Contributions to Background Reduction and Computer Simulations for CUORE & CUORE-0

A Senior Project

By

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1 Introduction

The Standard Model embodies our current understanding of particle physics. This set of observed rules dictates the allowed interactions and decay mechanisms. Due to the ambiguity in the governing particle classification/statistics, it is unclear whether or not the neutrino is a Dirac or Majorana fermion. Recent advancement in particle theory provides favorable energetics for the (now known to be) massive neutrino to be its own antiparticle [1]. Experimental observation would provide evidence for an elementary particle that is a Majorana fermion. This discovery would expand our framework of the Standard Model.

CUORE, the Cryogenic Underground Observatory for Rare Events, aims to substantiate this theoretical prediction by observing neutrinoless double beta decay (expressed more concisely as $0\nu\beta\beta$). Using a source known to undergo double beta decay, CUOREs detectors have been tailored to measure the energy of the emitted particles with extreme precision. By doing some careful book keeping, CUORE will be able to discern between the two neutrino- and neutrinoless double beta decay scenarios. If CUORE is to measure two beta particles whose energy sum to the discrepancy between parent and daughter particles, then it must be the case that no neutrinos were emitted. This occurs when the two ejected neutrinos act as a particle-antiparticle pair in the virtual state [2]. The essential result here is that the neutrino and antineutrino are the same particle.

Due to the rarity of this type of decay, CUORE needs to achieve an ultra-low background in the region of interest (ROI) in order to say with any statistical significance that the neutrinoless scenario of double beta decay has occurred. Currently, depleted alpha particles have a higher count rate in the ROI than the predicted decay rate, rendering it unobservable. To be successful, CUOREs detectors will have to be well calibrated to achieve the necessary resolution. All internal components will also need to be cleaned and tested for radio-purity to achieve the necessary background of 0.01 counts/keV/kg/year [3].

During the summers of 2010 and 2011, I contributed in two capacities to the CUORE effort. At Cal Poly, I ran computer simulations to better understand the detector behavior. I examined how a computer-generated signal attenuates along various parameters, and examined how the model is constructed to better understand potential flaws or limitations. These simulations also served to better understand the calibration schemes and sources that are being implemented. In the latter half of each summer, I travelled on behalf of the Cal Poly CUORE group to perform various on-site tasks. The main tasks I completed were cleaning the teflon couplings of various contaminants (as well as various other components), and assisted in leaking checking the CUORE-0 cryostat. The report will detail those efforts, however, a brief discussion of the governing theory and experimental approach is necessary.
2 Theory

2.1 The Standard Model

In short, the Standard Model is our current working theory of particle physics, and subatomic interactions. The theory incorporates our understanding of the most basic and indivisible constituents of matter and antimatter, as well as three of the four fundamental forces. The model consists of 61 fundamental particles which either appear in nature as stand alone particles, hadronize together to form more complex particles such as nucleons, or mediate forces between particles. Similar to the periodic table in structure, the Standard Model organizes these fundamental particles with respect to their intrinsic properties and their functions. Figure 1 below illustrates the organization technique employed by the Standard Model. In Figure 1 all fundamental particles (sans Higgs Boson) are represented [4].

At the most fundamental level, all matter and forces can be represented by the three groups: quarks, leptons, and force carriers (gauge bosons). The four gauge bosons on the right most column explain how particles of a certain charge type interact with each other, i.e. particles:

Figure 1: The table employed by the Standard Model to graphically depict all known fundamental particles. From these particles, matter, antimatter, and three of the four fundamental forces can be explained [5].
of electric charge experience coulombic attraction/repulsion due to exchange of photons or
the exchange of gluons to mediate the strong nuclear force for particles of color charge. The
remaining two gauge bosons, W and Z, are mediators of the weak nuclear force. Currently,
there only exists a hypothetical particle to explain the gravitational force, which is appropriately
deemed the graviton [4]. Other bosonic particles exists such as the Higgs boson, and mesons,
which are bosonic particles formed when a quark and antiquark hadronize [6].

Quarks fall under the Fermion classification of the Standard Model due to their obedience
of Fermi-Dirac statistics. Quarks rarely exist as free color charge; due to the high energy density
they will quickly hadronize to form more stable composite particles. As previously mentioned,
quarks and antiquarks can hadronize to form bosonic mesons, or three quarks can hadronize to
form baryons. From greek etymology, baryons or “heavy” particles are our most familiar particles
of matter and antimatter such as protons and neutrons. Just as three quarks may hadronize
to form baryonic matter, three antiquarks may hadronize to form baryonic antimatter [7]. One
of the current deficiencies in the Standard Model is a lack of experimentally observed or theo-
retically viable explanations for baryogenesis (or leptogenesis). With our current understanding
of the processes that occurred following the Big Bang, we have yet to incorporate the matter-
antimatter asymmetry into our understanding of particle interactions [8].

Similar to quarks, leptons are our other major constituent of matter and antimatter, and the
nature of which is the focus for CUORE. While leptons and quarks both follow Fermi-Dirac
statistics, leptons frequently appear as stand alone particles in nature, such as the case with
free electrons. Leptons appear in three generations or flavors; each flavor has a particle and
an associated neutrino [9, p. xiii]. The three charged leptons - electrons, muons, taus - are fairly well understood with their interactions being completely described by the electroweak
theory (the unification of quantum electrodynamics and the weak nuclear force). The charged
leptons, as well as the the quarks, are Dirac Fermions. The major physical implication of a particle satisfying the Dirac equation is that the particle is distinguishable from its antiparticle
counterpart [9, p. 225,230]. This level of classification becomes a grey area in particle physics
for neutrinos. Initially, neutrinos were assumed to be massless rendering them indistinguishable
from their antimatter counterpart, as is the case with the massless photon [9, p. 30]. Further
experimental and theoretical development showed the neutrino to have extremely small, non-
zero mass, and to be spin 1/2 particles [9, p. 230,290]. Presumptiously, this would be a Dirac fermion, however, Ettore Majorana proposed a mathematical formulation for neutral spin 1/2
particles to be their own antiparticles [10]. Although this has yet to be observed, Majorana
fermions are not completely inconsistent with our understanding of the Standard Model. The
evidence suggesting the neutrino be classified as a Dirac or Majorana fermion is detailed below
along with the repercussions on our understanding of particle physics.

2.2 Discoveries Pertinent to Neutrino Behavior and Existing Problems

The neutrino (represented as $\nu_\alpha$ - where $\alpha$ indicates the flavor) was originally hypothesized to
explain how fundamental quantities such as energy, angular momentum, and total momentum
could be conserved for such reactions as beta decay. The existence of such a particle was first substantiated by the Cowan-Reines neutrino experiment; in their experiment antineutrinos (represented as $\bar{\nu}_\alpha$) were used to cause protons to decay into neutrons and positrons [9, p. 27]. Equation 1 below depicts this process symbolically.

$$\bar{\nu}_e + p^+ \rightarrow n + e^+.$$  \hspace{1cm} (1)

Throughout early experiments, the neutrino, as previously mentioned, was assumed to be massless. The reasoning behind this initial assumption is somewhat ambiguous, coupled with the fact that even the upper bound for neutrino masses is extremely small (even by particle physics standards), the original assumption persisted until a problem in detecting the solar neutrino flux presented itself.

The advancement in theory provided by the formulation of the neutrino into the particle physics model allowed physicists to revisit a problem originally posed by Lord Rayleigh several decades earlier. Lord Rayleigh had attempted to calculate the age of the sun, however, arrived at an answer that disagreed with the possible age of the Earth. With the neutrino in place, the necessary tools were available for scientists to be able to probe the sun in order to better understand not only its age but, also, the mechanism which fuel its cycle. In the late 1960’s, Raymond Davis successfully detected solar neutrinos, yet only at a rate of approximately 1/3 of what was theoretically predicted [9, p. 387-390]. Neutrino oscillations were proposed as an explanation for this phenomenon which proved to be correct with the results of the Sudbury Neutrino Observatory (SNO) and Super-Kamiokane (SuperK) experimental results in the early 2000’s. Since Davis’s detector was only sensitive to electron-neutrinos, the neutrino oscillation explanation suggested he only detect a fraction of the neutrinos emitted by the sun [11]. Equation 2 below shows the probability of measuring an $\alpha$ muon-neutrino given initially an electron-neutrino. This calculation is based of a hypothetical universe with only two flavors of neutrinos [9, p. 392]. The importance here is the dependence of the masses.

$$P_{\nu_e \rightarrow \nu_\alpha} = \{\sin(2\theta) \times \sin\left[\frac{(m_2^2 - m_1^2)c^4t}{4\hbar E}\right]\}^2.$$ \hspace{1cm} (2)

The theoretical implications from the neutrino oscillation data show that the neutrino is a massive particle. The oscillation data also supports that there exists no neutrino of definite mass and definite flavor. Rather, any mass eigenstate is a linear combination of flavor eigenstates and vice versa. The fact that neutrinos must have mass suggests that the neutrino and antineutrino are distinct particles, and in fact, both neutrinos and antineutrinos have been detected. In addition, the neutrino is also known to be a spin 1/2 particle which classifies the particle as a fermion [11]. Seemingly, the properties of the neutrino are almost completely determined. The discrepancy arises from the fact that only neutrinos of left-handed helicity and antineutrinos of right-handed helicity have been observed. Massive Dirac spinors should not exhibit chiral symmetry, and thus the massive neutrinos and antineutrinos should have right-handed and left-handed counterparts, respectively [12, 9, p. 339]. This leads to two possible scenarios: the neutrino is a Dirac fermion whose right-handed counterpart does not behave as expected.
or is difficult to detect, or the neutrino may be a Majorana fermion which allows for massive particles to exist without opposite helicity counterparts as the particle may be its own antiparticle. CUORE’s goal is to indirectly observe the latter scenario for the neutrino. CUORE will observe double beta decays in $^{130}$Te, and measure the ejected beta particles with extreme precision [2]. If CUORE is to measure two beta particles whose energy sums to the difference between parent and daughter particles, it must be the case that no neutrinos were emitted. This would substantiate the the Majorana model for the neutrino.

2.3 Beta decay and Double Beta Decay

Before moving on to what we mean by a neutrinoless double beta decay (expressed symbolically as $0\nu\beta\beta$) or its physical implications, it is necessary to understand what beta decay ($\beta$-decay) is, and what is occurring during a double beta decay ($2\nu\beta\beta$) event. Beta decay is a type of nuclear decay in which a proton or neutron decays into one another by the emission of a beta particle. In the event of beta-plus ($\beta^+$) decay, a proton transforms into a neutron by emitting a $\beta^+$ particle (a positron) and a neutrino. In beta-minus ($\beta^-$) decay, the reverse occurs; a neutron transforms into a proton by emission of a $\beta^-$ particle (an electron), and an antineutrino [13]. Equation 3 shows the process of a $\beta^-$ decay (CUORE is concerned with the double beta-minus decay and further mention of double beta decay will refer to this scenario unless otherwise specified).

$$n \rightarrow p^+ + e^- + \bar{\nu}_e.$$  \hspace{1cm} (3)

The cause of the decay is simply the parent nucleus shifting to a state of higher stability. The emission of the neutrino or antineutrino accounts for the mass-energy discrepancy between parent and daughter particles, while also maintaining lepton number conservation [13].

The two-neutrino double beta decay is in essence two beta decays occurring simultaneously, albeit with reason to do so. For some decay channels, a single beta decay may result in a

Figure 2: During a double beta decay, two neutrons decay into two protons resulting in the emission of two electrons and two electron-antineutrinos [15].
daughter particle which is less stable while a double beta decay results in a daughter particle of higher stability. It is noteworthy to state that in either scenario ($\beta^+$ or $\beta^-$ decay), the two decay scenario is either two $\beta^+$ or two $\beta^-$ decays occurring. The essential result is that after a nucleus has undergone double beta decay, two beta particles and either two neutrinos or two antineutrinos are ejected, resulting in a nucleus of higher stability [14]. Using the Feynmann diagram approach, figure 2 (page 9) illustrates what is occurring during a double beta decay event.

2.4 Lepton Number Conservation

In our current framework, several conservation laws are observed. One such conservation law obeyed in the Standard Model is that of lepton number. Here the rule is quite simple: after assigning leptons a value of positive 1 and antileptons a number of negative 1 the sum of the values on each side of the interaction or decay must be equal. This conservation law is a result of direct experimental observation. In the two neutrino double beta decay event, the lepton number prior to the decay is 0; after the decay, two electrons (each lepton number +1) and two electron type antineutrinos (each lepton number -1) are present, the sum of which is 0 [13]. While the overall lepton number is conserved in any interaction, family lepton number conservation is only approximate and does not necessarily have to occur. Violation of family lepton number is observed in rare and exotic decays, or in instances of neutrino oscillations.

The conservation of lepton, and baryon, number in particle interactions and decays are constructs in the Standard Model that have become fundamental in our understanding of the weak force. While certain theoretically allowed chiral anomalies might explain baryogenesis, no mechanism currently explains leptogenesis [8]. Furthermore, no interaction has yet to be observed that violates either overall lepton number conversation or baryon number conservation. Violation of these laws would help explain why globally baryon and lepton number are greater than zero; in essence, why matter was favored over antimatter in the early universe [16].

2.5 Neutrinoless Double Beta Decay

The neutrinoless double beta decay scenario is based on the premise that the neutrino and antineutrino are Majorana fermions. If the neutrino and antineutrino are Dirac fermions, there would be no mechanism for such a decay to occur. In this type of decay, our system’s initial state consists of two neutrons which are about to undergo double beta decay (in $^{130}$Te nuclei there are 78 neutrons and 52 protons, however, we are concerned with the neutrons that are subject to the decay). The nuclei undergoes the two $\beta^-$ decays, however, in the final state only two protons and two electrons emerge. One of the intermediate processes allowed by the Majorana model is that one of the antineutrinos emitted in one of the decay events is absorbed as a neutrino in the other. In the virtual state, there then exists (in a sense) a particle-antiparticle pair [15]. The end result is that the two beta particles emitted from the decay “carry away” all the excess mass-energy (in this particular
Figure 3: In the neutrinoless double beta decay scenario, one of the antineutrinos generated effectively acts as a neutrino in the virtual state. The end result is that only two beta particles and two protons are present in the final state. The $\nu_M$ signifies that the neutrino/antineutrino is a Majorana fermion in this process [15].

If CUORE is to observe such an event, there would be several implications on our current understanding of the physical universe. The most obvious is that there are some particles that satisfy the Majorana equation, and thus are their own antiparticle despite having mass. The second major implication is that concept of lepton number conservation is not a requirement for an interaction or decay to occur. Within lepton number violation, there is a more subtle, yet important result. If lepton number is not conserved, there exists a mechanism which may explain why globally lepton number is positive. In this scenario, an antimatter particle acts as a matter particle in order to pair with another antimatter particle in the virtual state. The end result is that there is now an excess of matter, helping explain the matter-antimatter asymmetry.
3 Experimental Design

3.1 The Detector

The CUORE detector incorporates a host of critical subsystems in order to achieve the necessary resolution and temperatures to be able to witness such a rare decay in a reasonable amount of time. While some of the engineering is outside the scope of this report, an overview of some of the critical subsystems is appropriate.

If neutrinoless double beta decay is to occur, the lower limit of the decay half-life has been measured to be $2.8 \times 10^{24}$ years (approximately 10 trillion times the accepted age of the universe - set by Cuoricino in 2008) [26]. In order to witness a significant count rate, CUORE will employ a large amount of active mass. The total mass of the tellerium dioxide (TeO$_2$) crystals is approximately 741 kg (988 crystals at 750 grams each). Since tellurium has a natural abundance of 30 percent of isotope $^{130}$Te, the active mass of the detector is 206 kg. Each of these crystals is fitted with a neutron transmutation doped (NTD) thermistor such that changes in the crystal energy can be measured. In order to achieve the necessary resolution, CUORE detectors need to be cooled below 1 Kelvin; below this temperature, lattice vibrational energy is “frozen out” making it possible to detect the energy of incident particles. CUORE will utilize a tiered structure of thermal reservoirs in order to maintain the necessary operating temperature during the expected run-time of 5 years [2, 18]. Other necessary subsystems, such as the calibration system, will be housed within the cryostat. This configuration allows the cryostat to stay sealed, minimizing the risk of contamination or having to cool down the detector from exterior ambient temperature. Figure 4 shows a computer generated image of the detector layout.

![Figure 4: This CAD rendered image of the CUORE detector shows several of the vital subsystems and crystal array. The dark grey outer layer depicts low radioactivity lead shielding around several of the thermal reservoirs. Atop the detector is the necessary readouts for the electronics as well as the calibration systems [23].](image-url)
3.2 Bolometric Approach

CUORE and CUORE-0 are innovative experiments in both the scientific and engineering aspects. In order for the detector to differentiate between the two neutrino double beta decay and neutrinoless double beta decay events, the detector has to be capable of discerning the minute energy difference between the ejected electrons of the two scenarios. Utilizing a bolometric detector that also serves as the source for the decay event provides the necessary resolution [2].

Traditional bolometric detectors measure incident electromagnetic radiation by utilizing a reservoir and absorbing element to detect minute changes in temperature. This is accomplished either by measuring the temperature change of the reservoir directly or by measuring the change in electrical resistivity. Using the specifics of the bolometric material, e.g. specific heat capacity, thermal conductance, etc, the energy of the incident photon can be determined [19]. Since the bolometric material is only aware of changes in energy, they are well suited for particle physics applications as well.

CUORE and CUORE-0 employ bolometers operated at cryogenic temperatures that serves as both the detector and the source for the decay events. Rather than measuring electromagnetic radiation, the bolometric approach used in CUORE and CUORE-0 measures the change in thermal energy that occurs in the reservoir when particles are incident on the detector. This is achieved by operating the crystals at temperatures below 1 degree Kelvin; operating at such low temperature “freezes out” most of the lattice vibrational energy of the bolometric material. In this temperature regime, the detectors’ heat capacity is proportional to the temperature cubed, $T^3$. Any impact raises the vibrational energy thus raising the temperature appreciably. Using sensitive thermistors, the change in temperature can be measured. Similar to the traditional operation, specifics of the material can be used to determine the energy of the incident particle [2, 19].

This approach, while very well suited for the purposes of CUORE and CUORE-0, bears one critical disadvantage. The detector is capable of measuring any sort of energy deposited into the detector regardless of the incident particle and without anyway of discerning between types of particles. This mechanism thus lends CUORE and CUORE-0 to be very susceptible to background noise, the cause of which is to be discussed later [20].

3.3 Tellurium as a Candidate for Neutrinoless Double Beta Decay

Determining a material well suited for the purposes of CUORE is not a trivial process. In order to implement the bolometric and “source equals detector” mechanisms, a material must be selected that can, by the Majorana model for the neutrino, undergo neutrinoless double beta decay, but also serves well as a bolometric material.

The former criteria is determined by experimental evidence of the candidate undergoing two neutrino double beta decay. While the theory dictating whether or not a particle is capable of undergoing two neutrino double beta decay is beyond the scope of this report (although not entirely non sequitor), the essential fact remains that if the energetics of the two neutrino double
beta decay process are favorable and the decay is experimentally determined to occur, the particle is a candidate for neutrinoless double beta decay under the Majorana model for neutrinos. Two neutrino double beta decay, albeit rare, has been detected. With this knowledge, the Majorana model predicts that one of the antineutrinos produced will act as a neutrino in the virtual state. Since the final state contains no neutrinos or antineutrinos, the two electrons and nucleus recoil account for the energy difference between the parent and daughter particle [2, 15].

The latter criteria is critical for the operation of the detector and has little bearing on the candidacy for neutrinoless double beta decay. The bolometric properties of a material depend largely on crystal structure rather than on direct nuclear properties of the constituent atoms. $^{130}$Tellurium on its own does not necessarily fit this criteria, however, tellurium dioxide forms paratellurite, a compound well know for its crystal properties. Paratellurite crystals are commonly used as optical wave guides and acousto-optical modulators in photonics engineering applications [19]. These crystals also happen to be naturally abundant in Tellurium-130 (approximately 34 percent by mass), an isotope of tellurium that has been confirmed to undergo two neutrino double beta decay [2].

Tellurium dioxide crystals are one of few materials that satisfy the necessary criteria for the experimental approach of CUORE. While other bolometric materials might suffice if properly doped, few materials so readily fit the bill that are already so widely manufactured. Due to its candidacy, natural abundance in viable crystals, and cost-effectiveness, $^{130}$Te is the choice source for CUORE. Figure 5 shows the TeO$_2$ crystal situated in the copper housing.

### 3.4 Background Signal

The largest disadvantage to the experimental approach of CUORE and CUORE-0 is the detectors ability to measure any particle’s energy without the ability to track or recognize the particle. This has led to a strong background signal due to depleted alpha particles across a wide energy regime [20]. Without proper preparation of the experimental components, CUORE and
CUORE-0 detect a background signal at a higher rate than the theoretical signal of neutrinoless double beta decay, rendering it unable to detect whether or not there is a signal occurring from the event [3].

More specifically, approximately 70 percent of the background signal in the region of interest (ROI: 2474 - 2580 keV) has been determined to be from depleted alphas arising from $^{238}$Uranium, $^{232}$Thorium, as well as various Radon daughters. This strong alpha radiation is present due to contamination in the copper housing and crystal surfaces. The additional 30 percent of the signal is attributed to Compton events from the 2615 keV peak of $^{208}$Thalium and $^{232}$Thorium contamination in the cryostat. Another important source of background signal is believed to be caused by cosmic ray activation of copper, resulting in a 2505 keV $^{60}$Co peak [3]. The background spectrum is shown in Figure 6; the black line corresponds to background events while the red corresponds to calibration data.

Consequently, components used to situate and assemble the detectors have to undergo stringent cleaning procedures and tests to ensure radiopurity. Components such as the teflon couplings and copper housing are believed to be the largest contributors of contamination. The tellerium dioxide crystals also provide a substantial background, however, since they have only incurred surface level contamination due to the manufacturing process, are relatively easy to clean [22]. Within CUORE, several experiments have been completed in order to test the effectiveness of various cleaning methods, and quantify the background contribution from various components.

The most elaborate of these tests was the Three Tower Tests conducted in 2008. This experiment utilized a series of Cuoricino bolometers (a small scale proof-of-concept detector) to test various cleaning methods. This experiment tested three various cleaning methods for the copper housing as well as the tellerium dioxide crystal surfaces. This test also provided a metric for the amount of background resulting from crystal surface contamination. Copper components underwent three different treatments in the Three Tower Test (TTT): the first method involved...
a chemical etching treatment followed by a 50 micron polyetherene wrap; the second treatment involved passivation and chemical etching; the third treatment involved chemical etching and magnetron sputtering. The first and last methods proved to reduce the major component of the Curoicino background by a factor of 2 [23, 3]. The Three Tower Test helped quantify the copper framework and surface level contamination to the background signal as well as establish viable options to lower this particular fraction of the signal. The work was conducted at the Gran Sasso Laboratory by CUORE researchers supported by Cal Poly alumni Laura Sparks, and Alison Goodsell.

Other measures have been implemented to lower and control the background signal. One substantial method is the CUORE Crystal Validation Run (CCVR). These validation runs are approximately month long test runs of select crystals and components that are to be later used in CUORE. The validation runs are performed onsite by CUORE researchers in order to best simulate actual operating conditions. Functionality tests include testing the background rate of copper framework and crystals that have undergone the accepted cleaning methods, thermistors are tested for temperature dependence response, other various hardware components such as the PTFE couplings are tested for dimensional tolerances (radio-purity is measured indirectly by the amount of contaminant found in cleaning solutions before and after cleaning), and bolometers are tested under low temperature conditions similar to the conditions necessary for CUORE [24, 23]. These tests are critical as they provide a level of quality control while monitoring for components that could provide substantial background events. Another measure is the PTFE coupling and copper framework cleaning; this measure was implemented to help reduce background that results from the manufacturing and milling process of the various components that will be in direct contact with the detector. The work in this latter procedure was done largely in part by California Polytechnic State University undergraduates.
4 The Laboratory at Gran Sasso

One of the other unique features to CUORE is the laboratory in which the experiment is conducted. The CUORE detector is being assembled under approximately 1400 meters of rock (overburden: 3500 meters-water-equivalent) at the Gran Sasso National Laboratory (Laboratori Nazionali del Gran Sasso - LNGS) in Assergi, Italy. Such an environment is critical for experiments that necessitate ultra-low backgrounds as the surrounding earth provides shielding against cosmic events such as cosmic ray activation of detector components. In order for CUORE to achieve the target background of 0.01 counts/keV/kg/year in the ROI, the external environment of the detector is a critical limiting factor in the lowest possible background.

Aside from providing the necessary shielding, the facilities at Gran Sasso National Laboratory provide the ample space needed to assemble the large detector array as well as separate areas for research and development efforts. Shown in the picture above, CUORE has accommodations in two of the halls; the CUORE detector and clean room are being assembled in Hall A, next to CUORE-0 hut which at the time of this report is actively taking data to verify the assembly and cleaning methods set forth for CUORE, while additional ultra-clean storage for the CUORE crystals is provided in hall C. Additional support for CUORE is provided in the above ground facilities such as clean rooms for cleaning PTFE couplings, as well as additional laboratory and office space.

Figure 7: Shown above is a map of the underground portion of the LNGS facilities. CUORE and CUORE-0 are being assembled in Hall A, while a research and development crystal for CUORE is housed in Hall C [25].
5 Summer 2010 - Decontamination of PTFE Couplings

5.1 PTFE (Teflon) Couplings

Situated between each bolometric crystal and the copper framework is a polytetrafluoroethylene (PTFE - or known more commonly by its commercial name Teflon) coupling. PTFE couplings provide several advantages for CUORE. The couplings have low thermal and electrical conductivity, allowing them to be electrically isolated, and thermally isolated from the surrounding structure. PTFE also has a low coefficient of thermal expansion and a low coefficient of friction. These properties help ensure that the crystals are mechanically isolated and are not subject to movement as the detector is brought down to operating temperature. Additionally, PTFE couplings are cheap and quick to manufacture. The only disadvantage results from CUORE’s sensitivity. PTFE is subject to surface contamination during the manufacturing and milling process. Since the couplings are either in direct contact with or in clear line of sight of the crystals, any contamination contributes significantly to the background. For this reason, it is crucial the couplings are properly decontaminated and stored before being used in the detector assembly.

5.2 Cleaning Methods

The assessment of which cleaning regiment would be implemented was based off a few factors. The first of these factors was the result in radiopurity. Since the only way to test the radioactive signature from the PTFE couplings with such precision would be to use the CUORE detector itself, another less direct metric was used. This alternative metric involved measuring the contamination of heavy metals associated with the background spectrum of the candidate cleaning agents before and after using them to clean the PTFE components. The cleaning agents (Micro 90 soap and HNO$_3$ acid) were measured for concentration of $^{39}$K, $^{208}$Pb, $^{232}$Th, and $^{238}$U in parts per billion (ppb) to determine if an appreciable amount of contamination was removed from the couplings. The other key factor in determining a cleaning regiment was whether or not

<table>
<thead>
<tr>
<th></th>
<th>Soap</th>
<th>Acid</th>
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<tbody>
<tr>
<td></td>
<td>No. PTFE Couplings</td>
<td>Soap (mL)</td>
</tr>
<tr>
<td>Central-type</td>
<td>24</td>
<td>1.5</td>
</tr>
<tr>
<td>Corner-type</td>
<td>48</td>
<td>1.5</td>
</tr>
<tr>
<td>Side-type</td>
<td>48</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 1: Prescribed values for preparing the necessary cleaning solutions as well as the amount of each type of PTFE coupling per cycle. Each cycle consists of each bath for 30 minutes and a rinse in ultrapure water before being prepared for packaging.
<table>
<thead>
<tr>
<th>Pieces Per Bag</th>
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<tbody>
<tr>
<td>Central-type</td>
</tr>
<tr>
<td>Corner-type</td>
</tr>
<tr>
<td>Side-type</td>
</tr>
</tbody>
</table>

Table 2: Packaging specifics for each type of PTFE coupling. After being dried with inert nitrogen gas, the containers are filled with the specific PTFE coupling and nitrogen gas before being vacuum sealed in several layers of plastic.

The cleaning agents would cause any defects to the couplings. This factor arises from the high dimensional tolerances necessary of CUORE components.

The regiment that was ultimately employed required two separate baths in an ultrasonic agitator. The first consisted of an industrial soap solution for 30 minutes, and the second required an acid solution for 30 minutes. Upon completion, the components were dried with a flush of nitrogen gas, vacuum sealed, then stored in nitrogen flushed refrigerators. The dilution and packing specifics for each of the three types of PTFE couplings (corner-, side-, central-type) are listed in tables 1 and 2.

### 5.3 Decontamination and Storage

The decontamination, packaging, and storage of the PTFE couplings was done predominantly by myself, Cal Poly Physics major Samuel Meijer, and UCLA PhD candidate Brian Zhui in the above ground clean room during an approximate 5 week time period towards the end of August 2010. Additional support was provided by INFN researchers Lucia Canonica and Luca

Figure 8: Samuel Meijer and Ivo Plamenac prepare PTFE couplings for an ultrasonic bath to reduce background from alpha particles.
Pattavina, who had devised the original cleaning method and manual. The components are currently being stored in Hall C until CUORE is ready to be assembled. Random components were selected to be measured for dimensional tolerances by Cal Poly Physics major Michael Haskin and UC Berkeley post doctoral researcher Tom Banks.

Aside from the opportunity to contribute to the CUORE collaboration, even in a minute way, performing the PTFE coupling cleaning presented the chance to learn several other valuable skills. Most noteworthy, performing the PTFE coupling cleaning required learning proper clean room protocol not to further contaminate the components. Within the clean room I learned how to handle the necessary chemicals, such as the laboratory grade acid, as well as the necessary equipment to be competent in the lab. Sam and I were able to complete the necessary PTFE cleaning in a timeframe ahead of what was originally anticipated. Our efficiency and productivity allowed us to start contribute to other minor tasks. Although these miscellaneous tasks, including the PTFE coupling cleaning, are not necessarily novel or ground breaking research, our efforts were necessary for the forward progress of CUORE.
6 Summer 2011- Acid Etching of Copper Components and Leak Checking

6.1 Acid Etching of Copper Components

In the summer of 2011, I assisted INFN researcher Luca Pattavina in acid etching various copper components used for the CUORE detector. The copper contributes a radioactive background similar to the PTFE couplings, where embedded alpha particles near the surface are in direct line of site with the detector. Since the alpha particles are more massive particles, few escape from far below the surface and thus only the surface of the copper components has to be etched to ensure its radiopurity. The acid etching was accomplished in a very similar fashion to the PTFE coupling cleaning, where an industrial soap solution and acid solution were used. The methodology for the copper etching was determined in a similar fashion as the PTFE, however, other structural criteria had to be considered.

The optimal cleaning method for the copper components needs to reduce background contamination considerably in order to achieve the necessary background of 0.01 counts/keV/kg/year, while also maintaining the structural stability of the copper framework. Currently, alternatives are being explored to avoid problems that could arise from scaling up the detector to the size necessary for CUORE and CUORE-0, however, these alternatives are beyond the scope of this report.

6.2 Leak Checking the Dilution Refrigerator

My time at LNGS in the summer of 2011 was split between assisting the acid etching of the copper components and helping UC Berkeley PhD candidate Jon Oulette and INFN researcher Johnny Goette leak check the CUORE-0 cryostat in order to prepare the cryostat for cool-down and data acquisition. The CUORE-0 cryostat was the same cryostat used for Cuoricino (the small scale proof-of-concept experiment) however scaled to CUORE specifications.

After a small repair had been made to part of the cryostat shielding after the completion of Cuoricino, a leak allowing helium into one of the evacuated chambers appeared during the cool-down cycle. In order to have the cryostat reach the necessary operating temperature, it was imperative to rectify the low temperature leak. Since disassembling the cryostat was not a viable option, our methodology for identifying the location of leak required being able to monitor vacuum pressure and the process of elimination. Our procedure consisted of continuously filling and emptying the dilution refrigerator with liquid nitrogen to bring the cryostat down to cryogenic temperatures. During the cool-down cycle we inserted a line connected to a helium tank to fill various chambers with helium gas. We then used the vacuum pump system to evacuate adjacent chambers and monitor for vacuum pressure. To assist with the leak checking process, I had helped fill the cryostat with liquid nitrogen from the doer and operated the vacuum pump system.
Figure 9: Atop the CUORE-0 cryostat. The black tube that is visible was used to feed liquid nitrogen from the doer into the dilution refrigerator unit.

Our test concluded that the previous repair had proved to be faulty when cooled down to cryogenic temperatures. Since the necessary operating temperature of CUORE-0 is in the milli-Kelvin range, the appearance of the leak necessitated minor disassembly of the cryostat and for the faulty component to be rebonded. The repair was completed by INFN technicians.
7 Computer Simulations of Detector Calibration

Domestically, my advisor and I used a simulation package written for the GEANT4 platform, a particle physics simulation toolkit developed by CERN, and ROOT, a data analysis package developed by CERN, to model the CUORE calibration systems. While the actual design of the calibration system was the effort of the University of Wisconsin - Madison CUORE group, our efforts were on our own volition to better understand the detector behavior as well as design considerations.

The GEANT4, GEometry And Tracking-4, is a computer simulation platform developed by CERN for designing detector arrays and simulating the interaction of particles governed by our known laws of physics. The platform utilizes a Monte Carlo method to provide a random sampling of events such as certain particles undergoing decays. The CUORE simulation package was developed by Lawrence Livermore National Laboratory for the GEANT4 platform and provides the ability to simulate different calibration sources, strengths, and configurations. The output is examined with ROOT which provides the necessary libraries to analyze the number of events and total energy registered in each bolometric detector.

My studies began by calculating the theoretical amount of decay events due to various sources and strengths and examining the signal they would create within the detector. I then used this as a basis for determining the mass and time necessary to be able to observe the necessary signal in each bolometric crystal using different calibration configurations. The sources we examined were $^{56}$Co, $^{60}$Co, $^{228}$Th, and $^{232}$Th using various configurations that placed the sources along wires both inside and outside the detector.

Figure 10: The GEANT4 package is capable of simulating multiple events and accurately accounts for the physics of various particles such as alphas, betas, and gammas. In this figure various particles are tracked by different colors.
The second aspect of the detector I examined was the how simulation package actually constructed what was occurring and how different particles interacted with the detector. These exercises included sanity checks such as verifying that alpha particle tracks terminated when interacting with the detector, and exploring signal attenuation as different sources or strengths are used. Examining the signal attenuation also revealed approximations made by the simulation package; one such approximation was simulating a signal coming from within one of the bimetric crystals as simply a smear of decay events occurring on the bottom facing surface. This approximation proved to be consistent as different sources (\(^{56}\)Co, \(^{60}\)Co, \(^{228}\)Th, and \(^{230}\)Th) were used at various strengths. Figure 11 shows a graph of the signal strength at various locations along one of the towers for the different source/strength configurations.

Some of my studies using the CUORE simulation package were inconclusive, and some of the my calculations were unverifiable. Due to lack of documentation for the CUORE simulation package, some simulations did not behave as expected or were inconclusive in verifying the amount of time or mass needed. Despite the inconclusiveness of these studies, they still proved to be valuable. The studies familiarized myself with both the detector array and how it registers a signal, as well as, allowed me to better understand the nuclear decay chains of the various calibration source candidates. In addition, these studies served as an introduction to the data analysis process, and how to use computer simulations for nuclear physics purposes.

Figure 11: Simulation of different sources embedded in a crystal in the 5th layer of one of the CUORE towers. This graph shows how the signal from four different sources attenuates through the tower. This simulation was done at two different source strengths for each source.
8 Conclusion

Currently, CUORE scientists are preparing to have the full scale experiment running within the next few years, meanwhile, CUORE-0, the diagnostic intermediary, is actively taking data to verify the methodology prescribed thus far. CUORE-0 will provide the necessary information to make any adjustments as the collaboration pushes forward towards the full scale search for neutrinoless double beta decay in CUORE.

CUORE, regardless of its success in detecting neutrinoless double beta decay, will reveal important information about our physical universe. In the event that CUORE detects neutrinoless double beta decay, we will have substantiated the Majorana equation and better understand one of the mechanisms for leptogenesis. In the event that CUORE cannot detect neutrinoless double beta decay, we will still be able to more accurately set the lower limit on the half-life of the decay if it were to occur as well as better determine the nature of the neutrino mass hierarchy.

In addition to the contributions CUORE will make towards better understanding the neutrino, the research and development efforts to make CUORE possible have applicaions to other research. The background reduction techniques and development of bolometric detectors to achieve high sensitivity and resolution will play critical roles as scientists begin to probe dark matter. CUORE also has advanced cryogenic technology in order to achieve a higher level of efficiency for helium, a resource that is in short supply and high demand for scientific applications.

In short, CUORE has already proven to be a worthwhile scientific endeavor. With its contributions to both particle physics and the engineering of high sensitivity detectors, scientists are ready to begin answering fundamental questions about our physical universe. With the success attained thus far, the future of CUORE looks promising. Needless to say, the results, while still several years off, are much anticipated by the scientific community.

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References


