Michael's Awesome Italian Adventure (With a Bit of Science, Too)

A Senior Project

By

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Approval Page

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Abstract

This senior project will provide the reader with a brief background about neutrinos, neutrinoless double beta decay, and the CUORE experiment being constructed in the Gran Sasso National Laboratory in Assergi, Italy. The remainder of the paper will follow my experience working as an undergraduate researcher at the laboratory during the summer of 2012. It will discuss the process of performing a cool down with the CUORE-0 cryostat as well as quality assurance testing of Teflon spacers to be used in the CUORE towers.

Contents

1 Introduction

The Cryogenic Underground Observatory for Rare Events (CUORE) [1] is an experiment at the Gran Sasso National Lab in Assergi Italy. CUORE is designed to detect neutrinoless double beta decay in ^{130}Te. An array of tellurium dioxide crystals acts as both the detector and the substance undergoing decay. The crystals are kept at 10 mK so decays may be detected by measuring temperature fluctuations. The experiment is done inside of Gran Sasso Mountain to help shield against outside radiation and the tower is cooled in a highly shielded cryostat to prevent any excess noise from interfering. CUORE-0 consists of only one tower and will run during the time that CUORE is being built. It is hoped that CUORE-0 will start taking data within the next year.

I traveled to the lab during the summer of 2012 as an undergraduate researcher. During my time at the lab I helped assist with various tasks related to the CUORE-0 setup. This included preparing the cryostat for a test cooldown as well as quality assurance testing of Teflon spacers which hold the crystals in the frames.

2 Theory

2.1 Beta Decay

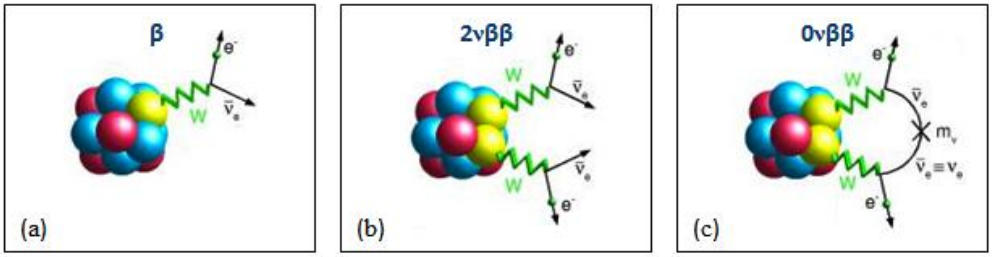


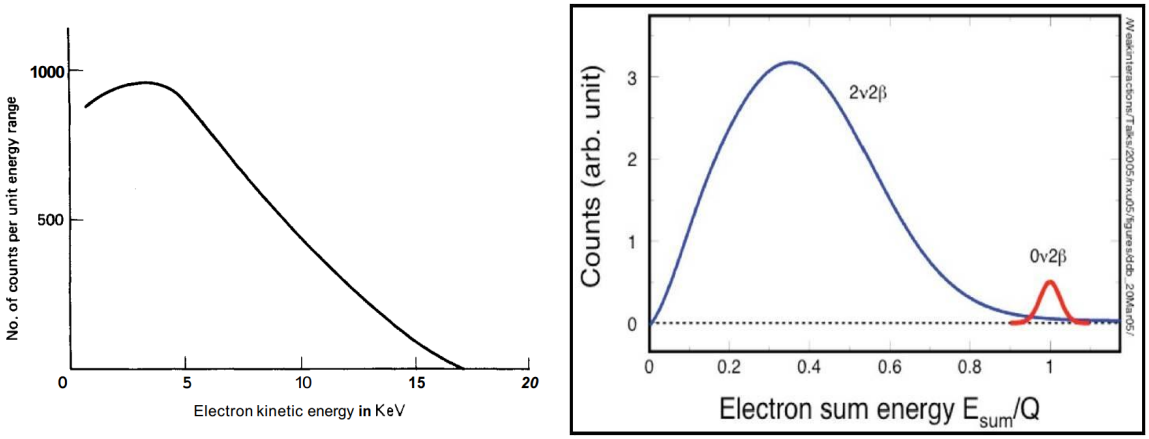
Figure 1: The three variations of beta decay: normal beta decay (a), double beta decay (b), and the theorized neutrinoless double beta decay (c). [http://www.astro.wisc.edu/ wolansky/pics/3d%20dbd.png]

The nucleus of an atom contains protons and neutrons, and an unstable nucleus will undergo decay, usually into a more stable form. One important decay process is beta decay, where a neutron decays into a proton, an electron and an antineutrino as seen in Figure 1(a). Similarly, double beta decay ($2\nu\beta\beta$) is when two neutrons inside the nucleus simultaneously decay into two protons, two electrons and two

antineutrinos which can be seen in Figure 1(b). In Figure 1(c) we have neutrinoless double beta decay ($0\nu\beta\beta$) which is an unobserved special type of double beta decay that can only exist if the neutrino is its own antiparticle. The products of $0\nu\beta\beta$, are only two protons and two electrons.

2.2 Neutrinos

Every reaction obeys one fundamental law; the total energy must be conserved. During early beta decay experiments, only the electron and proton were known products. With this, the energy given off by the reaction is expected to be carried off entirely by the electron. However, when the kinetic energy of the electron was measured, the researchers saw a whole range of energies below the expected value, thus apparently violating the conservation of energy. This can be observed for both beta decay as well as double beta decay in Figure 2.



(a) (b)

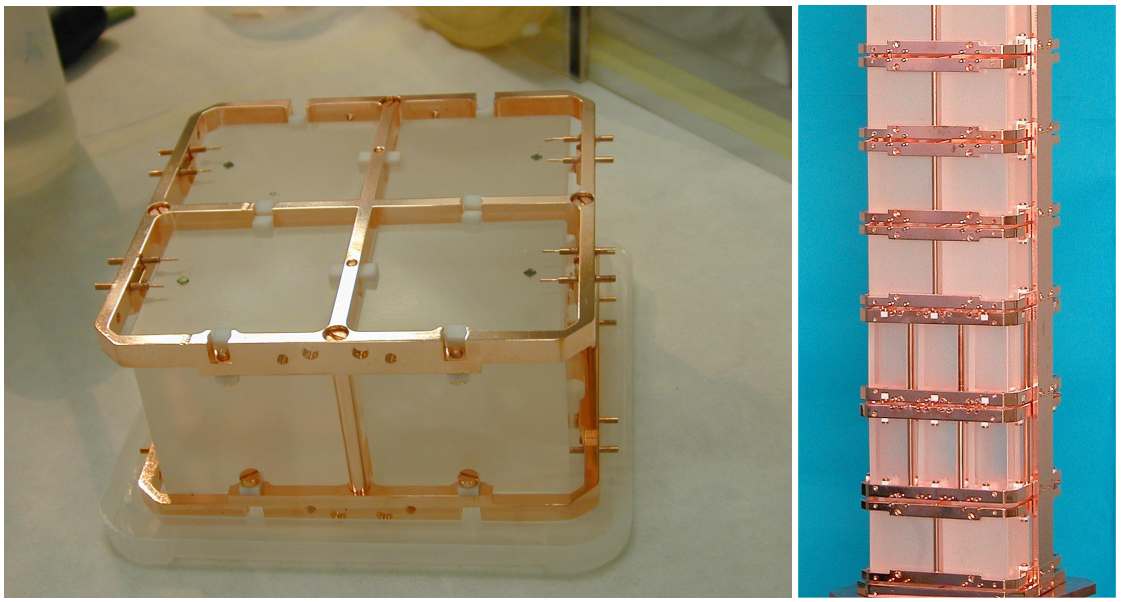
Figure 2: Energy spectrums for beta decay of tritium (a) [5] and a generalized plot of double beta decay (a).

It wasnt until 1930 when Wolfgang Pauli first predicted that there may be a third undetected particle, in addition to the proton and electron. He proposed that this particle was nearly undetectable because it was neutral of charge and interacted very weakly. In 1956 the neutrino was finally detected by Clyde Cowan and Frederick Reines [5]. Although scientists have since determined many properties about the neutrino, its weak interaction with everything makes it very difficult to study. The neutrino has some of the kinetic energy when released which gives the appearance that energy is not conserved. In Figure

2(b), normal double beta decay spectrum is shown in blue. If a peak forms similar to the red curve, the electron has received all of the energy and would suggest that no neutrinos or antineutrinos were products of the decay. This is what is expected of the theorized neutrino double beta decay, and the basis behind the CUORE experiment.

2.3 CUORE

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 3(a). The 988 crystals 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.



(a) (b)

Figure 3: 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).

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 limit in ^{130}Te is set by the CUORICINO detector, see Figure 3(b), 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 CUOREs 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

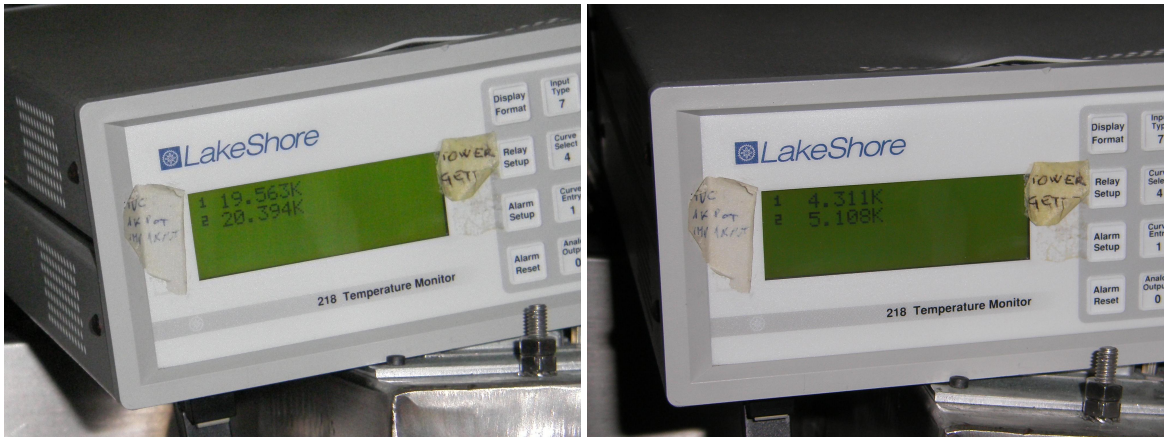
3.1 CUORE-0 Cryostat

The first half of my time at the lab was spent working inside the mountain assisting with various tasks related to the CUORE-0 set up under the supervision of Dr. Paolo Gorla . In the time immediately before my arrival to Italy, a leak had been detected in the CUORE-0 cryostat so it was warmed up to be corrected. On my first day at the lab, the cool down process was beginning again, to check if the leak had been fixed. To do this, liquid helium is pumped into the main bath. Quite a bit of liquid helium is needed for the cool down process because it is kept at a temperature of 4K and evaporates almost instantly when it comes into thermal contact with any relatively large temperature. In order to refill the main bath, we had to first retrieve one of the liquid helium Dewars from the refill station.

Figure 4: 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 Dewar has to carefully be rolled throughout the whole laboratory because liquid helium has an expansion ratio of 757:1. Every Dewar has a safety blow-out value which can activate if the contents expand to an unsafe amount. The pressure gauge was also monitored as an extra safety precaution. A long specialized pipe is inserted into the Dewar from the top and has a pipe that runs to the top of the cryostat, which can be seen in Figure 4. The valves are opened slowly as to not shock the system, and the rate of helium entering is controlled using a pump to create suction inside the main bath tank. As previously mentioned, the liquid helium evaporates as soon as it comes in thermal contact with a warm substance, such as the inside of the main bath. In order to compensate for that, we pumped out the evaporated helium to be recycled. We aimed to pump out at a rate of 35 liters/minute but we were able to achieve 30 liters/minute which is within the acceptable range. The whole set up was left to run over

the weekend and continue to slowly cool the cryostat.



(a) (b)

Figure 5: The temperature monitor indicates the temperature inside of the IVC (measurement #1) and the 1K Pot (measurement #2). The thermal gas is pumped out of the IVC when the temperature reaches ∼20K (a). The main bath begins to fill when the temperature reaches ∼4K (b).

Over the weekend a problem had arisen with the cool down process. The purpose of the liquid helium filled main bath is to cool the IVC to 4K, but the rate of cooling was found to be much too slow. The vacuum drastically lowers the thermal interaction and the lead inside the IVC does not conduct well with itself, so it was like there was a relatively hot object inside the chamber evaporating any liquid helium being pumped in. To work around this problem, helium gas is pumped into the IVC as a temporary thermal conductor. This increased the rate of cooling but it must be monitored carefully. When the temperature has reached 20K the thermal gas needs to be pumped out of the IVC as seen in Figure 5(a). If the gas is left inside the chamber, it will condense as soon as it reaches a cold enough temperature which can cause problems down the road. The thermal gas will be pumped out for 24 hours to ensure it all is properly evacuated. The helium Dewar was empty so it had to be replaced with a full one. During the transfer process the temperature raised from 5K to 11K because the transfer pipe is at room temperature and evaporating the helium to a gas before it was able to reach the bath. After a short while the temperature began to drop again down to approximately 4K as seen in Figure 5(b).

Now that the bath is the same temperature as the liquid helium it began to fill up. There is a gauge for measuring how much liquid helium is in the main bath. It is important to turn the gauge into high

sample rate to get an accurate real time idea of how full it is during the refill process. The main bath is full once the gauge reads 100% for 5 minutes to ensure the reading is stable. The gauge works by having a wire run from the top to the bottom of the main bath. When the wire is submerged in liquid helium it acts as a superconductor, so applying a current and measuring the resistance allows for the amount of liquid helium to be measured. However, taking a measurement requires a current to flow through the wire which transfers energy to the helium causing the bath to warm. To avoid evaporating excess helium, the gauge must be set back to low sample rate when the filling process is completed.

The cryostat was left for a couple days to sit but the next step was to check for any leaks in the IVC and work with the 1K pot. The special leak tester is a mass spectrometer that can detect masses of 2, 3, and 4. We connected it into the IVC circulation cycle and opened the values to direct the flow through the leak detector. First we needed to test for helium-4, which ideally would give a signal on the order of $10^{-7}\,\frac{\mathrm{mbar}\times\mathrm{L}}{\mathrm{s}}$ through the detector. We were measuring something on the order of $10^{-6}\,\frac{\mathrm{mbar}\times\mathrm{L}}{\mathrm{s}}$ but it was stable. Next we needed to test for the rare helium-3. Because helium-3 is very rare so a signal of $10^{-10}\,\frac{\mathrm{mbar}\times\mathrm{L}}{\mathrm{s}}$ is ideal. There is a getter inside the IVC that absorbs any helium that comes in contact with it. The getter has a resistor running through it that when heated, releases any trapped helium back into the IVC. We run the heating resistor for 5 minutes while measuring the helium-3 signal on the leak tester. Our signal was stable so we closed off all valves to the IVC, creating a closed vacuum again. The 1K pot uses some thermodynamic processes to bring the temperature from 4K down to 1K. This involves pumping in liquid helium and pumping it back out. We repeated this process 3 times which causes the temperature inside the 1K pot to fluctuate from 4K to 1K. The percentage full gauge for the 1K pot was broken so we took it apart and soldered the broken wire back on properly.

Our next step was to check the trap for any problems. The trap is submerged into a bath of liquid nitrogen to freeze out any foreign particles before they enter the cryostat. Any unwanted substance flowing through the cryostat can potentially pose a problem when dealing with such low temperatures. I was tasked with refilling the liquid nitrogen Dewar by making trips to the refilling station inside the mountain. While I was filling the Dewar, they found a problem with the trap which appeared to be a leak. Unable to determine the source we refilled the main liquid helium bath and let it sit for the night. The next day we disconnected the trap from the cycle and took apart what we could. We cleaned each O-ring

connection and then closed each end of the trap. Each side of the connection into the cycle was tested but they were both fine. Next we suspected that the hoses may be the culprit but each test came back negative. Finally we hooked the trap into the leak detector and we found the pressure was too high when it was tested. The problem seems to be within the trap itself, which can be fixed but not immediately.

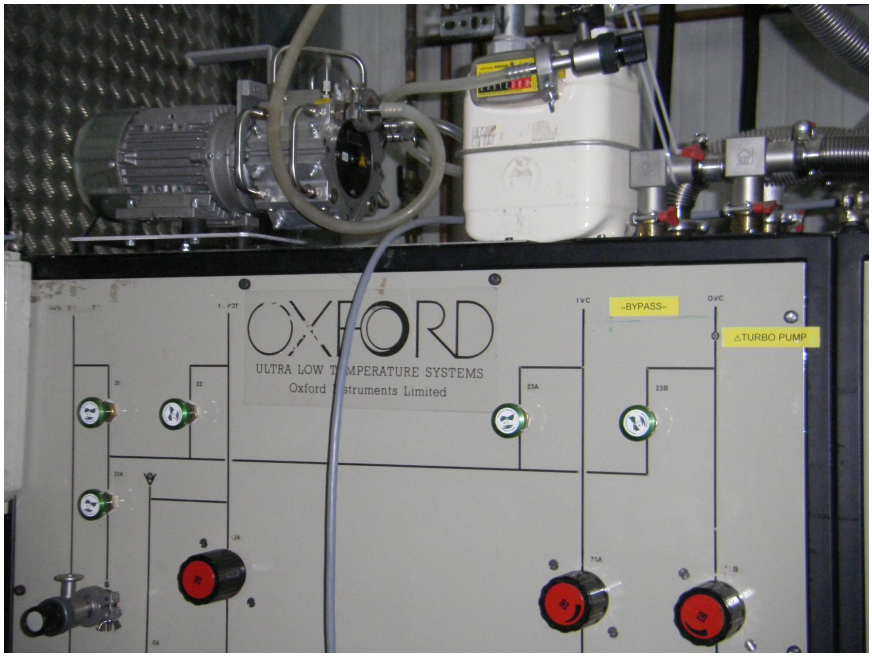


Figure 6: Part of the control board that allows the circulation to be directed to different parts of the system.

However, we are still able to test the overall cryostat circulation if we bypass the trap. We do not have a trap to condense the foreign particles in, so we must backflow the loop and condense it inside of the still. Once we believe the dirt has all been sufficiently frozen out we can start pumping in the proper direction. In order to do this, we need to access the top of the cryostat. First, I opened the dumps for the helium and then the filler to catch any dirt or residuals still left in the line. It is very important to open the front first and then wait a moment to open the back. The circulation is let flow until the rate is lowered. Then the cycle is switched from filling the dump to pulling gas out of the dump and into the system. The pressure in the line must not exceed 700 mbar. We found however that the line pressure only dropped slightly then would increase. This was another problem that must be dealt with. We checked the 1K pot levels and found it to be empty so we filled it to about 80% capacity from the main bath. The thermostats

inside the IVC and 1K pot were shut off because they dissipated too much heat to the liquid helium. We tested the circulation again but it was still not fixed. The next day I was authorized to go under the mountain alone and start up the circulation. One possible solution I tried was to allow it to condense for longer before proceeding. I followed the same procedure, opening the filler and starting the rotary pump but the pressure inside the line rose too fast, prompting me to shut it off. I closed a valve so it could fill the dumps and not pull from it. This lowered the line pressure, but even with the pump on there was no flow through the whole system. There is a major problem somewhere in the cycle so they postponed any more testing until it could be fixed.

3.2 Copper Frame Metal Pins

With the cool down being temporarily postponed on the cryostat, I was assigned to a new task in the CUORE-0 clean room under the supervision of Dr. Tom Banks. I was given a tour of the CUORE-0 clean room and prep area and set up to work in there for a few days. One of the main issues with trying to detect such a rare decay is the radioactive background noise. [3, 4] A source of noise that is within our power to control is the copper frame of the detector. By cleaning the copper very carefully we can minimize the amount of foreign radiation being detected. This however can be very resource and time intensive so the research and development unit of CUORE was working on an alternate project. The idea is to coat the copper in a parylene layer that will block the radiation from the copper. To save on materials, the old CUORICINO tower was disassembled and reused for this new project. The copper frames each have many pins used in the wiring of the detector. My job was to recover as many useable pins as I could.

I was given many sets of copper frames and instructed to melt off the epoxy holding the pins in place. This had to be done with care as to not damage the structure of the wire to pin connector. A soldering iron was used to heat each side of the pin until the glue was softened. Then using tweezers the pins would be pulled out of the frame and placed into a bag to be cleaned. I was able to successfully remove approximately 100 pins which were more than enough for the project. The pins still had epoxy on them so they must be cleaned before we can proceed further. We retrieved some glassware to bring to the chemistry lab outside of the mountain to be cleaned. When they finished cleaning we were able to head back under the mountain and move the pins into the CUORE-0 clean room. A specialized lab suit must

be worn, along with gloves and feet booties, in order to be allowed into the clean room. After proceeding through the first chamber we made our way to the fume hood.

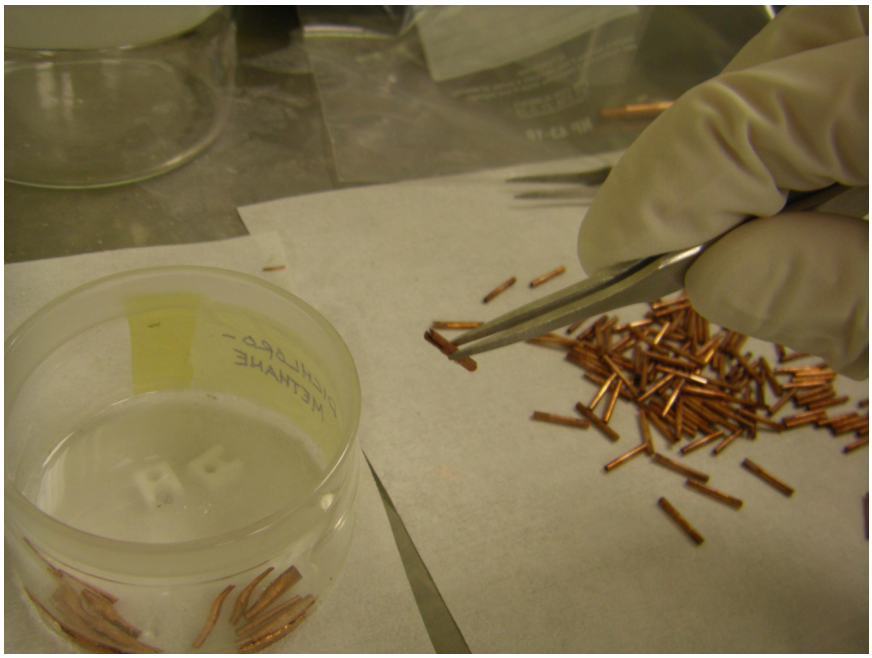


Figure 7: The set up for cleaning the epoxy off of the copper pins. The pins to be cleaned can be seen on the right, and the glass container on the left contains the pins soaking in the dichloromethane.

I was going to be using dichloromethane, which is a very strong solvent, to dissolve the epoxy from the pins. Cleaning the pins was a fairly simple but time consuming task. The pins needed to be soaked in the dichloromethane in small groups of 10-15. After about 5 minutes of soaking, each pin was removed from the bath. They then were hand cleaned and inspected to ensure all of the epoxy was removed from the center of the pin. In Figure 7 you can see part of the cleaning process. The pins on the right are waiting to be cleaning and the container on the left shows the pins being soaked. After every two rounds of pins, the dichloromethane needed to be replaced because the epoxy would start to build up. When all the pins were completed, I cleaned up the work station and the pins were taken to be put into storage until needed for the parylene project.

3.3 Teflon Spacer Measurements

The side project cleaning the copper pins was just enough time for my other supervisor to have my final project set up under the supervision of Dr. Lucia Canonica. This was located in the mechanical workshop building outside of the mountain. The crystals are held in the copper frames by Teflon spacers. Teflon was chosen because it can be cleaned to become almost radioactively pure and it behaves similar to the crystals at low temperature. In general, a solid will contract when it is cooled, which might cause problems if we used two substances that behave differently as we approach 10mK. It is important to the structural stability of the tower that the Teflon spacers meet the proper dimensions so the spacers must be measured precisely.

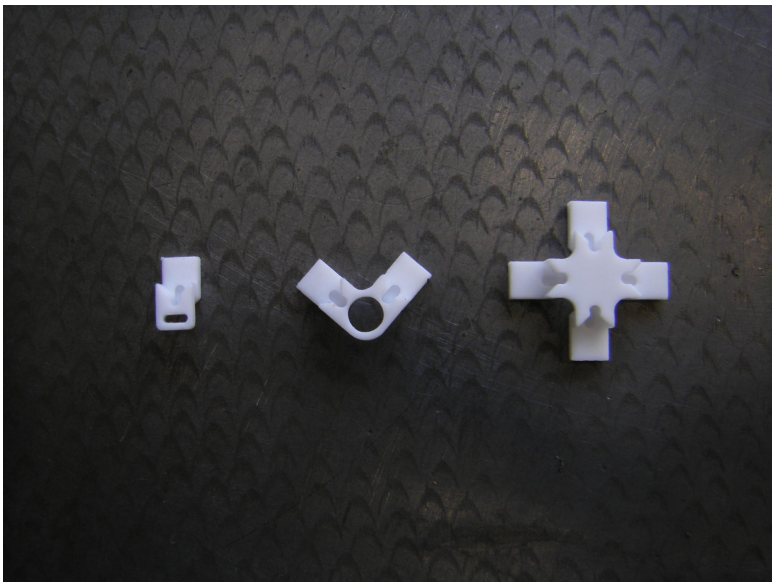


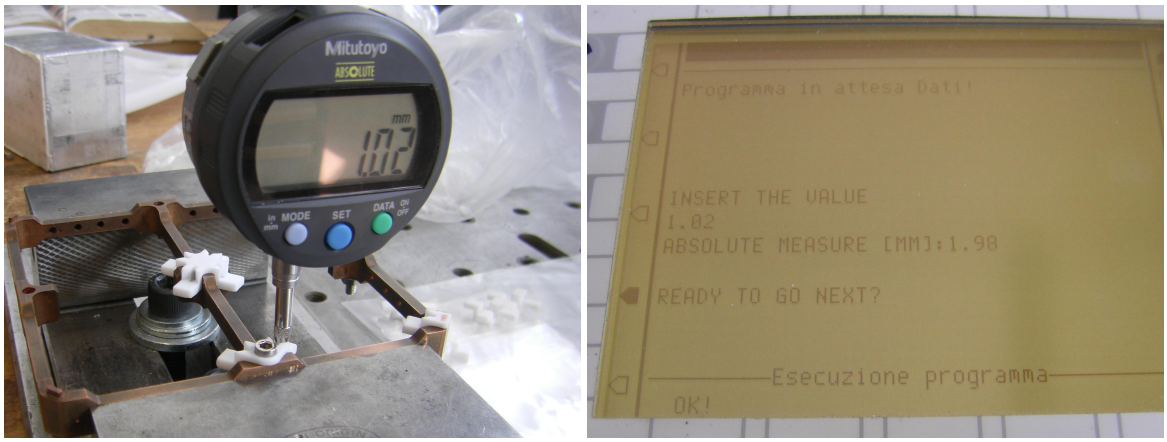
Figure 8: The three types of Teflon spacers. For practical purposes the pieces, from left to right, are ”small”, ”elbow”, and ”plus”. The elbow piece also has a left and right side with respect to its current orientation. The plus piece does not have a common reference point for each peice so each side is treated as the same.

In Figure 8 there are examples of each of the three separate spacer types. For practical purposes I will refer to the pieces as ”small”, ”elbow”, and ”plus” starting from the left. Additionally, the sides of the elbow can be uniquely distinguished as ”left” and ”right” with respect to the hole facing down. The plus piece has 4 sides, but any rotation looks the same so it is impossible to determine a reference point common to every plus spacer. Each piece is mounted onto a level copper frame and measured with an

electronic digital indicator connected to a 6-axis robot arm. Figure 9 illustrates a full frame with a plus spacer being measured.

Figure 9: A full frame halfway through a cycle. The arm begins by zeroing on the raised frame next to the small spacer and working its way around the frame counerclockwise.

One full cycle for the arm is programmed to measure in the following order: small, left elbow, right elbow, all 4 sides of the plus, left elbow, and finally right elbow. Before each cycle the digital indicator touches the top of the frame to be zeroed. The process is semi-automated with human input needed after each measurement to tell the arm to move to the next piece. The digital indicator does not measure the depth of the piece, but the relative change of altitude with respect to the top of the frame. An example of a measured value on the digital indicator can be seen in Figure10(a). To determine the depth of the piece, simply subtract the measured value by 3.0 mm. The controller is programmed to do this. It asks for the value and will return the absolute measure which tells us how deep we would like the pieces. The screen can be seen in Figure 10(b) displaying the input as well as the output.



(a) (b)

Figure 10: A measurement of a right elbow spacer. The value is read off of the digital indicator (a) and entered into the controller (b) where it returns the absolute measure.

After the data is recorded for the type of piece and the depth, the arm will move to the next spacer measurement. When the full cycle is completed the arm returns to the home position, up and away from the frame. The measured spacers are sorted into bags corresponding to the type and depth. An ideal piece will have a depth of 2.00 mm but due to the random nature of the manufacturing process this is not always the case. A spacer is allowed to have a tolerance of 0.10 mm above and below 2.00 mm to be able to be sorted into the good bag. If a measurement falls below 1.90 mm the piece is placed into a separate bag for spacers that are too small. The same is done for and Teflon piece that is found to be above 2.10 mm. The different types of pieces are kept separate from one another for organizational purposes. However, the elbow pieces and the plus pieces each have multiple measurements for an individual spacer and this must be taken into account. All sides of the spacer must be within the set tolerance or the whole piece is considered to be unusable and sorted as too large or too small. Doing this ensures that only the most precise pieces will be used in the tower. Just measuring and sorting the spacers did not seem like enough to ensure the quality of the pieces met the expectations. In the Data and Analysis section, I will analyze the raw measurements to get an idea just how well the Teflon spacers agree with the tolerance set by the experiment.

It should be noted that this method of measuring the Teflon spacers is brand new and still being developed. Throughout the time I spent working with the robot arm, a few things were tweaked to ensure

all of the measurements were accurate by minimizing experimental errors. If we had a suspicion that a set of measurements may not have been done properly, the pieces would be re-measured and the old data would be deleted. Improvements can be made in future tests by mounting a more stable frame on bracers to minimize tilt, and doing so would not require the frame to be re-leveled after each cycle. Overall, the method is very efficient as each piece is measured in exactly the same way every time and almost eliminates human error from the measuring process.

4 Teflon Spacer Data and Analysis

The measurements for each spacer are entered into a spreadsheet corresponding to the type of piece being measured. There are 4 different categories for the Teflon to be recorded in: small, plus, right elbow, and left elbow. Each data set is processed individually using a Matlab program I wrote for this specific purpose. As one might expect, the manufacturing process if subject to random error which leads me to believe the measurements should be governed by a Gaussian curve. The Gaussian distribution curve is modeled by equation (1) where $\bar{x}$ is the mean value of the raw data and σ is the standard deviation.

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\bar{x})^2/2\sigma^2} \tag{1}$$

A histogram is generated for each set with a bin size of 0.01 mm which outputs a graph with similar features to that of a bell curve. Using Matlab, a best fit Gaussian curve is plotted on top of the raw datas histogram. The Gaussian curve follows the histogram almost identically so this is the method we will use to analyze the measurements. To get a better idea of how accurate the fit is, we find the mean value of the raw data and solve for the standard deviation to get an idea of the spread. On each graph, both the average depth and the best fit depth are displayed with the uncertainty.

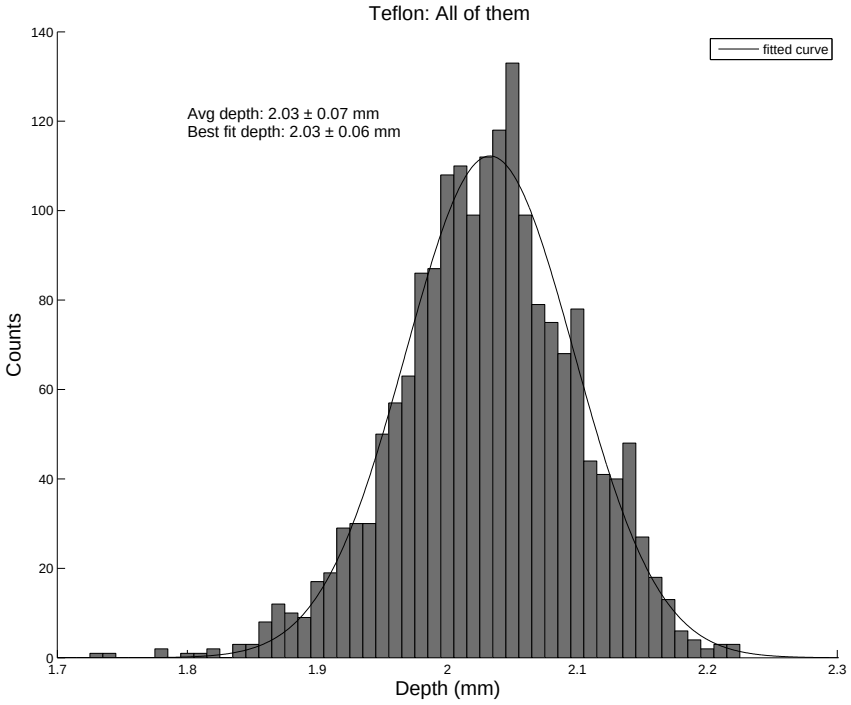


Figure 11: Histogram for all spacers measurements with a fit gaussian curve

In Figure 11 above, all of the measurements have been plotted onto one graph. Recall that the ideal spacer measurment is 2.00 ± 0.10 mm. From the analysis I found that the expected mean value from the best fit is 2.03 ± 0.06 mm which is acceptable within the conditions required. However, this does not tell us very much about how well each type of spacer meets these conditions. First the small Teflon spacer data was run through the code as seen in Figure 12. I found that the expected mean value from the best fit is 2.10 ± 0.04 mm which is on the upper limit of the acceptable sizes. This can pose a potential problem for mounting the crystals, so many of the pieces were sorted into the rejection bag. Next, the plus Teflon spacer data was analyzed as seen in Figure 13. The expected mean value from the best fit is 2.02 ± 0.04 which meets the conditions very well. There were a few outliers in the 1.70 mm range, but the majority of the spacers are within the 2.00 ± 0.10 mm tolerance.

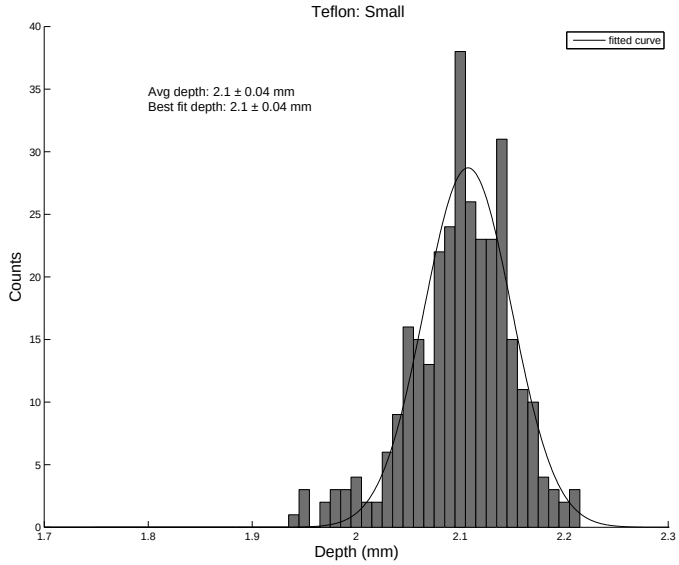


Figure 12: Histogram for the small spacers with a fit gaussian curve

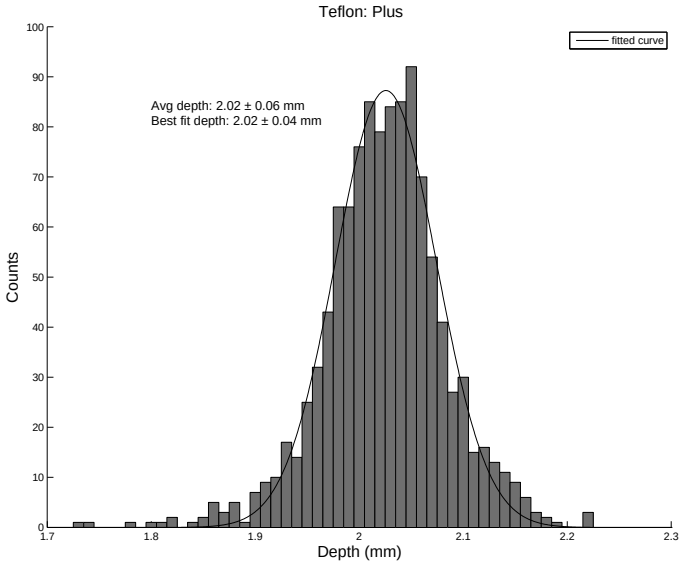


Figure 13: Histogram for all of the sides of the plus spacers with a fit gaussian curve

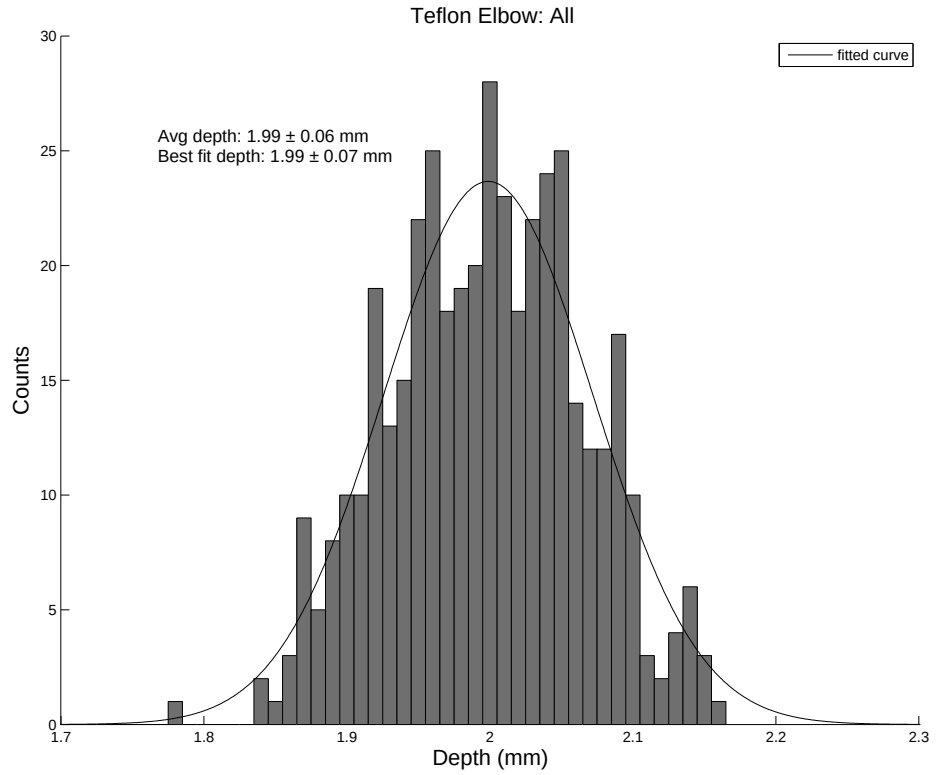
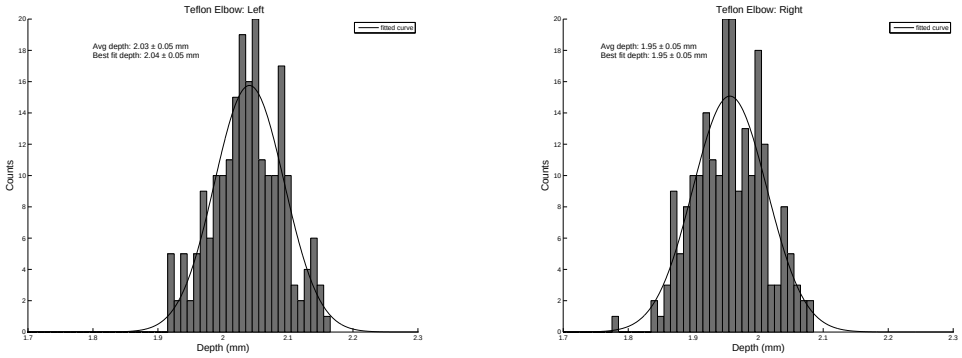


Figure 14: Histogram for the the combined right and left of the elbow spacers with a fit gaussian curve

The elbow pieces displayed some very interesting behavior. At first glance, the elbow pieces seem almost perfect because all of the measurements give us an expected mean value of 1.99 ± 0.07 mm as seen in Figure 14. Most of the values are within our tolerance and the number of outliers is relatively small compared to the total measurements. However, as mentioned before, the corner of the elbow can be uses as a reference point to differentiate the right and left sides. The data was then analyzed individually for the left and the right side as seen in Figure 15. The expected mean value for the left elbow is 2.04 ± 0.05 mm and the expected mean value for the right elbow is 1.95 ± 0.05 mm. I plotted both the left and the right elbow spacer measurements on the same graph in two colors which can be seen in Figure 16.



(a) (b)

Figure 15: Histograms with a fit gaussian curve for the left elbow (a) and the right elbow spacers (b).

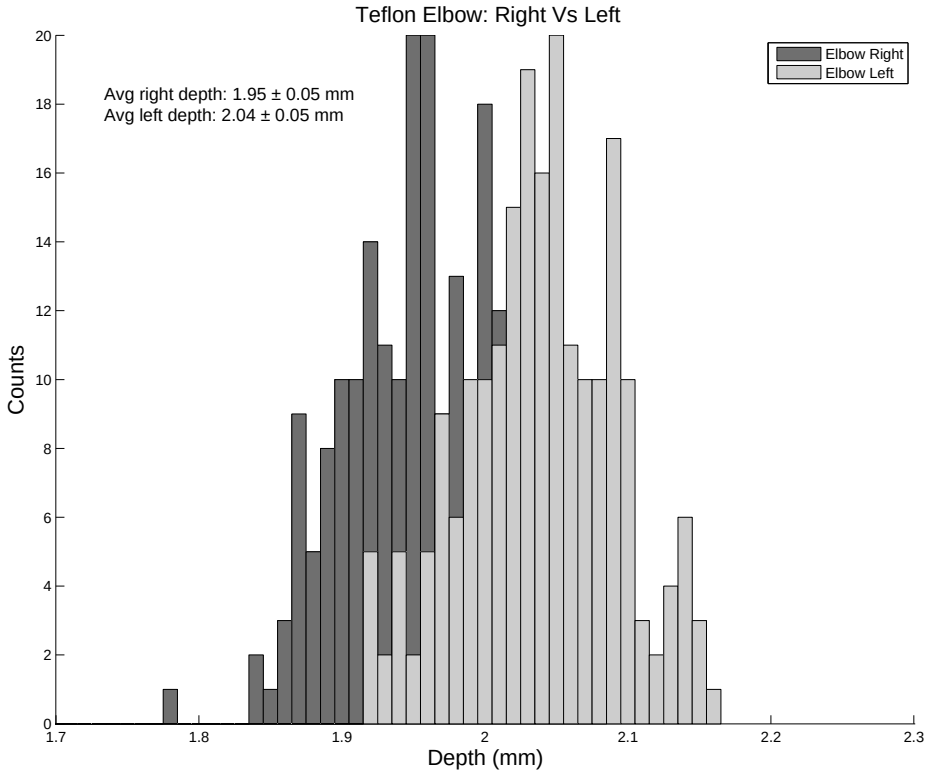


Figure 16: Side by side comparison of the right and left arms of the elbow spacers.

In order to determine whether this was just an experimental coincidence, I needed to check how the right and left sides of each elbow compared. To do this I subtracted the left side from the right side within the spreadsheet. This returns the difference in depth of each spacer. In Figure 17 it is apparent that the majority of pieces have a depth difference of about or above 0.09 mm between each side. The graph has very few counts in the negative which leads to the conclusion that the left side always has a greater depth than the right.

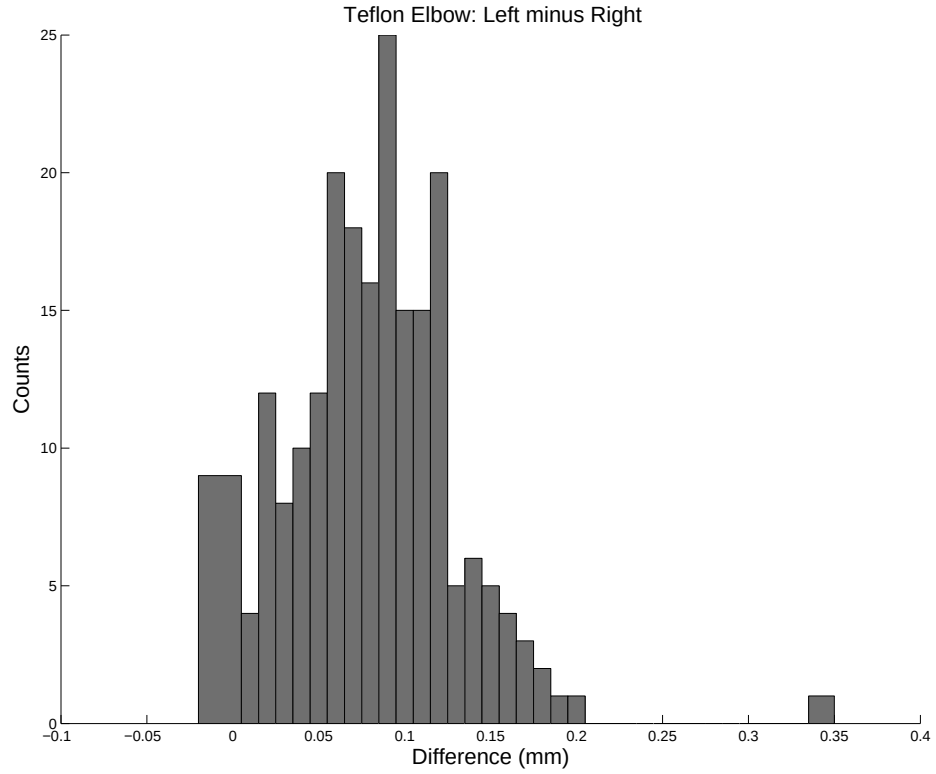


Figure 17: The difference between the right and left arms of each elbow spacers

When I first encountered this problem, I thought I might have been getting some sort of error caused by a tilting in the frame. In order to test this, the same spacer was measured in multiple elbow positions on the frame. If the frame was not level, the measurement should return values with either the right side being deeper or the two sides being equal depending on the orientation. After many tests I was

able to conclude that it was indeed the spacer, and not the apparatus, that was the problem. The data and analysis suggest that the Teflon elbow spacers were manufactured improperly and not to the specifications required by the experiment. Before anything can be said for certain, the measurements have been put on hold until it can be determined whether there is some sort of unaccounted systematic error in the data acquisition process.

5 Concluding Remarks

During my time working at CUORE I worked on three main projects. I helped with a test cool down of the CUORE-0 cryostat. A leak was discovered inside one of its many components and after a few futile efforts to fix it, the project was put on a temporary hold until it could be warmed up. I removed and cleaned copper pins from the dismantled CUORICINO tower frames. The pins will be used in a future test to determine if there is a more efficient method to block radiation from the copper frames.

Finally I worked with a 6-axis robot arm to measure the Teflon spacers to be used to hold the crystals in the CUORE towers. There are three types of spacers I measured: small, plus, and elbow. I plotted the depths and fit a Gaussian distribution curve to the collected data for each piece. I found that the small pieces were on the high end of the tolerance and the plus pieces agreed very well. The elbow pieces were interesting because the left and the right side could be differentiated from each other. From the analysis, it is clear there is a difference between the two sides. The left side was constantly much deeper than the right side. The project was put on hold until it could be determined what the best plan of action would be to move forward.

I contacted Dr. Canonica to follow up on the work with the spacers. I was informed the Teflon measurements have been postponed until and energy resolution can be determined for the detector. A bad energy resolution can be caused by vibrational noise of the crystals not being held tight enough into the copper frames due to faulty Teflon spacers.

6 References

References

[1] ”CUORE: A Cryogenic underground observatory for rare events,” CUORE Collaboration, http://arXiv.org/abs/hep-ex/0501010, 2005.

[2] ”130Te Neutrinoless Double-Beta Decay with CUORICINO,” Astropart. Phys. 34 (2011) 822831, http://arxiv.org/abs/1012.3266

[3] ”Validation of techniques to mitigate copper surface contamination in CUORE,” F. Alessandria et al., Astropart. Phys. 45 (2013), 13-22, http://arxiv.org/abs/1210.1107

[4] ”CUORE crystal validation runs: results on radioactive contamination and extrapolation to CUORE background,” F. Alessandria et al., Astropart. Phys. 35 (2012), 839849, http://arxiv.org/abs/1108.4757

[5] Griffiths, David J. Introduction to Elementary Particles. Weinheim Germany: Wiley-VCH, 2008. 22-28. Print.

7 Glossary

Acronym	Meaning
CUORE	Cryogenic Underground Observatory for Rare Events
CUORE-0	CUORE's single tower experment
CUORICINO	CUORE's precursor experiment
$0\nu\beta\beta$	Neutrinoless Double Beta Decay
$2\nu\beta\beta$	Two Neutrino Double Beta Decay
IVC	Inner Vacuum Chamber
OVC	Outer Vacuum Chamber
1K Pot	1-kelvin Pot

Table 1: Acronyms

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I'd like to thank the Academ- Ay yo hold up. Imma let you finish but this is the greatest senior project you have ever read. Can we just take a moment and savor all the amazingness your brain is processing. There was adventure and danger and action. Most of all, there was me, relaxing and enjoying life in the Italian countryside without a care in the world. Alrighty, now I can go back to thanking everyone for this once in a lifetime opportunity and how it wouldn't be possible without the best parents in the world and friends who convince you to take risks once in a while. I would also like to thank Dr. Tom Banks, Dr. Paolo Gorla, Dr. Lucia Canonica and everyone I met while in Italy for making my experience at the lab an enjoable one. Lastly, I would like to send a huge thank you to the amazing Cal Poly Physics department and my advisor, Dr. Thomas Gutierrez, to whom I am eternally grateful.

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