Geometry Correction in Efficiency of a Sodium Iodide (Thallium Activated), NaI(Tl) Detector

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ABSTRACT

The detector in experimental physics is an instrument that converts radiation energy into an electrical signal, and this is achieved basically either by ionization or excitation. The choice for any type of a detector (gas-filled, scintillation or semiconductor) for any application depends upon the x-ray of gamma energy range of interest. A working model is therefore developed which is capable of describing the overall NaI(Tl) detection efficiency as a function of several known parameters. The algorithms of this model permit the evaluation of a large variety of sample shapes, sizes, and single initial detector calibration. Therefore, based on the model, on the assumption that the thickness of the detector, T, is 1.0mm, the geometry of the detector, the absorption coefficient, μ, the penetration, ρ, the effective radius in the detector, r, and the distance from source to effective zone of interaction, d, were calculated to be 0.28863054 radian, 0.103198386 $\pm$ 0.016841325cm, 0.004999135 $\pm$ 2.20454 x 10^{-8}cm, 2.417012326$\pm$0.001689568cm and 3.140217836 $\pm$ 0.000142627cm respectively and finally, the efficiency, ε, was found to be 28.62791552$\pm$ 7.69750264 at x = 1.00cm

Keywords: Detector efficiency, absorption coefficient, energy calibration.

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INTRODUCTION

The instruments for detecting nuclear radiations, which were available to early workers in the field of radioactivity, were limited by the technology of the period. As new techniques and components have become available, a range of radiation detectors have been developed exploiting various basic methods of which the theory and technology are on a sufficiently firm basis to allow for a unified presentation [1]. In experimental particle physics, detectors are devices used for detecting, measuring and analyzing high-energy particles, such as produced by nuclear decay, cosmic radiation or reactions in a particle accelerator. The mechanism for the conversion of radiation energy into an electrical signal can be by ionization and excitation.

In ionization, an electron is stripped from an atom and the electron and the resulting ion are electrically charged; while in excitation, the electrons are excited to a higher energy level and when the vacant electron is filled, electromagnetic radiation is emitted. Scintillation detectors such as NaI, GBO, CsI, Polyvinyl Toluene (PVT) plastic scintillator and the neuron sensitive glass fibres are examples of scintillation detectors.

A scintillator is a material which exhibits scintillation – the property of luminescence[2] when excited by ionizing radiation. The basic principles behind this instrument are the use of a special material, which glows or "scintillates" when radiation interacts with it. That is, whenluminescent materials are struck by an incoming particle, energy is absorbedand scintillates.Scintillation detectors are the second most common type of radiation detecting instruments.

The first device which used a scintillator was built in 1903 by Sir William Crookes and used a ZnS screen[2][3]. The scintillations produced by the screen were visible to the naked eye if viewed by a microscope in a darkened room; the device was known as a spinthariscope. The technique led to a number of important discoveries but was

obviously tedious. Scintillators gained additional attention in 1944, when Curran and Baker replaced the naked eye measurement with the newly developed PMT. This was the birth of the modern scintillation detector[2].

Scintillation detectors are very sensitive radiation instruments and are used in both portable and stationary system. The properties of scintillation material required for good detectors are transparency, availability in large size, and large light output proportional to gamma ray energy. Relatively few materials are good properties for detectors. Thallium activated NaI and CsI crystals are commonly used, as well as a wide variety of plastics. NaI is the dominate material for gamma detection because it provides good gamma ray resolution and is economical.BGO is a pure inorganic scintillator without any activator impurity. There, the scintillation process is due to an optical transition of the Bi^{3+} ion, a major constituent of the crystal[4].

The high Z of iodine in NaI gives good efficiency for gamma ray detection. A small amount of Tl is added in order to activate the crystal, so that the designation is usually NaI(Tl) for the crystal. Many configurations of NaI detectors are commercially available, ranging from crystal for χ-ray measurements in which the detector is relatively thin, to large crystals with multiple phototubes.

Scintillators are used by the government as Homeland Security radiation detectors. This application has a huge impact on Homeland security inspection. Scintillators can also be used in monitoring systems, neutron and high energy particle physics experiments, new energy resource exploration, X-ray security, nuclear cameras, computed tomography and gas exploration. CT scanners and gamma cameras in medical diagnostics are another way scintillators are used. A few more applications of scintillators are how they are used as screens in computer monitors and television sets. Nuclear material can be monitored using certain types of scintillators. Scintillators also generate light in fluorescent tubes.Thallium-doped sodium iodide (NaI(Tl)) has two principal advantages: (1) it can be produced in large crystals, yielding good efficiency, and (2) it produces intense bursts of light compared to other spectroscopic scintillators.

Scintillation detectors are generally assumed to be linear. This assumption is based on two requirements: (1) that the light output of the scintillator is proportional to the energy of the incident radiation; (2) that the electrical pulse produced by the photomultiplier tube is proportional to the emitted scintillation light. The linearity assumption is usually a good rough approximation, although deviations can occur (especially pronounced for particles heavier than the proton at low energies)[1].

MATERIALS AND METHODS

WORKING MODEL AND DESCRIPTION FOR NaI(Tl) DETECTOR
In general, the analysis of a sample by gamma spectroscopy is considered to be non-destructive, certain sample/source preparation steps are essential for precise measurements. For example, it is necessary that the sample to be completely homogenized and measurement are carried out in the same geometry on used in the efficiency calibration. Ideally, the calibration source and the samples to be measured should have the same chemical composition and density. If this is not the case, correction must be made for differences in the degree of self-attenuation. Corrections may also have to be made for coincidence summing, which occurs with radionuclide which remit gamma ray cascade and which is particularly important for low source-detector distances.

To suppress background radiation and this improve sensitivity, a passive shield made from 'aged' lead or pre-world war II battleship steel must surround all gamma detectors. Actively shielded gamma-ray spectrometers, in which the intrinsic germanium detector is surrounded by a large NaI(Tl) coincidence shielded, have found application in ultra-level environmental studies (Hotel and Winkler, 1981; Wogman, 1981).

A practical model is developed that is capable of describing the overall NaI(Tl) detection efficiency as a function of several known or measurable parameters such as gamma-energy, source-to-detector distance, detector dimensions, source extension (area and volume), source composition and external absorbers.Detectors that have been calibrated for photopeak detection efficiency are used to obtain the absolute gamma emission rates and quantitative analysis by NaI(Tl) gamma spectroscopy.

Some of the principal source parameters taken into account aresource-to-detector distance, source extension in area and volume, self-attenuation by the various materials of a volume source and attenuations by external absorbers that may be interposed betweenthe sample and the detector. The attenuation of low energy radiations by NaI(Tl) dead layer is also considered.

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A basic premise of the model is that the overall efficiency can be treated as a product of two components: the intrinsic efficiency, which can also be defined as

$$\varepsilon_E = \frac{C_E \times d^2}{\gamma_E} \tag{1}$$

where;

ε_E = counting efficiency for gamma-ray of energy, ε, normalized to 1cm

C_E = net counts per unit time peak

γ_E = source emission rate of gamma energy ε, and

d = source-to-detector

and the source-to-detector geometry which is determined by the calculation of two hypothetical points is space, one at which all of the sample is saidto reside and another at which all of the sample is said to be concentrated. It should be noted that the detection efficiency is inversely proportional to the square of the source-to-detector distance, and equation (1) is the fundamental equation used by this model.

The equation (1) above can be transposed to yield photon emission ratios, γ_E for source of unknown intensity once a calibration curve (ε vs E) has been determined. A typical configuration for a cylindrical detector and a point source is shown in figure (1). To use equation (1), the parameter d must be assessed by using measured or calculated values for:
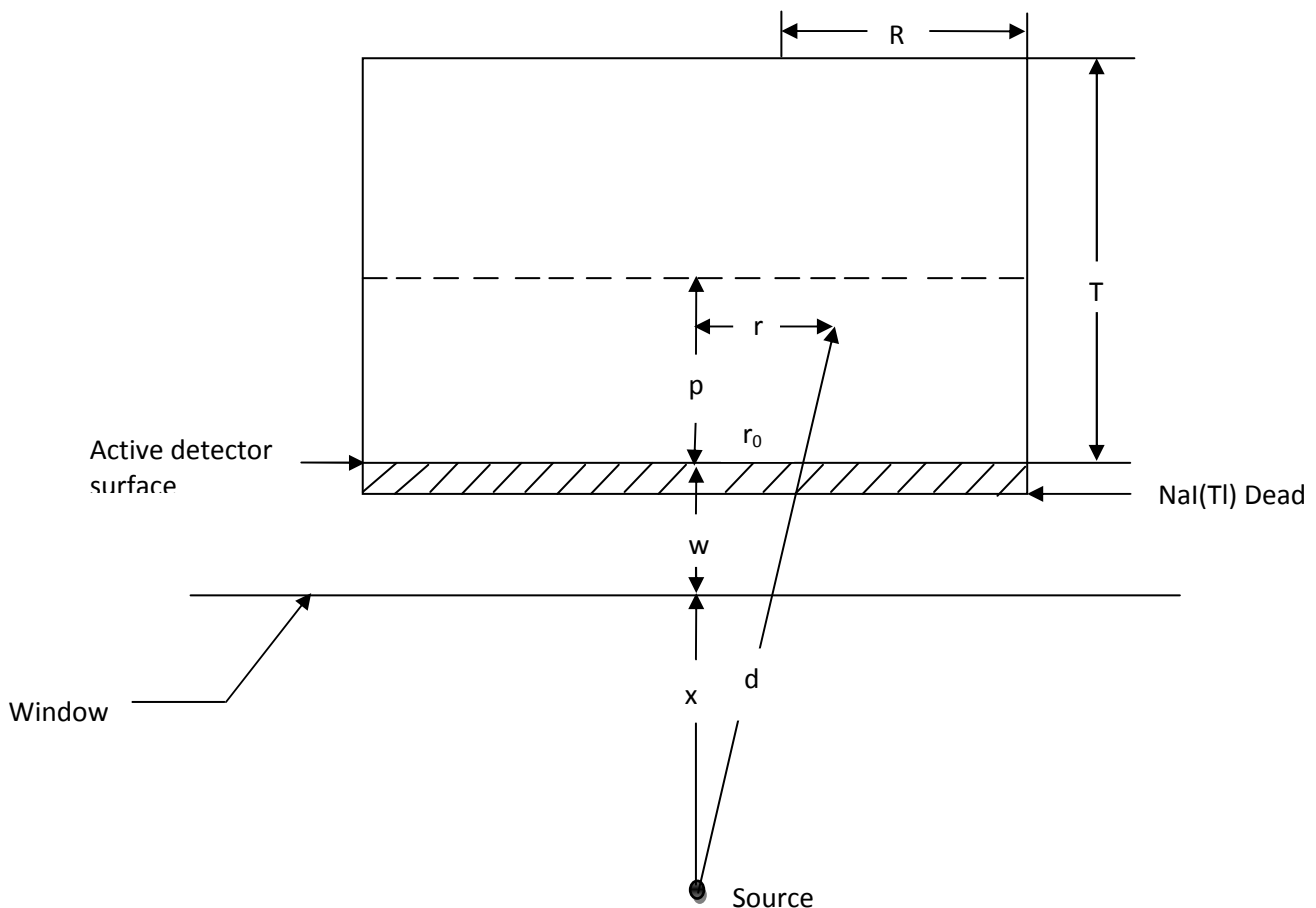

Figure 1: point source and cylindrical detector used in the model

x = distance from the source to window

w = distance from window to active detector surface

p = effective penetration of gamma-ray into detector

r = effective interaction radius in the detector

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r_0= limiting value of r at low energy

d = distance from source to effective zone of interaction

T = detector thickness

R= detector radius

From the simple geometry we have

$$d^2 = (x + w + p)^2 + r^2 \tag{2}$$

of these, x is the only measured parameter. The others must be empirically measured. The penetration value, p, which is dependenton the gamma-ray energy and has a limiting value of zero at low energy and one-half the detector thickness, T, at very high energy can describe by the equation:

$$p = \frac{1}{\mu}\left(1 - \frac{\mu T \exp(-\mu T)}{1 \exp(-\mu T)}\right) \tag{3}$$

whereμ is an appropriate energy dependent absorption coefficient.

The total absorption can be described by an empirical function given by:

$$\ln \mu = -2.316 + 4.2 \exp(-0.47 \ln E - 1.434) \tag{4}$$

The dependence of gamma-ray penetration on energy should be considered even when establishing relative efficiency curves. These variations in penetration result in efficiency curves of different shapes for different detector geometries. This effect becomes very pronounced at close-in coming geometries.

Table (1) shows the values of the absorption coefficient, μ, and the penetration, p, for each of the source using equations (3) and (4). It should be noted that the thickness, T, of the detector has been assumed to be 1.0mm thick.
It should be noted that detector designed specifications do not describe, w, accurately enough; its determination is always the first requirement in calibrating the total detector efficiency. The effective interaction, r can be defined for low energies. When the interaction is primarily photoelectric and occurs at the surface of the detector. In this case, r and r_0 are equivalent and can be used interchangeably.The exact detector efficiency and the effective radius can be computed from a simple geometry given by:

$$\text{Physical geometry} = \frac{1}{2}\left[\frac{1 - \ell}{\sqrt{\ell^2 + R^2}}\right] \tag{5}$$

Where $\quad\quad \ell = x + w \tag{6}$

in this model the geometry, G is described by:

$$G = \frac{K}{\ell^2 + r_0^2} \tag{7}$$

Where $K = \frac{R^2}{4}$, and is determined by normalizing the two expressions as ℓ goes to infinity. Consequently, one can now state the relationship between the effective interactions, r and the detector radius, r as:

$$r_0^2 = \frac{1 - C\ell^2}{C} \tag{8}$$

Where $C = \frac{2}{R^2}\left[\frac{1 - \ell}{\sqrt{\ell^2 + R^2}}\right] \tag{9}$

The effective interaction radius of the detector decreases from the initial value of $r$as the gamma-ray energyincreases as revealed by the study of experimental data. The effective radius of interaction for production of photopeaks decreases as the depth increases. The empirical algorithm used to describe this trend is given by:

$$r = r_0\left(\frac{1.1 - p}{\sqrt{T}}\right) \tag{10}$$

Thedistance from the window to the active detector surface, w is first determined when calibrating the total detector efficiency. This is accomplished by counting sources of different energy at several distances.

RESULTS AND DISCUSSION

CALIBRATION AND STANDARDS
The reliability of any radiation measurement depends both on the inherent consistency of the measurement procedure as well as on the accuracy of the instruments used. In practice, all instruments have to be calibrated since the results typically appear as numerical multiples of some appropriate units. Very few radiation measurements are conducted in absolute terms based on "first principles". Instead almost invariably one relies on a meter reading or a comparison standard that can be used to calibrate the system, that is, establish a firm scale of measurement.

The quantities determined in most radiation measurements are intensity ("number flux"), energy, absorbed dose or source strength, ("output or exposure"). The measurements employed to determine these quantities depends on the particular detector used, the type of radiation, the energy spectrum and the surrounding medium, are usually sensitive to variations in ambient temperature, cosmic radiation and background, atmosphere pressure, electrical supply variations as well as human factors.

ENERGY CALIBRATION AND ABSOLUTE EFFICIENCY DETERMINATION
When the energy calibration was carried out all the standard point sources could not be used. This was because; some of the standard point sources have completely decayed over the period of 10.4 years. Therefore only those standards point sources with favourable half-life were used and are shown in the table 3.0.

Before the counting, it should be noted that energy calibration was done with the exception of [22]Na, which was counted for 1200s due to its lower half-life, but all other sources were counted for 300s

The activity was calculated using the relation

$$A = A_0 exp\ (-\lambda t) \tag{11}$$

where A = current activity of the source
A_0 = original activity of the source
λ = the decay constant
t = time elapsed

The decay constant   is given by

$$\lambda = \frac{0.693}{T_{1/2}} \tag{12}$$

Where $T_{1/2}$ = half life of the source.

The product of the geometric efficiency and the intrinsic efficiency is the total efficiency, or the number of counts detected, relative to the total number of radiations emitted from the source. Therefore, after counting the standard point sources and determining the count rate in the energy photopeak areas of the various radionuclides, an empirical formula of the form:

$$\varepsilon = -7.410 \ln(E) + 58.905 \tag{13}$$

was found that relates the efficiency of the detector with energy in (keV) during the calibration of the detector [5].

CALCULATION
The Nal(Tl) detector being considered has an area of 7.6cm by 7.6cm, but the model adopted here was used for Ge(Li) detector which is a cylindrical detector. So, if we assume the NaI detector to be a cylindrical detector with base radius, R, then the cross-sectional area of the detector is given by

$$\text{Cross sectional Area} = \pi R^2 \tag{14}$$

where R is the detectors' radius.

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Table 1: the table shows the absorption coefficient and the penetration (in cm)

Source	Energy (keV)	Absorption Coefficient, μ	Penetration, $\wp$
^{241}Am	59.5	0.113720463	0.004999052
^{60}Co	1173.2	0.102094517	0.004999149
	1332.5	0.101888901	0.004999151
^{137}Cs	661.6	0.103198386	0.004999135
^{22}Na	511.0	0.103809053	0.004998849
	1274.5	0.101959305	0.00499915

Table 2: Data from 7.6cm x 7.6cm detector showing the distance(x) and count-rate at different energy peaks

Distance(x) (cm)	Count-rate	Energy peak (keV)
1.0	5050.09 $\pm$ 4.54	59.5 – ^{251}Am
2.0	3731.43 $\pm$ 3.73	
3.0	2705.07 $\pm$ 3.28	
4.0	2013.66 $\pm$ 2.84	
5.0	1540.94 $\pm$ 2.70	
6.0	1129.54 $\pm$ 2.26	
7.0	927.51 $\pm$ 1.95	
8.0	752.98 $\pm$ 1.79	
9.0	605.17 $\pm$ 1.69	

Distance(x) (cm)	Count-rate	Energy peak (keV)
1.0	443.54 $\pm$ 3.31	1332.5 – ^{60}Co
2.0	312.82 $\pm$ 2.62	
3.0	234.81 $\pm$ 2.22	
4.0	181.43 $\pm$ 1.91	
5.0	141.91 $\pm$ 1.69	
6.0	110.79 $\pm$ 1.56	
7.0	97.61 $\pm$ 1.31	
8.0	59.59 $\pm$ 1.47	
9.0	58.59 $\pm$ 1.26	

Distance(x) (cm)	Count-rate	Energy peak (keV)
1.0	2230.14 $\pm$ 2.72	661.6 - ^{137}Cs
2.0	1554.43 $\pm$ 3.10	
3.0	1112.50 $\pm$ 2.63	
4.0	837.76 $\pm$ 2.29	
5.0	639.61 $\pm$ 2.15	
6.0	507.70 $\pm$ 1.79	
7.0	418.23 $\pm$ 1.79	
8.0	315.00 $\pm$ 1.90	
9.0	277.96 $\pm$ 1.65	

Distance(x) (cm)	Count-rate	Energy peak (keV)
1.0	470.41 $\pm$ 2.41	511 – ^{22}Na
2.0	363.44 $\pm$ 1.86	
3.0	283.44 $\pm$ 1.86	
4.0	229.42 $\pm$ 1.89	
5.0	170.82 $\pm$ 1.52	
6.0	135.38 $\pm$ 1.42	
7.0	104.87 $\pm$ 1.30	
8.0	87.36 $\pm$ 1.24	
9.0	64.93 $\pm$ 1.14	

Distance(x) (cm)	Count-rate	Energy peak (keV)
1.0	90.26 $\pm$ 1.72	1274.5 – ^{22}Na
2.0	72.50 $\pm$ 1.36	
3.0	55.70 $\pm$ 1.12	
4.0	45.21 $\pm$ 0.96	
5.0	26.84 $\pm$ 0.99	
6.0	26.65 $\pm$ 0.84	
7.0	20.21 $\pm$ 0.85	
8.0	17.76 $\pm$ 0.79	
9.0	14.40 $\pm$ 0.77	

To convert this area to that of the detector of dimension 7.6cm x 7.6cm, we may write

$$7.6\text{cm x }7.6\text{cm} = \pi R^2 \tag{15}$$

Taking π=22/7, we have R = 4.286978169cm.

So, calculating for x = 1.0cm, 2.0cm, etc, with w = 0.999750079cm (from the graph of penetration, p against gamma energy), the physical geometry respectively 0.288630155rad, 0.308902362rad, etc. From equation (9) and calculating for x = 1.0cm for all point sources, we have C = 0.062820176, also substituting this value in equation (8), we have r_0 = 3.452455981cm.

Consequently, for each of the point source, the effective interaction radius, r of the detector can be obtained from equation (10), and substituting for x, w, p and r in equation (2) in order to obtain the distance from source to effective zone of interaction, d, of the detector for each of the point sources. These results are tabulated in table 4.

Table 3

Radio nuclide	Energy (keV)	Activity (Ao) (kBq)	Activity after time 't' (A) (kBq)
^{241}Am	59.5	59.08	58.69
^{60}Co	11732.5	48.27	12.30
	1332.6	48.2	12.30
^{137}Cs	661.6	37.92	29.89
^{22}Na	511.0	48.88	3.032
	1274.5	48.48	3.032

Table 4

Source	Energy (keV)	p (cm)	r(cm)	d(cm)
^{241}Am	59.5	0.004999052	2.417046366	3.140243974
^{60}Co	11732.5	0.004999135	2.417016093	3.14220729
	1332.5	0.00499915	2.441701253	3.140217992
^{137}Cs	661.6	0.004999151	2.417012326	3.140217836
^{22}Na	511.0	0.004999149	2.417012917	3.14021829
	1274.5	0.004998849	2.41711648	3.140297811

CONCLUSION

The two most important characteristics required when considering a detector most especially the Nal(Tl) detector are resolution and efficiency. Other characteristics to consider are peak-to-Compton ratio, crystal dimension or shape and price.During energy or efficiency calibration points source were measured or considered, however, the bulk property of the source also has to be considered. Hence, correction has to be made to the detector's geometry.Both the resolution and efficiency depends on several factors (such as measured radiation, solid, angle between sample and detector crystal, etc) which affect, the correction's that have to be made to the geometry of the detector.

We have assumed the Nal(Tl) detector to be a cylindrical detector in order to be able to use this model effectively. On considering when x =1.0cm, the value of r_0 was calculatedto be 3.452455981cm, the geometry, G, was found to be 0.288630154 radian and the values of r, and d, for each point source were also calculated as shown in table 4.Finally, the efficiency, ε were determined using the empirical equation (13) for thesources to be 28.62791552, 6.534896602, 10.7806102, and 12.69350134 for^{241}Am, ^{60}Co,^{137}Cs and ^{22}Na respectively.

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