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Optimization Studies for the COBRA Neutrinoless Double-Beta Decay Experiment and Results from a Prototype

by

Jerrad Wayne Martin

A dissertation presented to the Graduate School of Arts and Sciences of Washington University in partial fulfillment of the requirements for the degree of Doctor of Philosophy

May 2012

Saint Louis, Missouri
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by

Jerrad Wayne Martin
Abstract

The COBRA experiment uses Cadmium Zinc Telluride (CZT) room-temperature semiconductor detectors to search for the neutrinoless double-beta decay of $^{116}$Cd. While the experiment has produced globally competitive half-life limits with data from coplanar-grid CZT detectors, a future ton-scale iteration could set limits constraining the effective Majorana neutrino mass to less than 100 meV. The aim of this work is to determine the optimal CZT detector type for such an experiment. First, an overview of the relevant neutrino physics as well as an introduction to the COBRA experiment is presented. The performance characteristics and design criteria for CZT detectors are then covered, both in general and as they relate to COBRA. Simulations and prototype experiments have been performed using two of the detector design candidates. The method and results are discussed in detail. Finally, the prototype is compared with other CZT detector designs in the context of performance and scalability for a 420 kg COBRA experiment.
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Chapter 1

Synopsis

The aim of this work is to optimize the design of the neutrinoless double-beta decay ($0\nu\beta\beta$) experiment COBRA$^1$. As discussed in Chapter 2, $0\nu\beta\beta$ is an excellent process for studying the nature of the neutrino. While neutrino oscillation experiments have shown that neutrinos have mass, they are only sensitive to the differences between the mass eigenstates and not their absolute scale. Tritium decay experiments probe the absolute scale of the neutrino’s mass, but the largest new experiment will only set upper limits down to 0.2 eV. Not only is $0\nu\beta\beta$ decay more sensitive to the absolute neutrino mass, but if detected it would prove that neutrinos are Majorana particles, providing insights into the mechanism by which that mass is obtained.

In Chapter 3, the COBRA experiment is introduced. COBRA uses a room-temperature semiconductor material—cadmium zinc telluride (CZT)—in a source-equals-detector approach to the search. Up to 64 CZT detectors have been deployed

$^1$Cadmium zinc telluride $0$-neutrino double-$\beta$ decay Research Apparatus
underground at Laboratori Nazionali del Gran Sasso (LNGS) in Italy. To date, the experiment has produced globally competitive limits on the extremely long half-life of $0\nu\beta\beta$ decay, from which the neutrino mass is derived. The longest of these is on the order of $10^{20}$ yr. The experiment also made sixteen independent measurements of the fourfold-forbidden non-unique (single)$\beta$ decay of $^{113}$Cd. This represents the first time that a half-life as high as $10^{15}$ yr has been determined from a statistically relevant sample of independent measurements.

COBRA’s published results are all derived from up to 64 CZT detectors of the “coplanar grid”-type. This detector configuration offers a simple readout scheme and good energy resolution compared to, e.g., scintillator materials. However, there are other ways to design CZT detectors which improve both energy and spatial resolution, useful for particle identification and background reduction. Chapter 4 provides an introduction to the general behavior of CZT semiconductors, as well as the features of these detector designs: pixelated and cross-strip contacts in addition to the coplanar grid. In Chapter 5, the four designs and their performance characteristics are further explored. For coarse pixels and crossed strips—two excellent candidates for deployment in a large-scale COBRA experiment—results from experiments and simulations conducted at Washington University in Saint Louis (WUSTL) are discussed. Activities involving the fabrication of finely pixelated detectors at WUSTL are summarized.

Two prototype detectors of the coarse pixel design were tested in background-
measurement mode, as discussed in Chapter 6. The first was operated only 3.5 days at a surface-level background rate, and yet it yielded half-life measurements as high as $10^{18}$ yr. The second ran for 72 days in ultra-low background conditions at the LNGS facility. Its sensitivity extended to a half-life of $10^{20}$ yr.

Finally, in Chapter 7 a large-scale COBRA experiment is proposed which would deploy 420 kg of CZT in a search sensitive to half-lifes more than $10^{26}$ yr. The design proposal accounts for the numerous constraints involved in such a large experiment including cost, power consumption, and the physical layout of thousands of components. Two alternative designs are also proposed.

Chapter 8 summarizes the findings of this work.
Chapter 2

Neutrino Physics

2.1 Theoretical Prediction

The neutrino was first theorized as the answer to a problem in the early days of particle physics. During radioactive decay, an unstable parent nucleus releases energy to reach a lower energy state and emits a particle: a helium nucleus in the case of $\alpha$ decay or a photon in the case of $\gamma$-emission. It had been observed that $\alpha$ particles or $\gamma$-rays emitted by a nuclide always carried the same energy. This is due to the two-body nature of these decay mechanisms. The daughter nucleus recoils slightly from the emission, but otherwise, the full energy released in the decay (the “Q-value” of the decay) is carried away by the emitted particle. For a given parent–daughter transition, the Q-value is always the same and so the emitted particle always carries the same energy. This phenomenon results in a narrow peak or line in the energy spectrum for
any experiment which detects $\alpha$’s or $\gamma$’s. However, for $\beta$ decay—the emission of an
electron from the nucleus of an unstable atom—this is not the case. James Chadwick
[1914] discovered that electrons emitted during $\beta$ decay do not produce the spectral
lines characteristic of the previously discovered forms of radioactive decay. He instead
found that the electrons are emitted with a broad and continuous range of energies.

Chadwick’s discovery was initially interpreted in two ways. One possible explana-
tion was that electrons are emitted from their nuclei with a range of initial energies, in
apparent violation of energy conservation. Another interpretation suggested that sec-
ondary processes—occurring between emission of the electron and its detection—alter
the energy ultimately observed. This would cause an initially narrow peak centered
at the Q-value to be significantly broadened. The surprising result was confirmed
by Lise Meitner [1930]. Her rigorous calorimetric study found the average electron
energy to be much less than the Q-value, thus supporting the idea that the electrons
are emitted with a continuous range of energies.

Meitner’s finding also carried rivaling interpretations. Niels Bohr was a proponent
of the idea that perhaps energy conservation really may be violated in the $\beta$ decay
process. Wolfgang Pauli proposed another solution. He noticed that not only do
the electrons appear to violate the conservation of energy, but also that of angular
momentum. Electrons carry spin−1/2 and so a parent nucleus emitting an electron
should leave a daughter nucleus with total spin reduced by 1/2. Experiments had
always shown both the parent and daughter to both carry either integer or fractional
2.2 Experimental Confirmation

spin. In 1930, Pauli wrote an open letter to his colleagues in nuclear physics which predicted the discovery of a new spin–1/2 particle generated simultaneously with the electron. To conserve charge the particle had to be neutral. Also, while the average $\beta$ decay energy is always far from the Q-value, a few electrons are actually detected near that energy. Therefore, Pauli’s particle also had to be very light—probably less massive than the electron, he estimated. Being neutral and very light it would be difficult to detect.

The existence of such a particle would maintain spin conservation, but also explain the continuous energy spectrum. The electron and the new particle share the decay energy—if the new particle’s energy could also be measured, they would add up to the Q-value. Chadwick’s discovery of the neutron in 1932 allowed Enrico Fermi to construct his successful $\beta$ decay theory which incorporated Pauli’s new particle [Chadwick 1932; Fermi 1934]. Fermi called it the *neutrino*, Italian for “little neutral one”. It would be nearly 20 more years before the theorized particle would first appear in experiments.

2.2 Experimental Confirmation

The first indirect observation of neutrinos was in an experiment by Rodeback and Allen [1952]. When the unstable $^{37}$Ar nucleus captures an electron it is transformed into $^{37}$Cl and was theorized to emit a neutrino. This means electron capture is a
two-body decay, like α- or γ-emission. The nuclear recoil energy then must be fixed and proportional to the square of the neutrino energy and, in this case, nearly equal to the Q-value. Rodeback and Allen were able to measure the tiny nuclear recoil and show that some undetected particle must be leaving the nucleus.

The first direct neutrino signals were observed at nuclear reactors in the 1950’s by Cowan and Reines [1953]. The principle of their experiment was to observe the reaction

\[ \bar{\nu}_e + p \rightarrow e^+ + n. \]  

(2.1)

This reaction produces 511 keV photons when the positron annihilates, followed by more photons a few µs later when the neutron is captured by another nucleus. Cowan and Reines exposed a tank of CdCl₂ surrounded by liquid scintillator to antineutrinos from a nuclear reactor and measured the resulting coincident photon signals. After detecting a weak signal in 1953 the team moved to a new reactor, upgraded scintillator and shielding materials, and finally proved the existence of the neutrino in 1956. Even using reactors, the strongest neutrino sources of the day, the signal was tiny. The average cross-section for reaction was \( \bar{\sigma} = (11\pm2.6) \times 10^{-44} \text{ cm}^2 \), making the neutrino one of the most weakly interacting particles known [Reines and Cowan 1956].
2.3 Properties of Neutrinos

In the decades to follow, the field of elementary particle physics saw explosive growth. The construction of particle accelerators pushing to ever higher energies produced a menagerie of new particles and the theory continued to develop into the vaunted Standard Model.

The neutrino fits into the model as a member of the lepton family of particles and exists in three “flavors”: the electron neutrino $\nu_e$, the muon neutrino $\nu_\mu$, and the tau neutrino $\nu_\tau$. Each of these has a complementary anti-particle $\bar{\nu}$. They all have spin 1/2 and no electric charge. In the Standard model, neutrinos are considered to be massless Dirac particles.

Neutrinos only appear to interact via the weak force. As leptons, they do not participate in strong force processes, and with zero charge they cannot interact via the electromagnetic force.\(^1\) The weak force allows parity violation which, for neutrinos, gives rise to a preference in certain helicities over their mirror images. Helicity ($\mathcal{H}$) is the projection of a particle’s spin $\sigma$ onto the direction of its momentum $\mathbf{p}$:

$$\mathcal{H} = \frac{\sigma \cdot \mathbf{p}}{|\mathbf{p}|}.$$ \hspace{1cm} (2.2)

As allowed by parity violation, all neutrinos are produced with left-handed helicity and antineutrinos with right-handed helicity. If neutrinos were massless, the helicity

\(^1\)Even massless neutrinos still “interact” with gravity in the sense that, just like the massless photon, their paths are diverted by the warping of space-time due to massive bodies.
would be locked at generation. Flipping helicity would then require the existence of a reference frame which passes the neutrino, reversing the momentum vector. This would be impossible for a neutrino traveling at the speed of light. However, given the existence of a neutrino mass, this cannot be the case. Though the phase space is small, it is possible to observe right-handed neutrinos and left-handed antineutrinos. An important implication of this fact is discussed in Section 2.7.

2.4 The Solar Neutrino Problem

In the 1960’s, Raymond Davis and John Bahcall began collaborating on an experiment to detect neutrinos emitted by nuclear fusion processes inside the Sun [Davis 1964; Cleveland et al. 1998]. Bahcall had developed a model for solar neutrino emission and calculated how many of the particles should reach Earth and at what energies. Davis then devised a method with which to measure them. He installed a tank containing 615 ton of perchloro-ethylene (C\textsubscript{2}Cl\textsubscript{4}, essentially dry-cleaning fluid) deep underground at the Homestake mine in South Dakota. The depth of the mine provided 4100 m.w.e. (meters water equivalent) shielding against muons and other forms of background radiation present at the surface.

When a solar neutrino interacts with a $^{37}$Cl nucleus it is converted to $^{37}$Ar. If the neutrino carries more than 814 keV—as is the case for neutrinos generated via $^{8}$B fusion in the Sun—then the argon enters an unstable excited state with a half-life of
35 days. Davis’s experiment captured argon atoms generated in the fluid and counted them every few weeks via their radioactivity.

The experiment ran for 20 years, but astonishingly Davis only ever counted one third of the neutrinos that Bahcall’s models predicted. The models were scrutinized in the literature and consensus pointed to an error in Davis’s experiment. However, later experiments performed in Japan and elsewhere confirmed the solar neutrino deficit. Why could experiments not see the number of neutrinos expected to be produced in the Sun? This question went unanswered for nearly 40 years and became known as the “solar neutrino problem”.

2.4.1 The Solution

In 1999, the Sudbury Neutrino Observatory (SNO) came online and within three years had put the solar neutrino problem to rest. Like the Kamiokande experiment before it, SNO was a real-time water Cherenkov detector. This type of experiment consists of a large water tank observed by many light sensors, called photomultiplier tubes. When a neutrino scatters off an electron in a water molecule, the electron is ejected at ultra-relativistic speeds. As it moves through the water, this electron produces a Cherenkov light signature which is collected by the sensors. Energy and directional information can be reconstructed from this light signature. SNO differed from previous Cherenkov detectors by using heavy water in its tank. This opened up
the possibility of other reaction types. The most interesting of these is

\[ \nu + d \rightarrow \nu + p + n \quad (\text{NC}). \quad (2.3) \]

This neutral current reaction may be driven by a neutrino of any flavor, making SNO sensitive to the total solar neutrino flux. It was quickly determined that electron neutrinos only make up one third of the total solar neutrino flux, with the remaining presumably consisting of other-flavored neutrinos [Ahmad et al. 2002]. Davis and Bahcall had been correct all along—their experiment was simply not sensitive to interactions with neutrinos of other flavors. In 2002, Davis shared the Nobel Prize in Physics with two others for their “pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos”.

The resolution of the solar neutrino problem brought with it more problems than it solved. The Sun has no mechanism by which it may produce a \( \nu_\mu \) or \( \nu_\tau \). Why were electron neutrinos changing flavors? How could this happen? Within the Standard Model, particles are allowed to “oscillate” into other flavors—quarks exhibit such behavior—and the mathematics for how neutrinos might do this had been drawn up decades before. However, the Standard Model also defines the neutrino to be massless. For a neutrino to oscillate flavors like a quark, it cannot be traveling at the speed of light, which implies a non-vanishing rest mass and physics beyond the Standard Model.
2.5 Neutrino Oscillations

If the idea of massive neutrinos is accepted, then the time-dependent flavor oscillation of neutrinos can be understood using the Pontecorvo-Maki-Nakagva-Sakata (PMNS) matrix [Maki et al. 1962]. It describes the flavor eigenstates ($\nu_e$, $\nu_\mu$, and $\nu_\tau$) as “mixed” in a superposition of mass eigenstates ($\nu_1$, $\nu_2$, and $\nu_3$):

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\tag{2.4}
\]

Experiments are only sensitive to the flavor state of neutrinos. However, the contribution to a neutrino’s wave function from the mass eigenstates evolves with time. Therefore, a particle emitted as a $\nu_e$ may be detected as a different flavor some time later. By observing how neutrinos oscillate into different flavors over various distances, the elements of the above “mixing matrix” can be experimentally determined. These elements depend on the differences in the mass eigenstates and can help set limits on the mass of the neutrino. For example, the MINOS experiment has measured a difference between the squares of the masses for the $\nu_3$ and $\nu_2$ states to be $|m_3^2 - m_1^2| = 0.0024$ eV$^2$ [Adamson et al. 2006]. This implies that at least one neutrino mass state is no lighter than about 0.04 eV. However, beyond these limits, oscillation experiments produce little information regarding the absolute scale of the neutrino mass.
2.6 Direct Mass Searches

Historically, much has been learned about neutrinos from the study of $\beta$ decays. As discussed in Section 2.1, the neutrino was first introduced by Pauli as a solution to problems with the early understanding of the process. Pauli was also able to put a rough upper limit on the mass of the neutrino by observing how close the endpoint of the electron energy spectrum comes to the $Q$-value; the endpoint should be reached at $Q - m_\nu c^2$. As far as the instruments of the time could discern, some electrons carried energies right up to the $Q$-value. Therefore, Pauli concluded that the neutrino’s mass was on the order of the electron’s (511 keV) or lighter. To this day, the best limits on the neutrino mass are direct measurements taken from analysis of the endpoints of $\beta$ decay spectra.

In order to derive the absolute scale of the neutrino mass\(^2\) from a $\beta$ decay experiment on smaller and smaller scales, several considerations become important [Zuber 2004]:

- The statistics of electrons with an energy close to the endpoint region is small, making a small $Q$-value for the investigated nuclide advantageous.

- Good energy resolution is a necessity.

- Energy loss within the source cannot be neglected.

---

\(^2\)These experiments are sensitive to the square of the mass of the electron antineutrino, $\bar{\nu}_e$.\]
• The spectral shape must be well understood and depends on atomic and nuclear final state effects, as well as excited state transitions.

• A theoretical description of the involved wavefunctions is required.

These constraints show why large spectrometers (with excellent energy resolution) studying tritium decay have the most promise. Tritium has a low-energy Q-value at only about 18.6 keV and a relatively short half-life of 12.3 yr—both of which improve statistics. Also, with $Z = 1$, the small charge on tritium keeps it from interacting strongly with $\beta$-particles and causing energy loss. The features and final states of the decay,

$$^3\text{H} \rightarrow ^3\text{He}^+ + e^- + \bar{\nu}_e$$  \hspace{1cm} (2.5)

are fairly well understood. The difference in mass between $^3\text{H}$ and $^3\text{He}$ is known to four decimal places: $\Delta m = 18.5901 \pm 0.0017$ keV [van Dyck and Al 1993]. Accounting for the binding energies of molecular $^3\text{H}$ and $^3\text{He}$, as well as the helium ion’s tiny recoil energy, brings the Q-value to 18.574 keV [Ohsima and Kawakami 1994].

The best upper limit on the neutrino mass for a tritium spectrometer—indeed across all experiments and observations—comes from the Mainz experiment [Kraus et al. 2005]. They derive an upper limit of

$$m_{\nu_e} \leq 2.3 \text{ eV (95\% CL)}.$$  \hspace{1cm} (2.6)
2.7 Neutrinoless Double Beta Decay

The most sensitive tritium spectrometer yet, is KATRIN. The experiment employs a 1240 m$^3$ main spectrometer and should be sensitive to a neutrino mass as low as 0.2 eV. First measurements are expected in 2012 [Wolf 2010].

2.7 Neutrinoless Double Beta Decay

An indirect method of mass measurement may be possible via a special mode of double-beta decay ($\beta\beta$ decay). For some nuclei, decay via emission of a single $\beta$ electron is energetically disallowed, but conversion to a lower state via two subsequent $\beta$ decays through a virtual intermediate state is possible. The modes most frequently discussed are the neutrino-accompanied and the neutrinoless double-beta decays

\begin{align}
(Z, A) & \rightarrow (Z + 2, A) + 2 e^- + 2 \bar{\nu}_e \quad (2\nu\beta\beta) \quad (2.7) \\
(Z, A) & \rightarrow (Z + 2, A) + 2 e^- \quad (0\nu\beta\beta), \quad (2.8)
\end{align}

as depicted in Figures 2.1 and 2.2. The first mode is a higher order Standard Model process with half-lifes on the order of $10^{19}$ years or more, whereas the existence of the second process has not yet been confirmed. $0\nu\beta\beta$ decay is theorized to occur in cases of $\beta\beta$ decay where the two antineutrinos have annihilated. This should be impossible within the paradigm of the Standard Model—neutrinos are Dirac particles, meaning
they may only annihilate with their anti-particles. Additionally, the process violates lepton number conservation by \( \Delta L = \pm 2 \). However, if the neutrino is of a special type, called a Majorana particle, then it is indistinguishable from its antiparticle and \( 0\nu\beta\beta \) decay may occur.

2.7.1 Majorana or Dirac Particle?

For neutrinos to be Majorana particles, they must be truly indistinguishable from their antiparticles. How can we tell? Normally, we think of particles as having electric charge which is opposite that of their anti-particle. If they are neutral, what distinguishes a neutrino from an antineutrino? For massless neutrinos, the answer would be helicity. As discussed in Section 2.3, all neutrinos are produced with left-handed helicity and antineutrinos with right-handed helicity.

\(^{3}\)Neutrons also have no net charge, but as baryons (rather than leptons, like the neutrino) they are composed of quarks with opposite charge to the quarks in an anti-neutron.
For massive neutrinos, this distinction cannot be made. From a certain reference frame, a left-handed antineutrino may be observed. Because neutrinos are almost always ultra-relativistic, the phase-space for this observation is very small—on the order of $m_\nu/E$. For solar neutrinos, $E$ is in the 1 MeV range and opposite helicities would be observed in fewer than $10^{10}$ neutrinos.

With helicity no longer a conserved quantity which distinguishes the particles, we cannot rule out the possibility that the neutrino is a Majorana particle. Additionally, the helicity flip—only possible for massive neutrinos—will occur in some cases of $2\nu\beta\beta$ decay, allowing the Majorana neutrinos to annihilate. Observing $0\nu\beta\beta$ decay would provide positive confirmation that the neutrino is a Majorana particle with a finite mass.

### 2.7.2 Indirect Mass Measurement

In addition to confirming the existence of Majorana neutrinos, $0\nu\beta\beta$ decay half-life measurements also constrain the neutrino’s mass:

$$\left( T_{1/2}^{0\nu} \right)^{-1} = G_{0\nu}^{\nu}(Q, Z) \cdot \left| M_{GT}^{0\nu} - M_{F}^{0\nu} \right|^2 \cdot \frac{(m_{\nu_e})^2}{m_e^2}. \quad (2.9)$$

Here, $G_{0\nu}^{\nu}$ is the phase space integral which depends on the Q-value and the available transitions from the parent nucleus to the daughter. It is analytically calculable and
scales with $Q^5$, leading to shorter half-lifes for higher energy decays.\(^4\) $M_{GT}^{0\nu}$ and $M_F^{0\nu}$ are the Gamow-Teller and Fermi nuclear matrix elements which must be determined numerically and are a main source of error in $T_{1/2}^{0\nu}$ calculations [Zuber 2004]. $\langle m_{\nu_e} \rangle$ is the effective Majorana neutrino mass. It relates to the neutrino mass eigenvalues $m_i$ by

$$\langle m_{\nu_e} \rangle = \left| \sum_i U^2_{ei} m_i \right|,$$  \hspace{1cm} (2.10)

where $U_{ei}$ are the mixing matrix elements from Equation 2.4 and must be provided by oscillation experiments.

### 2.8 $0\nu\beta\beta$ Experiments

For its ability to inform on both the Majorana nature as well as the absolute mass scale of the neutrino, $0\nu\beta\beta$ decay is often considered the ideal process for probing the fundamental character of neutrinos.

The signal in a $0\nu\beta\beta$ decay experiment is a sharp peak at the endpoint of the $2\nu\beta\beta$ decay electron energy spectrum, shown in Figure 2.3. With zero neutrinos to carry away momentum, the summed energy from the two $\beta$ electrons exactly equals the Q-value of the decay. This means that neutrino-accompanied $\beta\beta$ decay is an irreducible background for the neutrinoless process and excellent energy resolution is required to separate the peak from the continuum.

\(^4\)The practical result is the opposite of tritium $\beta$ decay experiments—nuclides with \textit{larger} Q-values are preferred.
Experiments

Figure 2.3: Simulated $\beta\beta$ decay spectrum. Note the continuum of events for the $2\nu$ mode and the sharp peak at the endpoint for the $0\nu$ case.

$2\nu\beta\beta$ decay is an extremely rare process. The available phase space in which two neutrinos in a $\beta\beta$-decaying nucleus may have opposite helicities is tiny, making $0\nu\beta\beta$ decay even more rare by a factor of $\sim 10^6$. In order to measure the half-life of such a rare process it is important to minimize background as much as possible. Experiments must take place deep underground to reduce cosmogenic nuclide production and the atmospheric muon flux. Even deep underground, complex shielding schemes must be used to further reduce the muon flux, moderate neutrons, and avoid fluorescence photons. Laboratories must be ultra-clean environments to avoid external radiation sources, including primordial nuclides and their progeny as well as long-lived man-made radioactive contaminants, like $^{137}$Cs.

2.8.1 The Heidelberg-Moscow Experiment

To date, the best upper bound for $\langle m_{\nu_e} \rangle$ comes from the Heidelberg-Moscow experiment. The collaboration used 11 kg of high-purity germanium semiconductor
detectors enriched to \( \sim 86\% \) in the \( 0\nu\beta\beta \) isotope \( ^{76}\text{Ge} \). Running at the Gran Sasso Laboratory, they saw background as low as 0.2 counts/keV/kg/yr in the region of the Q-value. After accruing 53.9 kg·yr of data they observed no signal, setting a half-life limit of [Klapdor-Kleingrothaus et al. 2001a]

\[
T_{1/2}^{0\nu} > 1.9 \times 10^{25}\text{yr} \quad 90\% \text{ C.L.} \quad (2.11)
\]

which, for a particular choice of matrix elements, results in an upper bound of

\[
\langle m_{\nu_e} \rangle < 0.35\text{eV}. \quad (2.12)
\]

Later, a subgroup of the collaboration presented a claim to have actually observed a \( 0\nu\beta\beta \) signal after a Bayesian analysis of the data [Klapdor-Kleingrothaus et al. 2001b]. This was certainly controversial and the results were immediately challenged numerous times in the literature. The data was revisited in an attempt to alleviate these concerns and the claim of a measurement still stands. In fact, precision was increased. They claim to have measured the half-life and effective Majorana neutrino mass to be [Klapdor-Kleingrothaus and Krivosheina 2006]

\[
T_{1/2}^{0\nu} = (2.23^{+0.44}_{-0.31}) \times 10^{25}\text{yr} \quad 90\% \text{ C.L.} \quad (2.13)
\]

\[
\langle m_{\nu_e} \rangle = 0.32 \pm 0.03 \text{ eV}. \quad (2.14)
\]
Confirming or refuting these results is the aim of all $0\nu\beta\beta$ experiments in development today. Several are aiming to reach the ton-scale for their source masses and after a few years of operation should be sensitive to the neutrino masses on the order of 0.01 eV. Examples of large-scale experiments currently being deployed include EXO [Ackerman et al. 2011], CUORE [Bucci 2011], and GERDA [Ur 2011]. These experiments will be revisited in Chapter 7. They will be discussed in comparison with a proposed large-scale iteration of the COBRA experiment, discussed in the following chapter.
Chapter 3

The COBRA Experiment

The COBRA\(^1\) experiment uses the room-temperature II–VI semiconductor cadmium zinc telluride in a “source = detector” approach to the search for $0\nu\beta\beta$ decay [Zuber 2001]. Cadmium, zinc, and tellurium contain several $\beta\beta$ candidates, including some $\beta^+\beta^+$ and EC-$\beta^+$ decay channels. Table 3.1 lists each nuclide with its relative abundance in CZT as well as the type and Q-value of the decay. $^{116}\text{Cd}$ is the most important nuclide for COBRA, due to its relatively high Q-value of 2813.50 keV [Rahaman et al. 2011]. This has twofold benefits: higher Q-values produce higher $0\nu\beta\beta$ decay rates (see Section 2.7.2), and this value sits beyond the natural $\gamma$-ray backgrounds produced by U and Th.

\(^{1}\text{Cadmium zinc telluride 0-neutrino double-Beta decay Research Apparatus}\)
There are additional advantages to deploying cadmium zinc telluride (CZT) detectors:

- Semiconductors have excellent energy resolution and are intrinsically low in radioactive contaminants.
- The source-equals-detector approach maximizes detection efficiency.
- CZT is a room-temperature semiconductor which removes the complication of cryogenic cooling.

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>% CZT Abun</th>
<th>Q [keV]</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{116}$Cd</td>
<td>3.4</td>
<td>2814</td>
<td>$\beta^-\beta^-$</td>
</tr>
<tr>
<td>$^{108}$Cd</td>
<td>0.54</td>
<td>2771</td>
<td>$\beta^+\beta^+$</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>16.9</td>
<td>2529</td>
<td>$\beta^-\beta^-$</td>
</tr>
<tr>
<td>$^{64}$Zn</td>
<td>2.4</td>
<td>1096</td>
<td>$\beta^+/EC$</td>
</tr>
<tr>
<td>$^{70}$Zn</td>
<td>0.03</td>
<td>1001</td>
<td>$\beta^-\beta^-$</td>
</tr>
<tr>
<td>$^{128}$Te</td>
<td>15.9</td>
<td>868</td>
<td>$\beta^-\beta^-$</td>
</tr>
<tr>
<td>$^{114}$Cd</td>
<td>12.9</td>
<td>534</td>
<td>$\beta^-\beta^-$</td>
</tr>
<tr>
<td>$^{108}$Cd</td>
<td>0.4</td>
<td>231</td>
<td>2EC</td>
</tr>
</tbody>
</table>

Table 3.1: List of $0\nu\beta\beta$ nuclides in CZT. The abundances are listed as a percent of the number of atoms, not the mass. They assume Cd$_{0.9}$Zn$_{0.1}$Te with natural abundances. “Q” is the endpoint of the $0\nu\beta\beta$ decay spectrum in keV, and “Mode” presents the particle emission and/or capture process by which the decay progresses.

3.1 Experimental Details

COBRA is currently best characterized as operating in the R&D phase. The results described above are all derived from prototypes operated in a low-background condi-
Experimental details for the prototypes and their laboratory environment are provided below.

### 3.1.1 LNGS Site

The Laboratori Nazionali del Gran Sasso (LNGS) is an INFN-funded Italian national lab. It is located under the Gran Sasso mountain near Assergi, in the Abruzzo region of Italy—about 120 km northeast of Rome. The laboratory is accessed by a highway cutting straight through the mountain, connecting L'Aquila and Teramo.

LNGS provides a 1400 m dolomite rock overburden (\(\sim 3500 \text{ m.w.e.}\)) with convenient drive-up access. In addition to the six orders of magnitude reduction from surface-level muon flux (see Figure 3.1), the dolomite naturally contains quantities of Th and U which are below average compared to typical rock.

The laboratory is currently home to numerous experiments with low-background needs, including COBRA, OPERA, CUORE, GERDA, and Borexino. It is also the former site of the original Heidelberg-Moscow (H-M) \(\beta\beta\) decay experiment. In fact, COBRA moved in to the old H-M facility in 2011. The lab is a two-story “hut” set up in the access tunnel between LNGS Halls A and B. The DAQ computers which communicate with the experiments are housed in the upper level, while the experiment is located in COBRA’s half of the divided lower level. Part of the room is designated as “clean” and separated from the remainder by plastic curtains and has
3.1 Experimental Details

Figure 3.1: Muon flux vs depth for several underground laboratories. The figure gives the level of shielding in meters water equivalent (m.w.e.) and shows how the atmospheric muon flux is attenuated deep underground.

dedicated air filtration. COBRA is kept in a “cleanroom” because dirt and dust can contain environmental long-lived radioactive nuclides. The experiment itself consists of the “NEST” housing the CZT detectors and it’s multi-layered shielding. They are discussed in detail in the following sections and depicted in Figure 3.2.

3.1.2 Shielding

The outermost layer consists of neutron shielding provided by 7 cm of polyethylene bricks loaded with 8.7% boron. While the Gran Sasso overburden does effectively
Figure 3.2: Schematic of COBRA shielding layers (left) with photo (right). The photo was taken from inside the neutron shield and the Faraday cage visible around the back and sides of the lead. Refer to Section 3.1.2 for details on the shielding configuration depicted here.

remove the cosmic ray neutron flux, there are still muon interactions and some fission sources in the surrounding rock. The neutron flux is approximately three orders of magnitude less than at sea level, but cannot be neglected. This is because the \(^{113}\text{Cd}\) nucleus has one of the highest thermal neutron capture cross-sections existing in nature. Neutrons may create cosmogenic nuclides in the detectors and shielding, or generate \(\gamma\)-rays via inelastic scattering or during capture. The neutron shield encourages capture in the outer shielding by moderating the neutrons in the polyethylene and capturing them on the boron. Any induced \(\gamma\)-rays are stopped on the inner shielding layers.

Just inside the neutron shield, is a large copper enclosure. The enclosure surrounds the inner shield and—more importantly—the charge-sensitive preamplifiers just outside it. The main purpose of the enclosure is to protect the pre-amplifiers from electromagnetic interference (EMI). Because there are so many interfaces from
the outside into the EMI shield—cables for data and power, tubes for calibration sources and nitrogen supply—standard feedthroughs are impractical. Instead, all cables and tubes enter through an electromagnetic “trap”—a trough filled with copper pellets in contact with the EMI shield. In addition to being EMI “tight”, the enclosure is also airtight. The nitrogen tubes empty directly onto the detectors, but over time the entire enclosure is filled with nitrogen. The nitrogen is evaporated from liquid nitrogen—rather than released from bottles—and carbon-filtered. Liquid nitrogen treated in this manner contains significantly less radon than air.

The inner shielding consists of approximately 2 tons of lead surrounding another layer of copper. The lead stops any $\gamma$-rays originating from the neutron shield, Rn in the air outside the enclosure, the walls and ground surrounding the laboratory, etc. It surrounds the CZT detectors by at least 15 cm in every direction. Unfortunately, lead is often contaminated with $^{210}\text{Pb}$, part of the $^{238}\text{U}$ decay chain. The uranium contaminant appears in raw lead ore, coal used in the reduction process, and antimony which is often added for hardening. Relatively low-activity lead was chosen for placement at the innermost layers. In an attempt to further reduce the contribution of $^{210}\text{Pb}$, the final shielding layer is 5 cm of copper, which can be made very clean. The copper bricks used for COBRA have been electropolished and are of a very high purity. It is also important to have a layer of copper between lead and the detectors to absorb fluorescence X-rays generated by $\gamma$-ray absorption in the lead.
3.1 Experimental Details

Figure 3.3: Photos of the COBRA detector enclosure. In the left figure, some of the shielding has been removed and the readout and biasing cables can be seen entering the enclosure known as the “NEST”. In the right figure one of the Delrin trays can be seen loaded with four CPG detectors.

3.1.3 Detector Enclosure

Finally, inside the copper shield is the “NEST”, a copper frame for holding up to four trays of CZT detectors (see Figure 3.3). The trays are made of Delrin plastic (polyoxymethylene) which can be made very radioclean. Each tray can hold up to sixteen $1 \times 1 \times 1$ cm$^3$ CZT detectors. Four calibration tubes enter the NEST and can direct a source—affixed to the end of a long wire—over the center of each tray. Sheets of Kapton (a radioclean, flexible printed circuit substrate) connect each tray of detectors to the pre-amplifiers and high voltage via a kinked slot in the copper and lead shielding.

So far, all detectors tested in the NEST have been of the coplanar grid type (more on this in the following chapters) and manufactured by eV Products (now Endicott Interconnect). To reduce surface currents and long-term instability due to oxidation,
the manufacturer applies a passivation lacquer. Gold is the provided contact material used for the cathode and anodes. A low-activity conductive glue was developed in-house to bond the contacts to Kapton sheets.

### 3.2 Published Results

To date, COBRA has produced fourteen peer-reviewed journal articles. Measurements presented by Bloxham [2007] produced four world-best half-life limits on $0\nu\beta\beta$ decay modes (see Table 3.2).

The experiment’s current best half-life measurements for $0\nu\beta\beta$ decay were published by Dawson [2009]. The results come from 18 kg-days data exposure collected from 2006 to 2008 at the LNGS site. Sixteen 1 cm$^3$ CZT detectors were used, representing one quarter of the NEST’s designed capacity. The resulting limits were an improvement on the Bloxham measurements, but only one could improve on the standing world-best of the time. The lower-limit on the half-life of $^{120}$Te decaying via $0\nu\beta^+\text{EC}$ to the ground state was improved to $4.1 \times 10^{17}$ years—more than three times better than the Bloxham result and over twice as long as the best recorded by any other experiment. Table 3.3 summarizes the results and compares them to the best lower-limits at the time of their publication. Unfortunately, the limit for this decay was reset again the following year by the CUORICINO experiment with a vast improvement to $1.9 \times 10^{21}$ years [Andreotti et al. 2011].
### 3.2 Published Results

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Decay Mode</th>
<th>$T_{1/2}$ [yr]</th>
<th>C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{64}$Zn</td>
<td>$0\nu 2\text{EC}$ to g.s.</td>
<td>$&gt; 1.19 \times 10^{17}$</td>
<td>90%</td>
</tr>
<tr>
<td>$^{120}$Te</td>
<td>$0\nu \beta^+\text{EC}$ to g.s.</td>
<td>$&gt; 1.21 \times 10^{17}$</td>
<td>90%</td>
</tr>
<tr>
<td>$^{120}$Te</td>
<td>$0\nu 2\text{EC}$ to g.s.</td>
<td>$&gt; 2.68 \times 10^{15}$</td>
<td>90%</td>
</tr>
<tr>
<td>$^{120}$Te</td>
<td>$0\nu 2\text{EC}$ to $1171$ keV</td>
<td>$&gt; 9.72 \times 10^{15}$</td>
<td>90%</td>
</tr>
</tbody>
</table>

Table 3.2: First record-setting half-life limits published by COBRA [Bloxham et al. 2007]. While longer half-lifes were presented for other nuclides and/or decay modes in the same publication, these four improved upon all prior limits in the literature.

<table>
<thead>
<tr>
<th>Isotope and decay</th>
<th>Fit range</th>
<th>$T_{1/2}$ limit (years)</th>
<th>World best</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{113}$Cd to g.s.</td>
<td>2.2–3.2</td>
<td>$9.4 \times 10^{20}$</td>
<td>$1.7 \times 10^{23}$</td>
</tr>
<tr>
<td>$^{131}$Te to g.s.</td>
<td>2.2–3.2</td>
<td>$5.0 \times 10^{20}$</td>
<td>$3.0 \times 10^{23}$</td>
</tr>
<tr>
<td>$^{110}$Te to $536$ keV</td>
<td>1.7–2.3</td>
<td>$3.5 \times 10^{20}$</td>
<td>$9.7 \times 10^{22}$</td>
</tr>
<tr>
<td>$^{110}$Cd to g.s.</td>
<td>0.4–1.0</td>
<td>$2.0 \times 10^{20}$</td>
<td>$1.1 \times 10^{21}$</td>
</tr>
<tr>
<td>$^{120}$Te to g.s.</td>
<td>0.6–1.3</td>
<td>$1.7 \times 10^{20}$</td>
<td>$1.1 \times 10^{23}$</td>
</tr>
<tr>
<td>$^{64}$Zn $0\nu \beta^+\text{EC}$ to g.s.</td>
<td>0.5–1.1</td>
<td>$1.1 \times 10^{19}$</td>
<td>$4.3 \times 10^{20}$</td>
</tr>
<tr>
<td>$^{64}$Zn $0\nu 2\text{EC}$ to g.s.</td>
<td>0.5–1.3</td>
<td>$3.3 \times 10^{17}$</td>
<td>$1.1 \times 10^{20}$</td>
</tr>
<tr>
<td>$^{120}$Te $0\nu \beta^+\text{EC}$ to g.s.</td>
<td>1.0–2.0</td>
<td>$4.1 \times 10^{17}$</td>
<td>$1.9 \times 10^{17}$</td>
</tr>
<tr>
<td>$^{120}$Te $0\nu 2\text{EC}$ to g.s.</td>
<td>0.8–2.0</td>
<td>$2.4 \times 10^{17}$</td>
<td>$6 \times 10^{17}$</td>
</tr>
<tr>
<td>$^{106}$Cd $0\nu \beta^+\text{EC}$ to g.s.</td>
<td>0.5–2.0</td>
<td>$2.7 \times 10^{18}$</td>
<td>$2.4 \times 10^{20}$</td>
</tr>
<tr>
<td>$^{106}$Cd $0\nu 2\text{EC}$ to g.s.</td>
<td>1.4–3.0</td>
<td>$4.7 \times 10^{18}$</td>
<td>$3.7 \times 10^{20}$</td>
</tr>
<tr>
<td>$^{106}$Cd $0\nu \beta^+\text{EC}$ to $512$ keV</td>
<td>1.4–3.0</td>
<td>$1.6 \times 10^{17}$</td>
<td>$3.5 \times 10^{18}$</td>
</tr>
<tr>
<td>$^{106}$Cd $0\nu 2\text{EC}$ to $512$ keV</td>
<td>0.6–2.0</td>
<td>$4.6 \times 10^{15}$</td>
<td>$2.6 \times 10^{19}$</td>
</tr>
</tbody>
</table>

Table 3.3: Current best half-life limits published by COBRA [Dawson et al. 2009]. All of these limits improve on those previously published and one improved on the world-best standing at the time. This limit is shown in bold.

The sixteen-detector experiment provided other meaningful results. A prominent feature in the spectrum is a shoulder at low energies. This is caused by the fourfold-forbidden non-unique beta decay of $^{113}$Cd. Each of the detectors held enough counts to permit an independent calculation of the half-life. The combined result is

$$T_{1/2} = 8.00 \pm 0.11(\text{stat.}) \pm 0.24(\text{sys.}) \times 10^{15} \text{ years},$$

which agrees with prior results from an older COBRA prototype. The Q-value was deduced to be $322.2 \pm 0.3(\text{stat.}) \pm 0.9 \ (\text{sys.}) \text{ keV}$, in agreement with theoretical predictions.
Another result of the prototype was the identification of the two dominant background sources: radon, and the red passivation coatings applied directly to the CZT crystals. The radon background was identified while deploying the 64-detector array in 2008, and measures were immediately taken to reduce it—i.e. nitrogen flushing, as discussed in Section 3.1.2. Obtaining detectors with a radioclean passivation material proved more difficult. After collaborating with the coating manufacturer, four detectors with colorless passivation paint were produced and tested at LNGS in 2008. The combined effect of removing these contaminants was a reduction in background by about an order of magnitude in the signal region (see Figure 3.4). In light of this, there was no way forward for the 64-detector array until their red paint could be replaced. The full array, representing 0.42 kg of CZT—the largest such assembly to be constructed—has been dismantled. COBRA is currently exploring options to determine whether the remaining 60 detectors can be re-coated or if they must be replaced.
Figure 3.4: Recent LNGS background spectra from two data sets: before and after removal of the passivation lacquer with contaminated red dye. The “before” spectrum was published by Dawson [2009] and represents sixteen detectors with a total exposure of 18 kg-days. The “after” was taken with two prototype detectors using a new colorless lacquer, representing 2.8 kg-days exposure. The new lacquer results in a lower background by about an order of magnitude. Note the low-energy shoulder from the fourfold-forbidden non-unique beta decay of $^{113}$Cd. The endpoint for this decay is at 322 keV.
Cd$_{1-x}$Zn$_x$Te (CZT) is a wide-bandgap semiconductor material made from alloying small amounts ($x \sim 0.1$) of ZnTe with CdTe. The wide bandgap makes room temperature operation possible because thermal energy promotes fewer electrons into the conduction band, reducing noise due to leakage current. It is an excellent material for use in a variety of applications, particularly as an ionizing radiation detector. Its high average atomic number ($Z \sim 49$) gives it good stopping power for otherwise penetrating radiation such as $\gamma$-rays and high-energy charged particles.

In this chapter a general introduction to the behavior of CZT detectors is provided in addition to methods for their preparation and characterization in the lab. In Chapter 5, their performance characteristics are further explored.
4.1 Semiconductor Ionization Detectors

A high-energy charged particle loses energy during the process of ionization by interacting with electrons in matter, ejecting them from the atoms to which they are bound.\(^1\) Additional kinetic energy may be transferred to some of the ejected electrons, which in turn may ionize other atoms of their own accord. Both the initial charged particle and its energetic secondary electrons may also lose energy via bremsstrahlung photons. Photons in turn generate more energetic particles—via photoelectric absorption, Compton scattering, and pair production—which ionize atoms in the material as well. An ionization detector measures the energy lost by the high energy particle (and its secondaries, tertiaries, etc.) to ionization.

4.1.1 Electron-Hole Pairs

In a semiconductor, the energy necessary to ionize a single electron and promote it from the valence shell of an atom to the conduction band where it may move freely throughout the material is the band gap energy of the material. When this promotion occurs, a hole is also created. The hole represents the space vacated by the promoted electron and is also free to move through the detector, much like a distinct particle. This is because when a nearby valence electron moves to fill the hole, it leaves a new vacancy. This is regarded as the new position of the hole. If the detector is biased, the

\(^1\)Electrons are not “bound” to atoms in metals. Ionization occurs in gases and ionic crystals.
4.1 Semiconductor Ionization Detectors

electrons and holes will move through the electric field in opposite directions: electrons to the positive electrode (anode) and holes to the negative electrode (cathode). Thus, holes may be considered carriers of positive charge.

As a charged particle moves through a semiconductor detector, it can lose kinetic energy equal to the ionization energy—about three times greater than the band gap for most materials\(^2\)—for every electron-hole pair it creates. It continues to lose energy through ionization and other processes until it is absorbed or leaves the detector. If a beta particle from the decay of \(^{116}\text{Cd}\) is both created and absorbed (along with all secondaries) entirely within the detector, its full kinetic energy can be accounted for in the number of electron-hole pairs.

4.1.2 Charge Induction

Contrary to intuition, the signal current measured at an electrode is not due to the amount of charge reaching the electrode. As a carrier moves, the number of electrostatic field lines connecting it with the electrode will change (see Figure 4.1). It is this effect—dependent on the motion of the carrier—which induces current at the electrode. As a result, signal generation occurs throughout each carrier’s drift path, not just at its terminus.

This effect was studied independently by Shockley [1938], Ramo [1939], and others. Ramo, however, quantified it with a particularly elegant solution taking advantage of

\(^2\)Empirically, \(E_i \approx 2.8E_g + 0.6\text{ eV} \) [Spieler 2005].
4.1 Semiconductor Ionization Detectors

Figure 4.1: Diagram depicting the way in which charge is induced on electrical contacts by the movement of a charge \( q \) in their vicinity [Spieler 2005]. In the left image, \( q \) is equidistant from both contacts and the gaussian surfaces \( S_1 \) and \( S_2 \) enclose an equal number of field lines. By Gauss’s Law, charge \(-q/2\) is induced on each contact. In the right image, the charge has moved closer to the bottom contact and \( S_2 \) now encloses a greater number of field lines and a greater amount of charge is induced. While moving to this position the induced charge changed continuously, generating a current.

Green’s theorem. If a “weighting potential” \( \Phi_k \) is defined for a particular electrode \( k \), the instantaneous current \( i_k \) measured at that electrode for any position of the carrier is

\[
i_k = q(v \cdot \nabla \Phi_k),
\]  

where \( q \) is the charge of the carrier and \( v \) is its drift velocity. \( \Phi_k \) is obtained from the difference between the true local electric potential and the potential which would exist if the electrode of interest were held at unit potential with all others grounded, where both potentials are solutions to the Laplace boundary value problem and the difference is normalized to 1.

\( \Phi_k \) is obtained by setting the potential for the electrode of interest to 1 and holding all others at ground.
4.1 Semiconductor Ionization Detectors

The following properties of the weighting potential $\Phi_k$ are important:

- In general, $\Phi_k$ is different for every electrode and depends on its geometry.

- A single carrier induces current in every electrode with a weighting potential that crosses its drift path.

- In general, $\Phi_k$ is different from the true local electric potential $\Phi_E$ defined by $E = -\nabla \Phi_E$.

- The carrier’s drift path is determined by $E$ alone. $\Phi_k$ is only a mechanism for calculating induced current.

- Only in the simple case of two electrodes (e.g. a capacitor or a semiconductor with planar contacts) do $\Phi_k$ and $\Phi_E$ take the same form.

While electrons and holes carry opposite charge, they also travel in opposite directions through $\Phi_k$ and therefore induce current of the same sign. For example, electrons induce negative current in the anode as they drift toward it, while holes also induce negative current because they drift away.

Integrating the induced current over a particular segment of the drift path $(x_2 - x_1)$ produces the incremental induced charge $\Delta Q_k$:

$$\Delta Q_k = q(\Phi_k(x_2) - \Phi_k(x_1)). \quad (4.2)$$
Note, that if a carrier’s drift path takes it through the full gradient of the weighting potential, then the full charge of the carrier is reconstructed:

$$\Delta Q_k = q(\Phi_{k,\text{max}} - \Phi_{k,\text{min}}) = q(1 - 0) = q.$$ \hspace{1cm} (4.3)

As stated above, this measurement is directly proportional to the kinetic energy lost by a charged particle moving through the material.

\section*{4.2 Charge Carrier Transport in CZT}

Holes have both significantly lower electric mobility ($\mu$) and a shorter mean lifetime ($\tau$) in CZT than electrons. Low mobility means that holes take longer to cover the same distance during drift, making it likely that holes will not reach the cathode before all electrons are collected (i.e. induce their full charge). This requires longer collection times, introducing more noise. A short lifetime means that a hole is more likely to be trapped—reabsorbed into an atom in the lattice—before being collected. These two effects acting simultaneously create a compound problem which is quantified by the so-called “drift length”, $L$. The average charge remaining after carriers drift a distance $x$ falls exponentially:

$$q(x) = q_0 e^{-x/\mu E \tau} \equiv q_0 e^{-x/L} \hspace{1cm} (4.4)$$
Note that $L$ is proportional to the material properties $\mu$ and $\tau$ ($E$ is the electric field in the detector). The mobility–lifetime product—$(\mu\tau)_e$ for electrons and $(\mu\tau)_h$ for holes—is often used as a figure of merit for detector materials (refer to Table 4.1 for a list of these properties for a variety of detector materials). In detector-grade CZT, $(\mu\tau)_h$ is usually an order of magnitude lower than $(\mu\tau)_e$. The practical result is that holes contribute less to the total signal than electrons and that contribution is dependent on how far the holes must drift—i.e. how far from the cathode the holes are generated.

### Table 4.1: Electronic and physical properties of selected semiconductor detector materials.

$E_g$ and $E_i$ are the bandgap and ionization energies respectively. $\varepsilon$ is the relative permittivity, $\mu$ are the carrier mobilities—in units of cm$^2$/V/s—and $\tau$ their lifetimes. $\rho$ is the density in g/cm$^3$ and $\langle Z \rangle$ is the average atomic number. [Spieler 2005]

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_g$ (eV)</th>
<th>$E_i$ (eV)</th>
<th>$\varepsilon$</th>
<th>$\mu_e$</th>
<th>$\mu_h$</th>
<th>$(\mu\tau)_e$</th>
<th>$(\mu\tau)_h$</th>
<th>$\rho$</th>
<th>$\langle Z \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.12</td>
<td>3.6</td>
<td>11.7</td>
<td>1350</td>
<td>450</td>
<td>$&gt; 1$</td>
<td>$&gt; 1$</td>
<td>2.33</td>
<td>14</td>
</tr>
<tr>
<td>Ge</td>
<td>0.67</td>
<td>2.96</td>
<td>16</td>
<td>3900</td>
<td>1900</td>
<td>$&gt; 1$</td>
<td>$&gt; 1$</td>
<td>5.33</td>
<td>32</td>
</tr>
<tr>
<td>GaAs</td>
<td>1.43</td>
<td>4.2</td>
<td>12.8</td>
<td>8000</td>
<td>400</td>
<td>$8 \cdot 10^{-5}$</td>
<td>$4 \cdot 10^{-6}$</td>
<td>5.32</td>
<td>31.5</td>
</tr>
<tr>
<td>Diamond</td>
<td>5.5</td>
<td>13</td>
<td>5.7</td>
<td>1800</td>
<td>1200</td>
<td></td>
<td></td>
<td>3.52</td>
<td>6</td>
</tr>
<tr>
<td>4H-SiC</td>
<td>3.26</td>
<td>8</td>
<td>9.7</td>
<td>1000</td>
<td>115</td>
<td>$4 \cdot 10^{-4}$</td>
<td>$8 \cdot 10^{-5}$</td>
<td>3.21</td>
<td>10</td>
</tr>
<tr>
<td>GaN</td>
<td>3.39</td>
<td>8 – 10</td>
<td></td>
<td>1000</td>
<td>30</td>
<td></td>
<td></td>
<td>6.15</td>
<td>19</td>
</tr>
<tr>
<td>InP</td>
<td>1.35</td>
<td>4.2</td>
<td>12.4</td>
<td>4600</td>
<td>150</td>
<td>$5 \cdot 10^{-6}$</td>
<td>$&lt; 10^{-5}$</td>
<td>4.78</td>
<td>32</td>
</tr>
<tr>
<td>CdTe</td>
<td>1.44</td>
<td>4.43</td>
<td>10.9</td>
<td>1100</td>
<td>100</td>
<td>$3 \cdot 10^{-3}$</td>
<td>$2 \cdot 10^{-4}$</td>
<td>5.85</td>
<td>50</td>
</tr>
<tr>
<td>Cd$<em>{0.9}$Zn$</em>{0.1}$Te</td>
<td>1.572</td>
<td>4.64</td>
<td>10</td>
<td>1000</td>
<td>120</td>
<td>$4 \cdot 10^{-3}$</td>
<td>$1.2 \cdot 10^{-4}$</td>
<td>5.78</td>
<td>49.1</td>
</tr>
<tr>
<td>HgI$_2$</td>
<td>2.15</td>
<td>4.2</td>
<td>8.8</td>
<td>100</td>
<td>4</td>
<td>$3 \cdot 10^{-4}$</td>
<td>$4 \cdot 10^{-5}$</td>
<td>6.4</td>
<td>62</td>
</tr>
<tr>
<td>TlBr</td>
<td>2.68</td>
<td>6.5</td>
<td>30</td>
<td>30</td>
<td>4</td>
<td>$5 \cdot 10^{-4}$</td>
<td>$2 \cdot 10^{-6}$</td>
<td>7.56</td>
<td>58</td>
</tr>
<tr>
<td>a-Si</td>
<td>1.9</td>
<td>6</td>
<td>12</td>
<td>1 – 4</td>
<td>0.05</td>
<td>$2 \cdot 10^{-7}$</td>
<td>$3 \cdot 10^{-8}$</td>
<td>2.3</td>
<td>14</td>
</tr>
</tbody>
</table>

The depth dependence of CZT response degrades energy resolution in such a way that peaks in an energy spectrum will have a “low-energy tail”. This is best observed
with $\gamma$-rays as in Figure 4.2. The $\gamma$-ray resulting from the decay of $^{137}\text{Cs}$ has an energy of 662 keV. A $\gamma$-ray can deposit its full energy at a single site via the photoelectric effect. If this interaction occurs within about a millimeter of the cathode, the detector should collect the full charge of all electrons and holes to produce a signal equivalent to 662 keV. Ideally, all photoelectric events would be detected at 662 keV, and the energy spectrum would be sharply peaked. However, in CZT, events interacting farther from the cathode see incomplete hole collection and are detected at energies less than 662 keV. The effect continues to worsen across the detector, producing the tail—a continuum of events descending from the photopeak into the Compton edge.

Figure 4.2: Example of a CZT energy spectrum exhibiting a strong low-energy tail near the photopeak. Note how the photopeak at 662 keV is not Gaussian, but has a roughly exponential tail on its left (low-energy). The events below the shoulder near 500 keV are those which deposited less than the photopeak energy due to Compton scattering rather than the depth dependence described in the text.
4.3 Single-Polarity Detector Designs

All detector configurations discussed in this section are designed to counteract the depth dependence caused by incomplete collection of the slower charge carrier. To the extent possible, it is desired to screen the second charge polarity entirely. Devices of this type are referred to as single-polarity detectors. The physics associated with single-polarity charge sensing is discussed briefly for each detector type.

4.3.1 Frisch Grids in Gas Detectors

A similar depth dependence emerges in gas time projection chambers, another type of ionizing radiation detector. Instead of electron-hole pairs, gas detectors produce pairs of electrons and gas ions. The ions are much heavier than the electrons and drift very slowly. If fast detector response is required, there may not be time to wait for the ions to induce their full charge. However, if collection is stopped after the ions have induced a partial signal, a depth dependence emerges. Frisch addressed this problem by installing a grounded wire grid between the biasing electrodes, near the anode side [1944]. The purpose of the grid is to shield the anode from the movement of carriers throughout the rest of the detector (see Figure 4.3). Only charges which come very close to the anode induce a signal, and then only after passing through the grid. Ultimately, the detector still collects charge from the same number of electrons—preserving energy resolution—but the secondary carrier is screened completely.
4.3 Single-Polarity Detector Designs

Figure 4.3: Figure (a) depicts a gas detector with Frisch grid, (b) shows the charge induced with increasing distance from the cathode. There is no charge induced for carrier movement far from the grid, but the full charge is collected for carriers which move between the grid and the anode—i.e. electrons, unless the electron-ion pairs are generated very close to the anode in the first place.

4.3.2 Coplanar Grid CZT

While a coplanar grid (CPG) CZT detector bears little resemblance to a gas detector with a Frisch grid, both operate on a similar principle: minimize depth effects from asymmetric carrier transport by “screening” charge movement in the bulk. The canonical design is a two-anode configuration with a differential readout. The anodes take the form of closely interleaved combs (see Figure 4.4). Recall that in most cases the weighting potential for a contact does not simply match the electric potential in a detector. A charge carrier may induce charge on other contacts in addition to the one it ultimately drifts to. The spacing of the CPG strips is chosen such that the weighting potential far from either strip is linear and an electron will induce equal
4.3 Single-Polarity Detector Designs

Figure 4.4: Figure (a) depicts a CZT detector with coplanar grid (CPG), (b) shows the charge induced with increasing distance from the cathode, and (c) presents a photo of a real CPG detector fabricated at WUSTL. Note how in Figure (b), the signals (induced charge) on both anode contacts rise simultaneously for distances far from the anode. However, as the carrier comes closer to one contact than the other, the signals rapidly deviate. The differential signal mimics that of a Frisch grid gas detector. Figure (c) shows the two interleaved combs making up the anode side of a typical CPG detector.

charge on both over the majority of its drift path. Only at distances on the order of the center-to-center strip spacing (i.e. the strip pitch) does the electron begin to induce more charge on one than the other, as depicted in panel (b) in Figure 4.4. This distance is usually just a few hundred microns. By reading out only the difference between the two signals, the equal contributions from the rest of the drift path cancel. Every event now derives almost 100% of its signal from charge motion in the last millimeter before the anode, regardless of the depth of interaction. Figure 4.5 shows what implications this has for energy resolution improvements.
4.3 Single-Polarity Detector Designs

Figure 4.5: Comparison of CZT detector performance with planar contacts (left) and with a CPG (right). With planar contacts, the strong depth dependence leaves the photopeak nearly indistinguishable. With a CPG, the 662 keV photopeak is well resolved and easily separated from the Compton shoulder.

4.3.3 Pixelated CZT

Several advantages may be realized over the CPG design by segmenting the anode into many small contacts—pixels—whose signals can be read out separately. One advantage is the so-called “small pixel effect”. Very little charge is induced on a small pixel contact unless the carrier moves within a distance approximately equal to the pixel pitch.

Conceptualizing the small pixel effect is most easily done within the field-line-density paradigm described in Section 4.1.2. Induced current arises from the change in the number of electric-field lines intersecting the contact. This number is proportional to the solid angle subtended by the contact from the point of view of the carrier. Far from the anode side, all pixels appear to be the same size and each one is crossed by only a few field lines—very little is induced during this part of the drift. However, as the carrier approaches the anode side, the terminal pixel increases in size—and the
induced current with it—as $1/r^2$. The other pixels will increase in size briefly, before shrinking rapidly just before the electron impinges on the terminal pixel. Little net charge is induced in these pixels.

Similar to CPG and gas ion detectors, the effects of charge movement in the rest of the detector are lost and depth dependence is removed. In addition, the weighting potential rises so sharply that energy resolution is even better for pixelated CZT than for CPG detectors.

Perhaps the most important advantage of pixelated CZT is the information it provides regarding the 2D location of interaction (LOI). A result of the small pixel effect is that an electron only contributes significant signal to the pixel at the end of its drift path. If the electric field in the detector is homogenous, each electron will drift straight down to the pixel below it\textsuperscript{3} and the topology of a multi-pixel event will be projected as a 2D image onto the pixels. In Section 4.4 three-dimensional charge sensing is discussed.

One disadvantage of pixelated CZT is added complexity. Each channel in the pixel array requires a separate amplification and signal shaping circuit which increases complexity and power consumption. Data analysis also becomes more difficult when compared to a dual-anode CPG detector. Additionally, the number of channels—\textsuperscript{3}In Section 4.2 it was noted that hole collection is best near the cathode. Therefore, CZT is best operated with the cathode pointing toward the radiation source which is defined here to be “up”. For lower energy radiation, this maximizes the number of interactions near the cathode, improving resolution.
and thus the complexity—increases with the square of any position resolution gains. Halving the pixel pitch increases the number of channels by four.

**4.3.4 Cross-Strip CZT**

A new CZT detector type currently being tested by some groups is the cross-strip detector. These detectors have strips on both the anode and cathode sides, oriented orthogonally to one another. Events which trigger both one anode and one cathode strip provide $x$- and $y$-coordinates for the event and, thus, 2D LOI information. The primary advantage of the cross-strip design is that this 2D LOI information comes with a channel reduction from $N^2$ pixels to $2N$ strips. If the strips have a fine pitch, their energy resolution can be superior to CPG detectors and may be competitive with pixelated detectors. Two prominent disadvantages are noise related to capacitance in long strips and, notably, weak cathode signals. Unlike the planar cathode used on CPG and pixel detectors, cathode strips will exhibit a small pixel effect exactly like the anode. This is undesirable for the cathode because electrons will induce negligible charge, leaving holes as the only contributor. Holes generated far from the cathode may be trapped so strongly that no signal is detectable at all. Therefore, efficiency is degraded for applications where LOI information is required.
4.4 Depth Sensing with Cathode

For any particular event, the ratio of the anode signal to the cathode signal (cathode-to-anode ratio, or “CAR”) provides a good estimate of interaction depth [He et al. 1997]. For a detector with a planar cathode, the cathode signal drops almost linearly with interaction distance away from the cathode. In contrast, anode contacts exhibiting a strong small pixel effect will have a signal which is roughly the same magnitude regardless of the LOI. Of course, both signals also depend on the energy deposited, but the ratio of the two does not. Events with small CAR occur farthest from the cathode, where the cathode signal relies almost entirely on the heavily trapped holes.

Given the linear nature of the CAR-to-depth correlation, loss of energy resolution from depth dependence can be corrected for if monoenergetic calibration data is available. If so, the first step is to plot the normalized anode signal against the CAR. Figure 4.6 provides an example from real detector data. Note how the majority of events occur at an anode signal of 1 for most CAR values, but trend lower for small CAR. For the next step, the centroid of photopeak events is fitted with a polynomial function. The corrected anode signal for an event is then found by dividing the original signal by the value of the correction function at the event’s CAR. This works for any event at any energy because the function was obtained from the normalized anode signal and the CAR. If only the cathode signal were used to determine depth,

\[ \text{Note that a cathode signal is not always present. For example, interactions far from the cathode produce such a small signal that they are below the detection threshold.} \]
the correlation would be energy dependent and could only be applied to the energies used in the depth calibration.

Depending on the type of detector and its uncorrected performance, the 662 keV energy resolution may be improved from a few percent to < 1% (see Section 5.2 for examples).

Figure 4.6: Plot of normalized anode signal vs. cathode-to-anode ratio (CAR) for data from a 0.75 cm thick CZT detector tested with $^{137}$Cs $\gamma$-ray source (662 keV). Events with the lowest CAR occur close to the anode and contribute strongly to the tail-effect in the anode signal. The black line is a best fit to the correlation. This function is used to correct for the depth dependence and improve energy resolution.
4.5 Prototype Detector Development

In the following section, the specific methods of CZT detector fabrication and characterization we perform in prototype development are summarized. The COBRA prototypes discussed in Chapter 6 were prepared in this way.

4.5.1 Detector Fabrication

CZT crystals are obtained as off-the-shelf detectors grown and contacted by third parties. Specifically, the detectors used for the experiments described in Chapter 6 were purchased from Orbotech Medical Solutions and eV Products (now Endicott Interconnect). Both companies grow crystals using the Modified Horizontal Bridgman technique. Orbotech detectors are contacted with a planar indium cathode and a pixelated indium anode. eV Products detectors are delivered with platinum contacts. For detectors with a $2 \times 2$ cm$^2$ footprint—like those used in our prototypes—both companies apply $8 \times 8$ pixel grids with 2.5 mm pitch.

New detectors are characterized and calibrated—in the manner described in Section 4.5.3—using the manufacturer’s contacts as a quality control check. However, replacing the manufacturer’s cathode contact material with a Schottky material such as gold typically results in improved performance [Krawczynski et al. 2004]. Performance may also be improved by replacing platinum anode contacts with titanium or indium.
Detector re-fabrication is performed in a class-100 cleanroom facility, depicted in Figure 4.7. The first step is to remove the old contact pattern. To do this, the crystals are ground with successively finer grades of sandpaper before polishing on a cloth wetted with an alumina suspension fluid containing particles 0.05 µm in size. Subsequently etching the polished surface with a solution of 5% bromine and 95% methanol not only improves the electrical properties of the contacts, but also improves the adhesion of the contact material.

Photolithography is used to produce the contact pattern and is performed after
surface preparation. The crystal is pre-baked, then Shipley S1813 (positive) photoresist is applied via spin-coating. The photoresist is baked and then exposed with an unfiltered mercury-vapor lamp. The exposure pattern is determined by a mask placed between the crystal and the lamp. The masks can be designed and ordered with arbitrary patterns, and a variety of contact geometries have been produced using this method. After exposure, the crystal is post-baked and developed with Shipley Cd-30, dissolving away the exposed photoresist. A thin film of material is then deposited on the prepared surface using electron-beam vaporization. Afterwards, the crystal is submerged in acetone and the remaining (unexposed) photoresist dissolves, lifting away the metal on top of it. The remaining metal matches the exposure pattern of the photolithography mask. When only a simple planar contact is desired, the photolithography process is not needed, and the crystal is placed directly in the deposition chamber after etching.

4.5.2 Readout Electronics

The data acquisition system used for testing prototype CZT detectors is based on the “NCI-ASIC” developed at Brookhaven National Lab in conjunction with the Naval Research Lab [Wulf et al. 2007]. The ASIC (Application-Specific Integrated Circuit) is designed for the readout of X-ray and $\gamma$-ray signals from semiconductor ionization detectors. To this end, the ASIC provides—in a single package—a low-noise preamplifier, a signal shaping filter, a threshold comparator, and a peak detector with
analog buffer for each of 32 readout channels. These circuits are fabricated on a die with a footprint of 4.922 × 4.922 mm² on CMOS 0.25 μm technology. The resulting ASIC has excellent noise performance (from 1.0–1.5 keV FWHM), a large dynamic range (up to about 5,000 keV in CZT), and low power consumption (4 mW/channel + 38 mW/ASIC). Analog-to-digital conversion of the pulseheight signals is outsourced off-chip. The ASIC offers programmable shaping time (0.5 μs, 1 μs, 2 μs, and 4 μs) and gain (14.25 mV/fC 28.5 mV/fC, and 57 mV/fC). Maximum dynamic range is achieved with the lowest gain. Both experiments used this gain setting. The threshold discriminator level is also programmable both globally and on a per-channel basis. The global threshold may be set in 2 mV increments and each channel’s individual threshold may be trimmed up or down by 28 mV with 4-bit granularity.

In the implementation we have developed for pixelated detectors, two ASICs read positive-polarity pulses for 64 anode channels and a third ASIC reads negative-polarity pulses from the single cathode channel (for a planar contact). The three ASICs are surface-mounted to a custom readout board (shown in Figure 4.8) with an FPGA for control and analog-to-digital conversion. When in acquisition mode, the ASICs wait until any of their channels collects a signal that goes higher than the pre-programmed threshold for that channel. When one channel goes over threshold, there is a 3 μs delay to allow signals in other channels (and ASICs) to arrive, then the system latches a time stamp (incremented every 320 ns) and enters readout mode. The signal peaks are queued in the triggered channels’ buffers until the board requests them. One at a time, the readout board requests each analog pulseheight,
digitizes it using the same 12-bit ADC (4096 bins), and sends it over HDMI to the commanding PC-104 computer for processing and storage. When all data has been read out, the system returns to acquisition mode, waiting for the next signal. This process takes $\sim 200 \text{ } \mu s$, depending on the number of triggered channels, allowing fast kilohertz-scale data rates.

Figure 4.8: A photo of the custom ASIC-based readout board used for both COBRA prototypes. The reflective surface in the center is the cathode side of a CZT detector. The high-voltage biasing cable can be seen entering the box from the upper left. The HDMI port is just below.

4.5.3 Characterization and Calibration

The NCI-ASIC also features a 200 fF test capacitor which can inject charge directly into individual channels. Test charge data can be used to measure the readout noise (pulseheight “jitter”) of the ASIC or, by varying the amount of charge, to measure the linearity of the system. Both tests are performed on every detector used in the system to characterize and calibrate them, as well as to identify noisy channels.

The jitter test requires repeatedly pulsing each channel with a fixed charge and measuring the signal amplitudes returned. The variation in amplitude is the inherent
4.5 Prototype Detector Development

electronic noise of the channel and is typically only a few keV FWHM. The linearity test is performed by pulsing each channel while slowly ramping up the input charge. Of course, the ASIC should have a linear relation between input charge and output signal. The slope should also vary with gain, and so the test is performed for all three gain settings. A scatter-plot is generated to confirm the linearity (such as in Figure 4.9) of each channel and gain.

![Figure 4.9](image)

Figure 4.9: An example plot of the kind of linearity data taken with the ASIC-based readout system. The test confirms that the digital pulseheight values depend linearly on the input charge, as expected.

The linearity test is also useful because it shows the pedestal and saturation values for each channel. The pedestal is the digital pulseheight value which corresponds with zero input charge. Because the signals are digitized to 12 bits, there are 4096 (0–4095) values available to cover the dynamic range from minimum to maximum
signal. However, every analog signal which eventually reaches the ADC chip is riding on the preamplifier’s baseline operating voltage. This increases every signal by a DC offset. Therefore, a 0 keV signal will usually correspond to a digital pulseheight value of about 400 out of 4096. A line fit to the scatter-plot of output signal vs. input charge will cross $y$-axis at the pedestal. The pedestal is different for every channel and is, fortunately, very stable.

For similar reasons, the maximum possible signal is not 4095. Instead, signals saturate at some smaller value which differs for every channel. The linearity test shows this value as the output voltage (on the $y$-axis) which is not exceeded even as input charge is increased. Note that input charge above saturation will result in a Gaussian spread of output values with its mean at the saturation point and FWHM equal to the electronic noise. Therefore, to avoid the appearance of a false high energy peak, data should be rejected not just at the saturation value, but a few FWHM below it.

All new prototypes are first calibrated by flood irradiation with a $^{137}$Cs source, an emitter of 662 keV $\gamma$-rays. By determining the pedestal values electronically, it is possible to calibrate the detector with only one spectral line. The pulseheight-to-keV conversion factors are determined by taking the difference in the digital pulseheight values for the pedestal and the photopeak and dividing by the photopeak energy.

The detector thresholds are optimized during $\gamma$ irradiation as well. Each ASIC channel exhibits slightly different noise and gain properties. Therefore, the thresholds
should be adjusted on a channel-by-channel basis using the trimming capabilities of
the NCI-ASIC. It is often necessary to disable the noisiest channels to obtain the
lowest possible average threshold for the detector. This is because the dynamic range
of the trim is small compared to the variation in optimum channel thresholds. By
disabling as little as 5% of the detector, energy thresholds as low as 10 keV have been
achieved.

4.5.4 System Integration

The single-detector readout board with its three ASICs, FPGA, and other electronics
is mounted inside of a sealable copper box to reduce external electromagnetic inter-
fERENCE. The box has feedthroughs for HDMI data out, DC power for the board, and
high voltage for the detector bias. The CZT crystal is fixed to the board with an
Ultem plastic mount. The mount presses the crystal down onto gold-plated, spring-
loaded “pogo-pins” to connect the pixels with traces leading to the ASIC inputs (see
Figure 4.10). The pixels are held at ground and DC-coupled to the anode ASICs.
The cathode is biased at high voltage and AC-coupled to its dedicated ASIC.
Figure 4.10: A photo of the empty detector mount in the readout system for the COBRA prototypes. The gold points arrayed in a grid at the center are the “pogo-pins” which connect a detector’s 64 pixels to the input traces on the readout board.
Chapter 5

Comparison of Detector Types for COBRA

5.1 Coplanar Grid Detectors

The first single-polarity CZT detector was studied by Luke [1994]. Inspired by the virtual Frisch grid concept (see Section 4.3), a coplanar grid (CPG) employing an interleaved comb design was developed to remove the depth dependence of CZT detectors. In the 1994 study, a $5 \times 5 \times 5 \text{ mm}^3$ CZT detector with planar contacts was tested and found essentially no photopeak from 662 keV $\gamma$-rays, but instead a continuum of energies. After replacing the anode with a CPG, performance improved. A 662 keV photopeak was resolved to $\sim5\%$ FWHM.
A critical component of the CPG detector method is the subtraction circuit which leaves zero signal until the carriers get close to the grid. This negates the effect of the holes, but unfortunately does not remove all depth dependence. In 1995, Luke was already aware that correcting for the lesser effect of electron trapping could improve results. Later that year, a method of compensating for this effect—known as the “relative gain method”—was proposed. In this method, a relative difference in gain is applied between the two grid signals prior to subtraction. In doing this, some signal would still accumulate during drift far from the grid. By optimizing the gain, it was observed that electron trapping could be corrected for while reintroducing only a minimal contribution from the holes. This lead to an improvement in energy resolution to 2.4% at 662 keV for a thick 1 cm$^3$ detector.

The current best results for CPG detectors have been achieved by the He group at Michigan State University. Energy resolutions for a 1 cm thick CPG detector as low 1.65% FWHM at 662 keV have been observed using the cathode-to-anode ratio depth sensing technique [Sturm 2007]. This provides superior resolution to the relative gain method because the depth dependence caused by electron trapping can be corrected for without reintroducing dependence due to holes.

The depth information provided by this technique applies only to slices of equal depth across the entire detector. Unfortunately, because of the interleaved anodes, CPG detectors provide no 2D location of interaction information across the anode plane. For this reason, large detectors are rarely used. A common size is a cube
of 1 cm$^3$. With no depth sensing, the spatial resolution is then $1 \times 1 \times 1$ cm$^3$, but improves to $1 \times 1 \times \text{FWHM}(d)$ cm$^3$ when it is applied. The depth resolution FWHM($d$) is derived from the energy resolutions of the anode and cathode. In CPG detectors, FWHM($d$) improves with depth from the cathode side and can be fractions of a mm.

### 5.1.1 COBRA CPG Performance

In Chapter 3, recently published results from the COBRA experiment were discussed. These were derived from a prototype setup operated at LNGS. Because these were prototype measurements taken in unknown background conditions—before the passivation and radon components were characterized—cheaper, low-quality detectors were selected. However, it is interesting to compare their performance to the state of the art.

In the experiment, each detector was individually set with its own cathode bias voltage, grid bias voltage, and relative gain factor for the subtraction circuit. These parameters were tuned to optimize energy resolution at the 1274.5 keV line of a $^{22}$Na calibration source. Because COBRA attempts to set limits on $0\nu\beta\beta$ decay at a wide range of $Q$-values, the energy resolution of each detector was also characterized with photopeaks at 122.1, 511, and 2614.5 keV.

Across the four calibration energies, the resolution was found to closely follow a two-parameter function $\Delta E = \sqrt{a^2 + (bE)^2}$. Using this function it is possible to
determine the energy resolution at 662 keV. The best detector has a 2.8% FWHM energy resolution at 662 keV, while the worst has 10.5% resolution. The average over sixteen detectors was 4.5% FWHM. If higher quality detectors were purchased and the depth sensing technique employed, a factor of 2.5 improvement in energy resolution could be achieved.

5.2 Coarsely Pixelated Detectors

Since their introduction [Barrett et al. 1995], pixelated CZT detectors have seen widespread use in the field. They pair excellent energy resolution—afforded by the small pixel effect—with enhanced 2D spatial resolution. Early on, the Michigan State group was able to exploit the cathode-to-anode ratio depth sensing technique and extend the spatial sensitivity of these detectors into three dimensions [He et al. 1999].

Just as with CPG detectors, the depth information allows correction of the energy spectrum, resulting in improved energy resolution. To date, the best energy resolution observed comes from a $1.5 \times 2 \times 2$ cm$^3$ detector manufactured by eV Products with an $11 \times 11$ pixel grid (1.72 mm pitch) and tested by Michigan State. A corrected energy resolution of 0.48% FWHM at 662 keV was observed for the full detector volume [Zhang and Kaye 2009].
3D position sensitive CZT detectors can be constructed much larger than CPG detectors without penalty to the spatial resolution. Rather than slices, the location of interaction information becomes constrained to much smaller “voxels” for which size depends on the pixel pitch and cathode resolution. For a detector like the one described above, spatial resolution may be as fine as $1.72 \times 1.72 \times 0.05 \, \text{mm}^3$. The same detector would have resolution $20 \times 20 \times 0.05 \, \text{mm}^3$ in a CPG configuration.

5.2.1 Measurements with Coarsely Pixelated CZT

Results from prototypes developed at WUSTL were recently published in *Astroparticle Physics* by Li [2011]. Five CZT detectors of varying thickness were systematically characterized and reprocessed with different pixel pitches in the manner described in Section 4.5.

The study searched for trends in detector performance related to detector thickness, manufacturing process, and pixel pitch. Four of the detectors were manufactured by Orbotech Medical Solutions using the Modified Horizontal Bridgeman (MHB) method: two 0.5 cm-thick crystals, one 0.75 cm-thick, and one 1.0 cm-thick. The fifth detector was manufactured by eV Products (now Endicott Interconnect) using the High Pressure Bridgeman (HPB) technique and was 1.0 cm-thick. Each detector was systematically tested, polished, and reprocessed with new contacts: 2.5 mm pitch, 1.7 mm, and 1.3 mm. Calibration was performed by flood illumination with $^{57}\text{Co}$ (122 keV) and $^{137}\text{Cs}$ (662 keV) γ-ray sources.
5.2 Coarsely Pixelated Detectors

Relevant to COBRA, the study produced some remarkable results concerning the excellent energy resolutions achieved when combining these detectors with the low-noise NCI-ASIC readout system. They include some of the best energy resolutions ever recorded for $\geq 0.5$ cm thick CZT: 2.9 keV FWHM (2.39%) at 122 keV and 5.3 keV (0.87%) at 662 keV. In fact, the 2.9 keV result may be the best energy resolution ever observed at 122 keV in thick CZT (see Figure 5.1, left). Also, when a depth of interaction correction is applied, the best 662 keV resolution is reduced to 0.61% FWHM (see Figure 5.1, right).

![Figure 5.1: 122 keV (left) and 662 keV (right) energy spectra from a detector with 2.5 mm pixel pitch [Li et al. 2011]. The 122 keV spectrum exhibits an energy resolution of 2.39% FWHM, one of the best ever achieved in thick CZT at this energy. The 662 keV spectrum has been depth corrected and its energy resolution improved from 0.87% to 0.61% FWHM.](image)
5.3 Finely Pixelated Detectors

We refer to detectors with a pixel pitch of 1 mm or less as finely pixelated detectors. The primary benefit of such a design is the enhanced spatial resolution this provides. Another benefit one might expect is improved energy resolution from an even stronger small pixel effect. However, this tends to be counteracted by “charge sharing”. Charge sharing occurs when carriers drift into more than one pixel or into the spaces between pixels. In both cases, some of the signal may be lost. A discussion on the resolution limitations of finely pixelated CZT can be found in Section 5.3.5.

5.3.1 Fine Pixel Fabrication Activities

The costly development of ASICs which are capable of processing thousands of channels densely packed into a footprint on the order of cm$^2$ remains a great impediment to advancing the technology of finely pixelated CZT. For this reason, our approach to fine pixel research has involved fabricating prototypes which may be tested with ASICs already in development at collaborating institutions. Prototype detectors customized for two different ASIC systems have been prepared for this purpose and are currently being tested by collaborators.

The first of these detectors was fabricated for bonding to a 2048-channel ASIC with a 350 µm pitch. Collaborators at the University of Illinois in Urbana–Champagne
(UIUC) have published results from a thin CdTe detector array using the ASIC manufacturer’s proprietary readout system [Cai et al. 2010]. The ASIC is being developed for imaging applications and has been designed to provide a dynamic range of 12–200 keV, and energy resolution from 3–4 keV in that range. When reading out an array of eight detectors—a total of 16,384 pixels—resolutions as low as 3.51 keV (3%) FWHM at 122 keV have been observed in the best pixels.

Additional detectors were fabricated for the project at both 350 µm and 700 µm pixel pitches using the methods described in Section 4.5.1. I produced the 700 µm detector shown in Figure 5.2. Here, on a single crystal, pixels with different gap widths can be tested in addition to pixels with and without a “steering grid”. The steering grid resides in the inter-pixel gap and may be biased to “steer” carriers away from the gap and onto a pixel in order to combat charge sharing. Different widths for the grid are also present on this prototype.

In addition to prototype fabrication, we have also developed a custom readout board with a smaller footprint than the proprietary system. The prototypes have been bonded to the ASICs and are currently tested in the new system at UIUC.

The second fine-pixel ASIC for which I have fabricated prototypes has 608 channels with a 600 µm pitch and is being developed by Black Forest Engineering (BFE). Two detectors were produced and are shown in Figure 5.3. Both employ the same pattern with three pixel widths, where one of the widths is deposited with and without a steering grid. In the first detector, all contacts are formed by a single deposition of
5.3 Finely Pixelated Detectors

Figure 5.2: Photo of a CZT detector fabricated with a 700 µm pixel pitch. Only half of the detector will be bonded to the much smaller UIUC ASIC.

titanium. In the second, the steering grid is isolated from the CZT surface by a layer of gold which forms a blocking contact. The detectors are currently being tested by our collaborators at the University of California, Berkeley.

5.3.2 Performance of the NuSTAR ASIC

Astrophysics is one field which has recently focused on the development of finely pixelated CZT. One example application is NuSTAR, a satellite-borne telescope slated to launch Spring 2012 [Rana et al. 2009]. Its primary mission is to observe faint sources while performing a deep survey of hard X-ray emission (6–80 keV) from supermassive black holes. The two focal plane instruments each consist of four hybrid detectors: CZT crystals (purchased from eV Products) bonded directly to their readout elec-
5.3 Finely Pixelated Detectors

Figure 5.3: Wide-angle (left) and zoomed (right) views of a CZT detector fabricated with 600 μm pixel pitch. In the zoomed view, the gold blocking-layer is visible underneath the steering grid. Contacts were fabricated with detail as fine as 10 μm.

tronics (see Figure 5.4). Each crystal is 20.5 × 20.5 × 2.0 mm³ in size with a 32 × 32 pixel array (1024 total pixels) set at a pitch of 605 μm with a 50 μm.

Pixels on the NuSTAR detectors are read out with a custom designed low-noise ASIC. The team has characterized the electronic noise of their system to be less than 0.3 keV FWHM. The CZT/ASIC hybrids also meet the mission requirement of energy resolution less than 1.6 keV FWHM across the dynamic range. Figure 5.5 shows a sample spectrum from NuSTAR hybrid characterization data.

The team observed significant charge sharing effects in the hybrids. When flood illuminated with γ-rays, more than 40% of events showed signals shared between adjacent pixels. In order to achieve optimum spectral performance, NuSTAR plans to simulate a variety of multi-pixel event topologies in order to correct the spectra for signal loss due to charge sharing.
5.3 Finely Pixelated Detectors

Figure 5.4: Photo of the NuSTAR focal plane array consisting of four CZT detectors with 605 µm pitch.

Figure 5.5: Energy spectrum taken from a NuSTAR detector. The energy resolution shown here is about 1.5% at 86.5 keV FWHM.

5.3.3 Performance of the TimePix ASIC

The Timepix chip is another ASIC capable of reading very finely pixelated detectors. The chip is in active development at CERN for the purposes of high energy particle tracking. It has a footprint of 2 cm$^2$, with 256 $\times$ 256 pixel contact points at 55 µm pitch. It is a successor to the Medipix2 chip, to which it adds time-based readout for a total of three data acquisition modes: single particle counting, time over threshold (TOT), and arrival time. It is the TOT mode which enables the spectroscopic capability which is relevant to COBRA. Time $t_{\text{TOT}}$ over threshold TH is related to the energy deposited in the channel $E$ by the following expression:

$$t_{\text{TOT}}(E, a, b, c, TH) = aE + b + \frac{c}{E - TH}$$  \hspace{1cm} (5.1)

where calibration measurements yield the values $a$, $b$, and $c$. 
5.3 Finely Pixelated Detectors

First measurements with a 1 mm thick CdTe detector were performed with the ASIC configured to read out 110 \( \mu \)m pixels [Cermak et al. 2011]. The experiment produced spectra with 5.2% FWHM energy resolution at 662 keV and 1.6% at 1588 keV, as well as the particle tracks shown in Figure 5.6.

![Figure 5.6: Particle tracks produced from a CdTe detector with 110 \( \mu \) pixel pitch bonded to a TimePix ASIC. Easily differentiable are the short-range \( \alpha \)-depositions (a), the winding paths of \( \beta \)-electrons (b), and the long, straight tracks of muons (c).](image)

5.3.4 Simulated Background Reduction Capabilities

The ability of a pixelated detector to reduce background in a \( 0\nu\beta\beta \) search has been simulated by Bloxham [2007]. Different types of background events were simulated in order to determine with what accuracy they might be rejected given excellent spatial resolution. As seen in Figure 5.6, \( \alpha \) events are easily identifiable. Their short range of order 10 \( \mu \)m is distinct from the mm-long tracks of \( \beta \) electrons. Muons are also easily identified by their long and straight paths, when compared to the near-random walk of a \( \beta \). \( \gamma \)-rays may be discriminated in cases where Compton scattering or pair
production occurs, but photoelectric effect events generate secondary electrons with very $\beta$-like tracks. The most difficult task is discriminating single-$\beta$ electrons from $\beta$ pairs emitted during $0\nu\beta\beta$ decay\footnote{Of course, energy is the only way to discriminate the $2\nu$ mode from $0\nu\beta\beta$ decay.}.

The simulation results propose that a pixel detector with 200 $\mu$m pitch can discriminate single $\beta$’s from pairs with 70% accuracy. An algorithm for tagging single $\beta$’s as part of a decay chain was also developed. If an $\alpha$ event with an energy matching a step of the $^{232}$Th or $^{238}$U decay chains was observed, that segment of the detector was vetoed for several half-lifes. Combining the rejection of all these event-types, the study found a reduction in background of three orders of magnitude in the 2814 keV signal region, as shown in Figure 5.7.

It should be noted that the simulated detector with 200 $\mu$m pixels was 3 mm thick and carrier diffusion was not accounted for.

### 5.3.5 Limitations of Finely Pixelated Detectors

As discussed at the beginning of Section 5.3, charge sharing is the signal loss resulting from the drifting of carriers into more than one pixel or into the spaces between pixels. One cause of charge sharing is simply that the charge cloud is generated in such a position inside the detector bulk that its drift path brings it between pixels. Full charge is not induced on any contact when the carrier drifts to the inter-pixel gap.
5.3 Finely Pixelated Detectors

Figure 5.7: Simulated background spectra reduced by a series of particle discrimination and tagging cuts. “All decays” shows broad $\alpha$ lines at high energy and a continuum of events at lower energies representing the decay chains of $^{232}$Th and $^{238}$U. *Spectrum 1* filters out the events which are positively identified as $\beta$ rather than $\beta\beta$ decays. *Spectrum 2* includes the prior filter as well as $\alpha$ rejection. *Spectrum 3* is the fully reduced background after vetoing $\beta$-decays which are correlated with $\alpha$’s preceding them in the decay chain.

Another cause of charge sharing—and the reason it is possible for two pixels to share the charge from a single event—is the lateral spread of charges during drift. This spreading has two components: thermal diffusion of carriers and mutual electrostatic repulsion between carriers.

The repulsion effect decays rapidly after the charge cloud is created, but thermal diffusion continues over the entire drift path and is worse for thick detectors.\(^2\) Not only will diffusion cause some carriers to be lost in the gap, but if not enough carriers\(^2\)For simplicity diffusion—the dominant component—is hereafter used to refer to the combined effect of repulsion and diffusion.
drift to a second pixel for it to exceed its minimum threshold signal, all of those carriers will be lost. Any lost charge has the effect of degrading energy resolution.

Another consequence of diffusion is the degradation of spatial resolution as well. For this reason, thick detectors with very fine pixel pitches are impractical. At a certain point, spatial resolution becomes diffusion-limited. However, the use of thin detectors has several disadvantages which make them a poor choice for a large-scale COBRA experiment. First, thin detectors cannot efficiently stop high energy $\gamma$-rays, making them difficult to calibrate at the high energies where some $0\nu\beta\beta$ Q-values are expected. Extremely long calibration run times are necessary to obtain good statistics, meaning the operational time of an already low-mass detector will be significantly shortened. A second consequence of their inability to stop $\gamma$-rays is that detection efficiency for $0\nu\beta\beta$ decay is significantly reduced, especially the $\beta^+\text{-emitting modes. At 511 keV, annihilation photons will almost always escape a thin detector. Higher energy } \gamma\text{-rays may also be generated via bremsstrahlung and lost. Finally, the mass of the detector is outweighed by the nearby ASIC and other readout components, contributing to increased background levels.}

5.4 Cross-Strip Detectors

Cross-strip CZT detectors were studied by Kalemci and Matteson [2002]. The motivation for the study was to test simulations of charge sharing in CZT detectors using
thin strips with a sub-mm pitch. A $12 \times 12 \times 2$ mm$^3$ detector with 22 anode strips and
22 orthogonally oriented cathode strips each set at a 0.5 mm pitch. The measured
energy resolution was 3% FWHM at 122 keV, a width of only 3.7 keV. Given the
significant level of charge sharing observed, this is a good result. However, for thicker
detectors relevant to COBRA, the charge sharing would only worsen and degrade the
energy resolution.

More recently, studies on thick detectors at higher energies have been performed.
I have developed simulations of signal production in strip detectors and fabricated
prototypes. These activities, as well as the results of measurements are summarized
below.

5.4.1 Simulations of Cross-Strip CZT Performance

In order to optimize the design of CZT cross-strip detectors, I have performed de-
tailed detector simulations. The simulations account for both types of charge carri-
ers, electrons and holes. The signal induced on the anode and cathode contacts of a
$0.5 \times 3.9 \times 3.9$ cm$^3$ large-volume CZT detector is simulated in two dimensions.

As discussed in Section 4.1.2, the charge induced on a detector contact is deter-
mined by the movement of charge carriers through the weighting potential of that
contact. In this simulation, the weighting potential for a central anode strip in the
cross-strip detector is calculated by first finding the electric potential in the biased
detector (cathode at $-700$ V and anode strips set to ground). This is done using a finite-difference method over a grid, which solves the 2D Laplace equation for a detector inside a large grounded box. After many thousands of iterations, the electric potentials inside the detector and the surrounding box stabilize on the values shown in Figure 5.8.

![Figure 5.8: The simulated electric potential inside a $5 \times 5$ cm$^2$ grounded box containing a 0.5 cm thick CZT detector biased at $-700$ V.](image)

Next, the electric potential is re-calculated with the strip of interest negatively biased by a unit voltage relative to the other anode strips. By the mean-value theorem,
the weighting potential at any grid point is then the difference between the initial electric potential and the unit-biased potential at that point. Since the anode and cathode strips have the same geometry in this 2D simulation, their weighting potentials are identical in form. Thus, the potential used to calculate charge induced on the cathode is the same as the anode, but inverted and shifted to the other side of the detector. The weighting potential for a 1.05 mm anode strip is shown in Figure 5.9.

![Figure 5.9: The simulated weighting potential for an anode strip with a 1.05 mm pitch, inside a 0.5 cm thick CZT detector.](image)

An event is simulated by initializing unit charges of each polarity—representative of the electron-hole pairs liberated by the photoelectric absorption of a $\gamma$-ray—at a point on the grid under the anode strip of interest and tracking their drift paths through the electric field of the detector. The simulations assume electron and hole mobilities of $\mu_e = 1000 \text{ cm}^2/\text{V/s}$ and $\mu_h = 120 \text{ cm}^2/\text{V/s}$, respectively [Spieler 2005]. Electrons and holes each induce charge on both the anode and cathode over each step
of their drift paths as determined by the weighting potentials.\(^3\) The charge induced on the anode by electrons is then added to the charge induced by holes—along with a factor to apply a gaussian spread, matching a realistic detector resolution (0.5% FWHM at 662 keV for the anode and 2% for the cathode)—for a total anode signal and likewise for the cathode signals. In an ideal detector—which completely collects all carriers without charge loss—the total anode signal and total cathode signal each completely reconstructs the energy of the initial photoeffect event.

The above describes how the signal for one photoelectric effect event is simulated. To construct a spectrum, the process of charge initialization, tracking, and charge accumulation is repeated for many more grid points underneath the anode strip of interest. At 662 keV, photons have an almost equal probability of being absorbed at any depth in the detector. This is simulated by initializing events at every grid point an equal number of times. When simulating lower energies, the number of events per grid point further from the cathode is reduced exponentially according to the absorption length.

Due to the “small pixel effect”, the greatest amount of charge is induced near the contact (see Section 4.1.2). This means that carriers which drift away from the contact only deposit significant charge if they are created near it. Therefore, holes are not large contributors to the anode signal and electrons contribute little to the

\(^3\)This is the incremental induced charge \(\Delta Q_k = q(\Phi_k(x_2) - \Phi_k(x_1))\) from Equation 4.2.
5.4 Cross-Strip Detectors

cathode signal.\footnote{This, of course, only applies to cross-strip detectors which have the same contact geometry for both anode and cathode. In contrast, the majority of the signal induced in a planar cathode can be attributed to electrons.} In materials where there is minimal trapping of either carrier, such as silicon, this is not a problem. The total charge of the initial ionization event will still be observed when summing the electron and hole signals for either contact. In CZT, however, trapping cannot be neglected for either carrier. The simulation represents this effect by applying a decaying exponential to the value of the charge remaining after time $t$, like so:\footnote{Assuming a constant drift velocity, this is analogous to the description of trapping found in Equation 4.4.}

\[ Q(t) = Q_0 e^{-t/\tau}. \] (5.2)

The energy deposited by the initial photoeffect event decays with a time constant equal to the carrier lifetime $\tau_h = 1 \, \mu s$ for holes and $\tau_e = 4 \, \mu s$ for electrons [Spieler 2005]. The practical result is a low-energy tail on the anode photopeak and an extremely poor cathode signal due to significant hole trapping. Figures 5.10 and 5.11 show 662 keV photopeaks before and after applying carrier trapping in the anode and cathode respectively.

Hole drift times can be so long that the holes do not reach the cathode within the allowed integration time, i.e. the ASIC shaping time, even without trapping. This is simulated by simply ceasing to track carriers and accumulate charge after the shaping time is complete.
5.4 Cross-Strip Detectors

Figure 5.10: Simulated 662 keV anode photopeak with (left) and without (right) accounting for carrier trapping.

The detector was simulated many times to incorporate all combinations of four important parameters. The detector was simulated with three strip widths (525 μm, 1050 μm, and 2100 μm), three ASIC shaping times (1 μs, 2 μs, and 4 μs), with or without the hole contribution, and with a variety of μ and τ properties differing from the baseline values mentioned above.

Simulation Results

First, note that the combined effect of electron and hole trapping roughly triples the width of the anode photopeak, as seen in Figure 5.10 from the previous section. With no trapping, the peak is gaussian with a width matching the 0.5% resolution factor. When trapping is added, the width increases to 1.2% FWHM for the baseline μτ-products. The resolution continues to deteriorate as μτ is reduced.

Figure 5.12 shows the signals produced in an anode strip (left column) and a cathode strip (right column) by electrons (top row), holes (center) and both (bottom).
5.4 Cross-Strip Detectors

Figure 5.11: Simulated 662 keV anode photopeaks with (left) and without (right) accounting for carrier trapping. The severe degradation of the cathode photopeak is due to the comparatively stronger trapping effect of holes which are the primary component of its signal.

These results are for a detector employing a 1.05 mm strip width and 4 µs ASIC shaping time. The hole contribution substantially improves the photopeak efficiency as seen by comparing the anode signal produced by electrons alone (top left) with the anode signal produced by electrons and holes together (bottom left). Furthermore, the holes make substantially larger cathode signals than the electrons when comparing the cathode signals produced by electrons (top right) with the cathode signals produced by holes (center right).

Different ASIC shaping time settings may affect the signals produced by the anode and the cathode. Three shaping times: 1, 2, and 4 µs were simulated. Longer shaping times have been verified to give approximately the same results as the 4 µs shaping time. Figure 5.13 shows the cathode signals for two different shaping times: 4 µs (left) and 1 µs (right). It can be recognized that shaping times which are too short lead to a substantial signal loss for the cathode. The shaping time has little effect on
Figure 5.12: Simulated response to 662 keV photoeffect events of a CZT strip detector with 1.050 mm cathode and anode pitches. The left panels show the response of one anode strip, and the right panels the response of one cathode strip. The three rows show the energy spectra produced by electrons only (top), by holes only (middle), and the true signal consisting of electrons and holes together (bottom).
the anode signal. Our ASIC readout can use shaping times up to 4 $\mu s$, sufficiently long to collect most of the charge induced by holes.

Figure 5.13: Comparison of simulated 662 keV photoeffect events on a 1.050 mm cathode with 4 $\mu s$ (left) and 1 $\mu s$ (right) shaping times. 1 $\mu s$ is not long enough to allow complete hole collection.

Figures 5.14 and 5.15 show the comparison of signals for 0.525 mm (left) and 2.100 mm (right) strip widths for the anode and the cathode respectively. The size of the strip for the cross-strip detector affects the weighting potential of the strip, thus, altering the photopeak energy resolution. Figure 5.14 indicates that a narrower anode strip gives better photopeak energy resolution in the anode, while Figure 5.15 indicates that the cathode prefers a wider strip to collect the electron and hole signals.

5.4.2 Measurements with Cross-Strip CZT

A cross-strip detector was tested in 2010 after we acquired four large-volume 0.5 $\times$ 3.9 $\times$ 3.9 cm$^3$ CZT detectors from the company Orbotech Medical Solutions [Lee et al. 2010]. The detectors were delivered already contacted with 256 indium pixels.
5.4 Cross-Strip Detectors

Figure 5.14: Simulated 662 keV photoeffect events in a detector with a 0.525 mm anode (left) and a 0.525 mm cathode (right). Anode response is better than for a 1.05 mm strip, while cathode response is worse. Shaping time is 4 µs.

Figure 5.15: Simulated 662 keV photoeffect events in a detector with a 2.100 mm anode (left) and a 2.100 mm cathode (right). Cathode response is better than for a 1.05 mm strip, while anode response is worse. Shaping time is 4 µs.

(in a 16 × 16 grid) and a monolithic indium cathode. Before reprocessing the crystal into a cross-strip detector, the manufacturer’s pixels were tested. To do this, the detector was flood illuminated with 122 keV γ-rays from a ⁵⁷Co source. The detector was read out using a second generation system based on the same ASIC described in Chapter 6. The cathode was biased at −500 V and the anode pixels held at ground. An energy spectrum was generated for each channel and the photopeaks were fit.
with a Gaussian distribution superimposed with an exponential tail toward smaller energies. The detector’s FWHM energy resolution was then determined from this fit function: 6.7% FWHM at 122 keV.

Using both the manufacturer’s pixels and cathode required us to use a relatively low bias voltage of −500 V. This is because indium forms an ohmic contact on CZT and higher voltages generate large leakage currents which deteriorate the energy resolution. The indium cathode was replaced with gold using the detector fabrication process described in Chapter 6. Gold forms a blocking contact which exhibits far less leakage current at higher bias voltages. This allowed us to bias the detector to −1000 V. As depicted in Figure 5.16, this improves the energy resolution from 6.7% to 3.9% FWHM at 122 keV.

![Figure 5.16: 122 keV energy spectra for a 4 × 4 × 0.5 cm³ detector with the manufacturer’s contacts (left) and after replacing their indium cathode with gold. The energy resolution improves from 6.7% to 3.9% FWHM at 122 keV.](image)

After these tests, the anode and cathode contacts were replaced with crossed strips. I performed the fabrication of this cross-strip detector. The large footprint of the detector allowed the deposition of 30 strips per side, each 1.25 mm wide. Indium
was chosen for the anode contact material and gold for the cathode contacts. The anode and cathode strips are orthogonal to each other, forming a virtual grid of 900 pixels, each $1.25 \times 1.25 \text{ mm}^2$ in size. To reduce surface currents from the edges of the detector, the strips on each side are surrounded by their own guard ring of the same contact material. Figure 5.17 shows the cathode side of the detector and, for comparison, the same detector before the pixels were removed.

Figure 5.17: Photos of a $4 \times 4 \times 0.5 \text{ cm}^3$ detector with pixel anode contacts (left) and in a cross-strip configuration (right).

**Measurement Results**

The cross-strip detector was tested in two different readout systems: an ASIC-based system, and an analog system with discrete components. The ASIC-based system produced energy spectra with resolutions of 6.6% FWHM (8 keV) at 122 keV, and 3.5% FWHM (23 keV) at 662 keV (shown in Figure 5.18, left). These results are
competitive with the detector performance at low bias (\(\sim 500 \text{ V}\)), but not at high bias (\(> 1000 \text{ V}\)). For the cross-strip detector the best resolutions were observed at 800 V. There seems to be a higher leakage current with strips compared to pixels, even with a blocking cathode contact.

The analog system produced better results. An energy resolution of 1.7% FWHM at 662 keV was observed (see Figure 5.18, right). However, this measurement required excluding the 50% of events which interacted in the anode half of the detector.

The 1.7% resolution measured with the analog system approximately matches a simulated spectrum with \(\langle \mu \tau \rangle_e = 3 \times 10^{-3} \text{ cm}^2/\text{V}\). This \(\langle \mu \tau \rangle_e\) is in agreement with an independent measurement based on analysis of the change in photopeak position with detector bias.

Figure 5.18: 662 keV energy spectra for a cross-strip detector taken with an ASIC-based readout system (left) and analog system (right). With the ASIC system, the energy resolution is 3.3% FWHM at the photopeak. With the analog system, the energy resolution for the 50% of events nearest the cathode is 1.7% FWHM.
5.5 Applications in COBRA

The goal in using any of these detector types in the COBRA experiment is to measure the half-life of $0\nu\beta\beta$ decay. The half-life depends on a variety of experimental parameters: detection efficiency $\varepsilon$, detector mass $M$, total exposure time $t_{\text{tot}}$, the rate of background events $b$ in counts/keV/kg/yr, and the FWHM energy resolution $\Delta E$. Their effect on the half-life $T_{1/2}$ takes the form

$$T_{1/2} \propto \varepsilon \sqrt{M t_{\text{tot}} b \Delta E}.$$  \hspace{1cm} (5.3)

So far, the energy and spatial resolutions have been the focus of our discussion on the four detector types. Energy resolution appears explicitly in Equation 5.3. A better energy resolution allows the selection of events over a narrower energy range, which suppresses background.

Spatial resolution contributes to improved energy resolution when a depth correction may be applied, but it is also important because it aids in background reduction. For example, $\alpha$ particles may carry energies overlapping the $0\nu\beta\beta$ Q-values, but do not penetrate beyond the outer surfaces of CZT. A fiducial cut can significantly reduce the contribution these particles make to $b$. For CPG detectors, this is less effective. The cathode and anode surfaces can be cut, but there is no way to exclude the other four surfaces. Pixel and strip detectors need only exclude events which trigger the

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6The full equation and its derivation is presented in Section 6.1.
border pixels or strips. However, this comes with a cost. The background reduction must be balanced with the loss of detector mass. This is less practical with the relatively poor 2D spatial resolution in coarse pixels compared with fine pixels and the strip detectors tested.

CPG detectors are also less practical due to their low \( M \), typically about 6 g. As mentioned in Section 5.1, small detectors are required to optimize their already poor 2D spatial resolution. In contrast large-volume pixel and strip detectors as massive as 35 to 45 g have been discussed. Larger individual detectors reduce complexity and can be more cost effective, improving scalability (see Section 7.1.1). More importantly, they impact efficiency \( \varepsilon \), especially for the \( \beta^+ \)-emitting modes. Any photons which are generated are much less likely to escape a large-volume detector.

<table>
<thead>
<tr>
<th>Detector Type</th>
<th>( \Delta E ) FWHM</th>
<th>( M ) [g]</th>
<th>( \Delta x \Delta y ) [mm(^2)]</th>
<th>( \Delta d ) [mm]</th>
<th>relative ( b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coplanar Grid</td>
<td>1.7%</td>
<td>6</td>
<td>10 \times 10</td>
<td>&lt; 0.1</td>
<td>1\times</td>
</tr>
<tr>
<td>Coarse Pixels</td>
<td>0.5%</td>
<td>\sim 35</td>
<td>&gt; 1 \times 1</td>
<td>&lt; 0.1</td>
<td>0.1\times</td>
</tr>
<tr>
<td>Fine Pixels</td>
<td>2–3%</td>
<td>35</td>
<td>0.35 \times 0.35</td>
<td>&lt; 0.1</td>
<td>0.001\times</td>
</tr>
<tr>
<td>Cross-Strips</td>
<td>1.7%</td>
<td>\sim 35</td>
<td>1 \times 1</td>
<td>unknown</td>
<td>0.1\times</td>
</tr>
</tbody>
</table>

Table 5.1: Summary of performance characteristics for the four CZT detector types. The characteristics include: FWHM energy resolution in keV, typical/practical detector mass in g, 2D spatial resolution in mm\(^2\), depth resolution in mm, and relative background rate in counts/keV/kg/yr. The value representing the poorest performance for each parameter is in bold.

Table 5.1 summarizes the performance of all four detector types with regard to the relevant parameters. The value representing the poorest performance for each parameter is in bold. The table makes it clear that CPG detectors are the least favored, and that coarse pixels should perform better than strip detectors, especially
if depth sensing technology remains undeveloped. Less obvious, is the practicality of finely pixelated detectors. The claim of three orders of magnitude in total background reduction is very compelling. However, the practical limitations discussed in Section 5.3.5 cannot be ignored. Additionally, the background of $2\nu\beta\beta$ decay is irreducible and good energy resolution is needed to distinguish it from the neutrinoless events. If the search for $0\nu\beta\beta$ decay extends to half-lifes beyond $10^{26}$ years, the present technology available to finely pixelated detectors will be incapable of separating the two modes.
Chapter 6

Prototype Measurements

Prototype CZT detectors with coarse pixels were tested for their ability to reduce background and produce lower limits on $0\nu\beta\beta$ decay half-lifes which are competitive with published results from CPG detectors. The first prototype operated at surface-level in our laboratory in December 2008 and the second was under ultra-low background conditions at the LNGS underground facility in spring 2010.

Section 6.1 discusses the relevant analysis methods necessary to process the spectral data produced by the prototypes. It also provides equations which are useful in general when computing upper limits and sensitivity in low-background experiments. Experimental methods and analysis techniques are reported for each prototype in Sections 6.2 and 6.3. Results are summarized and compared in the final section.
6.1 Physics Analysis of $0\nu\beta\beta$ Data

6.1.1 Calculation of Half-lifes

As discussed in Chapter 2, the goal of these experiments is to determine the effective Majorana neutrino mass by measuring—or setting a limit on—the half-life of $0\nu\beta\beta$ decay for a particular nuclide. Half-life is inversely proportional to the decay rate. From the definition of exponential decay:

$$\frac{dN}{dt} = -\left(\frac{\ln 2}{T_{1/2}}\right) N_{\beta\beta}. \quad (6.1)$$

$N_{\beta\beta}$ is the number of atoms available for the decay of the nuclide in question (e.g. the number of $^{130}$Te atoms). It can be written as a function of the elemental proportions in CZT (e.g. $x = 50\%$ for Te), the natural abundance of the decaying isotope $a_{\beta\beta}$, its atomic mass $A$, Avogadro’s number $N_A$ and the total active mass of the detector, $M$:

$$N_{\beta\beta} = \frac{x}{A} a_{\beta\beta} N_A M \quad (6.2)$$

In Equation 6.1, the number of nuclei $dN$ which decay in the total exposure time ($t_{\text{tot}} \equiv dt$) is equivalent to the number of observed signal events $S$, reduced by the detection efficiency $\varepsilon$:

$$S \equiv \varepsilon \ dN \quad (6.3)$$
Table 6.1 shows $N_{\beta\beta}$ for the nuclides of interest per gram of CZT. Substituting Equations 6.3 and 6.2 into Equation 6.1 and rearranging it results in a formula for the measured half-life:

$$T_{1/2} = \ln 2 \frac{x a_{\beta\beta}}{A} N_A M \left( \frac{\varepsilon}{S} t_{\text{tot}} \right)$$

(6.4)

where the remaining parameters, $M$, $\varepsilon$, $t_{\text{tot}}$, and $S$ all come from the experiment.

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$N_{\beta\beta}/g$</th>
<th>% of Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{116}$Cd</td>
<td>$1.6 \times 10^{20}$</td>
<td>3</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>$9.4 \times 10^{20}$</td>
<td>18</td>
</tr>
<tr>
<td>$^{70}$Zn</td>
<td>$8.5 \times 10^{17}$</td>
<td>&lt;1</td>
</tr>
<tr>
<td>$^{128}$Te</td>
<td>$8.8 \times 10^{20}$</td>
<td>17</td>
</tr>
<tr>
<td>$^{114}$Cd</td>
<td>$6.3 \times 10^{20}$</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 6.1: The number of 0$\nu$\$\beta\beta$-decaying nuclei $N_{\beta\beta}$ per g of CZT is listed by nuclide. The third column is the percent of a detector’s mass represented by the given nuclide.

6.1.2 Calculation of Upper Limits

The most important result of a 0$\nu$\$\beta\beta$ experiment is the extraction of a signal $S$ from the counts observed in the signal region, $C$. When $C$ is dominated by background rather than signal, the method prescribed by Helene [1983] is used to calculate an upper limit, i.e. the largest value $S$ is likely to have given the level of the background.

The Helene method assumes that an ensemble of experiments will make different signal measurements $s$ which are distributed around the “true” value. Any one experiment’s likelihood of measuring $s$ will follow either a Poissonian or a Gaussian
probability density function (p.d.f.) defined as $\rho(s)$. In this case, the most probable value of $s$ is the mean of the p.d.f., set to be the difference between the observed number of counts $C$ and the expected background $B$ in the signal region. This makes sense: $S = C - B$. The p.d.f. has a standard deviation which depends on the uncertainties in $C$ and $B$: $\sigma = \sqrt{C + \sigma_B^2}$. It is normalized such that its integral equals 1 when excluding negative, non-physical values of $S$.

To determine the upper limit of the signal ($S$), the integral of the p.d.f. must be found which computes to the desired confidence limit (C.L.) when its limits of integration are set from 0 to $S$. Put another way, for C.L. = 90% the upper limit $S$ is the value of $s$ for which 90 out of 100 experiments will measure a smaller $s$ and only 10% of experiments will detect a larger signal.

When $C \gg 1$, a Gaussian p.d.f. should be used. In this case, the upper limit is the value of $S$ for which the following is true:

$$\text{C.L.} = \int_0^S N_1 \frac{e^{-(s-(C-B))^2/2C}}{\sqrt{2\pi C}} \, ds. \quad (6.5)$$

For cases where $C$ is small, a Poissonian p.d.f. is used:

$$\text{C.L.} = \int_0^S N_2 \frac{e^{-(s+B)(s+B)^C}}{C!} \, ds. \quad (6.6)$$

Footnote 1: The method used to determine $B$, as well as its uncertainty $\sigma_B$, is discussed in the following section.
6.1 Physics Analysis of $0\nu\beta\beta$ Data

$N_1$ and $N_2$ are normalization constants satisfying

$$\int_0^\infty N \rho(s) \, ds = 1. \quad (6.7)$$

In this work, the appropriate integral 6.5 or 6.6 (instances of both large and small $C$ appear in our data) is numerically solved to find the upper limit of signal counts $S$ for a C.L. of 90%. In order to represent the fact that $S$ is an upper limit and to explicitly show the C.L. used, the symbol $S_{90\%}$ is used hereafter.

6.1.3 Background Level

The quantities $C$ and $B$ both represent a population of the signal region: total observed counts $C$ and expected background counts $B$. In this work, the signal region is defined as the range of energy measurements $\pm 0.5 \Delta E_{\text{FWHM}}$ around the Q-value of the $0\nu\beta\beta$ decay (e.g. 2813.5 keV for $^{116}\text{Cd}$).$^2$ $C$ is then simply the number of energy measurements which fall inside this range. $B$ is an estimate, made by sampling the number of counts outside of it. There are four background sampling regions: two energy bins $\Delta E$-wide on either side of the signal region.

For a linear background, $B$ is simply the average of the four sample regions. In this case, the background is exponential and a simple average overestimates $B$. To obtain

---

$^2$Note that $\Delta E$ increases with energy, and so the signal regions are wider around higher decay energies. The specific $E-\Delta E$ relationship for each detector is outlined in the experiment-specific sections which follow.
a better approximation, the logarithm of each bin’s contents is used for averaging. This results in the following expression for the background:

\[
B = (B_1 B_2 B_3 B_4)^{1/4}.
\]  

(6.8)

Assuming an uncertainty of \(\sigma_{B_i} = \sqrt{B_i}\) for each background region, the total error on \(B\) is

\[
\sigma_B = \frac{B}{4} \sqrt{\frac{1}{B_1} + \frac{1}{B_2} + \frac{1}{B_3} + \frac{1}{B_4}}.
\]  

(6.9)

### 6.1.4 Sensitivity

In order to provide context to our measured results, a sensitivity metric \(F\) is introduced. It is defined as the half-life corresponding to a signal \(S\) which is just hidden—with confidence C.L.—in the background. The sensitivity \(F\) should be reported along with the half-life calculated from \(S_{90\%}\). This is especially important in any case where, by chance, a value for \(C\) which is smaller than \(B\) has been measured. This is because the Helene method returns a better upper limit \(S_{90\%}\) in these cases than for experiments which detect the same \(C\), but expect lower \(B\) a priori. Reporting \(F\) prevents rewarding a poorly understood background or a lucky measurement with a superior lower limit.

\(F\) is determined by calculating \(S_{90\%}\) in the manner previously described, but with \(C = B\). This special value \(S_{F,90\%}\) is then entered into Equation 6.4 from Section 6.1.1
to form the definition of $F$:

$$F \equiv T_{1/2} = \ln 2 \frac{x \alpha_{\beta\beta}}{A} N_A M \left( \epsilon \frac{t_{\text{tot}}}{S_{F,90\%}} \right)$$  \hspace{1cm} (6.10)$$

Sensitivity is also a useful tool for attempting to predict an experiment’s performance relative to other $0\nu\beta\beta$ experiments. For a given expected background rate $b$ (in counts/keV/kg/yr), the number of background counts $B$ in the $\Delta E$-wide signal region is $B = b\Delta E Mt$. For a signal which is hidden in the background with 90% confidence, $S_{F,90\%} = 1.645\sqrt{B}$.

Substituting in these relations, Equation 6.10 can be rewritten as

$$F = \ln 2 \frac{x \alpha_{\beta\beta}}{1.645 A} N_A \epsilon \sqrt{M t_{\text{tot}} \frac{\epsilon}{b\Delta E}}$$  \hspace{1cm} (6.11)$$

This method of estimating sensitivity will be employed later, in Chapter 7.

6.2 Surface-Level Prototype

I first tested pixelated CZT for COBRA in December 2008. A $2 \times 2 \times 0.75$ cm$^3$ Orbotech detector was mounted in the DAQ system described in Section 4.5. The detector used an $8 \times 8$ grid of indium pixels (2.5 mm pitch) on the anode with a gold cathode. It was operated for 3.5 days on at surface-level in our laboratory, measuring the room’s ambient radiation. The bias voltage was set to 1800 V and

\[3\] To understand this, note that $\sigma$ for the p.d.f. in Equation 6.5 is $\sqrt{C}$ and in this case $C = B$. The p.d.f. gets 68% coverage at $S = \sigma$, and 90% coverage at 1.645$\sigma$. 

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an ASIC shaping time of 1 \( \mu s \) was used. The detector was not shielded or moved below ground-level and so the background rate is significant compared to that of Gran Sasso or another low-background environment. Nonetheless, the experiment yielded interesting results.

The system was calibrated by comparing a single spectral line to the pedestal value for each pixel. The 662 keV line from \(^{137}\text{Cs}\) was used. After calibration, the spectrum from the cesium source was summed into a single histogram to find an average energy resolution: 1.8\% (11.9 keV) FWHM at 662 keV.

There is typically a square-root relationship between energy resolution and the detected energy:

\[
\Delta E \propto \sqrt{E/\text{keV}}
\]  

(6.12)

This relationship was assumed, and used to estimate the energy resolution in the regions of interest for \(0\nu\beta\beta\) decay. For example, at 2814 keV—the Q-value for \(^{116}\text{Cd}\)—the expected energy resolution is 0.9\% (25.2 keV) FWHM.

### 6.2.1 Analysis and Results for Surface-Level Prototype

In 3.5 days, the detector recorded 839,000 background events. During threshold optimization prior to calibration it was observed that 13 pixels were too noisy to be used. This is unfortunate because it reduces the active mass of the detector by 20\%, from 17.3 g to 13.8 g. The total quantity of data then comes to 0.048 kg \cdot days.
6.2 Surface-Level Prototype

Each event is an instance of one or more pixels going over threshold, and usually the cathode as well. Because there is a 3 \(\mu s\) delay between the first trigger and ASIC blackout, it is technically possible that uncorrelated ionizing particles could register as a single event in the readout. However, this possibility is ignored in analysis; in practice the rate of incoming events is less than 3 Hz. Instead, the energy read by all pixels associated with an event are summed together into a single spectrum.

This multi-pixel, summed spectrum was normalized to the number of counts per energy bin (in keV), per kilogram of source material, per year of exposure. The summed energy spectrum of counts/keV/kg/yr is shown in Figure 6.1 (red). In the region of interest around the 2814 keV Q-value of \(^{116}\text{Cd}\), the background rate is \(2 \times 10^4\) counts/keV/kg/yr. This is about 3 orders of magnitude higher than observed by COBRA at Gran Sasso. However, this may be improved upon. As discussed in Chapter 5, even coarsely pixelated detectors have superior background reduction capabilities to CPG detectors. By excluding events which trigger three or more pixels, or two non-neighboring pixels, the background can be greatly reduced while maintaining efficiency. The resulting spectrum is overlaid in Figure 6.1 (blue), and shows a decrease in background at the higher Q-values which is roughly a factor of three.

It was discussed in Section 5.5, how a fiducial cut can be useful in reducing background. To perform a fiducial cut on this detector, all pixels along the outer rim of the detector and the depth slices closest to the anode and cathode surfaces
6.2 Surface-Level Prototype

Figure 6.1: Two spectra from the data taken with the surface-level prototype. The red spectrum includes all events from the 0.048 kg·days of background data, while the blue spectrum is composed of only those events which trigger either a single pixel or two neighboring pixels. The difference in background level at the $^{116}$Cd Q-value is roughly a factor of three.

were excluded. The size of the depth slices is determined by the energy resolution for the cathode [He et al. 1997]. The cathode for this prototype was found to exhibit significant electronic noise, resulting in a cathode energy resolution of $\sim 70$ keV. This corresponds to a depth resolution of 0.8 mm FWHM. The noise in the cathode had the additional effect of requiring a high threshold the minimum signal. As a result, no depth information was available for events occurring in the 1.3 mm nearest the anode.

After cutting the anode and cathode surfaces, as well as the outer pixels, a reduction in the absolute number of background counts rate by $\sim 45\%$ was observed
6.3 Low-Background Prototype

in the region of the $^{116}$Cd Q-value. However, no reduction was observed in the rate of background counts/keV/kg/yr. I hypothesize that this is due to the surface-level background being dominated by highly penetrating muons and γ-rays compared to the relatively few α particles excluded by the surface cuts. The coarseness with which the cuts were made resulted in a reduction of the active mass by nearly 60%. This, coupled with the unchanged background rate, produces a net loss in sensitivity (see Equation 6.11).

### 6.3 Low-Background Prototype

A second pixel experiment was tested underground at LNGS in early 2010. The system used a $2 \times 2 \times 1$ cm$^3$ CZT crystal from eV Products. A gold planar cathode and titanium pixels were deposited at WUSTL. The pixels were set at a 2.5 mm pitch, but with a very fine inter-pixel gap of 200 µm (see Figure 6.2).

As our ASIC-based system is not constructed of low-background components, the prototype could not be placed within the inner shielding or it might contaminate the still-running COBRA CPGs. Therefore, the system operated in the space between COBRA’s inner and outer shielding layers, with 10 cm additional lead shielding (see Figure 6.3).

Two holes cut in the side of the copper DAQ box provided entrance ports for the nitrogen line and calibration sources, which are fed through the shielding layers
6.3 Low-Background Prototype

Figure 6.2: A photo of the $2 \times 2 \times 1$ cm$^3$ CZT detector used in the low-background prototype. There are 64 pixels with a 2.5 mm pitch.

Figure 6.3: A photo of the low-background prototype preparing for calibration inside COBRA’s outer shielding.

The prototype was calibrated with flood-illumination by $^{228}$Th and $^{22}$Na sources twice during the experiment: once at the beginning and again at the midway point to check for calibration drift. A total of six spectral lines were used: 511 and 1274 keV from $^{22}$Na, and 238, 583, 1592, and 2614 keV from $^{228}$Th. No drift in calibration was observed for the duration of the experiment.

During installation of the detector at LNGS, it was discovered that the cathode was not performing correctly, possibly due to damage during transport. It would “buzz”, producing noise events completely uncorrelated with any anode signal. However, there were still paired anode-cathode events which were thought to be acceptably correlated, though with poor cathode energy resolution. One month later, during the second calibration via remote control, it was observed that the cathode was in fact producing no useful data. The result is that no depth correction to the anode en-
ergy resolution, nor fiducial cut, could be performed with the detector deployed at low-background.

With multiple spectral lines available, it was attempted to confirm the square-root energy dependence of the resolution which was assumed in the previous experiment. Figure 6.4 shows that the dependence of the first five lines is more closely approximated by $E^{0.65}$, but even worse if the 2614 keV line is included. This high energy photopeak is composed mostly of events which trigger multiple pixels incurring the noise from each. In a coarsely pixelated detector, the energy resolution of a $0\nu\beta\beta$ peak would not be broadened in the same way because the range of MeV $\beta$-particles is much shorter than an MeV photon and, thus covers fewer pixels. Unfortunately, counting only single-pixel 2614 keV events, the statistics are too poor for a well-resolved line. Therefore, the line is excluded from fitting. The best fit results in a dependence of $E^{0.65}$ which produces an estimated energy resolution of 1.0% FWHM at 2814 keV.

The experiment ran from mid-January to mid-April and had a total live-time of 71.7 days. The total accounts for the mid-run calibration check, regular linearity checks, and data lost during a power outage in February.

### 6.3.1 Analysis and Results for Low-Background Prototype

In 71.7 days, the detector recorded only 1.7 million events—a rate of about one count every 45 seconds. However, because of the aforementioned cathode “buzzing”, the
6.3 Low-Background Prototype

Figure 6.4: Results of the low-background detector’s two calibration runs. The 511 keV and 1274 keV photopeaks were taken with a $^{22}$Na source and the others with a $^{228}$Th source. The $\Delta E \propto E^{0.65}$ function—representing the best fit to this data—was used to determine resolution at the Q-values studied. A line representing $\Delta E \propto \sqrt{E}$ is shown for comparison. The asterisk (*) on the resolution of the 2614 keV line represents the fact that it was excluded from the fit, as described in the text.

dead-time for the detector was nearly 10%. Correcting for dead-time and dead pixels (a total of 12), the total exposure of the system was 1.2 kg·day.

The analysis of the low-background data was complicated by an anomalous effect in the electronic readout system. After a few weeks of constant operation at low-background, it was discovered that some channels of the NCI-ASIC exhibit a small noise feature approximately in the center of their dynamic range. When binning all
6.3 Low-Background Prototype

detector events for the entire exposure period, these noise features sum up across channels and form a prominent peak at around 2300 keV. The differences in pedestal and gain between channels smeared out the summed peak to approximately match the detector resolution, making the peak appear to be a $\gamma$-ray line. However, no background $\gamma$-ray peaks were expected at this energy, especially with such intensity.

Figure 6.5: Low-background energy spectrum showing the anomalous peak in red. The spectrum after removal of the anomaly and correcting for the reduced exposure is shown in blue.

In an attempt to determine the source of the anomalous peak, a variety of characteristics were checked for correlation to the peak: timing between events in the peak, spatial location of the events, etc. This lead to the discovery that fewer than half of the channels actually exhibited the peak and that the width of the peak on the channel level was less than the detector resolution. In fact, the average width was less than 0.5% FWHM. This supports the hypothesis that the peak is not physical, but in fact an electronic anomaly.
In order to remove the summed peak, all events within $2\sigma$ of the channel’s peak were cut channel-by-channel. The full energy spectrum (in counts/keV/ky/yr) was then corrected by adjusting the exposure time normalization factor in the bins which were cut. Figure 6.5 shows both spectra: before and after removal of the anomalous peak.

Just as with the surface-level experiment, the background which includes all detector events was compared to that observed when excluding events which trigger three or more pixels, or two non-neighboring pixels. When including all events, the background rate in the signal region around 2814 keV for $^{116}$Cd was 29 counts/keV/kg/yr. After cutting on the number and location of triggered pixels, the background was reduced by more than half to 13 counts/keV/kg/yr. Figure 6.6 shows both the complete and reduced-background spectra, with the $^{228}$Th calibration spectrum overlaid for comparison. Figure 6.7 provides a zoomed view of the $^{116}$Cd signal region.

### 6.4 Summary of Results

The prototype installed at the LNGS facility observed background rates as low as 13 counts/keV/kg/yr. This is in fact superior to the level observed by the sixteen detectors in COBRA’s published work—prior to removal of passivation paint and radon contaminations—and competitive with their latest prototypes. Sensitivities as high as $10^{20}$ yr were achieved. Because of our competitive background rate, three
6.4 Summary of Results

Figure 6.6: Three energy spectra taken with the low-background prototype. The red spectrum includes all events from the 1.2 kg-days of low-background data, while the blue spectrum is composed of only those events which trigger either a single pixel or two neighboring pixels. The green line shows the $^{228}$Th calibration spectrum for reference.

times better energy resolution, and large detector mass, many of our half-life limits are within a factor of two from published results. This is in spite of a much shorter exposure time and inferior shielding.

Both prototypes saw significant background reductions when discriminating single site and neighbor-pixel events from the population of all events. The primary effect of this cut is to remove $\gamma$-ray and muon interactions. This is corroborated by the fact that the improvement is most dramatic at higher energies and for the unshielded surface-level detector.
Figure 6.7: Signal region energy spectra from the low-background prototype. The green line shows the average background level between 2.7 and 2.9 MeV. For single-pixel + two-neighboring-pixel events (blue) there are 13 counts/keV/kg/yr in this region, down from 29 counts/keV/kg/yr for the spectrum which includes all events (red).

These results, summarized in Table 6.2, provide a compelling case for deploying large-volume coarsely pixelated CZT for COBRA.
6.4 Summary of Results

**Surface-Level Prototype**

All Events, 0.048 kg · day

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$b$ [cts/keV/kg/yr]</th>
<th>$S_{90%}$</th>
<th>$T^{\text{up}}_{1/2}$ [yr]</th>
<th>Sensitivity [yr]</th>
</tr>
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<tbody>
<tr>
<td>$^{114}\text{Cd}$</td>
<td>$1.6 \times 10^6$</td>
<td>79.2</td>
<td>$8.8 \times 10^{17}$</td>
<td>$6.9 \times 10^{17}$</td>
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<td>$^{128}\text{Te}$</td>
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<td>27.6</td>
<td>$3.4 \times 10^{18}$</td>
<td>$1.3 \times 10^{18}$</td>
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<td>$2.5 \times 10^4$</td>
<td>23.0</td>
<td>$3.1 \times 10^{18}$</td>
<td>$3.8 \times 10^{18}$</td>
</tr>
<tr>
<td>$^{116}\text{Cd}$</td>
<td>$2.1 \times 10^4$</td>
<td>14.9</td>
<td>$7.7 \times 10^{17}$</td>
<td>$6.6 \times 10^{17}$</td>
</tr>
</tbody>
</table>

**Surface-Level Prototype**

1 + 2 Neighboring Pixel Events, 0.048 kg · day

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$b$ [cts/keV/kg/yr]</th>
<th>$S_{90%}$</th>
<th>$T^{\text{up}}_{1/2}$ [yr]</th>
<th>Sensitivity [yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{114}\text{Cd}$</td>
<td>$1.5 \times 10^6$</td>
<td>65.2</td>
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<td>$7.2 \times 10^{17}$</td>
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<tr>
<td>$^{128}\text{Te}$</td>
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<td>22.0</td>
<td>$4.2 \times 10^{18}$</td>
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<tr>
<td>$^{70}\text{Zn}$</td>
<td>$4.1 \times 10^5$</td>
<td>33.7</td>
<td>$2.9 \times 10^{15}$</td>
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<td>14.1</td>
<td>$5.0 \times 10^{18}$</td>
<td>$5.5 \times 10^{18}$</td>
</tr>
<tr>
<td>$^{116}\text{Cd}$</td>
<td>$6.4 \times 10^4$</td>
<td>10.5</td>
<td>$1.1 \times 10^{18}$</td>
<td>$1.2 \times 10^{18}$</td>
</tr>
</tbody>
</table>

**Low-Background Prototype**

All Events, 1.2 kg · day

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$b$ [cts/keV/kg/yr]</th>
<th>$S_{90%}$</th>
<th>$T^{\text{up}}_{1/2}$ [yr]</th>
<th>Sensitivity [yr]</th>
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<tr>
<td>$^{128}\text{Te}$</td>
<td>$5.1 \times 10^3$</td>
<td>12.8</td>
<td>$1.4 \times 10^{20}$</td>
<td>$6.8 \times 10^{19}$</td>
</tr>
<tr>
<td>$^{70}\text{Zn}$</td>
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<td>16.4</td>
<td>$1.2 \times 10^{17}$</td>
<td>$8.9 \times 10^{16}$</td>
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<tr>
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<td>5.7</td>
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<td>$1.8 \times 10^{20}$</td>
</tr>
<tr>
<td>$^{116}\text{Cd}$</td>
<td>29</td>
<td>5.6</td>
<td>$4.0 \times 10^{19}$</td>
<td>$5.2 \times 10^{19}$</td>
</tr>
</tbody>
</table>

**Low-Background Prototype**

1 + 2 Neighboring Pixel Events, 1.2 kg · day

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$b$ [cts/keV/kg/yr]</th>
<th>$S_{90%}$</th>
<th>$T^{\text{up}}_{1/2}$ [yr]</th>
<th>Sensitivity [yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{114}\text{Cd}$</td>
<td>$1.3 \times 10^4$</td>
<td>22.0</td>
<td>$6.3 \times 10^{19}$</td>
<td>$3.7 \times 10^{19}$</td>
</tr>
<tr>
<td>$^{128}\text{Te}$</td>
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<td>12.4</td>
<td>$1.5 \times 10^{20}$</td>
<td>$8.1 \times 10^{19}$</td>
</tr>
<tr>
<td>$^{70}\text{Zn}$</td>
<td>$2.1 \times 10^3$</td>
<td>11.8</td>
<td>$1.6 \times 10^{17}$</td>
<td>$1.1 \times 10^{17}$</td>
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<td>47</td>
<td>3.3</td>
<td>$4.2 \times 10^{20}$</td>
<td>$2.9 \times 10^{20}$</td>
</tr>
<tr>
<td>$^{116}\text{Cd}$</td>
<td>13</td>
<td>2.9</td>
<td>$7.8 \times 10^{19}$</td>
<td>$5.2 \times 10^{19}$</td>
</tr>
</tbody>
</table>

Table 6.2: Summary of results for the two prototypes, before and after excluding events which trigger more than two pixels or two non-neighboring pixels. $S_{90\%}$ is the upper limit on the number of signal counts at a 90% C.L.
Chapter 7

Large-Scale Experiment

A large-scale COBRA experiment composed of 420 kg of enriched CZT detectors could be sensitive to $0\nu\beta\beta$ decay half-lifes of more than $2 \times 10^{26}$ years. Depending on the choice of mixing matrix elements, such an experiment could probe Majorana neutrino masses below 50 meV. This assumes an average energy resolution of 1% FWHM and a background level of $5 \times 10^{-4}$ counts/keV/kg/yr in the signal region. Figure 7.1 shows how this sensitivity evolves over the operational lifetime of the experiment.

As discussed in Chapter 5, relatively coarse pixels provide the most practical balance between background reduction and energy resolution and could meet the goals stated above. Another benefit of using larger—and thus fewer—pixels is the reduced power consumption realized from the smaller number of amplification circuits required. For these reasons, coarse pixels are the optimum detector configuration.
7.1 Design Considerations

for deployment in a large-scale $0\nu\beta\beta$ search. In this chapter, I consider the design constraints for such an experiment and present my own proposal for a 420 kg COBRA.

![Graph showing sensitivity evolution over the lifetime of a 420 kg COBRA experiment. Three traces represent three different combinations of possible background level and energy resolution. The Heidelberg-Moscow claim, shown as the first dotted line, could be either confirmed or refuted within the first months of operation. The approximate sensitivity required to probe 50 and 100 meV neutrino masses are represented by the next two dotted lines, respectively. The exact positions of these sensitivity levels depends on the choice of matrix elements.]

Figure 7.1: Sensitivity evolution over the lifetime of a 420 kg COBRA experiment. Three traces represent three different combinations of possible background level and energy resolution. The Heidelberg-Moscow claim, shown as the first dotted line, could be either confirmed or refuted within the first months of operation. The approximate sensitivity required to probe 50 and 100 meV neutrino masses are represented by the next two dotted lines, respectively. The exact positions of these sensitivity levels depends on the choice of matrix elements.

7.1 Design Considerations

7.1.1 Maximize Detector Volume

In order to build an experiment which is sensitive to very long $0\nu\beta\beta$ decay half-lifes, a large mass of CZT must be obtained. This is most economically accomplished with
large-volume crystals. There are currently two large-volume designs commercially available. Redlen Technologies Inc. produces a 1.5 cm-thick crystal with the common $2 \times 2 \text{ cm}^2$ footprint for a total volume of $6 \text{ cm}^3$. Orbotech Ltd. has produced crystals with a very large $4 \times 4 \text{ cm}^2$ footprint and 0.5 cm thickness which have a total volume of $8 \text{ cm}^3$.

Deploying detectors with such large volumes has a great advantage over the current $1 \text{ cm}^3$ detectors as far fewer individual detectors are needed to achieve the same mass. This is important because some aspects of the experiment’s cost and complexity will scale with detector number rather than mass. For example, as total surface area increases, the required amount of anti-oxidation paint increases as well as exposure to background radiation from external alpha sources (e.g., radon gas and “dirty” electronics components). Depending on implementation, it is likely that the number and mass of electronic components and support structures will also increase. In addition to driving up cost, the extra components increase background if they are not free of long-lived radioactive nuclides. Extra inactive mass between detectors also reduces efficiency in cases where $\gamma$-rays from secondary processes following a $0\nu\beta\beta$ decay are lost.

### 7.1.2 Comparison of ASIC and Analog Readout Systems

Application Specific Integrated Circuits (ASICs) are special chips which can perform the duties of many discrete components in a data acquisition system (DAQ). For ex-
ample, a discrete DAQ system requires separate pre-amplifier, pulse-shaper, threshold discriminator, and analog-to-digital conversion (ADC) components. Some or all of these components can be built into a single ASIC chip for which the input is a raw current pulse signal from the sensor and the output may be an analog or digital pulseheight value or even a fully digitized waveform.

ASIC-based systems achieve superior noise performance because the miniaturization of components reduces capacitances and radio-frequency pick-up. However, minimizing the input capacitance requires the ASIC to be physically close to the sensor. In a low-background experiment this is a concern because electronic components are a principal source of long-lived radioactive contamination. In a discrete system, the preamplifier circuit must also be relatively close and may contribute as much background as a low-mass ASIC bonded directly to the sensor. If both system types contribute moderately to background, but ASICs offer greatly improved energy resolution as well as reduced complexity and physical size, they become the preferred system type for data acquisition.

### 7.1.3 Minimize Power and Heat

The power consumption of an experiment should be kept low both to minimize utility costs, and to avoid excessive heat generation. Compared to other experiments, the thermal budget for COBRA is relatively simple because the detectors do not require
cryogenic cooling. The only necessary cooling is for any high-power DAQ electronics (e.g. ASICs and FPGAs). The density of these components and the amount of heat they dissipate dictates what cooling methods may be used. For example, 1000 1-watt chips produce a lot of heat in aggregate, but spread over a cubic meter, it is easily dissipated.

Ideally this “heat density” will be low enough that passive cooling techniques, which require little to no maintenance cost, may be used. Depending on the geometry of the system this may be impractical. More likely, active systems will be needed to force a gas over heat sinks and cooling fins on the electronics. Such a system requires fans, ductwork, and heat exchangers along with regular maintenance. More complex systems involving liquid coolant or even cryostats should be avoidable for COBRA.

7.1.4 Minimize Cost

The price for a single CZT detector can vary widely, depending not just on the detector volume, but also the thickness. For example, a 1.5 cm-thick detector with a $2 \times 2 \text{ cm}^2$ footprint is approximately 5 times more expensive$^1$ than the 0.5 cm-thick detector with a $4 \times 4 \text{ cm}^2$ footprint discussed in Section 5.4.2. Given its 25% smaller volume, the thick detector has a cost which is nearly 7 times greater per gram. Yet the $4 \times 4 \text{ cm}^2$ detector is not significantly more expensive than other 0.5 cm-thick detectors.

$^1$Absolute prices are not particularly relevant to this discussion because they change so frequently in this young market. However, for reference, a 1.5 cm-thick detector cost $\sim 20,000$ in 2009.
7.2 Proposed Design for 420 kg COBRA

detectors with a $2 \times 2$ cm$^2$ footprint, 75% smaller. This is a strong driver for the use of
detectors which derive large volumes from their footprint rather than their thickness.

Since $^{116}\text{Cd}$ only composes about 3.5% of naturally sourced CZT by mass, and
half-life sensitivity scales directly with the abundance of the $0\nu\beta\beta$ isotope (see Equa-
tions 6.2 and 6.11), it is advantageous to use enriched cadmium in the crystal fabrica-
tion process. It is possible to enrich cadmium up to about 90% in the $^{116}\text{Cd}$ isotope at
an order of magnitude cost near $\sim$ $1000$ per gram given the technology available in
2012. This improves sensitivity by more than an order of magnitude while increasing
cost to approximately the same degree. While it may not seem worthwhile to incur
costs which are so high in absolute terms for a one-to-one increase in sensitivity, con-
sider that increasing other experimental parameters in Equation 6.11 offer no such
benefit. For example, one could increase the detector mass $M$ by purchasing 100
times as many detectors, but sensitivity would only improve by a factor of 10.

7.2 Proposed Design for 420 kg COBRA

The experiment would use $0.5 \times 3.9 \times 3.9$ cm$^3$ detectors from Orbotech Ltd. man-
ufactured using cadmium enriched to 90% $^{116}\text{Cd}$. This requires 9,555 detectors to
achieve a total mass of 420 kg CZT. If these detectors were fabricated with coarse
pixels at a pitch of 2.5 mm, there would be 256 pixels per detector. Brookhaven
National Labs has developed an ASIC which has 130-channels, depth sensing capabilities, and electronic noise at 2.5–3.0 keV FWHM [Zhang and Kaye 2009]. Two of these ASICs would be mounted on a radioactively clean delrin or teflon circuit board bump-bonded to each detector. It would be convenient for two detectors to share one FPGA chip, leaving the average power consumption per detector at about 1 watt. Figure 7.2 shows how detector pairs could be lined up—sharing a common high voltage power supply and data bus—to form one 32-detector module, 65 cm long. The module’s 32 watts of heat would be conducted away from the detectors through an electroformed copper heat sink with cooling fins. Nitrogen gas would be used for convective cooling in place of air to reduce the background from naturally occurring radon.

The proposed design requires 299 modules in total. The modules could be stacked very close together, as long as there were enough space for the cooling gas to flow between them. In fact, because the detector surfaces need not be cooled, the ideal configuration—as depicted in Figure 7.3 (left)—would be to have every other module in a column flipped so that the detector surfaces of two modules are millimeters apart. The spacing between two modules whose heat sinks face one another would need to be larger to allow even flow of the coolant gas. The same reasoning limits the number of side-by-side modules which form a row. If the row were too wide, the fans would need to run at very high speed to maintain the flow from one end to the other. The module arrangement described here would result in a power density on the order of 10 mW/cm³, which would be easily managed by a forced air cooling system.
Figure 7.2: Component view of one module for the proposed 420 kg COBRA experiment. The underside of the readout board is shown in the bottom left with copper heat sink removed, exposing the ASICs and the larger FPGA shared by two detectors. Next to it, is the same board flipped to show how the $0.5 \times 3.9 \times 3.9$ cm$^3$ detectors are mounted. One detector has been removed, showing the pixel traces. The second detector is seen with its cathode surface up and connected to the high-voltage line view the tower. 32 detectors make up the entire module, shown in the background.

as long as the rows are short, e.g., five modules wide. However, the rows could be stacked arbitrarily high. Thirty rows, five modules wide would produce system units of manageable-size. Only two such units would be needed to house all of the 9,555 detectors—one of which is shown in Figure 7.3 (right) and Figure 7.4.
7.3 Alternative Designs

7.3.1 420 kg with Fine Pixels

Another possible way to implement a 420 kg COBRA might be to deploy finely pixelated detectors. Such an experiment would require more power and cost due to its channel-dense ASICs, and current technology allows detectors which are incapable of probing half-lifes beyond $10^{26}$ yr. However, the background reduction capabilities it might afford make it a viable experiment for competing with the current generation of ton-scale experiments.

A design using presently available technology might deploy the ASIC discussed in Section 5.3.1 which has 2048-channels, a pitch of 350 $\mu$m, and a footprint of $1.1 \times 2.2$ cm$^2$. Two such ASICs side-by-side could cover a detector with a $2.2 \times 2.2$ cm$^2$ footprint. To maintain a large volume, the thickest possible detectors with
this footprint should be used. The closest is the 1.5 cm thick detector produced by Redlen Technologies. The company should be able to provide the desired crystals with dimensions $1.5 \times 2.2 \times 2.2 \text{ cm}^2$ in the quantity required. In this case, the number of detectors needed to reach 420 kg is 10,009.

For this system, simple forced air cooling may not be possible. The heat density is much higher. In the proposed design, the heat per detector is $\sim 1$ watt. The two UIUC ASICs would consume 3.4 watts inside a much smaller footprint. If the detectors are not spaced far apart, heat density could easily exceed the proposed design’s specification by an order of magnitude.
7.3.2 420 kg with Cross-Strips

Another possible implementation for a 420 kg COBRA experiment involves the use of cross-strip detectors. This method has the distinct advantage of being a very low-power alternative compared to the preceding two. If the large-footprint Orbotech crystals were used, a detector could be constructed with 30 anode and 30 cathode strips. These 60 channels would provide spatial resolution equivalent to 900 pixels with 1.25 mm pitch. Compare this result to the proposed design: one quarter as many channels and twice the spatial resolution.

Each side of the detector—cathode and anode—could be managed by a single low-power ASIC developed at the Brookhaven National Lab and currently available. The average power consumption per detector would be about 0.66 watts. The full experiment would require 9,555 detectors (the same as the “Coarse Pixel Design”). However, its mechanical design would be very different from the proposed experiment because the electronics would need access to 30 contact points on both sides of the detector rather than only a single cathode contact.

7.4 Comparison with Other Large Experiments

Several well-developed, ton-scale experiments are set to leave the R&D phase and begin data-taking in the next few years. These are the previously mentioned EXO,
GERDA, and CUORE searching for the $0\nu\beta\beta$ decay of $^{136}$Xe, $^{76}$Ge, and $^{130}$Te, respectively. The most sensitive of these will be the second phase of the EXO experiment, which will probe neutrino masses from 5–30 meV. GERDA and CUORE will have comparable sensitivity to the proposed COBRA experiment, but are expected to achieve it by roughly 2015, well before a 420 kg COBRA could be constructed. However, given the uncertainty in nuclear matrix elements inherent in these studies, it is important to search for $0\nu\beta\beta$ decay occurring in many different nuclides.

For COBRA, the main R&D needed to enable a ton-scale experiment is the purification of the detector material to radioactive contamination levels which are below $10^{-3}$ counts/keV/kg/yr, as much as three orders of magnitude below present levels. The other experiments also need to solve substantial R&D challenges. For example, EXO, GERDA, and CUORE all must construct massive cryostats. To achieve their claimed $10^{28}$ yr sensitivity in the second phase, EXO will have to further develop advanced spectroscopic techniques for tagging the barium daughter ion. In contrast, the proposed ton-scale COBRA is designed to incorporate existing technology which is commercially available.
Chapter 8

Summary

In this thesis, I explored different detector options for the COBRA neutrinoless double-beta decay experiment. One of the results of my study is that coarsely pixelated detectors are the best option, as they combine excellent energy resolutions with background suppression capabilities and modest complexity. The background reduction capabilities of two prototypes with this design were tested. The first measured the background rate in a surface-level laboratory. Despite having a background level 2–3 orders of magnitude higher than observed in the COBRA experiment’s underground facility, half-life sensitivities as high as $10^{18}$ yr were achieved. Exploiting the enhanced spatial resolution of these detectors, background was reduced by a factor of two or more. The second detector, operated in ultra-low background conditions at LNGS, observed a background level of 29 counts/keV/kg/yr in the region of the $^{116}$Cd $0\nu\beta\beta$ decay Q-value. Again, enabled by the spatial resolution of the detector,
γ-ray and muon interactions were rejected and the background level was reduced to 13 counts/keV/kg/yr. Coupled with the excellent energy resolution and large mass of our detector, this allowed the prototype to achieve sensitivities within a factor of two from those of a prior COBRA experiment using sixteen CPG detectors, but in a fraction of the exposure time.

For the three most relevant of the detector types assessed, I have participated directly in efforts which address their viability. Finely pixelated detectors were fabricated and are now being tested by various collaborators. Detailed simulations were developed to study the behavior of cross-strip detectors. The results of these simulations accurately predict real performance in the lab. Most importantly, coarse-pixel detectors were shown to produce competitive sensitivities to the half-lifes of several $0\nu\beta\beta$ nuclides.

I have presented a proposal for a ton-scale COBRA experiment which could also take advantage of the coarse-pixel detector’s capabilities. The design uses components which are commercially available today, rather than needing additional R&D. It would probe the effective Majorana neutrino mass down to 10’s of meV—comparable to contemporary experiments searching for $0\nu\beta\beta$ decay in other nuclides—and would confirm or refute the controversial Heidelberg-Moscow claim of evidence within months of commissioning.
Bibliography


Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 633, Suppl(0), S210

Chadwick, J.: 1914, Verh. der Deutschen Physikalischen Ges. 16(383)
Chadwick, J.: 1932, Nature 129(312)
Fermi, E.: 1934, Z. Phys. 88(161)
Frisch, O.: 1944, British Atomic Energy Report BR-49
He, Z., Li, W., Knoll, G., Wehe, D., and Berry, J.: 1999, Nuclear Instruments and Methods in Physics Research A 422, 173
Maki, Z., Nakagawa, M., and Sakata, S.: 1962, Progress of Theoretical Physics 28(5), 870
Rahaman, S., Elomaa, V.-V., Eronen, T., Hakala, J., Jokinen, A., Kankainen, A.,
Ramo, S.: 1939, *Proceedings of the IRE* 27(9), 584
*Proceedings of SPIE* pp 2–9
Wulf, E. A., Phlips, B. F., Johnson, W. N., Kurfess, J. D., Novikova, E. I., O'Connor,