DEPENDENCE OF RESOLUTION AND EFFICIENCY OF NaI(Tl) ON VARIOUS PARAMETERS

A dissertation

Submitted in partial fulfilment of the requirement for the award of

Degree of

Master of Science

In

Physics

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Dedicated to my

Respected

Parents

And

Teachers

CERTIFICATE

This to certify that the thesis titled **‘DEPENDENCE OF ENERGY RESOLUTION AND EFFICIENCY OF NaI(Tl) ON VARIOUS PARAMETERS’** submitted by Jaspreet Kaur Chahal (Roll no. 301804008) of M.Sc. Physics, Thapar Institute of Engineering and Technology, (Deemed to be University), Patiala, was carried out by me under the supervision and guidance of Dr. Sunil Devi. I have not submitted this material for credit towards any other degree at Thapar Institute of Engineering and Technology, (Deemed to be University), Patiala or any other university.

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ACKNOWLEDGEMENT

In the present world, there is a race of existence where only those succeed who come forward. This dissertation has been kept on track and been seen through to completion with the support and encouragement of numerous people including my supervisor, family and friends. My first and foremost thanks goes to my supervisor Dr. Sunil Devi who has guided me in this difficult situation (COVID-19) to complete my work, and her constant encouragement, valuable suggestions, blessings, useful comments, remarks, motivation and constant support provided throughout this dissertation.

I am greatly indebted to my parents who brought me up with love and encouragement to this stage. I would also like to thank my siblings and all members of my extended family, without their blessings, I wouldn’t have been able to complete this project.

At last but not the least, I am thankful to my friends (Gurneet, Anu, Kajal) for keeping me grounded, for hearing me and keeping me focused on important things in life: good food/drinks (pizza, zingy parcel), LUDO and laughter with family. Above all I would like to acknowledge the Almighty for blessings and positive energy which sustained me during all stages of this work.

Jaspreet Kaur Chahal

ABSTRACT

The purpose of this thesis is to measure energy resolution, total efficiency and photo peak efficiency (full energy peak efficiency) of the 2"×2"flat type NaI(Tl) with the gamma ray energies ranging from 122 to 1132 keV. In this work, five different gamma ray sources ^{22}Na, ^{57}Co, ^{60}Co, ^{137}Cs and ^{133}Ba were placed at four different distances to observe effect of distance between source and detector on the energy resolution, total efficiency and photo peak efficiency.

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Chapter: 1 Introduction

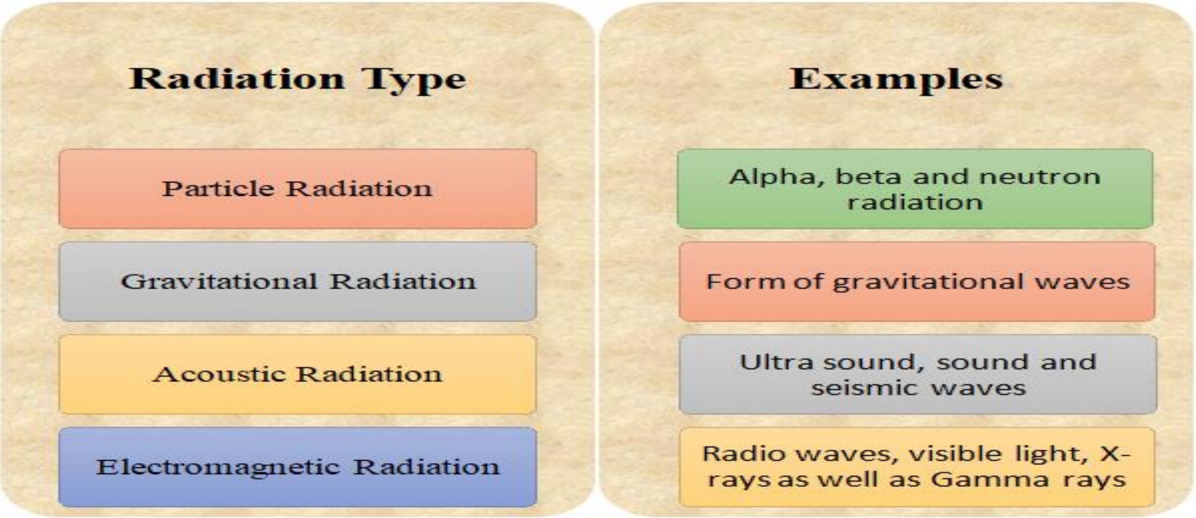
1.1 Introduction

Detection of gamma radiations is among the crucial aspects of the experimental nuclear physics. Gamma radiations are usually detected by two kinds of detectors: scintillation and semiconductor detectors. Scintillation detectors are generally used in various fields for instance: nuclear and higher energy physics, environmental studies and nuclear medicine [1]. In early years, the NaI(Tl) scintillation detector was introduced for gamma ray spectroscopy as these detectors are portable because of their small size [2].

With further development in features of detectors, efficiency and energy resolution of detectors was improved. NaI(Tl) has high density and atomic number which results in high detection efficiency as well as in reasonably good energy resolution to distinguish between two closely lying energy peaks [3]. The aim of this thesis is to calculate the efficiency and energy resolution of NaI(Tl) scintillator as a function of distance (between source and detector). This chapter involves the brief introduction on gamma rays and their interaction with matter.

1.1.1 Radiation

It is a form of energy which is emitted from a source and transmitted everywhere in the space or other medium. Radiations can be of two types: ionising and non-ionising radiations. Ionising radiations can easily dissociate the chemical bond (10eV) as compared to ionising radiations.



Radiation Type	Examples
Particle Radiation	Alpha, beta and neutron radiation
Gravitational Radiation	Form of gravitational waves
Acoustic Radiation	Ultra sound, sound and seismic waves
Electromagnetic Radiation	Radio waves, visible light, X-rays as well as Gamma rays

Table 1.1 Different kinds of radiations with suitable examples.

1.1.2 Electromagnetic Spectrum

Electromagnetic radiation spectra describe all types of radiations including visible light [4]. The chart shows the frequency from the range of 10^1 Hz to 10^{25} Hz which covers various kinds of the electromagnetic radiations, which can be seen in fig. 1.1

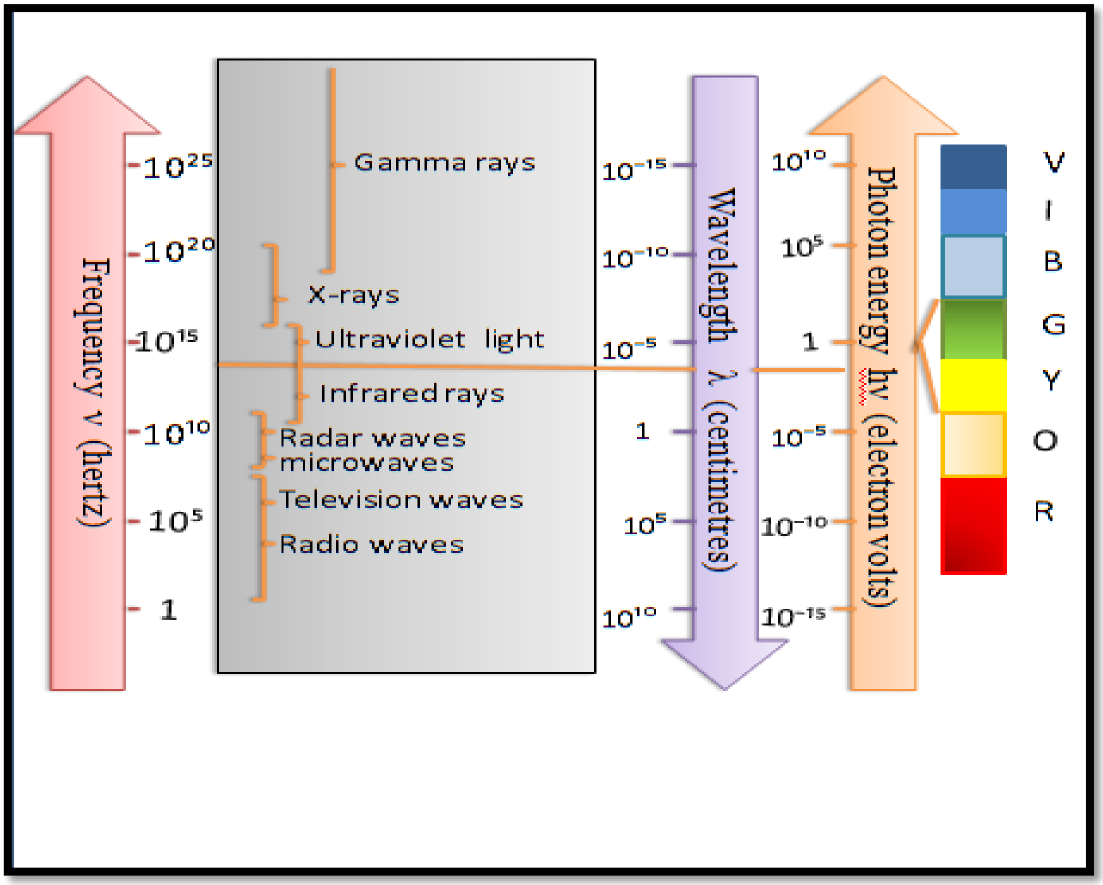


Fig.1.1 Electromagnetic spectra [5].

1.1.3 Gamma Radiations

Gamma rays are type of electromagnetic radiations which have high frequency i.e. higher energy or shortest wavelength [6]. This work is related to the detection of gamma radiations. In table 1.2, various properties of gamma rays are given.

Properties	Value
Wavelength	<100pm
Frequency	>1018Hz
Energy	>41.4keV

Table 1.2: Properties of gamma radiations.

❖ Production of Gamma Rays

The nucleus undergoes alpha or beta decay to produce daughter nucleus which sometimes is present in excited state. In order to get stabilise this excited state daughter nucleus undergoes a transition from excited state to ground state by emitting the energy in form of gamma rays. Thus we can say that gamma rays are produced due to alpha or beta decay.

❖ Interaction of Gamma Rays with Matter

Interaction of these rays cannot be compared with those of charged particles because gamma rays are uncharged particles with zero mass due to which it has the large penetrating power. The major interactions of gamma radiation with matter are shown in fig. 1.2

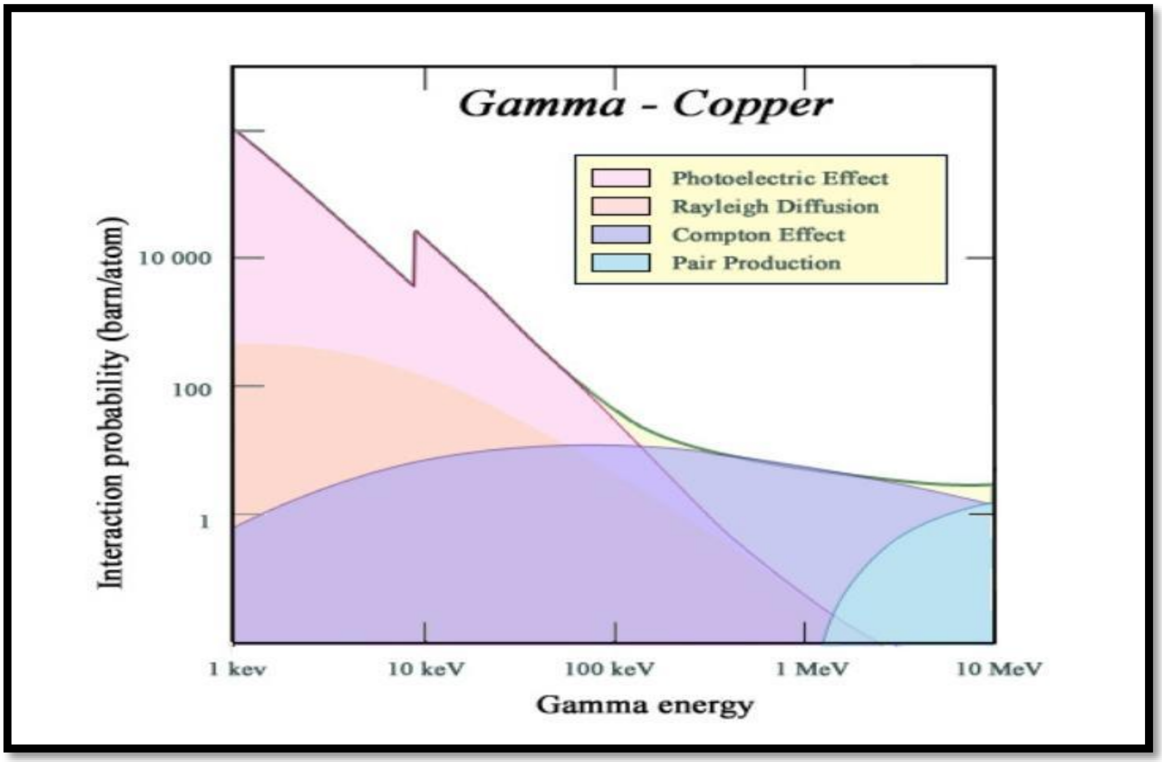


Fig. 1.2: Different kinds of gamma ray interactions as a function of gamma ray energies [7].

a) Photoelectric Effect

Incident gamma ray interacts with electron in the first shell and can also liberate the same electron. Difference between the striking photon energy (E_γ) and the dissociation energy of the electron (E_b) is equal to the liberated energy of the electron (E_e) which can be written as:

$E_e = E_\gamma - E_b$

This is called the photoelectric effect [8]. The procedure is shown schematically in fig. 1.3.

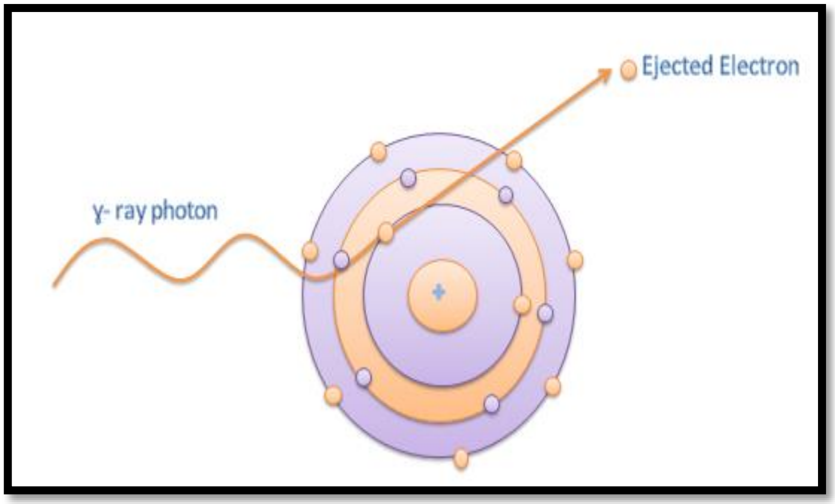


Fig. 1.3: A schematic showing photoelectric effect [9].

b) Compton Effect

c) In Compton effect, an incident γ-ray photon emits an electron from the atom whose energy is less than the energy of incident gamma ray photon. A schematic of Compton effect is shown in fig.1.4. The relation between energies of incident and emitted gamma rays can be given as:

$$E'_\gamma = \frac{E_\gamma}{1 + \frac{E_\gamma}{mc^2}(1 - cos\theta)}$$

Here, E_γ and E'_γ is the energy of incident and emitted gamma rays, mc^2 is the rest mass energy of the electron and θ is the angle of scattering [8].

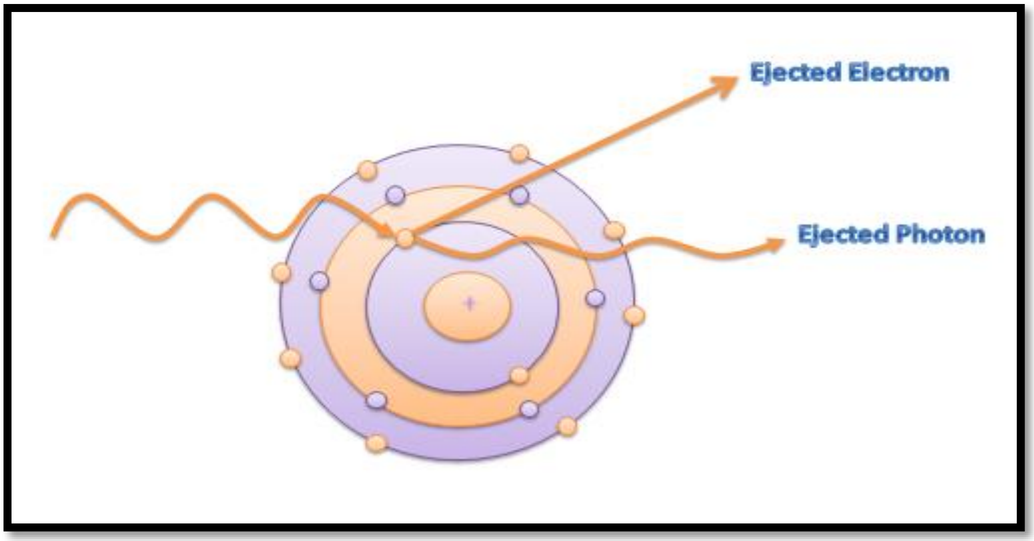


Fig. 1.4: A schematic showing Compton Effect [10].

d) Pair Production

In this process the photon energy is more than the 1.02MeV (which is the rest mass energy of two electrons), the incident photon produces electron positron pair by interacting with nucleus which is shown in fig. 1.5. As the rest mass energy of an electron as well as positron is 0.511MeV. Therefore, from energy conservation principle, gamma ray photon must have energy of 1.02MeV. Positron collides with an electron creating twice photons of same energy (511keV) by annihilation process [11].

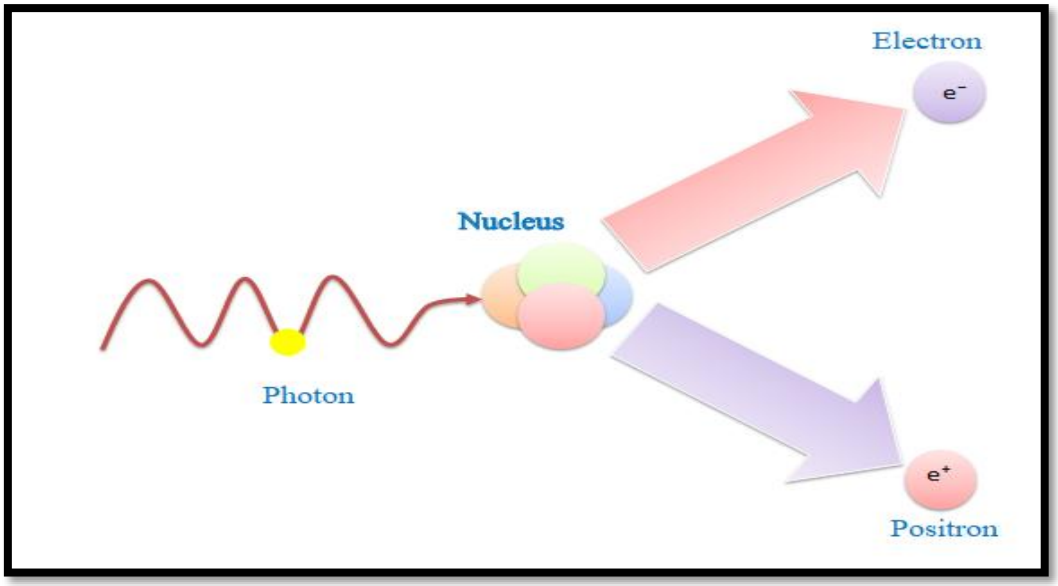


Fig. 1.5: A schematic showing pair production [12].

The following peaks will be observed in the spectrum:

- When the pair of annihilation photons is absorbed after that the photo peak is created in the spectrum.
- E - mc^2 is formed when one photon escapes while other photon is absorbed.
- E-2mc^2 is for the double escape peak energy, when both photons have escaped.

1.2 Energy Resolution

Detectors are rated by two parameters: energy resolution along with the detection efficiency. Energy resolution is a very important parameter of detector, which helps to distinguish two closely spaced gamma ray energy peaks detected by the detector [13].

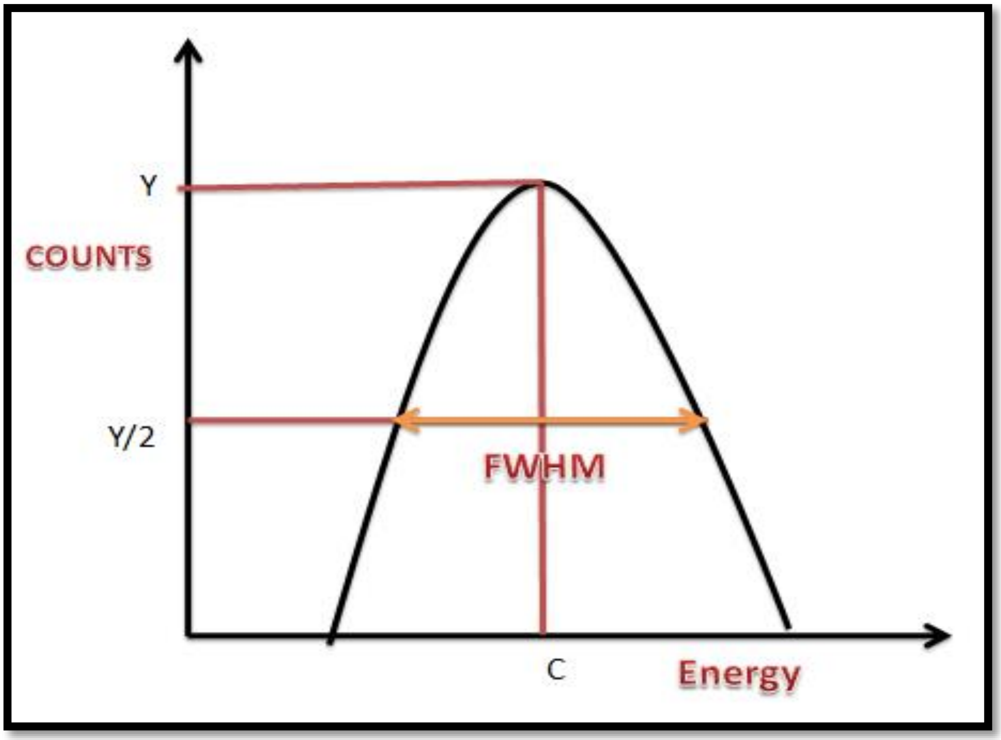


Fig. 1.6: A schematic showing FWHM for a Gaussian curve [14].

Resolution of a detector is defined as the ratio of the full width half maximum (FWHM) to the peak centroid (C) and it is given as:

$$R = \frac{FWHM}{C}$$

In gamma ray spectroscopy, NaI(Tl) detector has the resolution in the range between 5-10% [14]. A schematic showing FWHM for a Gaussian curve is shown in fig. 1.6.

1.3 Detection Efficiency

In gamma ray spectroscopy, another parameter is the detecting efficiency. Detectors used for uncharged radiations like gamma rays or neutrons do not have 100% efficiency for the incident radiations [14]. Detection efficiency can depend on various characteristics like the detector material, volume, shape, absorption cross section of the material and distance between sources and detector [15]. There are several ways to define the efficiency of the detector system:

Photo peak efficiency: As the name suggests, that when the gamma radiations strike to the detector then it stores the energy which is observed in the form of photo peak afterwards. It is ratio of net counts registered by the detector in the photo peak area to the number of photons energy E emitted by the source.

$$\varepsilon_{pe}(E) = \frac{N(E)}{A.t.p(E)}$$

N(E) is the number of net counts registered by the detector in the photo peak area, A is activity of the radioactive source, t is the time (in seconds) during which events were registered, p(E) emission probability of the gamma ray.

Total Efficiency: It is ratio of the total number of counts registered by the spectrum (resulting from all possible interactions of gamma rays) to the gamma radiation emitted by the source.

$$\varepsilon_{T}(E) = \frac{N_T(E)}{A.t.p(E)}$$

N_T is the total number of counts registered by the detector, A is the activity of the radioactive source, t is the time (in seconds) during which events were registered, p(E) emission probability of the gamma ray. [16].

1.4 References

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[16]. Urkiye Akar Tarim, Orhan Gurler, Source-to-Detector Distance Dependence of Efficiency and Energy Resolution of a 3"×3" NaI(Tl) Detector, European Journal of Science and Technology, No. 13, pp. 103-107, August 2018, doi: 10.31590/ejosat.443565.

Chapter: 2 Literature Review

I. **Akkurt, K. Gunoglu and S. S. Arda, Hindawi Publishing Corporation Science and Technology of Nuclear Installations, Vol. 2014, pp. 1-5:** In this paper, the detection efficiency and energy resolution were calculated by using the six different energies (511, 662, 835, 1173, 1275, 1332 keV) from the four radioactive sources (^{22}Na, ^{54}Mn, ^{60}Co, ^{137}Cs) at five different distances from 3"×3" NaI(Tl) detector face. At the end, it was concluded that detector efficiency and energy resolution relies on two things: incident photon energy as well as distance between source and detector. In case of high gamma ray energy, the energy resolution of detector reduced corresponding to Full Width Half Maximum. Detector efficiency decreases when source to detector face distance was increased.

II. **G. R. Pansare, S. J. Ansari and U. R. Kamthe, Research Journal of Material Sciences, Vol. 4(4), pp. 7-12, May (2016):** This paper shows that NaI(Tl) was used for various applications in different fields like in medical physics and industries. In this experimental work, the detection efficiency and energy resolution were calculated for various detector type, size and different detector operating parameters (Operating Voltage, Radius of detection window and source to detector distance). The source was placed at a 3.7cm distance from the window of the detector. The operating voltage was kept constant at 750V. For different gamma ray energies (122, 356, 511, 662, 1170, 1330keV), the detection efficiency as well as energy resolution both were measured. A result shows that detector efficiency and energy resolution (5-10%) both decrease with increases in gamma ray energies.

III. **Urikya Akar Tarim, Orhan Gurler, European Journal of Science and Technology No. 13, pp. 103-107, August 2018:** In this paper, 3"×3" NaI(Tl) detectors was used for energy calibration and calculation of photo peak efficiency, total efficiency and energy resolution. The source to detector distance was increased by 2cm for various sources from 2-12cm. It was reported that it gives the incorrect data points of efficiency at the 4cm source to detector distance. The energy calibration was performed and resolution as well as efficiency was calculated at six different distances for four radioactive sources (^{137}Cs, ^{60}Co, ^{22}Na, ^{241}Am). All sources were placed for 1 hour for measurements.

IV. **Demet Demir, Adem Un, and Yusuf Sahin, Instrumentation Science and Technology, pp. 291-301, 2008:** In this paper energy resolution as well as photo peak efficiency of thallium activated sodium iodide detector (Canberra Model 802) was calculated using the polyester coated radioisotope sources whose energy range was in between 23-1333keV and coarse gain of the amplifier was kept at 10.0, fine gain at 4.0, shaping time 12μs. The high detection efficiency was depend on: area of detector along with the photon energy. The increase in detection efficiency with increase in area covered by the detector and reduction with increase in photon energy was observed. In the case of energy resolution, the FWHM increases with the rise in gamma radiation energy.

V. **Urikye Akar Tarim, Orhan Gurler, Sezai Yalcin, Celal Bayar University Journal of Science, Vol. 14, pp. 195-199:** This work shows that, the Monte-Carlo algorithm method can be applied to explain the efficiency of the gamma radiation energy. The total, intrinsic as well as geometric efficiencies were simulated for the different energies range (150-3000keV). The cylindrical NaI(Tl) detector was used with a radius of 2.54cm and height 5.08cm for the point source with a source to detector distance being from 0.001 to 15cm. The result was compared with the literature and they agreed well.

VI. **M. Moszynski, A. Syntfeld-Kaazuch, L. Swiderski, M. Grodzicka, J. Iwanowska, P. Sibczynski, T. Szczesniak, Nuclear Instruments and Methods in Physics Research A, Vol. 805, pp. 25-35:** This paper shows the energy resolution of scintillation detector. Non-proportional response of scintillation detector shows the limitations of it and good resolution have a great importance for a scintillator. The light pulse shows the peak point of energy resolution which is measured by scintillator. In the case of large order of gamma ray energy the YAP, $LaCl_3$ and $LaBr_3$ have high energy resolution with better proportionality response of the light output. It shows that co-doping improves the non- proportionality response as well as intrinsic resolution of source. For halide crystals, the non-proportionality response is dependent upon the doping agents.

VII. **F. E. Cecil and F. J. Wilkinson III, R. A. Ristinen, Risto Rieppo, Nuclear Instruments and Methods in Physics Research A234 (1985), pp. 479-482:** In this paper, sodium iodide with activated thallium as well as lithium drifted germanium detectors response have been measured and the absolute efficiency and energy resolution of in the energy range of 2.6 to 16.1MeV was compared. Both the energy resolution and absolute efficiency were 2% for 10cm×10cm NaI(Tl) detector and full width energy resolution was 0.1% for the Ge(Li) detector. Ge(Li) gives the best value for energy resolution and NaI(Tl) shows best result for full energy peak as compared to peak region.

VIII. **A. Kadum and B. Dahmani, Instrumental and Experimental Techniques, 2015, Vol. 58, No.3, pp. 429-434:** 2"×2" NaI(Tl) well-shaped detector was utilized to calculate the efficiency. It shows that detector efficiency was reduced with rising in gamma radiation energy. This type of detector was helpful to determining the low level of radiation in concentration of different samples (^{238}U, ^{232}Th and ^{40} K).

IX. **Hossain, N. Sharip and K. K. Viswanathan, Scientific Research and Essays Vol. 7(1), pp. 86-89, 9 January, 2012:** In this paper, HPGe and NaI(Tl) detectors are used for calculating the energy resolution and efficiency. The diameter and length of HPGe are 60.5mm and 31.5mm respectively and a 2"×2" NaI(Tl) detector was used. Data was taken for 3hours or 10800seconds. Hence, NaI(Tl) detector has good efficiency as compared to the HPGe detector**.**

X. **Mohamed Abd-Elzaher, Mohamed Salem Badawi, Ahmed El-Khatib, Abouzeid Ahmed Thabet, World Journal of Nuclear Science and Technology, 2012, Vol. 2, pp. 65-72:** The photo peak efficiency (FEPE) was determined by applying empirical formula for scintillation detector for broad energy range of 59.5 to 1430keV at seven distinct axial distances from detector. The result shows that the efficiency was higher for the larger detector.

XI. **Jehouani, R. Ichaoui, M. Boulkheir Applied Radiation and Isotopes 53(2000), pp. 887-891:** This work shows the efficiency of NaI(Tl) with respect to the different geometrical parameters (shape, size of the detector and material) by comparing the Monte Carlo Method and Analytical Method**.** In the case of geometrical configuration the analytical method was used to determine the intrinsic efficiency. However, the results obtained from both methods were almost same. Gamma ray photon has large probability of being detected in the large radii and as the radii increases, so does efficiency.

XII. **M. Moszynski, SPIE Proceedings, Vol. 5922, pp. 1-7:** In this paper, the main focus was on the drawbacks of the energy resolution of NaI(Tl) detectors and non-proportionality of the light as well as intrinsic energy resolution of the crystals. It was concluded that the scintillator materials show their fundamental properties for non-proportionality response of the undoped oxides (BGO, CWO). Both the energy resolution as well as non-proportionality response were improved by co-doping of the crystals.

XIII. **Supriti Sen, Anirudh Chandra, Dibyadyuti Pramanik, M. Saha Sarkar, Proceedings of the DAE Symp. On Nucl. Phys. 58(2013), pp. 934-935:** In this paper, BICRON 6"×8" NaI(Tl) was used for measuring the intrinsic photo peak efficiency for ^{137}Cs at various detector to source distances. For 6"×8" crystal and 3"×3" crystal the data was recorded for 1800seconds and 3600seconds respectively. The minimum efficiency was observed at a source to detector distance of 3cm for 6"×8" crystal.

XIV. **Ari M. Hamad, Hiwa M. Qadr, Eurasian Journal of Science and Engineering, 2018, Eurasian Journal of Science and Engineering, Vol. 4, pp. 99-111:** In this paper, the energy response and efficiency for the scintillation detector at 500-750 volts were measured. Then experiment was performed using zirconium and tungsten material to measure the attenuation of gamma radiation to find out which material had better attenuation coefficient. Result shows that tungsten was a good shielding material because of the higher electron density and atomic number.

Chapter: 3 Conceptual Perspectives

3.1 Detection of Gamma Radiation

For the detection of any nuclear radiation, the detector's response for interaction of gamma radiation with material is very critical. Another thing is the dissipation of energy in the detector by that radiation. The main cause of the dissipation energy is the ionization of atoms in the detector. Detection of gamma rays also depends on the material properties like electron density as well as atomic number. In this chapter, scintillation detector is discussed in detail.

3.2 Scintillation Detector

3.1.1 Introduction:

When the nuclear radiations strikes to the zinc sulphide (fluorescent) material then it produces the light flashes, when flash of lights were observed then that is called scintillation and the material is called the scintillator [1].

TV screen is an example of the scintillation mechanism, in which the visible photons are emitted after the bombardment in the cathode ray tube. Scintillation is one of the oldest techniques for detecting the gamma rays [2].

In early years 1900s, Crooks in England and Elster and Gestel in Germany independently reported that the alpha particles are falling on the zinc sulphide screen then the flash of lights were observed with the help of microscope [1].

Main type of scintillator materials are: inorganic and organic crystals. Sodium iodide is one of the major inorganic crystals which are more used and these crystals have high density. However, these types of crystals cannot be used in pure form. On the other hand organic scintillators are more used for the beta spectroscopy due to the fast response time [3].

3.1.2 Inorganic Scintillators:

Crystal lattice determines the energy states, in inorganic material. The energy bands are classified on the basis of the material whether it is an insulator or semiconductor. The fully filled bands are called valence band and the electrons those have sufficient energy, jump into conduction band [3]. When a radiation falls on the material, then many electrons can jump into higher energy band leaving behind positively charged electrons called holes in the fully filled band. These electrons can come back to the valence band because of de-excitation by emitting photons in the case of pure crystal form. Due to the high energy of the emitted photon, this will not be present in the visible range. The addition of small amount of impurity can overcome this problem by emitting the photon of energy in the visible region. Due to the presence of this impurity additional energy levels are introduced within the forbidden energy gap [2, 3]. Some common inorganic scintillators are: NaI(Tl), ZnS(Ag), Cs(Tl), $LaBr_3(Ce_3)$, so on. Fig. 3.1 shows the energy band structure with the addition of thallium as an impurity.

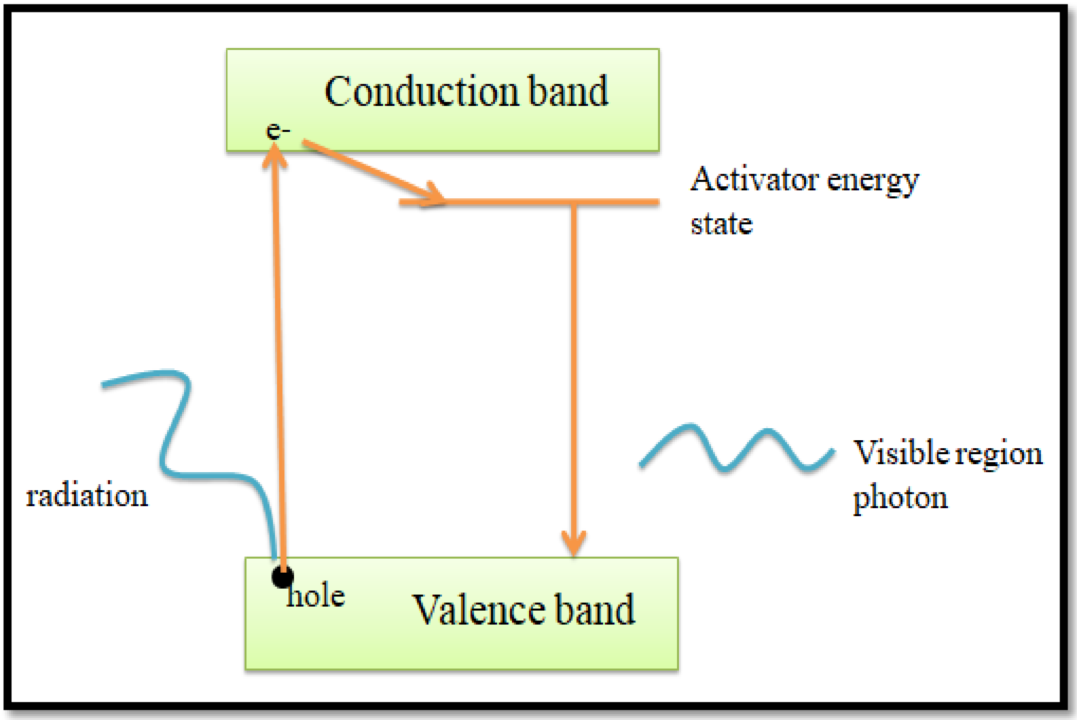

Fig. 3.1 Structure of energy bands of activated inorganic crystal [4].

3.1.3 Sodium Iodide scintillator activated by Thallium:

NaI activated by thallium is most preferred inorganic scintillator for the detection of gamma rays. In early years the use of sodium iodide with small amount of thallium impurity was reported by Robert Hofstadter in 1948 [3]. A small amount of scintillation is produced when the gamma rays interact with sodium iodide at room temperature. When an activator (thallium) is added to the sodium iodide then visible light photons are produced after the gamma ray interaction.

Sodium iodide scintillator with activation of thallium is used to detect the gamma rays because of high atomic number of iodine (Z = 53) as well as high density of detector [5]. Some properties of sodium iodide are given in table 3.1.

Properties	Value
Wavelength (nm)	410
Scintillation efficiency (%)	100
Decay time (µs)	0.23
Density (10^3 kg/m^3)	3.67
Refractive index	1.83

Table 3.1 Properties of Sodium Iodide [5].

Some of advantages are that if atomic number is high then interaction probability of gamma rays with crystal is increased and energy resolution is improved by the large conversion of photons. One of the major drawbacks is that NaI is hygroscopic in nature. It is placed in carton which is designed of aluminium.

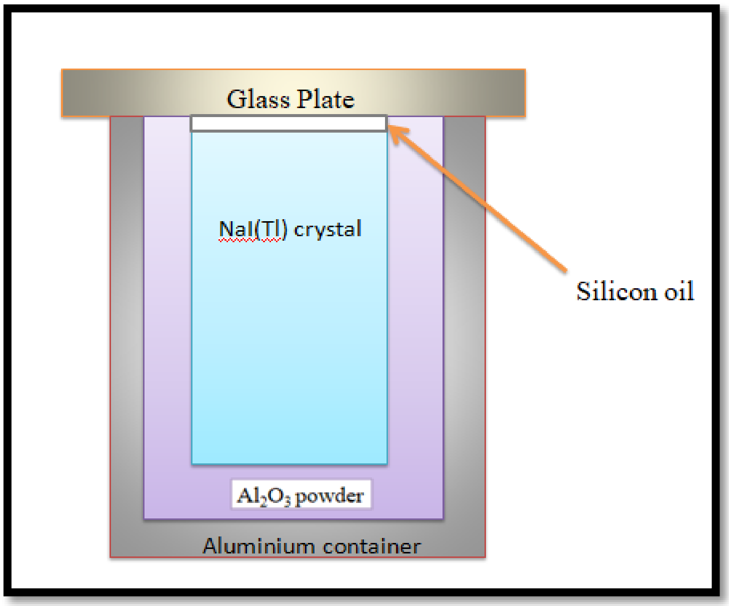

Fig. 3.2 NaI:Tl crystal with coated aluminium container [5].

The crystal is first polished to remove some irregularities and then is placed it in aluminium container where the surface is covered with the transparent glass. After that Al_2O_3 powder is filled in between the crystal and the aluminium container which is shown in fig.3.2. Due to the total internal reflection in aluminium oxide, no photons in visible range are scattered out from detector [6].

3.1.4 Functioning of Scintillation detector

Scintillation detector consists of some basic parts which include scintillator shielded of aluminium, photomultiplier tube and an amplifier etc. The structure of scintillation detector can be seen in fig.3.3.

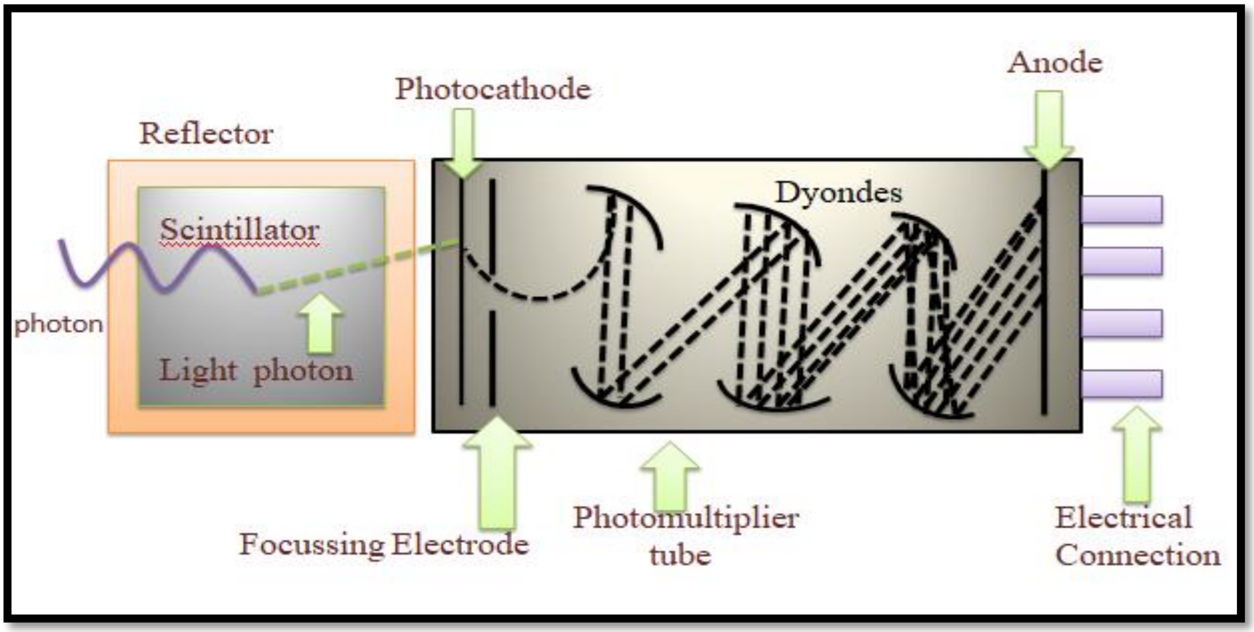

Fig.3.3 Sketch diagram of a scintillation detector [7].

<u>Photomultiplier Tube (PMT):</u>

In scintillation detector, one of the important part is the photomultiplier tube. The outer coating is made up of glass to control the vacuum from the inside. The fig.3.4 shows the schematic of a photomultiplier tube.

There are two processes that occur in the PM tubes: photoemission and secondary emission. The main function of photomultiplier tube is that it converts the incident photon light into electrons. When a flash of light hits the photocathode then it emits the photoelectrons. Electrons are directed towards the dynodes by applying a suitable increasing electric field. Borosilicate glass can be used to design windows of photomultiplier tubes.

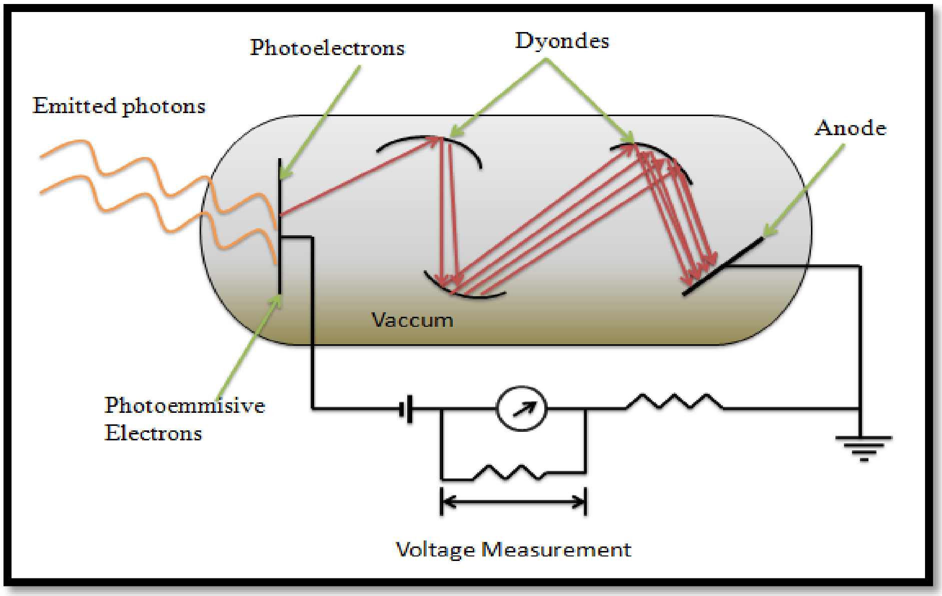

Fig. 3.4 Schematic of a simple photomultiplier tube [8].

The emitted photoelectrons have kinetic energy in the range of 1eV. Approximately 300 electrons will be emitted per 100 V of accelerating voltage for one electron [6].

3.3 References

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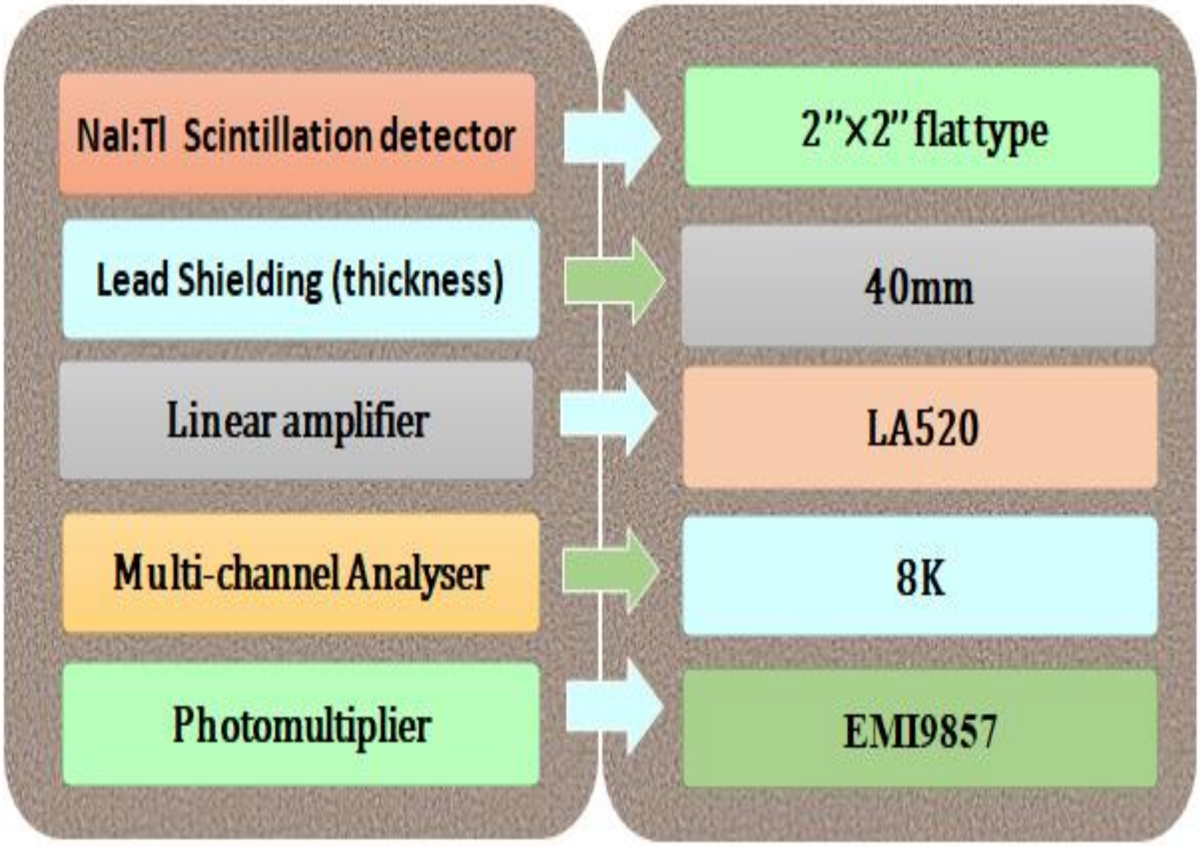
Chapter: 4 Experimental Details and Data Analysis

4.1 NaI:Tl Detector

Thallium activated sodium iodide scintillation detector is used for measurements is from NUCLEONIX Systems Private Limited. Some details of this detector are given in table 4.1 and a block diagram of the complete set-up is presented in fig. 4.1.

- <u>NaI:Tl Scintillation detector:</u> In this work, a 2"×2" flat type detector was used and this type of detector gives good resolution in the range of 8.0 to 9.5% for ^{137}Cs.
- <u>Lead Shield:</u> The detector was shielded using lead shielding. This is a made up of interlocking rings with top and bottom plates [1].



NaI:Tl Scintillation detector	2"x2" flat type
Lead Shielding (thickness)	40mm
Linear amplifier	LA520
Multi-channel Analyser	8K
Photomultiplier	EMI9857

Table 4.1 NaI(Tl) detector details.

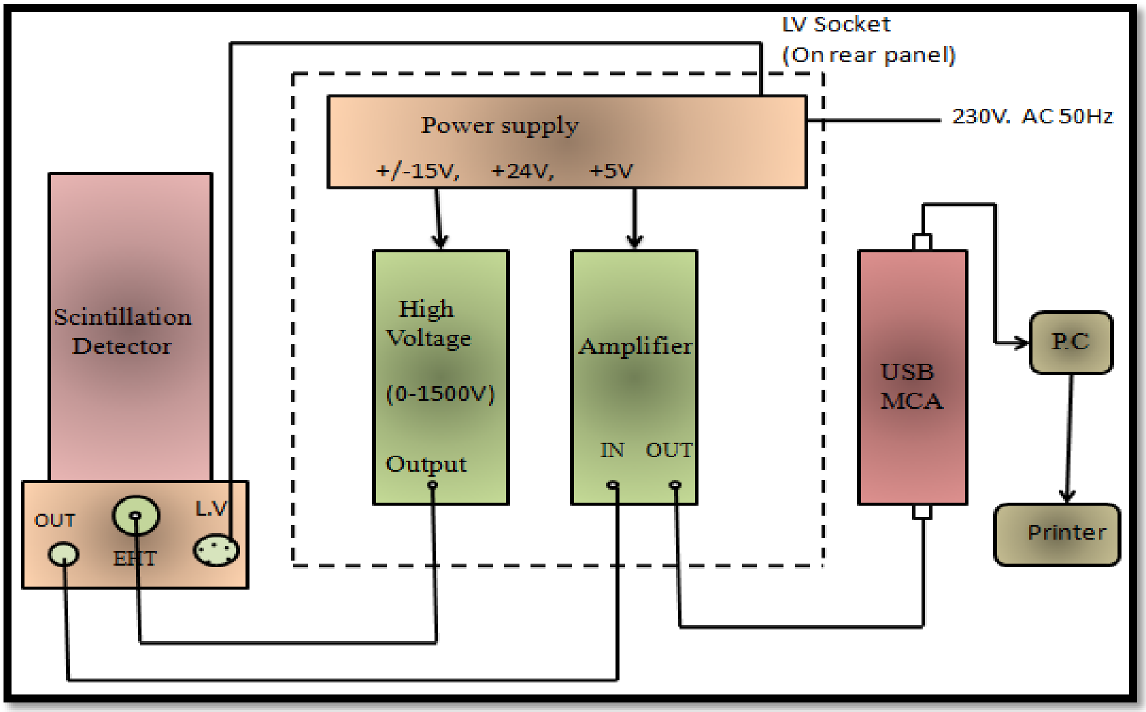


Fig. 4.1 Block diagram shows the NaI:Tl detector set up [1].

Gamma reference set: For these measurements, the gamma sources were used that were issued by BARC, India and were placed in a plastic material having diameter of 25mm and width of 5mm. The radioactive sources which are utilized for the experiment are mentioned in table 4.2.

Radioactive Isotope	**Energy(keV)**	**Normal Activity(µci)**	**Half-life(days)**
^{137}Cs	662	81.89	10979.7
^{60}Co	1173, 1332	102	1923.55
^{57}Co	122	29.38	270
^{22}Na	511, 1280	38.88	949
^{133}Ba	360	74.48	3832.5

Table 4.2 Radioactive sources used for the present measurements.

4.2 Method

In the experiments performed for this thesis work, ^{137}Cs, ^{60}Co, ^{57}Co, ^{22}Na and ^{133}Ba radioactive sources which will give gamma rays in energy range 122-1330keV were placed at four different distances from the face of the detector. The detector is shielded using 40mm lead on all faces of the detector to reduce the background radiations. For each radionuclide, data was recorded for 3600seconds so as to get the suitable statistics for the evaluation of each gamma peak. For all radionuclides, gamma ray energies, the gamma ray emission probability, source radioactivity at the time of manufacturing time and date of manufacturing are listed in the table 4.3.

Gamma sources	**Energy(keV)**	**Emission Probability(%)**	**Activity(kBq) (at the time of manufacturing)**	**Reference Date**
^{137}Cs	662	85.30	80	Feb. 2017
^{60}Co	1173 1332	99.85 99.98	34	April2018
^{57}Co	122	38.88	110	
^{22}Na	511 1280	178.00 99.94	110	
^{133}Ba	360	62.30	110	

Table 4.3 The various parameters of gamma sources used in the measurements.

The radioactive sources were placed at a distance of 4.5 to 16.5cm at step size of 4cm from Al window of detector to measure the energy resolution and efficiency. The following settings were used: Fine gain = 2.00, Coarse gain (×100) = 2.00 and operating voltage = 750V [3].

Experimental Set-up: The basic experimental set-up is shown in fig.4.2 and the shielding of lead on detector is shown in fig. 4.3

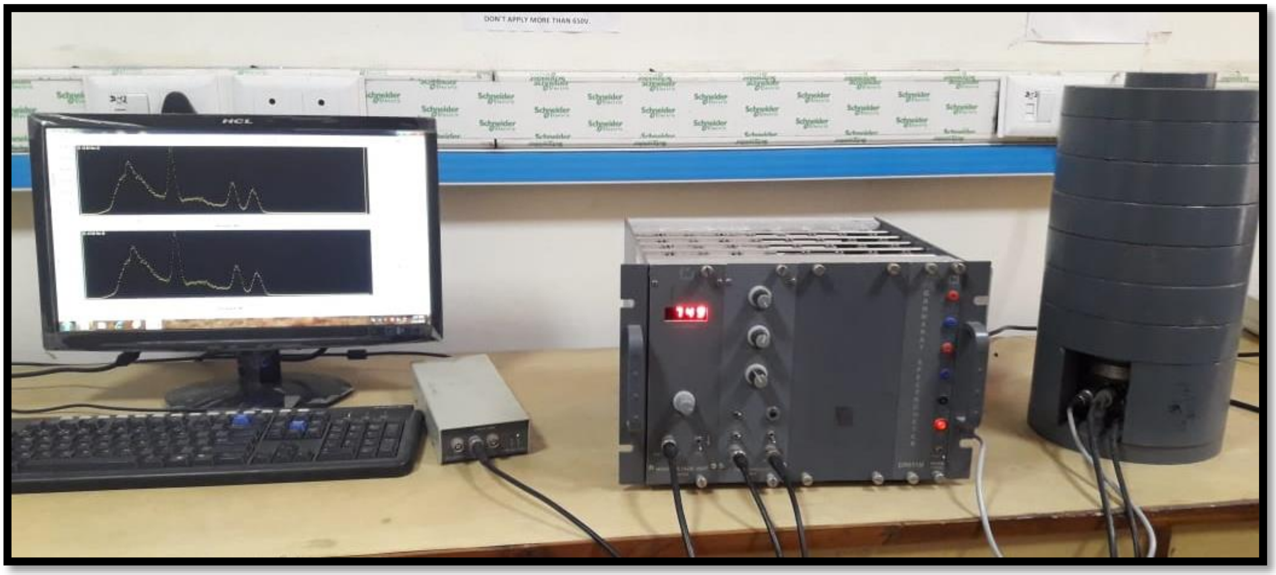


Fig. 4.2 Experimental set-up

Fig.4.3 Lead shielding

4.3 References:

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Chapter 5: Results and Discussion

5.1 NaI:Tl, Sodium Iodide Activated with Thallium Scintillation Detector Results

NaI(Tl) was for measuring for both energy resolution as well as detection efficiency for following radioactive sources ^{137}Cs, ^{60}Co, ^{57}Co, ^{22}Na and ^{133}Ba. Decay schemes for ^{137}Cs, ^{60}Co, ^{22}Na, ^{57}Co and ^{133}Ba are shown in fig. 5.1, 5.2, 5.3, 5.4 and 5.5 respectively.

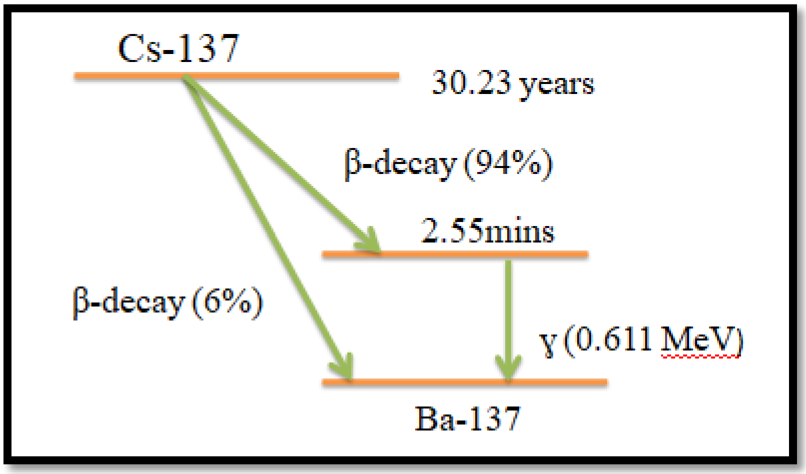

Fig.5.1 Decay scheme for Cs-137 [1].

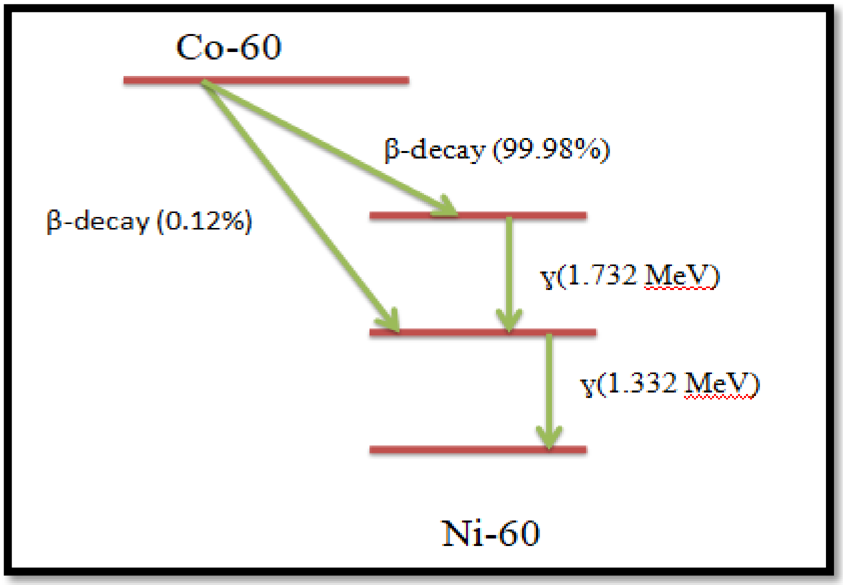

Fig.5.2 Decay scheme for Co-60 [1].

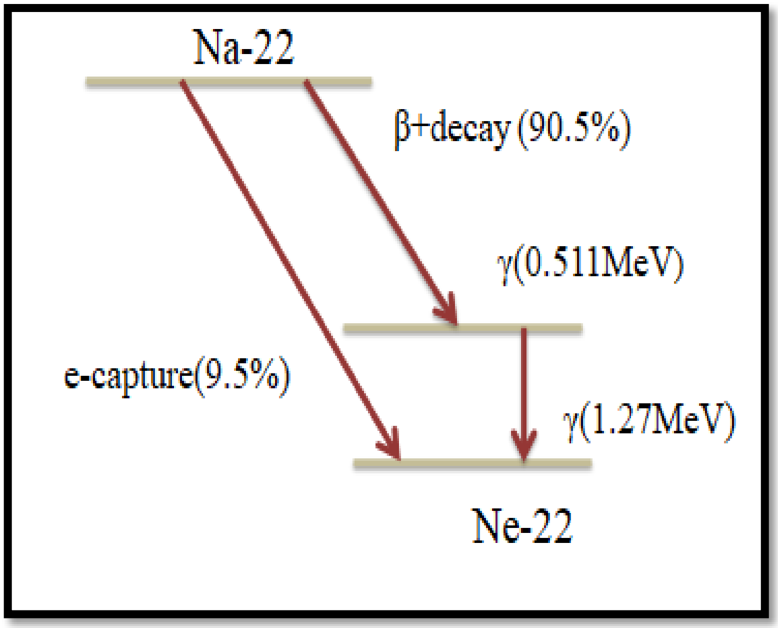

Fig.5.3 Decay Scheme for Na-22 [1].

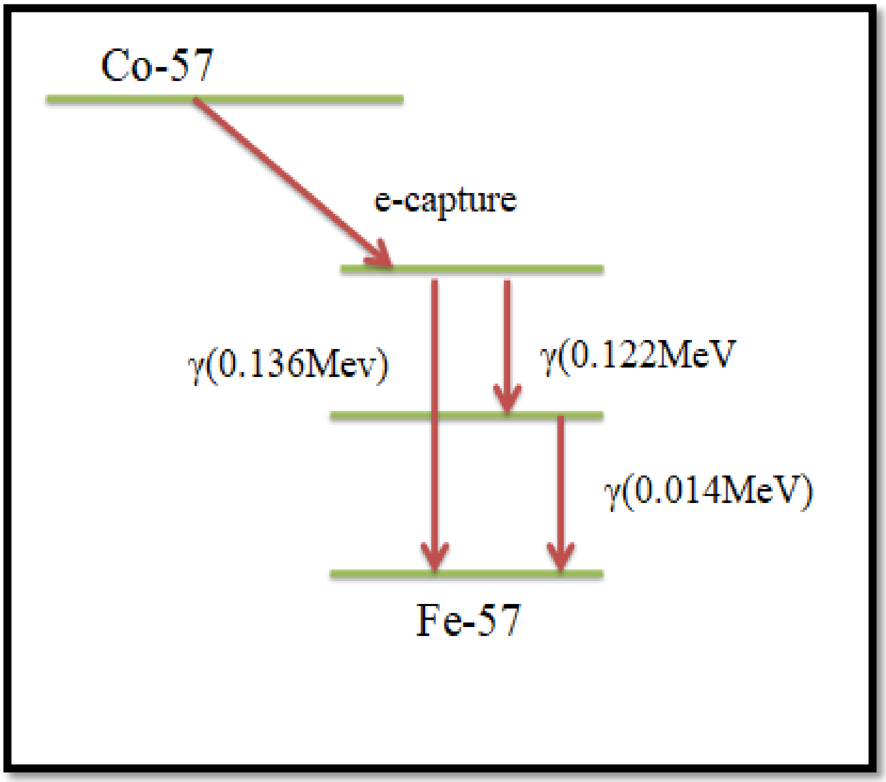

Fig.5.4 Decay scheme for Co-57 [1].

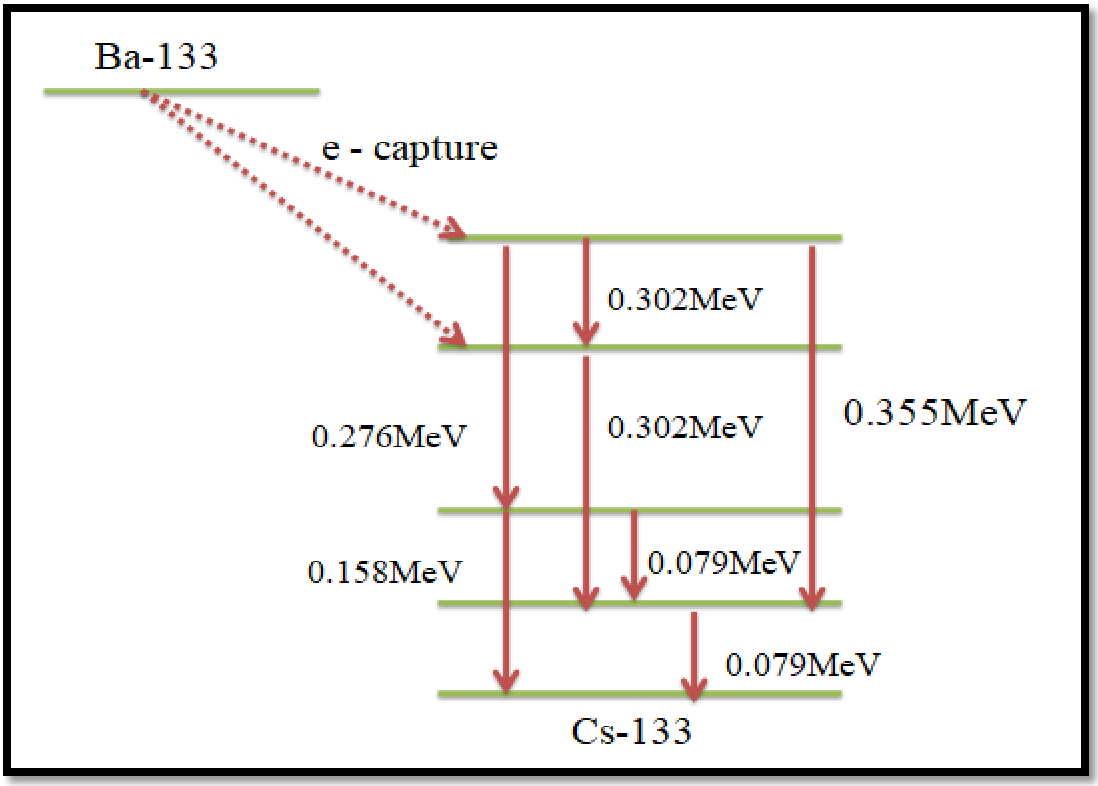

Fig.5.5 Decay scheme for Ba-133 [2].

5.2 Energy Resolution: To study the energy resolution of detector, five radioactive sources were used which produces gamma rays energy in the range of 122-1332keV. Energy resolutions were calculated for each gamma ray at four different sources to detector face distances and the results are listed in table 5.1.

Sources	Energy(keV)	Energy Resolution(%)			
		4.5cm	8.5cm	12.5cm	16.5cm
^{57}Co	122	16.8	16.0	14.6	15.1
^{133}Ba	360	10.1	9.48	9.16	9.28
^{22}Na	511	14.41	10.76	9.64	9.12
^{137}Cs	662	10.66	9.05	7.93	7.80
^{60}Co	1173	5.92	5.84	5.65	5.83
^{22}Na	1280	7.58	6.45	6.18	6.10
^{60}Co	1332	5.62	5.53	5.39	5.47

Table 5.1: The energy resolution of NaI(Tl) detector at different distances(4.5, 8.5, 12.5, 16.5cm) for various radioactive sources.

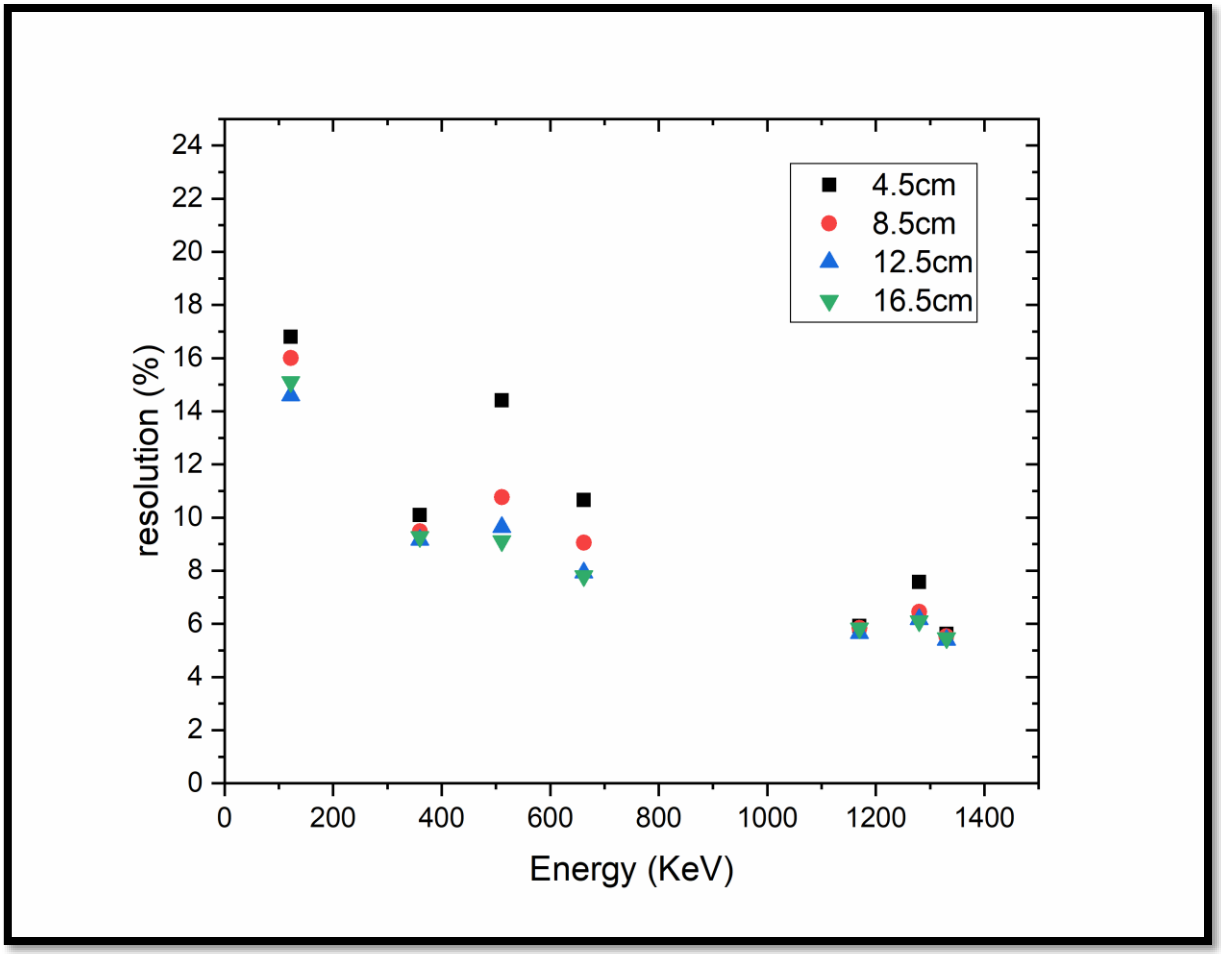

Fig. 5.6 The energy resolution of NaI(Tl) detector for various sources to detector distances for several energies of gamma rays.

From this graph, two conclusions can be drawn: Energy resolution improves with the increment in source to detector distance, energy resolution is significantly high at low gamma ray energies and the resolution improves significantly as gamma radiation energy increases. The energy resolution for 122keV gamma radiation is quite high (14.6-16.8%) whereas it improves significantly for gamma ray energies of above 1MeV. The improvement in energy resolution with increase in source to detector distance can be explained by the fact that there will be significant back scattering when source to detector distance is less. After certain source to detector distance, backscattering doesn’t affect the energy resolution due to which the energy resolution is similar for source to detector distance of 12.5 cm as well as 16.5 cm.

The spectrum of ^{22}Na can be seen in fig. 5.7.

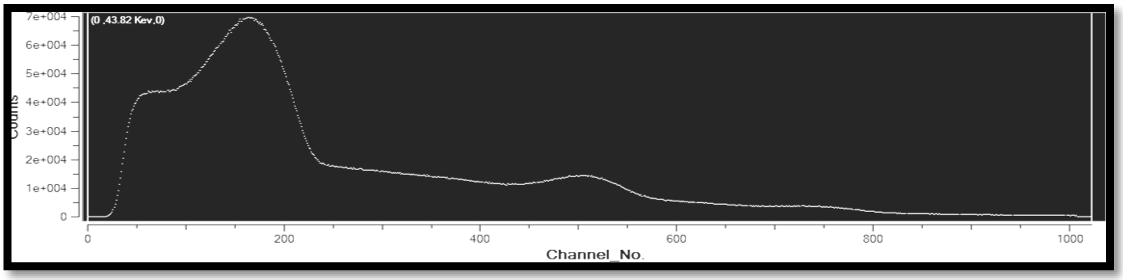

Fig. 5.7 The gamma ray spectrum of Na-22 from NaI(Tl) detector at a source to detector distance of 4.5cm.

The spectrum of Ba-133 is shown in fig. 5.8.

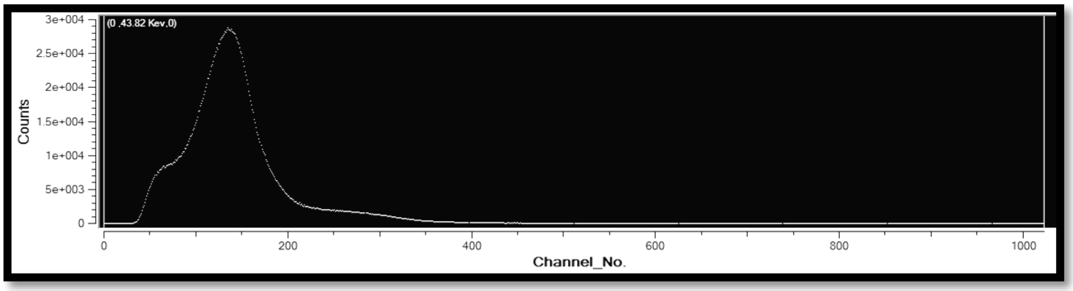

Fig. 5.8 The gamma ray spectrum of Ba-133 from NaI(Tl) detector at a source to detector distance of 4.5cm.

5.3 Efficiency calculation: Efficiency calculation depends on many factors like the shape and size of the detector, the type of material surrounding up the set-up. The tables 5.2-5.5 list the total detection efficiency for source to detector distances of 4.5, 8.5, 12.5, 16.5cm. Following equation is used:

$$\varepsilon_T(E) = \frac{N_T(E)}{A.t.p(E)}$$

Here, N_T is the total number of counts registered by the detector, t is the time (in seconds) during which events were registered, p(E) emission probability of the gamma ray, A is the activity of the radioactive source and it is calculated as:

$$A = A_o e^{-\lambda t}$$

Now, A_o is the initial activity of the radioactive source, t is the difference between the time of the manufacturing of the radioactive source and date of the experiment, λ is decay constant which is calculated as:

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

Here, $T_{1/2}$ is the half-life of the radioactive source.

Data is recorded for t = 3600seconds for this experiment.

Gamma sources	Energy (keV)	Emission Probability(%)	Activity(kBq) (at the time of experiment)	Date of experiment	Half-life(days)
^{22}Na	511, 1280	178.00, 99.94	81.89	6 March 2020	10979.7
^{133}Ba	360	62.30	102		1923.55
^{60}Co	1173, 1332	99.85, 99.98	29.38		270
^{57}Co	122	85.59	38.88		949
^{137}Cs	662	85.30	74.48		3832.5

Table 5.2: Parameters for gamma ray sources at the time of the experiment.

Total efficiency takes into account the geometric as well as intrinsic efficiency of the detector. Geometric efficiency depends upon several geometric factors including source to detector distance, size of source and detector and many more. Intrinsic efficiency can be defined as measure of detecting gamma rays once they have entered into the detector. Total efficiency is basically the ratio of total number of events recorded in detector to total number of gamma radiation emitted by the radioactive source. Total efficiency is also calculated for the sources which emit gamma rays of two different energies, the difference is due to the difference of emission probability.

Gamma ray sources	Gamma Energy(keV)	Gross counts	Net Counts	Activity(kBq) (at the time of experiment)	Total Efficiency(%)
^{22}Na	511, 1280	14697049	14550472	81.89	27.72, 49.38
^{133}Ba	360	6442558	6295981	102	27.52
^{57}Co	122	625986	479409	38.88	4
^{60}Co	1173, 1332	3383311	3236734	29.38	23.15 23.12
^{137}Cs	662	4819770	4673193	74.48	20.43

Table 5.3: Parameters for gamma sources and total efficiency when source to detector distance is 4.5cm. Net counts represent background subtracted gross counts.

Gamma Sources	Gamma Energy (keV)	Gross counts	Net Counts	Total Efficiency (%)
^{22}Na	511, 1280	6958744	6856186	13.06 23.27
^{133}Ba	360	2863302	2760744	12.06
^{57}Co	122	222762	120204	1.00
^{60}Co	1173, 1332	1637765	1535207	10.98 10.97
^{137}Cs	662	2256933	2154375	9.41

Table 5.4: Parameters for gamma sources and total efficiency when source to detector distance is 8.5cm. Net counts represent background subtracted gross counts.

Gamma Sources	Gamma Energy (keV)	Gross Counts	Net Counts	Total Efficiency (%)
^{22}Na	511, 1280	4114467	4016436	7.6 13.63
^{133}Ba	360	1657536	1559505	6.81
^{57}Co	122	161811	63780	0.53
^{60}Co	1173, 1332	1007882	909851	6.51 6.50
^{137}Cs	662	1354496	1256465	5.49

Table 5.5: Parameters for gamma sources and total efficiency when source to detector distance is 12.5cm. Net counts represent background subtracted gross counts.

Gamma Sources	Gamma Energy (keV)	Gross Counts	Net Counts	Total Efficiency (%)
^{22}Na	511, 1280	2703645	2607991	4.96 8.85
^{133}Ba	360	1073248	977594	4.27
^{57}Co	122	111893	16239	0.13
^{60}Co	1173, 1332	689132	593478	4.24 4.24
^{137}Cs	662	898827	803173	3.5

Table 5.6: Parameters for gamma sources and total efficiency when source to detector distance is 16.5cm. Net counts represent background subtracted gross counts.

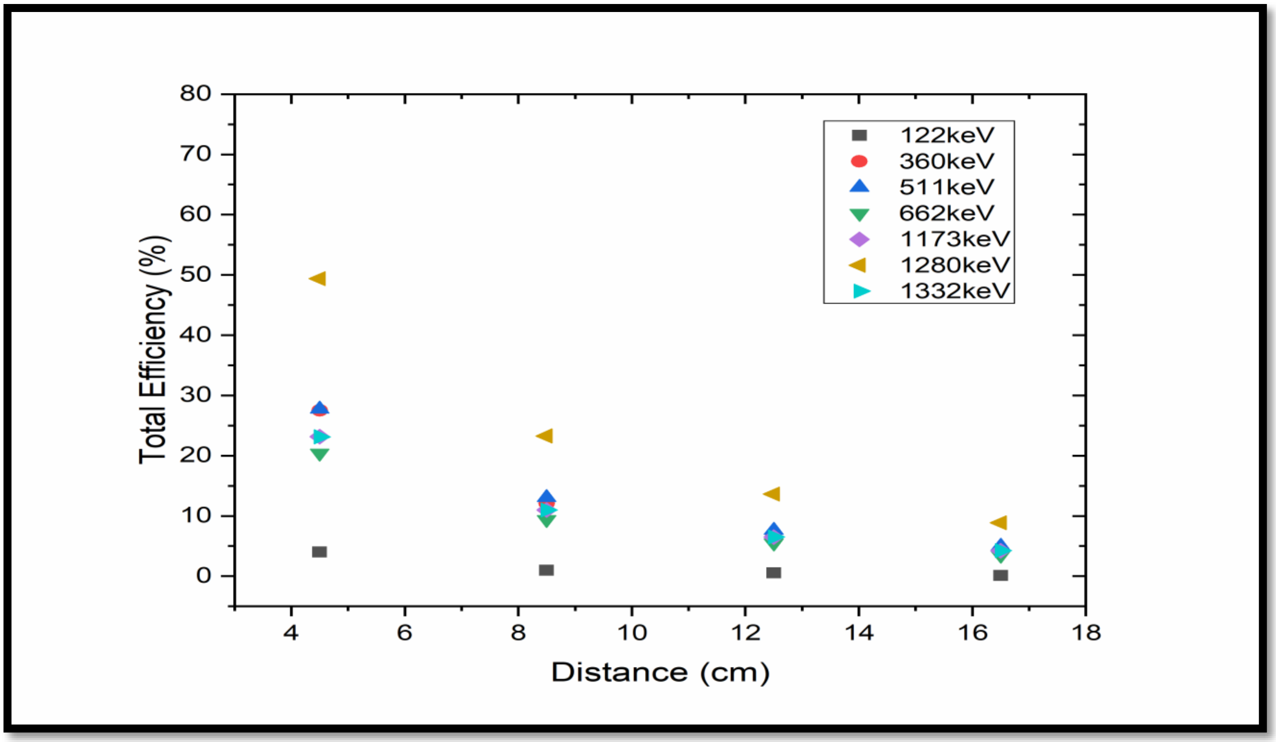

Fig. 5.9 The total efficiency of the NaI(Tl) detector at different source to detector distances for different gamma ray energies.

Fig. 5.9 illustrates that total efficiency of the detector has reduced with the rising on distance of source from the detector which is obvious. Larger is separation between source and detector less will be gamma rays falling on detector.

For the photo peak efficiency (full energy peak efficiency) calculations, the subsequent equation can be used:

$$\varepsilon_{pe}(E) = \frac{N(E)}{A.t.p(E)}$$

Here, N(E) is the number of net counts recorded by the detector in photo peak, A is known as activity of the sample on the day of measurement, t is the time (in seconds), p(E) emission probability of the gamma ray.

Table 5.7 lists the photo peak efficiency as well as some other useful parameters which can be used to determine the photo peak efficiency.

Gamma ray Sources	Gamma Energy (keV)	Activity(kBq)	Net Counts	PhotopeakEfficiency (%)
^{22}Na	511, 1280	81.89	4347872 858097	8.28 2.91
^{133}Ba	360	102	1265896	5.53
^{57}Co	122	38.88	505670	4.22
^{60}Co	1173, 1332	29.38	289472 259671	2.07 1.85
^{137}Cs	662	74.48	1865834	8.15

Table 5.7: Various parameters for gamma ray sources as well as experimental results obtained for photo peak efficiency when source to detector distance is 4.5cm.

Gamma Sources	Gamma Energy (keV)	Net Counts	Photo peak Efficiency (%)
^{22}Na	511, 1280	2107651 422476	4.01 1.43
^{133}Ba	360	806745	3.52
^{57}Co	122	114079	0.95
^{60}Co	1173, 1332	136585 128897	0.97 0.92
^{137}Cs	662	828110	3.62

Table 5.8: Various parameters for gamma ray sources as well as experimental results obtained for photo peak efficiency when source to detector distance is 8.5cm.

Gamma Sources	Gamma Energy (keV)	Net Counts	Photo peak Efficiency (%)
^{22}Na	511, 1280	1199240 249563	2.28 0.84
^{133}Ba	360	430444	1.88
^{57}Co	122	59953	0.500
^{60}Co	1173, 1332	76579 72709	0.54 0.51
^{137}Cs	662	466714	2.04

Table 5.9: Various parameters for gamma ray sources as well as experimental results obtained for photo peak efficiency when source to detector distance is 12.5cm.

Gamma Sources	Gamma Energy (keV)	Net Counts	PhotopeakEfficiency (%)
^{22}Na	511, 1280	786963 158858	1.49 0.53
^{133}Ba	360	324797	1.41
^{57}Co	122	14520	0.12
^{60}Co	1173, 1332	49898 46956	0.35 0.33
^{137}Cs	662	293348	1.28

Table 6.0: Various parameters for gamma ray sources as well as experimental results obtained for photo peak efficiency when source to detector distance is 16.5cm.

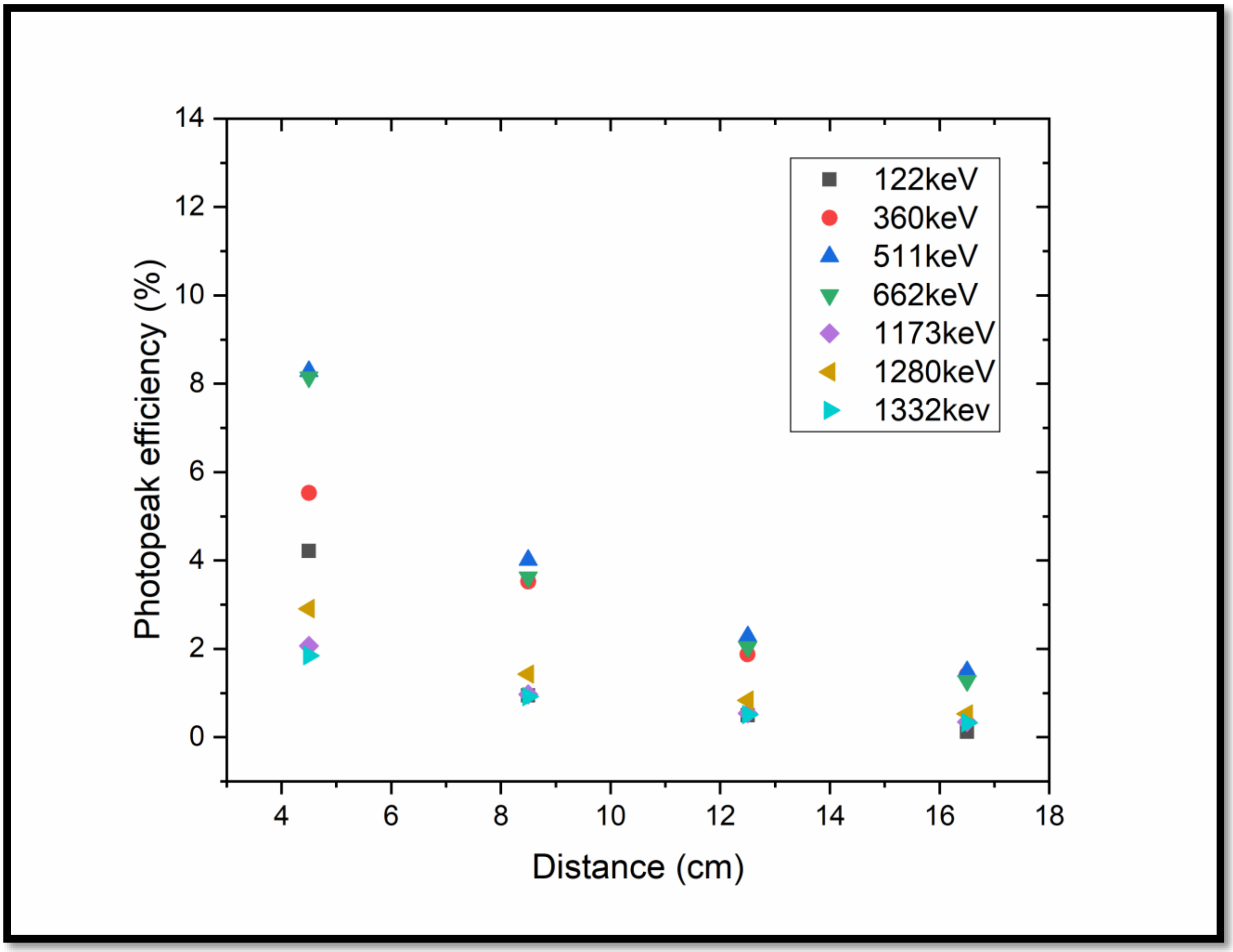

Fig. 6.0: The photo peak Efficiency for different source to detector distances for different gamma ray energies.

Photo peak efficiency as a function of detector to source distance for various gamma ray energies is shown in Fig. 6.0. Once again, photo peak efficiency too reduces as source to detector distance is increased.

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[1]. https://www.nndc.bnl.gov/nudat2/.

[2]. Bernd Crasemann, J. G. Pengra and I. E. Lindstrom, Radiation from ^{133}Ba, Physical Review, Vol. 108(6), pp.1500-1505.

Chapter 6: Conclusion

This work shows that the energy resolution, total as well as photo peak efficiency of Sodium Iodide with activation of Thallium (NaI:Tl) detector is calculated by measuring gamma rays of different energies for five gamma sources (^{137}Cs,^{60}Co,^{57}Co,^{22}Na and ^{133}Ba) at four different source to detector face distances (4.5 to 16.5cm). It can be concluded that energy resolution can be improved by increasing source to detector distance and gamma ray energies. At low energies, the energy resolution is significantly high. Due to backscattering, the energy resolution is increased with the decrease distance between source and detector. Total as well as photo peak efficiency both are decreased with increase in distance between source and detector. Larger is the separation between source and detector less will be gamma rays falling on the detector.

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