



# Source-to-detector Distance Dependence of Efficiency and Energy Resolution of a 3"x3" NaI(Tl) Detector

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## Abstract

NaI(Tl) scintillation detectors are widely used in measurements of environmental radioactivity, low level radioactive waste, prompt gamma ray neutron activation analysis, some nuclear physics experiments, geology, etc. This paper reports the results of the energy calibration, resolution and full energy peak efficiency and total efficiency calculations for a 3"x3" NaI(Tl) detector (Canberra Inc.) that are essential to specify the quality of the results of gamma spectrometry measurements. To investigate the effects of the gamma ray energy and the distance from source to detector center on detector efficiency, measurements were performed at different six axial distances for four point sources (Am-241, Cs-137, Co-60 and Na-22). Thus, fundamental data for further works with this detector system were obtained.

**Keywords:** Gamma ray, NaI(Tl), Full energy peak efficiency, Total efficiency, Resolution.

## 1. Introduction

With the start of using radioactive sources in a variety of different fields such as health physics, industry, energy, and environmental application, nuclear radiation detectors become the most fundamental instruments as radiation is hazardous for health. Scintillation detectors, in especial the NaI(Tl) detectors, have been widely used in various applications in several fields over the last 50 years (Casanovas et al., 2012). In radiation measurement studies an accurate knowledge of the detector spectral performance is essential (Akkurt et al., 2014). The quality of the results of gamma ray spectrometry measurements depends directly on the accuracy of the detection efficiency of the detector in the specific measurement conditions (Hassan Ali et al., 2014), and energy resolution is also one of the important parameters to be determined (Akkurt et al., 2014). The efficiency of a detection system strongly depends on the parameters such as the energy of gamma rays, detector dimensions, source dimensions, geometric arrangement of the detector and source, and density of the sample. Therefore, the efficiency calibration developed for one detector may not valid for another one (Karadeniz and Vurmaz, 2017). The most reliable method for all detectors is to determine the efficiency calibration by means of experimental methods in their natural conditions of use (Karadeniz and Vurmaz, 2017). Many studies for the determination of detector efficiency were

performed experimentally (Akkurt et al., 2014; Perez-Andujar and Pibida, 2004; Alexiev et al., 2008; Demir et al., 2008; Guss et al., 2010; Abd-Elzaher et al., 2012; Günay et al., 2018) or by using analytical method (Selim and Abbas, 1996; Selim et al., 1998; Abbas, 2010; Hamzawy, 2014; Badawi et al., 2013a; Badawi et al., 2013b) and Monte Carlo simulation (Casanovas et al., 2012; Ayaz-Maierhafer and DeVoi, 2007; Salgado et al., 2012; Anil Kumar et al., 2009; Jehouani et al., 2000; Rehman et al., 2009) by several authors in the literature. Furthermore, the non-proportional light response in scintillation detectors makes it essential to carry out a calibration based on peak width, which establishes the conformity between the peak width and energy that corresponds to peak channel, because it is the main source causing the energy resolution. Resolution calibrations are necessary for both the peak-analysis software to separate different gamma ray emissions in a narrow energy range and the Monte Carlo simulations to obtain desired, idealised spectral responses. Because the width of peak is often given by the full energy width at half the intensity maximum (FWHM) of the gamma peak at the gamma energy, this calibration establishes a function to describe the dependence of FWHM values on the gamma ray energy (Casanovas et al., 2012), the peak width versus the spectral energy.

This work is focused on assessment the detection efficiency and energy resolution of the studied NaI(Tl) detector that have great importance in nuclear investigations and in all experimental studies that measure radiation. Moreover, these characteristics of

detectors are the most important parameters used to determine the numerical results of a study (Karadeniz and Vurmaz, 2017). The effect of source-to-detector distance and energy on the full energy peak and total efficiencies for the studied gamma ray energies has also been investigated.

## 2. Material and Methods

### 2.1. Experiment

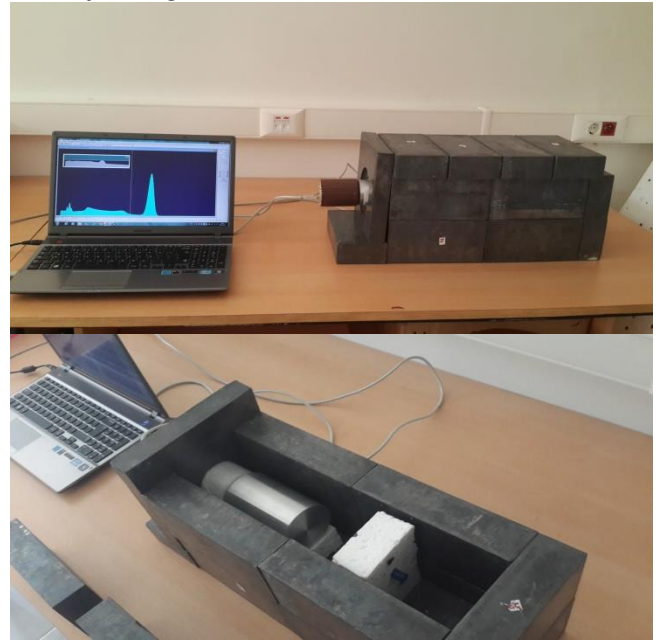
The detector used in this study the 3x3 inch NaI(Tl) detector was an ORTECs Model 905-4. The MAESTRO-32 multichannel analyzer emulation software (Ortec, South Illinois Ave., USA) was used for the spectrum analysis; auto- matic peak searching, peak evaluation, peak area calculations, energy calculation, along with changes in fitting the peak using the interactive peak fit interface when necessary to reduce the errors in the values of peak area.

The four different radiation sources,  $^{137}\text{Cs}$ ,  $^{60}\text{Co}$ ,  $^{22}\text{Na}$  and  $^{241}\text{Am}$ , that give 59.5, 511, 661.6, 1173.2, 1274.5, and 1332.5 keV gamma ray energy were placed at axial locations with respect to the detector axis, at six different distances from the face of the detector and the measurement has been performed for each source. The same radionuclides used also in the calibration process of the detector. The sources' activities, reference date and the half-life values of the studied radioisotopes and gamma ray emission probabilities per decay for all radioisotopes used in the work are listed in Table 1. The data related to the decay, the energies, half-life values and the emission probabilities were taken from International Atomic Energy Agency (IAEA) Nuclear Data Services.

**Table 1.** Information data of the radionuclides used for the determination of the NaI(Tl) detector efficiency for point source geometry

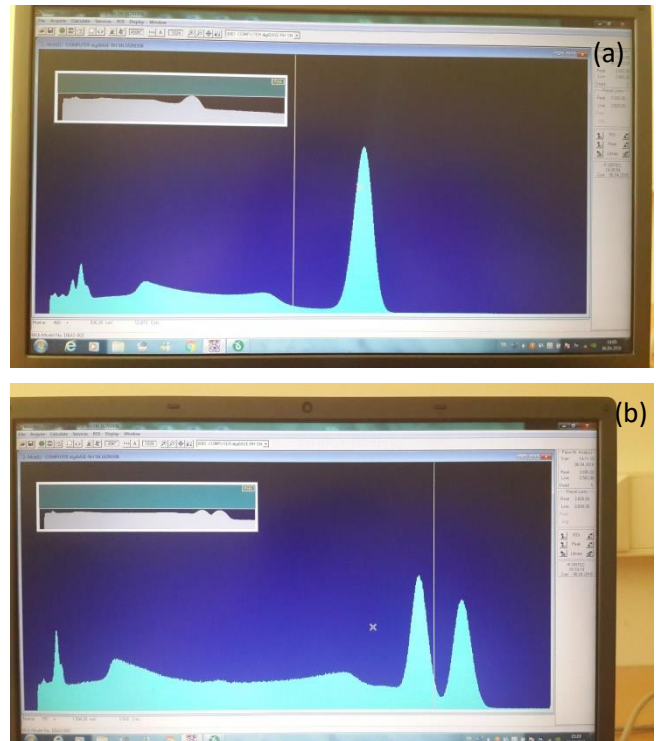
Nuclide	Energy (keV)	Emission probability (%)	Activity (kBq)	Half-life (year)	Reference Date
Am-241	59.5	35.92	74	432.6	
Cs-137	661.6	85.1	333	30.08	
Na-22	1274.5	99.94	74	2.6018	19/12/2006
Co-60	1173.2	99.85	74	5.2711	
	1332.5	99.9826			

The styrofoam holder is used to measure these sources at six different axial distances starts from 2 cm up to 12 cm with step 2 cm from the detector surface. In order to reduce the background level of the system, the detector is shielded using 5 cm lead on all sides. Two of photographs of the experimental system have been displayed in Figure 1.



**Figure 1.** Photographs of the experimental setup designed to obtain data for efficiency calculation

Each measurement has been done for a 60-minute time period to achieve good statistics in the evaluation of each gamma peak of each spectrum. Typical gamma ray spectrum for  $^{137}\text{Cs}$  and  $^{60}\text{Co}$  sources measured using the NaI(Tl) detector is shown in Figures 2(a) and (b).



**Figure 2.** Measured spectra of the radionuclides (a) Cs-137 and (b) Co-60

2.2. Calculation

It is possible to divide the calibrating procedure of NaI(Tl) scintillation detectors before their usage for spectroscopy of gamma rays into three sub-calibrations, namely the energy calibration, the resolution calibration and the efficiency calibration. This complex calibration provides more accurate assessment; allow correctly identifying the isotopes and determining the activity of the involved ones (Casanovas et al., 2012).

The detector system used in this work was calibrated before using in radiation detection in order to convert channel number to energy scale. <sup>137</sup>Cs, <sup>60</sup>Co, <sup>22</sup>Na and <sup>241</sup>Am radioactive sources, six different energy peaks, were used to get certain peak to see channel number. All the sources were counted for 3600 seconds.

The energy resolution, as another important characteristic of a detector system is obtained from the full width of a single peak (at a specific energy) at half its maximum height (FWHM) of a single using the following equation:

$$R = \frac{FWHM}{E_0} \times 100 \tag{1}$$

here  $R$  is energy resolution and  $E_0$  is the related energy.

The experimental full energy peak efficiency at energy  $E$  was computed by the equation below,

$$\varepsilon_{fep}(E) = \frac{N(E)}{A \cdot t \cdot p(E)} \tag{2}$$

where  $N(E)$  is the number of net counts recorded in the photopeak for that energy,  $A$  is the known activity of radionuclide,  $t$  is the preset counting time (in second) and  $p(E)$  is the gamma ray emission probability for each of applied radionuclides. And the experimental total efficiency was computed by

$$\varepsilon_T(E) = \frac{N_T(E)}{A \cdot t \cdot p(E)} \tag{3}$$

where  $N_T(E)$  is the total number of counts in the spectrum, and as mentioned above,  $A$  is the known activity of radionuclide,  $t$  is the preset counting time (in second) and  $p(E)$  is the gamma ray emission probability for each of applied radionuclides.

3. Results and Discussion

In this study, firstly the detector system was calibrated before using in radiation detection in order to convert channel number to energy scale. Detector response functions were obtained for four radioactive sources, six different energy peaks, to get certain peak to see channel number. This was done by using <sup>137</sup>Cs, <sup>60</sup>Co, <sup>22</sup>Na and <sup>241</sup>Am radioactive sources as they produce gamma ray energy of 661.6, 1173.2 and 1332.5, 511 and 1274.5, and 59.5 keV, respectively. In Figure 3, related calibration fit obtained for the source to detector distance of 6 cm is displayed.

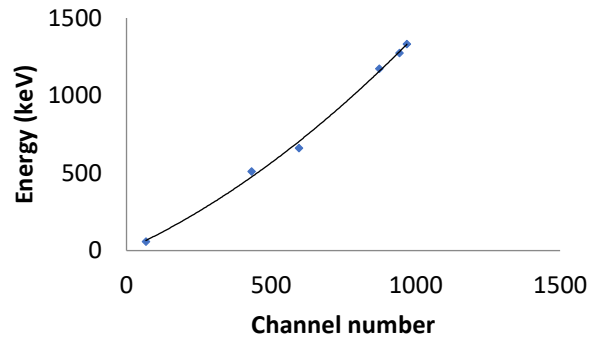


Figure 3. Energy calibration curve for the studied NaI(Tl) detector at the source-to-detector distance of 6 cm

Resolution provides the separation for two adjacent energy peaks which leads to identification of different nuclide in spectrum. The measured energy resolution of the NaI(Tl) detector for each of source-to-detector distance values is displayed in Figure 4 as a function of gamma ray energy. It can be seen from this figure that the energy resolution of the NaI(Tl) detector decreased with the FWHM with the increase in gamma ray energy. This result is confirmed by the results available in literature (Casanovas et al., 2012; Akkurt et al., 2014; Salgado et al., 2012).

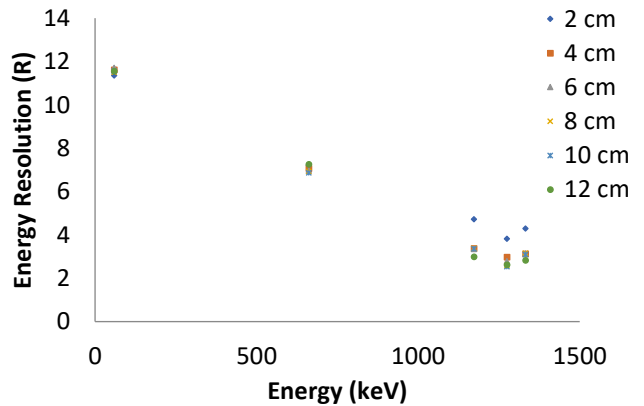


Figure 4. Energy resolution of the NaI(Tl) detector for several source-to-detector distances versus gamma ray energy

Full energy peak efficiency and total efficiency values of the NaI(Tl) detector used in measurements were obtained experimentally for five different gamma ray energies at six different positions (source-to-detector distance) and results were listed in Table 2.

Table 2. Experimental results for total and full energy peak efficiencies (FEPE) of 3"x3" NaI(Tl) detector

Energy (keV)		Source-to-detector distance (cm)					
		2	4	6	8	10	12
59.5	Total efficiency	0.1400	0.0765	0.0471	0.0311	0.0213	0.0156
	FEPE	0.1266	0.0685	0.0418	0.0277	0.0189	0.0137
661.6	Total efficiency	0.0835	0.0343	0.0311	0.0225	0.0166	0.0128
	FEPE	0.0402	0.0228	0.0150	0.0108	0.0077	0.0059
1173.5	Total efficiency	0.1213	0.0786	0.0526	0.0381	0.0291	0.0264
	FEPE	0.0175	0.0128	0.0081	0.0057	0.0042	0.0024
1274.5	Total efficiency	0.2260	0.1073	0.1050	0.0780	0.0610	0.0476
	FEPE	0.0196	0.0125	0.0081	0.0060	0.0045	0.0033
1332.5	Total efficiency	0.1211	0.0785	0.0525	0.0380	0.0290	0.0263
	FEPE	0.0148	0.0121	0.0078	0.0054	0.0039	0.0022

Whereas the energy and resolution calibrations only depended on the energy of gamma ray, the efficiency calibration depends on several factors, such as the position of the source relative to the detector, size and shape of the source, and the materials that surrounding the setup (Casanovas et al., 2012), i.e. efficiency is not a characteristic of the detector only. Calculating the energy dependent variation of the total efficiency and full energy peak efficiency of 3"x3" cylindrical NaI(Tl) detector for various source-to-detector distances and the corresponding results have been shown in Figures 5 and 6, respectively.

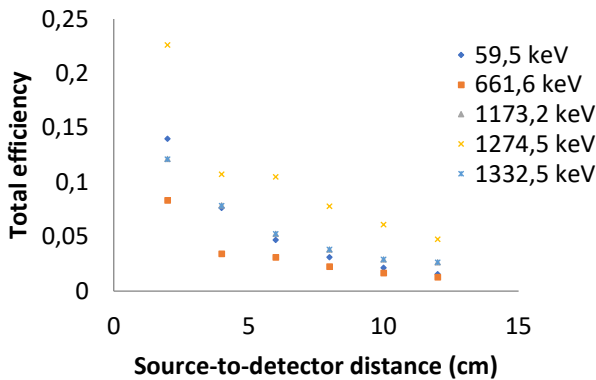


Figure 5. Variation of total efficiency values of the detector for several gamma ray energies versus source-to-detector distance

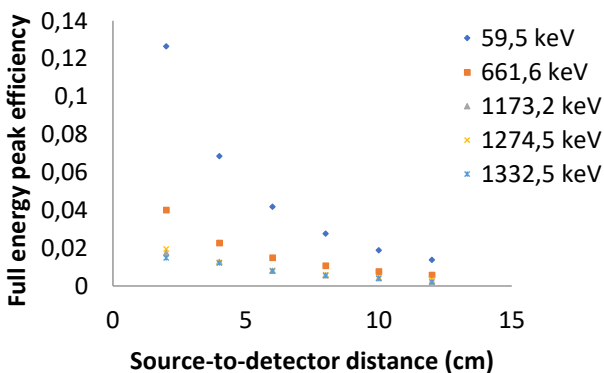


Figure 6. Variation of full energy peak efficiency values of the detector for several gamma ray energies versus source-to-detector distance

It can be seen from Figures 5 and 6 that the efficiencies have decreased exponentially with the increasing distance from detector face, this result is congruent with the previously presented results for the same size detector by Akkurt et al. (2014). This observed and expected variation may be attributed to change in the solid angle and as well as the change in a number of interactions possible due to oblique to nearly normal incidence of photons, as previously reported by Rehman et al. (2009). In Figure 5 and also in Table 2, some improper data points for the distance of 4 cm at energy 661,6 and 1274,5 keV draw the attention. This result specifies that the 4 cm distance of source-to-detector is not very suitable for gamma rays with these energies. On the other hand, these discrepancies can be expounded by some as the result of experimental errors.

When the results of this study are compared with those belonging to other workers (Casanovas et al., 2012; Hamzawy, 2014; Rehman et al., 2009), the observed differences between the values of this work and others' due to the parameters such as detector and the source dimensions, geometric arrangement of the detector and source, etc., that are effective on detector efficiency as mentioned in Introduction section.

#### 4. Conclusions

This paper presents the results for a complete calibration procedure of a NaI(Tl) detector (7.62 cm diameter and 7.62 cm long) to be used in gamma spectrometry. For energy calibration, resolution and efficiency calculations, measurements were performed by four radioactive sources positioned at six different distances to the detector. These parameters report the performance of the experimental set up. The variation of efficiency values with the gamma ray energy and detection distance was also investigated. This work provides important and fundamental data for further works with this system.

#### Acknowledgement

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