Characterization of LaBr$_3$(Ce) Detectors for Picosecond Lifetime Measurements

by

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ABSTRACT

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There has been a great deal of interest in the use of LaBr$_3$(Ce) detectors for fast timing measurements. Due to their excellent energy resolution, $\approx$ 3% at 1MeV, they offer an improved signal to background over BaF$_2$ which has $\approx$ 9% energy resolution. Many groups are planning arrays of LaBr$_3$ detectors. The 8$\pi$ collaboration has recently acquired a small array of 6 2” x 2” cylindrical LaBr$_3$ detectors to replace its BaF$_2$ detectors. We have been investigating the effects of detector-to-detector scattering on timing resolution. We have further investigated the use of Compton-suppression shields with LaBr$_3$ detectors. This will also be the first testing of the DANTE acquisition system in the 8$\pi$. A summary of the results of our optimization, scattering studies, and Compton-suppression tests will be presented.
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Chapter 1

Background Information

1.1 Overview

This thesis presents investigations into the potential of LaBr$_3$(Ce) scintillation detectors, developed by Saint-Gobain, for use in the Di-Pentagonal Array for Nuclear Timing Experiments (DANTE) of the 8$\pi$ array at the Tri-University Meson Facility (TRIUMF). The goals of this project are to optimize the timing resolution of these detectors; to perform investigations into the possible effects of scattering on such measurements; and to perform the first full test of the DANTE system. Timing resolution optimization and active suppression experiments have been performed in the 8$\pi$ spectrometer using a $^{60}$Co source. With the same source, passive Compton suppression tests have been performed with detectors on a table-top. Finally, the potential of DANTE was tested on its ability to make a measurement of the 121 KeV excited state in $^{152}$Sm. The cumulative results of this investigation are a measurement of the minimum timing resolution obtainable for these detectors, an understanding of the potential Compton suppression has to improve measurements, and a confirmation of DANTE before it is put to rigorous use in any experiment. These investigations
provide an excellent test of the LaBr₃(Ce) scintillation detector’s potential for use in future nuclear structure investigations. First will be provided a brief background in theoretical nuclear physics and nuclear physics instrumentation. Following this is documented the experimental setup, instrumentation, and data analysis tools utilized. Finally the experiments performed will be presented and the results discussed.

1.2 Physics Background

1.2.1 Radioactive Decay Statistics

Radioactive decay is a statistical process described by

\[ N = N_0 e^{-\lambda t} \] (1.1)

where \( N_0 \) is a measure of the initial amount of the decaying substance (ex. unstable nucleus, number of nuclei in an excited state), \( N \) is a measure of the amount remaining after time, \( t \), and \( \lambda \) is the decay constant related to half-life as

\[ \lambda = \frac{\ln(2)}{t_{1/2}} \] (1.2)

or

\[ t_{1/2} = \frac{\ln(2)}{\lambda} \] (1.3)

where \( t_{1/2} \) is the time required for half of the substance or excited state to decay. Activity, which is a measure of the rate of decay, can be expressed as

\[ A = \lambda N \] (1.4)

where \( A \) can be expressed in units of the Becquerel (1 Bq is equivalent to 1 decay per second) or the Curie (1 Ci is the activity of a gram of \(^{226}\)Ra and equals \(3.7 \times 10^{10}\) Bq)
Many situations involve parents which can decay to several possible daughter states. When there are more than one possible form of decay, a branching ratio $\alpha$ denotes the probability that a parent state will decay into each possible daughter state. Each possible decay branch then has its own constant $\lambda$; where the total decay constant satisfying Equation 1.4 is the sum of all individual branches.

$$\lambda = \lambda_1 + \lambda_2 + \lambda_3 + ...$$  (1.5)

### 1.2.2 Nuclear Beta Decay

Nuclear $\beta$ decay is a process by which a nuclear proton transforms into a nuclear neutron ($\beta^+$ decay) or vice versa ($\beta^-$ decay). In this process an unstable initial nucleus (known as the parent nucleus), with atomic number $Z$ and neutron number $N$, is transformed into a more stable final nucleus (known as the daughter nucleus), with atomic number $Z \pm 1$ and neutron number $N \mp 1$, as shown:

$$^{A \ Z}X \to ^{A \ (Z+1)}Y + \beta^- + \bar{\nu}_e$$  (1.6)

$$^{A \ Z}X \to ^{A \ (Z-1)}Y + \beta^+ + \nu_e$$  (1.7)

It is accompanied by the emission of a neutrino $\bar{\nu}/\nu$ and a $\beta$ particle ($e^-/\gamma$). The total atomic number is unchanged and many quantum numbers are conserved.  

The Q-value of these reactions, from the conservation of energy, is a measure of the energy released and is expressed as a difference between the initial- and final-state mass.

$$Q = (\sum m_{initial} - \sum m_{final})c^2,$$  (1.8)

\[^1\text{One such example of the non-conservation of quantum numbers is CP violation, such as those measureable in the decays of } K^0 \text{ and } B^0 \text{ mesons [10].}\]
where $\sum m$ is the sum over the bodies involved in the process.

All nuclei capable of $\beta^+$ decay are also capable of decaying by the competing process of electron capture, provided they are not entirely stripped of electrons. This process can be understood as a rearrangement of the $\beta^+$ decay process [Equation 1.7] in which a proton and electron combine to produce a neutron and neutrino. This process can be expressed as

$$\frac{A}{Z}X + e^- \rightarrow \frac{A}{Z-1}Y + \nu_e$$ (1.9)

$$Q = (\sum m_{\text{initial}} - \sum m_{\text{final}})c^2 - B_e$$ (1.10)

Its Q-value will be the same as described in equation 1.8 for $\beta^-$ decay, less the energy with which the involved electron was originally bound ($B_e$). The energy freed in $\beta$ decay will typically be distributed among the neutrino, the electron, and the nucleus.

In electron capture there is often a vacancy in one of the normally complete electron shells. This may be filled with an electron from a higher shell. When this happens the excess energy can be released in the form of X-rays. Alternatively this energy may be absorbed by another electron and provide it sufficient energy to escape the atom. Electrons emitted in this fashion are referred to as Auger electrons and typically have energy on the order of a few keV to tens of keV.

### 1.2.3 Gamma Ray Radiation from $\beta$-Decay

The daughter nucleus produced via $\beta$ decay will seldom be in its ground state and will often retain some of the available energy released in this decay process. There are often many nuclear excited states, each of which has its own half-life. Following a $\beta$ decay which has populated an excited state of a daughter nucleus, this excited
daughter nucleus will typically rid itself of energy via photon emission. Sometimes a cascade of photons will be released as the daughter nucleus loses energy and populates lower and lower energy states.

The branching ratio, denoted $\alpha$ in this work, is a measure of the probability that any one state will decay to any other lower-energy state. Henceforth, in this work, it will be used in reference to the probability that one excited nuclear state will populate any other lower-energy nuclear state.

An example of this is displayed in Figure 1.1 in which $^{137}$Cs undergoes $\beta^-$ decay to $^{137}$Ba. This can either populate an excited state with an energy of 662 keV or populate the ground state. In the event that it populates the excited state, this state will then decay to the ground state by the emission of a 662 keV $\gamma$ ray.

![Figure 1.1: The $\beta^-$ decay of radioactive $^{137}$Cs populating either the ground state or the 662 keV excited state of $^{137}$Ba](image)

An excited daughter nucleus may also de-excite via internal conversion, in which the nuclear excitation energy $E_{ex}$ is transferred directly to one of the orbital electrons of the atom (typically K- or L- shell). This results in the emission of electrons, particularly when nuclear $\gamma$ ray emission is somewhat inhibited, with energy

$$E_{e^-} = E_{ex} - E_b - E_{recoil}$$

(1.11)
where \( E_b \) is the energy with which the emitted electron was originally bound and \( E_{\text{recoil}} \) is the recoil energy given to the nucleus.

1.2.4 Electron Interactions with Matter

Before discussing some of the approaches to detecting individual radiations (see Section 1.3) it is important to understand the interaction of a few forms of radiation with matter. One relevant particle interaction to be considered is the interaction of fast electrons with matter. \( \beta \)-decay, the main generator of the states to be investigated in chapter 4, produces both fast electrons (detected with SCEPTAR) and \( \gamma \) rays (detected by both SCEPTAR and in the \( LaBr_3(Ce) \) detectors). The \( \gamma \) rays, to be discussed in section 1.2.5, will Compton scatter off many electrons in the scintillator material. These \( \gamma \) rays will transfer a portion of their energy to them, and are another source of fast electrons. The electron interactions relevant to this work induce ionization and excitation in the target material as a result of the Coulomb interaction with other electrons. With each interaction the electron will change direction. The path traversed will appear erratic and the result of many collisions. This can even result in scattering entirely out of a detector medium.

As the electron interacts in a material it will lose energy due to ionization and excitation \((\frac{dE}{dx})_c\) as well as Bremsstrahlung radiation \((\frac{dE}{dx})_r\). This can be expressed according to the equation:

\[
\frac{dE}{dx} = \left( \frac{dE}{dx} \right)_c + \left( \frac{dE}{dx} \right)_r, \tag{1.12}
\]

where

\[
-(\frac{dE}{dx})_c = \frac{2\pi e^4 NZ}{m_o v^2} \left[ \ln \frac{m_o v^2 E}{2I^2(1-\beta^2)} - \ln 2(2\sqrt{1-\beta^2} - 1 + \beta^2) \right.
\]

\[
\left. + (1-\beta^2) + \frac{1}{8}(1-\sqrt{1-\beta^2})^2 \right] \tag{1.13}
\]
\[-\left(\frac{dE}{dx}\right)_r = \frac{NEZ(Z + 1)e^4}{137m_0^2c^4} \left(4\ln\frac{2E}{m_0c^2} - \frac{4}{3}\right) \quad \text{(1.14)}\]

From this it is evident that the higher the number of protons (Z) in the target atoms, the greater the rate of energy loss. This can be roughly equivocated to an increase in the density of the target, implying a shorter range of the electrons. The same principal and equations apply roughly to positrons, except that near the end of their flight they will combine with an electron and emit two 0.511 MeV $\gamma$ rays.

Another important aspect of fast electron interaction to note is the relatively large chance of backscatter. Backscattering typically refers to an interaction in which the fast radiative particle undergoes sufficient deflection to exit the target medium, through the same surface as it entered, before losing all of its kinetic energy. This can have many effects on experiments, particularly those involving closely packed detectors. Backscatter is most likely to occur at lower electron kinetic energies. Some such effects are explained in section 1.3.2: Scintillation Detectors.

### 1.2.5 Gamma-Ray Interactions with Matter

Gamma rays are crucial for many measurements in nuclear physics. Their interaction with matter is thus of equal importance. In this work the two most important interactions are photoelectric absorption and Compton scattering. Pair production is another common interaction but is improbable at the energies relevant to this work. Pair production occurs when the $\gamma$ ray has sufficient energy (at least 1.02 MeV) to produce an electron-positron pair. When such a $\gamma$ ray is in the presence of the Coulomb field of a nucleus, it may disappear and spawn an electron-positron pair. Excess energy will be shared between the electron and positron. It is rare for this
to occur unless the $\gamma$ ray has significantly more than the energy sufficient for pair production. Even in the event of pair production in the detector medium it is unlikely that this will have any effect on a measurement of the energy of the initial $\gamma$ ray. In this case both the electron and positron will lose their energy. As explained in the previous section, the positron will undergo annihilation with another electron in the medium, and no energy should be lost\(^2\). It is thus unlikely that pair-production would play a significant role in this work.

Photoelectric absorption occurs when a $\gamma$ ray is absorbed by an atom and its energy is transferred to an electron. The energy of this electron is given by:

$$E_{e^-} = hv - E_b,$$  \hspace{1cm} (1.15)

where $E_b$ is the electron binding energy. This leaves the original atom ionized and with a vacancy in one of its lower shells. This is not the lowest energy configuration and the vacancy will either be filled via rearrangement within the atom, or through capture of a nearby free electron. In these processes characteristic photons will be emitted as electrons drop into lower energy holes/states.

The probability of photoelectric absorption ($\tau$) can be approximated as

$$\tau \approx C \frac{Z^n}{E_\gamma^3},$$  \hspace{1cm} (1.16)

where $C$ is a constant, $Z$ is the number for protons in the atom of the absorber medium, $E_\gamma$ is the $\gamma$ ray energy, and $n$ varies between 4 and 5. Essentially, higher-$Z$ materials are more capable of absorbing high-energy $\gamma$ rays.

Compton scattering occurs when the incident photon interacts with an electron

---

\(^2\) The exception to this is when one of the 511 keV $\gamma$ rays exits the detector, giving rise to the single-escape peak 511 keV below the expected peak; the loss of both 511 keV $\gamma$ rays results in the double-escape peak (with a shift of 1.02 MeV)
and is scattered by some angle $\theta$, thereby transferring some of its energy and momentum to the recoil electron. Assuming that the electron was initially at rest, the energy of the scattered photon can be related to its scattering angle $\theta$ by:

$$h\nu' = \frac{h\nu}{1 + \frac{h\nu}{m_e c^2}(1 - \cos \theta)}$$  \hspace{1cm} (1.17)

The probability that this $\gamma$ ray will scatter at any angle $\theta$ can be modeled by the Klein-Nishina formula for differential scattering cross section:

$$\frac{d\sigma}{d\omega} = r_o^2 \left[ \frac{1}{1 + \alpha(1 - \cos^2 \theta)} \right]^3 \left[ \frac{1 + \cos^2 \theta}{2} \right] \left[ 1 + \frac{\alpha^2(1 - \cos \theta)^2}{(1 + \cos \theta)[1 + \alpha(1 - \cos \theta)]} \right]$$  \hspace{1cm} (1.18)

where $r_o$ is the classical electron radius and $\alpha = h\nu/m_e c^2$

This is plotted in figure 1.2 for several different $\gamma$ ray energies. The obvious trend is that the higher the energy of the $\gamma$ ray, the higher the chance of forward-scattering.
Figure 1.2: Plot of Nishina formula for differential scattering cross-section for several values of photon energy

Taking the probabilities for each of these three $\gamma$ ray interactions into account, one can make an estimate of the mean distance a $\gamma$ ray will travel before interacting; its mean free path. The total probability of interaction is described by the mass attenuation coefficient ($M$) as:

$$\frac{I}{I_o} = e^{-M\rho t}$$  \hspace{1cm} (1.19)

where $M$ is the mass attenuation coefficient ($M = \frac{\mu}{\rho}$), $\rho$ the density of the medium,
and $\mu$ the linear attenuation coefficient. Integrating and normalizing the distance-probability relation one finds the mean free path ($\lambda$) is

$$\lambda = \frac{\int_0^\infty x e^{-M\rho x} \, dx}{\int_0^\infty e^{-M\rho x} \, dx} = \frac{1}{M\rho} \quad (1.20)$$

Of note is the inverse dependence on density of the mean free path.

Figure 1.3: The regions in which each type of gamma ray interaction is most probable. When well within the boundaries of each zone the other two effects can be considered negligible. From [1] modified by D.Cross

1.3 Radiation Detection Background

Having covered the relevant particle-matter interactions, the operation of radiation detectors follows naturally. There have been many approaches to the problem of detecting individual radiations, each having its merits. Those most relevant to this work (those which are implemented in the $8\pi$) include both solid-state detectors and scintillation detectors.
1.3.1 Solid-State Detectors

One form of detector is the solid-state detector. In these detectors the main information carrier is the electron-hole pair. When a charged particle, such as an electron, enters the detection medium it liberates many electrons along its path, creating many electron-hole pairs. Were there no electric field present the electrons and holes would ultimately recombine with one of their counterparts, releasing the excess binding energy in the form of electromagnetic radiation. If a high voltage is applied across the detector medium, however, the electron and hole will migrate towards the cathode and anode, respectively. This creates a small current across the detector medium, which forms the basis of the detection signal. The higher the energy of the incoming radiation, the more electron-hole pairs are created and thus the larger the electrical pulse. Noting that: 1. It takes a relatively small amount of energy, on the order of a few electron-volts, to produce an information carrier; and 2. That most-all of the information carriers can be collected, it is easy to see that the energy resolution of these detector systems is particularly high. Note also that these detectors can be built quite thin (typically on the order of 1 cm), allowing rapid charge collection, and thus can have excellent timing resolution (typically on the order of 10 ns).

Certain solid-state detectors can also specialize in the detection of γ rays. One example of this is the high-purity germanium (HPGe) detector. Like other solid-state detectors, these HPGe detectors boast an exceptional energy resolution, however these germanium detectors are lacking in timing resolution. To be able to catch energy from highly penetrating γ rays, they need be thicker than your typical solid-state detector.

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3Solid-state can also be tailored to be proficient at x-rays detection. An example of this is the lithium-doped silicon detector, which can be well suited to both charged particle and x-ray detection.
(typical thickness of $\approx 1$ cm). When compared to the time for light to travel across the detector medium, the drift of the electron-hole pair takes a long time.

### 1.3.2 Scintillation Detectors

There are several components to the scintillation detection of $\gamma$ rays. First the $\gamma$ ray interacts with the scintillation crystal as described in section 1.2.5. This often results in the freeing of one or more electrons whose behavior in the target medium will be as described in Section 1.2.4. This fast electron will deposit its energy in the form of excited atoms in the target medium, which we will hence-forth consider to be a LaBr$_3$(Ce) crystal. Each atom has its own excited energy levels. Mostly this is excited LaBr$_3$ but the crystal lattice has the occasional cerium excited in place of one of the lanthanum atoms. Due to lattice relaxation, about the cerium atom, there will be a stokes shift between the excitation and emission energy of some CeBr$_3$ molecular excited states. Wherever this happens there will be photons emitted which are not readily reabsorbed, lying in the band gap region of the crystal. The crystal is then transparent to these photons and they spread out unimpeded in all directions. Some of these photons make their way through the crystal to a photomultiplier (PM) tube on the back, used to determine the energy of the initial photon which was impinged on the crystal.

The $LaBr_3(Ce)$ have two types of output signal. The outputs are a fast-timing output (anode), the signal from which goes to the Constant Fraction Discriminator (CFD) for timing measurements, and a slower output (dynode) used to measure energy. The aptly named pre-amp (1) is provided to amplify the output signals prior to possible further amplification. A high voltage (HV) is supplied the PM tube base of the $LaBr_3(Ce)$ detector with the voltage difference to be applied across the
1.3.3 Photomultiplier Tubes

Those photons which strike the photomultiplier (PM) tube free electrons from a cathode at its front, as in the photoelectric effect. These electrons are accelerated down the tube by a high-voltage (HV) potential difference inducing a cascade of further freed electrons. Finally these electrons are collected and this small current forms the basis of the signal to be used in the analysis of that event. For a typical pulse, $10^7 - 10^{10}$ electrons give rise to the charge signal from the initial $\gamma$ ray scintillation event.
Figure 1.5: $\text{LaBr}_3(Ce)$ back panel with inputs labeled: (1) Pre-amp ; (2) Dynode ; (3) Anode ; (4) HV Supply
Figure 1.6: Basic elements of a photomultiplier tube [2]
Occasionally a significant electron pulse can be initiated in the PM tube by thermal liberation of electrons from the cathode. This can occur when an sufficiently energetic thermal photon - one with energy greater than the cathode metal work function - strikes the cathode. The probability of such photons as a function of energy is governed by the maxwell distribution at a temperature of approximately 298 K. This is also possible when a sufficient number of thermal photons from the environment strike the same electron, within the cathode, simultaneously. These photons will strike at random intervals, and so the probability that some number of them will strike within the same time-window can be modeled approximately with the Poisson distribution. The ideal PM tube has a linear signal response to incoming photons, however there are many sources of noise that interfere; one example being the aforementioned thermonic electron liberation.

Figure 1.7: An overlay of many raw anode signals from the LaBr$_3$(Ce) PM tubes. A $^{60}$Co source was used. Note that the two characteristic energy lines from $^{60}$Co are discernable as an increase in the density of this plot.
1.4 LaBr$_3$(Ce) Crystals

1.4.1 Growth

LaBr$_3$(Ce) crystals can be grown using the vertical self-seeding Bridgman technique. A desired molar ratio of CeBr$_3$ to LaBr$_3$ powders are charged in a quartz ampule. The ampule is itself in a chamber that has been evacuated of both oxygen and water. At the bottom of the ampule is a capillary tip in which the initial crystal formation takes place and seeds further growth. The ampule is sealed and evacuated before being removed from its chamber and moved into a 3-zone Bridgman oven.

![Two Vertical Bridgman Furnaces](image)

Figure 1.8: Two Vertical Bridgman Furnaces [3]

Such an oven contains a region of uniformly high temperature at its top, a region with a linearly decreasing temperature gradient in its middle, and a region of uniform lower temperature at its bottom. The quartz crystal is initially placed entirely in the
high-temperature region. It remains there until the LaBr$_3$ and CeBr$_3$ have melted and attained uniform temperature. Finally it is lowered slowly through the temperature gradient zone, in which the crystal begins to form.

Differences in the fundamental lattice spacing between LaBr$_3$ and CeBr$_3$, as well as a large thermal expansion anisotropy can cause the crystal to cleave. Like other halide crystals its tendency is to cleave along planes parallel to the [001] axis (c-axis) [6-4]. This puts a limitation on how large the crystals can be grown. According to Hongsheng Shi et al [11] and A. Iltisa et al [12] there is less chance of cracking, allowing a larger crystal, if the crystal is grown along the [001] plane. As the crystal is being lowered through the Bridgman oven this orientation will cause most of the uneven thermal contraction to occur along the axis of growth. When this axis is [001] the stress on the parallel planes will be minimized.

According to W.M. Higgins et al [3] the lowering speed, through the temperature gradient region of the Bridgman oven, has a large effect on the direction of crystal growth. When lowered at a speed of 1.0 mm/h, the crystal forms predominantly in the [001] plane (perpendicular to the upward axis) and if lowered at a speed of 0.5 mm/h, the crystal forms predominantly in the [100] plane. Using this technique relatively large LaBr$_3$(Ce) crystals can be formed. The BriLanCe®380 LaBr$_3$(Ce) crystals $^4$ investigated in this work were grown in this manner along the [100] axis.

1.4.2 Properties

The LaBr$_3$(Ce) lattice is a tricapped trigonal prism; a partial lattice is illustrated in Figure 1.5. What makes these crystals particularly special is the relatively large lattice relaxation which occurs after an electron is excited to a 4$f$ – 5$d$ state in Ce$^{+3}$.  

$^4$Grown by Saint-Gobain Crystals
This relaxation occurs to minimize energy, since the cerium in this electronically excited state is no longer in its minimal energy configuration. After this relaxation the $4f - 5d$ excited states will have a lower energy and may lie in the band gap region of the crystal. When a photon is emitted by the transition from this lattice-relaxed state it will have less energy than the normal $Ce^{+3} 5d$ and $4f$ de-excitation. Since these states lie in the semiconductor band gap region of the unexcited crystal they are capable of emitting photons at energies which the crystal is unlikely to absorb. This difference between the energy absorbed and that emitted, after relaxation has occurred, is referred to as a 'Stokes shift'. In the case of $LaBr_3(Ce)$ the Stokes shift is on the order of 0.55 eV.

These crystals also have a relatively linear proportional light yield at energies greater than 90 keV but show a light yield deficit at lower energies [13] [5] [3] [14]. This non-proportional response can be improved by decreasing the temperature of the crystals [13].

The density of the $LaBr_3(Ce)$ detectors is 5.5 g/cc [15]. Recalling the approximate relationships between density and penetration depth for both electrons and photons

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There is a poorly understood degeneracy in these states, $5d$ in particular, of $Ce^{+3}$ so it may not be that all of the relaxed $5d$ states lie in the band gap region.
Figure 1.10: Depiction of excitation and emission, in $Ce^{+3}$ and of the stokes shift resultant from lattice relaxation (Formulas 1.14 and 1.20, respectively), it is evident that this is an important property for a scintillator. A higher density permits that the full energy from higher energy photons can be fully absorbed with lower chance of scattering out of the crystal.

The concentration [% Ce dopant = 5% ] has been shown to affect the scintillation properties of $LaBr_3(Ce)$ crystals [6]. It was found that a 5% dopant concentration yielded the maximum light output per MeV of energy when exposed to 661.7 keV $\gamma$ rays; however this yielded at most a 5% increase in light output, compared with the other investigated dopant concentrations. This is evident in figure 1.13.

Of even greater interest to this work is the effect of dopant concentration on timing resolution. There is a large increase in timing resolution as dopant concentration increases, as is evident in figure 1.14.

\[\text{Crystal size was not necessarily consistent in this work}\]
1.4.3 Internal Activity

An ideal LaBr$_3$(Ce) scintillation crystal would be composed entirely of stable elements including $^{139}$La. Unfortunately there is inevitably going to be some amount of contamination with naturally occurring radioactive elements and isotopes. In these detectors the primary concern is the contamination with naturally occurring radioactive $^{138}$La (0.08881% abundance) and $^{227}$Ac, which replace the occasional $^{139}$La. This means that these crystals will occasionally detect their own decay products. This is referred to as internal activity. Recent work [7] has found the internal activity in the range of 0.07 – 3MeV to be $\approx 4.4$ cts/s/cm$^3$. This is sufficient to interfere with any long-term energy measurements but should not affect the scintillator’s ability to make precision fast-timing measurements so long as more than one energy gate is applied, as is the case in this work. It should be noted that there will be other radioactive elements including a 0.251% abundance of radioactive $^{138}$Ce and 0.185% abundance
Figure 1.12: The non-proportionality of light yield for Compton electrons in $LaBr_3(Ce)$ by various sources at various angles. FEP is the response to $\gamma$-rays, normalized to the 662 keV transition from $^{137}Cs$ [5]

of radioactive $^{136}Ce$, however these can be considered negligible due to long lifetimes and low concentration.
Figure 1.13: Effect of Dopant Concentration on Light Output of LaBr₃(Ce) [6]

Figure 1.14: Effect of dopant concentration on timing resolution of LaBr₃(Ce) irradiated by 0.511 MeV photon pairs (prompt) [6]
Figure 1.15: A natural background spectra presented in [7] using a 1”x1” cylindrical $LaBr_3(Ce)$ crystal in order to investigate internal activity.
1.5 The Constant-Fraction Discriminator

Key to the timing analysis of these scintillation detectors is the Constant-Fraction Discriminator (CFD) module. Given the raw signal, displayed in Figure 1.15, from the PM tube its task is to identify a consistent starting point of the signal. This is made complicated due to the fact that different signals will have slightly varying rise times, which often scales as energy, and the background noise present in any signal. The way in which the CFD does this is illustrated in Figure 1.17.

Figure 1.16: CFD module [8]

Figure 1.17: Breakdown of CFD zero-crossing selection for output signal

The CFD modules used in this work (implemented in the DANTE, described in Section 1.7) were ORTEC 935 quad CFDs. They operate by first taking in the raw timing signal and splitting it into two. One of these signals is largely attenuated and the other is delayed and inverted. It then sums these two signals and takes the
zero-crossing as the starting point for its output signal. This sum-signal can even be viewed on an oscilloscope via an output (the “M” output) on the front panel of the module. The most readily changed settings one may adjust on these modules include: threshold voltage, delay time, and zero-crossing. The adjustable threshold voltage on the CFD allows it to ignore any signals below said threshold. This means that any noise in the raw signal will be insufficient to trigger an output. The adjustable, and aptly named, zero-crossing voltage changes the voltage at which the CFD deems the sum signal to cross zero. The length of the delay between the attenuated and delayed-inverted signal is adjustable using external cables of known delay length. One may also affect the functioning of this module by the insertion or removal of three types of internal jumper, with attachment sites on the circuit board of the CFD. In this work only one jumper, W2-Updating/Blocking Mode, was inserted; the effect of this was to put the module into 'blocking mode'. Whilst in this mode the CFD will be incapable of triggering on a new signal while it is in the process of giving an output signal.

1.6 ISAC

The facility housing the $8\pi$ is the Isotope Separator and Accelerator I (ISAC-I) hall of TRIUMF. The cyclotron at TRIUMF produces a 500 MeV beam of protons which are directed to a target, inducing a spallation reaction (the fragmenting of a heavy nucleus into smaller parts). The target material is specifically chosen to produce a reasonable quantity of the desired isotope. These isotopes are mass-selected and sent through an evacuated beamline, with electric focusing elements, into any of the detector arrays in the ISAC-I experimental hall. This permits the study of rare and
highly unstable isotopes.

**ISAC I and ISAC II**

![Figure 1.18: ISAC Halls](image)

1.7 The $8\pi$

The array into which these detectors have been installed is the $8\pi$ spectrometer. It is an array of 20 BGO-suppressed high-purity germanium detectors; a Scintillating Electron-Positron Tagging Array (SCEPTAR) consisting of 20 thin plastic scintillators; a Pentagonal Array of Conversion Electron Spectrometers (PACES) consisting of 5 liquid nitrogen cooled Si(Li) detectors; a fast timing plastic scintillation detector; a Dipentagonal Array for Nuclear Timing Experiments (DANTE). The aforementioned are displayed in Figure 1.21. It forms a detector-sphere about the target of a low-energy beam transport line, devoted solely to this array. At the terminal of this beam
line, at the focal point of the $8\pi$ array, is a mylar tape-transport system. This system is used to trap incoming isotopes for measurement at the focal point and to remove them, with any longer-lived contaminants, once a measurement is complete. The used tape is stored behind a lead shield (Figure 1.20) to prevent photons emitted by any residuals on the tape from interfering with future measurements.

![Figure 1.19: Tape system in the downstream hemisphere of SCEP-TAR and at focal point of the $8\pi$](image1)

![Figure 1.20: Tape removed from the focal point of the array; one side of lead shield removed to make tape visible](image2)

The HPGe Detectors, with a relative efficiency of 20 – 25%, are arranged in a truncated isocahedral arrangement [16]. They are capable of making highly precise energy measurements on $\gamma$ rays emitted from excited states in the atomic nucleus of daughter nuclei, following the decay of a parent. Each is shielded with a high-efficiency bismuth germanate (BGO) scintillation detector. These shields allow Compton suppression of events in the BGO shields; they detect and veto unwanted events in which a $\gamma$ ray Compton scatters in to, or out of, the HPGe crystal. This prevents use of events in which only a portion of the $\gamma$ ray’s energy was deposited in any HPGe detector.
Figure 1.21: The $8\pi$ array, showing beam implantation direction, with detectors labeled: [1-4] BGO shielded HPGe detectors; [5] $LaBr_3(Ce)$ detector; [6] $BaF_2$ Detector; [7] SCEPTAR with both hemispheres closed

The SCEPTAR consists of 20 1.6mm thick plastic scintillators with a high efficiency (~80%), which immediately surround the beam implantation position. Each one lines up with an HPGe detector making it a practical detector of the positrons and electrons indicative of a $\beta$ decay.

The PACES is a set of five 5mm thick nitrogen-cooled Si(Li) detectors. It can be inserted to replace the upstream half of the SCEPTAR and used to detect conversion electrons. This is useful both where E0 transitions preclude the possibility of decay by $\gamma$ ray emission, as well as where internal conversion competes with $\gamma$ ray emission.

As PACES is able to replace the upstream half of SCEPTAR, a fast-timing plastic scintillation detector can also be inserted, replacing the downstream half of SCEPTAR. This detector is positioned along the axes of the incoming beam of isotopes (zero-degrees to this axis), earning it the title Zero − Degree Scintillator. It is able
to make extremely precise timing measurements of $\beta$ particles and, at low efficiency, $\gamma$ rays, but is incapable of distinguishing different particles and of measuring the energy thereof.

The DANTE is most relevant to this work, in that it is this system in to which the $LaBr_3(Ce)$ detectors are being incorporated. It consists of ten Barium Fluoride (BaF$_2$) or LaBr$_3$ detectors in the ten open pentagonal positions in between the HPGe Detectors. These detectors have highly accurate timing resolution and are capable of measuring the half-lives of nuclear excited states down to the pico-second range.
Chapter 2

Data Fitting

The data to be fitted includes measurements of the half-life of the 121 keV excited state of $^{152}$Sm and of the prompt timing response of the system (both of which will be further explained in Section 3.2.1 and 3.6). In order to fit the decay curve to an equation, and extract the half-life, a program was required. This was created with the help of the Gnu Scientific Libraries. This program (jfit) uses the Levenberg-Marquardt technique to perform non-linear parametric $\chi^2$-minimization of the fit with data. This is done to fit in three ways

1. To fit exponential tails of the skew-Gaussian where the constant in the exponential is the decay constant of that excited state.

2. To fit the entire skew-Gaussian.

3. To fit the Gaussian data from prompt (less than a picosecond) response of the setup.
2.1 Convolution Theorem

2.1.1 Form of Skew-Gaussian Fit

The form of the function for a Gaussian and inverse exponential are well known to be

\[ g(x) = \frac{A}{\sigma \sqrt{2\pi}} e^{-\frac{(x-\bar{x})^2}{2\sigma^2}} \]  

(2.1) and

\[ f(x) = e^{-\lambda x}, x \geq 0, \]  

(2.2) respectively. In equation 2.1, \( A \) is the amplitude, \( \sigma \) the standard deviation, and \( \bar{x} \) the mean value. In equation 2.2, \( \lambda \) is the decay constant and the function is only used for \( x \geq 0 \) for obvious reasons. A skew-Gaussian can be obtained via the convolution of a Gaussian with an inverse exponential. Two functions are called causal when they both depend on the same variable and contribute to the final form of an equation.

By the convolution theorem, any two causal equations \( f(x) \) and \( g(x) \) can be combined as:

\[ c(u) = \int_{-\infty}^{\infty} f(x)g(u-x) \, dx \]  

(2.3)

In the case of an exponential and a Gaussian distribution this becomes:

\[ c(u) = \frac{A}{\sigma \sqrt{2\pi}} \int_{0}^{\infty} e^{-\lambda x} e^{-\frac{(u-\bar{x}-x)^2}{2\sigma^2}} \, dx \]  

(2.4)

This form is not easily implemented in C and so a more useful formulation must be implemented. Combining and expanding the exponentials gives

\[ c(u) = \frac{A}{\sigma \sqrt{2\pi}} \int_{0}^{\infty} e^{-\lambda x} e^{-\frac{(u^2 + x^2 - 2ux - 2u\bar{x} + 2x\bar{x} + 2\sigma^2 \lambda)}{2\sigma^2}} \, dx \]  

(2.5)
Pulling out the terms not being integrated over one obtains

\[ c(u) = A e^{-\frac{(u^2 + \bar{x}^2 - 2u\bar{x})}{2\sigma^2}} \int_{0}^{\infty} e^{-\frac{(u^2 + \bar{x}^2 - 2u\bar{x} + 2\sigma^2\lambda)\bar{x}}{2\sigma^2}} \, dx \]  

(2.6)

Simplifying and arranging the exponential into the form \((x - B)^2 - B^2\)

\[ c(u) = A' \int_{0}^{\infty} e^{-\frac{-(x - u + \sigma^2\lambda + \bar{x})^2}{2\sigma^2}} \, dx \]  

(2.7)

\[ c(u) = A'' e^{-\frac{(x - \bar{x} - \sigma^2\lambda)^2}{2\sigma^2}} \int_{0}^{\infty} e^{-\frac{(x - u + \sigma^2\lambda + \bar{x})^2}{2\sigma^2}} \, dx \]  

(2.8)

the integral can be shifted with the following substitutions

\[ x' = \frac{x - u + \sigma^2\lambda + \bar{x}}{\sqrt{2}\sigma} \]  

(2.9)

\[ dx = \sqrt{2}\sigma \, dx' \]  

(2.10)

\[ Z = x'(x = 0) = \frac{-u - \sigma^2\lambda + \bar{x}}{\sqrt{2}\sigma} \]  

(2.11)

\[ A'' = A' e^{-\frac{(x - u + \sigma^2\lambda + \bar{x})^2}{2\sigma^2}} \]  

(2.12)

permitting further simplification to

\[ c(u) = A'' \int_{0}^{\infty} e^{-\frac{(x - u + \sigma^2\lambda + \bar{x})^2}{2\sigma^2}} \, dx \]  

(2.13)

and penultimately

\[ c(u) = A'' \sqrt{2}\sigma \sqrt{\frac{\pi}{2}} \left[ \frac{2}{\sqrt{\pi}} \int_{Z}^{\infty} e^{-(x')^2} \, dx' \right] \]  

(2.14)
In the square brackets of equation 2.14, one can recognize the form of the conjugate error function $1 - erf(z)$. Thus the form of the skew-Gaussian equation to be used is

$$c(u) = \frac{A}{2} e^{-u\lambda + \bar{x}\lambda + \frac{1}{2}\sigma^2\lambda^2} \left[1 - erf\left(\frac{\sigma^2\lambda + \bar{x} - u}{\sqrt{2}\sigma}\right)\right] \quad (2.15)$$

### 2.1.2 Error Function Simplification

The final form of the skew-Gaussian contains an error function which must be solved in C. In order to keep complete control over calculations in the fitting code it is useful to use an approximation of this function. The approximation chosen to represent the error function, from Abramowitz and Stegun [17], is

$$erf(x) \approx 1 - \frac{1}{(1 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4)^4}, \quad (2.16)$$

where $a_1 = 0.278393$, $a_2 = 0.230389$, $a_3 = 0.000972$, $a_4 = 0.078108$. This is quoted to have a maximum deviance of less than $5 \cdot 10^{-4}$. In order to verify this it was compared against both the error function algorithm in the C library math.h and that in Maple13. It did not deviate from either by more than the quoted error and so was used in all calculations of the skew-Gaussian function.
2.2 Levenberg-Marquardt $\chi^2$ Minimization

The non-linear $\chi^2$ regression can be performed by the Levenberg-Marquardt algorithm. It is an iterative process by which a function $f(z, x_i)$ of parameters $x_i$ is fitted to a set of data points $y(z)$. To be implemented it requires that several things are known

1. The form of the fitting function $f(x)$.
2. The partial derivatives of this function with respect the each parameter $x_j$
3. An accurate initial guess of the parameters $x_j$

This algorithm calculates the $\chi^2$ (see Equation 2.17) in order to determine the goodness of each fit.

$$[\chi(z_i, x_j)]^2 = \sum_{i=1}^{n} \frac{[y(z_i) - f(z_i, x)]^2}{\sigma_i^2}$$  \hspace{1cm} (2.17)
where \( n \) is the number of data points, \( y(z) \) is the data to be fitted, and \( f(z, x) \) is the function to be fitted to said data.

In the first iteration it tests a 'step' of size \( D_i \) along the gradient of the function with respect to each variable. The step in the function can be approximated, to first order, as

\[
f'(z_i, x_j + D_j) \approx f(z_i, x_j) + \sum_{j=1}^{n} \frac{\partial f(z_i, x_j)}{\partial x_j} D_j \tag{2.18}
\]

This can be combined with the \( \chi^2 \) equation to produce:

\[
\chi(z_i, x + D) \approx \left[ y(z_i) - f(z_i, x_j) - \sum_{j=1}^{n} \frac{\partial f(z_i, x_j)}{\partial x_j} D_j \right]^2 \tag{2.19}
\]

The step sizes, \( D_j \), must be determined. Where it is optimized, one should expect that the gradient of the \( \chi^2 \) equation with respect to \( D_j \) should be zero. Differentiating both sides with respect to \( D_j \) and setting it equal to zero leaves us with a set of linear equations. These can be solved for \( D_j \).

\[
0 \approx \left[ \sum_{j=1}^{n} -y(z) \frac{\partial f(z_i, x_j)}{\partial x_j} + f(z_i, x_j) \frac{\partial f(z_i, x_j)}{\partial x_j} + \left[ \frac{\partial f(z_i, x_j)}{\partial x_j} \right] D_j \right]^2 \tag{2.20}
\]

After this step the \( \chi^2 \) is recalculated, as in equation 2.17, and compared with the previous \( \chi^2 \) value. If it has become smaller then that step was considered a success and the parameters \( x_j \) are incremented by that step \( D_j \); the next iteration will start now using these updated parameter values. If not, the step is considered a failure. In this case the parameters will retain their original values and, depending on the implementation, the next iteration may proceed with a smaller step.

Finally, when no step can be found that minimizes the \( \chi^2 \) value, the function’s parameters have been optimized. It should be noted that this method is only truly successful where a single minima exists, or where parameters are chosen to be sufficiently close to their optimal values.
2.3 Fit Potential Using Test Data

Figure 2.2 displays the skew Gaussian with arbitrary selection of parameters: $A = 188; \bar{x} = 20; \sigma = 11; \lambda = 0.03$. A low amplitude ($A$) value was chosen in order that, with random Gaussian noise, this test data would be a decent approximation of low-statistics data.

The initial guess at parameter values, which must be provided for a LM fit, were: $A = 140; \bar{x} = 3; \sigma = 1; \lambda = 0.1$. Obviously, this initial guess is far off since, for test data, we already know the parameter values. This was done intentionally such that the ability of the algorithm could be well tested; one which requires an accurate initial-guess would be less useful.

After 17 iterations towards a minimization of $\chi^2$, the program converged on the following parameters: $A = 184 \pm 4.96; \bar{x} = 20.02 \pm 0.44; \sigma = 9.56 \pm 0.35; \lambda = 0.03099 \pm 0.00075$, with a $\chi^2$ value of 1.23; an excellent result considering the poor statistics.
and wretched guess of initial-parameters.
Chapter 3

Experimental Setup

The experiments performed in this work can be broken down into three general categories. The first being a table-top setup in which two LaBr$3$(Ce) detectors, both outside of the array, were used in tandem; this was used to test the effect of passive suppression on the timing resolution of said detectors. The second setup implemented involved having the detectors mounted in the 8π array discussed in Section 1.7. This setup was employed both to investigate the potential of active Compton suppression and to measure the timing resolution of a single detector, permitting optimization thereof. The final category pertains to the further testing of the DANTE system. It includes the first two categories, which will test the prompt response of this system, but goes further on to look at the ability of the DANTE to measure the half-life of the 121 keV excited state in $^{152}$Sm.

3.1 Motivation

There are three main objectives in this research:

1. Optimize and test the timing resolution of the new LaBr$3$(Ce) detectors.
2. Investigate the potential of both passive and active Compton shielding in increasing precision of timing measurements.

3. Investigate the potential of these crystals in the DANTE system

By optimizing the array’s time-response to signals from the \(LaBr_3(Ce)\) detectors one can extract the most precise possible half-life measurements.

The Compton suppression could cause a large increase in the quality of the data collected. By removing those Compton scattered events, in cases where the peak of interest lies on a Compton background, the timing resolution of these detectors can be improved. This will be particularly useful when the peak of interest is also at an energy \(\lesssim 150\) keV below which there is a significant chance of backscatter, illustrated in Figure 1.2. Light can travel approximately 0.3 meters in a nanosecond and, since this is on the order of the distance between our detectors, it is highly possible that Compton scattering could be detrimental to our timing resolution.

Testing of the DANTE system with \(LaBr_3(Ce)\) detectors is crucial before they are heavily used in any experiment. With this testing the abilities and limits of this system in making precise timing measurements can be determined. This is particularly important given that measurements on the timescale of several hundreded picoseconds are difficult and the system’s signal-response cannot easily be predicted. It will be the first test of the system’s capabilities. Testing with both \(^{60}Co\) and \(^{152}Eu\) will provide information on how the system responds: to high- and low- energies, respectively; to peaks which do/do-not lie on a Compton background, respectively; and to prompt/nanosecond decays, respectively.
3.2 In-array Experiments

The \( \text{LaBr}_3(\text{Ce}) \) detectors were inserted in the place of 5 of the \( \text{BaF}_2 \) detectors used in the DANTE. They were incorporated into the DANTE data stream, to be described with more detail in section 3.4. The two types of experiments performed in-array were timing optimization and the tests of active suppression using BGO shields.

3.2.1 Timing Optimization

For timing optimization the \( \text{LaBr}_3(\text{Ce}) \) scintillation detectors were mounted in the DANTE, replacing several \( \text{BaF} \) detectors, and connected to the DANTE signal processing streams (see section 3.4). The following analysis was used to optimize each detector.

A \(^{60}\text{Co}\) source \(^1\) was mounted at the focal point of the array. Cobalt was chosen because when it decays to nickle it emits two characteristic \( \gamma \) rays (energies 1.332 MeV and 1.173 MeV) within a picosecond of each other. This is referred to as a prompt decay and is well below the timing resolution of our detectors.

\[ \begin{array}{c}
\text{Co}^{60} \\
\text{Ni}^{60}
\end{array} \]

Figure 3.1: The beta-decay of radioactive Cobalt-60 populating excited states of Nickle-60

\(^1\)Activity at time of experiment: 22400 Bq
The zero-degree plastic scintillator was used in coincidence with a $LaBr_3(Ce)$ detector since it has an excellent timing resolution and is well adjusted for timing measurements. This permits the optimization of a single lanthanum detector. Had there been two lanthanum detectors in coincidence it would have been necessary to optimize both simultaneously, doubling the number of variables that require simultaneous adjustment.

All but one of the $LaBr_3(Ce)$ detectors were biased with an HV of 1500V, which meant that the energy spectra of all detectors were reasonably well aligned. The detector labeled LaBr Q-092 was run at 2000V, as was required to bring its energy spectra approximately in line with the others. Certainly this is concerning and this point will be discussed further in Section 4.1. The hemisphere of the $8\pi$ containing the detector being tested was closed and the other left open to reduce scattering.

When the $\gamma$ ray strikes the detector, a raw signal is sent to the constant fraction discriminator (see Section 1.5). In this simplified model the CFD converts this into a logic pulse, which is sent to the Timing to Amplitude Converter (or TAC). The TAC
then measures the time between these pulses; between a start signal from one detector and a stop from the other. Since there is a delay in one of the paths, and since the $\gamma$ rays strike the detectors at effectively the same time, we expect that the TAC should always measure the same time between pulses (corresponding to the length of the delay in the circuit).

Figure 3.3: Ideal TAC spectra in which the time between events is constant and corresponds to the delay inserted between the start and stop signal.

Figure 3.4: A realistic TAC spectra in which the time between events forms a Gaussian distribution about the actual value of the delay.

In an ideal world the TAC spectra would look like figure 3.3. In the real world the LaBr-DANTE system will have some uncertainty and the actual spectra will resemble a Gaussian. The FWHM of said Gaussian will correspond to the resolution of the setup. It is by fitting this Gaussian that one can quantitatively judge which settings optimize the timing resolution, minimizing the FWHM of the prompt Gaussian time response.

CFD settings which require optimization (for a LaBr$_3$-ZDS coincidence) include the selection of a delay length and adjustment of the zero-crossing voltage. Blind optimization of two variables would be hugely inefficient and so a technique is required to decrease this from a 2-D optimization problem to a 1-D; this can be done using
an oscilloscope with a rapid sampling rate and high-accuracy. Using the M-output of the CFD one can view individual sum-signals. However, by setting the oscilloscope to overlay all recorded waves, it is possible to see the spread with which all of the signals cross zero. By adjusting the zero-crossing voltage to minimize this spread one can, rather quickly, select a zero-crossing setting which is close to optimal. This decreases our 2-dimensional optimization problem to a 1-dimensional (CFD delay length) problem with a small perturbation (adjustment of the zero-crossing voltage).

![Figure 3.5: M output from CFD front panel displaying an overlay of many sum-signals](image)

Optimization proceeded by choosing an arbitrary CFD external delay-length and starting a collection. The TAC spectra from this was viewed online with a gate applied about the 1332 keV $^{60}$Co peak. After some time the online fitting function was used to extract a FWHM of this TAC peak. By repetition of the following steps it was possible to examine the effect of perturbing the zero-crossing voltage about its visually optimal setting.
1. Allowing the data to collect for some time

2. Fitting the TAC peaks

3. Adjusting the zero-crossing slightly

4. Reset the TAC spectra

By this method it was observed that one can, by adjusting the walk on the CFD while viewing the summation signal on the oscilloscope, indeed produce an optimal TAC peak. It is worth noting that improperly adjusted settings resulted in TAC peaks that no longer appeared so perfectly Gaussian.

By taking data with various different external delay-lengths, it was possible to determine an optimal value and thus optimize the timing resolution of the setup.

It should be noted that the timing resolution for such a measurement can be improved by applying an energy gate. By looking at only those time events which are associated with an event of specific energy, in principle one can select for the desired transition and measure the lifetime of excited states. Furthermore, by removing all events outside of this energy window one can decrease the possibility of Compton scattered events interfering with precise time measurements. Typically when two detectors are used in coincidence, one can apply a gating condition to energy events from both detectors.

3.2.2 Active Suppression

To test the utility of active Compton suppression, it was necessary to mount the detectors in the $8\pi$ array in place of a couple of HPGe detectors. The $LaBr_3(Ce)$ detectors were specially designed such that they fit perfectly into the HPGe’s BGO
Figure 3.6: Typical gating limit selection from $^{60}$Ni excited state energy spectra from $\beta$-decay of $^{60}$Co

shielding. A $^{60}$Co source $^2$ was chosen because of the large number of Compton events present at in the range of energies $<900 \text{ keV}$. In order to know which events to veto it is necessary to record the events from the BGO shields. A simplified schematic is displayed in Figure 3.9. The BGO shields are biased and signals therefrom are fed through the TFA in the DANTE stream. It is then a simple matter to gate and remove those events in which the BGO detectors were triggered. This is more powerful than a hardware gate in that it allows us to examine the difference between the suppressed (BGO events removed) and unsuppressed (no BGO gate) events.

$^2$solid metal Co-60. Activity at time of experiment: $4.0310^5 \text{Bq}$
Table 3.1: The settings used in the timing optimization of the $LaBr_3(Ce)$ detectors. CFD thresholds were set at their minimum values, which varies between CFD modules. The maximum recommended HV for the PM tubes on the lanthanums is 1500V, however by the time this experiment was begun one had already been run for a some time at 2000V; likely done in an attempt to make it function as well as the others.

<table>
<thead>
<tr>
<th>Detector</th>
<th>CFD Acceptance Threshold (mV)</th>
<th>Voltage (V)</th>
<th>DANTE Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>LaBr 208</td>
<td>192</td>
<td>1500</td>
<td>2</td>
</tr>
<tr>
<td>LaBr 205</td>
<td>186</td>
<td>1500</td>
<td>6</td>
</tr>
<tr>
<td>LaBr 206</td>
<td>197</td>
<td>1500</td>
<td>7</td>
</tr>
<tr>
<td>LaBr Q-092</td>
<td>197</td>
<td>2000</td>
<td>8</td>
</tr>
<tr>
<td>LaBr 209</td>
<td>194</td>
<td>1500</td>
<td>3</td>
</tr>
<tr>
<td>LaBr 207</td>
<td>189</td>
<td>1500</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 3.7: Illustration of BGO shields on HPGe detectors from [9]

Figure 3.8: Illustration of BGO shields on LaBr3 detectors from [9]
Figure 3.9: Simplified schematic of BGO shields on LaBr3 detectors hooked up to CFD, TAC and CPU
3.3 Table-top Setup (Passive Suppression)

The table-top experiments were designed to test the potential of using passive shielding to improve accuracy of timing measurements. If it were possible that passive shielding had a similar effect on timing resolution to that of active shielding then it would not be necessary to waste the time, money, and the array’s solid-angle coverage needed for active suppression. In order to best examine and understand this effect it is most beneficial to use a variety of setups. Those used in this work are illustrated in figure 3.10. Again, the $^{60}\text{Ni}$ $^{\gamma}$-ray emissions are utilized. By fitting the prompt response of the setup, one is given a quantitative method of determining with certainty how this suppression effects timing measurements.

Setup S5 differs from the other setups in several ways: The passive shielding between the detectors in Setup 5 consists of a 1.22 cm lead block and a 0.614 cm copper block used side-by-side, whereas the rest of the setups employed only a 2.94 cm thick lead block; It was run both with and without said shielding; Signals from Setup 5 were fed into DANTE streams 6 and 7, where the other setups used streams 0 and 1; And it is unique in that it was run longer to achieve better statistics. This setup is the primary setup used to investigate the effect of passive shielding. Other setups were mainly employed to attempt replication of a strange signal observed in Setup 5 (see figure 4.8).

In order to increase the probability of scatter, the scintillators were placed in close proximity. This maximizes the solid-angle in which scattered photons will scatter from one scintillator to the other. If there were a significant scattering effect in the array then this setup should exaggerate it. It is also possible that there are a large number of $\gamma$-rays rebounding throughout the array prior to scattering between detectors. To

$^{3}$Cobalt source: solid kapton, aluminized Co-60. Activity at time of experiment $2.0510^4$Bq
increase the number of $\gamma$-rays scattering about in the vicinity of these detectors, large lead blocks were added to some of the setups (S5, S7, and S8) and placed in reasonable proximity to the source.

It is hoped that with these experiments the potential of passive suppression, to improve timing resolution, can be tested.
Figure 3.10: The LaBr₃(Ce) – LaBr₃(Ce) coincidence setups used in testing passive suppression with a Cobalt-60 source
3.4 DANTE Signal-Processing

The simplified schematics displayed in Section 3.2 are useful to show the general method of processing coincidence timing between two detectors; however it is important that any two detectors are capable of acting as a start or a stop for any other detector. This is trivial with two detectors but becomes more complicated with each additional detector. An elegant solution to this, which does not require the use of an unreasonable number of modules, is to use both Fan-In Fan-Out (FIFO) and Logic modules. This was originally set up to be used with the 10 BaF$_2$ detectors and so is capable of making a coincidence measurement with any 1:1 pairing of 10 detectors.

It is also necessary that the energies from these detectors are recorded. This is done using the Dynode signal from the LaBr$_3$(Ce) PM tube. This has already been pre-amplified using an ORTEC 113 Pre-Amplifier but is again amplified using an ORTEC 855 Amplifier. These signals are fed into an ORTEC ADC module.

3.4.1 MIDAS

The MIDAS (Maximum Integrated Data Acquisition System) is a web-based experiment control and monitoring program. It logs all experimental data processed by the many modules in the 8π shack and run through the front-end computer $^4$. It allows automation of the tape-moving system in the 8π, can vary both the acquisition triggering condition and data collection cycles and much more etc.. To do all of this, MIDAS makes use of a slew of sub-programs, each with its own use. One such program, used in these experiments to view online data, is the Analyzer. The Analyzer can compute crude fits of data to a variety of functions, can be used to

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$^4$ The vmic front end is a linux running computer on a VME card that interfaces to the 8π electronics through FERA memories, scalers, and a CAMAC branch highway driver.
Figure 3.11: More detailed schematic showing the DANTE signal-flow for 4 detectors in the $8\pi$ array [9]

re-examine logged experiments, and can even be set up to apply gating conditions to online spectra.
Figure 3.12: Logic processing schematic which allows coincidence pairing between any two detectors. “A” denotes output for detectors 1-4, 9 and 10. FIFO inputs are labeled by dark circles, with outputs labeled as “out”. Logic inputs are labelled with both filled and empty circles; empty denoting that there is a self-timing block applied in the logic to prevent any detector from acting as its own stop signal. Stops from the logic modules are labeled by the TAC module to which they are bound. [9]
Figure 3.13: The $LaBr_3(Ce) - LaBr_3(Ce)$ coincidence setups used in testing passive suppression
3.5 TAC Characterization

Since the precise timing of events is crucial to the characterization of these detectors, it is essential that the behaviour of the TAC be well understood. The time range on these TAC modules can be changed to either 50, 100, or 200 nanoseconds. There is also a rotary switch allowing the use of a time-range multiplier by a factor of 1, 10, 100, 1k, and 10k. In this work the 100ns time range was used with a multiplication factor of 1. Thus with the time-range histogrammed on the 8192 channels recorded, there should be approximately $\frac{100000}{8192} = 12.207$ picoseconds/bin. Unfortunately this is not necessarily a perfect assumption and so must be calibrated for precision measurements. This was done for 4 of the TAC modules by David Cross in his masters work [9] by sending prompt signals to the start and stop of the TAC modules and varying the delay between said signals. By fitting these peaks and determining their centroid locations one can fit the relationship between centroid location and delay length with linear regression. By this method he determined that the bin per channel of TAC modules one through four are: 12.5963, 12.4876, 12.4238, and 12.5968 ps/chan, respectively, each with an uncertainty of 0.016ps/ch. Since they did not deviate far from an average of 12.526 ps/ch the behaviour of other TAC modules used in this work were assumed to be this. To fully account for the possible variation in other modules used, the uncertainty was taken as $\frac{1}{2}[(12.5968 + 0.016) - (12.4238 - 0.016)] = 0.10$ ps/chan. This will result in larger uncertainties for TAC modules other than those in DANTE streams 0-3; it will account for variation about this average calibration value.
3.6 Further DANTE Tests

Further testing of the DANTE system, beyond those investigations in sections 3.2 and 3.3, was performed with a $^{152}$Eu source. By using this system to measure the half-life of the 121 keV excited state of $^{152}$Sm, populated during the $\beta$-decay of the aforementioned $^{152}$Eu source, the abilities of the DANTE can be put to rigorous test. The half-life of this excited state is accurately measured at 2060 (25) ps [18] and is extracted from a timing spectra which has the form of a skew-Gaussian, as discussed in section 2.1. This source was mounted at the focus of the 8$\pi$ array and a long-term data acquisition was run. Since there are many excited states of samarium populated in this decay, it takes a significant amount of time (on the order of a week) to collect sufficient statistics for a precise measurement. It should then be possible to extract a half-life from the timing spectra by fitting it to a skew-Gaussian as described in Chapter 2.

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5Activity of Europium-152 source at time of experiment: 31863 Bq
Chapter 4

Results and Analysis

The following is a presentation of the findings from the experiments outlined in Chapter 3.

4.1 In-Array Unsuppressed Experiments

4.1.1 Timing Optimization

The fitting algorithm outlined in Chapter 2 fitted these spectra well. While being quite similar to a Gaussian distribution, however, they were not completely so. Note that the higher the number of counts in the fitted spectra the higher the $\chi^2$ of the fit.

Figure 4.2 displays the results of the optimization of one of the detectors, LaBr206, with various external CFD delay lengths. These minimum values were fairly consistent from detector to detector, with the exception of LaBr-Q-092. This detector not only required a higher voltage of 2000V \(^1\) to operate in the desired energy range (see Table 4.1), but also had a far poorer time resolution than all other detectors (see appendix A for the best fit from this detector. The best spectra from the optimization of

\(^1\) All other detectors were run at 1500V
LaBr 206 is displayed with its fit in Figure 4.1. The optimized detector resolutions, with respective uncertainties, are presented in Table 4.1. There is evidently some variation of optimized time resolution detector-to-detector.

With FWHM values of $\approx 240$ ps, and assuming that the timing resolution of the fast plastic scintillator is negligible, it is expected that the prompt time resolution of any lanthanum-lanthanum pair should be in the range of 340 ps. This is because the convolution of a gaussian with another gaussian is itself a gaussian with a sigma value equal to the sum of the others in quadrature. Since the plastic scintillator used will still have a measure of uncertainty, it is probable that a lanthanum-lanthanum pairing will have a combined uncertainty smaller than this. ²

Figure 4.1: A fit of the optimized, gated prompt timing spectra of lanthanum detector number 206

Having optimized the processing of timing signals from the lanthanum detectors

²Note that it is possible to measure the uncertainty of a single detector by measuring the timing resolution of a pair of lanthanum detectors in coincidence as well as individually with the fast timing plastic scintillator. The resultant prompt timing resolutions of each pairing should produce a system of 3 equations for the sigma of each Gaussian time distribution in terms of three unknowns, the sigma of each detector’s individual timing resolution.
it was found that external delays of 3, 2.6, 2.6, 2.8, and 3 nanoseconds were optimal for detectors 205-209, respectively, and produced prompt time responses which closely resembled the Gaussian it was assumed to be. In setup for the possible use of the mirror-symmetric difference method [19] a delay of 2.8 was used for further measurements. This being a median value it was chosen to help ensure all coincidence time peaks would have a symmetric and overlapping partner in the other coincidence channel. It turned out that this method was impractical due to time-asymmetries and shifts in time spectra. Returning to the very slightly improved delay lengths is a simple matter now that it is known one can adjust the zero-crossing visually.

\[\text{Figure 4.2: A plot of the prompt FWHM response using several different CFD external delay cable selections to find an optimal setting}\]

\[\text{It is also useful to note that variations in resolution around the minimum value, for differing delay lengths, were small and within uncertainty margins}\]
### Table 4.1: The results of the timing optimization of the lanthanum detectors. Uncertainty is calculated as the sum in quadrature of the uncertainty in the fit and the uncertainty in TAC time/channel characterization

<table>
<thead>
<tr>
<th>Detector</th>
<th>Detector Position</th>
<th>Optimized FWHM (ps)</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>LaBr 208</td>
<td>2</td>
<td>247.1</td>
<td>4.5</td>
</tr>
<tr>
<td>LaBr 205</td>
<td>6</td>
<td>249.9</td>
<td>5.5</td>
</tr>
<tr>
<td>LaBr 206</td>
<td>7</td>
<td>266.2</td>
<td>4.9</td>
</tr>
<tr>
<td>LaBr Q-092</td>
<td>8</td>
<td>316.6</td>
<td>4.5</td>
</tr>
<tr>
<td>LaBr 209</td>
<td>3</td>
<td>235.6</td>
<td>3.2</td>
</tr>
<tr>
<td>LaBr 207</td>
<td>1</td>
<td>243.6</td>
<td>2.7</td>
</tr>
</tbody>
</table>

4.1.2 Active Suppression

Results from active suppression indicate the excellent potential of using these detectors in tandem with the BGO shields. Removing the events which coincided with BGO triggering significantly cleaned up the energy spectra as seen in Figure 4.3. This suppression removed almost none of the events in the desired energy range containing the peaks of interest (see Figure 4.4) where there was little Compton scatter.

![Figure 4.3: An overlay comparing the BGO suppressed and the unsuppressed energy spectra](image)

Figure 4.3: An overlay comparing the BGO suppressed and the unsuppressed energy spectra

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Figures 4.4 and Figure 4.6 show the effect of this suppression on timing resolution. It makes intuitive sense that when suppression is applied in a region that does not lie on a Compton background, there would be little-to-no effect on timing resolution. This is exactly what is observed. In this region an energy gate is sufficient to remove all unwanted Compton contributions to the timing spectra.

The factor by which the energy spectra is improved can be expressed as the percentage of events removed by the suppression. Table 4.2 outlines the factor of suppression ($factor = 1 - \frac{\text{eventsRemoved}}{100}$). Summing over the whole range of energies below the characteristic $^{60}\text{Co}$ $\gamma$-rays, it is found that an average of $\approx 61\%$ of the Compton events were removed.

An important note, which will be discussed further in section 4.3, is the presence of a strange peak $\approx 4.2\text{ns}$ to the left and right of the main time peaks from these experiments. It is present in both spectra, though flipped between streams. This spectrum is plotted in Figure 4.8.
Figure 4.5: A comparison of the timing spectra from the BGO suppressed spectra and the unsuppressed spectra. These time spectra were not energy gated.

<table>
<thead>
<tr>
<th>Energy (KeV)</th>
<th>Channel Range</th>
<th>Suppression Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>700</td>
<td>996-1000</td>
<td>0.538</td>
</tr>
<tr>
<td>750</td>
<td>1360-1364</td>
<td>0.400</td>
</tr>
<tr>
<td>800</td>
<td>1723-1727</td>
<td>0.355</td>
</tr>
<tr>
<td>850</td>
<td>2087-2091</td>
<td>0.330</td>
</tr>
<tr>
<td>900</td>
<td>2451-2455</td>
<td>0.338</td>
</tr>
</tbody>
</table>

Table 4.2: The effect of suppression where Suppression Factor is the number of counts in the suppressed spectra range specified ($N_s$) divided by the counts in the same range of the unsuppressed spectra ($N_u$). $S.F. = \frac{N_s}{N_u}$. Energy is approximate.
Figure 4.6: A comparison between the energy-gated and BGO suppressed timing spectra with the energy-gated, unsuppressed timing-spectra
4.2 Table-Top Scattering Experiments

4.2.1 Setup S5

In the investigation into the potential of using passive suppression to improve timing resolution, it was found that passive suppression has the opposite effect. The timing resolution of a lanthanum-lanthanum coincidence for a prompt decay is on average 25 picoseconds worse when passive suppression was used. Table 4.3 shows the difference between the timing resolutions where there was/was-not passive shielding in place and are the results from setup S5, illustrated in Figure 3.10.

<table>
<thead>
<tr>
<th>DANTE Stream</th>
<th>D6 Peak Gated</th>
<th>D7 Peak Gated</th>
<th>Unshielded FWHM</th>
<th>Passively Shielded FWHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>1173 KeV</td>
<td>1332 KeV</td>
<td>308.9 ±4.7 ps</td>
<td>330.2 ±4.9 ps</td>
</tr>
<tr>
<td>6</td>
<td>1332 KeV</td>
<td>1173 KeV</td>
<td>309.3 ±4.7 ps</td>
<td>340.8 ±4.9 ps</td>
</tr>
<tr>
<td>7</td>
<td>1173 KeV</td>
<td>1332 KeV</td>
<td>285.6 ±4.6 ps</td>
<td>308.5 ±4.7 ps</td>
</tr>
<tr>
<td>7</td>
<td>1332 KeV</td>
<td>1173 KeV</td>
<td>283.7 ±4.6 ps</td>
<td>314.3 ±4.8 ps</td>
</tr>
</tbody>
</table>

Table 4.3: This table shows the difference between the fitted prompt time-peak FWHM of the passively shielded and unshielded detectors. It is the result of the analysis of the data collected from Setup 5. Note that for each detector there are two measurements of the FWHM. This is the result of gating the two detectors on each of the two gammas from the decay of Cobalt-60. “D6 Peak Gated” indicates the peak gated on for DANTE stream 6.

The presence of a strange peak present only in the timing spectra of the passively shielded detectors is noteworthy. It lies approximately 4 ns away from the main timing peak and is present in timing spectra from both streams \(^4\). The peak indicates that some of the signals from detector stream 6 occasionally arrived approximately 4 ns late. This is most likely not the result of cross-detector scattering as the time of flight between the detectors should be on the order of 200 ps at the vacuum speed of light. Attempts to replicate this peak in streams 0 and 1 with setups S6-S10 failed.

\(^4\)DANTE streams 6 and 7
Figure 4.7: A fit of both a passively shielded and unshielded timing spectra from setup 5. These have had an energy gate applied.

4.2.2 Setups S6-S10

Setups S6-S10 were primarily employed to replicate this bizarre peak and so were not run to the same level of statistics as S5, which was used for the measurements above. There was, however, another strange effect observed in these experiments. It was found that while one stream measured the same time between pulses consistently (see Figure 4.9), the other stream showed signs of an apparent time-shift (see Figure 4.10). Particularly in S9 there is a bizarre shift present which appears to be an overlap of two Gaussians approximately 0.8 ns apart.

It is expected that one would find symmetry between the timing spectra in DANTE streams 0 and 1, however there is no sign of such a shift in stream 0. Despite with the exception of S10 where we might expect a change in detector time response with the change in applied HV bias of the detector in DANTE stream 2
Figure 4.8: Energy-gated timing spectra from DANTE stream 7 displaying the presence of a strange peak present in all the setup-5 TAC spectra for which the passive suppression was used. Also plotted is an unshielded spectra. This is found that there are the same number of counts in complimentarily energy gated time spectra between streams 0 and 1 (see Table 1 of Appendix B). This effect is not yet understood but does support the hypothesis that there is a shift in the time spectra as opposed to extraneous signals being processed.
Figure 4.9: Overlay of energy-gated Cobalt-60 time-spectra from Setups S6-S10 (DANTE stream 0). Note that HV PM-tube bias was changed for S10 resulting in a shifted time peak.
Figure 4.10: Overlay of energy-gated Cobalt-60 time-spectra from Setups S6-S10 (DANTE stream 1). An inexplicable shift in time is observed between measurements.
4.3 Attempted Europium Measurements

4.3.1 The Measurements

To rigorously test the response of the DANTE system and of these detectors it is a good idea to investigate more than just the prompt response to cobalt. By using this setup to make a measurement of the half-life of the 121 keV excited state in $^{152}$Sm, this system could be tested. Unfortunately it appears as though this system is not functioning as hoped, nor is it even working with consistency between different streams. The energy spectra from these detectors appeared excellent, however the timing response of the lanthanum detectors in DANTE were not understood.

![Europium Spectra Collected with a Lanthanum Scintillation Detector](image)

Figure 4.11: The energy spectra from the Beta-decay of Europium-152

By gating on the 121 keV peak of interest $^6$ for a coincidence measurement it is

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$^6$Typical gating limits for Europium measurement are illustrated in figure 2 of Appendix A
possible to view the states which feed it on the other detector’s energy spectra. A measurement of the $\beta$-decay of $^{152}\text{Eu}$ was made for over a week in hopes that an extremely accurate measurement could be made. Unfortunately this was not possible and many strange aspects are evident in these time spectra. A fit of the best time spectra (see Appendix B figure 3) yielded a half-life of $1582 \pm 18$ picoseconds. Not only is this quite far from the accepted value of $1430 \pm 15$ ps but, though it was the spectra which most resembled a skew-Gaussian, it was quite obviously not perfectly of this form.

4.3.2 The Time Puzzle

Many figures relevant to this puzzle appear in Appendix B.

There is an asymmetry in timing spectra from a single detector pair (see Figure 4.13). This indicates that there is a difference in the way these signals are processed in the DANTE streams. None of the spectra, however, appeared to have the form of a
skew-Gaussian. Though some were close, none were correct and some were completely different. See Appendix B, Figures 3 and 4 for examples.

When the most promising spectra from this experiment (those which appear most like a skew-gaussian) a half-life of $1582 \pm 18$ ps is extracted from the fit. Since the spectra is not of the expected form, however, this cannot be said to be a successful measurement. Those which appeared least like a skew-gaussian were so poor there was no point in fitting them to this form. There also appears to be some time-consistent lump present. One interpretation of this is that the location of the prompt response of the system is shifting. This is not necessarily the case, however, as is evident when examining an overlay of individual runs (Appendix B, Figure 4) many of which have the same approximate form. Some streams behave entirely different and show quite large shifts as well as a change in the general functional form.

There is a strange peak present in a prompt time spectra as discussed in Section 4.2.2 which could not be replicated in another stream pair. In the other setups S6-S10, implemented with DANTE streams 6 and 7, a timing shift was observed in one stream but not in the other.

In time-constrained attempts to track down the problem in these measurements a few more small tests were performed. In a short experiment, data were collected with an alteration made briefly to the logic processing such that a detector could act as its own stop-signal. The self-timing peak (see Figure 5 in Appendix B) looked exactly as one might hope for; a small narrow peak with a FWHM on the order of 23ps.

A similar experiment was done wherein the signals from one detector were split with a coaxial “T” and fed into two CFD modules. This splitting was done in two cases: splitting into cables of identical length, 1.2m; and into cables of differing

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7See figure 3 in Appendix B for an example of such a fitted time-spectra
lengths, 0.30m and 0.77m. This was done in the hopes that an impedance mismatch might replicate something similar to the strange timing peaks. Example time spectra are plotted in Figures 6 and 7 of Appendix B. In the first case an ideal gaussian time spectra was produced with a FWHM of 30ps. In the second case somewhat more broad peaks were produced; the widest of which had a FWHM of 100ps. This effect might help explain in-part the fairly large difference in the some of the optimized timing resolution measurements of the LaBr$_3$ detectors which was done in different DANTE streams. That in stream 6 had a slightly worse resolution than those in streams 0 and 1. In neither case was anything like the bizarre peaks produced.

![Figure 4.13: Overlay of the $^{152}$Sm TAC spectra from: [red] Detector stream 6 gated on the 121 keV peak; [blue] Detector stream 7 gated on the 244.7 keV peak](image)

Figure 4.13: Overlay of the $^{152}$Sm TAC spectra from: [red] Detector stream 6 gated on the 121 keV peak; [blue] Detector stream 7 gated on the 244.7 keV peak
4.4  $LaBr_3(Ce)$ and Comparison with $BaF_2$

The $LaBr_3(Ce)$ detectors can be used in place of the $BaF_2$ detectors as part of DANTE. It is useful to note the difference between these detectors such that one can make the most informed choice between detectors for any experiment. The main differences between these detectors lie in their energy resolution, timing resolution, and efficiency. Note also that the lanthanum detectors were designed to be used with the BGO shields of the HPGe detectors, allowing another experimental option.

The energy resolution of these detectors is approximately 2.9% at 1332 keV, measured as the FWHM of the peak divided by the peak channel. This was measured using an HV bias of 1665 V. Quoted value from manufacturer: 2.6% at 650 keV. The energy resolution of the $BaF_2$ detectors it replaces is at best 9.1% at 662 keV. This gives the lanthanum detectors an advantage where the energy spectra being acquired has many peaks in close proximity. In addition to this it means that applying an energy gate condition on the lanthanums will remove more unwanted Compton background events than a similar condition applied to a $BaF_2$ energy spectra.

<table>
<thead>
<tr>
<th>Detector Stream</th>
<th>Peak Channel</th>
<th>Detector HV Bias (V)</th>
<th>Energy Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5647</td>
<td>1650</td>
<td>3.03%</td>
</tr>
<tr>
<td>1</td>
<td>5579</td>
<td>1665</td>
<td>2.90%</td>
</tr>
<tr>
<td>6</td>
<td>5277</td>
<td>1695</td>
<td>2.77%</td>
</tr>
</tbody>
</table>

Table 4.4: Energy resolution of lanthanum detectors at 1332 KeV. Measured using the 1332 KeV gamma emission from Cobalt-60 decay

The average timing resolution of the barium fluoride (for a $BaF_2 - BaF_2$ coincidence) detectors is 270 ±8 picoseconds [9] where the timing resolution of the lanthanum bromide detectors is approximately 300 picoseconds \(^8\). These values are

\(^8\)This is the average of 4 values for a single pair of detectors in streams 6 and 7 with two different gating conditions applied between each (see table 4.3). Note that other streams show
fairly close and so, if all else were equal, the barium fluoride detectors would have a slight advantage.

Efficiency is the final major criterion by which these detectors should be evaluated. With a slightly higher density and a larger crystal size it is thus slightly advantageous to use a lanthanum detector where experiment run-time is a major constraint.

Figure 4.14: An overlay of the $^{60}\text{Co}$-decay energy-spectra from both a lanthanum-bromide and a barium-fluoride detector

Figure 4.15: A fit of the energy linearity in lanthanum detectors using peaks from both $^{152}\text{Eu}$ and $^{60}\text{Co}$ sources. Plotted in red is the 1-$\sigma$ bounds on the uncertainty in the measurement of the slope.

better resolution (see table 4.1) than this but were not used in experiments with a prompt coincidence measurement.
Chapter 5

Conclusion

5.1 Potential of LaBr$_3$ Detectors

The LaBr$_3$(Ce) detectors have excellent potential for further use in systems including, but not limited to, the 8$\pi$ detector array. In addition, use of Compton-suppressive BGO shielding has a strong potential to improve on this already excellent performance. The replacement of the BaF$_2$ detectors in the 8$\pi$ array can further the reach in many situations: where beam-time is a constraint, where there is a strong Compton presence at the energy range of interest, and where the level density is too great for effective use of BaF$_2$ detectors.

5.1.1 Active Suppression

Tests of active suppression performed with a $^{60}$Co source demonstrate the shields are remarkably successful at removing Compton events. Applying this suppression to a measurement of the energy spectra from $^{60}$Ni an average of 61% of the unwanted events were successfully removed in the Compton region. This indicates that this
method can be utilized for multiple purposes. One possibility is that of improving measurements of energy spectra. Including suppression capability into such measurements allows peaks to better stand out from the background. In another application it is possible to improve timing measurements. Particularly where one wishes to measure the half-life of short-lived excited-states which lie on a Compton background. Compton scattered events can be detrimental to timing measurements in at least two ways: having a longer average time before detection corresponding to the time of flight between detectors; and coming from states with different lifetimes than the one being measured. Those $\gamma$ rays originating from higher-energy excited states, losing the right amount of energy in scattering, can lie in the energy range of the peak of interest. Energy-gating will fail to remove all such events.

5.1.2 Timing Resolution

The timing resolution of these detectors demonstrates their exceptional ability. An average prompt time-response of 248.5ps (FWHM) was measured in lanthanum detectors, with fast-plastic coincidence measurement, gated on the 1332 keV excited state in $^{60}$Ni. This permits measurement of the half-lives of excited nuclear states that exist for only a few 10’s of picoseconds to be measured directly. Of note is the disparity between detector timing resolutions in the passive suppression tests. A difference between the timing resolution indicates strongly that the signals are being processed with significant difference in separate DANTE streams.

5.1.3 In TIGRESS with fast RF pulses

These detectors also have some potential for use in the TIGRESS array. One such possibility is their potential utility in the search for an Electric Dipole Moment
(EDM). The high density and efficiency of these detectors allows the high count-rate which would be crucial for such measurements. The energy resolution of these detectors, while superior to the $BaF_2$ detectors, is far inferior to the HPGe detectors. GEANT4 simulations were performed by E.Rand in his masters work at the University of Guelph [20] confirming this potential for use in RnEDM experiments. These simulations indicated the main obstacle to this implementation is the aforementioned energy resolution. This work indicates, however, that the energy efficiency of these detectors is as good as twice that (Table 4.4) considered in said work. An efficiency of at most 3.03% at 1.332 MeV is measured in slight contrast to the assumed 6.9% at 1 MeV.

5.2 The DANTE

The most likely candidate for the trouble encountered in making measurements was due to the complexity of the DANTE time signal-processing. A broken symmetry between detector-detector timing signals was observed both in measurements on $^{60}Co$ and $^{152}Eu$ sources. Furthermore, there was a large-scale time-shift observed in both measurements. Combined with the disparity between timing resolutions in a lanthanum-lanthanum prompt coincidence (as in passive suppression) it is highly evident that the current method of time-signal processsing is operating at a sub-par level. The oddity of the timing response is not fully understood and merits further investigation.
5.3 Future Work

Before performing any modifications to the current setup it is important to show with certainty that the DANTE time-logic is to blame. Future work might find useful insight in tracking down exactly where the problem lies. With a better understanding of where the problem lies it might be possible to find an elegant solution to the problem. It would also benefit any future attempts to use this equipment to such high precision.

A less elegant solution to this builds from work done by D.Cross in his masters work at TRIUMF [9]. It was shown therein that a series of FIFO modules could be successfully used to make a system of 4 $BaF_2$ detectors act in coincidence with all possible start-stop pairings. With a greater number of these modules it should be possible to perform logic operations without having a large number of modules in series. I have taken the liberty of designing one which should be capable of a 10-detector coincidence setup using 6 FIFO modules and 10 TAC modules found in Appendix C Figures 8 and 9. This possible upgrade requires only one extra module than does the current logic setup.

The Centroid Difference Method is a powerful tool in making highly precise timing measurements. It is possible that with the new timing setup all signals will be processed with a similar time response to permit use of this method. Future work may involve the testing of this system’s symmetric time response to permit use of this method. This would allow for three techniques by which half-lives could be extracted from skew-Gaussian data: The Centroid Difference Method, direct fitting to a skew-Gaussian directly (using program created for this work), and fitting of the exponentially linear tail.
Appendix A

Figure 1: A fit of the optimized time spectra from the LaBr-Q092 detector. Measurement was made in coincidence with the ZDS and an energy gate applied to the 1332 keV gamma peak from a $^{60}\text{Co}$ source.
Figure 2: Typical $^{152}$Sm energy gates for time spectra. Peaks gated on in this work are the 121 keV and the 244 KeV peak which strongly feeds it.
Appendix B

<table>
<thead>
<tr>
<th>Setup</th>
<th>Det 0 TAC Gate:1.17MeV Peak Area (ch)</th>
<th>Det 1 TAC Gate:1.33MeV Peak Area (ch)</th>
<th>Det 0 TAC Gate:1.33MeV Peak Area (ch)</th>
<th>Det 1 TAC Gate:1.17MeV Peak Area (ch)</th>
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<td>S10</td>
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<td>2244</td>
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</tr>
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</table>

Table 1: Counts under time peaks from DANTE channels 0 and 1 gated on cobalt-60 prompt gammas

Figure 3: Fit for one of the best timing spectra. Spectra is from DANTE stream 0 - stream 6 coincidence. Stream 0 and stream 6 energy gates were applied to the 121 and 244 keV excited states in $^{152}$Sm, respectively.
Figure 4: Stream 6 energy-gated timing spectra for a Stream0-Stream6 coincidence. Stream 0 gated on the 121 keV excited state in $^{152}$Sm. In red is the sum of all runs 1-14.
Figure 5: A short run with a $^{60}\text{Co}$ source in which the logic was temporarily switched to permit self-triggering in Stream 0.

Figure 6: Experiment with a $^{60}\text{Co}$ source in which the raw timing signals from Stream 0 were split with a coaxial “T” and fed into DANTE streams 0 and 1. In this case cables of identical length (1.20m) were used to transmit signals from the “T”.
Figure 7: Experiment with a $^{60}$Co source in which the raw timing signals from Stream 5 were split with a coaxial "T" and fed into DANTE streams 5 and 6. In this case cables of differing length were used to transmit signals from the "T". Streams 5 and 6 were attached to connector with 0.30m and 0.77m cables, respectively and
Appendix C

Figure 8: Representation of 10 TAC modules showing start signals in green region and stop signals in red region. In order to minimize the number of FIFO modules used a split-input must be applied to the TAC stop. This would need to be tested to confirm no impedance echos would interfere with measurements.
Figure 9: A representation of the 24 fan slots available with 6 FIFO modules. Green region indicates stream in (from the CFD) and red region labels the output signals. This logic will permit minimal use of FIFO modules to allow any of the 10 detectors in DANTE to operate in coincidence with any of the other 9 detectors.
Bibliography


[10] T. Aaltonen et al. Measurement of cp-violation asymmetries in d0 to ks pi+ pi-.


