On-Sight Shifting at the Cryogenic Underground Observatory for Rare Events

A Senior Project

By

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1 Introduction

1.1 Beta Decay History

Research at Laboratori Nazionali del Gran Sasso (LNGS) draws from all branches of physics. The Cryogenic Underground Observatory for Rare Events (CUORE) is one of the eleven experiments that are housed at LNGS. The science behind most recent experiments at CUORE can be traced back to twentieth century physicist Wolfgang Pauli, who spurred world-wide interest in a hitherto undiscovered particle, the neutrino. Most well-known for the Pauli Exclusion Principal, Pauli was an Austrian-born Swiss and American theoretical physicist. A Nobel Prize recipient in the field of physics, Pauli is one of the pioneers of quantum physics, having collaborated with names like Niels Bohr, Werner Heisenberg, and Albert Einstein [2]. However, it is not the Pauli Exclusion Principal that is most important in the context of CUORE; it is the violation of conservation of energy that Pauli discovered in beta decay.

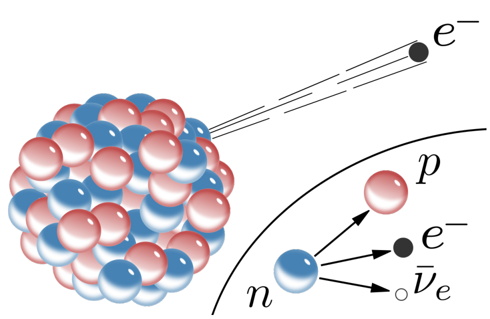

Figure 1: Beta decay diagram

Beta decay occurs when, in a nucleus with too many protons or neutrons, one of the protons or neutrons transforms into the other. There are two types of beta decay: beta minus decay and beta plus decay. In beta minus decay, a neutron decays into a proton, an electron, and an antineutrino. In the second, a proton decays into a neutron, a position, and a neutrino [1].

According to the laws of conservation of energy and momentum, which are rigid and unforgiving, particles resulting from beta decay should be emitted at a specific energy that correlates with the energy required for the decay itself. Similar to many phenomena in physics, beta decay simply does not behave as expected [5]. Wolfgang Pauli discovered that the energy required for beta decay does not match the energy of the emitted particles - back to the drawing board for the physics community.

Through experiments carried out in 1914 by James Chadwick, another Nobel Prize in Physics recipient, it was observed that electrons are emitted in a continuous energy spectrum rather than at a consistent quantity of energy -a daunting violation of energy conservation. How can the same physical process produce varying quantities of energy?

Cue the familiar Wolfgang Pauli. Pauli theorized in a letter to the Federal Institute of Technology, Zrich, that an undetected particle was carrying away the observed difference between the energy, momentum, and angular momentum of the initial and final particles. This particle was later dubbed the ”neutrino” by Enrico Fermi, a word play on the Italian name of the ”neutron”. He proposed an updated theory of beta decay which included a new particle and obeyed the law of conservation of energy.

In true scientific fashion, the mere theorization of the neutrino was not sufficient for the scientific community. Nineteenth century physicists Frederick Reines and Clyde Cowan, also fellow Nobel Prize in Physics recipients, took on this challenge and were the first to detect evidence of this elusive particle in 1956.

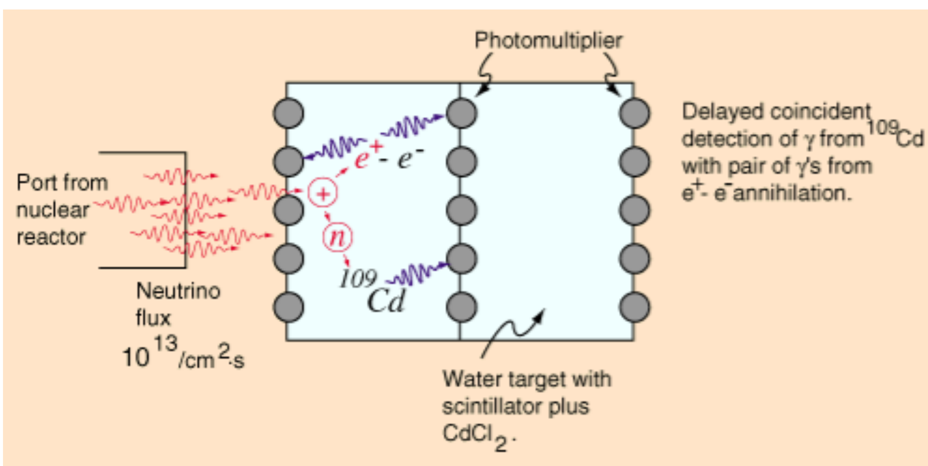

Figure 2: Reins-Cowan experimental setup

Cowan and Reines used the experimental setup pictured below. In beta decay, the predicted electron antineutrino should interact with a proton to produce a neutron and a positron - the antimatter counterpart of the electron. The result is emission of two gamma rays: one from the positron finding an electron and annihilating each other, and the other from a nucleus capturing the neutron. In the experiment a nuclear reactor was used as a source of a neutrino flux of 5×10^{13} neutrinos per second per square centimeter. Two tanks of water were used because hydrogen atoms in water molecules have a single proton for a nucleus - exactly what is needed for beta decay. Neutrinos from the reactor interacted with protons in the water, creating neutrons and positrons. Annihilation of the positron and electron emitted a pair of gamma rays, as explained above. By flanking the water with two tanks filled with liquid scintillator, these gamma rays were detected. Lights were flashed each time a gamma ray was given off. This flash was measured by a photomultiplier tube. To add even more certainty, they detected the neutrons by placing cadmium chloride in the tank, which is a highly effective neutron absorber and gives off a gamma ray when it absorbs a neutron. After months of data collection, the results were conclusive; neutrinos exist. They are denoted by the greek letter ν while antineutrinos are denoted by $\bar{\nu}$.

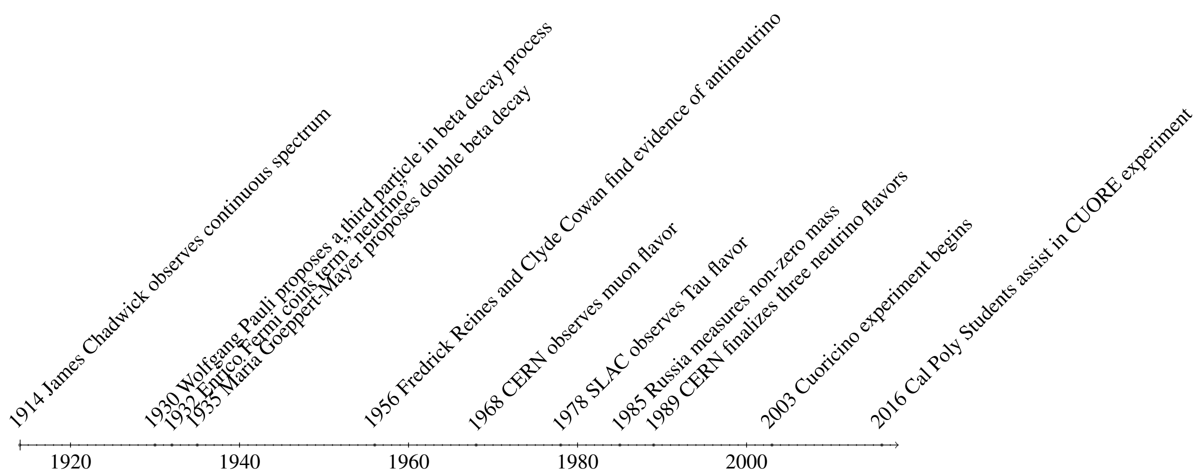

Figure 3: Timeline of Beta Decay

1.2 Neutrinos

The particle responsible for the peculiar behavior of beta decay exists -now what? Since their observation, neutrinos have been the subject of world-wide physics research. Here is what is known so far. While being one of the least understood particles, neutrinos are a fundamental part of the make up of the universe. They are similar to the familiar electron but without the electric charge. Thus, they are not affected by the electromagnetic force; they are only acted on on by the "weak" force. Because of this they can travel through great distances of matter without being affected by anything, making them especially useful in the field of astronomy. There are three families or "flavors" of neutrinos: electron neutrino, muon neutrino, and tau neutrino [3]. Each of these names are related to the charged particles. Neutrinos oscillate between different flavors when they travel. For example, an electron neutrino produced in a beta decay may be detected as a muon or tau neutrino. Neutrinos have a very small (non-zero) mass, or as Reins would say, ”the tiniest quantity of reality ever imagined by a human being.”

The last fact is especially important. The current standard model of physics accounts for a massless neutrino, as seen in the figure below. However in 1985 the IMB experiment, a collaboration of: University of California, Irvine; University of Michigan; and the Brookhaven National Laboratory, discovered that neutrinos are in fact not massless. Neutrinos have a very small but non-zero mass. A massive neutrino is a different ball game, as the standard model has to change in order to compensate for it. Neutrinos are proving to be very problematic for the physics community.

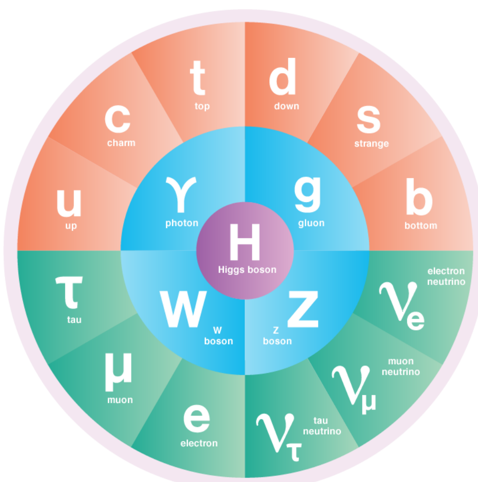

Figure 4: Current Standard Model

2 Theory

2.1 Dirac and Majorana Particles

The plot thickens. To further complicate things, neutrinos have yet to be classified as Dirac or Majorana particles. Before that is defined, it will be useful to define a number known as ”lepton number”. Lepton number is a conserved quantum number that represents the number of leptons (an elementary particle) minus the number of antileptons in a particle reaction. Out of all nuclear reactions known to science, lepton number has never been violated. Current physics cannot explain exactly why this number is always conserved; lepton number is a nuclear characteristic that just simply is.

If neutrinos are Dirac, by definition neutrinos and antineutrinos are different particles and lepton number is conserved. If they are Majorana particles, neutrinos and antineutrinos are the same particle. In this case lepton number is not conserved - red flag [11]. To prove that neutrinos are Majorana, evidence of neutrino and antineutrino annihilation needs to occur. A process called neutrinoless double beta decay, denoted as $0\nu\beta\beta$, is a decay that theoretically exists, and is the top candidate for demonstrating neutrino and antineutrino annihilation. In order to understand neutrnioless double beta decay, it will first be useful to define double beta decay.

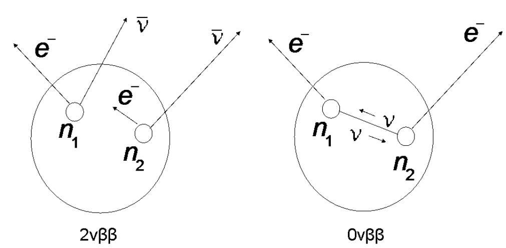

Figure 5: Left: double beta decay featuring the emission of two electrons and two neutrinos
Right: neutrinoless double beta decay

2.2 Double Beta Decay and Neutrinoless Double Beta Decay

Beta decay was previously defined as ”in a nucleus with too many protons or neutrons, one of the protons or neutrons is transformed into the other.” Double beta decay, proposed by Maria Goeppert-Mayer in 1935, is simply a type of radioactive decay is which two protons are simultaneously transformed into two neutrons or vice versa. This process also results in the emission of two neutrinos denoted by ν

in the diagram above.

β Beta Decay	n (0)	$\rightarrow$	p (0)	+	e^- (1)	+	$\bar{\nu}$ (-1)
2β Double Beta Decay	2n (0)	$\rightarrow$	2p (0)	+	$2e^-$ (2)	+	$2\bar{\nu}$ (-2)
$0\nu2\beta$ Neutrinoless Double Beta Decay	2n (0)	$\rightarrow$	2p (0)	+	$2e^-$ (2)		

Figure 6:
Lepton number comparison between Beta, Double Beta, and Neutrinoless Double Beta Decay

In neutrinoless double beta decay, the reaction emits a neutrino and antineutrino which annihilate each other. This results in two extra leptons on the right side of the reaction, which can be seen above [6]. Neutrino/antineutrino annihilation intuitively makes sense because of particle duality. However, if neutrinos are Majorana, neutrinos and antineutrinos are the same particle. The idea of annihilation suddenly becomes hazy. How can a neutrino annihilate itself?

2.3 Context to CUORE

The relationship between neutrinos and their antiparticles is what CUORE aims to investigate. As seen above, if observed, neutrinoless double beta decay will violate lepton number conservation [12]. Observing the two excess leptons in the product of neutrinoless double beta decay will showcase asymmetry in an otherwise very symmetric universe [9]. Asymmetry between leptons and antileptons is referred to as ”leptogenesis”. Leptogenesis will demonstrate a universal preference toward particles, rather than antiparticles. In a larger picture (literally), physicists speculate that observation of neutrinoless double beta decay could give insight into why there is so much more matter than antimatter in the universe.

3 Experiment

3.1 How to Detect $0\nu\beta\beta$

When nuclear reactions occur, a minute amount of energy is released into the surrounding environment. Neutrinoless double beta decay is no different. This release of energy translates to a slight temperature increase, which can be converted to an electrical signal using a thermistor (a temperature dependent resistor). As the temperature around the thermistor changes, so does its resistance. Essentially, CUORE's goal is to observe a change in resistance that is converted to a change in temperature which correlates to the theoretical process of neutrinoless double beta decay.

To do so, CUORE uses a cryostat and a bolometer. A bolometer is a highly sensitive electrical instrument for measuring radiant energy. The bolometer at CUORE is made of ulta-cold tellurium dioxide (TeO_2) crystals containing the candidate isotope ^{130}Te. ^{130}Te is just one of many candidate isotopes thought to undergo the process of neutrinoless double beta decay. This particular isotope is chosen for its radio purity, excellent energy resolution, and relatively easy accessibility.

A cryostat controls the temperature of a system and can be reduced to just a few thousandths of a degree above absolute zero through a very long and complicated cooling process. For reference, absolute zero is equivalent to -459.67 degrees Fahrenheit! Since the energy emission of a single nuclear process, and thus the corresponding change in temperature, is so small, the experimental strategy at CUORE is to place the crystals in an environment with ideally zero thermal energy. When the crystals theoretically undergo $0\nu\beta\beta$, the change will be very apparent because of its "energy-less" surroundings.

3.2 Cuoricino and CUORE-0

The buildup to the experimental phase of CUORE has been a long journey. Before CUORE there was CUORE-0, and before that there was Cuoricino. Cuoricino was the first large-mass array of $^{130}\mathrm{Te}$ crystals, holding 62 of them arranged into 13 floors for a total mass of 40.8 kg. Cuoricino's largest contribution was setting a very limit on the half-life of ^{130}Te. More importantly, Cuoricino as a bolometric detector paved the way for CUORE-0. Cuoricino runs found that background noise in the apparatus was dominated by decay from contaminants in the copper structure that held the crystals. CUORE-0 set out to improve this.

CUORE is LNGS' response to everything that Cuoricino lacked. Cuoricino had one tower; CUORE has 19. Data was taken when the first of those 19 towers was installed in the CUORE cryostat. This was CUORE-0. As mentioned above, background noise from the copper structure on Cuoricino obstructed the data quite a bit. To combat this, the structure was redesigned so that less material was used. Additionally, more thorough cleaning techniques were used on the new copper. Perhaps the largest contribution from CUORE-0 however, was the newly designed tower construction system. A semi-robotic and semi-manual assembly procedure was developed to preserve cleanliness and improve uniformity of the towers. The results: background was reduced by a factor of 6, and the crystals showed better resolution. Although CUORE-0 found no evidence of $0\nu\beta\beta$, it did set the lower limit half-life to be $4.0\text{x}10^{24}$ yr [13].

The team was ready for CUORE.

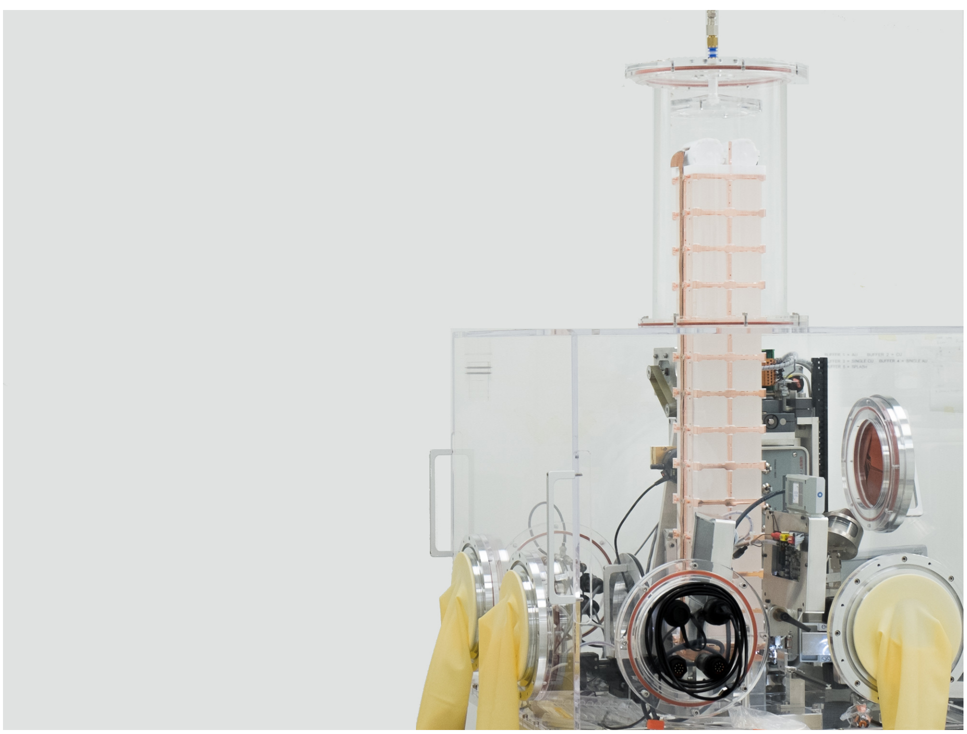

Figure 7: Semi-robotic and semi-manual tower assembly procedure

3.3 CUORE

CUORE is CUORE-0 on a much larger scale. At a total mass of 1-ton, the CUORE detector holds an array of 988 TeO_2 crystals featuring 19 towers. These towers were assembled using the same semi-robotic and semi-manual assembly procedure as CUORE-0. This is the largest bolometric mass every operated and will create the coldest cubic meter in the known universe. This a daunting fact.

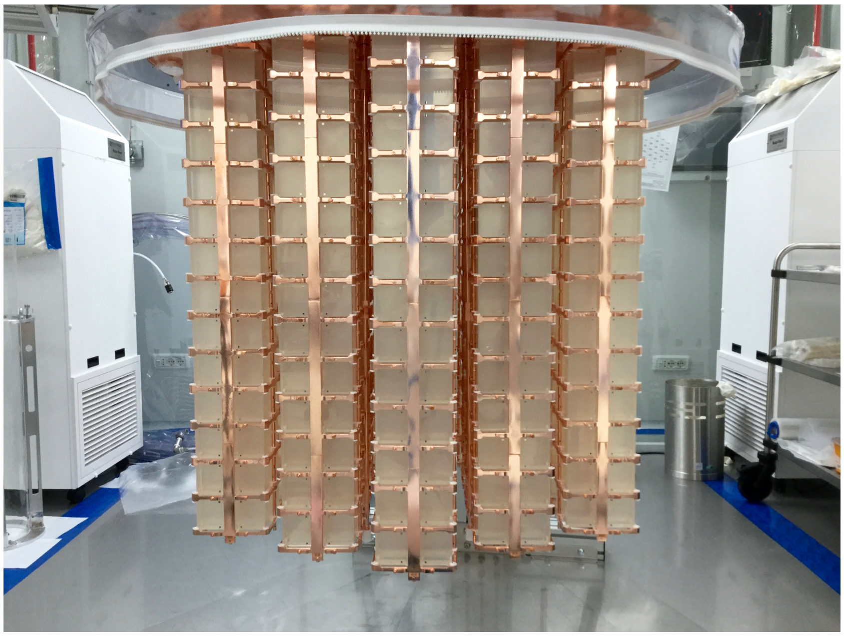

Figure 8: Te Towers

The 19 towers are arranged inside the cryostat in a tightly packed array. This cryostat is the largest and most powerful helium dilution refrigerator ever constructed. Cooling the system works in stages. First the system is cooled to a few degrees above absolute zero using pulse tube cryocoolers. Most cryostats cool their systems using liquid helium or liquid nitrogen. The downside of this method is the boil off over long periods of time. Pulse tube cryocoolers were used in this case so the towers can stay cold over a period of years.

The second stage of cooling brings the temperature down to a few miliKelvin. To do so, CUORE takes advantage of the unique properties of the two isotopes ^{3}He and ^{4}He. At very low temperatures these two isotopes cannot be mixed, similar to the behavior of oil and water. This separation creates two phases: the dilute ^{3}He phase and the ^{4}He concentrated phase. A pump outside the cryostat pulls ^{3}He across the boundary of separation from concentrated to dilute. Doing so absorbs energy, cooling down the system even further. The ^{3}He then returns to the concentrated phase to repeat the process.The cryogenic system is covered with several tons of copper and lead shielding to reduce background radiation.

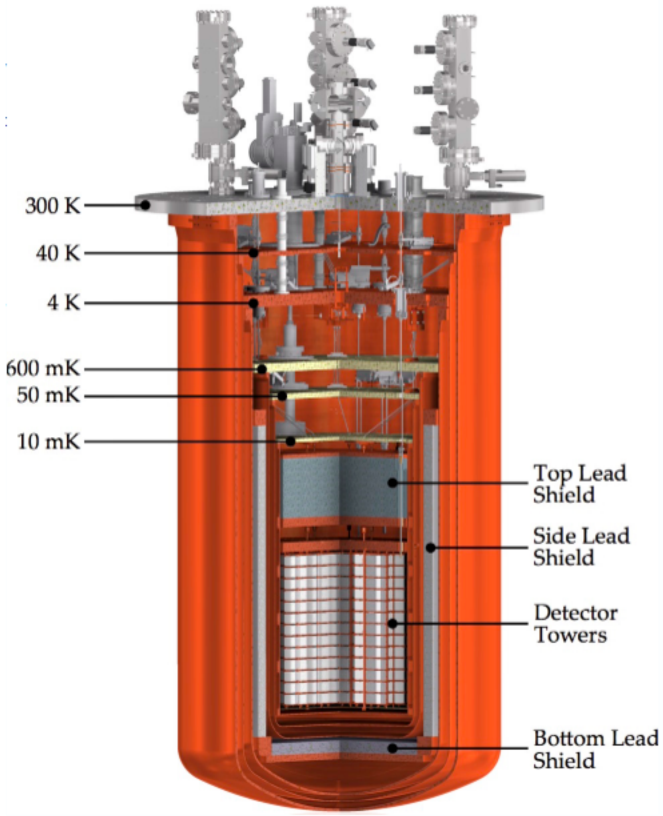

Figure 9: Side-view of the CUORE cryostat

3.4 Onsight Shifting During Installation

California Polytechnic State University, San Luis Obispo contributed to the CUORE project during the summer of 2016 by sending four students to fill onsight shifting positions for seven weeks during the tower installation phase of the experiment.

CUORE is housed in an underground facility with a series of seven cleanrooms: CR1, CR2, CR3, etc. The actual experiment takes place in CR7. These seven cleanrooms are monitored very closely using cameras multiple sensors. The onsight shifter's responsibility is to supervise one of the most critical phases of the experiment by monitoring these cameras and sensors. Below is the monitoring control desk. Everything that the shifter needs is on those two computer screens. The screen on the left shows alarms, cameras, and is used to communicate with the installation team below. The screen on the right allows the shifter to check parameters.

Figure 10: Monitoring Team Control Desk

The parameters monitored during installation are: CUORE Radon Abatement System Status, GERDA Radon Detector Level, Air sampling from CR6, UPS and Water Cooling Power Status, Air Cleanliness, and LN2 Level. Five of the six critical parameters are displayed on the Central Monitoring VI on the left screen. If any one of these indicators flash red, something is wrong with the experiment. The onsight shifter's responsibility is to report this to the appropriate person as soon as possible.

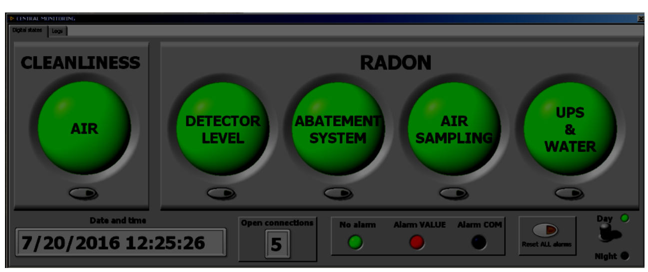

Figure 11: Central Monitoring VI

As with any experiment, there is no simple solution when an alarm goes off. For an Air Cleanliness, the fix could be as simple as closing the lab door properly. Conversely, an Abatement System alarm could have five possible solutions. Here is a general guide for the first four alarms taken straight from the shifting manual.

AIR (cleanliness)

Cause: The level of dust in the CR6 is too high.

Description: The particle counter devices, setup in CR6, is registering a level of ?dust? too high.

What to do: Warn the Support Team and contact the responsible. CHANGE?

DETECTOR LEVEL (Radon detector). Extremely critical

Cause: The level of radon content in CR6 too high

Description: The GERDA Radon monitor has registered (in its last time window) a level of Radon, in the CR6, too high.

What to do: Warn urgently the installation team (CR7 operation should start as soon as possible), the support team, the responsible and contact Radon System Expert(s) [David Biar or Giovanni Benato].

ABATEMENT SYSTEM

Cause: Something goes wrong at the Radon System level.

Description: Parameter(s) of the Radon System are currently out of range(s). The air supply by the Radon System toward CR6 could still be fine.

What to do: warn the responsible, contact Radon System Expert(s) [David Biar or Giovanni Benato] and check very closely the Radon level in CR6.

AIR SAMPLING

Cause (most probable): At GERDA ground floor level, the pump or the MFC are be in default.

Description: The air flow from CR6 to GERDA monitor is currently inadequate (too low). The GERDA Radon monitor is not able to measure properly any content Radon in the air from CR6 anymore. The Radon content in the CR6 could still be fine, we just do not have any information about it.

What to do: Warn the responsible and contact Radon System Expert(s) [David Biar or Giovanni Benato].

As for the cameras which are also on the left computer screen, the shifter can remotely control the cameras in CR5 from the monitoring desk. This is useful to see what stage of the installation the team is performing. For example, sometimes the Air Cleanliness alarm would sound when researches left and entered CR6. Rather than reporting every alarm, the shifter can use the cameras to check this when alarm sounds and conclude that there is no cause for concern.

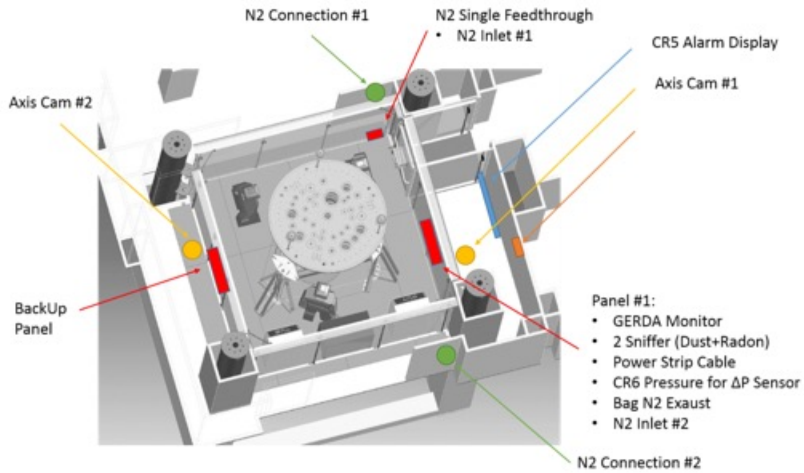

Figure 12: CR6 Equipment

On the right computer screen is the LabView interface for monitoring radon levels, air sampling charts, and particle counters. Here are some examples of the graphs that the shifter analyzes. Any spikes in this data usually is usually reported.

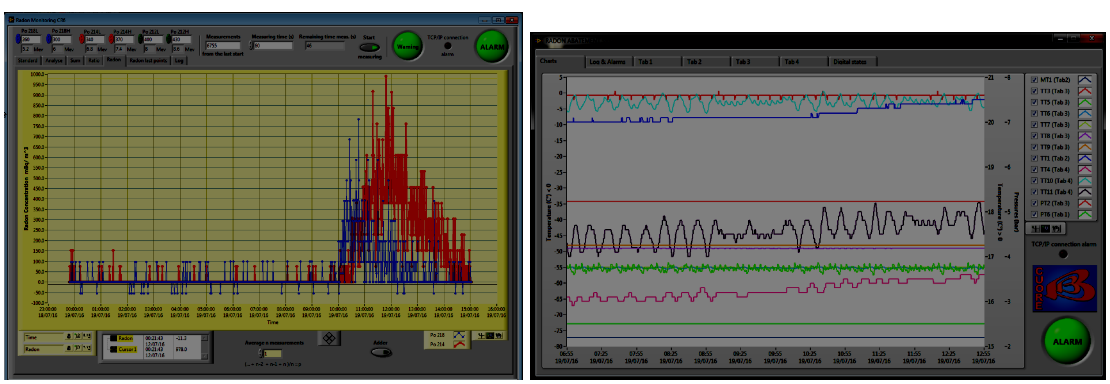

Figure 13: Radon, Abatement System, and Particle Counter Charts

3.5 Moving Forward

The future of CUORE is bright. It is expected to beat CUORE-0's unprecedented lower limit of half-life within just the first two months of running! In addition, CUORE will have a half-life sensitivity of $9.5\text{x}10^{25}$ yr at a 90% confidence level, further surpassing CUORE-0 [14].

4 Conclusions

CUORE is a true testament to the power of scientific ingenuity and international collaboration. When brilliant minds from all over the world come together, the product is groundbreaking science. Creating the coldest cubic meter in the known universe is an incredible feat, yet that is just one of the many records that CUORE broke. Today's CUORE is setting the standard for nuclear research. Having to opportunity to be a part of this international effort is humbling and a privilege.

Traveling to Italy to contribute to this experiment facilitated growth not only as a physicist but also as a human being. I learned what it takes to earn a doctorate in physics. I dove deep into a field of physics that I never knew existed. I observed first hand the diligence required to practice ”good” science. By living with scientists and working at a national lab, I was surrounded by infinite bounds of knowledge and wisdom from all around the world. As for growth as a human being, I gained confidence in my own capabilities. I traveled throughout Italy by myself. I made Italian friends who do not speak English. I dedicated six weeks of my life to an opportunity of a lifetime.

CUORE's first data runs are soon to be analyzed. This is a highly anticipated milestone for the collaboration. I, along with the rest of the scientific community, cannot wait.

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