emission probability (%)	Activity (uCi)
^{22}Na	2.602	511	178	0.1
		1275	99.94	
^{137}Cs	30.07	661.65	84.6	0.1
^{60}Co	5.27	1173.24	99.87	0.1
		1332.51	99.98	

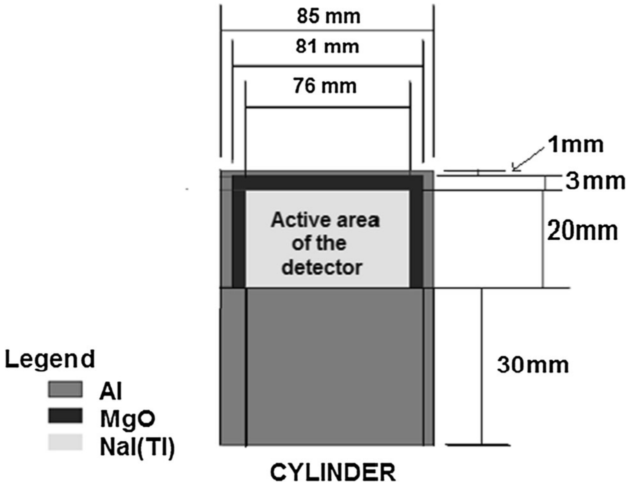

Fig. 3 The NaI(Tl) detector physical setup for FLUKA simulation

3. Results and discussion

Some quantity such as response function, energy calibration, figure of merit and resolution calibration are important parameters for an experimental characterization of any radiation detector and therefore in this study, those parameters were meausred and compared with the simulation done by FLUKA code.

3.1. Energy calibration

Energy calibration of the gamma ray spectrometer is an important parameters and it establishes a relationship between the channel number of the MCA and the pulse height signals of detector. This is essential for spectrum analysis as it should be known where exact peak is located and which energy it is realted. Thus in order to interpret channel number into energy in spectrum, the energy calibration should be done. The energy calibration is expressed as the expected relation between the channel number and known gamma ray energy and it should be done under laboratory conditions as closely as possible with the experimental conditions. In normaly 3 different energy is good enough (at least 3 point are necessary for statistical line) for this purposes but the calibration is done using ^{22}Na, ^{137}Cs, ^{60}Co radioactive sources which emit 511, 662, 1173, 1275, and 1332 keV in this study. Those sources were placed in fixed geometry in front of detector. The channel numbers of MCA of the electronic unit and related certain energies due to the radioactive sources are displayed in Fig. 9. As can be seen from this figure that energy spectrum obtained for 511, 662, 1773,1275 and 1332 keV from sources (in Fig. 4A) and related calibration fit for channel number energy relation (in Fig. 4B).

3.2. Energy resolution

The energy resolution of a detector is an important parameter for detection system as it is needed to discriminate gamma rays especially closer energies peak which represent different nuclei in the spectrum. The energy resolution of the detector system has a photopeak Gaussian distribution and its centroid represents the central value, and the full width at half maximum (FWHM) represents its width at half of the counts associated with the centroid value. The FWHM is described as its proportional relationship to the standard deviation. Resolution calibration is useful to ensure that all photopeak areas are correctly measured. This is vital to know how useful the detector is for clearly separating two adjacent energy peaks and, hence, for unambiguous nuclide identification. The energy resolution measurement of the 3″ × 3″ NaI(Tl) detector were obtained in the photopeaks of energy spectrum for all sources (Figs. 5, 6, 7). An example has been given in Fig. 5 which is for ^{137}Cs source where 662 keV photopeak is located. It can be seen from this figure that the FWHM value for our 3″ × 3″ NaI(Tl) detector is about 49 keV and the resolution at this energy it is 7.4% for 662 keV gamma ray. This is about a similar value of the energy resolution of a NaI(Tl) detector is usually reported for 662 keV gamma rays emitted by the ^{137}Cs source. The reported resolution values for this type of cylindrical detectors, varies from 7.0 to 8.5%, such values can be easily obtained from commercially available detectors. The measured FWHM values as a function of gamma ray energies has been displayed in Fig. 6 where it is compared with the results obtained by FLUKA. It can be clearly seen from this figure that the FWHM increased with the increasing gamma ray energies

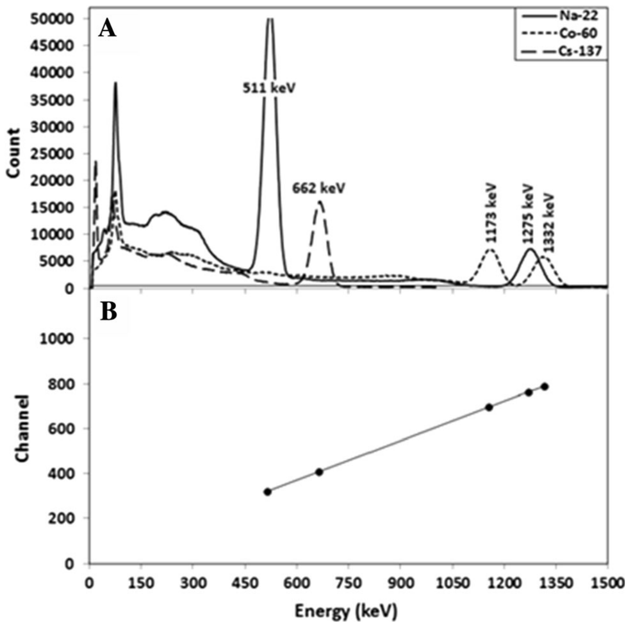

Fig. 4 Energy spectrum obtained for 511, 662, 1773,1275, and 1332 keV (in **A**) and related calibration fit for channel number energy relation (in **B**)

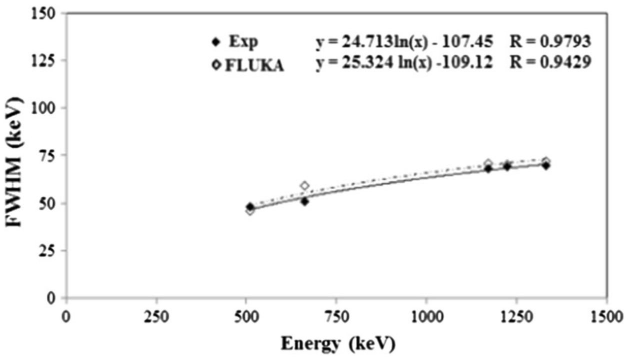

Fig. 6 Variation of FWHM with the gamma energy obtained by both measurement and FLUKA calculation

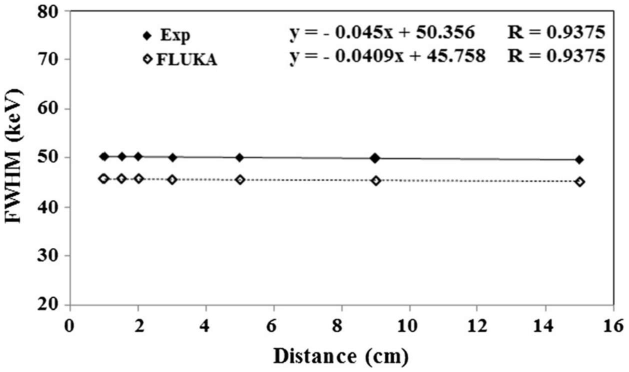

Fig. 7 FWHM as a function of source distance to detector obtained for 511 keV gamma ray

for both results and a good agreement was found between those measurement and FLUKA simulation. In order to see variation of FWHM with the source-detector distance, it was also measured for 7 different distances. The experimental results is shown in Fig. 7 as a function of source-detector distance for 511 keV gamma rays and the results were compared with the FLUKA simulation. It can be seen from this figüre that the agreement between those two results are good. For the case of all measured results including all energies (511, 662, 1173, 1275, and 1332 keV) and distance (1, 1.5, 2, 3, 5, 9, and 15 cm) as 2D and also as 3D figure is displayed in Fig. 8. It can be seen from these figures clearly that the FWHM decreased with the increasing source to detector distance for the same gamma ray energy while the FWHM is increased with the increasing gamma-ray energy for the same source to detector distance. For experimental results, the energy resolution R(%) has been extracted from the full width at one-half of the maximum height (FWHM) of the energy spectrum. This is formulated in Eq. 1.

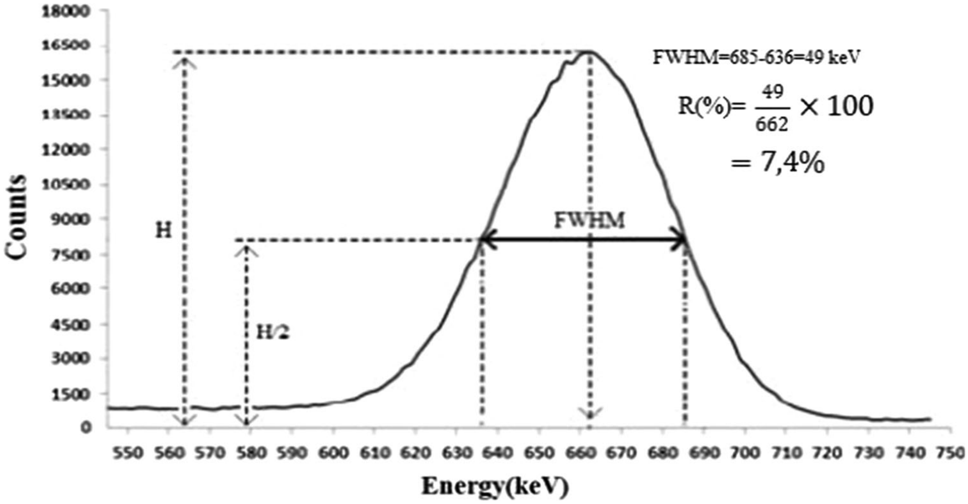

Fig. 5 The FWHM obtained from experimental work for NaI(Tl) detector at 662 keV gamma-rays

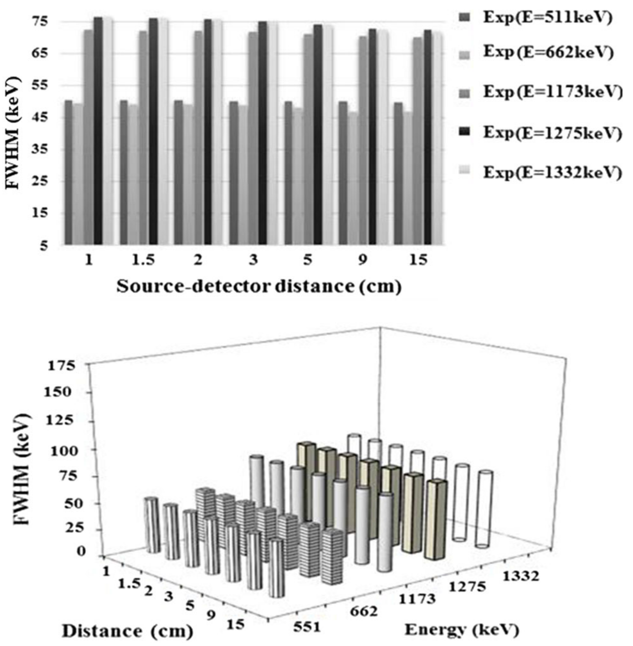

Fig. 8 Experimental variation of FWHM with the gamma ray energy and sources distance to detector as 2D and 3D plot

$$R(\%) = \frac{\mathrm{FWHM}}{E_o} \times 100 \quad (1)$$

where $R(\%)$: energy resolution; FWHM: width at half maximum of the photopeak; E_o: energy central of photopeak.

The simulated energy resolution by FLUKA for all 5 energy has been displayed in Fig. 9 where it is compared with the measured [33] energy resolution. It can be seen from this figure that the resolution is descreased with the increasing gamma ray energies and measured and calculated results are in good agreement. For the case of source distance to detector it is also descreased with the increasing detector distance to source. This can be seen in measured results [33] as shown in Fig. 10 obtained for 511 keV gamma rays and comparison with the FLUKA simulation.

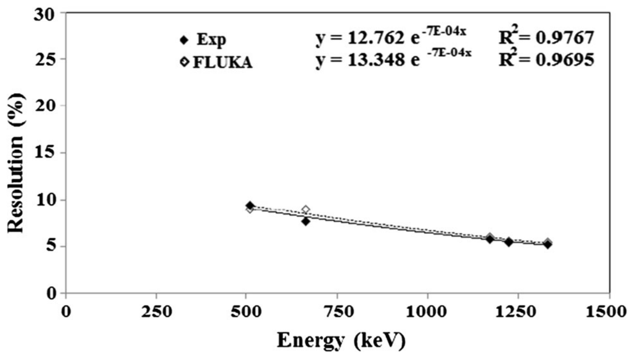

Fig. 9 Energy resolution as function of gamma ray energy obtained by measurement [33] and FLUKA (for 1 cm distance to detector)

3.3. Energy response function and gamma ray spectrum of the system

In order to determine detector performance, the energy spectrum from NaI(Tl) detector has been obtained for 3 different gamma ray sources of ^{22}Na, ^{137}Cs, and ^{60}Co which emit 5 different gamma rays at the energy of 511, 662, 1173, 1275, and 1332 keV. The obtained spectra were shown in Figs. 11, 12 and 13 where measured results were also compared with spectra obtained by FLUKA simulations. Besides a clear photo peaks at 511, 662, 1173, 1275,

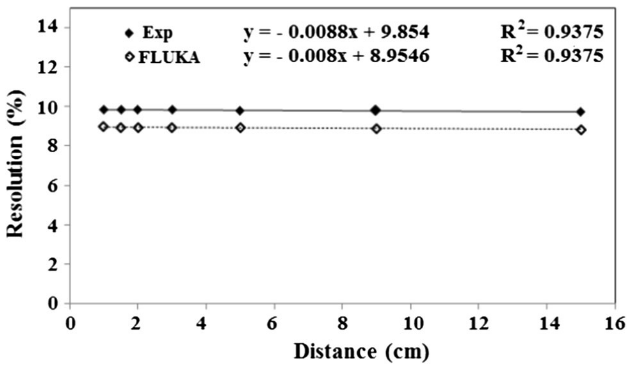

Fig. 10 Energy resolution as function of sources distance to detector obtained by measurement [33] and FLUKA (for 511 keV gamma ray)

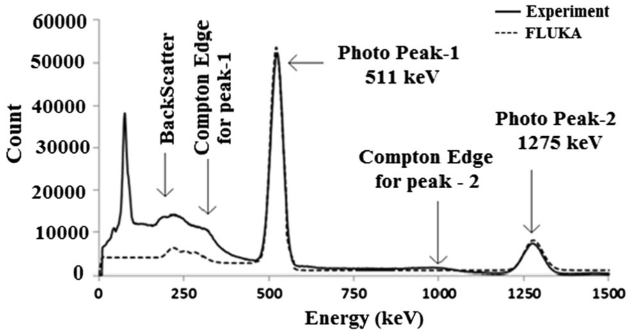

Fig. 11 Measured gamma-ray energy spectrum and comparision with FLUKA simulation for ^{22}Na source

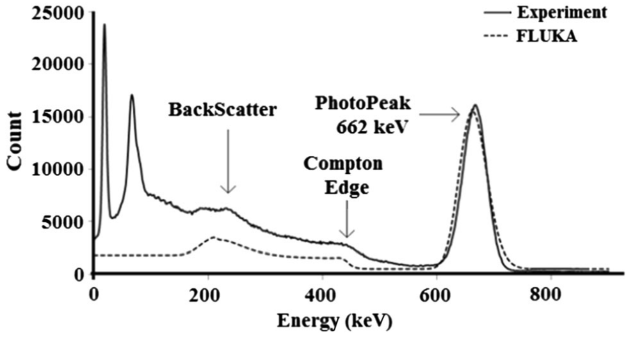

Fig. 12 Comparison between measured and simulated gamma-ray spectra for ^{137}Cs source [36]

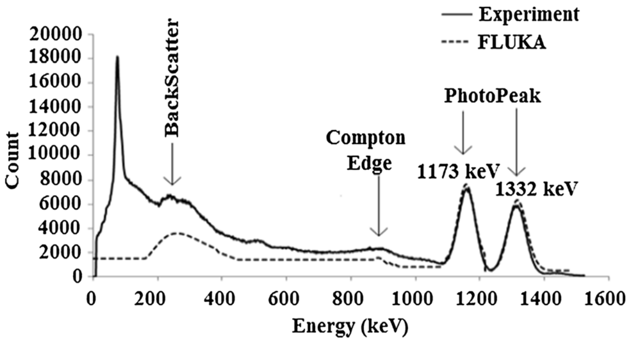

Fig. 13 Measured gamma-ray energy spectrum and comparision with FLUKA simulation for ^{60}Co source

1332 keV in the spectra, the compton edge and backscattering peaks are also clearly seen in those three Figures. A good agreement between measurements and FLUKA simulations has been obtained where photopeaks are located and most of other distribution. On the other hand, a systematic difference in the low energy region (below about 400 keV) has been observed for all sources. At this energy region the calculated results were lower than experimental data for all sources. The differences could be due to the gamma rays scattered by surrounding materials of detector system [34] or due to tail effect or some noise effect on detector.

Discriminating of closer peaks are important radiation measurements. The is the case for ^{60}Co source which emit two closer energies and thus in spectrum, two different peaks of 1173 and 1332 keV are seen. For this purposes a parameter called Figure of Merit (FoM) has been obtained in order to determine those peaks separation quality as given Eq. 2 [35]:

$$\mathrm{FoM} = \frac{E_{1332} - E_{1173}}{\mathrm{FWHM}_{1173} + \mathrm{FWHM}_{1332}} \qquad (2)$$

where E_{1332} and E_{1173} are peak positions of in the spectrum and FWHM_{1173} and FWHM_{1332} are the widths at half-height for the corresponding peaks as shown in Fig. 14.

The calculated and measured results by FLUKA have been displayed in Fig. 15 as a function of source to detector distance. It can be seen from Fig. 15 that all value is less than 2.5 which indicates a good fit irrespective of background conditions and variations in peak sizes and shapes [37].

It can also be seen from this figure that the FoM increased with the increasing distance to detector. This shows that resolution of peak increased if the flight path of gamma rays increased.

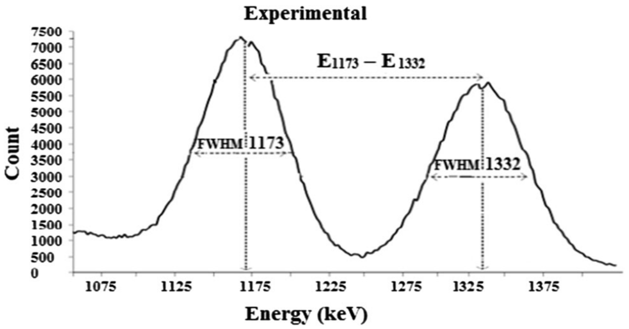

Fig. 14 Definition of FoM for 1173 and 1332 keV peaks measured from ^{60}Co source

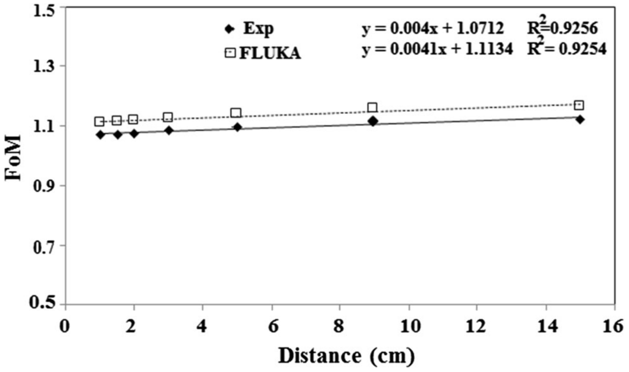

Fig. 15 Measured and FLUKA results for FoM as a function of distance for 1173 and 1332 keV peaks from ^{60}Co source

4. Conclusions

The detector parameters are important quantity in radiation measurement which is important especially for human health. The works done in this study shown that the detector response function, detector resolutions are important and also related to measured gamma ray energies and also detector distances to radiation sources. Any radiation detection system is used those parameters should be taken into account. Those were seen in both measured and calculated data obtained by FLUKA. It may clearly be concluded from this work that the detector resolution depends on energy of the source and distance of this source to detector during measurement, FoM which is an important parameter for peak discrimination is important for gamma ray measurement and it depends of energy and it effects detector resolution, FoM depends on source to detector distance and it increased with the distance increased, the FWHM was obtained about %7.4 at 662 keV energy. It was found that the FWHM increased with the energy of gamma rays while it decreased with the increasing detector source distance. It was also found that the energy resolution decreased with the energy of gamma rays while it also decreased (but slightly) with the increasing detector source distance.

This work is a clear evidence that the measured results and FLUKA calculations are in good agreements and this may lead that the FLUKA can be applied to detector parameters when it is difficult to set up an experimental measurement.

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