Ultrasonic Bonding for the CUORE Collaboration

A Senior Project

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Abstract

This paper will give the reader a brief introduction to the Standard Model, Neutrinoless Double Beta Decay ($0\nu\beta\beta$), and the CUORE experiment under construction at Gran Sasso National Lab in Assergi, Italy. The remainder of the paper will describe the bonding process used to connect the heater pads and NTDs to the copper housings of the tower structure. Extensive details of the troubleshooting and calibration period are presented as a way for the reader to better understand the concepts involved during the bonding stage of the assembly process.

Acronym	Meaning
CUORE	Cryogenic Underground Observatory for Rare Events
BM	Bonding Machine
CUORE-0	A prototype for CUORE
NTD	Neutron Transmutation Doped Germanium Thermistors
Heater	Heater Chip
GB	Glove Box
LNGS	Gran Sasso National Laboratory

Table 1: Acronyms

1 Introduction

The Standard Model is a mathematical model used to describe subatomic interactions in our universe. Formulated in the middle of the 1900's, it served as the basis for predicting the next half-a-centuries worth of discoveries in particle physics. Additionally, with the inclusion of the recently discovered Higgs-Boson, every particle predicted by the Standard Model has been discovered. It is a daunting task to propose a revision to this model that has directed the work of some of the best and brightest minds of the past century. Nonetheless, this is what the CUORE (Cryogenic Underground Observatory for Rare Events) collaboration has proposed to do. The basis of the experiment comes from some unexpected results in previous experiments; namely, that neutrinos have mass. This opens up the possibility that they may be a class of Majorana fermions, or, electricaly neutral particles that are also their own antiparticle. Thus far, there are no known fundamental particles that are Majorana fermions. If, however, the neutrino is a Majorana particle, a rare decay process known as neutrino less double-beta decay ($0\nu\beta\beta$) is theoretically possible [1]. In $0\nu\beta\beta$, the Majorana neutrino appears in the virtual state as a kind of "placeholder" in the equation, resulting in two emitted electrons and the daughter particle in the final state. Several experiments around the world are searching for $0\nu\beta\beta$ using various methods. The focus of this paper, CUORE is one such experiment. If CUORE is successful in finding $0\nu\beta\beta$, it would help to bring new discoveries related to neutrinos into the framework of the Standard Model.

This paper will give a brief introduction to CUORE as part of the overarching structure, however, the main focus of my senior project will be my experience traveling to LNGS during the summer of 2013 to assist with the bonding stage of the experiment. COURE relies on creating an environment with extremely low background radiation in order to distinguish $0\nu\beta\beta$. As such, each stage of assembling the experiment must be done in a precise and contained manner, else contamination of the experimental mass could mask potential signals of $0\nu\beta\beta$. The bonding process creates electrical connections between sensors on the experimental mass and the housing of the experiment itself, allowing the mass to be monitored over the course of the data taking process. During the bonding, the crystal tower structure is housed in a clean room in a nitrogen-fluxed box to prevent contaminants from reaching the materials. The opportunity arose to become an assistant bonding technician and to assist with the bonding process inside the clean room.

2 Theory

2.1 Beta Decay

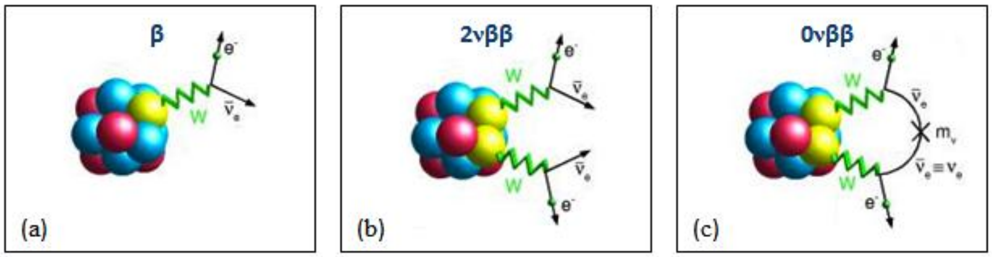


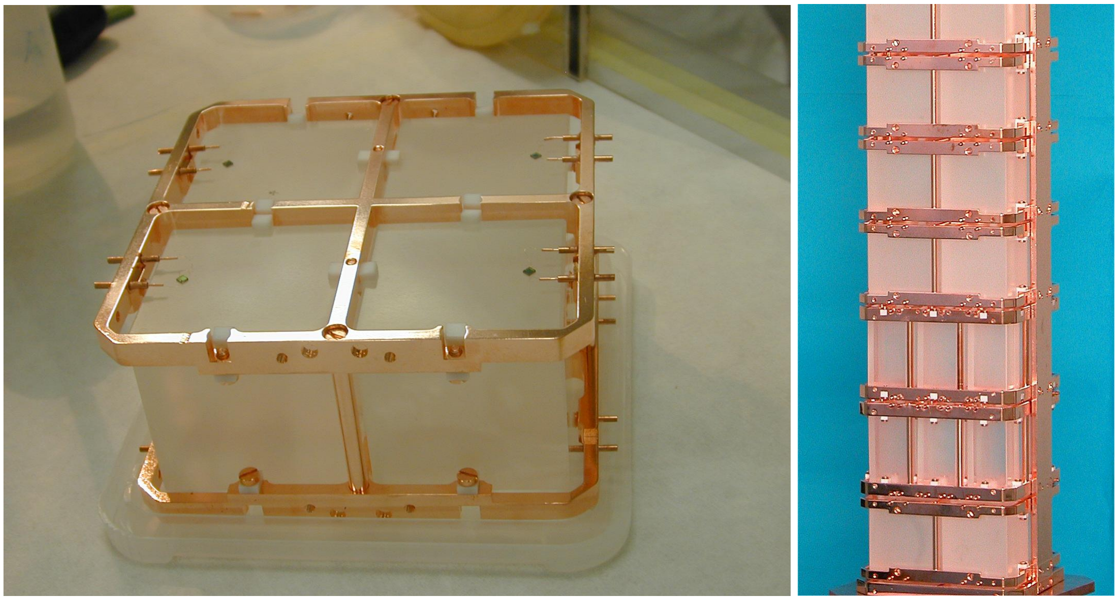
Figure 1: The three variations of beta decay: normal beta decay (a), double beta decay (b), and the theorized neutrinoless double beta decay (c). [http://www.astro.wisc.edu/ wolansky/pics/3d%20dbd.png]

Nuclear decay is the process undertaken by unstable nuclei in order to reach a more favorable stable energy state. There are many different varieties including alpha decay, where a large nucleus emits an alpha particle with the same structure as a helium nucleus (very harmful if inside the human body), and gamma decay, where radiation is given off as light. The decay process that CUORE concerns itself with is beta decay, where a neutron decays into a proton, an electron, and an antineutrino (Figure 1a). Double beta decay is when two neutrons simultaneously decay inside the nucleus resulting in two protons, two electrons, and two antineutrinos (Figure 1b). The specific type of decay CUORE is concerned with is known as neutrinoless double beta decay ($0\nu\beta\beta$) (Figure 1c), an unobserved type of decay existing only if the neutrino is its own antiparticle and so the resultant neutrinos/antineutrinos only appear in virtual states resulting in only two protons and two electrons.

2.2 Neutrinos

One of the most basic and intriguing laws of the universe is the conservation of total energy for a system. So, it came as quite a shock to the original beta decay experimenters when the total energy of the resultant electron was less than the expected value. With the detection and verification of neutrinos in 1956 (CITE), physicists were finally able to resolve the energy discrepancy of the previous results. Since then, scientists have discovered more properties about the neutrino, however, it's weak interaction with everything means measurements are still fundamentally difficult.

2.3 CUORE



(a) (b)

Figure 2: CUORICINO has set the current half-life limit on the theorized $0\nu\beta\beta$ decay in ^{130}Te and is CUORE's precursor experiment. Four crystals are being held in the frame (a) which makes up the fully constructed tower (b).

CUORE is an experiment being built at the underground Gran Sasso National Laboratory in Assergi, Italy. It is designed to measure $0\nu\beta\beta$ decay using the ^{130}Te isotope of Tellurium. Tellurium is toxic in its elemental form, so CUORE uses TeO_2 crystals, which can be seen in Figure 2. The 988 crystals, which comprise 19 separate towers of 52 crystals each are kept at a very low temperature (10mK) because the crystals also act as the detector and the low temperature also lowers their specific heat, which makes them more sensitive to energy deposited in the lattice.

When decay occurs inside the crystal, a small amount of energy is released, and this is measured as a small increase in the crystals temperature. Because the energy released is so small, the detector must be equally as sensitive. The decay has never before been seen, but if observed would indicate the neutrino is its own antiparticle, changing the Standard Model of particle physics. The current half-life lower limit in ^{130}Te is set by the CUORICINO detector, (FIGURE) at $T_{1/2} > 2.8 \times 10^{24}$ years, over 200 trillion times the age of the universe. [2]

The CUORE experiment is currently being constructed and CUORE-0 will collect data in the meantime. CUORE-0 is a prototype of one of CUORE's many towers, and will provide the researchers with an idea how CUORE will perform. The old CUORICINO cryostat is being reused for the CUORE-0 experiment. The cryostat is composed of many chambers and the main components are: the outer vacuum chamber (OVC), main bath, inner vacuum chamber (IVC), and 1K pot. The main bath is filled with liquid helium, which is approximately 4 kelvin. Each vacuum chamber drastically decreases thermal transfer from the outside. The 1K pot is connected to a dilution refrigerator which keeps the tower around 10mK.

3 Experiment

3.1 CUORE-0 Cryostat and Data Taking

Figure 3: Liquid helium dewar being used to fill the main bath. The pipe coming out of the top is connected to the top of the cryostat which allows the main bath to be filled.

The first few weeks at the lab involved assisting with the daily operations of the CUORE-0 set up with Andrew Bianco, a fellow Cal Poly Physics undergraduate, under the supervision of Dr. Paolo Gorla and Agnes Weirgiluk, a UCLA grad student. In order to maintain the low temperature of the cryostat, regular refills of liquid helium and nitrogen are required because the helium evaporates instantly when in contact with any substantial temperature. Andrew and I would take turns assisting the lab technicians in the refill process every 48 hours. To refill the main bath, a large dewar was used for transport of the highly pressurized chemical. On the dewar were several important safety measures including a blow-out valve in case the pressure got to be too great for the dewar, and a pressure gauge as an added safety precaution. When handling the dewar or any of the components feeding in and out of it, thick gloves also needed to be worn, else burns would appear on hands due to the extreme cold (similar to instantaneous frostbite). Specialized pipes were used to transfer the liquid helium from a massive holding tank to the dewar, which was then reattached to the cryostat of CUORE-0. The attachment of the dewar to the main bath was the part I assisted with the most. Using a specialized hose and pipe, the lab tech and I would insert the end into the dewar first, allowing the hose to cool down so as not to add excess heat to the main bath. Once the hose was sufficiently cool, the other end was fully inserted into the cryostat main bath to continue the process of maintaining incredibly low temperature and subsequent background radiation.

The other part of the CUORE-0 shift was the daily data taking. Due to the incredibly long half-life of tellurium, the experiment isn't expected to have more than one detected event per month. And because of the infrequency of these events, data must be taken continuously, for approximately 3-5 years, in order to find anything meaningful. Fortunately, the system is set up so that everything can be done remotely. For non-refill days, I would connect to the remote server, stop the current run of data, typically the previous 24 hours, save it onto the experimental server, run a couple system checks, and then restart the next data taking process. On refill days, the process is very similar, except that during the refill time, meaningful data cannot be taken so there needs to be a way to distinguish each set. After stopping and saving the previous days run, instead of starting a new data set, instead we would run a refill set for the two hours it takes to refill the helium reservoir. After the refill is complete, I would stop the refill set, run the tests, and then begin the next sequence of actual data taking. There were a variety of factors that would lead to unusable data. The main one was the refills every other day, however, whenever maintenance needed to be done, or somebody was in the experiment housing, or the main bath hadn't cooled sufficiently yet, or if there happened to be an earthquake in Timbuktu, any of these factors could register on the sensors and unfortunately render the data unusable, though interesting.

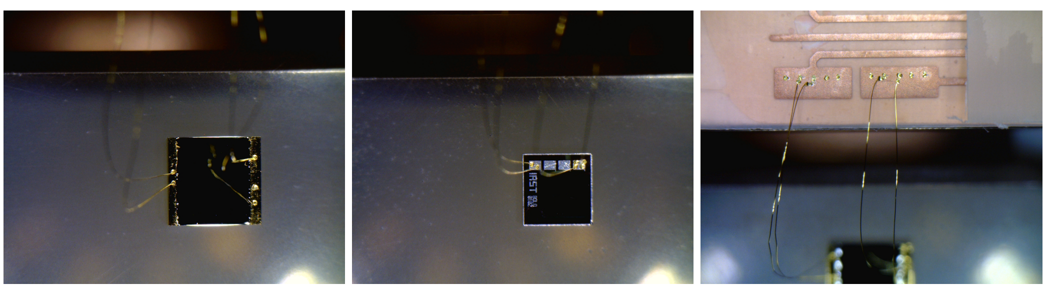
One of the final tasks as a CUORE-0 shifter was to report the results weekly to the analysis group, located in various parts of the world. I never spoke much, but would help put slides together of each run that had been taken that week, as well as reasonings for why some were unusable. It was very interesting to experience the massive amounts of communication and collaboration it takes to facilitate this process, before results can even begin to be fathomed.

3.2 CUORE Bonding

After a few weeks of being a CUORE-0 shifter, I was recruited by Dr. Thomas O'Donnell to be his assistant in the bonding process for the continuing assembly of CUORE. I was given a tour of the CUORE clean room and assembly area where I would be working for the next several weeks. One of the main issues of trying to detect such a minuscule decay is the background radiation and the subsequent noise it creates in the signals CUORE is trying to analyze. As such, the assembly process requires the strictest discipline and documentation when it comes to maintaining the chain of cleanliness for all of the components of the experimental system.

Before working on the tower itself, I practiced the technique and read about the equipment with Dr. O'Donnell. We used a Mitutoyo measurement device to make sure that all of our movements were very precise with the bonding equipment, down to the millimeter. It was crucial to map out our distances so that we would create useable connections and so that we wouldn't waste any material.

3.2.1 The Bonding Process



(a) (b) (c)

Figure 4: Useable bonds for an NTD chip (a), heater chip (b), and copper pad (c).

For the bonding process itself, there were five main steps to the process [3]. The first step, after setting up the bonding capillary at the correct distance and focussing the video feed, was to put the initial bead bond onto either the heater or the NTD pads. The bead bond is a relatively high heat and high ultrasonic bond that welds a bead of gold onto the pad of each chip. The second step was to draw out the gold wire through the capillary so that there was just enough to create a connection between the chips and the copper pads of the detector. These bonds averaged in length to about 7.5 mm. The third step in the process was the wedge bond. The wedge bond is much weaker than the bead bond because the capillary starts the bond with wire trailing out of its end which it must then break off and weld to a soft copper pad, all in a matter of milliseconds. The failure rate of our wedge bonds was much higher than that of the bead bonds for this reason. Additionally, because of the relative weakness of the wedge, the heat and ultrasonic pressure of the bonding machine needed to be lowered so as not to damage the experimental tower. Thankfully, these changes could be accomplished by programming various sequences into the bonding machine itself, however, we reached a point where far too many of the wedge bonds were failing and the entire bonding machine needed to be calibrated. The fourth part of a successful bond was called the security bond. As stated previously, due to the relative weakness of the wedge bonds, an additional bead of gold was placed over the wedge as a back-up bond to hold the wire in place. Since the security bond is the same as the bead bond, once it was successfully placed, we could be reasonably assured that that wire would hold. However, as a redundancy measure, we would repeat the process for every single pad and chip so that there were two successful bonds at each location. The fifth and final step was to document the final bond for review. To do this, pictures were taken using a high resolution camera and a program written by a previous CUORE student researcher.

3.2.2 Troubleshooting

For reference, about 1 in 5 bonds failed or had some issue and needed to be reworked, resulting in significant troubleshooting time for the bonding team. When the process was going well we could get 4 successful bonds onto a chip and documented in a little over 10 minutes. With 2 chips per crystal, and 52 crystals per tower, if we could work perfectly, the process would have taken a minimum of 18 hours for the complete tower. Factoring in the time it took to flush the bonding chamber with nitrogen, move the tower round, remove debris, and unclog and replace capillaries, the total bonding time for the tower was closer to 50 hours, spread out across two weeks. This does not include the three days it took to recalibrate the bonding machine midway through the process.

Figure 5: Changing a blocked capillary inside the glove box. The tower has been lowered into its housing.

The most common delay in the bonding process would occur whenever a capillary got clogged with melted gold. The capillaries are made of ceramic, a material that is greatly resistant to both heat and pressure, however, the gold thread running through the middle of each ceramic needle is not and had a tendency to break or clog the inside of the capillaries. When this happened, Dr. O'Donnell and I had two choices: either replace the capillary completely with a clean one, or attempt to re-thread the capillary after clearing the blockage. Both took significant time away from the bonding process, however, once we gained more experience, we would hope to either clear the blockage or replace the capillary in 15 minutes. To clear the blockage, we used thin pieces on tungsten wire, useful because of its strength and stiffness compared to the gold stuck inside the capillary. Much like a plunger, the tungsten wire would be threaded through the blocked pipe of the capillary in an attempt to push the loose gold out of the way.

When it worked, it saved us the time it took to completely replace the capillary; when it didn't, we would have to replace the capillary anyway and the process would take even longer. Additionally, it should be noted that a great portion of this cleaning/changing process was in moving the experimental tower up and down into its secure housing so that no debris would touch it while equipment was changed out. When a capillary needed to be changed, the gold wire needed to be removed from the capillary and the capillary itself had to be carefully removed with tweezers from its housing on the bonding machine. Then, a clean capillary would be inserted into the machine and the gold wire re-threaded though the middle. Once this was accomplished, a couple of test bonds were always made using the new capillary before bringing the tower back up out of its secure housing.

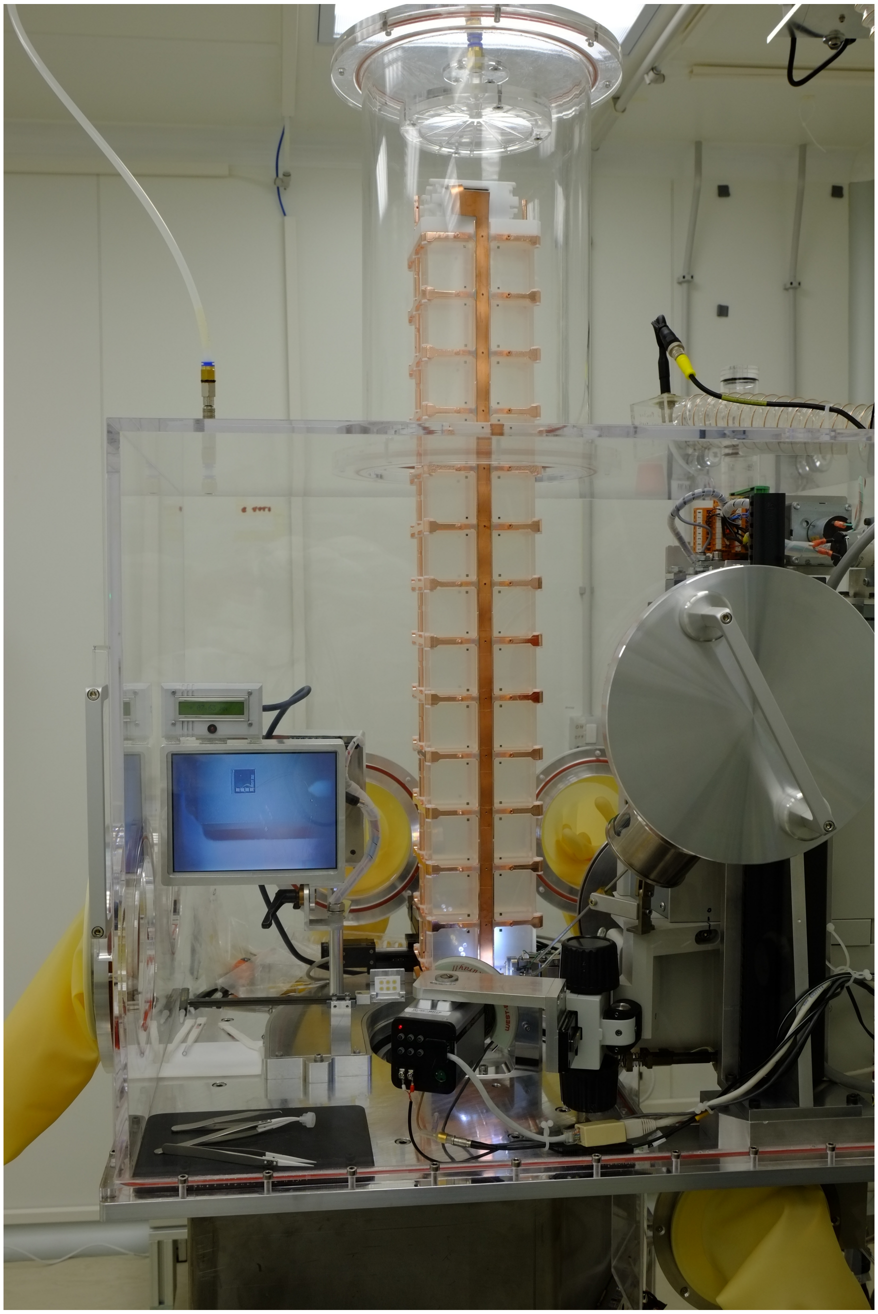


Figure 6: Completed tower inside glove box with bonding machine.

4 Conclusions

During my time working at CUORE I worked on two main projects. I helped with the data taking and helium refills for the currently running prototype, CUORE-0, which needed to occur on a daily basis. I also worked as an assistant bonder for the bonding stage of the assembly process for the full sized CUORE experiment. This involved creating, testing, and documenting electrical connections between the NTD chips, the heaters, and the copper tower housing. The process took approximately 40 hours to completely bond tower 4.

I contacted Dr. O'Donnell to follow up with the assembly work for CUORE and since last summer 18 of the 19 towers have been completely bonded and are in the finishing stages of assembly getting ready to begin with the experiment.

This has been an exciting and educational time period in my life, and the scope and detail of this project has given invaluable insight into the world of scientific research. This project culminated with my selection to represent the CUORE collaboration and Dr. Gutierrez in the state capital where outstanding Cal Poly students were recognized for their achievements and research.

References

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5 Acknowledgements

This senior project represents not only one of the greatest experiences of my life but some of the most difficult and committed work I have done. It would not have been possible without my amazing advisor, Dr. Thomas Gutierrez, who was willing to take me on as a student and fund my travel to Italy. The work he puts in towards development of students like myself is truly exceptional and I am eternally grateful.

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