university of groningen

Characterising NaI(Tl) Scintillator Detectors for Gamma-ray Measurements: Evaluating Energy Resolution and Performance

Author:
Diede Wesseling (S3812383)

Supervisors:
Dr. M. Kavatsyuk
Prof. dr. E. van der Giessen

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Abstract

Neutron cross-section information, particularly inelastic cross sections and (n,xn) cross sections, is crucial for nuclear reactor studies. At the GELINA facility in Geel, the GAINS spectrometer uses High-Purity Germanium detectors for gamma-ray spectroscopy to measure these cross sections. An alternative to these detectors could be NaI(Tl) scintillator detectors, which are assessed in this research paper. The primary objective of this study is to characterise three NaI(Tl) detectors to evaluate their operational performance. Cobalt energy spectra were analysed using these detectors, showing expected shapes, and distinct energy peaks for different gamma decays were clearly distinguishable. By determining the energy resolutions and plotting them against corresponding energies, the NaI(Tl) detectors were characterised. The performance of the detectors were assessed by fitting the data points to an equation which incorporates a constant linked to data loss of the detector. All three detectors demonstrated excellent energy resolutions below 7%, proving their capability to accurately detect gamma radiation. However, to enhance the reliability of the results, certain improvements are needed. The current dataset used for fitting covers only a limited energy range, anc the inclusion of data on gamma rays with higher energies would refine the fitting process. Additionally, grounding and shielding the detectors could be helpful to eliminate unnecessary noise and background radiation in future research.
Overall, this research presents valuable insights into the application of NaI(Tl) detectors as an alternative to High-Purity Germanium detectors for measuring gamma radiation cross sections. The findings offer promising prospects for advancing neutron cross-section studies and nuclear reactor studies.

Contents

1 Introduction

Electricity consumption has been steadily increasing around the world over the last few years, and is expected to increase even more in the future. The effects caused by this require us to change our energy policies so that they minimise the environmental impact and our quality of life. The use of low-emission energy sources is significant in achieving this goal. One very promising low-emission energy source is nuclear energy, which is being generated in a nuclear power plant [1]. Nuclear reactors are the core of a nuclear power plant, they house and regulate nuclear chain reactions, which generate heat via fission. This heat is harnessed to produce steam, which drives a turbine and ultimately generates electricity [2]. In 1957, the first big nuclear power reactor started producing electricity. The subsequent decades of the 1960s and early 1970s witnessed a rapid expansion of nuclear power as the energy crisis drew attention to the potential of nuclear power in numerous countries. This was followed by a slowdown in the 1980s due to various factors like low oil prices and the accidents at Three Mile Island and Chernobyl. The ageing of nuclear power plants gained attention, leading to the establishment of programs and conferences focused on addressing this issue. By the 1990s, the number of older reactors was set to increase significantly. International cooperation and research on long-term operation (LTO) continued, ensuring safe reactor operation. Today, there is ongoing interest in LTO, with several countries considering extending the operational lifespan of reactors [3].

There are a few reasons for nuclear energy to be very promising. One the reasons is the low Cost of Electricity (COE) for nuclear energy, which is very small compared to COE for both coal and gas energy. Also, the greenhouse gas emissions of nuclear energy production is significantly low compared to other energy sources, as can be seen in Figure 1.

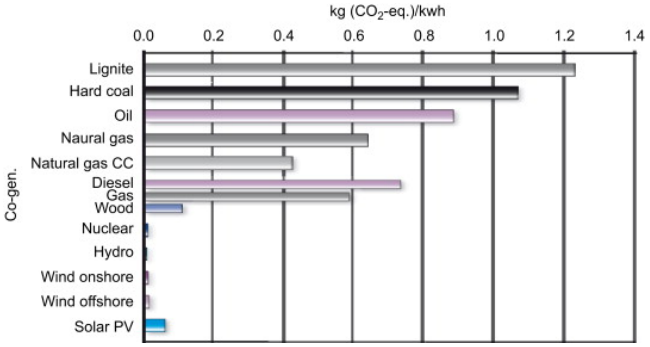

Figure 1: Greenhouse gas emissions of several energy chains in 2009 (Source: [4])

In order to better establish nuclear energy in our society, the performance of a nuclear reactor needs to be optimised. The operating mechanism of a nuclear reactor will not be discussed in depth here, but it is important to know that to design such a reactor and predict its behaviour, knowledge on nuclear reactions and its components are needed. From existing nuclear databases, it becomes clear that a few processes have not been extensively studied. The processes regarding inelastic cross sections and (n,xn) cross sections lack a lot of important information. (n,xn) processes refer to a type of nuclear reaction that involves the collision of a neutron (n) with a target nucleus, resulting in the emission of one or more neutrons (xn) from the target nucleus. ”xn” denotes the emission of ”x” number of neutrons. Because of the lack of information on these processes, the experimental measurements of these reactions’ cross sections are limited and have significant uncertainties. However, these processes are very important, for safety of nuclear energy generation as well as for nuclear waste management. Therefore, more information on these cross sections needs to be obtained [5].

1.1 GELINA and GAINS

One facility that aims to collect data for these reactions is the GELINA (Geel Linear Accelerator) neutron time-of-flight (TOF) facility. GELINA [6] is one of the most unique facilities for the production of neutrons and its measurements. The first process in the TOF facility is the emitting of electrons by an electron gun. Once the electrons are produced in pulses, they are injected into the electron accelerator tube. There, they are accelerated using radio waves until they reach nearly the speed of light. At the end of the electron accelerator, a solid uranium disc is located. The accelerated electrons are stopped in this uranium target, producing bremsstrahlung [6]. This

bremmstrahlung induces (γ, xn) and (γ, fission) reactions. From these reactions, bursts of neutrons are generated [7], most neutrons are stopped by concrete walls, but some enter the flight paths trough openings in the walls. These neutrons travel along a 200m flight path, where they hit a secondary target material, which is surrounded by gamma-ray detectors [8].

The Gamma Array for Neutron Inelastic Scattering (GAINS) spectrometer is a high-purity Germanium array. It is used to obtain reliable neutron inelastic cross-section data, especially data on (n,xnγ) cross sections, which is interesting for nuclear reactor studies. When a neutron interacts with a target nucleus, it can induce nuclear reactions that result in the emission of gamma (γ) -rays. The GAINS spectrometer is used to detect and analyse these gamma rays to calculate the time-of-flight. As mentioned above, the GAINS spectrometer has an array of gamma-ray detectors surrounding the target material, which is the material that is used as the target nucleus. The array is placed at a distance of 200m from the neutron source. The detectors are designed to measure the energy, intensity, and angular distribution of the gamma rays emitted from the target. During an experiment, a beam of neutrons that entered the flight path is directed at the target material, and the resulting gamma rays are detected by the array of detectors. By analysing the energy and angular distribution of the detected gamma rays, valuable data can be obtained that can be used to draw conclusions about the neutron cross-sections of the reactions [5] [9] [8].

The GAINS spectrometer currently uses high-purity Germanium to measure gamma rays. Germanium is a semiconductor with a very good energy resolution [5], so it functions as a good detector for gamma rays [10]. However, the Germanium detectors have a low efficiency for high energies [8]. Also, these detectors exhibit slower response times because the signal generation relies on the movement of charges across relatively long distances. Consequently, in many cases, scintillator detectors are preferred [2].

One detector that could be used in the GAINS spectrometer instead of the High-Purity Germanium detector is the Sodium Iodide (NaI) detector, which also has the ability to measure gamma rays. The NaI-detector is a detector based on scintillations. It uses a scintillating material to detect and measure radiation. Scintillators are materials that emit light when they interact with high-energy particles or photons. When ionising radiation, such as gamma rays, enter the scintillator material, it interacts with the molecules of the material, causing them to become excited. The excited electrons in the scintillator material return to their ground state by releasing the excess energy in the form of photons (light). This light emission is known as scintillation. The emitted photons within the scintillator material are then detected by a photomultiplier tube (PMT). This convert the photons into electrical signals that can be measured and analysed. By detecting the scintillation light, scintillator detectors can provide information about the energy and intensity of the incident radiation. The intensity of the light produced is proportional to the energy of the incoming radiation in the scintillator material [10].

1.2 Research Aim

The aim of this research project is to examine the performance of three NaI detectors, and to establish how well they measure gamma radiation. The gamma radiation that is used in this research originates from a Cobalt-60 source. The three detectors will be characterised by determining the energy resolution of the detected gamma rays. This paper aims to answer the question: How well do the detectors operate to measure gamma radiation? To answer this question, multiple other problems need to be assessed too. This report will start by providing some background on nuclear reactions and the specific data we are interested in. Then, information about different detectors is provided to get an idea of the variety of detectors and their properties. Once the different detectors have been assessed, we will zoom in on the detector which is investigated in this research. Subsequently, the operating mechanism of the detector is explained together with the methods for data extraction and data processing. Then, the results are given and discussed and a conclusion of the research will be provided.

2 Theory

2.1 Nuclear fission

Nuclear fission is a process in which the nucleus of an atom is split into two or more smaller nuclei, which releases a significant amount of energy. The process of nuclear fission can be initiated by bombarding the nucleus of a fissile material with a neutron. This neutron is then absorbed by the nucleus, causing an unstable compound nucleus. The compound nucleus then splits into two or more smaller nuclei, along with the release of additional neutrons and a large amount of energy. This energy is released in the form of kinetic energy of the resulting smaller nuclei, as well as the kinetic energy and electromagnetic radiation carried by the emitted neutrons and gamma rays. The mass of the products of the reaction is smaller than the mass of the initial nucleus. According to Einstein's equation,

$$E = mc^2 \tag{1}$$

this energy release is a thus a result of the conversion of mass into energy. The fission process also produces several highly energetic neutrons. These neutrons can cause a chain reaction if they are captured by other fissile nuclei nearby, leading to a self-sustaining reaction with the release of more energy and additional neutrons. This chain reaction is the basis for the operation of nuclear reactors [11].

2.2 Nuclei and Nuclear Decay

In radioactive decay, an unstable nuclide, also called a 'parent', decays into a more stable nuclide, called a 'daughter'. If the daughter is also radioactive, the decay chain continues until a stable product is formed. Unstable nuclei can be described as either proton-rich or neutron-rich, and they both decay toward stable nuclei. This is shown in Figure 2 [12].

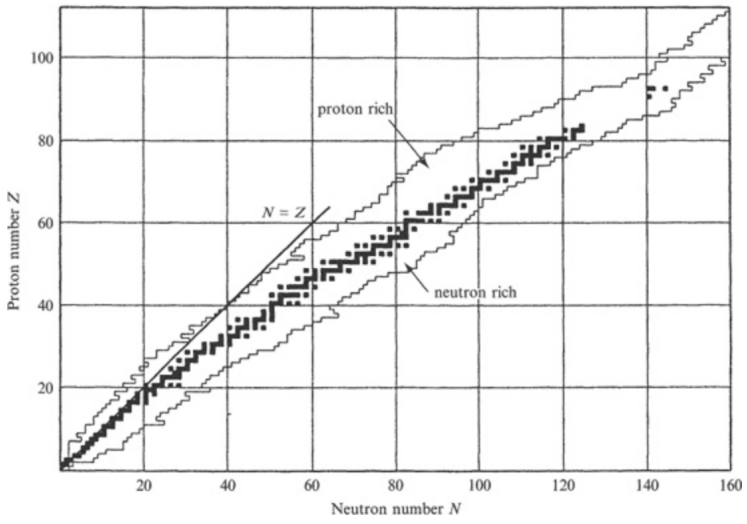

Figure 2: "Stable and unstable nuclei plotted according to proton number Z and neutron number N. Regions of known proton-rich and neutron-rich unstable nuclei are indicated on either side of the band of stable nuclei (and very long-lived unstable nuclei), which are represented as black squares." [12]

The decay of an unstable nucleus is arbitrary and cannot be predicted, but we can predict the half-life of a nucleus, which is defined as the time it takes for half of the original nuclei to decay. It is thus a measure of the stability or rate of decay of a specific radioactive isotope. The half-life can be used to describe the exponential decay of radioactive substances.

All radioactive nuclei exhibit one or both of the following types of decay: alpha-decay (α-decay) or beta-decay (β-decay). These decays result in the emission of alpha particles, beta particles, and sometimes also gamma radiation.

Alpha-decay occurs spontaneously and random, and unlike other light particles it doesn't need an input of energy in order to be emitted. When a parent undergoes alpha decay, it loses both mass and charge, since it emits a helium nucleus. This decay results in the daughter being closer to the band of stable nuclei.
Beta-decay consists of the emitting of beta-particles. The parent can emit a negative beta-particle, which is identical to a negatively charged electron. Hence, if a parent emits a beta-particle, the charge of its nucleus increases by one unit. It can also emit a positive beta-particle, which is called a positron. A positron has the same mass as an electron and behaves like a positively charged electron. Beta-particles are emitted with a continuous spectrum of energies.
Following a β^- or β^+ decay, or the emission of an α particle, the atomic nucleus often ends up in an excited state rather than in its ground state, and it has to lose extra energy. The transition from these excited states to the ground state often result in the emission of gamma rays [10].

2.3 Neutron Cross Sections

As mentioned earlier, the current nuclear database lacks a lot of information, one important example is the lack of knowledge on neutron cross sections [5]. When a particle such as an electron, photon, or neutron moves through any piece of material, there is a chance that it will interact with the nuclei or electrons within that substance. Considering a thin segment of matter, this chance is directly related to the thickness of the segment and the density of potential target particles in the material. Additionally, it is influenced by the specific type of interaction taking place. The intrinsic part of this probability is quantified using a term called the cross section. The cross section is a useful measure for analysing particle interactions within a material [10].

When a particle crosses perpendicularly through a thin segment of matter, the probability of interaction depends on the cross section σ as:

$$dW = dx\, N\, \sigma \tag{2}$$

where dW is the probability to undergo an interaction of a certain type, dx is the thickness of the thin segment of matter and N is the number of scattering centres per unit volume [10].

2.3.1 Cobalt-60

The gamma source used during this study is cobalt-60 (Co^{60}). It is an unstable radioactive isotope of cobalt and it undergoes beta-decay. The daughter nucleus resulting from this decay is nickel-60 (Ni^{60}) [13]. The decay scheme of Co^{60} is shown in Figure 3.

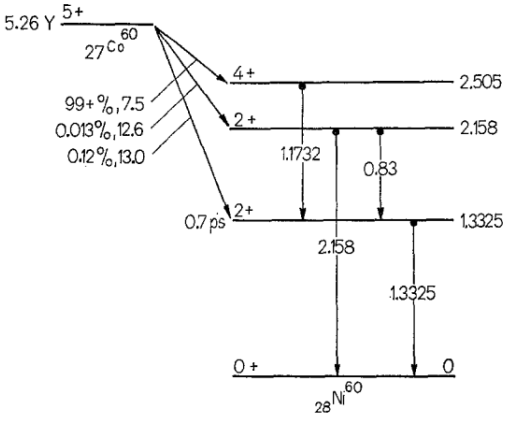

Figure 3: "The decay scheme of Co^{60}. All energies are in MeV" [13]

During the decay of cobalt-60, gamma radiation is emitted. This is due to the fact that the nucleus is not yet in its ground state when is has emitted beta-particles and it loses its excess energy via gamma radiation. As can be

seen in the figure above, cobalt-60 decay gives rise to gamma radiation with energies of 1173 keV and 1332 keV. This can also be seen in the spectrum shown in Figure 4, which clearly shows the two cobalt-60 spectra for an NaI(Tl) and an HPGe detector. This spectrum is also what is expected to be seen in the results of the detectors in this research.

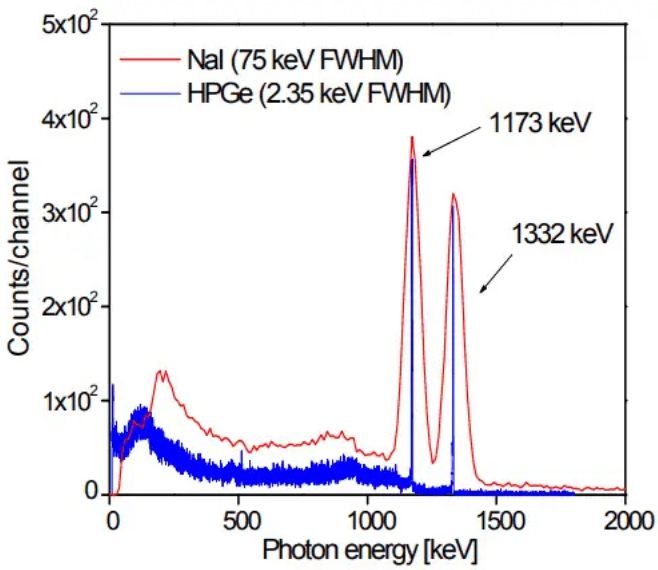

Figure 4: Energy spectrum of Cobalt-60, measured by a Sodium Iodide detector (red) and a High-Purity Germanium detector (blue) [14]

3 Detectors

When a high energy particle, or in our interest, a γ-ray hits a material, it can interact with it in several ways. Since only charged particles can undergo coulomb interaction, only these particles can directly transfer their kinetic energy to a material. Since the incident gamma-rays are neutral, they need to be converted to charged particles. The converting of neutral gamma-rays to charged particles can be done by each of the following three processes [10]:

The first one is called the photoelectric effect. In this process, the incoming γ-ray, or photon, transfers all of its energy to an electron, the electron gets excited and an electron-hole pair is formed. The electron-hole pair created in the detector causes an output pulse, which is proportional to the energy of the incident γ-ray. The photoelectric effect accounts for incident gamma energy of 0-150 keV, and mostly for energies under 100 keV [10] [15].

The second process is called the Compton effect, or Compton scattering. Compton scattering is the elastic collision between a photon and an electron and it occurs when these particles interact, resulting in the photon scattering off the particle. The photon changes its direction and thus loses some of its energy. This change in direction and energy is due to the conservation of energy and momentum in the collision. Also the wavelength of the scattered photon increases, resulting in its energy decreasing compared to the incident photon. This can be verified from Planck's equation, which is given in Formula 3. Here E is energy, h is Planck's constant, c is the speed of light and λ is the wavelength [10] [15].

$$E = \frac{hc}{\lambda}\textbf{[10]} \tag{3}$$

Lastly, the pair-production process or pair creation. Pair creation refers to the process in which a photon interacts with a nucleus or an electron and has such a high energy that it can create both an electron and a hole. This process only occurs for photons with energies of at least 1.02 MeV, since that is the amount of energy it takes to create an electron and a positron.

When the detector has a good energy resolution, genuine captured events can be differentiated from random gamma rays emitted by radioactive targets and other sources of background capture events [16]. This is differentiation is desirable, which is why obtaining a good energy resolution is the main goal of this research project.

3.1 Semiconductor Detectors

There are several classes of materials that can be used for radiation detectors. One of them is the class of semiconductors, and the other class is luminescent materials, which are also known as scintillators [17]. A semiconductor is a material that has the electrical conductivity between that of a conductor and an insulator. In a material, the valence band and the conduction band are defined as energy bands that are formed by the arrangement of electrons in the material's atomic structure. The energy of these bands play a crucial role in determining the electrical properties of the semiconductor [18]. The valence band is defined as the highest energy band that is completely filled with electrons at absolute zero temperature. It contains the valence electrons of the semiconductor atoms. The valence band electrons are tightly bound to their respective atoms and generally do not contribute to electrical conduction. They are in a lower energy state and require energy to move into higher energy levels. The conduction band is the energy band located just above the valence band. Between the two bands there is an interval called the band gap. An electron can never be in a stationary state with an energy that is located in this energy gap. The size of the band gap of a semiconductor is between that of a metal and an insulator, as can be seen in Figure 5. The energy needed to form an electron-hole pair is equal to the energy corresponding to this band gap and is denoted by E_g [18] [10].

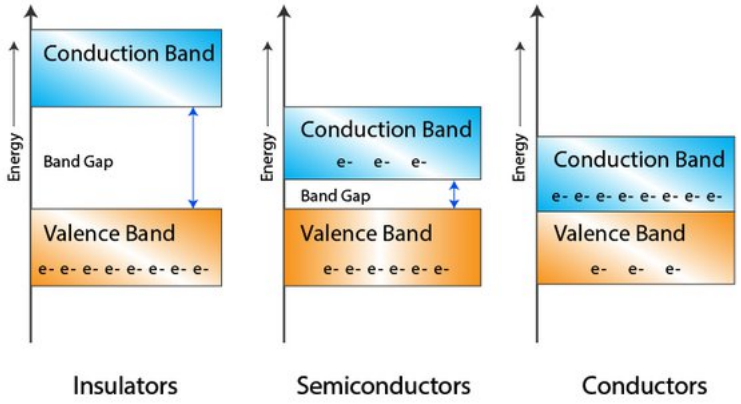

Figure 5: Bandgaps of Insulators, Semiconductors and Metals, from [19]

In conductors such as metals, the valence and conduction bands overlap, allowing electrons to move freely and conduct electricity easily. In insulators, the band gap is relatively large, and electrons require a significant amount of energy to move from the valence band to the conduction band, resulting in minimal electrical conductivity [18].

For semiconductors, at absolute zero, the conduction band is typically empty or only partially filled with electrons. Electrons in the conduction band have higher energy levels and are relatively free to move within the semiconductor material. To conduct electricity, electrons need to move from the valence band to the conduction band. This can be done by exciting electrons in the valence band. When the electrons are excited to the conduction band, they can move freely through the semiconductor material, which creates an electric current.

Semiconductor detectors detect electron-hole pairs that are created in the material by ionising radiation. An electron-hole pair arises when an electron in the valence band absorbs sufficient energy to excite to the conduction band, leaving behind an unoccupied energy state in the valence band, also known as a hole. Semiconductors, compared to other materials, need a relatively low amount of energy to create such a pair, that is why it functions well as a detector. On the other hand, it is hard to obtain charge multiplication in semiconductors. Because of this, the signals of a semiconductor are relatively small. Therefore, very accurate low noise electronics are needed to properly measure the signals. Also, semiconductors are relatively expensive [10].

3.1.1 Germanium detectors

As mentioned before, the detectors currently used in the GAINS spectrometer are High-Purity Germanium (HPGe) detectors, the setup for GAINS is shown in Figure 6.

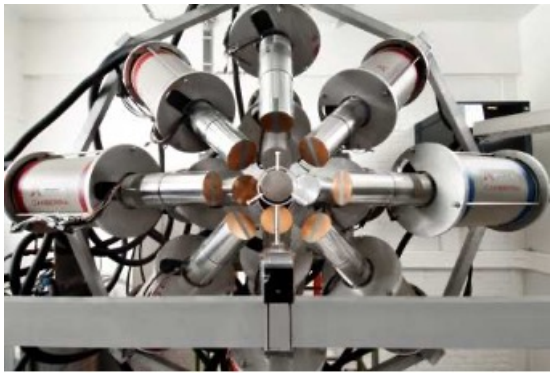

Figure 6: The GAINS spectrometer (Source: [5])

Germanium is a semiconductor, and it has a face-centered diamond-cubic structure [18]. At zero Kelvin the valence band is completely filled. The conduction band is separated from the valence band by a band gap of 0.7 eV for Germanium [20]. A few important characteristics of the HPGe detector are that it has a high atomic number, low ionising energy is required to produce an electron-hole pair, high conductivity, compact size, high resolution and relative simplicity of operation. What we're interested in in this research project, is the way that the material interacts with incoming γ-rays. As mentioned earlier, the most important processes are the photoelectric effect, the Compton effect and the pair-production effect. In Germanium, the pair-production process can also provide a total absorption of the energy of a γ-ray. The γ-ray enters the detector and forms an electron-hole pair. The pair production process is illustrated in Figure 7.

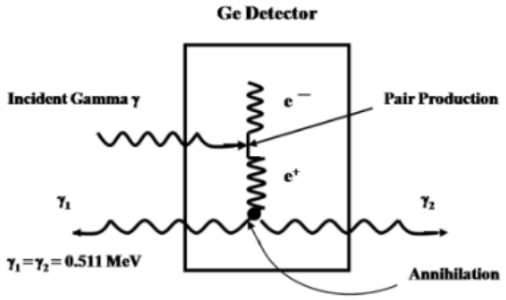

Figure 7: Process of pair production in Germanium [15]

The electron e^- will produce a pulse which relates to the energy of the electron, and the hole e^+ will produce a pulse which relates to the energy of the positron. Since the creation of an electron and hole are simultaneous, the output pulse of the detector will be equal to the sum of the two separate pulses. When the positron interacts with an electron in the detector, annihilation radiation is produced (γ_1 and γ_2), if this radiation escapes from the detector, it will not make a photoelectric interaction in the detector and the final measured energy will be lower than the energy that entered the detector. The incident γ-ray must have an energy of at least 1.022 MeV, since that's the energy needed to excite an electron and make an electron-hole pair. Thus, if the annihilation radiation escapes, the final energy will be 1.022 MeV lower than the energy of the incident γ-ray. It could also be that only the energy of γ_1 is absorbed in the detector by making an photoelectric interaction, and γ_2 escapes, or the other way around. In this case, the total final energy would be 0.511 MeV less than the incident energy of the γ-ray. If none of the γ-rays escape, all the incident energy will be absorbed in the detector, resulting in a higher energy deposition. Pair production is primary responsible for incident γ-rays with an energy of 5000 keV or higher [15] [10].

3.2 Scintillator Detectors

When ionising radiation interacts with matter, a large number of molecules will be excited. The electrons get excited to a higher energy state due to the energy from the radiation, and when the electrons return to their ground state, energy is released. This excess energy result in the emission of photons in the visible light spectrum. This process is called scintillation. Some materials are more efficient at converting excitation energy into visible light photons than other materials. These materials are known as scintillators. Scintillators can be divided into two groups, namely inorganic and organic scintillators. These two groups have a significant difference in their radiation length, which is defined as the mean length into the material at which the energy of an electron is reduced by a certain amount due to interactions with the material it passes through. Organic scintillators mostly contain atoms with a small atomic charge, which results in them having a longer radiation length. Inorganic scintillators on the other hand, have a large amount of atoms with a high atomic charge, which means that they have a shorter radiation length. Because of this, inorganic scintillators are better suited for gamma-ray detection than organic scintillators [10]. In this research, inorganic scintillators will not be further discussed. The focus of this research will be on inorganic scintillators, namely Sodium Iodide (NaI).

3.2.1 Inorganic Scintillators

Inorganic scintillators are typically ionic crystals. They create an amount of scintillation light when they get hit by a high-energy particle like a gamma-ray, and the physical process behind this will be explained in this section.

In a scintillator, electrons must move towards the closest luminescence centre. Once they reach the luminescence centre, photons are generated by the electrons. If the material is transparent, the light signal can then be extracted from the detector. In order to act as a detector for ionising radiation, the crystal should be transparent at the same wavelength as the scintillation light that is created, so it can escape from the material. In order for the scintillation light to escape from the detector, luminescence centres are needed that have localised levels in the crystal. These localised levels can arise due to various factors such as impurities, defects, or imperfections in the crystal lattice structure of the material. To create such a level, a dopant is often added to make a scintillator more efficient [10].

When a gamma-ray interacts with a scintillator crystal, a chain of events is initiated. The energy of a gamma-ray can extract a deeply bound electron and elevate it to an energy level within the valence band, or often to an even higher energy level. The excess energy carried by the electron will then be transferred to other electrons, causing them to become excited and move from the valence band or deeper bands to the conduction band. As a result, electrons from outer bands fill the gaps left in the core bands, and the excess energy continues to bring more electrons from the valence band to the conduction band. Consequently, a single gamma-ray generates a multitude of vacancies (holes) in the conduction band and an equal number of electrons in the valence band. These electrons settle at the lower end of the conduction band, while the holes accumulate at the top of the valence band. The energy of the incoming gamma ray is rarely exactly equal to E_g, so there is a part of the initial energy is converted to phonons, which is thermal energy resulting in a lattice vibration in the material [18] [10].

In order for a scintillator to function properly, it is important for the electrons and holes to migrate towards the luminescence centres. However, the understanding of this process is a little more difficult than the simplified model where charges move freely in the crystal lattice. Imperfections in the crystals create traps that can capture and hinder the movement of free charges towards the luminescence centres. These traps often have low binding energies and can be overcome if the temperature in the crystal is high enough to provide sufficient thermal energy for the charges to be released from the traps [10].
In a scintillator, when electrons and holes are free to move, a hole can interact with other atoms or molecules. The hole can ionise molecules, and subsequently, an electron may be trapped at an energy level within the material. This trapping is efficient when the energy levels involved are suitably positioned with respect to the valence band and the conduction band of the material.
Once an electron is trapped, it can quickly transition to a lower energy level within the material. This transition typically occurs through allowed processes, which may involve changes in electron configuration or other electronic interactions. These transitions are relatively fastand contribute to the scintillation process.
The luminescence mechanism in inorganic scintillators is complex, and there are additional considerations to avoid problems such as self-absorption of the emitted light within the crystal. If this is the case, the crystal will not be transparent to its own scintillation light. This problem is avoided by a mechanism called the Stokes shift, where the spatial distribution of charges influences the equilibrium positions of neighbouring atoms or molecules, allowing for efficient light emission. The stokes effect allows a luminescence centre to have a longer wavelength for emitted light than for absorbed light, so self-absorption won't occur. An example of the stokes shift is shown in Figure 8 [10].

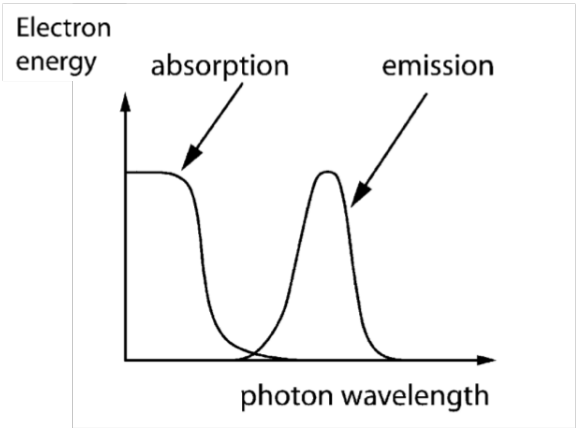

Figure 8: Emission and absorption spectra for electron transitions in a lutetium ortho-oxysilicate crystal doped with cerium [10].

3.2.2 Sodium Iodide Detector

Sodium iodide is an inorganic scintillator and thus operates as explained in the previous section. The detectors used in the experiment are sodium iodide detectors doped with thallium, hence NaI(Tl) detectors are used throughout the research. A schematic representation of the detector is given in Figure 9.

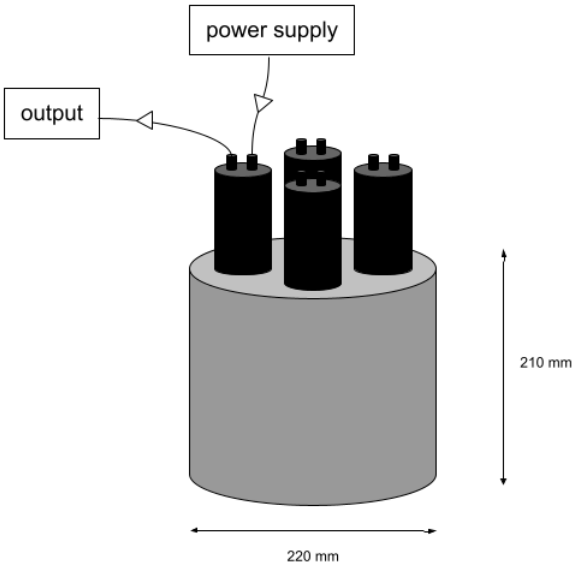

Figure 9: Schematic of the NaI(Tl) detector, four photomultiplier tubes on top of the encapsulated crystal. Diameter is 220 mm and height is 210 mm, PMTs are not drawn to scale

The NaI(Tl) crystal is encapsulated inside the grey cylinder shown in the picture above, which is made out of metal. When the crystal detects Co-60, it is expected that the two energies corresponding to the gamma-rays with energies of 1173 and 1332 keV give rise to two clear peaks in the spectrum, as shown in Figure 4.

4 Experimental Methods

The goal of this study is to investigate the performance of three sodium iodide (NaI) detectors, and to find their energy resolutions. NaI detectors could serve as an alternative for the high-purity germanium detectors that are currently used to measure gamma-rays in the GAINS spectrometer. Sodium iodide is an inorganic scintillator, and in this research a sodium iodide detector doped with thallium will be assessed.

To investigate the performance of this scintillation detector, first the energy resolution has to be determined for each detector. This is done by measuring the energy output of the detector and fitting the peaks of the energy that corresponds to the detected gamma-rays. The output signals of the detector originate from the light pulses generated by the scintillating crystal and are extracted from photomultiplier tubes.

4.1 Photomultiplier tubes

When using scintillators detectors, some instrument is needed to convert the energy of the generated light pulses into something that can be measured electronically. A photodetector is a device designed to convert such light signals into electrical signals. It detects and measures the presence and the intensity of light by utilising the photoelectric effect [10].

The photodetector used during this research is the photomultiplier tube (PMT). This is a vacuum tube, which is typically made of glass, containing a photocathode, several dynodes, and an anode. A schematic representation of such a PMT is given in Figure 10.

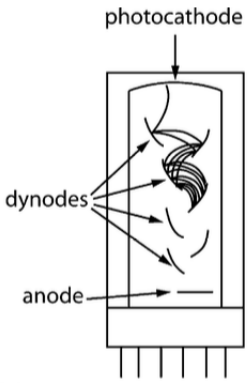

Figure 10: Schematic of a photomultiplier tube [10]

A photocathode emits electrons when it gets hit by photons with their wavelength in the visible or near-to-visible spectrum, these electrons are then accelerated towards a series of dynodes, which are arranged in a specific order. Each dynode is at a higher voltage potential than the previous one. The first electron will thus be attracted by the first dynode because this dynode has a positive potential relative to the cathode. The electron is accelerated to a kinetic energy that is equal to the potential difference between the cathode and the dynode. As the accelerated electron strikes this first dynode, it releases multiple secondary electrons. These secondary electrons are then accelerated towards the next dynode, where the process is repeated, and so on. The number of electrons at each stage increases, leading to an amplified electrical signal at the final anode of the tube. This signal can be amplified up to an electron multiplication of 10^6 or more [21] [10].
The operating voltage of the PMT was found using an oscilloscope. The PMTs of all three detectors turned out to respond to an operating voltage between 800V and 1000V. The operating voltage of 1000V yielded clear signals on the oscilloscope, so this was chosen to be the operating voltage during data collection.

4.2 Measurement Techniques

As shown in Figure 9, there are four photomultiplier tubes connected to the crystal. To examine the light collection of the entire crystal, the outputs of these photomultipliers have to be combined together to form one signal describing the output of the entire crystal. Different methods were used to combine the signal from the four

photomultiplier tubes, the method that provided the best energy resolution was used to characterise all three detectors.

There were three different methods explored to combine the signals coming from the four PMTs. One method was combining the four PMTs using a linear fan-in/fan-out from Lecroy, model 428F. Another approach was to combine the four PMT outputs using two Dual Sum and Invert Amplifiers from Ortec, model 433a. Comparing these two methods showed that the latter provided better energy resolutions. The energy resolutions obtained from the data measured using fan-in/fan-out, were between 1.5 % and 3.2% higher than the energy resolutions obtained from the data measured using dual sum and invert. This difference only got bigger as the energy peaking was set to higher values. The third method was to amplify the signal coming from the detectors and combine it via a simple box made up of only five resistors, containing four inputs and one output, which combines the signal without adding unnecessary noise. This provided energy resolutions that were between 0.5 % and 1 % higher than the energy resolutions obtained for the dual sum and invert combined PMTs. Since we are talking about energy resolutions in the range between 0 and 10 %, these differences are significant.

The four PMTs were thus combined using two Dual Sum and Invert Amplifiers model 433a, since this provided the best energy resolutions. The optimal settings for data extraction in the used program were also determined by inspection of the difference in energy resolution. Different settings for energy peaking provided different energy resolutions, varying up to fluctuations of 1 % for steps of 100 in energy peaking. The optimal energy peaking value that resulted in the best energy resolution turned out to be 240, so this value was used during data collection.

Once the four PMT signals were combined and the optimal operating settings were determined, the cobalt source was placed near the crystal and data sets of a duration of 4 minutes were collected from the detector. The energy of the generated photons measured in this time, as well as the counts, is thus extracted from the detector in the form of electrical signals. The counts can be plotted against the energy to obtain a spectrum from which the energy resolution can be determined.

4.3 Statistics

The energy of the incident photons is related to the counting number of photons via:

$$E = \alpha N \tag{4}$$

where E is the energy, N is the counting number of photons and α is an arbitrary proportionality constant. The variance of the energy is given by:

$$\sigma^2 = \mathrm{Var}[E] = \alpha^2 \mathrm{Var}[N] = \alpha^2 N \tag{5}$$

The energy spectrum of a NaI detector behaves according to Poisson statistics, and the standard deviation is given by:

$$\sigma = \alpha\sqrt{N} \tag{6}$$

and thus

$$\frac{\sigma}{E} = \frac{\sigma\sqrt{N}}{\sigma N} = \frac{1}{\sqrt{N}} \sim \frac{1}{\sqrt{E}} \tag{7}$$

where σ is related to FWHM as

$$\mathrm{FWHM} = 2\sqrt{2\ln 2}\cdot\sigma \tag{8}$$

[22] [23].

4.4 Determining Performance of Detector

The energy resolution of a detector refers to its ability to clearly distinguish two peaks, and it depends on the FWHM (Full Width at Half Maximum) value. When the FWHM value is smaller, it means the detector is more sensitive, enabling it to effectively tell apart two gamma rays with similar energies arriving at the detector from the radiation source [22].

The data processing is done using a provided code. This code has a few applications, two of them being the plotting and fitting of the obtained graphs. These graphs represent the number of counts as a function of energy. The resulting graphs are fitted to a Gaussian to determine the FWHM and mean of each peak.

When these values are known, the energy resolution can be determined by using [22]:

$$R = \frac{\text{FWHM}}{\text{mean}} \tag{9}$$

Once the energy resolution is calculated for different settings in the data processing program, the settings that provide the lowest energy resolution are chosen to be used during data collection of all three detectors.

The next step is to plot the energy resolution of the detected peaks as a function of the corresponding energy. There are three peaks used as data points for this fitting, namely the two gamma peaks of 1173 keV and 1332 keV, but also the sum peak of these two, which will be explained in the results. Since the FWHM is proportional to σ, and E in Formula 7 represents the energy at the peak and is thus the same as the mean value, we can expect this plot to be of the shape:

$$R \sim \frac{1}{\sqrt{E}} \tag{10}$$

So the obtained data is fitted to an equation of this form, where E refers to the energy peak position. Ideally, the curve would approach zero for higher energies, however, some of the photons escape from the detector, so not all photons are captured by the PMTs. Because of this, some of the information is lost. Therefore, Formula 10 is rewritten with an additional constant to describe the energy data losses. Also, a scaling factor is added to optimise the fitting. Consequently, the formula that the data will be fitted to is:

$$R = \frac{C}{\sqrt{E}} + D \tag{11}$$

Where C is the scaling factor and D is the additional constant. In the ideal situation where all the photons are captured by the detector, no information will get lost, so then D would be equal to zero. From this we can conclude that the lower the value of D, the better the detector operates.

5 Results

The three detectors tested in this research will be referred to as detector A, B and C. All three detectors are scintillation detectors containing a Sodium Iodide crystal which is doped with Thallium.

5.1 Energy Spectra

The obtained energy spectra for the gamma-rays measured by the detectors look similar to the expected shape in Figure 4. The 1173 keV and 1332 keV peak are clearly observed, as shown in Figure 11.

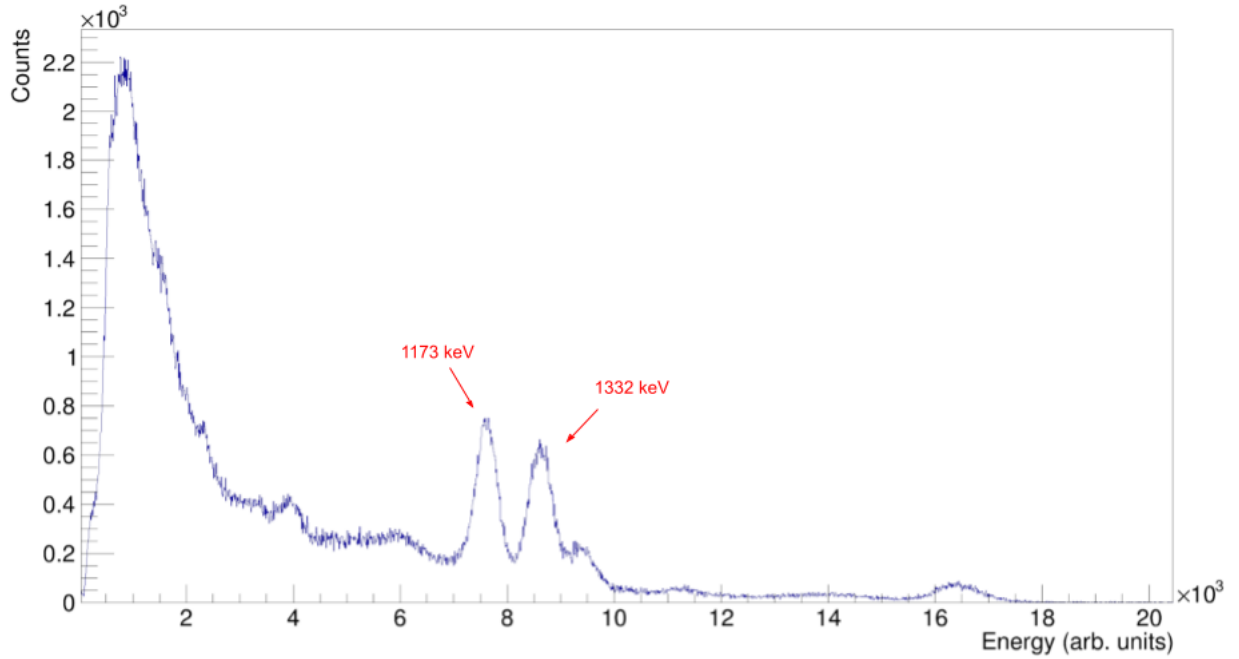

Figure 11: Energy spectrum of Co-60, measured by detector A. The peaks corresponding to the gamma radiation are marked with red arrows

The y-axis represents counts and the x-axis represents energy in arbitrary units. As we can see from this graph, there are multiple energy peaks that appear in the spectrum. The peaks in Figure 11 will be assessed from left to right.
The first big peak corresponds to background radiation and noise of the equipment. As can be seen, these are significantly many counts for relatively low energy values.
Between the background peak and the peaks marked in red, Compton scattering can be observed. As explained in the beginning of section 3, Compton scattering is the elastic collision between a photon and an electron, resulting in the photon scattering off the particle. During this, the photon's direction is changed and it thus loses some of its energy, this is why it appears at a lower energy. Subsequently, the two energy peaks for gamma-radiation appear, with a small peak next to the 1332 keV peak. What this peak originates from is questionable and will be assessed in the discussion section. The small peak at the end of the spectrum represents the sum peak, this is a result of coincident detection of the two gamma rays with the energies of 1173 keV and 1332 keV. The probability of this happening in Co-60 decay is 99.90% so this sum peak will appear in almost every spectrum of Co-60 decay [24]. As mentioned earlier, this sum peak is also used as a data point. The other two detectors show similar shapes, and are shown in Figures 12 and 13.

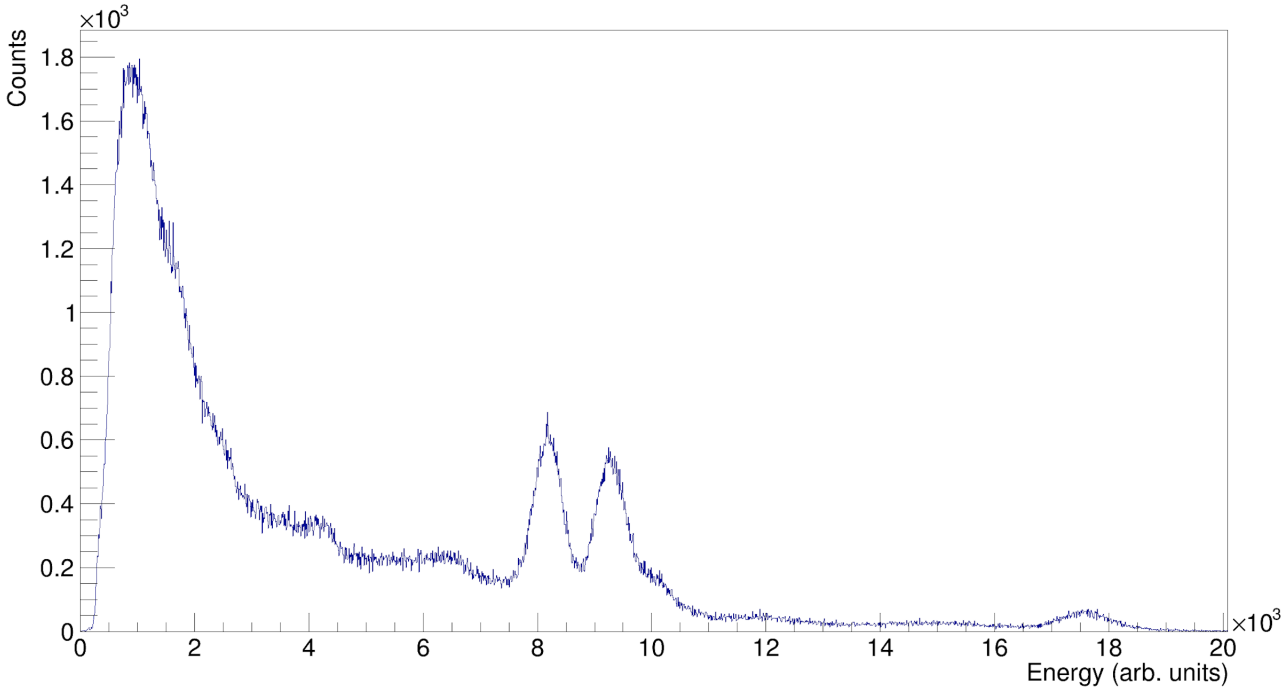

Figure 12: Energy spectrum of Co-60, measured by detector B

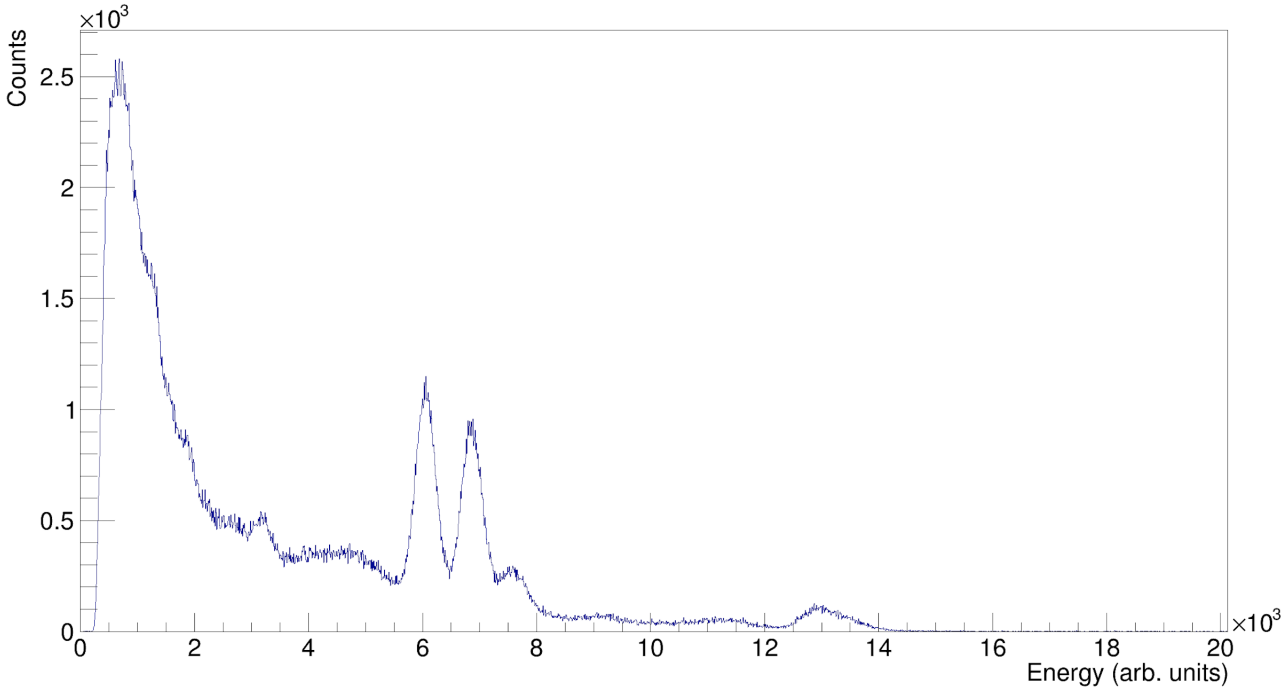

Figure 13: Energy spectrum of Co-60, measured by detector C

5.2 Energy Resolution

As explained in Section 4.4, the performance of the detectors will be characterised according to the value of the additional constant D in Equation 11. The data points obtained during the research will be plotted as energy resolution against energy and the function will be fitted through these data points. This is done with the use of a python code. First, the results of the energy resolutions will be displayed below in table 1.

energy peak (keV)	Energy Resolution (%)		
	Detector A	Detector B	Detector C
1173	6.09	6.57	6.86
1332	5.87	6.15	6.14
2505 (sum)	5.70	5.35	5.87

Table 1: Results used for data points

The energy resolution is plotted as a function of energy, and fitted to the function given in Equation 11, this results in the plots given in Figures 14, 15 and 16.

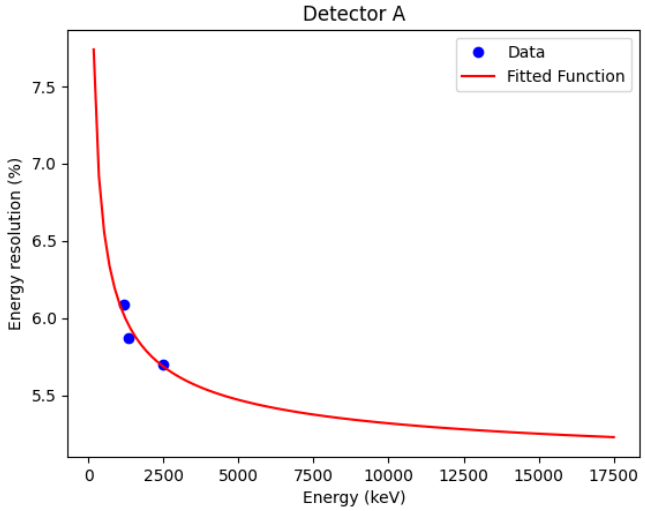

Figure 14: fitted plot for data points of detector A

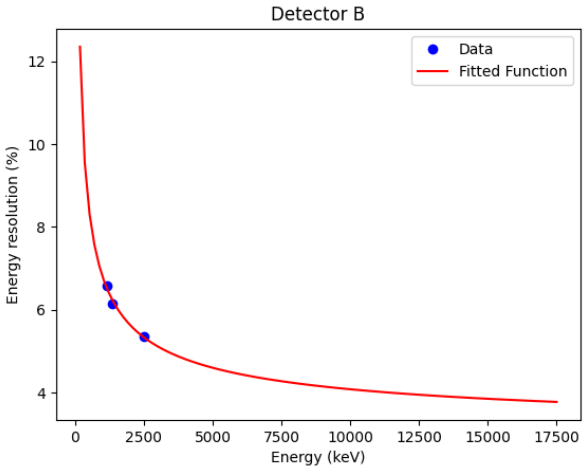

Figure 15: fitted plot for data points of detector B

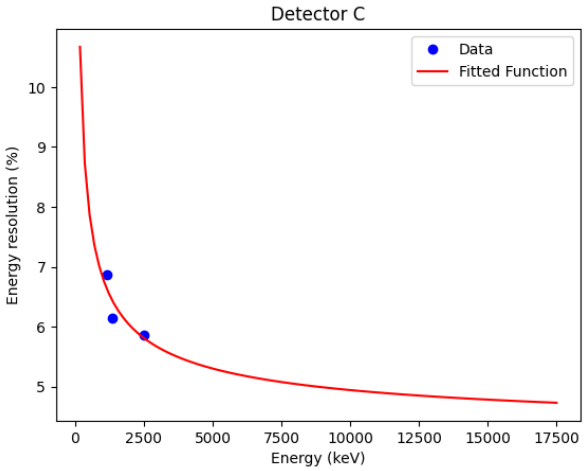

Figure 16: fitted plot for data points of detector C

The python code used to obtain these results provide also the values of constants C and D in Equation 11. Since C is the scaling factor, it's value doesn't contribute to the characterisation of the detectors. As explained earlier, D does determine how well the detector operates. The values for D for each detector are given in Table 2.

Detector	Value of C	Value of D
A	36.66117	4.950857
B	125.2089	2.827263
C	86.72368	4.076299

Table 2: Optimized values for constants in Equation 11, for detector A, B and C separately

As can be seen from these results, all three detectors operate sufficiently. The energy resolution of the detectors for the consulted energies are all below 7%,

6 Discussion

The energy spectra obtained for the gamma-rays measured by the detectors displayed the expected shape, as shown in Section 5.1. The spectra showed clear peaks of 1173 keV and 1332 keV, corresponding to the gamma radiation emitted by the cobalt source. Additionally, a small peak next to the 1332 keV peak was observed in the spectra. The origin of this peak is not known with certainty, but it is expected that the crystal detected gamma-rays originated from potassium-40, since this isotope emits 1460 keV gamma-rays during its decay, which is a little above 1332 keV [23]. Potassium is a naturally occurring radioactive isotope [10], so it is plausible to state that this is where the extra peak originates from. We can confirm this by calculating the exact position of the unknown peak. This is done as follows: The provided code that is used to fit the energy peaks of 1173 and 1332 keV, can also be used to fit the unknown peak. This fitting gives mean values of all three peaks. Since the energies are given in arbitrary units (Figure 12, the value of the unknown peak has to be calculated through scaling. The energy difference in the first two peaks is known to be 159 keV, this knowledge can be used to determine a scaling factor and calculate how far the unknown peak is from the 1332 peak. This turned out to be 142.14 keV, which results in an energy of 1474 keV for the unknown peak. This deviates from the literary value, but well within the resolution of the detector. From this it can be concluded that the extra peak probably originates from potassium.

The results of this research are promising. The energy resolutions obtained for the detectors are all under 7%, and fitting of the data points showed that the constant value accounting for instrumental effects like data losses approaches a low number. From the research could be concluded that detector B operates best compared to the other two detectors, but all three of them operate sufficiently.

It should be noted that the three detectors do not display the exact same behaviour, even though they operate using the same crystal. There is a variety of factors that could explain this behaviour, one of them being that even though the crystals are the same, the orientation within it not necessarily are. One detector could have a defect in a place where the other one does not, so the excited electrons could be trapped as a result of this defect, while it might be trapped elsewhere, or not at all, in another detector.

The detectors are characterised using three energy peak values and their corresponding energy resolutions. The fitting was thus done using only three data points. To increase validity of the results, more data points should be used. The data points used now are only a very small portion of the energy spectrum. The validity of the characterisation could thus be improved in future work, by using gamma radiation from different isotopes, to be able to use data in a wider energy spectrum.

Additionally, the noise present in the data could be reduced by grounding of the detectors. Grounding provides a low-resistance path for electromagnetic interference (EMI) to flow away from the detector. EMI is unwanted electrical noise, which in this case could be caused by nearby electronic devices, or noise from the used cables and the power supply [25]. As for background radiation, shielding the detector with a dense material like lead could decrease the detection of unwanted radiation [10]. The source used for measurements would then have to be placed inside the shield, to obtain more accurate energy spectra of that specific source.

7 Conclusion

Information on neutron cross sections are important in nuclear reactor studies. Information on inelastic cross sections and (n,xn) cross sections is of great importance for this purpose, and the current nuclear data base lacks information on these processes. At the GELINA facility in Geel, the GAINS spectrometer is located, which is used to measure these cross sections by using gamma-ray spectroscopy. GAINS currently operates using High-Purity Germanium detectors to measure gamma radiation. An alternative to this could be the use of scintillator detectors, more specifically, NaI(Tl) detectors.

This research paper aims to characterise three of these detectors to determine how well they operate. The energy spectra for cobalt was shaped as expected and the energy peaks for different gamma decay were clearly distinguishable. There occurred an extra peak in two of the three energy spectra, which seems to originate from potassium. The NaI(Tl) detectors were characterised by determining their energy resolutions and plotting that against the corresponding energies. The performance of the detector was then determined by fitting the data points to an equation which includes a constant that is related to the data lost during the detection of gamma rays, from this fit the performance of the detector could be determined. All three detectors have good energy resolutions, which all lie below 7%, and the detectors behave sufficient to accurately detect gamma radiation. Improvement of the experiment is needed to make the results more reliable. The data points that were used to fit the function only covered a small portion of the energy range, so the fitting would be better if there would also be data on gamma rays with higher energies than the one measured now. Also, grounding and shielding of the detectors should be considered to get rid of unnecessary noise and background radiation.

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