My Contributions to the Cryogenic Underground Observatory for Rare Events Experiment And the Utilization of Geant4 in Their Analysis

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Approval Page

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Acronym	**Meaning**
N	Newtons
J	Joules
s	Seconds
K	Kelvin
y	Years
kg	Kilograms
ev	Electron Volts
$\hbar$	Planck's Constant
$\hbar/2\pi$	Reduced Planck's Constant
Q	Phase Space Variable
W^-	Negative W Boson
W^+	Positive W Boson
Z^0	Z Boson
n^0	Neutron
p^+	Proton
e^-	Electron
e^+	Positron
ν	Neutrino
$\bar{\nu}$	Anti-Neutrino
He^2	Helium-2 Isotope
He^3	Helium-3 Isotope
TeO_2	Tellurium Dioxide
QFT	Quantum Field Theory
CUORE	Cryogenic Underground Observatory for Rare Events
LNGS	National Laboratory of Gran Sasso
GERDA	The Germanium Detector Array
LUNA	Laboratory for Underground Nuclear Astrophysics
LHC	Large Hadron Collider
ATLAS	A Toroidal LHC Apparatus
HARP	Hadron Production Experiment
ROI	Region of Interest

Table 1: Acronyms

Abstract

First, a brief introduction and background of the basics of particle physics and the Standard Model is discussed in order to give context to nature of the neutrinoless double beta decay ($2\nu\beta\beta$) and why it is so interesting to particle physicists. Next, the Cryogenic Underground Observatory for Rare Events (CUORE) experiment is discussed in detail, explaining the rational behind the experimental setup and detection process. Finally, I conclude by discussing Geant4, an important software toolkit used in particle physics, and how it is utilized in the CUORE experiment.

1 Introduction

1.1 Particles and Antiparticles

The universe as we know it is made up of sub-atomic particles. These particles have intrinsic quantities unique to them that allow them to be identified with respect to other particles. Some of these quantities include a mass (and therefore energy), electric charge, color charge, spin, lepton number, and more. There are two primary types of sub-atomic particles that are differentiated by their intrinsic spin: fermions and bosons. Fermions are particles that have an intrinsic spin that is an integer multiple of $\frac{1}{2}$ ($\frac{1}{2}, -\frac{1}{2}, \frac{3}{2}, etc.$). Bosons are particles that have an intrinsic spin that is an integer multiple ($0, -1, 1, etc.$). These differences in intrinsic quantities leads to different behaviors, which will be discussed later in this section. It is also crucial to mention that these particles must obey certain conservation laws in order to interact properly with one another.

It is necessary to point out that "[f]or each kind of particle, there is an antiparticle that shares essentially all the properties of the particle except that it is of opposite charge" [1]. An example of a particle and antiparticle pair would be the electron and positron. Antiparticles are actually theorized from relativistic quantum mechanics and arise from the Dirac equation. Below is the 1-D Dirac Equation for a free particle [1]:

$$(i\hbar\gamma^{\mu}\partial_{\mu} - mc)\psi = 0 \tag{1}$$

where $\hbar$ represents the reduced Planck's constant ($\frac{h}{2\pi}$) in $J \cdot s$, γ^{μ} represents the 4 by 4 gamma matrix, ∂_{μ} represents the time and spatial derivative operator, m represents the particle mass in kg, c represents the speed of light in m/s, ψ represents the wave function, and i is the constant $\sqrt{-1}$. By generalizing the Schrödinger equation and including relativity and spin, we obtain Eq.(1), and it becomes apparent that positive and negative energies are allowed as solutions. What does negative energy mean? One interpretation is that an antiparticle state can be seen as a single unoccupied negative energy state in a 'sea' of filled negative energy states. This new conception of an antiparticle can help us understand how particles with no charge may also have their own antiparticle, such as the neutrino.

1.2 The Standard Model and The Neutrino

The Standard Model is a model developed in particle physics that details the primary particles involved in mediating the fundamental electroweak, and strong force interactions. Gravity is also considered one of the fundamental forces, but is excluded in the definition of the Standard Model as no particles have been found that mediate it. The Standard Model focuses on the particle physics we know and understand currently. In order to better understand the Standard Model, its important to introduce QFT. QFT describes two primary classes of particles in the universe; particles that experience a force (fermions), and particles that manifest as the force itself (bosons) [1].

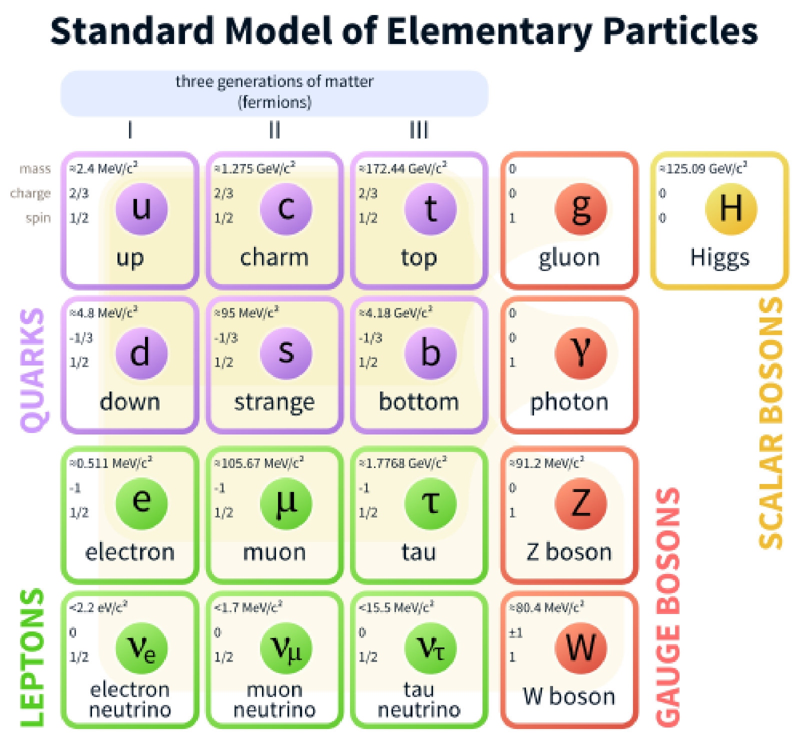

Figure 1: A graphic that shows the fermions (columns $1 - 3$) and bosons (columns $4 - 5$) that make up the Standard Model [2]

Referring to Figure (1), the first three columns represent the three generations of fermions (from lightest to heaviest from left to right). These three columns are broken up into quarks (purple) and leptons (green). The primary difference between these two is that quarks can interact via the strong force (as well as the electroweak and gravity) but leptons cannot. Quarks are able to interact with the

strong force because they possess an intrinsic quantity known as color charge, which can manifest as red, green, blue, anti-red, anti-blue, and anti-green. Because of this strong force interaction, quarks have the ability to combine and create other particles known as hadrons. An important branch of hadrons are the nucleons, which are the protons and neutrons that make up the nucleus of the atom. These particles interact via the bosons in the fourth column, which mediate the forces between the quarks and hadrons. These bosons are constantly being exchanged between fermions. Gluons (g) primarily mediate the strong force, while photons (γ), W^-, W^+, and Z^0 mediate the electroweak force. The electromagnetic part'[1] of the electroweak force is mediated by a virtual[2] photon (γ) that is massless, while the weak 'part' is mediated by W^-, W^+, and Z^0 which have varying masses [1]. Figure (2) shows a couple of Feynman diagrams in order to illustrate these interactions. The fifth column consists solely of the Higgs Boson, which is responsible for generating the mass of sub-atomic particles [4].

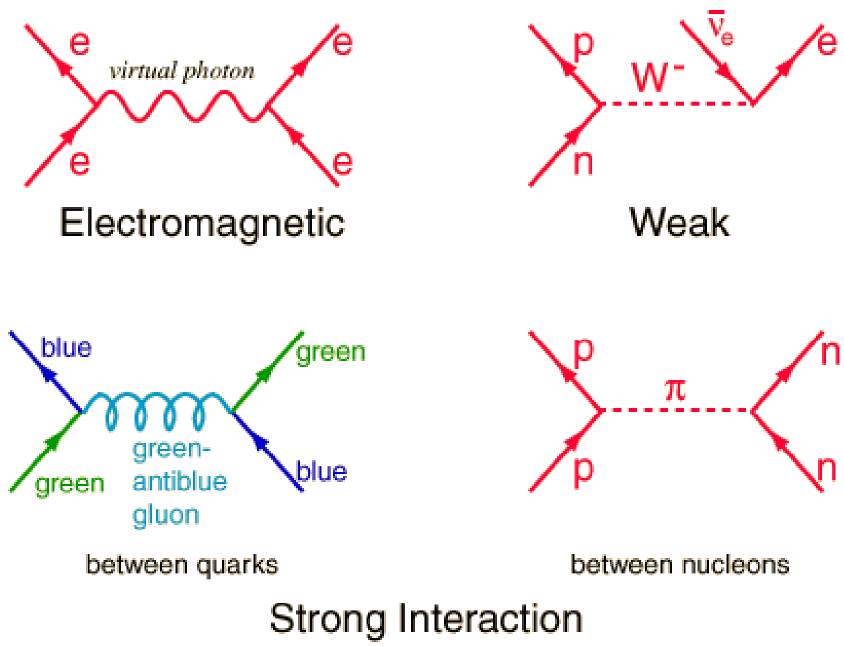

Figure 2: Examples of a couple of Feynman diagrams for different force interactions [3].

An interesting feature of the Standard Model is the neutrino (ν). Neutrinos were first theorized by

[1] for lack of a better descriptor

[2] "Mediating particles do not obey the usual momentum and energy rules in the way that 'real' particles do, and for this reason, the particles exchanged to convey force are known as **virtual particles**"[1].

Wolfgang Pauli in 1931 after studying the $\beta-$ decay and recognizing a violation of energy conservation [5]. At the time, only the proton (p^+) and electron (e^-) were observed from the decay; the energy signature of the electron antineutrino ($\bar{\nu_e}$) was too minuscule to be detected by the instrumentation. It wasn't until the $1950's$ that the $\bar{\nu_e}$ was discovered by Clyde Cowan and Fred Reines [6]. Later in the $1960's$, solar neutrinos were detected by Raymond Davis Jr. and others [10]. Inside the sun, ν are generated through proton/electron collisions, which only generates ν_e.

$$p^+ + e^- \rightarrow n^0 + \nu_e \tag{2}$$

However, the other flavors of neutrinos (ν_μ, and ν_τ) were theorized [10] but still undetected. It wasn't until much later in the late $1990's$ and early $2000's$ that neutrino flavor oscillations[3] were successfully detected, proving the existence of these neutrinos [11, 12]. These neutrino oscillations gave evidence that the neutrinos have mass, however the exact mass is currently unknown [9]. There is significant research being done currently in neutrino physics to help answer this question [13].

1.3 The Neutrinoless Double Beta Decay

An important decay in particle physics is the double beta ($2\nu\beta\beta$) decay [9].

$$2\, n^0 \rightarrow 2\, p^+ + 2\, e^- + 2\, \bar{\nu_e} \tag{3}$$

This decay is two $\beta-$ decays that occur at the same time, and has a decay rate of $\tau \geq 10^{18}$ y [9]. This decay isn't simply two decays that happen simultaneously; this happens when the decay puts the nucleus into a more favorable energy state. It is important to recognize that Eq.(3) conserves a special quantity known as the lepton number. Leptons (such as the ν_e) have a lepton number of 1, while antileptons (such as the $\bar{\nu_e}$) have a lepton number of -1[8]. All physics experiments thus far confirm the conservation of the lepton number in particle interactions. Cowan and Reines were the first to take note of this [8]. This explained why reactions like Eq.(4) were observed, while reactions like Eq.(5) were not.

$$\bar{\nu_e} + p^+ \rightarrow n^0 + e^+ \tag{4}$$

$$\bar{\nu_e} + n^0 \rightarrow p^+ + e^- \tag{5}$$

[3] A flavor oscillation is simply $\nu_\alpha \rightarrow \nu_\beta$, where α and β represent different flavors of neutrino. [9]

However, in theoretical physics, there is a reaction known as the neutrinoless double beta ($0\nu\beta\beta$) decay with a decay rate of $\tau \geq 10^{25}$ y [9].

$$2\,n^0 \rightarrow 2\,p^+ + 2\,e^- \tag{6}$$

This decay is called neutrinoless because the electron pair gains (kinetic) energy that is usually reserved for the neutrinos.

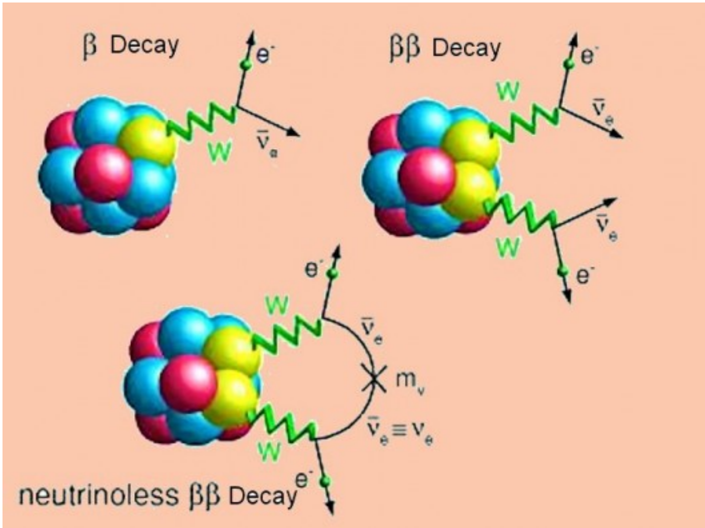

Figure 3: A diagram of a $\beta-$ decay (top left), a $2\nu\beta\beta$ decay (top right), and a $0\nu\beta\beta$ decay [14]

If this decay is detected, than it would disprove lepton conservation, give an absolute mass to the neutrino, and prove that the neutrino is actually its own antiparticle [9, 13]. If detected, this would require changes to the Standard Model, one of the fundamental cornerstones of contemporary particle physics.This extremely rare decay is highly sought after in particle physics. Multiple experiments are being conducted to measure this decay, and one experiment has even claimed to discovered it[4] [15].

2 CUORE

2.1 National Laboratory of Gran Sasso

CUORE (Cryogenic Underground Observatory for Rare Events) is a lab located in Assergi, Italy at the National Laboratory of Gran Sasso (LNGS). There are two locations associated with LNGS; above

[4]Though the claim is controversial.

Figure 4: Beautiful picture of the above ground offices (white buildings at the bottom) at the base of Gran Sasso [17].

ground office spaces located near the Assergi village and at the base of the Gran Sasso[5], and below ground laboratories where multiple experiments are conducted, including CUORE[6].

[5]Gran Sasso is a beautiful national park mountain range near the Assergi Village [17]

[6]There are many different experiments such as GERDA, LUNA, DarkSide50, and more [16]

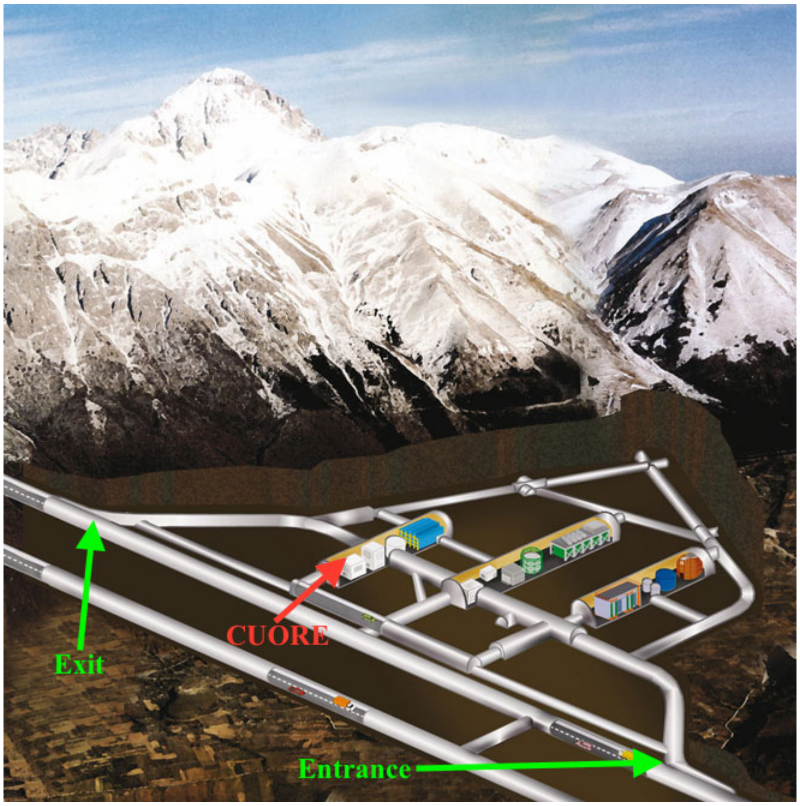

Figure 5: A diagram of the below ground lab, imbedded underneath the Gran Sasso mountain range [18].

The purpose of this experiment is to detect the $0\nu\beta\beta$ decay via super cooling of a cubic meter of TeO_2 crystals [16]. TeO_2 crystals are used because ^{130}Te is one of several elements theorized to experience the $0\nu\beta\beta$ decay [13], and a plethora of crystals are used to increase the chances of detecting the decay [20, 21, 22]. Detectors are set to record the energy of the particles emitted in the decay. The fact that the lab is underneath a large mountain mass is pertinent to the neutrino experiment. Cosmic rays are constantly colliding with and moving throughout the Earth at any one time, any of which can collide with the detector and smear the experimental readings. The large amount of mountain mass prevents particles from interfering with the CUORE experiment. However, background readings are still captured as a perfect experimental setting is impossible in principle. Therefore extreme care is taken with respect to the purity of the TeO_2 crystals, and the set-up and execution of the CUORE experiment to ensure maximum accuracy. Further elaboration on the CUORE experiment and the equipment used is detailed in the following section.

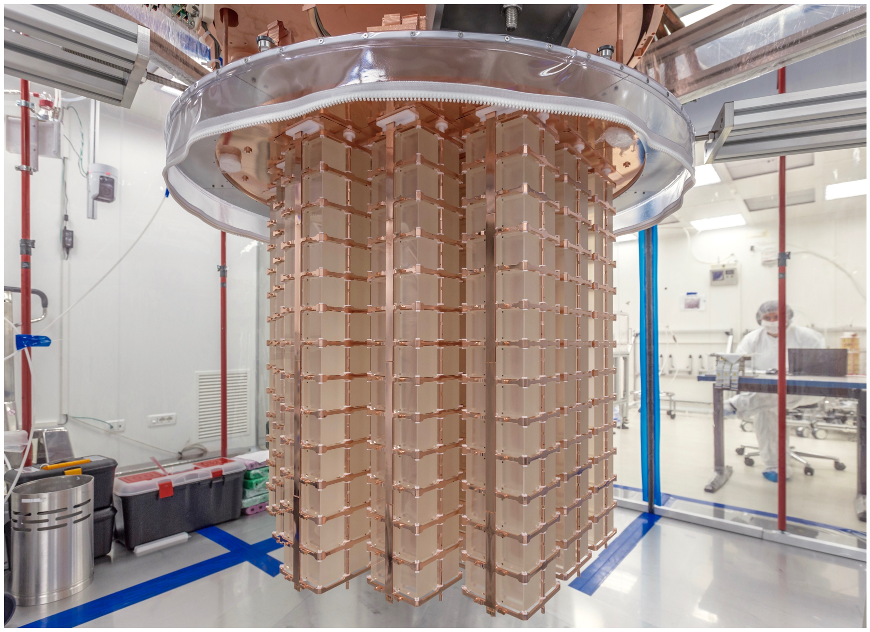

Figure 6: The TeO_2 crystals organized in a cubic meter [19]. All the towers are connected to a plate known as the tower support plate (TSP), which is connected to the cryostat.

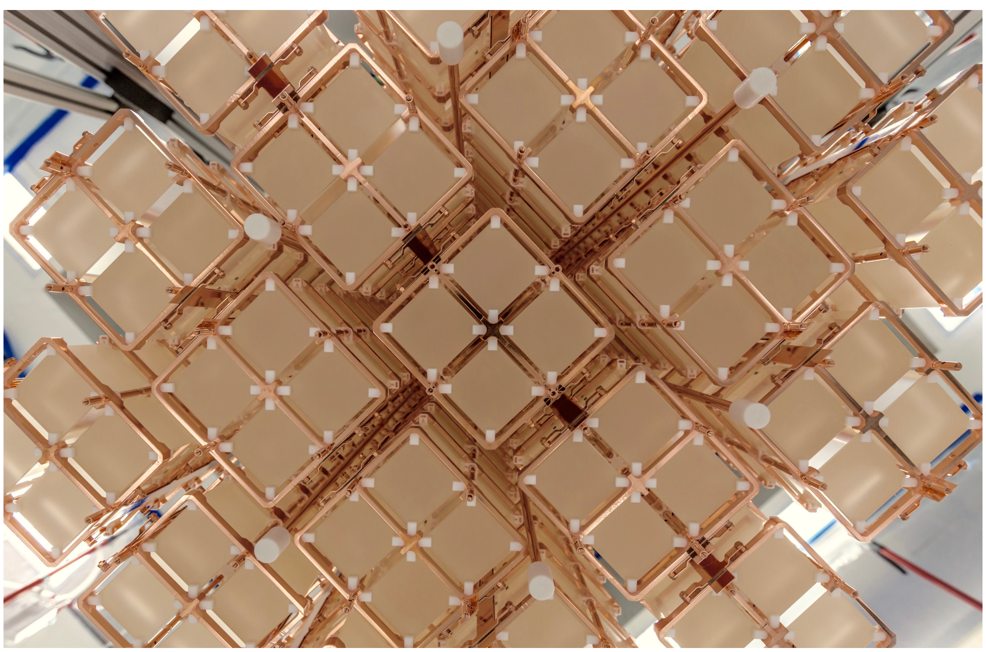

Figure 7: Looking at the towers from below [19].

2.2 Detecting the $0\nu\beta\beta$ Decay

The particle detectors used for CUORE are known as bolometers [9, 19]. A bolometer is a detector typically made out of the material that is being observed[7] that can measure the energy of a particle through calorimetry. Calorimetry is the amount of heat exchanged between a well-defined system and its surroundings. The system in this experiment will be the particles undergoing the $0\nu\beta\beta$ decay, and the surroundings encompass the rest of the particles in the system. When any event occurs (not just the $0\nu\beta\beta$ decay), the particles emitted have kinetic energy. When these particles collide with other nearby particles, the moving particles impart their energy to the (essentially) fixated TeO_2 crystal. This imparting of energy results in a very minute temperature increase that is picked up from a thermal sensor[8] (See the NTD Germanium Sensor on Figure(8)).

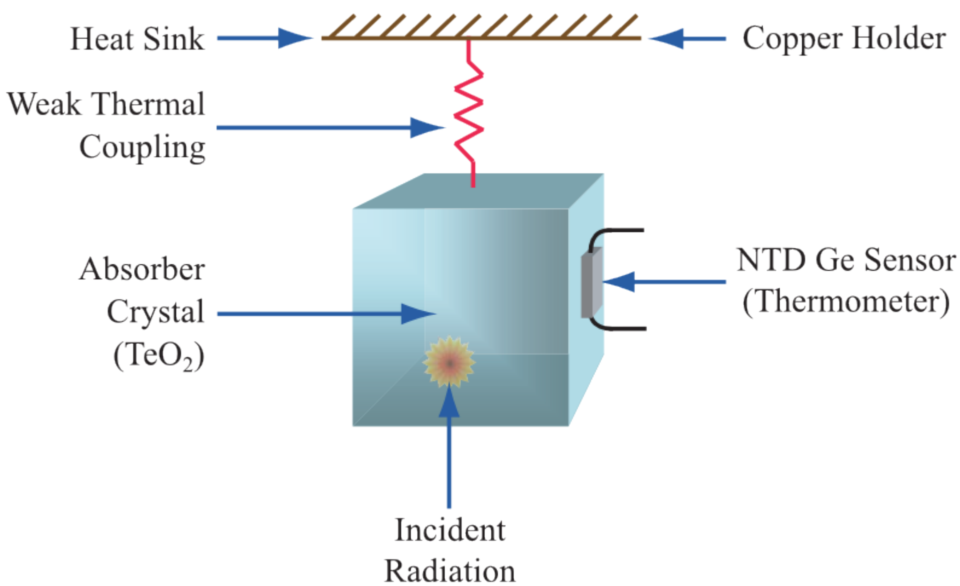

Figure 8: A schematic of a bolometeric detector [19].

Since the change in energy is extremely minute, the crystals must be super cooled in order for this change to be recognizable[9]. Therefore, one of the largest cryostats in the world is used in order to ensure

[7]This gives us great energy resolution and efficiency when conducting the experiment [9].

[8]This thermal sensor is a resistor that is changes resistance based on temperature. The electrical signals are sent from the TeO_2 crystal and converted into a temperature

[9]In thermodynamics, it is shown that lowering the temperature near absolute zero decreases the specific heat of the material, which allows small energies to be recognizable.

the cubic meter of TeO_2 crystals reach a temperature of 10 mK (10^{-2} K). This is achieved via exploiting the properties of ^{3} He and ^{4} He at very low temperatures. At very low temperatures, these two isotopes of helium cannot be mixed together and always separate into two distinct phases of ^{3} He and ^{4} He[10]. A pump is used to push the ^{3} He into ^{4} He; an endothermic process designed to absorb energy from the surroundings and therefore decrease the temperature. The ^{3} He moves back into its phase, and the process is restarted until the desired temperature is reached [19].

The next problem is, how do we know when the event has occurred? Figure (10)[11] shows a graph of the energy of the electron pair emitted in the $2\nu\beta\beta$ decay. If the decay happens, then we would expect the red peak to appear in our readings. However, since the decay is so rare, not many counts would be recorded, making it increasingly difficult to distinguish it from random background counts. This is the main criticism of *Allen, S. W., et al.* (2003) [15], where it was argued that their $0\nu\beta\beta$ peak was an actual peak and not just background readings. This results of this paper are still controversial. CUORE is taking considerable measures to make sure that the energy readings are legitimate evidence of the $0\nu\beta\beta$ decay.

2.3 My Contribution to CUORE

The large cryostat and cubic meter of TeO_2 crystals are stored at the underground lab in a 3-story structure known as the CUORE hut. The first floor contains miscellaneous tools and other equipment important for the running of the cryostat. The second floor contains a couple of rooms known as "clean rooms". These "clean rooms" are special rooms that are cleaned constantly for any bacteria or particulates, as these rooms are where the TeO_2 crystals are stored[12]. Established protocol requires that any person that enters these rooms must wear a disposable plastic clean suit, face mask, a couple pairs of gloves, goggles, booties and a hair net. Extra protocols are taken when people enter the main clean room that houses the TSP, as this is the primary location of where the experiment will take place once the installation phase of the experiment is complete. The TPS is covered with a large plastic container when nobody is working on it to ensure the TeO_2 crystals don't get contaminated. I was lucky enough to go into the second floor a couple of times, but never was I allowed into the primary clean room.

[10] Think about mixing water and oil; they always stratify into two distinct phases

[11] The Q variable on the x-axis is a parameter that is associated with the material we are looking for the decay in; for this experiment $Q_{Te} = 2528.8$ keV [9].

[12] Remember, the crystals must be as pure (uncontaminated) as possible for the experiment to work properly.

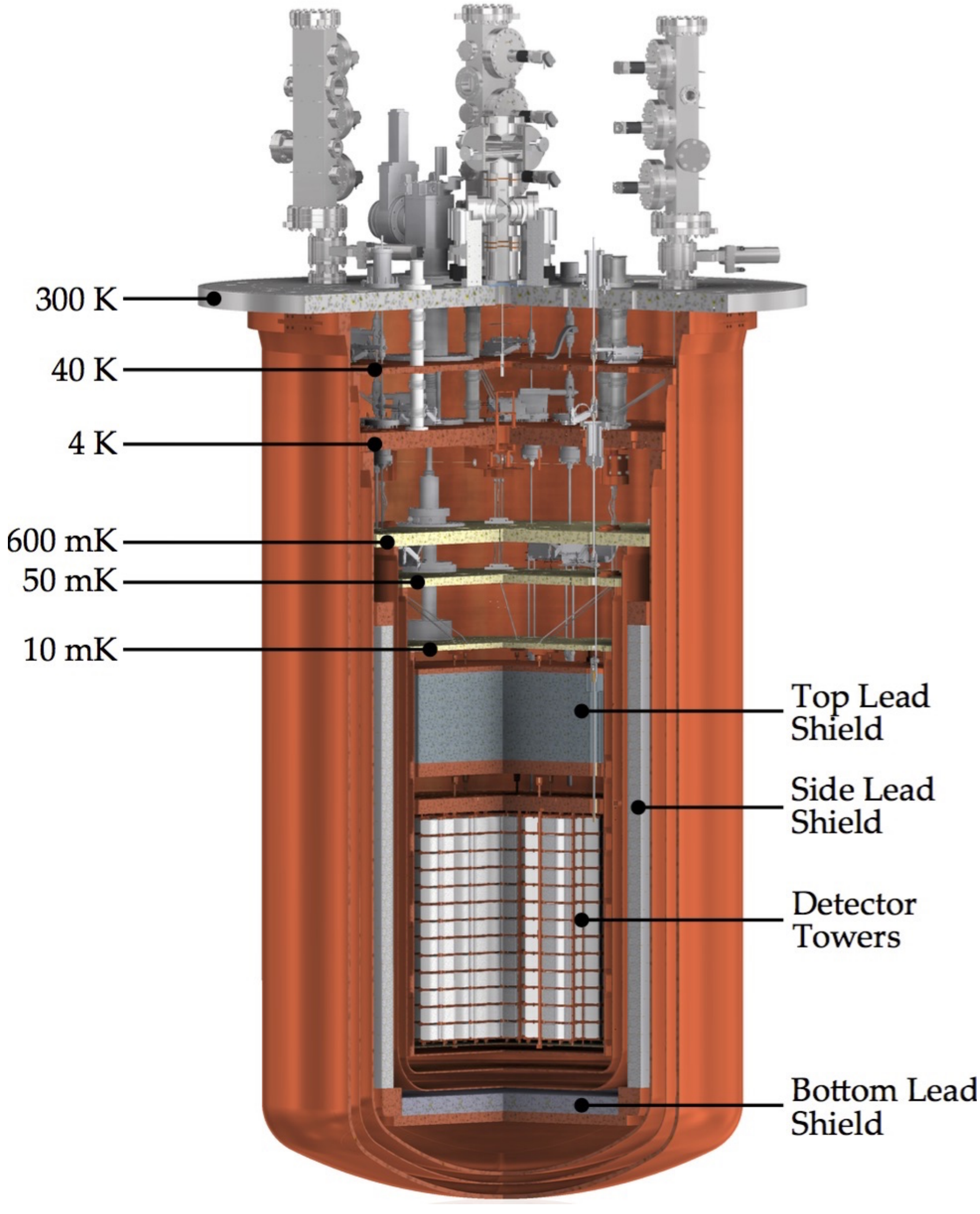

Figure 9: A diagram of the cryostat being used by CUORE [19].

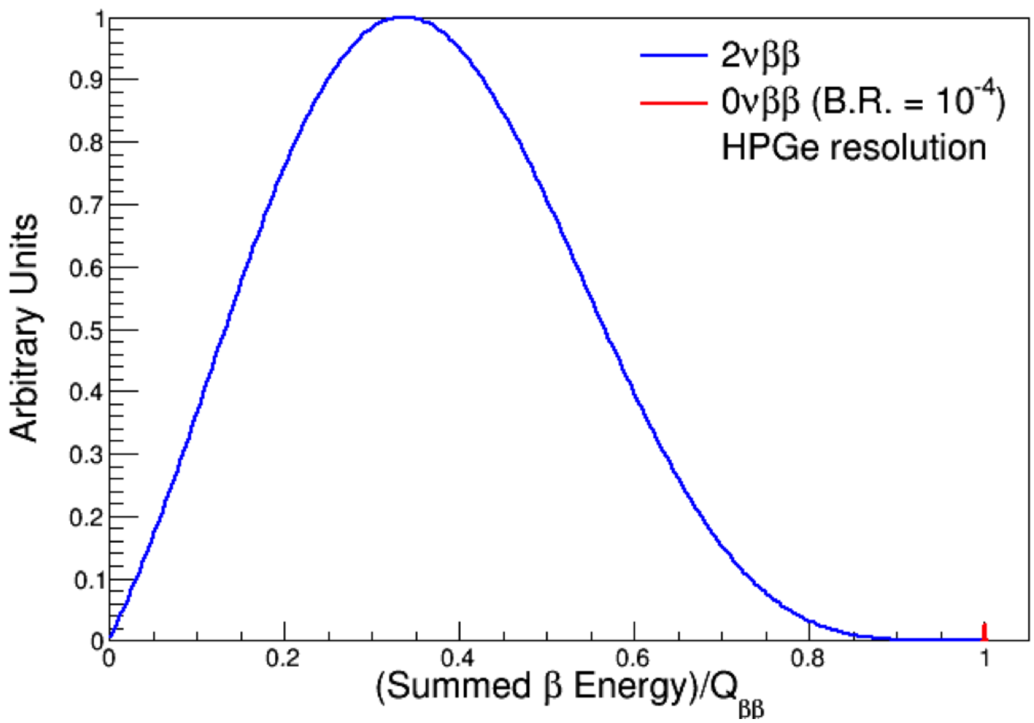

Figure 10: An energy spectrum that shows the smearing of the electron pair energy for the $2\nu\beta\beta$ decay (blue line), and the theoretical electron pair energy of the $0\nu\beta\beta$ decay [23] in an High Purity Germanium (HPGe) detector. The y-axis represents the amount of counts for that particular energy (x-axis).

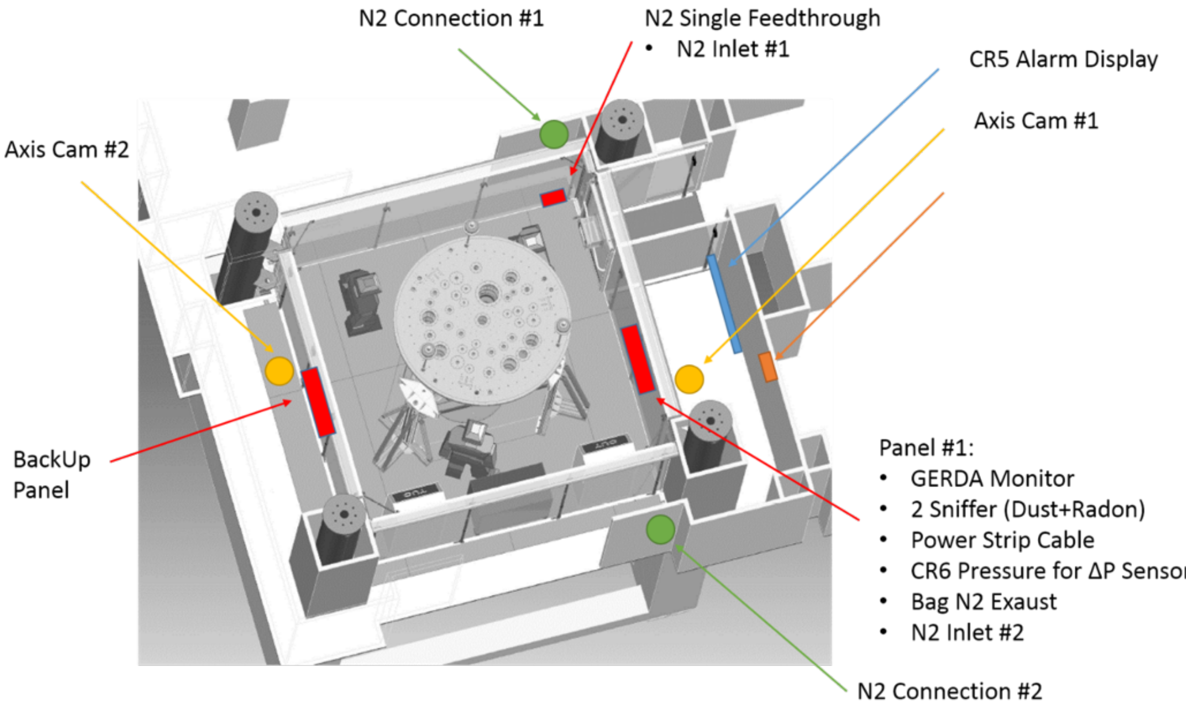

Figure 11: A diagram of the primary clean room where the TSP is located.

The third floor consists of many computers, the primary component of the large cryostat (Figure blank), and a desk with two computers that allow you to monitor the activities going on inside of the clean room. There is also a telephone that allows communication between people in the clean rooms and people on the third floor. This is where I primarily worked as the onsite shifter for the installation of the TeO_2 towers, which was an extremely important moment in the CUORE timeline[13].

[13]I stayed in Assergi, Italy for 6 weeks, from $8/5/16 - 9/18/16$

Figure 12: My partner Aaron Skyping with another collaborator, who is telling him how to fix a problem with the cryostat. This is on the third floor of the CUORE hut.

Before explaining a typical day as the onsite shifter, I would like to give a little background to the computer programs and sensors being run to keep this experiment operational. There are 5 primary parameters that are monitored via a LabView interface; air, detector level, abatement system, air sampling, and UPS (electrical power) and water.

The air parameter keeps track of the particle count in the main clean room. If there is too many particulates in the room, the alarm will go off. The detector level measures the amount of radon contaminate inside the main clean room. If there is a problem with the radon abatement system, then too much radon will leak into the room and set the alarm off. This is an extremely important parameter as it has the potential to not only ruin the experiment, but hurt/kill anybody thats inside the clean room.The abatement system parameter will go off, if an internal problem with the radon system itself is detected.

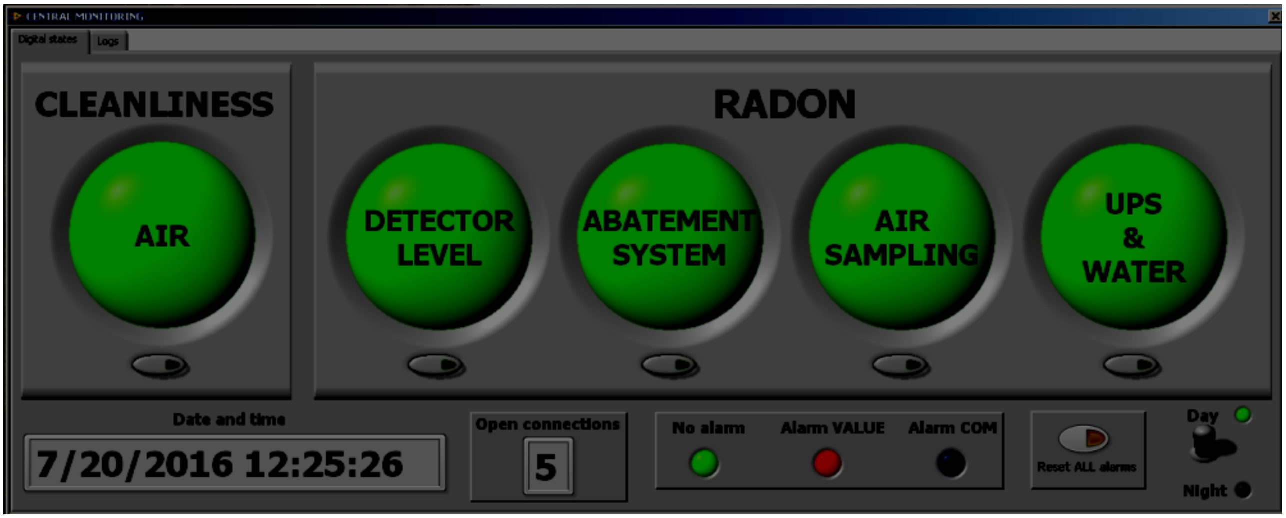

Figure 13: A screen shot of the 5 critical parameters [24].

If something wrong happened within the system, then large amounts of radon could leak into the room. Air sampling is another important parameter that measures the amount of air flow into the clean rooms. If there is a problem with air getting into the clean room, then this alarm will go off. Finally, there is the UPS and water parameter, probably the most important one of them all. If this alarm goes off then one of two scenarios has happened; the normal power went off and everything is operating on back up power[14], or the UPS system isn't working and regular power is still being supplied. The first incident is much scarier than the second, as there is approximately 15 minutes of back up power before the entire system stops working [24].

A typical day as onsite shifter consisted of arriving at the above ground lab at around 7:30 in the morning and taking a shuttle to the below ground lab, where I would arrive around 8:00. On my way to the CUORE hut, I checked the liquid nitrogen levels to make sure they weren't too low. If they were low, then I had to notify one of the collaborators at the above ground lab about it so they could begin to fix the problem[15]. Next, I had to make sure that the pumps that pump cooling water in and out were at their appropriate levels. If they were off, then there was a potential serious problem with the pump system, and I would have to notify one of the technicians so they could fix it. After this, I would go to the third floor of the CUORE hut. I had to keep a log of my actions throughout the day, and submit

[14]This actually happened when I was an onsite shifter. A very scary moment in the installation of these towers!
[15]This is a recurring theme, as I am an undergrad among doctorates and post-doctorates.

a small update on the work being done in the clean room hourly to an CUORE website that would be read by all collaborators to make sure everything was going smoothly. My first duty was to check the particle counter and take note of any spikes in particle counts that occurred over the night. Next, I set up Skype connections with the people getting ready to enter the main clean room, so I would be able to communicate with them instantly if anything went wrong. The installation team would go into the primary clean room around 9:00, and I would remotely control cameras into the room to watch them. I would take notes all day about what they were doing inside the room, as well as constantly making hourly updates on the website[16]. If any of the alarms went off, I was to first notify the workers in the clean room, then if the problem was serious enough, I would notify one of the experts at the above ground lab who would come to the below ground lab to diagnose the problem. At the end of the day, I had to upload footage from cameras inside the clean rooms[17] onto a website that showed these towers of TeO_2 being installed. This was only done for the tower installation, and stopped once the tower installation was complete. The purpose of this was to let other collaborators that weren't in the clean rooms to be able to double check the footage and verify that every action taken was done correctly and precisely. At the end of the day, I had to set the cameras to monitor the liquid nitrogen levels being pumped into the tower system, so that an offsite shifter[18] would be able to notify the onsite shifter if the nitrogen levels were off. I also had to submit a final hourly report that summarize what was done for the day, and any extra instructions for the offsite shifters to follow. Being accurate and precise was extremely important, as miscommunication could me ruining the entire experiment.

Another important job I had when I was not the onsite shifter was offsite shifter. There are 3 offsite shifters working 8 hour shifts everyday; when one offsite shifter is done, another takes their shift. The offsite shifter was to monitor the clean room via a website that showed Figure (13), as well as the views from the cameras, which would typically be on the liquid nitrogen levels, and the pressure of the plastic container encompassing the towers. If there was anything wrong with these parameters, the offsite shifter would call the onsite shifter and notify them of this problem. Most problems were easily solvable and as easy as resetting the radon abatement system. Other problems were much more complicated and required

[16]See Appendix A for my entire Onsite Shifter Log.
[17]These are not the same cameras that I was using to watch the installation team.
[18]The duty of the offsite shifter will be explained in the next paragraph

midnight trips to the underground lab to solve. Offsite shifters are required to check these parameters every 30 minutes in order to ensure that nothing bad is happening. Both of these jobs were integral to the success of the overall experiment, and I am proud to have been a part of it[19].

3 Geant4

3.1 What is Geant4?

Geant4 is a "free software package composed of tools which can be used to accurately simulate the passage of particles through matter" [25]. Geant4 allows for the construction of highly detailed experimental environments and detectors, and allows the user to shoot a myriad of particles at the detectors. The system tracks the particle, as well as documenting the various events that happen inside your simulated environment. All events are derived from verified physical laws and theories related to radioactive decay, particle parameters (such as spin, mass, lepton number, etc.), particle-particle interactions, and more. The user writes an executable file making calls to certain Geant4 functions that will develop the environment, detector, and particles being shot at the detector. The large amount of functions allow you to construct complex and unique geometries for the detectors and other materials, and determine what materials they're made of, allowing people to test any type of experimental setup imaginable. When you execute the file, Geant4 lists all the events that occur during the current simulation, and plots the trajectories and events in a graphics window. Figures (14, 15, and 16) outline a Geant4 simulation I ran. The simulation I ran is simply utilized as a learning tool, and is not related to the CUORE research.

[19]To see pictures from my trip to Italy, as well as the labs themselves, see Appendix B

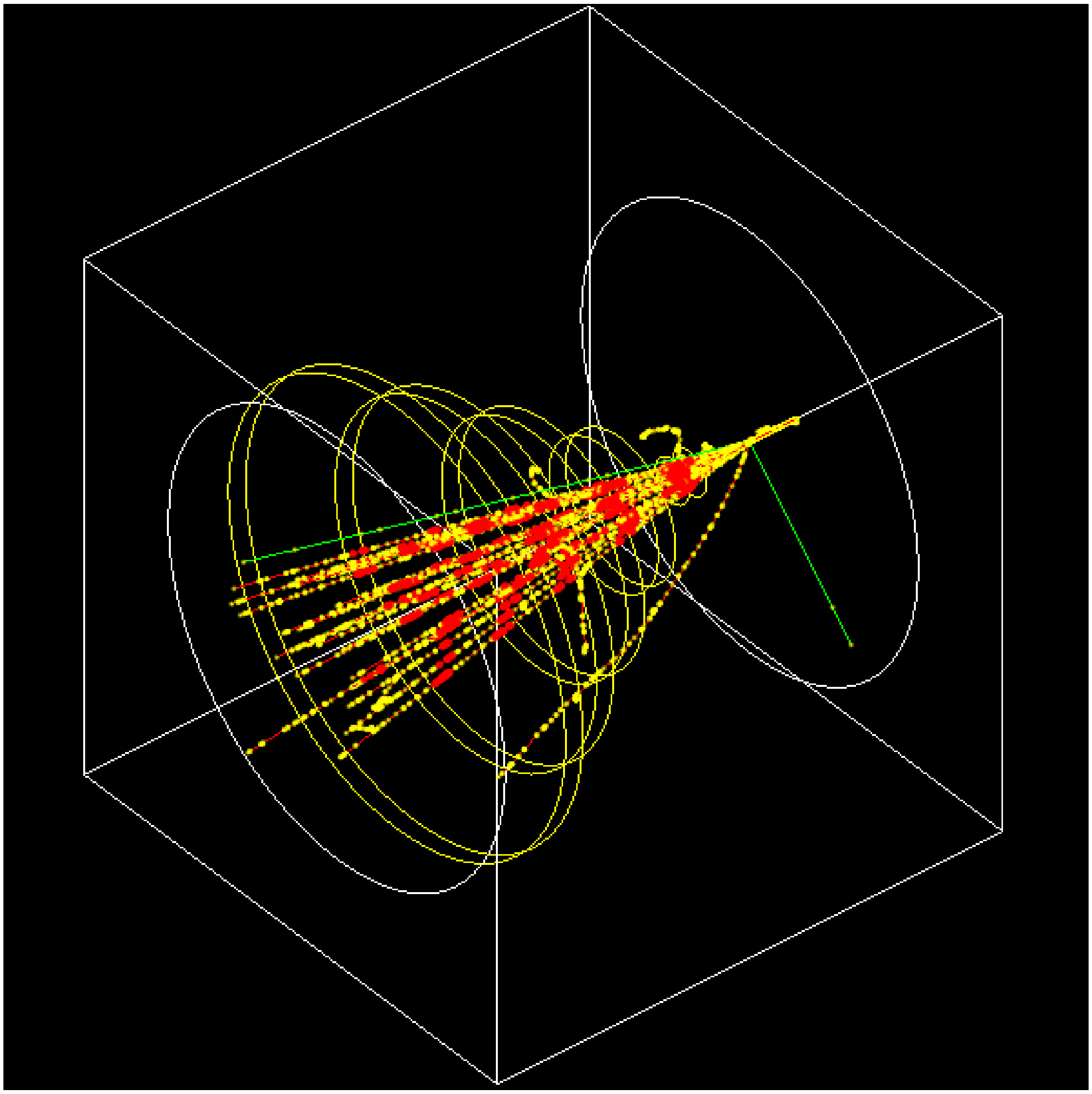

Figure 14: I ran a simulation where I shot 20 300 MeV μ^- particles through several layers of lead to hit a xenon source. The whole simulation takes place inside the cubic environment. The trajectories are plotted, where the colors of the trajectories represent the charge of the particles. Red represents a negative charge, green represents a neutral charge, and blue represents a positive charge [28]. The yellow points along the trajectories represents an event, where the yellow cylindrical plates represent lead.

```
***** Table : Nb of materials = 3 *****

 Material:    G4_AIR    density:  1.205 mg/cm3  RadL: 303.921 m    Nucl.Int.Length: 710.095 m
                        Imean:  85.700 eV   temperature: 293.15 K  pressure:   1.00 atm

   --->  Element: C (C)   Z =  6.0   N =    12   A = 12.011 g/mole
         --->  Isotope:   C12   Z =  6   N =  12   A =  12.00 g/mole   abundance: 98.930 %
         --->  Isotope:   C13   Z =  6   N =  13   A =  13.00 g/mole   abundance:  1.070 %
          ElmMassFraction:   0.01 %  ElmAbundance   0.02 %

   --->  Element: N (N)   Z =  7.0   N =    14   A = 14.007 g/mole
         --->  Isotope:   N14   Z =  7   N =  14   A =  14.00 g/mole   abundance: 99.632 %
         --->  Isotope:   N15   Z =  7   N =  15   A =  15.00 g/mole   abundance:  0.368 %
          ElmMassFraction:  75.53 %  ElmAbundance  78.44 %

   --->  Element: O (O)   Z =  8.0   N =    16   A = 15.999 g/mole
         --->  Isotope:   O16   Z =  8   N =  16   A =  15.99 g/mole   abundance: 99.757 %
[        --->  Isotope:   O17   Z =  8   N =  17   A =  17.00 g/mole   abundance:  0.038 %
         --->  Isotope:   O18   Z =  8   N =  18   A =  18.00 g/mole   abundance:  0.205 %
          ElmMassFraction:  23.18 %  ElmAbundance  21.07 %

[  --->  Element: Ar (Ar)   Z = 18.0   N =    40   A = 39.948 g/mole
[        --->  Isotope:  Ar36   Z = 18   N =  36   A =  35.97 g/mole   abundance:  0.337 %
[        --->  Isotope:  Ar38   Z = 18   N =  38   A =  37.96 g/mole   abundance:  0.063 %
         --->  Isotope:  Ar40   Z = 18   N =  40   A =  39.96 g/mole   abundance: 99.600 %
          ElmMassFraction:   1.28 %  ElmAbundance   0.47 %


 Material:     G4_Pb    density: 11.350 g/cm3   RadL:    5.613 mm   Nucl.Int.Length:  18.248 cm
                        Imean: 823.000 eV

   --->  Element: Pb (Pb)   Z = 82.0   N =   207   A = 207.217 g/mole
         --->  Isotope: Pb204   Z = 82   N = 204   A = 203.97 g/mole   abundance:  1.400 %
         --->  Isotope: Pb206   Z = 82   N = 206   A = 205.97 g/mole   abundance: 24.100 %
[        --->  Isotope: Pb207   Z = 82   N = 207   A = 206.98 g/mole   abundance: 22.100 %
[        --->  Isotope: Pb208   Z = 82   N = 208   A = 207.98 g/mole   abundance: 52.400 %
[         ElmMassFraction: 100.00 %  ElmAbundance 100.00 %


 Material:     G4_Xe    density:  5.485 mg/cm3  RadL:  15.462 m    Nucl.Int.Length: 324.297 m
                        Imean: 482.000 eV   temperature: 293.15 K  pressure:   1.00 atm
```

Figure 15: This particular piece of code displays the type of material used in the simulation. I generated 3 different materials in the environment: air (which itself is composed of carbon, nitrogen, oxygen, and argon), lead, and xenon. Isotopes of each atom are given along with their atomic number (Z), total number of nucleons (N), and the mass number (A), as well as their abundance.

```
hIoni:   for  proton    SubType= 2
      dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
      Lambda tables from threshold to 100 TeV, 7 bins per decade, spline: 1
      finalRange(mm)= 0.1, dRoverRange= 0.2, integral: 1, fluct: 1, linLossLimit= 0.01
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
               Bragg :  Emin=        0 eV    Emax=        2 MeV
          BetheBloch :  Emin=        2 MeV   Emax=      100 TeV

hBrems:   for  proton    SubType= 3
      dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
      Lambda tables from threshold to 100 TeV, 7 bins per decade, spline: 1
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
               hBrem :  Emin=        0 eV    Emax=      100 TeV

hPairProd:   for  proton    SubType= 4
      dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
      Lambda tables from threshold to 100 TeV, 7 bins per decade, spline: 1
      Sampling table 17x1001; from 7.50618 GeV to 100 TeV
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
           hPairProd :  Emin=        0 eV    Emax=      100 TeV

CoulombScat:   for  proton, integral: 1     SubType= 1  BuildTable= 1
      Used Lambda table of anti_proton
      180 < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
  eCoulombScattering :  Emin=        0 eV    Emax=      100 TeV

msc:   for GenericIon    SubType= 10
      RangeFactor= 0.2, stepLimitType: 0, latDisplacement: 0
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            UrbanMsc :  Emin=        0 eV    Emax=      100 TeV

ionIoni:   for  GenericIon    SubType= 2
      dE/dx and range tables from 100 eV  to 100 TeV in 84 bins
      Lambda tables from threshold to 100 TeV, 7 bins per decade, spline: 1
      finalRange(mm)= 0.1, dRoverRange= 0.2, integral: 1, fluct: 1, linLossLimit= 0.02
      Stopping Power data for 17 ion/material pairs
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            BraggIon :  Emin=        0 eV    Emax=        2 MeV
          BetheBloch :  Emin=        2 MeV   Emax=      100 TeV
```

Figure 16: This is the output that details the events that happen throughout the simulation. The code is split into multiple segments that describe individual events. The first word that starts every segment of code states the type of physical interaction that is taking place (i.e. hPairProd implies a pair production event) followed by multiple parameters that describe the interaction itself. To learn what these parameters mean consult the official Geant4 website [29].

3.2 Geant4 and CUORE

Geant4 is utilized by CUORE in order to generate data on the expected background rate via Monte Carlo simulations in the region of interest (ROI) where the $0\nu\beta\beta$ reaction is theoretically predicted to take place [30]. This is extremely important as this establishes solid criterion for what constitutes a $0\nu\beta\beta$ decay. Geant4 is utilized to simulate the experimental setup and "propagates particles through the CUORE gemeotry until they are detected in the TeO_2 crystals" [30]. On top of the meticulous detail given to simulate the geometry of the detector and experimental setup itself, there was also considerable information given on the contamination of the materials used in the experimental setup. This is very important as cosmic rays and particles created from radioactive decays may interact with these contaminations and produce an energy comparable to the $0\nu\beta\beta$ reaction. γ and α spectroscopy were utilized to screen the detector material for contaminations. These values are also utilized in the Geant4 simulation to make the data more reliable.

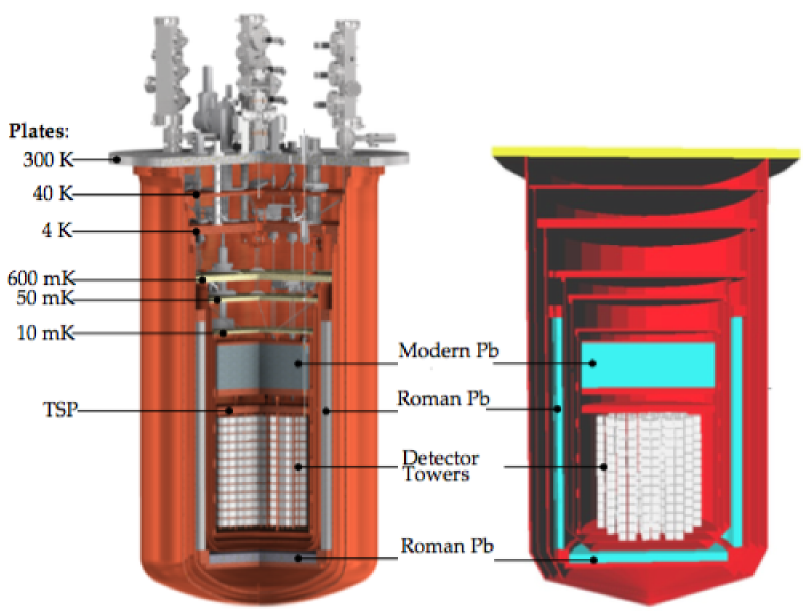

Figure 17: "In the simulation the geometries of the detector, of the cryostat, and of the internal and external shields are reproduced, ... namely: the TeO_2 crystals, the copper structure holding the array (i.e. frames and columns), the [polytetrafluoroethylen] supports, the wire trays, the NTD [germanium] thermistors, the calibration source guiding tubes, the lead support steel bars, the various thermal shields and other cryostat parts, the internal and external lead shields, and the external polyethylene shield." [30].

By using accurate values of density, surface area, purity of material, and more, the Geant4 simulations are able to give predictions as to the background index (BI) that the TeO_2 crystals will detect from multiple sources. To summarize there are 3 primary sources that can cause a detection in the ROI: 1. isotopes of ^{238} U and ^{232} Th and daughter nuclei from radioactive decays, 2. cosmogenically activated isotopes from TeO_2 and $CuNOSV$[20], and 3. ^{238} U and ^{232} Th interactions with the materials shielding the bolometric detectors. For each of the three sources, Geant4 Monte Carlo simulations are done on all 988 of the bolometric detectors. Data is collected in the form of an energy spectrum, similar to Figure (10). The source efficiency (ϵ_{Source}) is then calculated as the total number of counts within the ROI (N_{ROI}) divided by the total number of simulated decays (N_{Decays}). A lower ϵ_{Source} is better for the experiment as this implies that a low amount of events will take place in the ROI, and make it easier to detect the $0\nu\beta\beta$ decay.

$$\epsilon_{Source} = N_{ROI}/N_{Decays} \tag{7}$$

Another important quantity is the instrumental efficiency (ϵ_{Instr}) which is independent of the source being looked at. These two efficiencies are the primary parameters in the calculation of the BI for a particular source, given in Eq. (8).

$$BI = \frac{A \times \epsilon_{Source} \times \epsilon_{Instr}}{\Delta \times M_{TeO_2}} \tag{8}$$

where A is the activity of the source, Δ is the width of the ROI (100 keV), and M_{TeO_2} is the mass of the TeO_2 crystals [30]. This equation gives BI in units of counts/keV/kg/y. Figure (18) summarizes the results found by CUORE as of 4/28/17.

[20]The apparatus that holds the crystals in place is made of this material.

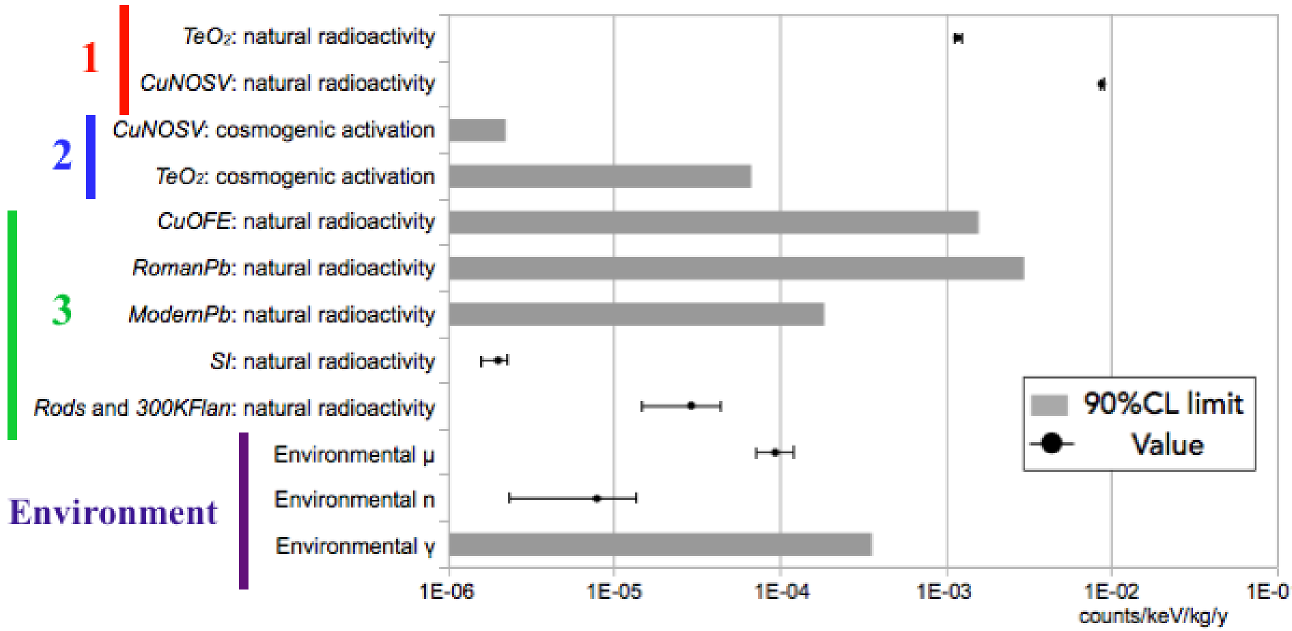

Figure 18: This histogram diagrams the BI from the 3 different sources, as well as from the environment. The bars represent values with 90% confidence level (CL) upper limits, while the dots plotted with 1σ uncertainties represent derived values from the CUORE-0 experimental data [30].

The Geant4 simulations indicate that the background levels in the ROI from these different sources are within the desired BI for the experiment, which is 10^{-2} counts/keV/kg/y. This demonstrates the utility of Geant4, and why it is such a powerful tool in the field of experimental particle physics in that it validates experimental designs without having to carry out the experiment by hand, which saves massive amounts of time and money.

4 Conclusion

In conclusion, the $0\nu\beta\beta$ decay is an important reaction in the field of particle physics, and its discovery would require a change in the Standard Model of particle physics. CUORE is one of the primary collaborations working on this problem, and I had the pleasure to contribute to the collaboration during one of the most important moments in the experiment: the installation of the towers. The experimental

apparatus should be operating sometime in 2017, and they will start to analyze the data in real time. If the $0\nu\beta\beta$ decay is found, then it will contribute to solving one of the biggest mysteries in science: why there is more matter than anti-matter in the universe.

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Appendices

A Onsite Shifter Journal

Disclaimer: When I refer to particle count (in the 1000's), I am talking about the particles that have a size of .3 micro meters (unless I specify otherwise). These are the most common particles in CR6 that set off the alarm. Other times, when I don?t specify the exact amount of particles, it is usually .5, 1, or 2.5 micrometer particles that set off the alarm. These thresholds are relatively low compared to the .3, so I do not bother trying to list the exact particle size and number (except sometimes when I felt like it). Also, I was pretty sloppy when I was taking these notes, so I apologize for the poor grammar.

08/12/2016

9:00 Arrive at the CUORE hut

9:25-9:30 Radon was steadily increasing until it reached a level of 95. It decreased shortly after. This event also disconnected me from the particle counter. All alarms are flashing blue and yellow.

9:34 The Installation team has entered CR6 with the new tower. They are continuing with the disconnected particle counter. I tried to call Stefano, but the phone wasnt connecting. Problems with the telephone.

9:40 Finished first ELOG.

9:46 Still disconnected from the particle counter.

9:50 Called Giovanni to help fix the particle counter connection. Deferred to Laura.

9:55 Called Laura. She said she will come by to help fix the particle counter

9:59 Particle counter is back online. All alarms (except AIR) stopped flashing blue and yellow. Air is still flashing red and yellow. The particle counter isn?t updating with any values however. It is just a blank graph. It is not registering Temp, RH, or particle count.

10:00 Tried to reset the alarm, but it won?t reset. The alarm is no longer flashing red and yellow, but it is staying red. I am still not registering anything for the particle counter.

10:00-10:10 Po214 levels are steadily increasing. It reached a maximum of 40 and started decreasing after 10:10.

10:29 Laura fixed the particle counter. We are receiving values for temperature, particle count, and RH.

Rh is currently at 5.1%, Temperature is 21.1 C, and the particle counter spiked up to 1100, but immediately went back down. Possibly someone moved near the counter? Radon levels are stable.

10:56 The particle counter shot up to 3200 due to a glove change.

11:11 The particle counter spiked up to 3200 also due to glove change.

11:18 The bag has been removed from the tower for a while. The installation team is still prepping it to be placed on the TSP.

11:15 - 11:21 Temperature has increased from 21.1 to 21.6

11:23 The particle counter alarm went off for two particle sizes, but immediately went back down. Not cause for concern.

11:25 The bag has been removed and the installation team is moving into CR7 to install the tower.

11:30 Particle counter alarm went off due to a glove change.

11:46 Temperature has increased up to 21.9. RH has dropped to 4.9%.

11:52 Particle counter spiked to 1000, no alarm set off.

11:53-11:58 Po214 stayed at 45. Tell Stefano if these levels persist for more than 7/8 minutes

11:59 The Po214 went back down to 0.

12:01 Looks like the support team wrapped (?) some material around the frame of the cryostat

12:12 All members of the installation team are on the ground (looking for something?)

12:13 They seem to be streaming video to someone else so they can see the configuration of the towers on the TSP.

12:14 RH has risen to 5.7%

12:19 RH has risen to 6.1%

12:19 The installation team is sealing up the bag. Tower installation is complete.

12:26 The installation team is tampering with the electronics above the cryostat.

12:36 The installation team is cleaning the room and packing up their tools.

12:52 Temperature increased to 22.2. RH has increased to 6.7%

12:58 The installation team is leaving CR6. Particle counter spiked up to 6000 because they opened the door. The Bag Flowmeter reads 55 like it should.

1:02 The installation team has left CR6. The installation is successful.

LUNCH

2:25 Changed the threshold of the temperature to 25 and RH to 20.

2:42 RH is almost back down to 0%. Temperature is 21.4. Radon is fluctuating between 0 and 15.

2:54 NAS is still giving us trouble with regards to uploading video files.

4:15 The support team has entered the vestibule with a tower

4:23 The tower is placed in a plastic container inside the vestibule. It is being pulled into CR6.

4:27 RH has increased from 0% to 2.2%

4:31 Nitrogen tank is refilled back to green

4:37 The tower is hooked up to the tower bubbler/ flowmeter. The tower bubbler is bubbling and the pressure is constant. The tower flowmeter is at 5 (It doesn?t look like its raised that much but it is).

4:48 RH reached a maximum of 5.2%

4:56 Bag flowmeter is bubbling at 50 as opposed to the normal 55. Support team is checking it out.

5:06 The pressure from the tower bubbler was raised slightly above 5.

5:11 Tower successfully connected and ready for installation on Monday/Tuesday.

5:19 Po218 reached warning level of 60 but dropped back down

5:27 Po214 reached warning level of 62 but dropped back down

5:31 Po218 rose again to 60 but fell shortly after.

REMINDER: DON?T FORGET TO PUT THE VIDEOS FROM 8/10 ONTO NAS OS!!!! ALSO PUT UP THE VIDEOS FROM 8/11, 8/12, 8/16, and 8/17!!!!

08/16/2016

9:35 Get into lab

10:06 Finished alarm check. Apparently the wifi in the CR is not working and I must call Stefano before doing the alarm check. Communication to the team via Skype/ iPad is not possible right now.

10:10 Po218 spiked up to 40 but immediately went back down.

10:13 The installation team has entered CR6. RH has begun spiking, and temperature has started to increase.

10:16 The tower has been wheeled next to the bag, installation onto the TSP will begin shortly.

10:18 Temperature is at 22.2 and RH is at 2.2

10:19 Spike in particle counter due to a glove change. Spikes reached 6500 (.3) and around 900 for the other particle sizes. This is normal for a glove change.

10:32 RH has reached 5.4%

10:33 Installation team has begun removing the tower from its container. The tower and bag flowmeter have been disconnected so they can begin installing the tower. Also the tower bubbler has stopped bubbling.

10:37 The particle counter spiked up to 2750 due to a glove change. Radon has also spiked to 60 and has stayed there for a minute. If it stays for one more minute, I will notify Stefano.

10:40 Temperature has reached 22.2 and RH is at 6.7%

10:43 The team is dismantling the case for the tower.

10:51 RH has reached 7.6% and the temperature is 22.4.

11:01 The installation is taking electrical measurements. Also the Po218 has reached 60 (Warning levels). If this persists than I will notify Stefano.

11:24 RH has reached a max of 7.9% at around 11:00, but it has been steadily decreasing ever since.

11:27 Glove change but no alarm.

11:31 Temperature has reached 23

11:33 Stefano called asking about the wifi password (Babil0nia)

11:39 Glove change caused an alarm to go off.

11:46 Restarted the router so hopefully the people in the clean room will have access to wifi.

11:47 The bag has been removed. Tower installation has begun.

11:57 Wifi disconnected again.

12:01 Installation team is taking electrical measurements of the cryostat to make sure its working properly.

12:04 Po214 has just spiked up to 60.

12:12 RH has reached 8.6%

12:29 The tower has been connected to the TSP.

12:30 RH has reached 9% at 12:15, but started descending.

12:41 Team took a picture with the installed towers. Temperature is 23.3 and RH is 8.4%

12:43 Spike in Po218 (60). Will notify Stefano if it gets higher or plateaus.

12:46 Po218 has spiked again up to 60. Nitrogen is at 331. The team is closing up the bag.

12:48 The bag flowmeter is reading 50.

12:51 The installation team has exited the Vestibule. Tower installation is successful.

EARLY DAY

08/17/2016

8:20 Get into lab

8:56 The installation team enters the vestibule with the tower.

8:59 Sound check for the alarm is complete.

9:09 Installation team enters CR6

9:11 The bag flowmeter is disconnected by Claudia

9:25 The 2nd installation team has entered the vestibule for a total of 5 people in CR6. RH is increasing a lot.

9:27 Po218 levels have reached 60 (warning levels). Will contact Laura if they get any higher.

9:30 Po218 levels have reached 60 again and is staying there.

9:33 Po218 spiked to 80. Called Laura, she said to call her if it reaches 90 or stays there for a long time.

9:34 Two people left CR6, so only three people left to install the tower.

9:36 Po218 has deceased back down to 40. Temperature and RH are steadily increasing. Particle counter spiked to 1000, probably due to an open door.

9:43 Temperature is 21.9, RH 5.7%, and Particle count is around 100-700.

9:48 One of the cases is removed from the tower.

10:01 Po218 spiked up to 60

10:02 The team is still setting up the tower for installation on the TSP.

10:13 Glove change but no alarm went off.

10:19 Po214 levels have been steadily increasing and have spiked up to 75. Will notify Laura if this trend continues.

10:22 Po214 has just spiked up to around 95, it then fell back down to 75. The values are now constantly falling.

10:25 The particle counter spiked up to 1300, possibly due to a glove change. Rh reached a max of around 8.1% in the past 30 minutes. Temperature is at 22.2 and is steady increasing. Don?t call support team at 779, call 706 instead.

10:32 Olivero has taken over the right screen so I cannot view the radon, temperature, particle count, or RH.

10:37 The team is just about ready to open the bag and begin installing the towers.

10:38 Called Laura and confirmed that the radon levels are good. The team is ready to begin the installation process.

10:40 Particle counter spiked up to 3500 due to a glove change.

10:45 Po214 spiked up to 60 and then again to 75.

10:49 Po214 spiked up to 90 then down to 75 and then back up to 90.

10:50 Po214 went back down to 30.

11:05 The bag has been opened.

11:08 The particle alarm just went off due to pulling out plastic bags.

11:39 Po214 has spiked up to 75. Temp is at 22.2, RH is 7%, and Particle count has remained low for the past 20 minutes (0-1100).

11:40 The installation team has brought the tower underneath the TSP.

12:27 The tower has been successfully attached to the TSP. The team is taking a picture to commemorate the tower being installed.

12:32 The installation team is sealing up the bag.

12:36 The bag flowmeter has been attached and it is at 55. Po214 has just spiked to 60. The installation team has left CR6. Tower installation successful.

3:18 Support team entered the vestibule. Alarm check completed.

3:26 Support team has entered CR6 with the tower.

3:36 Po218 spiked up to 60. I will notify Laura if it persists.

3:37 The tower is hooked up to the bubbler and flowmeter. Pressure is at 2 ticks above 5. The tower

flowmeter is at 5 and the bag bubbler has been disconnected.

3:44 RH reached a max of 3.1%. The bag flowmeter is back on and is at 55. The tower bubbler pressure is at 5.

3:47 The Support team has left CR6. The tower is ready for installation tomorrow.

08/18/2016

8:45 Giovanni fixed the system, as all alarms were disconnected from the main computer.

8:50 The alarms are disconnected once again. Notified Giovanni. He?s starting to fix it.

NOTE: When this happened, there was actually a massive problem with the back up power supply and the liquid nitrogen pump to the cryostat itself. This was an extremely panicky moment during my stay in Italy. A lot of people had to stop what they were doing in order to trouble shoot this problem. I primarily remember Giovanni, the new post-doc from Berkeley, stressing out the most as the primary LabView tech for the radon system and running between the above and below ground lab all throughout the day. I definitely remember the stress throughout the lab as a random blackout would jeopardize the experiment. And I definitely remember the thorough chewing out the repair technicians got by Paolo when they arrived very late to repair the back up battery. Good memories!!

9:05 Alarm check done.

9:13 Installation team has entered CR6.

9:18 Glove change, but no alarm went off.

9:20 The tower has been disconnected from the flowmeter and bubbler. The bag has also been disconnected from the flowmeter (probably as soon as the installation team walked in, but I just noticed now).

9:22 Temperature and RH are rising. Temp = 21.4, and RH = 4.4%. Radon levels have remained surprisingly low.

9:28 Small spike due to glove change (900).

9:49 The installation team is taking electrical measurements of the tower (or container?).

10:00 RH reached a maximum of around 7.7%

10:34 Glove change but no spike in particle count.

10:35 Po218 has spiked up for the first time this morning into the warning levels. It is right underneath

60. It immediately went back down.

10:38 Po218 spiked up again to just below 60.

10:40 Particle counter spiked up to 1000, but I am not sure why.

10:43 Temp has reached a max of 22.2

10:58 Installation team is opening up the bag

11:21 The team has attached the tower to the TSP. Also, the temperature reached a max of around 22.5/22.6

11:46 The team is sealing up the bag. The tower has been successfully installed onto the plate.

11:52 RH reached maximum of 7.9%

12:03 Temperature is 22.7

12:25-12:29 The installation team has left CR6. Installation was a success. Also, particle counter spiked up to 1400, possibly due to a door opening. The bag flowmeter is connected and is reading 55. RH reached a max of around 8.3% immediately after the particle counter spike.

LUNCH

3:30 Support team entered with tower. Alarm check done.

3:45 Support team entered CR6 with tower. Prepping the tower for installation tomorrow.

3:54 Tower is hooked up to bubbler and flowmeter. Bubbler pressure is about two ticks above 5. Bubbler is working fine. Tower flowmeter is at 5.

3:57 Radon spiked up to 97. Will call back if it persists.

4:10 The support team has finished bringing in the tower, they are now moving into the vestibule.

08/26/2016

*NOTE: **VIDEOS ARE STILL NOT UPLOADING TO THE WEBSITE/ CONTACT SOMEONE ABOUT THIS***

SIGN OUT OF YOUR EMAIL ON THE SHIFTER PHONE

8:38 Inspected CR4. There are no more towers in CR4 so there is no need to check the CR4 bubblers anymore.

8:46 The installation team has entered the vestibule.

8:47 Alarm check done.

8:57 Installation team enters CR6. RH and temperature have started to increase.

8:59 Tower is disconnected from the flowmeter and bubbler. Tower installation has begun.

9:10 Glove change but no significant spike in particle count.

9:23 Installation team is doing electronics check on the tower.

9:29 RH is at 7.1% and Temp is at 22.2. They are steadily rising.

9:34 The casing has been removed from the tower. The bag is going to be opened soon.

9:39 Particle counter went off due to a glove change.

9:40 Radon levels have reached warning levels of around 60. RH reached a maximum of around 8.2%

9:41 ? ?

9:48 Radon levels have reached warning levels of around 60 again. I will notify the team if this persists for awhile.

9:49-9:52 ? ?

9:59 The particle counter spiked up to realy high levels. Tried to call support team but the line was busy. Will call once I see the support shifter hang up on camera. RH has reached a max of around 8.5%. The bag has been opened and tower installation onto the TSP has commenced.

10:14 RH reaches 9% approximately

10:23 Called Tommy to ask about the Nitrogen re-fill. He says he believes its today, but will double check

10:36 Tower is being attached to the TSP.

10:39 Tower successfully attached to the TSP.

10:46 RH has reached a max of 10%. Looks like its starting to go down. Temp is at 22.7.

10:47 Bag is being sealed up.

10:53 The team is checking the electronics on the cryostat.

11:00 RH hit a max if 10.8%. Temp has reached max of 22.7.

11:28 Particle counter went off. Probably due to moving around too fast.

11:29 Particle counter went off again. It looks like one of the members of the installation team is opening a type of valve next to the vestibule.

11:30 Particle counter went off again. Possibly due to moving around near the detector.

11:33 Bag flowmeter has been attached and it is moving around 55/60. Installation team has exited out of CR6. The installation of the final tower was a success!

LUNCH

2:50 returned from lunch. Nitrogen has been refilled.

3:15 Cleaning team has entered the vestibule. Alarm check done. Everything is working okay.

3:25 Cleaning team has entered CR6. Radon levels are low.

3:38 Cleaning team is wiping the floor all around CR6. The particle count spiked up to 1200, but immediately decreased (kicking dust up from cleaning). RH is steadily increasing and is currently at 4.9% and temp is at 22.2.

3:46 Particle alarm went off, probably due to dust being kicked up in the air.

3:51 Radon has reached warning levels. Will let Oliviero know if the problem persists.

3:53 Radon went up from 60 to 80.

3:56 Radon levels dropped back below warning levels. Bag flowmeter is on and is at 55.

3:57 Cleaning team has left CR6. Cleaning complete.

NOTE FOR LAST ELOG: ALL TOWERS ARE OFFICIALLY INSTALLED! THEREFORE, THE TOWER FLOWMETER AND BUBBLER ARE NOT ON. PLEASE DO NOT CALL ABOUT THIS.

08/29/2016

9:45 I noticed that there was no alarm display in CR5. I notified the support team and they are working on fixing it.

9:53 Called Giovanni and now it is all fixed.

10:08 The installation team has entered the vestibule. I believe there may be a problem with the wifi connection.

10:13 Alarm check done. The wifi connection with the iPad is not working.

10:15 Disconnected and reconnected the wifi router to see if that fixes the problem. The problem has been fixed!

10:19 The team has entered CR6.

10:21 Particle counter went off (1micrometer). It looks like it could be caused from a box opening in

CR6 next to the particle counter.

10:24 Po214 has spiked up to warning levels (60). It went back down immediately after.

10:31 RH and temperature have been steadily rising since the team entered CR6. Right now, the values are at around 3.7% and 22.7 degrees respectively.

Update 10:44 So far, the team has been tampering with the TSP. I am not completely sure what they are doing but they have been tampering with the top of the TSP since they have walked in. Radon, Particle count, RH, and temperature are all at stable levels. The temperature spiked up to 23 but immediately went back down to around 22.7

11:20 Particle counter went off (1 and 2.5 sizes). I could not see what caused it as one of the team members was out if view (near the particle counter). I would suspect this is from a glove change though.

11:20 RH has peaked at around 5.5% but has begun to decrease

From 11:20- 11:40 It would appear that the temperature has spiked to around 23.3 around 5 or 6 times. It went back down immediately after. Now the temperature is stable at 23. Radon levels have been surprisingly low this whole time.

11:59 The team is still working with the electronics of the TSP.

1:00 update: The temperature has reached a maximum of around 23.5 but went back down at around 12:30. It is now at 23.3. Particle count has been relatively low this entire time, with small spikes correlating to boxes opening or fast movement. The team is still installing the electronics on the TSP. RH reached a maximum of around 5.9% at around 12:50 but is decreasing now. Radon levels have been low this entire time. Nothing interesting has happened in the past hour.

1:11 The team is done working on the TSP and has left CR6.

LUNCH

2:46 Returned to Cuore hut. No significant spikes in radon or particle count since I?ve been gone. RH is close to 0, which is normal. Nitrogen is still low. They will be refueling today

3:02 Someone has entered the vestibule.

3:04 Alarm check has been done. Waiting approximately 10 minutes before they enter.

3:12 Person enters the vestibule

3:14 The bag flowmeter has been disconnected (It was at 55). Another person has entered the vestibule.

3:24 The second person has entered the vestibule. RH and temp are steadily rising.

3:47 Nitrogen monitors are disconnected and won?t give me a readout. I notified Giovanni and he said he was going to talk to Carlo.

4:08-4:10 Po218 has reached warning levels (60).

4:11 Po218 has gone back down

4:20 The RH is increasing and is currently at 3.5%. temperature is at 23. Particle count has remained low.

4:31 Particle counter spiked (3800) but this can be attributed to the vestibule door opening up. The particle counter immediately went back down after this event. Support team is still in CR6 however, I am not sure why they opened the door.

4:34-4:35 Po218 has reached warning levels (60).

4:37 Po218 has reached warning levels again (60). This is probably attributed to the fact that the door from CR1 to the vestibule was opened and thus air leaked in.

4:40 Photographer enters CR6 to take pictures of the towers. With a third person the RH is rising rapidly but not to any dangerous levels.

4:56 RH has increased to 8.2%

5:06 RH has reached a peak of 9.6%.

5:10 RH has increased again to 10.1%. Temperature is at 23.3

5:46 Particle counter (.5 and 1.0) went off due to a glove change.

5:49 The bag has been unzipped to take pictures of the towers.

5:50 RH reached a maximum if 10.4%

6:00 The bag is being zipped up. RH reached a max of 10.6%

6:04 Particle counter went off (.5 and 1). I am not sure why. RH has risen to 11.1%.

6:06 The team exits CR6 into the vestibule and then exits the vestibule. The flowmeter to the bag has been attached and it is around 55.

08/30/2016

9:40 Arrived at Cuore hut (late). Installation team was already in CR6 installing some wires around the

TSP. Temperature is at 22.7 and the RH is at around 7.6%. Particle count and radon levels have been low for this morning. Although, the particle counter went off at around 8:00 am this morning.

9:55 Luigi called asking for a status report. Reported that everything was operating smoothly. Also, RH peaked up to 8.2%, and gas been slowly decreasing/remaining stable.

9:58 The particle counter has gone off due to a glove change next to the particle counter (.3/ 3600 & .5/1400).

10:05 Checked the CORC website and it looks like the Po218 reader is up and running again.

10:19 Temperature has reached 23. Small spike in the particle count probably due to a glove change.

10:43 The team has taken off the bag for the towers.

10:47 Tried to call Luigi regarding uploading the videos onto NAS. Will try again in 10 minutes.

10:48 Person enters the vestibule and drops off a box (tools?). They leave immediately after.

10:51 Glove change but no spike in particle count.

10:52 Temperature spiked up to 23.3.

11:00 RH is at 8.6%

11:33 Small particle spike of around 2000. This could be attributed to the fact that there is a worker by the tool table tampering with some tools.

11:44 The particle counter went off for .5, 1, and 2.5. I am not sure why. I contacted support team and they don?t seem to know either.

11:49 Particle counter went off again for 1.0.

11:49 ?11:50 Po214 has reached warning levels of 60.

11:57 The installation team has finished work on the towers. They are now zipping up the bag and sealing it with some tape.

12:02 Particle counter alarm went off (.5). This is probably due to a glove change near the particle counter.

12:04 The flowmeter has been attached to the bag and it is at a value between 50 and 55. The team has left CR6. Installation is a success.

LUNCH

2:48-2:49 Po214 reached Warning levels (60)

2:49 Got a call from Daria to confirm that I am in the hut. Installation team will enter soon.

2:53: Po214 reached warning levels again (60).

3:00 Team enters vestibule holding big piece of material.

3:04 Alarm check has been done.

3:06 Po218 has reached warning levels (60)

3:09 Po218 has reached 80

3:10 Po218 went back down to 70. Also, the team has entered CR6.

3:16 The flowmeter to the bag is still connected (it is usually disconnected right away).

3:20 Po218 reached warning levels (60).

3:21-3:23 Po218 went up to 80.

3:24 Po218 went up to 100. This can be attributed to Daria opening the door to the vestibule and someone opening the vestibule (from CR6) to get what Daria dropped off. Since there was no 10 minute waiting period, the radon spiked.

3:26 Radon has dipped to 40

3:28 RH is steadily rising and is currently at 4.8%. The temperature was at 22.7.

3:32 The team has gone back into the vestibule to get some additional materials needed for the installation (I?m assuming this is what Daria was referring to earlier).

3:34 Po218 has spiked again to 100. Probably due to the vestibule door being opened. They are waiting to enter CR6 again.

3:35 Po218 has started dipping (80).

3:37 The team has left the vestibule. We are done for the day.

08/31/2016

8:46 Team enters vestibule.

8:50 Alarm check is done.

8:56 Team enters CR6

9:00 The particle counter went off due to a glove change next to the counter (.5 / 850).

9:07 The bag has been removed from the towers/TSP. RH and temperature are increasing pretty rapidly

(4.4% and 22.2 respectively).

9:12 Particle counter went off again (.5/900) due to movement/glove change next to counter.

9:16 The team has pulled out a copper plate and it looks like they are about to install it underneath the 19 towers.

9:31 One half of the plate has been installed. They are beginning to install the second half.

9:37 RH has reached a value of 8.4% and the temperature is at 22.4/22.7 (The reader is fluctuating between the two).

10:00 Particle counter went off (.3/3200, .5/ 2200, 1/1200) due to a glove change. RH peaked at 9.1%.

10:09 It would appear that the installation team is done installing the plate.

10:12 Someone has entered the vestibule. It would appear that they were talking with someone on the other side of the door. Will keep an eye out for increases in radon levels.

10:27 Temperature just spiked up to 23.

11:00 Particle alarm went off (.5 / 850) but this was due to a glove change.

11:04 Particle alarm went off (.3, .5, 1.0) due to Daria dropping off extra tools down at the vestibule and one of the members retrieving the items. In hindsight, it would have been better to wait a bit longer so the dust could settle. The spikes went back down immediately after.

11:21-11:24 Po218 levels have reached warning levels (60).

11:25 The team is sealing up the bag.

11:33 The team is sealing the bag with tape. The flowmeter is on and it is fluctuating between 55 and 50.

11:34 The team leaves CR6 into the vestibule. Installation was a success!

LUNCH 2:55 Called support team to let them know that I?m in the hut.

3:32 Someone dropped off some equipment in the vestibule but left immediately after. No one has entered into CR6 yet.

3:48 People have been bringing in equipment into the vestibule but no one has entered yet.

3:59 Daria called saying that the team is going to enter into CR6 soon.

4:05 The team has entered the vestibule. The iPad is not connecting again.

4:15 The team enters CR6 and the flowmeter is disconnected from the bag. Particle counter spiked up a bit, but no alarm. Temp is at 23, RH is at 4.3% and rising.

4:37-4:38 The particle alarm (.5 and 1) were both going off like crazy. Contacted the members in CR6 through the iPad to figure out what was happening. They are not too sure what was happening either. They went back down shortly after.

4:40 Particle counter went off again but this was due to a glove change.

5:09 A team member went back into CR1 and came back out into the vestibule. Looks like they are waiting to enter CR6 again.

5:29 ? 5:30 Po218 reached warning levels (80). Will notify support team if the trend continues.

5:31 Po218 has dropped down to 60. Temp has reached a max of 23.5 (wow).

5:33 RH reached a max of 7.5%.

5:38 The team has entered the vestibule. It looks like they are waiting to re-enter because the flowmeter is not attached to the bag.

5:42 Two members of the installation team left, Claudia is left in CR6.

5:43 Claudia reattached the flowmeter to the bag. It is reading at 45 right now.

5:46 It is back up to 55 now.

5:57 Claudia has entered the vestibule and exited CR6. Successful day!

09/1/2016

8:57 Installation team (4 people instead of 3) enter the vestibule.

8:59 Alarm check is done.

9:08 The installation team enters CR6. I expect RH and temperature to rise rapidly and reach their max today since there are 4 people inside CR6 at once. Also, particle count spiked up (.3) to 700 when they entered. This value lingered for a minute or two before it subsided.

9:19 Rh is at 4.9% and temperature is at 21.9. both are increasing pretty rapidly.

9:23 The team is unzipping the bag.

9:26 Metal ring with metal rods sticking out of the top has been placed on top of the bag. Maybe it?s a device to measure how even the plate is?

9:32 Temperature who 22.2. RH is at 7.6%.

9:37 ? 9:38 Po218 reached warning levels (60)

9:39 Po218 has spiked up to 80.

9:40 Po218 dropped back down to 60. RH is at 8.4% and temp is at 22.4.

9:45 The metal ring (from before) has been removed from the TSP.

10:30 Everything has been going smoothly. RH has started to even out around 10%. Temperature is surprisingly low for the amount of people in CR6 (22.7).

10:33- 10:35 Po214 has spiked up to warning levels (60).

10:36 Now Po218 has spiked up to warning levels (55).

10:37 RH peaked at around 10.2%

10:50 Temperature is fluctuating between 22.7 and 23.

10:54 Turned the router off and on so the team can try to connect with iPad.

10:57 The particle counter spiked up but no alarm was triggered (.3/1400). Probably due to a lot of movement around the particle counter/ tool table.

11:17 Connection to the iPad has been reestablished.

11:28 Particle counter spiked up to 1900 but I?m not too sure why. No alarm was triggered so it?s not serious. 11:50 Temp spiked up 23.2

11:51 RH has been steadily decreasing since 11:20. It is now at 7.8%.

12:48 RH reaches a low of 6%.

1:03 Particle counter went off (.5/1300 1/800) probably due to a glove change. The cameras were either reloading (disconnected) or not facing the part of the room where they put on extra gloves. Also, RH has begun picking up again. It is at 6.4%

1:20 Daria called to let me know why its been taking so long. Apparently there were problems aligning the TSP and that?s why it took so long. The problem has been fixed and we are expecting to leave around 2:00pm.

1:50 The installation team is closing up the bag. The particle counter spiked up during this moment (.3/1700). RH has risen back up to 9.4% and is increasing slowly. Temperature has reached an all-time high of 23.8.

2:10 RH has reached a high of 10.2%. Particle count and radon have been really low this entire time. The installation is applying some finishing touches to the cryostat.

2:24 RH has reached a high of 10.8%.

2:43 RH has reached a high of 11.7%.

2:50 I believe it has also reached 12%

3:08 The flowmeter has been attached to the bag and it is reading at 55. There was also a spike in the particle counter as a person opened the vestibule door. No alarm went off.

3:12 The installation has left CR6. The alignment was a success. Temperature and RH are starting to drop.

3:14-3:44 Break time

3:56 Support Team enters the vestibule

3:57 Alarm check done.

4:06 Support team is entering CR6. Radon levels are low, along with RH and particle count. Temp is at 23.

4:32 The support team went back into the vestibule. I think they might just be getting some tools.

4:34 The team has left the vestibule. We are done for the day!

09/13/16

10:29 Team enters the vestibule.

10:31 Alarm check is done.

10:39 Team enters CR6.

10:48 Spike in particle counter (.3//1200). Also, it looks like the team is testing the electronics of the cryostat by using a voltmeter.

10:50 Cameras are disconnecting more frequently.

11:58 RH reached a max of 5.1% about 20 minutes ago. It is now at around 4.8%. The temperature has reached 22.7.

12:10 The team is cleaning the floor of the room.

12:11 Particle alarm goes off twice (.5//1200, 1400, 1600 1.0//1000, 1200). This is due to dust being knocked up from cleaning the floors.

12:13 The team exits CR6.

4:28 Cameras are set up to view the TSP during the shake test.

09/14/16

10:00 Get into CUORE.

10:05 Refresh cameras, and the team is already in CR6.

10:08 Alarm check done.

10:11 Bag has been unzipped.

10:15 Particle counter spiked up (.3//7000, .5//3000, 1.0//1000). This was due to a glove change, by all three of the team members.

10:20-10:23 Po218 has reached warning levels (60).

10:29 RH is currently at 5.9%.

10:41 A fourth person has entered the vestibule with a camera and is going to take pictures with it. Also, temperature is at 22.7 and RH is at 6.2%.

10:50 Fourth person has entered CR6. RH has started to increase rapidly (7%).

10:58 Particle counter went off (.5//900). Could?ve been dust that was kicked up. Photo op is continuing.

11:07 RH has reached a high of 10.6% and the temperature has reached 23.

11:18 RH has increased up to 12.7%.

11:28 Particle counter goes off (.3//6000). I am not sure what caused this as they?re all on the floor.

11:49-11:54 Po214 reached levels of 75 (11:49) and has gone down to 60. Still in warning levels

12:00 Particle counter went off (.3//2500, .5//1800). Glove change.

12:06 Fourth person left sometime between 12:00 and 12:06

12:09 Call from Luigi. He wants me to contact the team in CR6 and tell them to move a pipe that?s in front of camera 2. Tried calling but the line is busy.

12:14 The team is zipping up the bag.

12:18 The team is exiting CR6.

12:24 The bag flow is operating at 60.

3:33 Team enters the vestibule. The alarm check has been done.

3:43 The team has entered CR6 carrying a large object. This has set off the particle counter off (.5//900).

3:51 Temperature is at 22.2 and RH is at 4.8%

4:01 Po218 has reached warning levels (55).

4:02 -4:04 Po218 has reached 60.

4:16-4:17 Po218 has reached warning levels (60).

4:23 There has been a lot of activity on the particle counter, but no alarm has been set off. Lot of little spikes.

4:26 RH is at 8.6% and temperature is at 22.4.

4:40 Po214 spiked up to 60. RH reached a max of 9.5%. Temperature is at 22.4.

4:45 RH is at 10%.

4:53 Laura called, asking if I could see the screen on the oxygen sensors installed above the cryostat. Blue one was clear but orange one is not. Donatello is changing the orientation to fix it.

5:00-5:02 Po214 reached warning levels (60).

5:20 Team has left CR6. Flowmeter is reading at 60.

B Pictures from CUORE trip (8/5/16 - 9/18/16)

Figure 19: A close up of the above ground offices where the CUORE team was located.

Figure 20: Assergi from the above ground offices.

Figure 21: The parking lot behind the main building in Figure (19). This is where we waited for the shuttle bus to come around and take us to the below ground lab.

Figure 22: Street signs at the above ground offices.

Figure 23: The main office where the Berkeley team worked. We primarily worked with them the entire trip.

Figure 24: Giovanni Benato, an Italian post doctorate from Berkeley lounging in the office.

Figure 25: Large hallway that connected the main chambers of LNGS. This is the corridor that connects all 3 main chambers of LNGS in Figure (5).

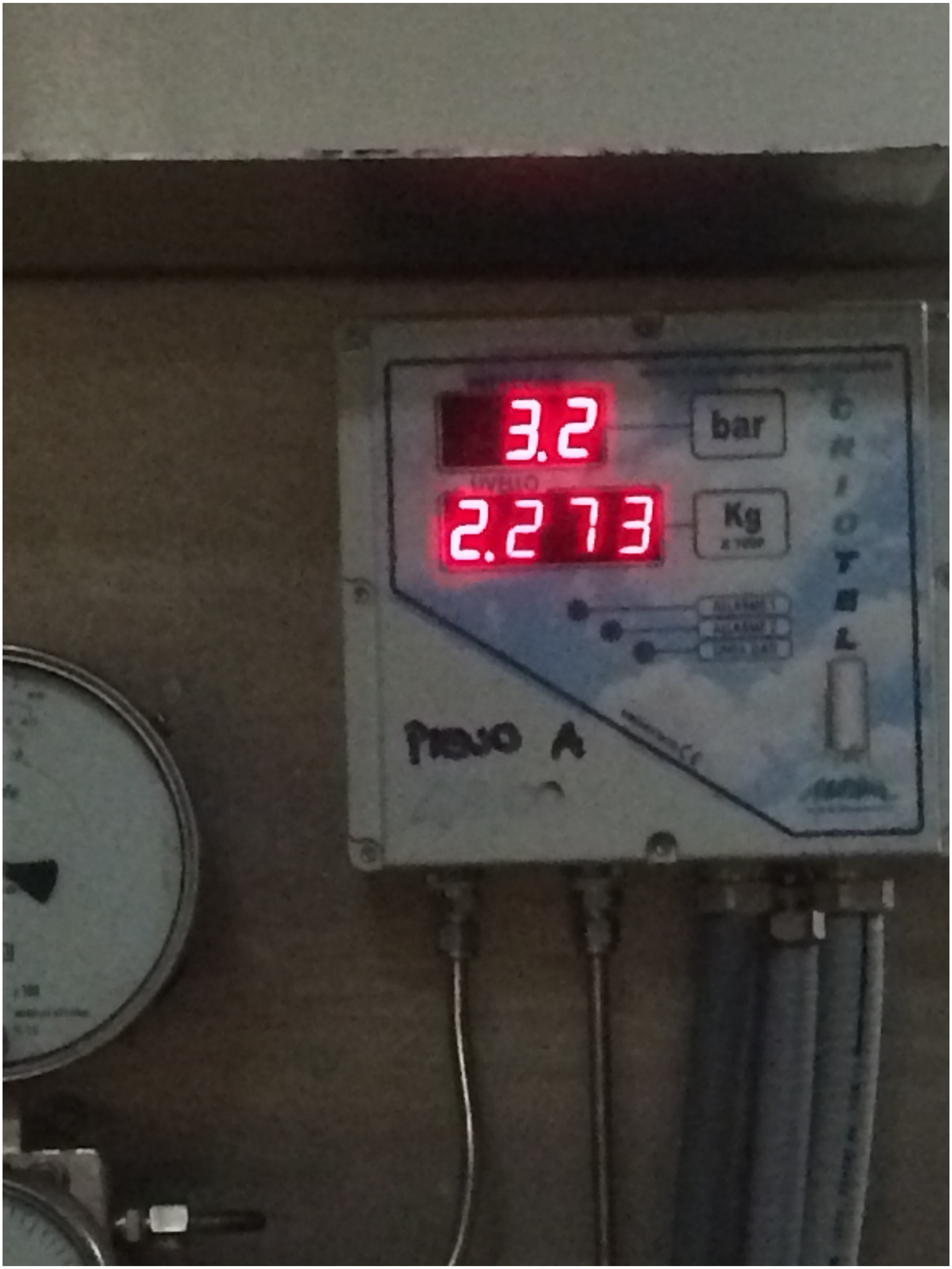

Figure 26: Indicator on the liquid nitrogen tank that conveyed the pressure and mass of the liquid nitrogen.

Figure 27: Emergency exit near the CUORE hut in case of an emergency. This exit leads to the tunnel where all automobiles and shuttles drive through.

Figure 28: Liquid nitrogen tanks being refilled for all experiments taking place at LNGS.

Figure 29: The main station where I worked, on the third floor of the CUORE hut. The fan was extremely helpful as it got really hot in that room from all the computers.

Figure 30: Large computers that do the necessary calculations for the cryostat to operate.

Figure 31: Giovanni posing fabulously.

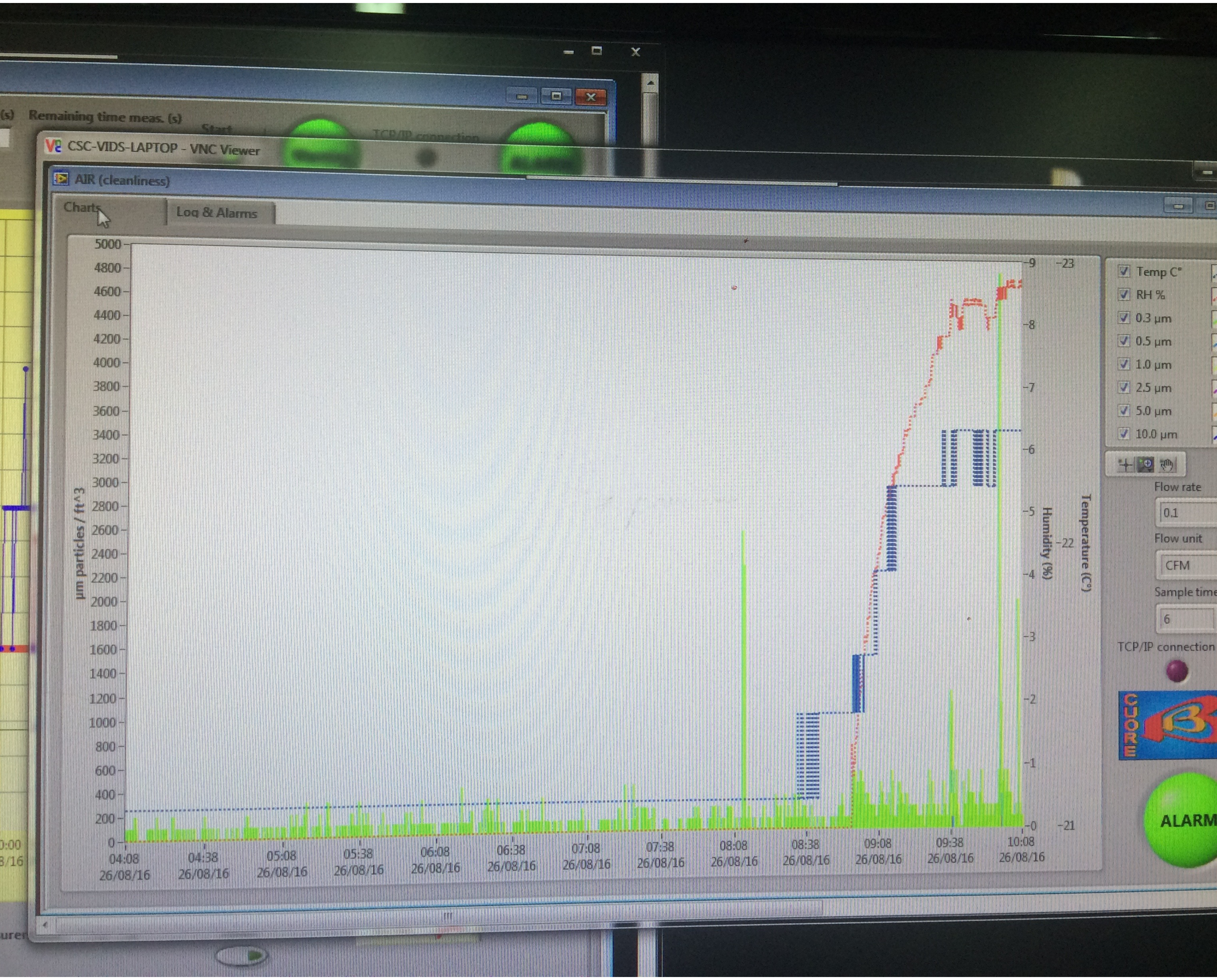

Figure 32: Particle count (green, sky blue, yellow, purple, orange, blue) , humidity (red), and temperature (dark blue) plotted against time for the primary clean room. This is one of the plots that constantly needs to be monitored, and signals which parameters set off which alarms.

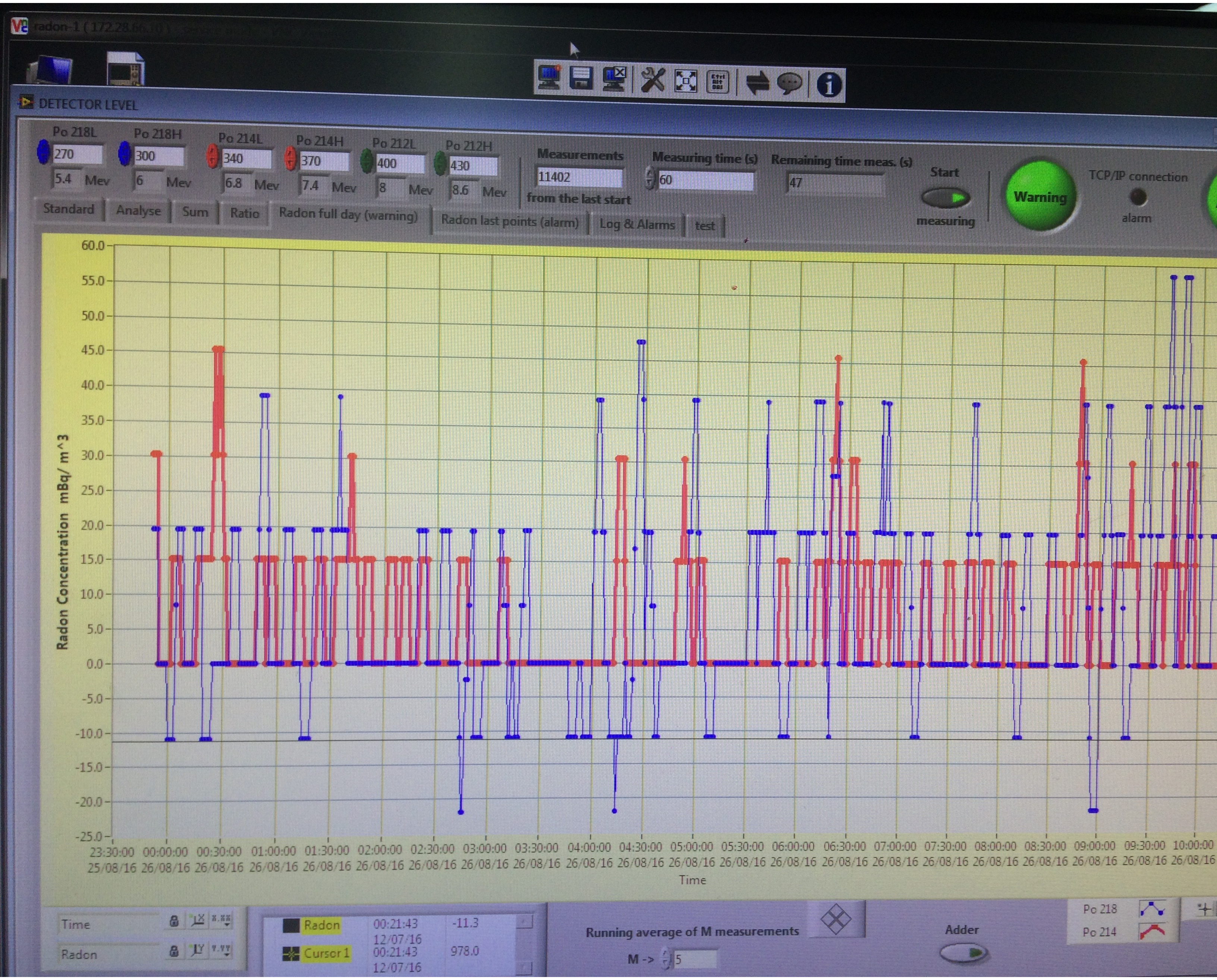

Figure 33: Plot that shows the concentration for different daughter nuclei of radon. Whenever one of these values spiked, I had to notify the workers in the clean room immediately, as a sustained high level of these nuclei could be life threatening.

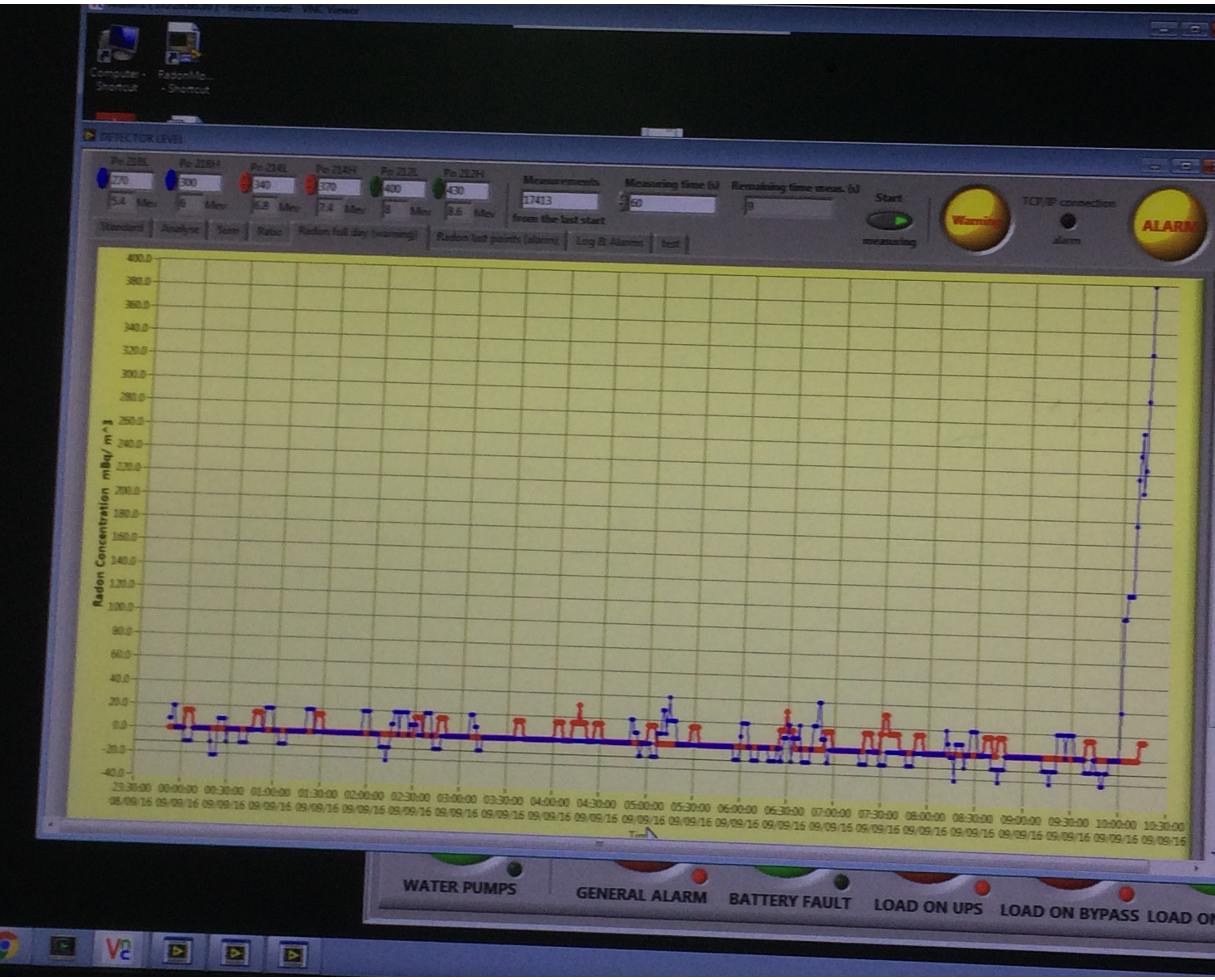

Figure 34: Screenshot of the previous plot when the UPS system failed, and everyone was panicking. Very scary moment in the timeline of CUORE as all the research and years upon years of work was almost compromised in these couple of days, as we waited for a technician to come to Assergi and fix the system.

Figure 35: Houses in Assergi were still being rebuilt from an earthquake that struck a nearby town named L'Aquila in 2009. A local resident named Mathew (he was actually from Australia and grew up in Italy) who worked at a place known as Hotel Giampy (hotel and restaurant) told me about some of the government corruption that takes place at the local level, and how many of the foundations of the buildings weren't structured with cement, but with a mixture of cement and sand because it was cheaper. The constant rain eroded many foundations over time, and they fell easily when the 5.8 earthquake hit.

Figure 36: Beautiful landscape of Assergi and Gran Sasso.

Figure 37: Another beautiful landscape of Assergi and Gran Sasso. In the background you can see a ski lift going up Gran Sasso (the red objects on the mountain side). Apparently, this was the same mountain where Benito Mussolini was rescued by German paratroopers in World War 2.

Figure 38: Stark differences in architecture like this were all around the city. This, of course, is because of the earthquake. Some buildings, like the one on the right, were abandoned and not renovated.

Figure 39: This figure is a continuation of the previous figure. The abandoned building extended down the block. Also, the streets were tiny and cobblestone, which is common in Europe because they maintain a lot of the older architecture developed centuries ago. These tiny streets lead to the tiny cars you see all over Europe. Utilizing older architecture is also why the buildings fell easily during the earthquake.

Figure 40: Many people had their own gardens where they grew fresh tomatoes, basil, apples, pears, etc. I believe this was one of the reasons why the Italian food was so delicious; practically all the food being used by any nearby restaurant was made with home grown vegetables, spices, and fruit.

Figure 41: Garden in Assergi.

Figure 42: Two men that I met as I was walking around taking pictures. These guys were extremely nice and welcoming to a foreigner. In fact, the man on the right with no shirt actually said he used to live in California (which is where I'm from) and said he used to be a 'dancer' (whatever that means) which is to no one's surprise considering he had no shirt on.

Figure 43: Graffiti on the wall of the entrance to the graveyard.

Figure 44: Fountains like these were all over Italy. They dispensed clean drinking water, as it was illegal to dispense non-pottable water if there was no sign in front of the fountain stating so.

Figure 45: One day when I was taking photos around Assergi, this dog started leading me around the village. He would stop when I would stop to take a picture and wait for me to continue to walk. He stayed with me for a couple hours until we reached Hotel Giampy. His owner pulled up in a car while I was eating pizza and he hopped right in. It amazed me how conscientious this dog was. He is also in some of my previous pictures if you pay attention close enough.

Figure 46: One of the perks of coming to Italy around Ferrogusto, was the parties! The arrosticini was a favorite in the Abruzzo region. Arrosticini can be described as chunks of goat meat cooked on this special grill, coated in salt (their favorite two ingredients for every food was olive oil and salt, which works surprisingly well).

Figure 47: Hotel Giampy, a hotel/restaurant that we spent a lot of time at.

Figure 48: Il Parco, the main building of the bed and breakfast that welcomed us into Italy. They owned a pink house in Assergi that we stayed at.

Figure 49: Mother and daughter who helped run the bed and breakfast. Two brothers were the primary owners, and the bed and breakfast is maintained by them and their wives and daughters. This idea of family owned and run businesses was a common theme in rural Italy.

Figure 50: The Pink House.

Figure 51: Beauty of rustic Italian architecture.

Figure 52: The beautiful view from the Pink House.

Figure 53: Nearby church. This fountain had the freshest, cold water I've ever had in my life.

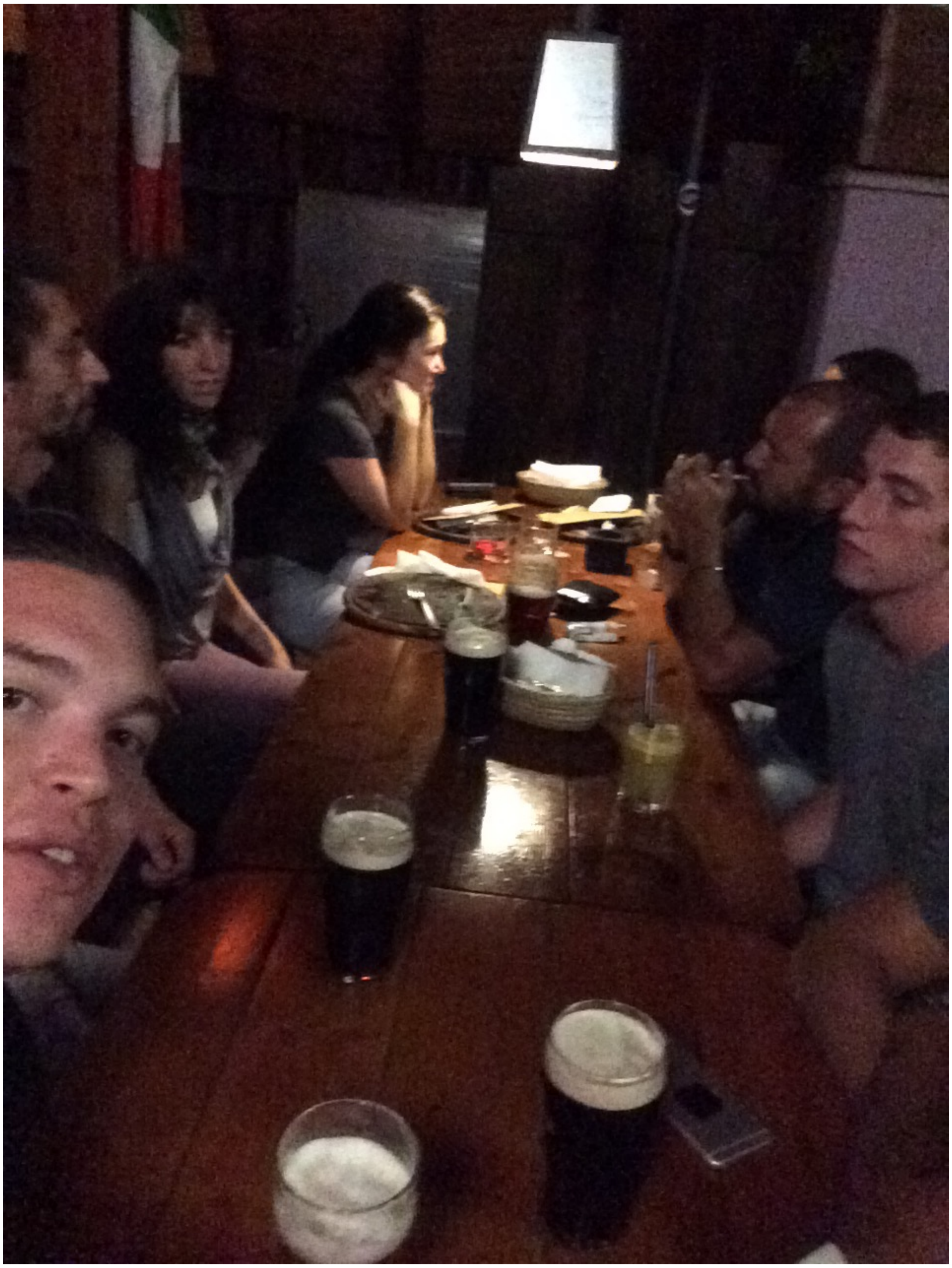

Figure 54: This was taken at a restaurant known as Poco Loco, that served delicious (of course) American food including hot dogs, hamburgers, french fries and more. This picture includes some people from the CUORE collaboration as well as some people from the GERDA collaboration, who also works at LNGS.

Figure 55: Massive hamburger from Poco Loco. And they say Americans are fat!

Figure 56: Beautiful restaurant hidden from the main roads of L'Aquila (a city near Assergi). They have a lake in the back with fish, that they serve fresh.

Figure 57: Dinner with the Berkeley and Italian collaborators at Assunta. This meal lasted approximately 5 hours, as eating was an entire activity in this culture. 5/6 course meals were completely normal, and if you look at the table, you can see a deck of cards as we were playing an Italian card game. Playing games and conversing was normal during meals in Italian culture.

Figure 58: The interior of the Berkeley house, which is an apartment in the middle of Assergi that housed some of the doctorates and post-docs from Berkeley.

Figure 59: Alexey Dorbachev, September 2016.

Figure 60: Delicious bruschetta served at one of my favorite restaurants from the trip, La Unico Posto. The atmosphere at these restaurants was much more relaxed and friendly then the restaurants in America, in that the restaurant owner gave us free stuff simply because he enjoyed our company, encouraging us to come back.

Figure 61: One of the dinners at Hotel Giampy. To be honest, it wasn't as good as the other restaurants I had but it was still delicious.

Figure 62: Another dinner with a couple of the Berkeley collaborators.

Figure 63: Ryan, Kevin, and I completed a challenge to eat 50 arrosticini (3kg of meat), and we got these shirts and our pictures on the wall.

Figure 64: Dinner with the people who worked to install the towers. One of the hardest working group of people I've ever met.

Figure 65: Picture with Tommy ODonnell, one of the post-docs from Berkeley, the day before he left to the United States to begin work as an assistant professor at Virginia Tech. He was definitely one of the most kind and funny people I met on the trip, and was always open for stimulating conversation. Hope you are doing well, along with all the other amazing people that I met on the trip.

Figure 66: These people were amazing physicists with interesting personalities that taught me a lot about the world of experimental physics, European (primarily Italian) culture, and life.

Begin forwarded message:

From: Oliviero Cremonesi <Oliviero.Cremonesi@mib.infn.it>
Subject: Re: [CUORE] CUORE tower installation completed
Date: August 26, 2016 at 3:57:45 AM PDT
To: CUORE Collaboration <cuore@mib.infn.it>

Dear all,
today we have reached another very important milestone for our experiment. I had the honour and the luck to be the logging shifter for the 19th tower and it was really an incredible emotion to follow so closely the installation phases. The 19 towers are now suspended from the cryostat and we have maintained a very large number of active channels. That's really great. The work is not yet finished but this is an historic moment and a great accomplishment.
A special thank to Tommaso for the professional design and preparation, the other members of the installation team Alberto, Lucia, Mauro and Matteo , Carlo and Paolo for sitting at the director's table, the guardian angels of the support team Claudia, Marco, Donatello and Davide, the rescue team Chiara, Marco and Tommy and the monitoring team Luigi, Giovanni and David, the local shifters Aaron, Bridget, Marco, Ryan, Surya, and the Kevins, the loggers Laura, Maria and Stefano,Laura for managing the shifts,v the CR6 installers Joe, Alexey and Tyler, and all the collaboration that has contributed to the process controlling continuously that everything was fine. I'm sure I'm forgetting some relevant contribution and I apologize for that.
This is a great moment and I believe thsi has been a great experience for our Collaboration.
Oliviero

Figure 67: The email thanking everyone who helped with the final tower installation. I was taken aback that he mentioned the Cal Poly Team (Kevin Armenta, Kevin Phung, Aaron Wong, and Ryan Werth) for helping in the installation of the towers, even though it seemed like our responsibilities were tiny compared to theirs. They were very appreciative and I'm ecstatic to be a part of this group of great physicists and engineers who are contributing to the legacy of particle physics.