BUILDING AN ARRAY OF BARIUM FLUORIDE RADIATION DETECTORS FOR NUCLEAR LIFETIME MEASUREMENTS

by

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ABSTRACT

DANTE, the Di-Pentagonal Array for Nuclear Timing Experiments, is an array of ten Barium Fluoride detectors placed in the pentagonal gaps of the existing $8\pi$ array of High Purity Germanium detectors, which is currently in use at TRIUMF for beta decay experiments. DANTE complements the high energy resolution of HPGe with the good timing resolution of BaF$_2$ crystals coupled to fast photomultiplier tubes. This thesis will discuss the initial assembly and testing of the detectors used for the array, followed by a DANTE commissioning experiment using a $^{152}$Eu source to measure the half-life of the 121.8 keV state in $^{152}$Sm.

Keywords: nuclear science, radiation detectors, TRIUMF

Subject Terms: lifetime measurements, barium fluoride
DEDICATION

This is dedicated to the pioneers of nuclear and particle physics, among them Henri Becquerel, Marie Curie, Frederick Soddy, Enrico Fermi, Niels Bohr, Richard Feynman and Glenn Seaborg.

Without these peoples’ work I would not be able to enjoy learning more about the most fundamental building block of nature, the nucleus of the atom.
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CHAPTER 1: INTRODUCTION AND THEORY

1.1 Thesis Overview

This thesis covers the assembly, testing and usage of the Di-Pentagonal Array for Nuclear Timing Experiments (DANTE) in the $8\pi$ array at TRIUMF-ISAC. The motivation for developing such an array is to be able to measure the lifetimes of nuclear excited states in the range of 100 nanoseconds to a few picoseconds after populating these states via radioactive decay. The results from laboratory stage testing are reported, along with the results obtained from an experiment at the $8\pi$ array involving the electron capture decay of $^{152}\text{Eu}$ ($t_{1/2} = 13.537$ years) into $^{152}\text{Sm}$. The stable isotope $^{152}\text{Sm}$ has nuclear excited states with lifetimes measurable by DANTE [1]. The radioactive source, manufactured by Isotope Products Laboratories, had a measured activity of 97.3 kBq as of 19 April 2007.

First, this thesis discusses some theoretical underpinnings of nuclear science associated with the above-mentioned experiment, as well as the methods of detecting radiation and various experimental techniques used to measure lifetimes. Following the background material, this thesis discusses the characterization of DANTE detector properties, and the analysis of an experiment using DANTE to measure the lifetime of the first excited state in $^{152}\text{Sm}$. Finally, the measurements are reported along with some remarks on future directions in research using the DANTE array.
1.2 Nuclear Quantum Properties

The origin of ground and excited state nuclear spins and parities is theoretically explained by the shell and collective models [2--4]. The nuclear spin is an angular momentum, composed of the vector coupling of intrinsic proton or neutron spin and the orbital angular momentum in the potential well. It is analogous to atomic spin.

The nuclear spin is denoted either by J or I. This work will use I as the symbol. The nuclear spin is either integer or half-integer, and can be measured experimentally. Nuclei also have definite parity, which is a property of their wavefunctions under reflection within a symmetric potential. The parity is denoted by the symbol \( \pi \). This parity is either positive (+) or negative (–).

1.3 Nuclear Processes: Decays and Transitions

The spontaneity of any nuclear process is governed, on thermodynamic grounds, by the sign of the Q-value. This is the energy released or absorbed during a process, or equivalently, the change in mass:

\[
Q = \left( \sum m_{\text{before}} - \sum m_{\text{after}} \right) c^2
\]

(1).

In radioactive decays, the ‘before’ situation is the parent isotope, and the ‘after’ situation is the daughter isotope. The Q-value is usually stated in units of keV or MeV. As written, a positive Q-value means that the process is exothermic, or exoergic, while a negative Q-value means the process is endothermic (endoergic). Tables of mass defects are used to allow the quick calculation of Q-values. The mass defect is defined as the difference between the measured
mass of a nucleus and its mass number \(A\) (the sum of the protons and neutrons), in units of amu or MeV/c^2:

\[ \Delta = M - A \tag{2} \]

The reference value for mass defects is \(^{12}\text{C}\), which has \(\Delta = 0\), since \(M = 12.00000\) amu exactly, and \(A = 12\) amu. Q-values can be expressed in terms of the difference between mass defects,

\[ Q = \Delta_{\text{before}} - \Delta_{\text{after}} \tag{3} \]

### 1.3.1 Radioactive Decay

Radioactive decay is a purely statistical process. It is not possible to isolate a nucleus and predict when it will decay; it is only possible to take a large number of nuclei (\(N\)) and measure the length of time it takes half of the sample to decay. Since the number of nuclei is discrete, not continuous, Poisson statistics is used to mathematically treat radioactive decays. By starting out with a given number of nuclei, \(N_0\), with a decay constant \(\lambda\) in units of the reciprocal of time, over a period of time \(t\), the number of nuclei at a given time decreases exponentially, and is analogous to first-order reaction kinetics. It is derived by starting with

\[ -\frac{dN}{dt} = N\lambda = A \tag{4a} \]

\[ N(t) = N_0 e^{-\lambda t} \tag{4b} \]
The variables $N$ and $N_0$ in equation 4b can be changed to $A$ and $A_0$, which express activities in decays per unit time; all subsequent analysis is unaffected by the change. The unit of activity is either the Curie (Ci) or the Becquerel (Bq). For historical reasons, the Curie was defined in terms of the activity of one gram of $^{226}\text{Ra}$. The definition of the Becquerel is a decay per second. Thus, one Ci = $3.7 \times 10^{10}$ Bq.

The uncertainty in any decay measurement, given $N$ ($A$) as the number of nuclei (activity), is expressed in terms of the deviations about a central value,

$$\sigma = \Delta N = \sqrt{N} \quad (5a)$$

$$\sigma = \Delta A = \sqrt{A} \quad (5b),$$

when the number of nuclei or the activity is large relative to the decay rate.

If one solves equation 4b to obtain the time at which half the sample of $N$ nuclei has decayed (or the activity has declined to half its value), the half-life formula is derived:

$$t_{1/2} = \frac{\ln 2}{\lambda} \quad (6).$$

The half-life $t_{1/2}$ has units of time, which comes from the reciprocal of the decay rate $\lambda$. A related quantity is the lifetime or mean-life,

$$\tau = \frac{t_{1/2}}{\ln 2} \quad (7).$$
1.3.2 Beta Decays

Beta decays are manifestations of the weak interaction which, on thermodynamic grounds, change the proton-to-neutron ratio towards a maximum binding energy for nuclei of a given mass number $A$. There are three types of beta decay; beta minus ($\beta^-$), beta plus ($\beta^+$) and electron capture (EC). In each of the three decays below, a neutrino or antineutrino is involved to balance the lepton number$^a$:

$$^A_Z X_N \rightarrow ^{A+1}_{Z+1} Y_{N-1} + \beta^- + \bar{\nu}_e$$  \hspace{1cm} (8)

$$^A_Z X_N \rightarrow ^{A-1}_{Z-1} Y_{N+1} + \beta^+ + \nu_e$$  \hspace{1cm} (9)

$$^A_Z X_N + e^- \rightarrow ^{A}_{Z-1} Y_{N+1} + \nu_e$$  \hspace{1cm} (10).

Decay energies, distributed among the decay products$^b$, are expressed, in terms of mass defects (including the threshold of 1.022 MeV/$c^2$ in $\beta^+$ decay):

$$Q_{\beta^-} = \Delta_{parent} - \Delta_{daughter}$$  \hspace{1cm} (11)

$$Q_{\beta^+} = \Delta_{parent} - \left( \Delta_{daughter} + 2m_e c^2 \right)$$  \hspace{1cm} (12)

$$Q_{EC} = \Delta_{parent} - \Delta_{daughter}$$  \hspace{1cm} (13).

In beta decay, the transition can be from the ground state of the parent to the ground state of the daughter. Alternatively, the transition can proceed to

---

$^a$ It should be noted that there are several conservation laws applicable to nuclear science beyond the usual well-known ones of mass-energy, momentum and angular momentum. One of them is the need to conserve the number of leptons (particles that do not feel the strong interaction). Another is the requirement of baryon (particles that do feel the strong interaction) number conservation.

$^b$ Neglecting the recoil of the daughter, the kinetic energy of the beta particle is not discrete but has a continuum ranging from ~0 MeV to the maximum decay energy.
excited states of the daughter. Therefore, the energy available for the decay is decreased by the energy of excitation,

\[ Q_{\text{decay}} = Q_{gs \rightarrow gs} - E_{\text{exc}} \]  \hspace{1cm} (14).

These excited states can then decay by gamma emission, as discussed in further detail in the next section.

1.3.3 Gamma Transitions

Gamma transitions (sometimes referred to as gamma decays) are purely electromagnetic processes. The quantum mechanical description utilizes the dipole, quadrupole, and higher multipole operators governing the transitions, and their operations on the appropriate nuclear wavefunctions involved.

Since the electromagnetic interaction conserves parity, gamma transitions are therefore governed by selection rules that arise from the form of the appropriate operator which is used in the matrix element which, squared, yields the transition strength (see Section 1.5). Since the parent and daughter are the same, the formula to describe energy changes is approximately\(^c\)

\[ \Delta E = E_\gamma = E_2 - E_1 \]  \hspace{1cm} (15),

where \(E_2\) and \(E_1\) represent energies of the higher and lower states in the nucleus. Similarly to beta decay, a higher transition energy and greater wavefunction overlap will result in increased decay rates.

\(^c\) This formula neglects the recoil of the nucleus.
The electric dipole operator can be considered to be a spherical harmonic with one unit of angular momentum. Because the product in the matrix element must be overall even, or symmetric, and since the dipole operator is antisymmetric, then the initial and final states must have opposite parities. The strongest nuclear transitions are electric dipole (E1) in nature, followed by magnetic dipole (M1) transitions. The magnetic dipole operator is symmetric, so for this reason no change of parity is required for this transition.

Another very common transition is the electric quadrupole (E2) transition. The quadrupole operator is proportional to the square of distance, so it is symmetric. As a result there is no change of parity between the initial and final states. E2 transitions tend to be very prevalent in nuclei, owing to the presence of vibrations and rotations, discussed in more detail in Section 1.4.

Given initial and final eigenstates $|i\rangle$ and $|f\rangle$, in which the operators $\hat{\mu}_E$ (electric dipole), $\hat{\mu}_B$ (magnetic dipole) or $Q_E$ (electric quadrupole) operate on the initial eigenstate, the associated transition matrix elements are as follows:

\[ \langle f | \hat{\mu}_E | i \rangle = M(E1) \quad \text{nonzero under change of parity} \]

\[ \langle f | \hat{\mu}_B | i \rangle = M(M1) \quad \text{nonzero under retention of parity} \]

\[ \langle f | \hat{Q}_E | i \rangle = M(E2) \quad \text{nonzero under retention of parity} \]

The higher-order transitions beyond E2 have smaller intensities as the decay rates are much slower. The degree of spin change is related to the
multipolarity of a transition, and this is governed by the vector coupling of the spins of the initial and final states ($I_i$ and $I_f$), subject to the triangle inequality,

$$\left| I_f - I_i \right| \leq L \leq I_f + I_i$$  \hspace{1cm} (16).

Here, $L$ is the angular momentum change of the transition. The dominant electromagnetic transition always has the smallest $L$ possible. As an example, $^{152}\text{Sm}$ [1] has a ground state $I^\pi = 0^+$. It has an excited state at 366.5 keV of $I^\pi = 4^+$, and a lower one at 121.8 keV of $I^\pi = 2^+$. In considering transitions between the 366.5 keV and the 121.8 keV states, the vector-coupling formula in equation 16 yields changes of angular momentum ranging from 2 to 4. Since there is no change of parity, the allowed transitions are E2, M3, and E4. In practice, the transition is likely to be pure E2, with very little M3 or E4 character.

A process which competes with gamma ray emission is called internal conversion, which is an important aspect of the spectroscopy of nuclei. Unlike the atomic/molecular process of radiationless relaxation (essentially transferring electronic excitations into thermal energy), this nuclear process refers to the interaction of the nuclear multipole fields with electrons in the atom. This results in a transfer of the energy of decay to an atomic electron, ejecting it into the continuum. The kinetic energy of an internal conversion electron is decreased by the atomic binding energy of the electron compared to that of the gamma ray emitted in the competing process.

The analogous atomic process is called the Auger process, and in fact, Auger electrons can be emitted in radioactive decay instead of X-rays, when
electrons de-excite to fill gaps in the inner shells after electron capture or internal conversion, causing the ejection of other electrons.

The probability of internal conversion occurring as a result of the nuclear interaction with a given atomic shell is the internal conversion coefficient \( \alpha_K, \alpha_L, \) etc. It is proportional to \( Z^3/n^3 \), where \( Z \) is the atomic number of the nucleus and \( n \) is the principal quantum number of the atomic orbital. Total internal conversion coefficients can also be determined; the total coefficient \( \alpha \) is the sum of the individual shell coefficients. These coefficients can be measured experimentally or calculated theoretically. The experimental calculation of the coefficient is based on the equation

\[
\alpha = \frac{\lambda_e}{\lambda_\gamma} = \frac{N_e}{N_\gamma}
\]

(17),
given the decay rates associated with the internal conversion (\( \lambda_e \)) and gamma-ray (\( \lambda_\gamma \)) emission processes and the measured values of the number of electrons emitted \( N_e \) and the number of gamma rays emitted \( N_\gamma \) [2]. Equation (17) is equally applicable to individual shell coefficients or the total internal conversion coefficient.

The total internal conversion coefficient is one way to determine the multipolarity of a transition, as it is sensitive to the change of angular momentum.
between the initial and final states [2]. Another usage of internal conversion coefficients is to use calculations\textsuperscript{d} to correct gamma ray intensities.

It is of general interest to nuclear spectroscopists to develop detectors sensitive to the emission of internal conversion electrons. An example of such detectors is the array of silicon detectors which can be placed in the $8\pi$, called the Pentagonal Array for Conversion Electron Spectroscopy (PACES), which can be used to observe internal conversion transitions in nuclei.

1.4 Rotations and Vibrations: The Collective Model

While the shell model can be invoked to explain the origin of ground-state spin and parity being $I^\pi = 0^+$ for all even-even nuclei [2,3], on the basis of nucleon preference for spin-pairing over spin multiplicity so that an even number of protons and an even number of neutrons cancel all their spins, it becomes computationally intractable in explaining the origin of excited-state spin-parities for nuclei not near closed shells, and which have been found to be deformed away from spherical shapes. These excitations appear to have a collective nature of either vibrational or rotational origin.

If one attempts a shell-model calculation for a typical $\approx 150$ nucleus, incorporating all the nucleons potentially responsible for excitations, the nuclear shells involved form a model space involving the diagonalization of matrices on the order of $10^{12}$ by $10^{12}$ in size, which is not computationally feasible. Instead, all \textsuperscript{d}Two common calculations that are available to researchers are the Hager-Seltzer (1968) [53] and Band-Raman (1977, 2002) [54]; the latter includes contributions from the M, N and higher atomic shells while the Hager-Seltzer uses only the K and L shells. The difference is commonly at the third decimal place of the total conversion coefficient.
the nucleons are treated macroscopically in order to understand the nucleus as a whole, as first done in the work of Bohr and Mottelson [4] using the adiabatic approximation, which assumes that the frequency (energy) of rotation or vibration is much smaller than that for single-particle excitations, based on the assumption that the change of nuclear radius, $\Delta R$, is small relative to its average radius $R_{\text{avg}}$ (this is analogous to the Born-Oppenheimer approximation of separating nuclear motions from the movement of the electrons in vibrational motion of a molecule).

One difference between molecular physics and nuclear science, in terms of the applicability of analogies between them, is that the energy scales of electronic (particle), rotational and vibrational excitations are very different at the molecular level, so that, for example, infrared spectroscopy usually does not concern itself with the fine structure of peaks from coupling to rotational states. Conversely, pure rotational spectroscopy involves energy differences in the microwave region in which molecules will remain in the vibrational ground state.

However, in the nuclear realm, the energy range covered by these excitations is not as broad, being in the $\sim 100$ keV range for rotations to the $\sim 1$ MeV range for vibrations and single-particle excitations. However, they can still be separated from one another. Thus, nuclear gamma ray emissions can be classified in terms of origin: rotational, vibrational, or single-particle transitions.
Figure 1. Qualitative level schemes (not to scale) showing the ground and some excited states of even-even rotational and vibrational nuclei (note that $\omega_{\text{rot}} < \omega_{\text{vib}}$). Note the theoretically degenerate grouping of the two-phonon excited states in a vibrational nucleus.

Figure 1 shows qualitative level schemes of the ground states and some of the excited states in even-even rotational (left side) and vibrational (right side) nuclei. This discussion will focus on the rotational and vibrational states of even-even nuclei only, as other nuclei (even-odd, odd-even, odd-odd) have more complex level schemes.

The adiabatic approximation requires a separation of the energy scales of single-particle excitations and rotational or vibrational excitations. As shown by experimental data, introduced via the example nuclei in this section, this approximation does not hold well for vibrational nuclei, but does hold well for rotational nuclei.
1.4.1 Vibrations

The excited-state oscillations of nuclear shape about a mean radius are quadrupole vibrational modes. Excitations and de-excitations can be considered as originating from the addition or removal of a phonon, a bosonic quantum with a spin of 2. A vibrational nucleus may be modelled as a harmonic oscillator.

Under consideration of the symmetry requirements for the interaction of the phonons, the spins and parities of the one-phonon and two-phonon states are $I^\pi = 2_1^+$, and a degenerate triplet with $I^\pi = 0_2^+, 2_2^+$ and $4_1^+$ (i.e. the second occurrence of the $I^\pi = 0^+, 2^+$ states and the first occurrence of the $I^\pi = 4^+$ state) respectively. The states are equally spaced as the energy difference between them is proportional to the frequency of vibration and not on angular momentum. The harmonic oscillator selection rule $\Delta n = \pm 1$ (n being the number of phonons) leads to only one peak in a gamma ray spectrum, in theory.

The square of the transition matrix elements (called transition strengths, as discussed in Section 1.5) between the two-phonon states and the one-phonon state should be equal to each other, and twice that of the $I^\pi = 2_1^+ \rightarrow 0_1^+$ transition strength [4].

An example of a vibrational nucleus is $^{112}$Cd, which has a one-phonon excited state at 617.52 keV ($I^\pi = 2_1^+$) and a closely-spaced triplet of two-phonon excited states at 1224.46, 1312.39, and 1415.58 keV, which have spin-parities, $0_2^+, 2_2^+$ and $4_1^+$ [5], respectively. The loss of degeneracy of the triplet is attributed to anharmonicities in the nucleus [4]. Given the energy scales of these
excitations it is clear that the adiabatic approximation should be applied with care to vibrational excitations.

### 1.4.2 Rotations

A rotational nucleus can be treated similarly to a rotating molecule, in which a rotational band has level energies which are proportional to the square of the nuclear spin $I$ [2],

$$E = \frac{\hbar^2}{2J} \left( I(I + 1) - K^2 \right)$$

(18),

where $J$ is the nuclear moment of inertia, and $K$ is the projection of the nuclear spin onto the rotational symmetry axis; for a ground state rotational band, $K = 0$. A nuclear rotational band resembles a molecular rotational band, indicating that adapting the rotor model to a many-body system appropriately characterizes these transitions.

The transition strengths of rotational nuclei increase with increasing excited state angular momentum, as discussed in more detail in Section 1.5. The origin of rotational-band spins and parities is due to requirements on the appropriate symmetry of the wavefunctions involved. If rotational eigenstates are labelled by their spins ($I$) and projections of those spins ($K$) onto the nuclear symmetry axis, the resulting wavefunctions are [4]:

$$|\phi\rangle = |I, K\rangle + (-1)^{I+K} |I, -K\rangle$$

(19).
When \( K = 0 \), the ground state rotational band produces eigenstates whose odd-spin values cancel to zero. Therefore only even spins remain. Rotational states in a ground state band will have positive parity.

An example of a good rotor is \(^{174}\text{Hf}\) [6], which has a first rotational excited state \((I^\pi = 2^+)\) at 91 keV, and the second excited state at 297 keV \((I^\pi = 4^+)\). This shows that the adiabatic approximation is more applicable to rotational excitations, as the energy differences are smaller than those for vibrations.

### 1.4.3 Differentiating Rotational and Vibrational Excitations

Because rotational and vibrational excitations lead to states whose spins and parities are the same, one way to differentiate them is by calculating energy ratios of the \( 4^+ \) state to the \( 2^+ \) state. For a purely vibrational spectrum this ratio ought to be 2 [2], while for a purely rotational spectrum this ratio ought to be 3.33, as deduced from equation 17. Considering \(^{174}\text{Hf}\), the ratio of the 91 keV level and the 297 keV level yields 3.27; it is very close to being purely rotational. By contrast in \(^{112}\text{Cd}\), the ratio of the \( 2_1^+ \) level at 617.52 keV and the \( 4_1^+ \) state at 1415.58 keV is 2.3. For the other states in the two-phonon triplet, the ratios are 2.0 \( (E(0^+_2):E(2_1^+)) \) and 2.1 \( (E(2^+_2):E(2_1^+)) \); \(^{112}\text{Cd}\) thus shows vibrational behavior.

Additionally, nuclei can have properties intermediate between that of pure rotational or pure vibrational character. The energy ratio of the \( 4^+ \) and \( 2^+ \) states in \(^{152}\text{Sm}\) is 2.7 [1]. However, ratios of energies are not the only diagnostic of vibrational or rotational behavior. A better diagnostic is the magnitude of the transition strength, as discussed further in Section 1.5.
1.4.4 **Rotational-Vibrational Coupling**

The coupling of vibrations and rotations creates additional rotational bands, which are separate bands built on vibrational excitations. One of these couplings is to the gamma (\(\gamma\)) vibration, which gives rise to a \(K = 2\) rotational band according to equation 24. Physically, the \(\gamma\) vibrations along the principal rotational axis are analogous to pushing and pulling on the sides of an American football [2].

The presence of rotational-vibrational coupling complicates matters quite quickly for the nuclear spectroscopist seeking to study even-even nuclei and extract level schemes for them. The nucleus \(^{152}\text{Sm}\), used in this work primarily for demonstrating the reliability of the DANTE array in lifetime measurements, is the subject of research into the behavior of rotational nuclei [7].

1.5 **Properties of Nuclear Excited States**

Spectroscopic transitions between two nuclear states are sensitive to the overlap of the nuclear wavefunctions of the states involved. As a result the matrix elements governing the transitions, as briefly discussed in Section 1.4, can be related to other nuclear properties, such as the nuclear shape, which is characterized by the quadrupole moment as discussed later in this section.

Specifically for E2 transitions these relationships exist, from which the transition strength \(B(\text{E}2)\) can be determined [8]:

\[
\lambda(\text{E}2) = \frac{1}{\tau_{\text{E}2}} = \frac{\Gamma(\text{E}2)}{6.582 \times 10^{-16}} = \frac{B(\text{E}2) \downarrow \gamma E_\gamma^5}{8.156 \times 10^{-10}} = \frac{|M(\text{E}2)|^2 E_\gamma^5 A^{4/3}}{1.374 \times 10^{-8}}
\]  

(20)
These formulas convert among partial decay rates ($\lambda$) in s$^{-1}$, partial lifetimes ($\tau$) in seconds, partial widths ($\Gamma$) in eV, downward transition probabilities ($B(E2)$) in e$^2$-fm$^4$, and the squares of matrix elements ($|M(E2)|^2$) in Weisskopf units (W.u), incorporating $E_\gamma$ in MeV and $A$ as the dimensionless mass number. Formulas for other transitions (E1, M1, etc) are listed in Appendix 1.

The lifetimes of nuclear transitions are thus related to transition probabilities, also called transition strengths, which are related to the square of the matrix element; these are analogous to the Einstein A and B coefficients of atomic spectroscopy. The transition strength may either be given in e$^L$-fm$^{2L}$, or Weisskopf units (W.u.), which incorporates the dimensionless mass number of the nucleus under study, and indicates deviations from single-particle excitations.

The transition strength indicates how likely or unlikely it is to occur; a comparison of a transition strength measurement to a Weisskopf estimated value is an indication of the nature of the transition (single particle being $\sim$1 W.u., versus rotational or vibrational being $\geq$10 W.u.). These can be determined either via lifetime measurements or Coulomb excitation.

Statistical factors affect the measurement of the transition probability, so it is possible, depending on the nature of the experiment, to measure the de-excitation (downward) probability or the excitation (upward) probability. The correction factor is

$$B \uparrow = \frac{2I_f + 1}{2I_f + 1} B \downarrow$$

(21)
with the up arrow representing excitation and the down arrow, de-excitation, and where \( I_i \) and \( I_f \) are the initial and final spins, respectively. Upward probabilities are generally determined via Coulomb excitation while downward probabilities are determined from lifetime measurements.

B(E2) values can be used to definitively distinguish rotational and vibrational transitions from one another [4]. Vibrational transitions will have \( B(E2; 4_1^+, 2_1^+, 0_2^+ \rightarrow 2_1^+) \) values which are all twice that of the \( B(E2; 2_1^+ \rightarrow 0^+) \) value. Rotational transitions will not obey this relationship; their transition strengths will increase in proportion to the Clebsch-Gordan coefficients connecting the two states and their projection onto the rotational symmetry axis, as discussed below on quadrupole deformations.

The \( B(E2; 2^+ \rightarrow 0^+) \) value can be related to a structural feature of nuclei which have rotational excited states, which is the degree of their deformation. It is denoted by two parameters: \( \gamma \), the deviation from axial symmetry, and \( \beta \), the deformation proportional to the difference between the nuclear semimajor and semiminor axes. These are related to the nonspherical distribution of charge, called the quadrupole moment \( Q_o \). It can be calculated, given the atomic number \( Z \), and the root mean square nuclear radius \( R_o \) [9]:

\[
Q_o = \frac{3}{\sqrt{5\pi}} Z R_o^2 (\beta \cos \gamma)
\]  

(22).

This is directly related to the transition strength [4]:

\[
B(E2; I_i \rightarrow I_f) = \frac{5}{16\pi} e^2 Q_o^2 \left| \langle I, 2K0 | I, 2I_f K \rangle \right|^2
\]

(23a).
The squared integral between the differing spin representations is the Clebsch-Gordan coefficient, which transforms the initial and final spins into a representation in terms of the initial spin and its projection onto the nuclear symmetry axis, or vice versa. Specifically, the $B(E2)↓$ in a ground state rotational band ($K = 0$) can be derived, using $I_i = 2$, and $I_f = 0$,

$$B(E2; 2^+ \rightarrow 0^+) = \frac{5}{16\pi} e^2 Q_o^2 \left| \langle 2200|2200\rangle \right|^2$$  

(23b).

In this instance the Clebsch-Gordan coefficient is $1/5$, after squaring. Substituting yields

$$B(E2; 2^+ \rightarrow 0^+) = \frac{1}{16\pi} e^2 Q_o^2$$  

(23c).

Equation 22c can be used to determine the quadrupole deformation of a nucleus and the nature of the associated transition. Since the lifetime of a transition is inversely proportional to its $B(E2)$, these measurements are good probes of nuclear structure. The only information that cannot be obtained from the $B(E2)$ in this manner is the sign of the quadrupole moment, which would distinguish a prolate or oblate nuclear shape.

In the context of equation 22, a prolate shape implies a positive value for the quadrupole moment ($\beta > 0$) and conversely, an oblate shape implies a negative quadrupole moment ($\beta < 0$). Scattering experiments, or Coulomb excitation, would provide this information as they are sensitive to the distribution of charge in the nucleus. It is also of interest to researchers to understand how
nuclei deform and under what conditions a prolate vs. oblate shape is energetically favorable [10,11].

1.6 Detecting Ionizing Radiation: General Overview

The experimentalist in nuclear science faces the problem of dealing with high-energy radiation and charged particles which are not visible to the eye. To meet this challenge, various methods of detecting charged particles, beta particles and gamma radiation have been developed.

Silicon semiconductor detectors have been developed to detect charged particles emitted from nuclei during decays or reactions. In addition they are also sensitive to electrons emitted during beta decay or internal conversion. High-Purity Germanium (HPGe) semiconductor detectors have been developed to detect gamma rays with high energy resolution. Additionally, inorganic scintillator crystals have also been developed to detect gamma rays. Organic scintillators, sensitive to beta particles, have also been developed which are optimized for good time resolution characteristics.

1.7 Interactions of Ionizing Radiation with Matter

The exact method by which ionizing radiation interacts with matter is through the formation of ions in the medium with which it interacts. Unlike non-ionizing radiation, these interaction processes are more destructive to the atoms involved, and so ionizing radiation is hazardous to human beings, owing to cellular and DNA damage that can occur. Also, repetitive exposure can degrade detection apparatus over time, although some detectors can be restored to
normal operating condition or use materials which are not very prone to radiation damage.

Positively charged heavy particles (including the alpha particle), beta particles, and gamma rays have different modes of interaction with matter.

1.7.1 Heavy Charged Particles

Alpha particles, as well as heavier ions, have been found to have a very definite range-energy relationship in absorbers. The energy loss $\frac{dE}{dx}$, in the nonrelativistic limit, can be defined, where $Z_1$ denotes the atomic number of the incoming ion with a velocity $v$, and $Z_2$ denotes the atomic number of the absorbing medium, and given a matter density $n$ of the absorber [12]:

$$
\frac{dE}{dx} = \frac{4\pi Z_1^2 e^4 n Z_2}{m_e v^2} \ln\left( \frac{2m_e v^2}{\bar{I}} \right)
$$

(24).

The mean ionization energy $\bar{I}$ of the electrons in the absorber can be parameterized empirically. The form of equation 24 reflects the experimental observation that heavy charged particles tend to not scatter appreciably as they travel through a medium. Thus, for ions of a certain atomic number and kinetic energy, they all travel approximately the same distance in a given absorbing material. As they approach the end of their range, this is where the bulk of the kinetic energy is lost to the absorbing medium.

The two primary modes of interaction of heavy charged particles depend on the energy regime. They may interact primarily with the electrons in the absorber (electronic stopping) at higher energy, or primarily with the nuclei of the
absorber (nuclear stopping) at very low energy [8]. Since the value of dE/dx for nuclear stopping becomes essentially constant at ~0.1 MeV or greater, the primary mode of interaction for highly-energetic charged particles (e.g. alpha particles emitted from the decay of Uranium) is with the electrons of the surrounding medium, and since they are much heavier than the electrons this is the reason for very little scattering.

1.7.2 Beta Particles

By contrast to the well-defined behavior of heavy charged particles, beta particles show a very poorly-defined range-energy relationship, as they scatter at large angles when interacting with the electrons in an absorbing medium. The major processes by which electrons lose energy are by collisions with electrons in the absorbing medium and by Bremsstrahlung radiation, which is not discrete.

1.7.3 Gamma Radiation

Gamma radiation tends to follow an exponential decay relationship analogous to that of Beer’s Law for visible light through a liquid medium,

\[ I = I_0 e^{-\mu x} \tag{25}, \]

which attenuates the intensity in a manner that assumes absorption is a continuous process through a material. The symbol \( \mu \) (a property of the material and gamma ray energy) is the linear absorption coefficient (analogous to the molar extinction coefficient), \( I_0 \) is the intensity before passing through a given absorber, and \( I \) is the intensity after travelling over a distance \( x \) through the absorber.
The three major modes of interaction of gamma rays with matter are [13]:

1. Photoelectric absorption. The gamma ray is completely absorbed in the material and leads to the emission of electrons via the photoelectric effect.

2. Compton scattering. In this process, a gamma ray interacts by inelastic scattering off atomic electrons. The gamma ray energy is reduced after this occurs. This process has a dependence on the cosine of the scattering angle.

3. Pair production. This is the interaction of a gamma ray with a nucleus in such a fashion as to produce a positron-electron pair. There is an energetic threshold because of conservation of mass-energy; the gamma ray must be at least 1.022 MeV in energy as it must give up that energy to the pair-production event; the remainder of the energy is transferred to the positron and electron. This process dominates when the gamma ray is very high in energy (>10 MeV)

For this work, gamma rays were recorded to a maximum of approximately 2 MeV. The predominant modes of interaction of gamma rays in the $^{152}$Sm experiment (discussed in chapter 3) are the photoelectric and Compton effects (Figure 2) for both Germanium (Z = 32) and BaF$_2$ (Z = 50 and Z = 9; $Z_{avg} \approx 45$).
1.8 Radiation Detectors

The detection of radiation at the 8π in TRIUMF-ISAC is via use of semiconductor and scintillation detectors (much of the material in this section is derived from the work of Glenn Knoll and Stephen Derenzo [12,15]). The scintillation detector type, in particular, forms the basis of this thesis.

Gamma ray spectroscopy is characterized by the following three phenomena, which can be understood in terms of interactions of gamma rays with matter (Section 1.7.3) in a detector of finite size⁶:

---

⁶ A detector of infinite size would register only photopeak events since all gamma ray interactions would be detected. In practice, a finite detector size allows the opportunity for gamma rays to leave the detector before interacting, which leads to the existence of the Compton continuum and the pair production single and double escape events.
1. The energy of the gamma ray can be recorded at the Full Energy Peak (FEP), also termed the photopeak.

2. At energies below the photopeak, Compton interactions, governed by the dependence on the scattering angle, result in a continuum if a gamma ray scatters once or several times before leaving the detector and thus not depositing its full energy; these escape events can be used to suppress Compton contributions to gamma ray spectra, as discussed in Section 1.11. There is a termination of the Compton continuum at an energy up to 250 keV below the photopeak called the Compton edge. The scattering-angle ($\theta$) dependence, where $E$ is the incident gamma ray in MeV, and $E'$ the scattered gamma ray in MeV, is given by:

$$
E' = \frac{E}{1 + \frac{E}{0.511(1 - \cos \theta)}}
$$

(26).

3. The annihilation of the positron after a pair production event results in the production of two 511 keV gamma rays which may escape the detector. If one (single escape) or both (double escape) of the 511 keV gamma rays leaves the detector then the energy of the peak will be shifted by the energy of the 511 keV gamma ray which does not interact with the detector.

\[\text{The exact energy difference depends on the incoming gamma ray energy and reaches the limit of 250 keV at high energies. At 662 keV the Compton edge terminates at 181 keV below the photopeak.}\]
A GEANT4 simulated gamma ray spectrum (Fig. 3) depicts these events occurring in a large volume HPGe detector from a radioactive source which emits a single gamma ray at ~2.2 MeV as it decays.

**Figure 3.** GEANT4 simulated gamma ray spectrum. This spectrum shows the photopeak (Full Energy Peak) at 2.2 MeV, the escape peaks associated with pair production events, and the Compton continuum under these escape peaks terminating at the Compton edge. Additionally note the 511 keV peak from positron annihilation. Image courtesy Smarajit Triambak.

Chronologically, inorganic scintillators were developed first and used in various experiments as far back as the 1920s, followed by the semiconductor type coming into use in the 1960s.

The type of ionizing radiation that scintillation detectors can detect depends on whether the scintillator is organic or inorganic. Organic scintillators (e.g. plastic) tend to have poor gamma ray detection efficiencies due to their low average atomic number ($Z_{avg} \approx 12$ for plastic), and so their primary use is in detecting alpha or beta particles. An example of the process of detection would
involves a high-energy beta particle striking an anthracene molecule, exciting one of its π electrons into a π* orbital, followed by fluorescent de-excitation.

As inorganic scintillator crystals have higher average Z values than organic scintillators, they have higher gamma ray detection efficiencies. The same factor gives rise to higher detection efficiencies compared to HPGe.

![Energy level diagrams](image)

**Figure 4.** Qualitative energy levels of inorganic scintillators without an activator (left) and with an activator (right), showing how their excitations and de-excitations manifest as UV/Visible photons.

An example of an inorganic scintillator is Sodium Iodide, doped with Thallium (NaI(Tl)), the mainstay of nuclear science facilities from the 1950s through to about the 1970s, and still used today. Typically, a dopant, or activator, is required in an inorganic scintillation detector to bring its valence and conduction bands closer together, as shown in Figure 4.

The process of de-excitation in an inorganic scintillator yields a light pulse which is directed into a photomultiplier tube (PMT), and the PMT’s resulting electrical output pulse may be viewed on an oscilloscope or further processed with a computer.
In scintillation detectors, several processes contribute to unavoidable reduction of the energy resolution of such detectors compared to semiconductor detectors:

1. Self-absorption in the crystal, due to interactions of the emitted UV-Visible light in scattering processes, or with crystal defects.

2. Scattering events at the surface of the crystal which send light pulses away from the photomultiplier tube.

3. Variability in light collection from different points in the crystal, resulting in statistical fluctuations from event to event of the number of photons emitted per MeV.

4. As the molecular excited states are short-lived in a scintillator, their linewidths will be broadened. This is due to the uncertainty principle.

After a light pulse strikes the PMT, there is further broadening of the output signal, for several reasons:

1. There is inherent spread in transit times of ejected photoelectrons from the photocathode to the first dynode because of the broadening of the incoming light pulse. This leads to photoelectrons being ejected with slightly different outgoing kinetic energies.

2. The quantum efficiency of the PMT in converting a light pulse to photoelectron emission is less than 100%. In practical terms it is approximately 30%, so that if ~10000 photons for a 1 MeV gamma ray are emitted by a scintillator, only 3000 electrons will be ejected from
the surface of the photocathode, assuming no other losses at the quartz face of the PMT.

3. External magnetic fields deflect photoelectron paths; this effect may not be entirely cancelled by μ-metal shielding. Focussing elements using electric fields can be used to mitigate the magnetic-field spreading of photoelectron arrival times at the first dynode.

4. Gain dependence. Since the spread of arrival times at the first dynode cannot be reduced to zero, this effect propagates through the PMT, and is amplified as electron emission from the subsequent dynodes is a statistical process. Therefore, additional stages in a PMT increase the gain at the expense of resolution.

Figure 5 shows an overview of the interactions of ionizing radiation in a typical scintillation detector assembly. Also, the gamma ray interactions described in the figure apply to semiconductor detectors as well.

In contrast to the scintillation type of detector, the semiconductor detector has superior energy resolution; the only major drawback of such detectors is the requirement to use large-volume crystals to compensate for lower gamma-ray detection efficiency, as the overall probability of gamma ray interactions (the absolute efficiency) is proportional to \( Z^2 \) of the material.
The superior energy resolution of a semiconductor (e.g. HPGe) is due to the single-stage process of excitation of electrons from the valence band into the conduction band, as opposed to the inefficiencies introduced by the multiple stages of conversion in a scintillator. Additionally, the inherent statistical fluctuations resulting from the excitation of electrons is smaller since a scintillator can emit $\sim 10^4$ photons per MeV of incident radiation, but a semiconductor can produce $\sim 10^5$ excited electrons per MeV.
However, the excitation of charge carriers into the conduction band does not result in de-excitation and photon emission; instead, these charge carriers are collected out of the depletion region to complete an electric circuit and produce an output pulse. This is inherently slower than the excitation of electrons and the subsequent emission of a light pulse in a scintillator, and this is why HPGe detectors have somewhat worse timing resolution compared to scintillation detectors.

It is necessary to operate HPGe detectors at very low temperatures (typically at 77 Kelvin, which is that of liquid nitrogen) in order to reduce thermal noise. This increases the cost of the equipment and its maintenance, but given the energy resolution characteristics of HPGe, is an acceptable cost for the benefit achieved.

**Figure 6.** Typical pulse shapes of HPGe (left) and BaF$_2$ (right) detectors; note their common shape, but that the horizontal scales are different, showing that the return to baseline is much faster for the scintillation detector (the rise time of the left curve is 174 ns; for the right curve, it is 2.4 ns). Also, note the slight flattening of the exponential tail in the BaF$_2$ pulse signal. This is a consequence of the two-component nature of the fluorescent light signal (see text).
The pulse shapes arising from the different radiation-detection responses of scintillation versus semiconductor detectors, illustrating their different timing characteristics are shown in Figure 6. In comparing fall-from-baseline times (“rise times”), the HPGe detector has a rise time of 174 ns. The BaF$_2$ detector’s rise time is 2.4 ns. Both of these are typical of the intrinsic behaviors of the detectors, with ~100 ns charge collection time in HPGe, and ~5 ns UV-Visible de-excitation time in scintillators [12]. Therefore, in a coincidence experiment the time resolution of two HPGe detectors firing would be on the order of 100 ns, while two BaF$_2$ detectors firing would be on the order of a few ns.

Two spectra illustrating the different energy-resolution characteristics of HPGe versus scintillation detectors are shown in Figures 7 and 8, respectively. These spectra were acquired from a $^{152}$Eu source in the singles mode.

Figure 7. Energy spectrum from $^{152}$Eu, acquired by use of the 8π’s HPGe detectors, showing gamma rays emitted by its daughters, $^{152}$Sm and $^{152}$Gd. The gamma ray lines compared to those detected in BaF$_2$ are labelled with boxed numbers containing their approximate energies, in keV.
Figure 8. Energy spectrum from $^{152}\text{Eu}$, acquired by use of the $8\pi$'s BaF$_2$ detectors. For comparison to the previous figure, note that several gamma rays become essentially unresolvable from their immediate neighbors, so that the discrete 1085 and 1112 keV lines in HPGe, as examples, are broadened into an indistinguishable peak in BaF$_2$.

1.9 Measuring Lifetimes of Nuclear States

There are several methods to measure nuclear state lifetimes. The Recoil Distance (plunger) Method (RDM) and the Doppler Shift Attenuation Method (DSAM) have been used to measure nuclear state lifetimes ranging from femtoseconds to tens of picoseconds [8]. Fast electronic timing techniques have been used to measure lifetimes on scales ranging from picoseconds to nanoseconds [8].

The RDM and DSAM methods are optimized for studying the products of nuclear reactions in a beam-on-target environment. The products of these reactions (called recoils) either slow down within the target, or a stopping material attached to the target, or exit the target and enter a stopping material
(plunger) downstream of the target. However, in the case of beta decays, these methods are ineffective since the daughter nuclei of beta decays have negligible recoil velocities.

1.9.1 Recoil Distance Method

![Figure 9](image.png)

Figure 9. Basic overview of the plunger technique. The plunger (stopper) can be moved closer to or further away from the target; this allows mathematical analysis of the lifetime of a desired state. Used and modified with permission. [17]

This technique was developed in the 1950s, and with the advent of HPGe detectors, has been refined owing to the superior energy resolution of these detectors over NaI(Tl) detectors. The basic principle of this method is shown in Figure 9. The plunger moves closer to or further away from the target. Gamma rays are recorded with a detector placed a fixed radial and angular distance away from the target. As noted in Figure 9, the intensities of the peaks detected will
depend on plunger distance, and the energy difference between them depends on the Doppler shift, which is determined by the velocity of the exiting recoils.

Gamma rays emitted from nuclei in flight are Doppler-shifted, while nuclei that have stopped in the plunger emit unshifted gamma rays. While the recoil velocity is determined by the kinematics of the reaction, it can be confirmed by the separation of the shifted versus unshifted peak. Plotting the intensity of the unshifted peak as a function of plunger distance yields the lifetime of a nuclear excited state from the slope of a semi-logarithmic plot through conversion of the decay constant into a lifetime (Figure 10). Under good experimental conditions this peak is resolvable from its shifted counterpart and so will decrease to zero intensity as the plunger moves further and further from the target.
There are corrections that must be applied when the nuclear state lifetime becomes very short and comparable to the length of time the nuclei take to stop in the plunger material. Such corrections require analysis of the Doppler line shape. Independent of this, velocity corrections must be made because in the nonideal case, recoiling nuclei from the target actually possess a distribution of velocities partly due to inherent broadening of the incoming beam, and partly due to straggling both when leaving the target, as well as when striking the plunger.

1.9.2 Doppler Shift Attenuation Method

This technique was also first pioneered in the 1950s, and again, HPGe detectors have improved the usefulness of this technique in probing nuclear lifetimes from the femtosecond range into the few-picosecond range. The apparatus is similar to that of the plunger method, but the stopping material is attached to the target and does not move with respect to it.

There are two methods of employing the DSAM. One is via the shift of the centroid of the emitted gamma ray from the state of interest; the other is via analysis of the line shape of the emitted gamma ray peak. Both methods use the fact that the reaction recoils emit gamma rays within the stopping material. They may either be completely stopped, or exit with a lower velocity; the DSAM only depends on the lifetime of the state being short enough that the gamma rays emitted are within the target and backing. Figure 11 depicts the situation where the recoil has not exited the stopping material.
Figure 11. Diagram showing how a $^{15}$O recoil of the reaction discussed in ref. [19] moves through a gold backing and comes to rest while emitting gamma rays; the degree of Doppler shift is proportional to $\beta$, which is the recoil velocity as a fraction of the speed of light. Used with permission.

Researchers at TRIUMF have used the DSAM to extract lifetimes of short-lived states in light nuclei, such as $^{19}$Ne [20], or $^{15}$O [19].

1.9.2.1 Centroid Shift Method

The centroid shift method (Figure 12) uses detectors positioned at the same radial distance from the target, but at different scattering angles. Multiple detectors may be used simultaneously, or a single detector can be moved during the course of the experiment.

The energy of the Doppler-shifted gamma ray $E_\gamma$ in this technique is dependent on the scattering angle [8]:

$$E_\gamma = E_\gamma^0 (1 + F(\tau) \beta \cos \theta)$$  \hspace{1cm} (27).
$E_γ$ is the unshifted gamma ray, $β$ is the ratio of $v/c$, and $F(τ)$ is the attenuation factor.

Figure 12. The DSAM method. The detector at zero degrees can be kept at that position to measure line shapes, or may be moved to different angles in the centroid-shift method. Used and modified with permission. [19].

Plotting the degree of energy shift as a function of $\cos \theta$ yields $F(τ)β(0)$ from the slope. If $β$ is non-relativistic\(^9\), then the lifetime of the state can be measured without needing further corrections, since $F(τ)$ can be calculated as a function of lifetime if the stopping power $(dE/dx)$ of the recoil-absorbing medium is known very well.

The use of the silicon $\Delta E$ and $E$ detectors is to detect the charged-particle reaction products that leave the stopping material. They allow the determination of the direction of the recoils which stop in the target backing, since the Doppler shift of the emitted gamma rays is sensitive to the motion of these recoil nuclei. Additionally the sensitivity of this pair of detectors to the linear energy loss of the

\(^9\) In the relativistic regime, further corrections must be applied but the DSAM is still viable as a lifetime-measurement technique.
particles which strike them allows for setting gates on a desired charged particle emission to isolate the reaction of interest. In the example in Fig. 12, the desired charged particles were the outgoing alphas in the stripping reaction producing $^{15}$O in the gold target in which a layer of $^3$He was embedded.

### 1.9.2.2 Line Shape Analysis Method

Alternatively, in the DSAM a single detector can be mounted at a fixed angle and radial distance away from the target (Fig. 12). The intrinsic HPGe detector response and a calculated Doppler broadened line shape due to the decay as the ions are slowing down can be used to determine the lifetime of the state of interest, by means of Monte Carlo simulations and knowledge of the stopping power (dE/dx) of the backing material.

![Figure 13. Simulated gamma ray peaks emitted by a 6.791 MeV state in $^{15}$O of $\tau \approx 2$ fs – 3 ps in a reaction of $^{16}$O with $^3$He at 50 MeV, with a gold backing material to stop the reaction products. The x axis is the Doppler shifted energy in keV; the y axis is intensity in arbitrary units. Image courtesy of Naomi Galinski.](image)
Examples of calculated Doppler broadened lineshapes for various lifetimes are shown in Figure 13, which simulates gamma ray emissions from a 6.791 MeV state in $^{15}$O, populated by a stripping reaction involving $^{16}$O with a beam energy of 50 MeV bombarding a target of $^3$He implanted in Au. These calculated peaks can be compared to experimental data to ascertain the lifetime of the state.

1.9.3 Fast Timing Measurements with Scintillation Detectors

The measurement of nuclear lifetimes in the nanosecond to picosecond range can be done by following radioactive decays of nuclei at rest, such as at the 8π in TRIUMF. Overlap of time scales in the picosecond range allows fast-timing delayed-coincidence methods to complement the RDM; however the primary use of fast timing techniques is to extend lifetime measurements into the nanosecond range, as the DSAM and RDM are not optimized for such long lifetimes.

Prior to the discovery of the fast component of the light output from BaF$_2$ crystals which established the usefulness of BaF$_2$ detectors in measuring lifetimes of short-lived nuclear excited states [21--23], fast timing measurements were done by using combinations of NaI(Tl) and plastic scintillation detectors in which beta-gamma coincidences could be measured, conversion electron and gamma ray coincidences could be measured, or in the case of two plastic scintillation detectors in coincidence, conversion electron-conversion electron coincidences could be measured. The delayed-coincidence method was
successfully employed in the first measurement of the lifetime of the $I^e = 2^+$ excited state of $^{152}\text{Sm}$ in 1955 [24], and in several measurements since then [25].

Collectively, these fast-timing delayed-coincidence methods come under the heading of Fast Electronic Scintillator Timing (FEST). FEST can be applied to various nuclear level schemes, as illustrated in Figure 14, ranging from simple (Fig. 14(a)) to complex (Fig. 14(c)).

![Figure 14](image_url)

**Figure 14.** Decay schemes that can be handled by FEST. Varying levels of complexity are shown here, with a) being the simplest, and b) and c) showing increased levels of complexity. Image courtesy of Paul Garrett.

The basic principle of FEST is that combinations of coincidence-correlated events can be used to extract information about the nuclear excited state through which those events transit. For example, Figure 14(a) represents a beta-gamma event utilizing a plastic scintillator (for beta particles) and an inorganic scintillator (for gamma rays). Figures 14(b) and 14(c) represent successively more complex nuclear level schemes in which more versatile detector arrays can be used, such
as multiple scintillation detectors which can detect two gamma rays in succession which transit through a state. Figure 14(b) shows that detecting $\gamma_2$ in coincidence with $\gamma_1$ would yield the lifetime of the state labelled by $\tau_1$, as an example.

By combining an array of HPGe detectors and BaF$_2$ detectors, the energy spectra of radioactive daughter products can be acquired with the HPGe detector array to gate transitions, while the BaF$_2$ detector array can be used to measure lifetimes. Trigger conditions can be set where gamma rays may be detected in a sequence of HPGe-BaF$_2$-BaF$_2$ (an example of a triple coincidence) to set an energy gate on a gamma ray which is known to feed a lower state, then using the subsequently emitted gamma rays detected in BaF$_2$ detectors to measure the lifetime of a state which is populated in the cascade. This would be represented by isolating $\gamma_4$ in Figure 14(c) with an energy gate in an HPGe detector, then requiring that two BaF$_2$ detectors fire in coincidence; energy gates can be applied onto the BaF$_2$ detectors (though limited by their resolution) to further isolate the cascade of interest, which would be that of $\gamma_2$ followed by $\gamma_1$.

A simpler trigger condition would be a BaF$_2$-BaF$_2$ coincidence condition, in which two gamma rays in a nuclear cascade are detected; energy gates can be used to isolate the state of interest if feasible.

The 8$\pi$ array can be modified to use the beta-gamma method as briefly discussed above, by means of a single plastic scintillator placed behind the beam spot, as shown in Figure 17(c). Thus, the combination of DANTE and the plastic scintillator would allow for isolation of excited states which are directly populated
in beta decay, which is advantageous if the structure of the daughter under study is not well-known.

For the specific situation of $^{152}$Sm, its structure is well-known and the gamma rays of interest are resolvable in a BaF$_2$ detector. Furthermore, since the decay process of interest involves electron capture, a plastic scintillation detector was not mounted. Thus, coincidences between the BaF$_2$ scintillators, or between the HPGe and BaF$_2$ scintillators, may be used. This will be discussed in more detail in chapters 2 and 3.

1.10 ISAC at TRIUMF

![Figure 15](image-url) The ISAC experimental hall (foreground) with the superconducting LINAC and ISAC-II experimental hall (empty room, at back). The $\beta\gamma$ apparatus is shown in the stopped-beam area along with the TRINAT, $\beta$-NMR and (now defunct) LTNO experimental apparatus. Image courtesy of Design Office, TRIUMF.
The Isotope Separation and Acceleration (ISAC) facility is shown in Figure 15. Several research groups conduct their activities with radiation detectors and other equipment in this experimental hall, all of which depend on the production of radioactive ion beams, produced via spallation reactions (which are the break-up of the heavy nuclei into smaller ones under impact from small, energetic projectiles) by bombarding 500 MeV protons on selected production targets.

Radioactive beams are produced at TRIUMF using the Isotope Separation Online (ISOL) technique [26]. ISOL uses a mass separator dipole to deliver beams of a given mass. After the mass separation, the beam is delivered to the hall level where, in the case of the $8\pi$, the beam, of a few tens of keV kinetic energy, is stopped on the aluminized Mylar tape inside the $8\pi$ target chamber. The radioactive ions, at rest, emit beta particles and gamma rays into the detectors surrounding them.

1.11 The $8\pi$ at TRIUMF-ISAC

The $8\pi$ detector array at TRIUMF-ISAC consists of twenty HPGe detectors in a truncated icosahedral arrangement [27]. The HPGe detectors are surrounded externally by Bismuth Germanate (abbreviated to BGO; its formula is $\text{Bi}_4\text{Ge}_3\text{O}_{12}$) Compton-suppression shields; there are also internal BGO suppressors which are directly behind the HPGe crystal. The HPGe detector assembly is schematically depicted in Figure 16.
The BGO detector suppression mode operates either in a hardware or software veto configuration, in which a gamma ray detected in an HPGe detector is not recorded if a scattered gamma ray is detected at the same time in the BGO suppressors.

The HPGe detectors have 2.54 cm thick hexagonal Heavimet (an alloy primarily consisting of Tungsten) collimators mounted directly in front of them, with apertures approximately 2.5 cm in diameter. These collimators prevent gamma rays from striking the external BGOs, thereby reducing false veto events. The Heavimet also suppresses backscattering events, in which a gamma ray scatters off one detector and enters the detector opposite, at lower energy. Additionally, Delrin plastic shields may be mounted on the Heavimet collimators to suppress Bremsstrahlung from high energy beta particles.
Figure 17. Clockwise from top left: (a) View of east half of the $8\pi$ array adjacent to the upstream half of the target chamber showing SCEPTAR. (b) PACES replacing SCEPTAR in the upstream portion of the target chamber. (c) The downstream half of the target chamber showing the Mylar tape and plastic scintillator. (d) The lead-shielded tape box attached to the downstream portion of the target chamber.

The arrangement of the HPGe detectors and their hexagonal collimators leaves pentagonal gaps in the $8\pi$ frame, into which the DANTE detectors are mounted. Additionally, because a cross-section through the $8\pi$ would reveal two
pentagonal configurations of the DANTE detectors, this is the origin of the name Di-Pentagonal Array for Nuclear Timing Experiments.

When joined together, the two halves of the $8\pi$ frame form essentially $4\pi$ solid angle coverage of the target chamber. The HPGe detectors themselves subtend approximately 13% of the $4\pi$ solid angle [28].

The $8\pi$ HPGe and DANTE arrays surround a black Delrin target chamber of approximately 16 cm diameter; a view of half the array around the upstream half of the target chamber is shown in Figure 17(a). Inside this target chamber is the Scintillating Electron Positron Tagging Array (SCEPTAR), which contains twenty plastic scintillators designed in such a way that each plastic scintillator is directly in front of an associated HPGe detector [29]. These detectors are sensitive to beta particles and can be used to correlate beta decay events to gamma ray events.

If internal conversion electrons need to be detected during an experiment, the upstream half of SCEPTAR can be removed and replaced with the Pentagonal Array for Conversion Electron Spectroscopy (PACES), as seen in Figure 17(b). These are five circular silicon detectors capable of detecting internal-conversion electrons.

Figure 17(c) shows the aluminized Mylar tape in the downstream half of the target chamber. The Mylar tape forms a continuous loop through a lead-shielded tape box, which can be seen in Figure 17(d). This shields the detector array from activity on the tape if the experimental design requires periodic tape movement to remove built-up activity from the beam spot.
CHAPTER 2: DETECTOR CHARACTERIZATION

2.1 Purpose and Overview

The $8\pi$ gamma ray spectrometer at TRIUMF has been optimized for studying $\beta$-decaying nuclei, which populate excited states in their daughters that emit gamma rays. The DANTE array of BaF$_2$ detectors is well-suited to extend the $8\pi$'s capabilities. Adding lifetime measurement capability and high gamma ray detection efficiency have motivated the integration of DANTE into the $8\pi$.

Theoretical estimates show that BaF$_2$ detectors are capable of reaching an energy resolution of 7% of the 662 keV peak of the $^{137}$Ba daughter of $^{137}$Cs [30]. Previous work has shown instrumental prompt response times on the order of 290 picoseconds Full Width at Half Maximum (FWHM) of a coincidence timing peak using BaF$_2$ detectors [31].

Characterizing the properties of the TRIUMF-assembled BaF$_2$ detectors to be used in the DANTE array was done by first testing them individually in a laboratory setup with $^{137}$Cs and $^{60}$Co sources.

2.2 The $8\pi$ DANTE Detectors

2.2.1 Detector Properties

The DANTE scintillation detectors consist of BaF$_2$ crystals coupled to Photonis XP2020/URQ fast photomultiplier tubes. Several characteristics of the detectors were chosen to optimize DANTE for fast timing experiments, based on
previous work by Mach and Moszyński [22,23,32]. The crystal shapes were designed for optimum light collection to obtain optimal energy and time resolution [33], while the photomultiplier tubes were specifically chosen for their spectral characteristics and fast rise times [23].

The BaF$_2$ crystals are of cylindrical base diameter 40 mm, height 17 mm, above which they are truncated cones of end-cone diameter 20 mm and height 30 mm. The total volume of each crystal is 12.5 cm$^3$ [31].

![Photoluminescent emission spectrum of BaF$_2$. The energy of the light is on the x axis in electron-volts, while the y axis is light intensity in arbitrary units. The dashed line marked “3” indicates the slow-component emission; the dotted line marked “4” is the fast-component emission. Both are at temperatures of 300 K; other lines in the graph correspond to cooler temperatures. The peak at 4.3 eV corresponds to approximately 300 nm; at 5.5 eV, it is ~225 nm. The peak at 6.4 eV corresponds to ~195 nm. Reprinted with permission. [34]](image-url)

Like some other scintillator crystals, BaF$_2$ has a two-component decay of its fluorescence. The fast component, with a decay time constant of 600 ps, has a wavelength of 220 nm and provides ~20% of the total light output of a pulse. The slow component, with a decay time constant of 630 ns, has a wavelength of...
310 nm and provides the remaining ~80% of the total light output [12]. The photoluminescent emission spectrum of BaF$_2$ is shown in Figure 18. It can be seen that a third peak is detectable in the light emission of BaF$_2$ at approximately 195 nm, but it is not of importance as it is likely to be partially absorbed by the front faces of the photomultiplier tubes used for DANTE.

![Graph](image)

**Figure 19.** UV-Visible response curve for Photonis XP2020/URQ Photomultiplier tubes. The radiant sensitivity (ratio of cathode current to visible light flux at a given wavelength) is on the y axis, wavelength on the x axis. [35]

The PMTs, which have bi-alkali photocathodes, were chosen to match the light-emission characteristics of BaF$_2$. The front faces are 52 mm in diameter and are covered with fused silica glass. The operating voltage range is 2200 V to 3200 V. The pulse rise time is 1.4 ns, with a transit time of 27 ns, and transit time spread of 150 ps [35]. The spectral characteristics, showing the wavelength sensitivity of the XP2020/URQ, are shown in Figure 19.
An optical gel couplant is normally used with inorganic scintillation detectors to protect the clear front face of the PMT and the base of the scintillator crystal from scratching each other, as well as to fill in air gaps between the mated surfaces to provide consistent transmission of light into the photocathode. Additionally, optical couplants should have light transmission properties well-suited to the intended application, in terms of spectral absorbance and refractive index. In assembling the DANTE detectors, the optical couplant was specifically chosen to have a similar refractive index to that of the front face of the PMTs, as well as similar UV-Visible properties to those of the BaF$_2$ crystals.

![Absorption spectra of Dow Corning and specialized silicon-based optical gels. Higher absorbance means less light is transmitted through the gel. The y axis is Absorbance (no units), while the x axis is the wavelength in nanometers. The feature in each of the curves at 340 nm is not a property of the gels; the apparatus changes detectors from UV to visible above 340 nm. Note the much higher ultraviolet cutoff of the conventional Dow Corning gel (blue triangles) versus the specialized gel (purple squares).](image)

**Figure 20.** Absorption spectra of Dow Corning and specialized silicon-based optical gels. Higher absorbance means less light is transmitted through the gel. The y axis is Absorbance (no units), while the x axis is the wavelength in nanometers. The feature in each of the curves at 340 nm is not a property of the gels; the apparatus changes detectors from UV to visible above 340 nm. Note the much higher ultraviolet cutoff of the conventional Dow Corning gel (blue triangles) versus the specialized gel (purple squares).
Figure 20 compares the UV and visible absorption spectra, which were acquired on a Perkin-Elmer UV-Visible spectrometer at Simon Fraser University, for a Dow Corning Q2-3067 optical gel, which is commonly used at TRIUMF for scintillation detectors, and the specialized silicon-based gel used for the BaF$_2$ detectors, provided by Henryk Mach. It can be seen that the conventional gel would transmit the slow component but absorb the fast component, thus degrading the timing resolution of the DANTE array.

### 2.2.2 Detector Assembly and Mounting

To assemble a DANTE detector, first the conical part of the crystal was wrapped completely in white Teflon gauze to ensure light emissions would be reflected through the base. Then the photomultiplier tube was oriented in an upright position, and a minimum amount of the optical gel was placed on the clear front face. After this, the crystal was carefully mated to the surface of the PMT, using its own weight to spread the gel evenly. Finally, black electrical tape was used to secure the crystal against the PMT, as well as electrically and optically insulate the entire assembly. The detectors were then stored for ~24 hours to allow dark currents (induced by the exposure to ambient light) to decay prior to testing. Figure 21 shows the components used to assemble a DANTE detector, and Figure 22 shows a completely assembled detector in its test rig.
2.2.3 Laboratory Testing Regime

For initial testing, one or two detector(s) and associated electronics were set up on a bench top in the ISAC-II counting room. The detectors were mounted
on metal frames, as shown in Figure 22, to allow for coincidence testing of two detectors for timing measurements. The test rigs did not have the μ-metal shields which were later used in the $8\pi$ during the experiment involving the $^{152}\text{Eu}$ source. These shields keep external magnetic fields from deflecting electrons away from the dynode chain of the PMT. As discussed in Section 1.8, photoelectron deflections away from the dynode chain would degrade the energy and timing properties.

The specifications for the PMTs state that a parallel magnetic field of 0.12 mT, or a perpendicular field of 0.15 mT, will reduce detector gain by 50% [35]. The Earth’s magnetic field is approximately 0.5 Gauss, or 0.05 mT. Assuming that the gain reduction is linear in proportion to the external magnetic field strength, then the gain would be reduced by approximately 15%. This was compensated by increasing the applied voltage by 15%.

### 2.2.4 Apparatus for Characterizing DANTE Detectors

In the lab, the assembled BaF$_2$ detectors were connected to a CAEN high voltage supply which was set to deliver approximately –2500 V to the PMTs. An Ortec 4001C NIM crate was used to power and house analog electronic modules during testing.

The block diagram for acquisition of energy spectra in the singles mode in the laboratory environment is shown in Figure 23. Singles mode is the acquisition of any signal from the detector regardless of origin (e.g. a gamma ray from a source, or room background, or simply noise in the circuit). This mode is typically
used to acquire a high number of counts from a radioactive source when its activity is much higher than background.

![Diagram](image)

**Figure 23.** Equipment connections and pulse shapes for quantitatively determining energy resolutions by means of a $^{137}$Cs source.

The dynode from the PMT emits positive pulses with exponential tails, with rise times on the order of 2 ns and amplitudes between zero and ~50 mV, depending on the energy of the gamma ray striking the BaF$_2$ crystal. The Ortec 113 pre-amplifier shapes the sharply-rising pulse from the dynode, via a combination of RC and transistor circuitry, into a smoother semi-Gaussian pulse with an exponential tail. These pulses have amplitudes from zero to ~500 mV with rise times of 100 ns, and are inputs to the Ortec 671 amplifier, set at a pulse shaping time of 1 µs and with a coarse gain set to 100 or 200 to cover the range from zero to 10 V (which corresponded to 0 to 1 MeV at a gain of 200, or 0 to 2 MeV at a gain of 100). The Ortec 671 then outputs these pulses to the Multi-Channel Analyzer (MCA).

In the laboratory setup, a PC-based MCA with an analog to digital converter (ADC) expansion card, allowing the digitization of analog signals, was
used to run a software package called Maestro. It can display and store spectra, allowing for the export of these spectra for analysis after acquiring data.

Figure 24. Schematic of coincidence testing with a single channel analyzer for quantitatively determining timing resolutions by means of a $^{60}$Co source.

The block diagram in Figure 24 shows the set-up of NIM modules for the acquisition of data on timing characteristics in a coincidence-mode configuration of the detectors. This requires two events to occur within a given time window; for example, the emission of two gamma rays from a nucleus. This mode is typically used when background activity is significant, and is well-suited for measuring the lifetime associated with a two-step transition, be it a beta-gamma coincidence or gamma-gamma coincidence. The detectors themselves are mounted a fixed distance apart in a 180 degree arrangement.

The anode negative pulses from the voltage divider output have a rise time of approximately 2 ns. The amplitudes of the pulses are dependent on the
applied voltage to the PMT, as well as the energies of the gamma rays striking the BaF$_2$ crystal. At –2500 V these pulses were typically between 0 and –7 V for the energy range of 0 to 1.3 MeV.

![Schematic diagram of walk reduction using a CFD](image)

**Figure 25.** A schematic overview of walk reduction using a CFD. Note the process of attenuating the original signal, then inverting the input, delaying it, and adding it back to the attenuated signal.

The Ortec 935 Constant Fraction Discriminator (CFD) takes input negative pulses between 0 and –10 V and outputs fast NIM-standard negative pulses of adjustable width and approximate amplitude –1 V. An external delay cable may be used with the CFD to adjust its time discrimination behavior. Usually, 3 ns cables were used for the external delays during testing.
Constant fraction timing minimizes the energy dependence of time measurements, called walk, by attenuating the input signal, and simultaneously inverting and delaying the unattenuated signal, then adding this back to the attenuated signal. Figure 25 shows this process at each stage of the constant fraction timing method. The resulting output crosses over the baseline (“zero-crossing time”) at a constant fraction of the original incoming pulse (i.e. it is independent of the amplitude).

Some walk remains mainly due to slight differences in pulse rise times and noise in the pulses, which can be reduced to a minimum by manual adjustment of a potentiometer in the CFD. If it is set improperly it causes early crossover in low-amplitude pulses and late crossover in higher-amplitude pulses. Once the potentiometer is set properly, all pulses cross over the baseline at a zero-crossing point which has as small a size as possible. Further removal of the energy dependence of timing can be done by use of energy gating to reject undesired timing signals.

The Ortec 935 CFD also has an adjustable lower-level discriminator, which allows it to reject pulses below a certain energy. In the laboratory setup, the threshold was normally set slightly above the noise level, unless a specific testing regime required a higher setting.

The Ortec 566 TAC takes NIM-negative pulses at the start and stop inputs, and can optionally be externally strobed to gate the output. The TAC operates by opening a time window (this window is user-selectable, and for the Ortec 566 it ranges from 50 ns to 2 ms) when it receives the start pulse. It waits
for a stop pulse to occur within the time window. Once it receives the stop signal, it outputs a linear pulse whose amplitude is proportional to the length of time between the detection of the start and stop signals.

In the laboratory testing phase the time window was set either to 50 or 100 ns. A 16 or 32 ns delay cable was placed between the CFD output of the “stop” detector and the “Stop” input of the Ortec 566 Time to Amplitude Converter (TAC). The “start” detector was connected with a short (~2 ns) delay cable to the “Start” input of the TAC.

If the start and stop signals were to occur at the same fixed time apart, then the TAC spectrum would have a delta function at that time interval. Further, in timing spectroscopy, placing an external delay on the stop signal shifts the timing peak into the middle of the spectrum where it is more convenient to analyze, and also prevents the TAC from rejecting stop pulses occurring too close in time to the start pulse due to its intrinsic start-to-stop conversion interval, specified at 5 ns for the Ortec 566. This output can be monitored with an oscilloscope or via a Multi-Channel Analyzer (MCA). However, there is broadening of this delta function into a Gaussian distribution, attributable to intrinsic limitations on the resolution of the detectors involved. The FHWM of the peak is the time resolution due to the detector responses and the instrumentation used to process the signals, and is one figure of merit to be optimized in a coincidence experiment. Figure 26 shows the effect of distributing the start and stop pulses in a Gaussian manner.
Figure 26. The input start and stop pulses are shown, with the TAC conversion of those pulses shown below the solid black line. The TAC spectrum shown under actual conditions reflects Gaussian-distributed incoming CFD pulses.

To set up the energy gate as shown in Figure 24, the bipolar output of the Ortec 671 amplifier was connected to the Tennelec 451 Single Channel Analyzer (SCA). The SCA has adjustable lower and upper levels which can be set to their extreme limits to open the energy gate, or they can be set at intermediate values to permit only certain energy signals to be passed through. It outputs a positive square pulse, which, in this setup, was routed to an Ortec 416A gate and delay generator.

The Ortec 416A gate and delay generator, set to a 500 ns width, changes the positive output pulse of the SCA to a negative input strobe of −6 V. The purpose of using a gate and delay is to shift the strobe signal into the same time range as the stop pulses entering the TAC, and therefore gate its output. The Ortec 542 Linear Gate Stretcher is required to ensure the MCA reliably accepts
the linear pulses (which are different in shape than amplifier pulses) from the TAC.

The procedure for setting up the SCA upper and lower limits is not shown in Figure 24. This was done by passing the output of the Ortec 416A Gate and Delay Generator to the MCA as a strobe and connecting the unipolar output of the Ortec 671 amplifier to the input port of the MCA. The resulting spectrum was visually examined to ensure acceptance only of the 1332 keV gamma ray from a $^{60}$Co source by adjusting the SCA (discussed in Section 2.2.6). After its lower and upper levels were set, all the modules were re-wired back to the configuration in Figure 24.

2.2.5 Energy Resolution Measurements

A $^{137}$Cs source was used in the lab to measure the energy-resolution characteristics of the BaF$_2$ detectors. This radioactive isotope’s decay scheme is shown in the inset of Figure 27.

The usual practice for scintillation detectors is to quote their energy resolution in terms of the ratio of the FWHM of the 662 keV peak from a $^{137}$Cs source to the centroid of its position in a gamma ray spectrum [15].

Energy spectra were acquired from a $^{137}$Cs source mounted approximately 2-4 cm away from the end of the BaF$_2$ crystal. The spectra were written to disk for subsequent analysis with a program from the RadWare package, called gf3 [36], designed for analyzing gamma ray spectra, by fitting the peaks to obtain
centroids, areas and FWHMs. Typical gamma ray peaks are approximately Gaussian in shape [12].

![Image of gamma ray spectrum](image)

**Figure 27.** A typical $^{137}\text{Cs}$ spectrum acquired in the singles mode in the lab with detector DANTE04. The resolution of the 662 keV peak is 9.5% for this detector.

The $^{137}\text{Cs}$ energy spectra were fitted and the centroid and FWHM of the 662 keV peak for each detector were obtained. A typical $^{137}\text{Cs}$ energy spectrum acquired using detector DANTE04 is shown in Figure 27. The resolution of the 662 keV peak in the spectrum was measured at 9.5%.

Additionally, a $^{60}\text{Co}$ source was used, which has two cascading photopeaks emitted by its daughter, $^{60}\text{Ni}$, as shown by the decay scheme inset of Figure 28. The gamma ray spectrum of the $^{60}\text{Co}$ source spectrum (Fig. 28) indicates that a properly functioning BaF$_2$ detector can resolve the two photopeaks; at 1332 keV the resolution is approximately 9%. These spectra were primarily used to qualitatively determine peak resolvability.
2.2.6 Timing Resolution Measurements

The two cascading photopeaks of well-defined energy from $^{60}$Co are well suited for use in coincidence experiments to establish detector timing characteristics when the response is dominated by instrumental effects (the states which de-excite have negligible lifetimes). The prompt timing resolution of the detectors is measured by the FWHM of the TAC output signals.

The coincidence-mode setup shown in Figure 24 was used to first examine timing behavior with a wide-open energy gate. This allowed the investigation of adjustments to the CFDs and their effect on timing characteristics. The two effects considered initially were the mode of operation (which may be set to blocking or updating), and the effect of energy threshold adjustment on the CFD.
Figure 29. Coincidence timing spectra from initial tests of the DANTE detectors in (a) the blocking mode and (b) updating mode, using a $^{60}$Co source without an energy gate. The FWHM of the peak in (a) is $253 \pm 7$ picoseconds, and in (b), $273 \pm 11$. Differing peak centroid positions are due to replacement of a loose connection on a delay cable.

The updating mode of operation of a CFD extends its output pulse if it detects a second input signal from a detector closely following the initial signal. By contrast, the blocking mode of operation will cause the CFD to ignore incoming signals succeeding the initial signal for the duration of its output pulse. It was found that the blocking mode of operation (Figure 29(a)) produced better timing results than the updating mode of operation (Figure 29(b)). The updating mode results in poorer timing characteristics due to increased probabilities of acceptance of random coincidences.

It was found that raising energy thresholds to approximately 800 keV (as determined from pulse heights on an oscilloscope) caused timing characteristics to improve (Figure 30) as compared to operation with low thresholds (Figure 29(a)). This improvement is due to the elimination of low-energy contributions due to Compton scattering. This energy dependence of timing behavior can
equivalently be reduced by using a Single Channel Analyzer (SCA) to set an energy gate on the region of interest in a gamma ray spectrum, as discussed in Section 2.2.4.

![Coincidence timing spectrum from initial tests of the DANTE detectors in the blocking mode, with high CFD thresholds corresponding to approximately 800 keV, using a $^{60}$Co source. The FWHM of this peak is 224 ± 4 picoseconds.](image1)

**Figure 30.** Coincidence timing spectrum from initial tests of the DANTE detectors in the blocking mode, with high CFD thresholds corresponding to approximately 800 keV, using a $^{60}$Co source. The FWHM of this peak is 224 ± 4 picoseconds.

![The energy gate region around the 1332 keV peak is shown with black bars in this $^{60}$Co spectrum.](image2)

**Figure 31.** The energy gate region around the 1332 keV peak is shown with black bars in this $^{60}$Co spectrum,

The energy gate region was set between approximately 1250 and 1400 keV (Fig. 31). The 1332 keV peak was used due to lower background
underneath this photopeak compared to the 1173 keV peak. This gate was set on the detector producing the “stop” signal of the coincidence setup, since the TAC does not have the facility of being easily strobed by two different SCAs. This gating technique can also be done with computer software in analysis of experimental data. Software gating is often more versatile than hardware gating, if the data contains all the necessary information on an event by event basis to usefully apply the energy gate.

The application of the energy gate produced a narrower time spectrum, as shown in Figure 32. The effect of this energy gate proved to be similar to that of applying high thresholds on the CFDs.

![Figure 32. Coincidence timing spectrum using a $^{60}$Co source with an energy gate. The FWHM of this peak is 221 ± 6 picoseconds.](image)

Table 1 shows the energy resolutions and coincidence testing results for all the available detectors tested under the laboratory conditions outlined previously. These final results were found to be similar to reference data collected from detectors borrowed from the University of Surrey, and qualified all the DANTE detectors as being suitable for mounting in the $8\pi$ array. The average
time resolution was found to be 199 ps and the average energy resolution was 10.5% at 662 keV.

Table 1. The characteristics of the BaF$_2$ detectors used in the 8π array after bench top testing. The first column refers to the numbering of the detectors in the 8π array. The second and third columns are serial numbers assigned to the PMTs and crystals by the manufacturers.

<table>
<thead>
<tr>
<th>DANTE Det. #</th>
<th>PMT Serial #</th>
<th>Scionix Crystal Serial #</th>
<th>Energy Resolution at 662 keV (%)</th>
<th>Time peak FWHM (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>42036</td>
<td>0568</td>
<td>12.0</td>
<td>203.2</td>
</tr>
<tr>
<td>02</td>
<td>42152</td>
<td>0565</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>03</td>
<td>42138</td>
<td>0567</td>
<td>9.9</td>
<td>194.1</td>
</tr>
<tr>
<td>04</td>
<td>42186</td>
<td>0563</td>
<td>9.5</td>
<td>183.1</td>
</tr>
<tr>
<td>05</td>
<td>42205</td>
<td>0566</td>
<td>10.1</td>
<td>191.7</td>
</tr>
<tr>
<td>06</td>
<td>42222</td>
<td>0562</td>
<td>10.1</td>
<td>196.5</td>
</tr>
<tr>
<td>07</td>
<td>42225</td>
<td>0571</td>
<td>11.1</td>
<td>210.0</td>
</tr>
<tr>
<td>08</td>
<td>42228</td>
<td>0564</td>
<td>11.1</td>
<td>197.1</td>
</tr>
<tr>
<td>09</td>
<td>42232</td>
<td>0569</td>
<td>11.5</td>
<td>202.6</td>
</tr>
<tr>
<td>10</td>
<td>42233</td>
<td>0570</td>
<td>9.9</td>
<td>212.4</td>
</tr>
</tbody>
</table>

Further optimization of timing was also conducted by systematically changing each CFD's external delay cable length. Plotting the FWHM of the prompt timing peak versus delay cable length showed identifiable minima. The majority of detectors were found to operate best when their external delays were 2.8 to 3.2 ns long, with two outliers at 2.2 and 3.8 nanoseconds.

h This detector had been disassembled and so was not tested.
CHAPTER 3: EXPERIMENTAL

3.1 Motivation and Objective

This chapter outlines the experimental testing of the DANTE detectors after integrating them into the $8\pi$ array. The objective was to test the performance of the array in fast timing experiments. As in the laboratory testing stage, $^{137}$Cs and $^{60}$Co sources were used to measure energy and prompt timing characteristics of the detectors when used in the $8\pi$ array.

Figure 33. Electron-capture and beta minus decays of $^{152}$Eu, showing partial level schemes (not to scale) with electron-capture and beta minus branching ratios into the excited states of $^{152}$Sm and $^{152}$Gd. The level energies, transition energies and gamma emission branching ratios from each state are shown; literature half-lives are shown for the first $2^+$ and $4^+$ states. (Raman et al [25] provide the $^{152}$Sm 121.8 keV state half-life; The Nuclear Data Sheets [1] provide $^{152}$Sm level energies and other half-lives, and all $^{152}$Gd level energies and half-lives)
The performance of the DANTE array with regard to conducting measurements of half-lives of nuclear excited states was tested with the radioactive isotope $^{152}$Eu. It decays (Fig. 33) either by beta minus emission to $^{152}$Gd, or via electron capture to $^{152}$Sm, both of which are stable daughters.

The isotope $^{152}$Sm has an excited state ($I^\pi = 2^+$) at 121.8 keV with $t_{1/2} = 1428 \pm 17$ ps [25], whose half-life was measured using the DANTE array. It will be shown later that the measurement obtained using DANTE is more precise than most previous measurements [25].

### 3.2 Integrating the DANTE Array into the 8$\pi$ at TRIUMF-ISAC

#### 3.2.1 Instrumentation Setup and Connections

The DANTE detectors were mounted in the 8$\pi$ frame, and the dynode outputs from their voltage dividers were connected to Ortec 113 pre-amplifiers for each detector. These pre-amplifiers were then connected to Ortec 855 dual amplifiers for processing dynode energy signals. The anode outputs were connected to Ortec 935 quad CFDs for processing timing signals. All three outputs available from each CFD in the Ortec quad module were used. One of the outputs was connected to the start input of an Ortec 566 TAC, which was not externally strobed. The second output was connected to a LeCroy 429A FIFO (Fan-In/Fan-Out) module, which fed signals to an Ortec CO4020 four-input logic module that is hardware-designed to do OR logic and send stop signals to the TACs (Figs. 34 and 35). The logic modules were set to prevent detector self-timing. The third output of the CFD sent signals to trigger logic circuitry which
gated the associated ADC readouts. The energy threshold of the CFD was used to remove noise triggering from the timing and energy readouts in the electronics. The width of the output pulse from each CFD was set to 200 ns.

Figure 34. Simplified schematic of signal flow in the $8\pi$ with four BaF$_2$ detectors operating. The flow of data is shown up to the readout of the ADCs.

Figure 34 shows the input and output connections of the FIFO and logic modules for the full array of ten DANTE detectors, although at the time of the experiment, only four of the ten were fully-instrumented as shown in Figure 35. The remaining input connections to the FIFOs for detectors 5 through 10 were not used, though all outputs from the FIFOs were connected as inputs to the logic modules stopping detectors 1 through 4.
The TAC and amplifier outputs were connected to Ortec AD413A ADCs, which are Fast Encoding Readout ADC (FERA) bus compatible modules, capable of binning digitized data into 8192 channels. Energy and time signals can be read out from these modules on an event by event basis.

3.2.2 The 8π MIDAS Data Acquisition System

At TRIUMF, data acquisition is done using a program called the Maximum Integrated Data Acquisition System (MIDAS) [37], with a web-based interface as shown in Figure 36. MIDAS controls subprograms which acquire different streams of data from the ADCs connected to the various detectors in the 8π
array. These raw data streams are written to computer disk in binary format if the user sets an option to do so. MIDAS also interfaces with the Experimental Physics and Industrial Control System (EPICS) [38] which is used to display, in real time, scaler readouts from the $8\pi$ detectors. It is also used with a slow control system to monitor vacuum pressure, electronics shack temperatures, etc.

![Figure 36](image)

Figure 36. The MIDAS control window, showing a typical situation in which a run has been stopped, but otherwise all aspects of the DAQ are operational except for EPICS.

MIDAS utilizes an Online Database (ODB), which contains experimental parameters alterable on a run by run basis. The ODB contents are written to disk each time a new run is initiated. Some important parameters include the run
number, time stamp, trigger condition, beam cycle time, tape movement cycle, etc. Most of the parameters can be modified as desired by the user\(^1\).

An analyzer program, which is part of MIDAS, performs histogramming of spectra recorded from FERA modules connected to the SIS301 Versa Module Europa (VME) crate in the \(8\pi\) electronics shack. In the online mode, it runs in conjunction with the other programs that MIDAS controls. In the offline mode, this program can be run to reprocess (play back) binary data streams from the computer disk, which contain all the events which were recorded under a given trigger condition. This analyzer code was used for subsequent post-experiment analysis of data from the decay of \(^{152}\text{Eu}\).

### 3.2.3 Calibration of TACs

The TACs were set to 100 ns time windows. The \(8\pi\) DAQ (like the PC-based MCA) processed TAC output signals into spectra with discrete bins of 8192 channels, with nominal bin sizes of 12.21 picoseconds per channel\(^\dagger\). To account for instrumental effects, an Ortec 462 time calibrator was used to determine the actual bin size for each TAC. This module outputs start and stop pulses which produce delta functions. A dispersion amplifier in the calibrator produces stop signals spread in a Gaussian distribution to enable a more precise determination of the centroids of the timing peaks. The Ortec 462 module has a specified calibration uncertainty of ±10 ps per 10 ns period, producing a 0.1% systematic uncertainty. It was set to a period of 0.01 \(\mu\)s and a range of 0.08 \(\mu\)s,

---
\(^1\) In principle, all of them (even the run number) could be changed at any time but it is likely that changing such parameters in the middle of a run would render that run’s data set unusable.
\(^\dagger\) Dividing 100000 picoseconds (100 nanoseconds) by 8192 channels = 12.21 ps/ch.
outputting pulses over a 20 – 100 ns range, separated by 10 ns for each TAC being calibrated. This is similar to the time distribution of the TAC spectra during the $^{152}$Eu experiment.

Two calibrations were performed; one was undertaken two weeks prior to the experiment and a second one immediately after the experiment. The results for the second calibration are reported here. There was an overall drift of $\pm 0.009$ ps/channel between the first and second calibration, included as a systematic contribution in the uncertainties reported here.

The calibration spectrum for TAC 1 is shown in Figure 37. Other TACs showed similar spectra. Peak centroids were determined by Gaussian fits, after which a weighted linear regression of centroid channel number against time was used to determine the TAC bin size in picoseconds per channel. The TACs in the

Figure 37. TAC calibration spectrum for TAC 1 in the $8\pi$ electronics shack.
$8\pi$ electronics shack binned time events at $\sim12.5$ picoseconds per channel; detailed results are shown in Table 2.

**Table 2.** Results of TAC calibrations. The total error adds, in quadrature, the statistical error, TAC drift, and the intrinsic accuracy of the TAC Calibrator and converts to an absolute error.

<table>
<thead>
<tr>
<th>TAC</th>
<th>Slope (ps/ch)</th>
<th>Statistical Unc. (ps/ch)</th>
<th>TAC Calib. Unc. (ps/ch)</th>
<th>TAC Drift Unc. (ps/ch)</th>
<th>Total Unc. (ps/ch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.5963</td>
<td>0.0029</td>
<td>0.013</td>
<td>0.009</td>
<td>0.016</td>
</tr>
<tr>
<td>2</td>
<td>12.4876</td>
<td>0.0019</td>
<td>0.013</td>
<td>0.009</td>
<td>0.016</td>
</tr>
<tr>
<td>3</td>
<td>12.4238</td>
<td>0.0038</td>
<td>0.013</td>
<td>0.009</td>
<td>0.016</td>
</tr>
<tr>
<td>4</td>
<td>12.5968</td>
<td>0.0018</td>
<td>0.013</td>
<td>0.009</td>
<td>0.016</td>
</tr>
</tbody>
</table>

**3.3 Experimental Run**

**3.3.1 Preparation of Software and Instrumentation**

A $^{60}$Co source, mounted at the beam-spot position of the $8\pi$ target chamber, was used for calibration purposes to measure timing characteristics dominated by instrumental effects and to check TAC drift. The $^{60}$Co data was analyzed to check for any degradation in the detectors between the lab testing phase and mounting of the DANTE detectors in the $8\pi$.

The results from using the $^{60}$Co source yielded an average FWHM of 270 ± 8 picoseconds in the timing peaks; details are noted in Table 3. These results were obtained by applying a software double energy gate, requiring that one detector of a coincidence pair detect an energy signal in range 1 of Figure 38, and that the other one detect an energy signal in range 2. Only then was the event accepted in the time spectrum for that coincidence pair.

Although the time resolutions obtained were slightly worse than those obtained in the lab testing phase, they did not differ appreciably from one another
when the detectors were mounted in the $8\pi$. This is not unexpected, given the presence of longer cables and more complex instrumentation of the $8\pi$ array.

![Figure 38.](image)

**Figure 38.** The regions “1” and “2” of this $^{60}$Co energy spectrum show the two energy gates taken, one in each detector of a coincidence pair, to establish prompt timing characteristics in the $8\pi$ for the DANTE detectors.

**Table 3.** The characteristics of the BaF$_2$ detectors used in the $8\pi$ array at the time of the $^{152}$Eu experiment. Timing resolutions are quoted only for detectors actually used in the experiment. Compare to Table 1.

<table>
<thead>
<tr>
<th>DANTE Det. #</th>
<th>PMT Serial #</th>
<th>Scionix Crystal Serial #</th>
<th>Energy Resolution at 662 keV (%)</th>
<th>Time peak FWHM (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>42036</td>
<td>0568</td>
<td>12.0</td>
<td>N/A</td>
</tr>
<tr>
<td>02*</td>
<td>42152</td>
<td>0565</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>03</td>
<td>42138</td>
<td>0567</td>
<td>9.5</td>
<td>268</td>
</tr>
<tr>
<td>04</td>
<td>42186</td>
<td>0563</td>
<td>9.1</td>
<td>242</td>
</tr>
<tr>
<td>05</td>
<td>42205</td>
<td>0566</td>
<td>10.9</td>
<td>N/A</td>
</tr>
<tr>
<td>06</td>
<td>42222</td>
<td>0562</td>
<td>9.7</td>
<td>N/A</td>
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<tr>
<td>07</td>
<td>42225</td>
<td>0571</td>
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<td>259</td>
</tr>
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<td>09</td>
<td>42232</td>
<td>0569</td>
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<tr>
<td>10</td>
<td>42233</td>
<td>0570</td>
<td>11.3</td>
<td>N/A</td>
</tr>
</tbody>
</table>

\* This detector was not mounted in the array.
The energy resolutions of the DANTE detectors were measured using a $^{137}$Cs source to check for degradation of energy resolution. The results are summarized in Table 3. In general there did not appear to be a systematic effect on energy resolution; some detectors had slightly improved resolutions while others had slightly degraded resolutions, compared to the lab test results.

The Ortec 935 CFD energy thresholds were set slightly above the noise level, which corresponded to approximately 30 keV. The CFD walks were adjusted, as explained in section 2.2.4, to ensure optimal timing characteristics. The Ortec 855 amplifier gains were set to produce output energy signals over the range of zero to 2 MeV, corresponding to approximately 0.25 keV per channel.

Figure 39. The east (a) and west (b) halves of the 8$\pi$ are shown with numbered cylindrical-conical crystals (brown) showing the placement of the DANTE detectors in the gaps of the existing HPGe array’s frame, as well as the BGO Compton suppressors (red), Heavimet collimators (blue) and HPGe front faces (green). Images courtesy Smarajit Triambak.
The four detectors which were used in the coincidence timing measurements have two numbering schemes. One scheme is their physical positioning in the array as shown in Figure 39(a) and 39(b). A second scheme, used in the post-experiment processing and $8\pi$ DAQ, relates the physical positioning to the alternate numbering, denoted by the numbers in parentheses in Fig. 39(a) and (b) and in Table 4. The detectors will be exclusively referred to by the second scheme for the remainder of this thesis.

<table>
<thead>
<tr>
<th>Physical Detector</th>
<th>Logical Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>DANTE07</td>
<td>Det #1</td>
</tr>
<tr>
<td>DANTE08</td>
<td>Det #2</td>
</tr>
<tr>
<td>DANTE03</td>
<td>Det #3</td>
</tr>
<tr>
<td>DANTE04</td>
<td>Det #4</td>
</tr>
</tbody>
</table>

**Table 4.** Correlation between physical detector placement and logical detector numbering in the post-experiment analysis.

3.3.2 Experimental Data Acquisition

A $^{60}$Co source, as mentioned previously, was used to monitor TAC drift between the start and end of the experiment. It was found that the prompt timing peaks shifted by approximately $1.4 \pm 0.4$ channels between the beginning and end of the experiment. This had a negligible effect on the results obtained.

During the course of the experiment, both singles and coincidence mode data were taken with the $^{152}$Eu source mounted at the beam-spot position of the $8\pi$ target chamber. The singles mode data was taken once per day to check for amplifier gain drift. The coincidence mode data (usually taken over a 24-hour period between singles runs) was used for timing measurements. TAC drift was negligible during the experiment. This was qualitatively assessed by overlaying
the TAC spectra from different runs. On the other hand, energy spectra exhibited sizable gain drifts due to temperature fluctuations. Some high-energy gamma ray peaks drifted by up to 25 keV between some runs. This effect was corrected in software.

The coincidence mode trigger logic allowed for double coincidences of two BaF$_2$ detectors. Alternatively a triple coincidence between one HPGe detector and two BaF$_2$ detectors was accepted. The BaF$_2$-BaF$_2$ coincidence data was used to measure lifetimes, while the HPGe-BaF$_2$-BaF$_2$ coincidences can be used to place an energy gate on a known gamma ray in the cascade of $^{152}$Sm to attempt to improve lifetime measurements$^1$.

A total of 30 million coincidence events were recorded; the BaF$_2$-BaF$_2$ doubles events (including those in which the HPGe array provided the initial trigger) were used to construct the spectra used in offline analysis via the analyzer.

---

$^1$ This technique was not used, owing to very poor statistics when attempting this gating method.
Table 5. Simplified structure of a BaF$_2$-BaF$_2$ coincidence event, showing the portions relevant to the analysis of lifetimes.

<table>
<thead>
<tr>
<th>Detector Event Type</th>
<th>Number of Amplifier ADC signals</th>
<th>Number of TAC ADC signals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector # i</td>
<td>Detector # j</td>
<td></td>
</tr>
<tr>
<td>ADC number i</td>
<td>ADC number j</td>
<td></td>
</tr>
<tr>
<td>Energy readout from ADC</td>
<td>Energy readout from ADC</td>
<td></td>
</tr>
<tr>
<td>TAC number i</td>
<td>TAC number j</td>
<td></td>
</tr>
<tr>
<td>TAC readout via ADC</td>
<td>TAC readout via ADC</td>
<td></td>
</tr>
</tbody>
</table>

BaF$_2$-BaF$_2$ coincidence events are those in which any two detectors numbered $i$ and $j$ ($i \neq j$, where $i = 1 \ldots 4$, $j = 1 \ldots 4$) sent signals to the DAQ. There are six unique combinations of coincidence pairs: (1, 2), (1, 3), (1, 4), (2, 3), (2, 4) and (3, 4). Table 5 outlines the important components of the event structure.

3.4 Post-Experiment Analysis

3.4.1 Gain Matching

As mentioned in the previous section, the peak centroids in the ADC spectra from HPGe and BaF$_2$ detectors were found to drift over the course of the experiment. This was mainly due to temperature-dependent gain drift in the HPGe and BaF$_2$ detector amplifiers and photomultiplier tube gain drift for the BaF$_2$ detectors.

Before the start of the experiment, the $^{60}$Co source was used to initially gain match the BaF$_2$ and HPGe detectors using the 1173 and 1332 keV peaks, so that all the ADC spectra showed peaks at the same channel numbers. However owing to the above-mentioned drift during the experimental run, off-line software correction (gain matching) of the spectra was required. Successful gain
matching results in complete alignment of the gamma rays in all energy spectra summed over all runs.

For this procedure, first the raw ADC spectra from the individual detectors were extracted on a run by run basis. Then, gamma ray peaks from the $^{152}$Eu source with precisely-known energies were Gaussian fitted and their centroids were recorded.

The next step was to use a quadratic fit,

$$E_n = a_n x^2 + g_n x + o_n$$  \hspace{1cm} (28),

to conduct a weighted regression of peak energies versus their centroids. The resulting fit coefficients were stored on a run by run basis, with each detector having its own set of gain correction coefficients.

In equation 28, for the $n$th detector, $E_n$ is the gain matched energy, $x$ is the channel number, $a_n$ represents the nonlinearity term, $g_n$ represents the gain, and $o_n$ represents the offset. Quadratic fits were used for gain matching both HPGe and BaF$_2$ ADC spectra. The nonlinearity term for BaF$_2$ detectors was found to be negligible, being on the order of $10^{-6}$ keV/channel$^2$.

3.4.2 Half-Life Measurements

3.4.2.1 Selection and Application of Energy Gates

The data from the experiment and the code to analyze the data were copied to a separate computer for offline re-analysis. Several modifications were made to this offline analyzer program, which are discussed later in this section.
The purpose of the experiment is to determine the half-life of the 122 keV state in $^{152}$Sm, using the gamma ray of the same energy in coincidence with gamma rays that feed the state. Coincidence events consist of one detector detecting a 122 keV gamma ray while the other detector detects gamma rays which feed the state from above, as seen by following the decay scheme in Figure 33. Since the gamma rays are well-separated in energy, the method of double energy gating can be used, similar in principle to that employed on $^{60}$Co spectra, as discussed in Section 3.3.1.

![Figure 40](image.png)

**Figure 40.** A gain matched coincidence mode spectrum from detector #4 in coincidence with detector #1, 2, or 3, labelled with gamma ray energies in keV. The black bars show the chosen energy gate region which was applied to that detector to extract time spectra. The region below 70 keV has been omitted.

In order to apply double energy gates, the analyzer program was modified to output gain matched energy spectra for all unique detector coincidence pairs by using the gain coefficients extracted via the procedure discussed in section 3.4.1. The energy gating region about the 122 keV peak associated with the
transition was selected from the gain-matched spectra (Fig. 40). The effect of Compton scattering from higher-energy gamma rays was established by comparing the ratio of peak to background areas for the full peak width and for the region covered by the energy gate, which was approximately over the range of the FWHM.

The ratio of peak to background area for the full peak width at 122 keV was $1.164 \pm 0.005$, while the peak to background over the FWHM range was $1.372 \pm 0.007$. The Compton scattering contribution to the prompt timing was thus reduced by approximately 15% by applying the stringent energy gate as shown in Figure 40 by the black vertical lines.

After setting the energy gate, the coincidence mode data sets were sorted. During the sorting, the analyzer created data files consisting of energy-gated energy-time matrices (which are two-dimensional file structures in which the y axis contains energies and the x axis, TAC signals). In the case of the detector pair used as an example in this section, the energy-gated time signals from detector #4 and the energies recorded by detector #3 were binned in an E vs. T matrix, referenced in terms of the (x, y) axes of the matrix as a $(T_4, E_3)$ matrix. More generally, these matrices are labelled as $(T_j, E_i)$ for a gate on the 122 keV transition seen in $E_i$, where $i$ and $j$ have been defined in Section 3.3.2.

The energy-time matrices were written in a format which could be read in by gf3m, a modified version of gf3 [39]. Twelve separate energy-gated matrices were written, which consisted of events associated with gated $(T_j, E_i)$ pairs, ranging from $(T_1, E_2)$ to $(T_4, E_3)$. 
The y-projection of the energy-time matrix, as shown in Figure 41 from the \((T_4, E_3)\) matrix, shows the gated energy spectrum for detector #3. As expected, the intensity of the 122 keV peak has been reduced. The remaining intensity of the peak in the gated spectrum shows that there were events where Compton-scattered gamma rays from higher energy peaks entered the 122 keV gate on detector #4 in coincidence with the 122 keV transition in detector #3.

Further, the noticeable reduction in intensity of the 344 keV peak, associated with the \(^{152}\text{Gd}\) daughter of \(^{152}\text{Eu}\) shows that the energy gate applied to the 122 keV transition was largely effective in removing contributions from that daughter’s excited states.

**Figure 41.** The energy spectrum projected out for detector #3 after gating on the 122 keV gamma ray in detector #4. The black lines represent two energy gate regions, a narrow energy gate taken around the 244 keV peak (region 1) and a wider energy gate from approximately 200 keV to 1500 keV (region 2). The region below 70 keV has been omitted.

The second energy gate was set, after projecting the y axis of the matrix file, either in a region around the 244 keV gamma ray (which is the gamma ray
which directly feeds the 122 keV state), or on a region from 200 to 1500 keV, both of which are shown in Figure 41. The time projection from the \((T_4, E_3)\) matrix with the wider energy gate is shown in Figure 42.

![Figure 42](image)

**Figure 42.** The time spectrum from the \((T_4, E_3)\) matrix after double gating the 122 keV transition in detector #4 and the 200-1500 keV range in detector #3.

3.4.2.2 Fitting Time Spectra to Obtain Half-Lives

After the double gate was applied, the resulting projected time spectra were written to disk as ASCII files for input to a fitting algorithm modified from one originally designed for precision half-life measurements for the superallowed beta-decay program conducted by the 8π group at TRIUMF [14,40,41]. The program, called 8pifit, is designed to determine half-lives via a \(\chi^2\) minimization process of initial guesses provided to it.

In the limit of a large number of counts in each bin of a time spectrum, each data point has a randomly distributed uncertainty equal to the square root of the value in that bin; this assumes the uncertainty is distributed in a Gaussian
fashion. This is *not* a good approximation when the number of counts is not very large, and is a result of Poisson statistics governing radioactive decay rather than Gaussian statistics. In such cases, the error is best expressed by the ‘maximum likelihood’ and the fitting program described previously was designed specifically to calculate data point errors by that method. An excellent overview of the use of maximum likelihood in fitting experimental data is described by M. Trinczek [42], as well as G. F. Grinyer [40].

The program conducts a $\chi^2$ minimization using the Marquardt-Levenberg algorithm [43] after being provided with initial guesses for parameters of a fit function. It reads in the data set from the time spectrum and outputs a half-life based on the fit function

$$f(t) = A_0 e^{-\lambda t} + Bkg$$

(29).

**Table 6.** Parameters for half-life measurements using the fit function in equation 29.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_0$</td>
<td>Extrapolated to $t = 0$ by 8pifit</td>
<td>Normalization constant</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>$\ln(2) / 1450$ ps = 0.0004780 ps$^{-1}$</td>
<td>$^{152}$Sm decay rate</td>
</tr>
<tr>
<td>Bkg</td>
<td>0.1 counts/ps</td>
<td>TAC random coincidences</td>
</tr>
</tbody>
</table>

Table 6 describes the free parameters used for the half-life measurements and their initial values. Convergence to a result was required prior to 500 iterations. The 8pifit program displayed the following outputs for each time spectrum that was fitted:

- The fitted value half-life and uncertainty,
- The background level, which was typically on the order of 0.01 counts per picosecond,  
- The $\chi^2/\nu$ of the fit, which was typically very close to 1.
Deconvolution of the prompt peak from a decaying exponential component is more challenging. Therefore, the technique of channel chopping was employed to determine the region of the fit in the time spectrum where half-life measurements are not affected by prompt or instrumental contributions.

To employ the technique of channel chopping, first the data in the time spectrum from Figure 42 was reversed.

![Figure 43. A typical exponential fit of the time spectrum in Figure 42. The time base is 12.49 ± 0.02 ps/channel. The half-life was measured to be 1478 ± 17 ps. The $\chi^2/\nu$ of this fit is 0.97.](image)

The reversing of the data set was required to correctly fit it using the model expressed in equation 29. Figure 43 shows a typical range over which the spectrum was fitted. The region over which the fits were made was chosen to ensure that the decay is exponential in nature with only the constant background contributing to the activity being measured.
The instrumental response also affects the time spectrum in a non-negligible fashion when the activity of the excited state reaches background levels. The end channel of a fit region must be chosen such that this instrumental influence does not affect the precision of the measurement of the half-life.

The systematic chopping of channels was done by choosing an initial range from the prompt peak to 1000 channels after it. Channels were removed from the beginning of the fit in steps of twenty channels at a time. The half-life was determined each time. Figure 44 shows the influence of the prompt contributions to half-life measurements.

![Graph showing the effect on the half-life of removing channels from the beginning of the range of the time spectrum shown in Figure 56 to use with an exponential fit. The step size was 20 channels removed per fit iteration.](image)

**Figure 44.** Graph showing the effect on the half-life of removing channels from the beginning of the range of the time spectrum shown in Figure 56 to use with an exponential fit. The step size was 20 channels removed per fit iteration.

A similar process was undertaken to determine the effect of removing channels from the end of the time spectrum, by fixing the start channel at 300
channels after the prompt peak, and chopping from the end channel systematically. Initially the end channel number was set at 1200 channels after the prompt peak. Figure 45 shows the effect of instrumental response on the half-life measurement.

![Graph showing the effect on the half-life of removing channels from the end of the range of the time spectrum in Figure 56 to use with an exponential fit. The step size was 20 channels removed per fit iteration.](image)

**Figure 45.** Graph showing the effect on the half-life of removing channels from the end of the range of the time spectrum in Figure 56 to use with an exponential fit. The step size was 20 channels removed per fit iteration.

After the channel chops were done for all double energy-gated time spectra for the twelve detector combinations, it was found that when chopping channels from the beginning of the time spectra, stabilization of the measurements occurred no later than 260 channels after the prompt peak for any detector combination. When chopping channels from the end of the time spectra, the half-life measurements remained stable well into the middle of the time spectra.
The differences in the nature of the stabilization between Figures 44 and 45 (which are representative of the general channel-chopping results for all time spectra) show that the half-life measurements are insensitive to instrumental effects when doing repeated channel chopping from the end of the fit region. By contrast, repeated channel chopping from the beginning of the fit region shows that the half-life measurements are very sensitive to prompt and instrumental contributions at the beginning of the time spectrum, so this technique is particularly valuable for determining the best ranges for the fit regions in order to measure the half-life of interest.

3.4.2.3 Results of Fitting Time Spectra with a Wide Energy Gate

Table 7 shows the effect of changing both the start and the end channels in a systematic manner, keeping the same number of channels for all twelve fits. The individual detector pair results are reported along with weighted averages whose uncertainties have been increased by multiplying them by the square root of the $\chi^2/\nu$, if larger than one (as recommended by the Particle Data Group [44]), prior to reporting the final results. This adjustment accounts for systematic contributions to the data sets whose origin is not immediately identifiable.

When taking a wide second energy gate from 200 – 1500 keV, the fit ranges from 300 past the prompt peak to 1000 or 1100 channels yielded data sets with $\chi^2/\nu$ values of 3.09 and 2.98, respectively. By comparison, the fit ranges from 400 to 1000 or 1100 channels resulted in data sets with $\chi^2/\nu$ values of 0.91 and 1.11, respectively. This indicates that variation of the start channel has a systematic effect, but variation of the end channel does not. This is also borne
out by the intermediate $\chi^2/\nu$ value of 1.43 for the intermediate fit range of 350 – 1050 channels.

Table 7. Summary of half-lives and errors for various fit ranges using a wide energy gate. Each range is the start and stop channel number relative to the location of the TAC prompt peak. Errors in the weighted averages are the statistical errors adjusted for the $\chi^2/\nu$ of the data sets.

<table>
<thead>
<tr>
<th>Detector Pair</th>
<th>Half-Life (ps) (300 to 1000)</th>
<th>Half-Life (ps) (300 to 1100)</th>
<th>Half-Life (ps) (350 to 1050)</th>
<th>Half-Life (ps) (400 to 1000)</th>
<th>Half-Life (ps) (400 to 1100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1v2</td>
<td>1468.8 ± 15.2</td>
<td>1449.5 ± 12.7</td>
<td>1434.4 ± 17.1</td>
<td>1425.4 ± 24.5</td>
<td>1405.4 ± 19.5</td>
</tr>
<tr>
<td>1v3</td>
<td>1486.8 ± 16.9</td>
<td>1472.4 ± 14.1</td>
<td>1448.2 ± 18.9</td>
<td>1450.7 ± 27.6</td>
<td>1437.0 ± 22.0</td>
</tr>
<tr>
<td>1v4</td>
<td>1396.4 ± 14.2</td>
<td>1412.2 ± 12.2</td>
<td>1436.6 ± 17.6</td>
<td>1391.6 ± 24.4</td>
<td>1420.1 ± 20.2</td>
</tr>
<tr>
<td>2v1</td>
<td>1435.7 ± 15.2</td>
<td>1438.5 ± 12.9</td>
<td>1454.6 ± 18.1</td>
<td>1419.1 ± 25.4</td>
<td>1426.7 ± 20.6</td>
</tr>
<tr>
<td>2v3</td>
<td>1453.1 ± 16.0</td>
<td>1457.8 ± 13.5</td>
<td>1448.7 ± 18.6</td>
<td>1440.4 ± 27.0</td>
<td>1452.8 ± 21.9</td>
</tr>
<tr>
<td>2v4</td>
<td>1424.9 ± 15.0</td>
<td>1431.4 ± 12.7</td>
<td>1450.0 ± 17.9</td>
<td>1425.3 ± 25.6</td>
<td>1435.0 ± 20.7</td>
</tr>
<tr>
<td>3v1</td>
<td>1425.7 ± 14.3</td>
<td>1437.8 ± 12.1</td>
<td>1421.4 ± 16.6</td>
<td>1416.1 ± 24.3</td>
<td>1441.0 ± 19.8</td>
</tr>
<tr>
<td>3v2</td>
<td>1414.2 ± 13.9</td>
<td>1426.2 ± 11.9</td>
<td>1419.0 ± 16.4</td>
<td>1408.8 ± 23.9</td>
<td>1432.0 ± 19.6</td>
</tr>
<tr>
<td>3v4</td>
<td>1478.0 ± 16.7</td>
<td>1482.1 ± 14.0</td>
<td>1493.3 ± 19.9</td>
<td>1495.0 ± 29.0</td>
<td>1497.2 ± 23.0</td>
</tr>
<tr>
<td>4v1</td>
<td>1426.6 ± 14.3</td>
<td>1416.1 ± 12.0</td>
<td>1423.8 ± 16.7</td>
<td>1439.8 ± 24.8</td>
<td>1417.3 ± 19.6</td>
</tr>
<tr>
<td>4v2</td>
<td>1440.7 ± 15.2</td>
<td>1437.8 ± 12.9</td>
<td>1420.5 ± 17.5</td>
<td>1443.2 ± 26.2</td>
<td>1438.7 ± 21.1</td>
</tr>
<tr>
<td>4v3</td>
<td>1456.8 ± 15.9</td>
<td>1462.9 ± 13.4</td>
<td>1459.5 ± 18.6</td>
<td>1429.8 ± 26.3</td>
<td>1447.4 ± 21.4</td>
</tr>
<tr>
<td>Wt. Avg</td>
<td>1440 ± 8</td>
<td>1442 ± 6</td>
<td>1440 ± 6</td>
<td>1430 ± 7</td>
<td>1436 ± 6</td>
</tr>
<tr>
<td>$\chi^2/\nu$</td>
<td>3.09</td>
<td>2.98</td>
<td>1.43</td>
<td>0.91</td>
<td>1.11</td>
</tr>
</tbody>
</table>

The half-life values themselves and their weighted averages are not statistically different from one another within their overlapping uncertainties, showing that the measurements are valid over different fit ranges within the limits established by the channel chopping method. The weighted average of twelve independent measurements from the rightmost column of Table 7 is shown in Figure 46. The rightmost column has a $\chi^2/\nu = 1.11$, and yields a half-life of 1436 ± 6 picoseconds.
Figure 46. Graph of data from the rightmost column of Table 7. The weighted average and its error bars are shown by the black and dashed lines, respectively. The data set has $\chi^2/\nu = 1.11$.

3.4.2.4 Results of Fitting Time Spectra with a Narrow Energy Gate

A similar process of channel chopping was done on time spectra extracted using a narrower energy gate on the 244 keV peak only (refer to Figure 41 for the region of this narrower gate). The projected time spectrum from the $(T_4, E_3)$ matrix using this double-gating method is shown in Figure 47(a). A representative fit of the reversed time spectrum is shown in Figure 47(b). Examples of the effect of channel chopping are shown in Figures 47 (c) and (d).
Figure 47. (a) Time spectrum from the \((T_4, E_3)\) matrix after double gating the 122 keV transition in detector #4 and the FWHM of the 244 keV peak in detector #3. (b) Typical exponential fit of the spectrum in (a) with time base 12.49 ps/channel; measured half-life \(t_\frac{1}{2} = 1473 \pm 43\) ps. \((\chi^2/\nu\text{ of fit } = 0.98)\). (c) Effect on half-life due to removing channels from the beginning of the range of data in (b). (d) Effect on half-life due to removing channels from the end of the range in (b).

The energy gating method in which only the regions of 121 and 244 keV are used produced results with essentially no systematic contribution, as evidenced by the \(\chi^2/\nu\) values for all five fit regions chosen, shown in Table 8. Figure 48 shows a plot of the rightmost column of the table. While this method better isolates the gamma rays of interest, the uncertainties in the results are larger due to lower statistics at each data point.
Table 8. Summary of half-lives and errors using narrower double energy gates. Each range given is relative to the location of the TAC prompt peak. Errors in the weighted averages are the statistical errors adjusted for the \( \chi^2/\nu \) of the data sets.

<table>
<thead>
<tr>
<th>Detector Pair</th>
<th>Half-Life (ps) (300 to 1000)</th>
<th>Half-Life (ps) (300 to 1100)</th>
<th>Half-Life (ps) (350 to 1050)</th>
<th>Half-Life (ps) (400 to 1000)</th>
<th>Half-Life (ps) (400 to 1100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1v2</td>
<td>1449.7 ± 39.5</td>
<td>1428.5 ± 33.0</td>
<td>1393.5 ± 42.7</td>
<td>1308.1 ± 56.1</td>
<td>1310.0 ± 46.4</td>
</tr>
<tr>
<td>1v3</td>
<td>1486.9 ± 46.1</td>
<td>1479.4 ± 38.3</td>
<td>1459.2 ± 50.8</td>
<td>1372.7 ± 67.6</td>
<td>1389.9 ± 55.5</td>
</tr>
<tr>
<td>1v4</td>
<td>1381.4 ± 39.0</td>
<td>1426.5 ± 34.1</td>
<td>1490.0 ± 52.6</td>
<td>1406.6 ± 69.5</td>
<td>1481.6 ± 58.9</td>
</tr>
<tr>
<td>2v1</td>
<td>1408.8 ± 39.8</td>
<td>1420.1 ± 33.9</td>
<td>1439.4 ± 47.7</td>
<td>1393.8 ± 67.1</td>
<td>1415.9 ± 55.1</td>
</tr>
<tr>
<td>2v3</td>
<td>1369.6 ± 37.9</td>
<td>1396.8 ± 32.8</td>
<td>1361.5 ± 43.9</td>
<td>1382.1 ± 67.4</td>
<td>1432.9 ± 56.5</td>
</tr>
<tr>
<td>2v4</td>
<td>1432.7 ± 42.4</td>
<td>1470.8 ± 36.2</td>
<td>1452.0 ± 49.6</td>
<td>1380.1 ± 67.8</td>
<td>1458.8 ± 57.3</td>
</tr>
<tr>
<td>3v1</td>
<td>1418.0 ± 37.2</td>
<td>1388.3 ± 31.1</td>
<td>1378.0 ± 42.5</td>
<td>1437.4 ± 65.0</td>
<td>1380.5 ± 50.5</td>
</tr>
<tr>
<td>3v2</td>
<td>1474.8 ± 39.6</td>
<td>1485.2 ± 33.2</td>
<td>1496.2 ± 47.1</td>
<td>1506.9 ± 69.9</td>
<td>1513.7 ± 55.2</td>
</tr>
<tr>
<td>3v4</td>
<td>1504.3 ± 46.9</td>
<td>1522.3 ± 39.0</td>
<td>1569.2 ± 56.6</td>
<td>1435.4 ± 72.7</td>
<td>1483.0 ± 59.5</td>
</tr>
<tr>
<td>4v1</td>
<td>1426.0 ± 38.6</td>
<td>1437.2 ± 32.8</td>
<td>1407.9 ± 44.1</td>
<td>1399.0 ± 64.2</td>
<td>1427.9 ± 52.7</td>
</tr>
<tr>
<td>4v2</td>
<td>1440.7 ± 37.8</td>
<td>1423.5 ± 31.7</td>
<td>1421.3 ± 43.6</td>
<td>1477.4 ± 67.9</td>
<td>1439.1 ± 53.1</td>
</tr>
<tr>
<td>4v3</td>
<td>1473.8 ± 42.8</td>
<td>1476.6 ± 35.8</td>
<td>1456.6 ± 48.0</td>
<td>1425.8 ± 68.8</td>
<td>1444.9 ± 55.9</td>
</tr>
<tr>
<td>Wt. Avg</td>
<td>1435 ± 11</td>
<td>1442 ± 11</td>
<td>1435 ± 16</td>
<td>1406 ± 16</td>
<td>1425 ± 17</td>
</tr>
<tr>
<td>( \chi^2/\nu )</td>
<td>1.00</td>
<td>1.31</td>
<td>1.41</td>
<td>0.66</td>
<td>1.12</td>
</tr>
</tbody>
</table>

Comparing the data in the rightmost columns of Tables 7 and 8 shows that the method of energy gating does not systematically change the half-life results within their uncertainties. This implies that the results from the higher-statistics data using the wide-gate method can be used for half-life determinations. In addition, the resulting weighted average half-lives themselves from each of the columns are consistent with one another within their uncertainties from both data sets, further indicating that there is no statistically significant systematic effect caused by the energy gating method.
Figure 48. Graph of data from the rightmost column of Table 8. The weighted average and its error bars are shown by the black and dashed lines, respectively. The data set has $\chi^2/\nu = 1.12$.

One possible systematic effect arising from differences between wide gating and narrow gating involves the 60 ps half-life of the 366 keV state in $^{152}$Sm, as noted in Fig. 46. Since any transition above the 122 keV state might trigger the start of a TAC, if a transition feeds the 366 keV state and the 244 keV gamma ray which it emits is not detected, there is an additional delay before the 122 keV gamma ray is detected and stops the TAC. This would, if the time spectra were fitted very close to the prompt peak, introduce an additional grow-in contribution to the decay curve, since a rise in population of the 122 keV state would occur with a time constant characteristic of the 60 ps half-life of the 366 keV state. However, since the fits started at 300 channels (~3750 ps), or even
further, past the prompt peak, this does not affect the present analysis, as borne out by the half-life measurements in Tables 7 and 8.

3.4.3 Presence of $^{154}\text{Gd}$ Contamination

3.4.3.1 Origin of $^{154}\text{Gd}$ Contamination

The $^{152}\text{Eu}$ source was prepared via a high-flux neutron bombardment in a nuclear reactor. The cross-section (denoted by $\sigma$) for neutron capture reactions with $^{151}\text{Eu}$ is between 5000 and 9000 barns [45,46], depending on the incoming neutron energy in the thermal/epithermal region\(^m\). However, since the commercial source was prepared from Europium in which some $^{153}\text{Eu}$ was likely present, there is some contamination from $^{154}\text{Eu}$, since $\sigma_{\text{neutron capture}} \approx 300$ b for $^{153}\text{Eu}$ [45]. This radioactive contaminant would not be an issue if its daughters emitted gamma rays from nuclear excited states with lifetimes $\leq \sim 10$ ps.

However, the $^{154}\text{Gd}$ daughter of $^{154}\text{Eu}$ has an almost-identical low-energy structure to that of $^{152}\text{Sm}$ [47] (Fig. 49), containing a 123 keV state ($I^\pi = 2^+$) of half-life 1.184 ns, fed by a 1274 keV prompt gamma ray emanating from a state at 1398 keV, as well as a 1005 keV gamma ray from a state at 1128 keV. Furthermore, a 248 keV transition ($I^\pi = 4^+ \rightarrow 2^+$) exists in $^{154}\text{Gd}$. Neither the 248 nor the 123 keV transitions in $^{154}\text{Gd}$ can be resolved from the 244 or 122 keV transitions, respectively, with BaF$_2$ detectors.

---

\(^m\) Thermal neutrons have a kinetic energy of approximately 0.025 eV. Epithermal neutrons have kinetic energies in the region of 1 eV; some broader definitions state that epithermal neutrons have energies from 1 eV – 1 MeV.
Figure 49. Electron-capture and beta minus decays of $^{154}$Eu, showing partial level schemes (not to scale) with electron-capture and beta minus branching ratios into the excited states of $^{154}$Sm and $^{154}$Gd. The level energies, transition energies and gamma emission branching ratios from each state are shown; literature half-lives are shown for the first 2$^+$ and 4$^+$ states for $^{154}$Gd. (The Nuclear Data Sheets [47] provide all level energies and half-lives)

Thus, either method of taking double energy gates (narrow or wide) will result in the detection of coincident gamma rays from $^{154}$Gd in addition to the desired coincident gamma rays from $^{152}$Sm. This means the decays of the 123 keV state of $^{154}$Gd can affect the measurement of the half-life of the 122 keV excited state in $^{152}$Sm.

Figure 50 shows that a peak at ~1274 keV is clearly visible above the background in the HPGe energy spectrum, indicating the presence of $^{154}$Gd from the decay of $^{154}$Eu.
3.4.3.2 Measurement of Contamination

In order to correct the measurement of the half-life of $^{152}$Sm $2^+_1$ state for the contamination of the $^{154}$Gd, the summed singles spectrum from the HPGe detectors can be used in order to obtain the ratio of $^{154}$Eu to $^{152}$Eu in the source by means of a relative efficiency curve to account for the energy-dependent detection response of the array and utilize its superior energy resolution for this determination.

To determine the relative efficiency of the HPGe array in the region of 1274 keV, the gamma rays chosen from the $^{152}$Eu source were 1112.069, 1212.948 and 1408.006 keV from $^{152}$Sm, and 1299.140 keV from $^{152}$Gd whose energies and normalized intensities are well-known [1]. The peaks were fitted
with Gaussians and their areas were determined. The background-subtracted areas had uncertainties of less than 1%.

The peak areas were corrected for absolute intensities per 100 decays of the parent isotopes to produce relative efficiencies. The logarithm of relative efficiency was then plotted against the logarithm of energy. The fit formula used was

\[ \ln(\varepsilon) = a_0 + a_1 (\ln E) \]

(30),

where \( \varepsilon \) is the relative efficiency, and \( E \) is in keV. A weighted fit was performed, yielding the coefficients shown in Table 9, which were used to generate the curve in Figure 51.

The \( \chi^2/\nu = 0.12 \) for the fit parameters from the input data, showing that a linear fit is appropriate because the range of energies chosen, being only 20% of full-scale, is in a region where the \( 8\pi \) HPGe detectors have been shown to have a generally linear relationship between \( \ln \varepsilon \) and \( \ln E \) [40,41,48] in the energy range 400 keV – 2000 keV.

Table 9. Coefficients obtained for equation 30.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Value</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_0 )</td>
<td>15.41</td>
<td>0.17</td>
</tr>
<tr>
<td>( a_1 )</td>
<td>-0.797</td>
<td>0.023</td>
</tr>
</tbody>
</table>
Figure 51. Relative efficiency curve for the region from 1200 to 1450 keV, using four known gamma ray peaks in $^{152}\text{Sm}$ and $^{152}\text{Gd}$ in the vicinity of the 1274 keV peak. The energy in keV is on the x axis (note the logarithmic scale) and the relative efficiency, in arbitrary units, is on the y axis.

If the 1274 keV gamma ray was emitted from $^{152}\text{Eu}$ (i.e. if it was emitted from a pure source of $^{152}\text{Eu}$, assuming the transition existed in its daughters), its relative efficiency data point should lie along the curve in Figure 51. However, since the source is not pure, the predicted relative efficiency will differ from the relative efficiency obtained by correcting the peak area for the absolute intensity of the gamma ray per 100 decays of the parent $^{154}\text{Eu}$.

After substituting $E = 1274.426$ keV into equation 30, the predicted relative efficiency can be divided by the corrected relative efficiency. This yields the ratio $C$ (denoting the activity of $^{154}\text{Gd}$ as $A_{154}$ and the activity of $^{152}\text{Sm}$ as $A_{152}$ and similarly for their associated relative efficiencies) expressing the presence of contamination,
\[ C = \frac{E_{154}}{E_{152}} = \frac{A_{154}}{A_{152}} \]

(31a).

Numerically obtaining this ratio follows:

\[
\frac{(\ln\epsilon)_{\text{corrected}}}{(\ln\epsilon)_{\text{predicted}}} = \frac{4.75 \pm 0.02}{9.7166 \pm 0.0006}
\]

(31b).

\[
C = \frac{\exp(4.75 \pm 0.02)}{\exp(9.7166 \pm 0.0006)} = \frac{115 \pm 2}{16590 \pm 11} = 0.00699 \pm 0.00003
\]

(31c).

The uncertainty was calculated by adding, in quadrature, the relative uncertainties in the efficiency values and converting to an absolute error.

3.4.3.3 Quantifying the Effect of $^{154}$Gd Presence on Half-Life Measurements

To determine the effect of $^{154}$Gd, an additional contribution to the decay curve was modelled as a decaying background of a given intensity and known half-life. Thus, the fit function was modified:

\[
f(t) = A_0 e^{-\lambda t} + A_1 e^{-\lambda' t} + B_{\text{kg}}
\]

(32).

The parameters as defined for equation 29 are the same here. The new parameter $A_0'$ is the intensity of the $^{154}$Gd contaminant, and $\lambda'$ is its decay constant.

The value of $A_0'$ includes an adjustment to the contaminant percentage due to the differing relative intensities of the $^{152}$Sm and $^{154}$Gd $2_1^+ \rightarrow 0^+$ transitions, as they both enter into coincidence events. The intensity of the 122 keV gamma ray from $^{152}$Sm, minus direct feeding by electron capture, is 26.87%.
The intensity of the 123 keV gamma ray from $^{154}\text{Gd}$, minus direct feeding by beta minus decay, is 34.78%. Therefore, the corrected ratio $C'$ is

$$C' = 0.00699 \times \frac{I_{^{154}\text{Gd}}(2^+)}{I_{^{152}\text{Sm}}(2^+)} = 0.00699 \times \frac{0.3478}{0.2687} = 0.00905 \pm 0.00003 \quad (33).$$

This new ratio is then corrected for the decay of the excited states of $^{152}\text{Sm}$ and $^{154}\text{Gd}$, denoting the activities of the states at some time after the prompt peak, $t_{\text{elapsed}}$ (on the order of 3750 ps or longer), by $A'_{^{152}\text{Sm}}$ and $A'_{^{154}\text{Gd}}$ respectively,

$$\frac{A'_{^{154}\text{Gd}}}{A'_{^{152}\text{Sm}}} = C' \left( \frac{e^{-\lambda_{^{154}\text{Gd}} t_{\text{elapsed}}}}{e^{-\lambda_{^{152}\text{Sm}} t_{\text{elapsed}}}} \right) = C'e^{-(\lambda_{^{152}\text{Sm}} - \lambda_{^{154}\text{Gd}}) t_{\text{elapsed}}} = C'' \quad (34a),$$

$$\therefore A'_{^{154}\text{Gd}} = C''A'_{^{152}\text{Sm}} \quad (34b).$$

The new $t = 0$ is redefined to the first bin of the truncated data set. The approximation is made that $A_0' \approx A'_{^{154}\text{Gd}}$ and that $A_0 \approx A'_{^{152}\text{Sm}}$. Thus, the value of the first bin in the truncated set is multiplied by the correction factor derived in equations 33a and 33b to obtain $A_0'$.

Table 10 describes the parameters used in the fitting, whether they were fixed or free, and their initial values. After setting the new parameters, the 8pifit program was re-run. All the data points in Figure 55 (rightmost column of Table 7) shifted upward by an average of 1 picosecond. The weighted average also shifted by this much, as discussed in the next section.
Table 10. Parameters for half-life measurements using the fit function in equation 32.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda'$</td>
<td>$\ln(2) / 1184 \text{ ps} = 0.0005854 \text{ ps}^{-1}$</td>
<td>Contaminant decay rate</td>
</tr>
<tr>
<td>$A_0'$</td>
<td>(fixed)</td>
<td>Contaminant intensity</td>
</tr>
<tr>
<td>$A_0$</td>
<td>(free)</td>
<td>$^{152}\text{Sm}$ intensity</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>$\ln(2) / 1450 \text{ ps} = 0.0004780 \text{ ps}^{-1}$</td>
<td>$^{152}\text{Sm}$ decay rate</td>
</tr>
<tr>
<td>Bkg</td>
<td>0.1 counts/ps</td>
<td>Random TAC coincidences</td>
</tr>
</tbody>
</table>

3.4.4 Final Results

After fitting the time spectra, accounting for contamination from $^{154}\text{Gd}$, the resulting weighted average half-life became $1437 \pm 6 \text{ ps}$ after multiplying by the square root of $\chi^2/\nu$, which was 1.11 for the data set. Table 11 compares the central values of the weighted average half-lives and their associated uncertainties, with a total uncertainty obtained by adding the individual uncertainties in quadrature. The systematic contribution from the $^{154}\text{Gd}$ contaminant is already accounted for in the weighted average quoted in the rightmost column.

Table 11. Summary of half-lives and associated errors.

<table>
<thead>
<tr>
<th></th>
<th>Without Contaminant</th>
<th>With Contaminant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half-life</td>
<td>1436 ps</td>
<td>1437 ps</td>
</tr>
<tr>
<td>Half-life Uncertainty</td>
<td>6 ps</td>
<td>6 ps</td>
</tr>
<tr>
<td>TAC Calibration</td>
<td>2 ps</td>
<td>2 ps</td>
</tr>
<tr>
<td>Total Uncertainty (in quadrature)</td>
<td>7 ps</td>
<td>7 ps</td>
</tr>
</tbody>
</table>

A systematic uncertainty of $\pm0.016 \text{ ps/channel}$ noted in the TAC calibration section, inherent to the conversion of channel numbers to time units, is also included in the error budget of the half-life measurement. This systematic
uncertainty produces an additional error of ±2 ps, arrived at by multiplying the relative TAC uncertainty by the half-life and rounding.

3.4.5 Comparison to Previous Literature Values

There have been many previous measurements of the half-life associated with the $2^+ \to 0^+$ transition in $^{152}$Sm. An evaluation, which was compiled by S. Raman, C. W. Nestor, Jr., and P. Tikkanen in 2001 [25], contains all known previous work from 1955 to 2001. For the ease of comparison to the values shown in the evaluation, the half-life obtained in this work will be converted to a lifetime (sometimes termed a mean-life), and the uncertainty appropriately scaled. Thus, the $t_{1/2}$ of 1437 ± 7 ps is equal to $\tau = 2073 \pm 10$ ps.

Most of the previous work done on $^{152}$Sm has been either via Coulomb excitation using proton or alpha particle beams, or by FEST (called delayed coincidence in the evaluation). The delayed coincidence measurements primarily used $^{152}$Eu populating the state via electron capture, but there is a measurement involving the $\beta^-$ decay of $^{152}$Pm, denoted by “1991He03” [49].

The evaluation adopts a lifetime of 2060 ± 25 ps; the method by which the uncertainty is obtained utilizes weights which are proportional to the reciprocal of the uncertainties, not their squares. A weighted-average calculation (using the reciprocals of the squares of the individual uncertainties) of the data set, omitting this work as well as two measurements with extremely large error bars from the late 1950s is shown in Fig. 52. The resulting $\tau_{average} = 2043 \pm 7$ ps ($\chi^2/\nu = 1.23$).
The literature values do not appear to have a systematic bias over time. However, $\chi^2/\nu = 1.23$ is very high for the weighted average involving thirty-four measurements, indicating possible systematic effects.

The value of $2073 \pm 10$ ps, obtained in the present work, is three standard deviations away from the weighted mean. The most precise value reported previously, $(1988\text{Ka}21$ [50]) of $\tau = 2014 \pm 10$ ps also differs by three standard deviations from the weighted mean. Removing this value from the total data set in Figure 52 shifts the weighted average lifetime, by three standard deviations, to $2065 \pm 9$ ps, in agreement with the present work, and reduces the $\chi^2/\nu$ to 0.81, an acceptable value.
After combining the present value with all previous measurements the weighted average becomes $2052 \pm 6$ ps ($\chi^2/\nu = 1.38$); omitting “1988Ka21” yields a new weighted average of $2068 \pm 7$ ps ($\chi^2/\nu = 0.79$), shown in Fig. 53.

![Figure 53. Compilation of thirty-four measurements of the lifetime of the first $2^+$ state of $^{152}$Sm, including the present work and omitting the value of 1988Ka21. The weighted average lifetime is shown with a black line; its error bar is shown by the dashed lines above and below. The data set has $\chi^2/\nu = 0.79$. (Data is from this work and [25])](image)

### 3.4.5.1 Delayed-Coincidence Method

The delayed-coincidence technique subset (including the present work), yields a weighted average lifetime of $2041 \pm 7$ ps with $\chi^2/\nu = 1.86$ (Fig. 54). If the work labelled “1988Ka21” is omitted, the resulting new weighted average lifetime is $2061 \pm 9$ ps, with $\chi^2/\nu = 0.97$. 

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Figure 54. Compilation of thirteen delayed-coincidence measurements of the lifetime of the first 2\(^+\) state of \(^{152}\)Sm, along with the present work shown on the far right. The weighted average lifetime is shown with a black line; its error bar is shown by the dashed lines above and below. The data set has \(\chi^2/\nu = 1.86\). (Data is from this work and [25])

3.4.5.2 Coulomb Excitation Method

The Coulomb excitation measurements show a clear divergence from the weighted average of the delayed coincidence measurements. The weighted average lifetime from all the Coulomb excitation results (Figure 55) was calculated to be 2088 ± 15 ps (\(\chi^2/\nu = 0.49\)). These lifetime values were converted by the evaluators from B(E2) values utilizing the formulas in equation 19, modified to account for internal conversion:

\[
\tau_{E2} = \tau(1 + \alpha) = \frac{8.156 \times 10^{-10}}{B(E2) \downarrow E_{\gamma}^3}
\]

(35).
Raman et al use a theoretically calculated value $\alpha_{\text{total}} = 1.141$ to convert the experimental $B(E2)$ values into associated lifetimes. The experimental $\alpha_{\text{total}} = 1.145 \pm 0.029$ [1].

![Compilation of sixteen Coulomb excitation measurements of the lifetime of the first $2^+$ state of $^{152}\text{Sm}$, along with the present work shown on the far right. The weighted average lifetime is shown with a black line; its error bar is shown by the dashed lines above and below. The data set has $\chi^2/\nu = 0.49$. (Data is from this work and [25])](figure55.png)

**Figure 55.** Compilation of sixteen Coulomb excitation measurements of the lifetime of the first $2^+$ state of $^{152}\text{Sm}$, along with the present work shown on the far right. The weighted average lifetime is shown with a black line; its error bar is shown by the dashed lines above and below. The data set has $\chi^2/\nu = 0.49$. (Data is from this work and [25])

### Comparing the Delayed-Coincidence and Coulomb Excitation Results

Statistical tests can be used to determine whether the Coulomb excitation and delayed-coincidence methods are, in fact, different enough to be statistically significant. Calculating a weighted average of $\tau_{\text{del.coin.}} = 2041 \pm 9$ ps and $\tau_{\text{Coulex}} = 2088 \pm 15$ ps yields $2054 \pm 21$ ps with $\chi^2/\nu = 7.30$ (one degree of freedom). A comparison to a standard $\chi^2$ table of values indicates that the probability of the $\chi^2$ value being greater than this is 0.5%, and there is a statistically significant
systematic difference between the two methods. This also indicates that the quoted uncertainty of the data set in Fig. 52 should be increased to ±21 ps.

If the 1988 work is removed, $\tau_{\text{del.coin}} = 2061 \pm 11$ ps. The weighted average of these two averages is $2068 \pm 12$ ps, with $\chi^2/\nu$ reduced to 2.43. This result still indicates a statistically significant systematic difference between the measured values obtained by the two techniques, increasing the uncertainty in the weighted mean calculated for the entire data set of Fig. 53 to ±12 ps from ±7 ps.

One possible source of this discrepancy between the weighted mean values obtained by the two techniques arises from the present experimental uncertainty in the internal conversion coefficient required to convert a B(E2) into a lifetime, as noted in Section 3.4.5.2.

Some remarks should also be made about the work by Karle et al in 1988 [50], as their experimental value is of the same precision as the present work but differs by six standard deviations. This experiment involved two BaF$_2$ detectors using cylindrical large-volume high-efficiency crystals of 9 cm diameter and 9 cm height. They tested their prompt coincidence width and obtained 375 ps FWHM using a $^{60}$Co source. A $^{152}$Eu source was then used to re-measure the lifetime of the 122 keV transition in $^{152}$Sm.

Karle et al measured the lifetime both via deconvolution of the prompt detector response from the delayed curve ($\tau = 2017 \pm 8$ ps), and by measuring the slope of the delayed portion of the time spectrum ($\tau = 2010 \pm 9$ ps). Raman et al have weighted these two values to obtain $\tau_{\text{avg}} = 2014 \pm 10$ ps.
The energy gating technique employed to obtain these lifetime values involved gating the 122 keV transition and a region about 1.32 MeV; however, the structures of $^{152}$Sm and $^{152}$Gd (Fig. 33 and Ref. [1]) do not show any transition of appreciable intensity in that energy range. An attempt to replicate this energy gating method using the experimental data from this work yielded very poor statistics. It is likely that a typographical error was made in Ref. [50] regarding the energy gating regions.

In addition, the method by which the $^{152}$Eu source was prepared for the work by Karle et al is not given; there is no adjustment indicated for the presence of $^{154}$Eu in the sample. As established in Section 3.4.3, the presence of this contaminant will affect half-life measurements and can be quantified. Therefore, neglecting the presence of $^{154}$Eu in Ref. [50] would be one possible reason for a lower reported lifetime value.

### 3.4.6 Other Properties of $^{152}$Sm

From the half-life measurement of 1437 ± 7 ps ($\tau = 2073 \pm 10$ ps) obtained in this work, it is possible, as explained in Section 1.5, to obtain the $B(E2)$ associated with the 121.8 keV transition, and thereby the magnitude of the quadrupole deformation, given a partial lifetime:

$$B(E2) \downarrow = \frac{8.156 \times 10^{-10}}{\tau_{E2} E^5_{\gamma}}$$

(36).

Conversion of the measured lifetime into a partial lifetime [25] requires the experimentally obtained internal conversion coefficient, $\alpha_{E2} = 1.145 \pm 0.029$ [1]:

---

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\[ \tau_{e2} = \tau(1 + \alpha) = 2073(1 + 1.145) = 4447 \pm 112 \text{ ps} \quad (37). \]

This results in the B(E2):

\[ B(E2) \downarrow = 6846 \pm 174 e^2 \text{ fm}^4 = 0.6846 \pm 0.0174 e^2 b^2 \quad (38). \]

In terms of Weisskopf units, the B(E2)\downarrow is 142.2 ± 3.6 W.u., indicating that the transition \( 2^+ \rightarrow 0^+ \) is of a collective nature.

In order to correctly express the quadrupole moment in units consistent with formulas that relate this deformation to the dimensionless parameter \( \beta \) (Section 1.5 and [2]), the unit \( e^2 \) from the B(E2) will be accounted for when converting this electric quadrupole moment:

\[ eQ_o = \sqrt{16 \pi \times B(E2; 2^+ \rightarrow 0^+)} = 5.83 \pm 0.15 \text{ eb} \quad (39). \]

This is a magnitude only; the sign of the quadrupole moment cannot be determined solely from the lifetime.
CHAPTER 4: CONCLUSION

4.1 Summary of Results

The DANTE BaF$_2$ detector array has been characterized with an average energy resolution of 10.5% at 662 keV, which did not change appreciably when the detectors were mounted in the $8\pi$ array. Intrinsic prompt timing peak FWHMs averaged 199 ps, which increased to an average of 270 ps after mounting the detectors into the $8\pi$.

The detector array has been shown to be capable of measuring half-lives of nuclear excited states reliably in the nanosecond range, with multiple detectors improving the statistical precision of such measurements over previous work. This is evidenced by the re-measurement of the half-life of the first $2^+$ excited state of $^{152}$Sm, having a transition energy of 121.8 keV, at $t_{1/2}$ of 1437 ± 7 ps, being more precise and in good agreement with all previous measurements except one of equal precision.

Further, the combination of the HPGe detectors and BaF$_2$ detectors at the $8\pi$ array has already proven of value in utilizing the superior energy resolution of HPGe detectors to ascertain the presence of contamination in a $^{152}$Eu source, and thus quantitatively determine if that contamination will have an effect on measurements. By extension, in-beam experiments involving isobaric contaminants can be treated similarly if necessary.
The DANTE array, as of this writing, is suitable for use in a nanosecond-level half-life measurement for any state populated by a beta-decaying isotope capable of being produced at TRIUMF-ISAC.

4.2 Further Directions

4.2.1 Gamma Backscattering Elimination

The presence of high-Z materials such as Heavimet, BGO, Barium and Lead in the $8\pi$ array has the undesirable side effect of causing a high degree of gamma ray scattering in the array. This affects timing peaks because there is a finite time difference between gamma rays correlated by multiple scattering events. These show up as extra peaks shifted away from the true prompt peak when using a $^{60}$Co source. Previous workers have observed the problem as well even when using only two BaF$_2$ detectors [51]. A sample time spectrum containing these backscattering events is shown in Figure 56(a) from the detector pair 1 and 4, which are situated 120 degrees from each other.

Detectors situated 120 degrees from one another exhibited backscattering events in their prompt timing peaks; the physical placement of the detectors shown in Fig. 39 thus becomes of importance when understanding how to eliminate this effect, which has been done by moving the detectors slightly further away from the target chamber. This shields DANTE detectors from each other since the intervening material is Heavimet and BGO. This was found to greatly reduce the effect of scattering events on prompt or quasiprompt events, as shown by the same detector pair in Figure 56(b).
Figure 56. Time spectra from the coincidence pair of detectors #1 and #4 (located 120 degrees from each other) when using a $^{60}$Co source. (a) Backscattering is present as indicated by the peak to the right of the true prompt peak. (b) Backscattering is essentially completely reduced by moving the detectors ~1 cm further away from the target chamber.

Measuring the half-life of the 366 keV state in $^{152}$Sm was not possible in the present work because these backscattering events significantly affected the shape of the delayed portion of the time spectrum after applying energy gates in a similar way to the extraction of time spectra for the decay of the 122 keV state. Both the application of exponential fit and the centroid shift methods to this lifetime measurement are affected as both require the peaks to be skewed Gaussians. In addition, the TACs, being set at 100 ns, were not optimized for such short lifetimes.

4.2.2 Centroid-Shift Measurements

The change in the arrangement of the BaF$_2$ detectors should lead to more accurate lifetime measurements using the DANTE array, in particular at the few-picosecond level in which the centroid-shift technique must be used. The essentials of this technique are based on the fact that the introduction of a
lifetime into a gamma transition introduces a broadening of the timing signal in an asymmetric fashion. This shifts the centroid of the detected timing peak relative to a true prompt peak.

There are several ways to ascertain the true prompt peak characteristics; one way is to use a $^{60}$Co source, but care must be taken to account for the energy-dependent broadening effect in a prompt timing peak. Another method is to use Compton continuum regions in the gamma spectra of interest to determine prompt gamma-ray behavior.

To first order, fitting the prompt and shifted peaks with skewed Gaussians will show a difference in the centroids and subtracting the two yields the half-life of the excited state of interest. In practice there are other contributions that must be taken into account, as noted in the detailed analysis undertaken by Seo [51], and as established by Mach et al [52] which notes the energy dependence of the prompt FWHM in timing analysis.

### 4.2.3 Use of the Full Array

Since the experiment which formed the basis of this thesis was carried out, the FIFO and Ortec CO4020 logic modules have been fully-instrumented to use all ten BaF$_2$ detectors in the DANTE array. Since an array of four detectors has already shown a notable improvement in the statistical precision of excited-state half-life measurements, the full array of ten detectors would further enhance this to the point where statistical errors would become negligible and the TAC calibration uncertainty (a systematic error) would dominate. In the present work a
comparison of the statistical and systematic errors shows that the statistical uncertainty of ±6 ps is greater than the systematic uncertainty of ±2 ps by a factor of three.

To first order, the decrease in statistical error is calculated by the ratio of the square root of the number of unique combinations of detectors. Thus, for ten detectors, there are ninety unique combinations for ten detectors as compared to twelve for four detectors, which yields an approximate factor of three

Assuming that the same source as used in this work was used with the fully operational DANTE array, the statistical error would have been approximately ±2 ps as opposed to ±6 ps. This promising improvement will certainly motivate future experiments involving other radioactive isotopes whose daughters have excited states with half-lives in the picosecond to nanosecond range, and also shows that the systematic errors will tend to dominate in data from DANTE when high-rate experiments are conducted.

4.2.4 HPGe Energy Gating

While the concept was discussed of HPGe detectors being used to gate triple coincidences, this technique was not employed in the analysis which formed the body of this work, owing to poor statistics when attempted.

An experiment involving a stronger (~500 kBq) isotopically pure $^{152}$Eu source is planned for August 2009 by W. D. Kulp et al to measure intensities of E0 transitions in $^{152}$Sm at the 8π. Because DANTE will be usable in addition to $^{152}$

\[ (90 / 12)^{\frac{1}{2}} = 2.739. \]

\[ ^{152}\] Eu source is planned for August 2009 by W. D. Kulp et al to measure intensities of E0 transitions in $^{152}$Sm at the 8π. Because DANTE will be usable in addition to
PACES, and given the potential for high statistics in this experiment, it will be possible to not only confirm the analysis thus far, but improve upon it in several ways:

1. The presence of $^{154}$Eu will be of comparable magnitude and can be more accurately assayed.

2. Improvement of the statistics in the data from BaF$_2$-BaF$_2$ coincidences, as well as HPGe-BaF$_2$-BaF$_2$ coincidences.

3. The application of an energy gate on triple coincidences of HPGe-BaF$_2$-BaF$_2$ will remove the sizable Compton contribution to the measurement of half-lives.

4. The centroid shift measurement of the half-life of the 366 keV state will be feasible.
APPENDIX 1

Supplementary equations from [8] for partial decay rates ($\lambda$) in $s^{-1}$, partial lifetimes ($\tau$) in seconds, partial widths ($\Gamma$) in eV, downward transition probabilities ($B(EL)$) in $e^2$-$fm^{2L}$ where $e$ is the fundamental unit of charge, ($B(ML)$) in $\mu_N$-$fm^{2L-2}$ where $\mu_N$ is the nuclear magneton, and the squares of matrix elements ($|M(EL/ML)|^2$) in Weisskopf units (W.u), incorporating $E_\gamma$ in MeV and $A$ as the dimensionless mass number of the nucleus being studied.

\[
\lambda(E1) = \frac{1}{\tau_{E1}} = \frac{\Gamma(E1)}{6.582 \times 10^{-16}} = \frac{B(E1) \downarrow E_{\gamma}^3}{6.287 \times 10^{-16}} = \frac{|M(E1)|^2 E_{\gamma}^3 A^{2/3}}{9.754 \times 10^{-15}}
\]

\[
\lambda(E2) = \frac{1}{\tau_{E2}} = \frac{\Gamma(E2)}{6.582 \times 10^{-16}} = \frac{B(E2) \downarrow E_{\gamma}^5}{8.156 \times 10^{-10}} = \frac{|M(E2)|^2 E_{\gamma}^5 A^{4/3}}{1.374 \times 10^{-8}}
\]

\[
\lambda(E3) = \frac{1}{\tau_{E3}} = \frac{\Gamma(E3)}{6.582 \times 10^{-16}} = \frac{B(E3) \downarrow E_{\gamma}^7}{1.751 \times 10^{-3}} = \frac{|M(E3)|^2 E_{\gamma}^7 A^2}{2.947 \times 10^{-2}}
\]

\[
\lambda(M1) = \frac{1}{\tau_{M1}} = \frac{\Gamma(M1)}{6.582 \times 10^{-16}} = \frac{B(M1) \downarrow E_{\gamma}^3}{5.697 \times 10^{-14}} = \frac{|M(M1)|^2 E_{\gamma}^3}{3.181 \times 10^{-14}}
\]

\[
\lambda(M2) = \frac{1}{\tau_{M2}} = \frac{\Gamma(M2)}{6.582 \times 10^{-16}} = \frac{B(M2) \downarrow E_{\gamma}^3}{7.391 \times 10^{-8}} = \frac{|M(M2)|^2 E_{\gamma}^5 A^{2/3}}{4.479 \times 10^{-8}}
\]

\[
\lambda(M3) = \frac{1}{\tau_{M3}} = \frac{\Gamma(M3)}{6.582 \times 10^{-16}} = \frac{B(M3) \downarrow E_{\gamma}^7}{1.586 \times 10^{-1}} = \frac{|M(M3)|^2 E_{\gamma}^7 A^{4/3}}{9.612 \times 10^{-2}}
\]
APPENDIX 2

I was involved in all stages of the construction and testing of the BaF$_2$ detectors under laboratory conditions and after integrating them into the $8\pi$ array; with primary responsibility for data acquisition and analysis.

In addition, I acquired the absorption spectra to determine the properties of the optical gels used to couple BaF$_2$ crystals to the photomultiplier tubes. These spectra verified the importance of transmitting the fast component of the ultraviolet emission wavelengths of BaF$_2$ to optimize timing resolution.

Finally, I independently re-analyzed the lifetimes compiled by Raman et al. and have identified some sources for the discrepancies observed in the Coulomb Excitation method of obtaining lifetimes compared to those obtained by the fast-timing delayed coincidence method.
REFERENCE LIST


[33] S. J. Williams (private communication).


[40] G. Grinyer, *High-Precision Measurements of $^{26}$Na Beta Decay* (University of Guelph, 2004).


