Cryogenic Camera for High Voltage Monitoring in Liquid Xenon

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The evidence that has been found for Dark Matter becomes increasingly more prevalent as the years pass and scientific technology becomes more sensitive and advanced. Direct detection of Dark Matter through the use of the XenonnT detector in Gran Sasso is the largest most precise vessel currently constructed. The REU students in the Xenon group were able to construct and test a vessel to house a camera in cryogenic conditions that would be able to record the interactions between Dark Matter and Xenon nuclei.

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1. INTRODUCTION

1.1. Dark Matter

Early astronomers focused much of their calculations and observations of space on the luminous matter that was able to be understood based on the scientific advancements created by their predecessors. One of the earliest more concrete possible examples of the existence of Dark Matter in our universe comes from the astronomer Fritz Zwicky in the 1930s. Zwicky used the luminosity of galaxies to calculate their velocity. Zwicky focused on the Coma Cluster of galaxies and found a huge discrepancy in the values of velocity he calculated using luminosity based on his use of the Hubble parameter[1]. This large difference in values allowed him to hypothesize that a large factor of the matter found in these galaxies and ultimately in the universe, is non-luminous matter.

The evidence of dark matter in the cosmos has been an integral part of the creation of the standard model for cosmological use. The free non-reactive properties of dark matter are predicted to be the matter that molded the self-interactive clumping of luminous matter in the beginnings of the universe[2]. Thus the clustering of galaxies and stars in the night sky can be attributed to dark matter’s observed properties (See Figure 1). Given the many calculations of the speed and rotational curves of stars that have been calculated, scientists are forced to consider that there is matter fixing these stars in the space of their galaxies rather than flying off into deep space.

1.2. The Bullet Cluster

Another more prevalent example of direct evidence for Dark Matter and its properties is the observation of the interactions of the Bullet Cluster. The two galaxies crossed paths and were able to carry on unaffected by the other. The hot gas clouds surrounding them reacted with one another and pulled them off of the galaxies
FIGURE 1. Galaxy formation over time due to Dark Matter and its web-like properties

(see Figure 2). This allowed astronomers to recalculate the masses of the galaxies by using gravitational lensing[3]. Gravitational lensing occurs when large amounts of matter distort light from stars behind them because of the magnitude of their gravitational field. Researchers were able to witness the gravitational properties of the dark matter surrounding the galaxy by the significant increase in the amount of light that was bent by the observed matter. This is great evidence for the existence of dark matter because the comparison between previous gravitational lensing and this experiment shows how the dark matter around the galaxy increased the amount of gravitational pull that the matter in that region experienced. Based on what we know from many observations about dark matter's gravitational abundance, this offers a clear example of an increase in gravity that has no other reasonable explanation. Similarly, this is great evidence for the low self-interactions of dark matter because of the lack of reactions between the dark matter surrounding each galaxy as they collided. Without the dark matter, we would expect to see clear reactions between the atoms in the galaxies, giving us great evidence for the existence of dark matter in the formation of our galaxies.

1.3. Methods for understanding Dark Matter

There are a few different methods for studying and understanding dark matter that scientists have come up with over time. We employ these options of detection and production in order to gain more knowledge of the dark matter, identify individual dark matter particles, and observe possible interactions that are non-gravitational. Direct detection of dark matter focuses on the interaction of the dark matter and atoms we have studied and understand. Indirect detection focuses on searching for dark matter using γ rays, charged cosmic rays, X-rays, microwaves, etc. Production experiments focus on trying to create dark matter on earth in experiments such as CERN, LHC, etc.

2. THE XENON EXPERIMENT

This form of detection of dark matter is considered the scattering of atoms. The Xenon experiment uses a very large dual-phase time projection chamber (TPC) that records interactions between Xenon nuclei and dark matter particle candidates such as weakly interacting mega particles or WIMPs (See Figure 3).

The liquid Xenon atoms in motion excite some of the surrounding Xenon atoms and ionize others. The excited atoms emit photons of light detected by the Photo-multiplier tubes lining the top and bottom of the vessel. We call this light scintillation light and it is denoted in this step as the S1 signal output.

The electrons freed by ionization are then drawn
towards the anode where they will react again with the molecules of gaseous Xenon in the second phase of the chamber. The strong electric field in the gaseous Xenon section of the chamber accelerates these electrons enough to cause a larger flash of light upon collision which we denote as the S2 signal output.

The pattern of the S2 signal gives data relevant to the transverse position of the interaction of molecules inside the chamber, as well as allowing the researcher to separate the interactions classified as Dark Matter collision events and events of other radioactive contaminants. While the time between reactions in S1 and S2 tells researchers the depth of the reaction inside the chamber.

We house this experiment inside of the Gran Sasso mountain in Italy for many reasons. First, the experiment is very large so the space needed to house this experiment needed to be very big in order to safely complete it. Secondly, the location is important for performing scattering experiments on earth because experimenters must ensure that the interactions they are witnessing are that of actual dark matter candidates and not other particles and matter. Housing this deep inside the mountain ensures that cosmic radiation and rays are not able to make it through the water tank and the many layers of the mountain’s rock. We use the Monte Carlo simulations to set a basis for the types of interactions we expect to encounter during the experiment to rule out impossible scattering.

2.1. The 2021 REU Project

The impacts of COVID-19 are still making lab work and collaboration strained as safety regulations force countries to remain separate and communicate through online channels such as zoom. Despite these complications, the students chosen for the 2020 summer program were offered the chance to participate in the summer of 2021 despite any changes in eligibility. The students were also allowed to attend the program in person if they so chose to. This allowed the 2021 XENON group students to take part in an exciting hands-on project of the experimental design of a cryogenic camera vessel to record the interactions between Xenon nuclei and dark matter particles inside the XENONnT and future versions. The students began with research and reading into the XENON experiments, cryogenic hardware, cryogenic camera testing, etc. The students began with basic tasks to prepare for the construction of the camera vessel. Sanitizing flanges, copper gaskets, and the inside of the vessel itself. Proper sanitization was important for keeping the conditions of the chamber at expected values. We also wanted a pure system to ensure we could recycle the Xenon for future use. The students gained great experience with wire working and electrical understanding. Students were able to unsolder multipin connectors, solder wiring, prepare wires for connection, etc. To prepare the wires, students cut the connector side of the AC wire off, stripped the smaller wires inside, and crimped the individual loose wires with ferrules for easier and cleaner connection of the PAX-P and PAX-T output controllers (See Figures 5 and 6).

The construction of the outer chamber involved carefully connecting flanges, making sure not to scrape any metal pieces to ensure the connections would be true with no possible leaks. As well as tightening the screws and learning to use torque wrenches to tighten
Once the connections were made and the vessel is closed, students got the chance to experience testing the connections they tightened for any potential leaks in the system using a Helium leak test. This included creating a diagram of all connections they needed to test and recording the values of Helium detected by the connected system to see any changes of more than a magnitude of 10 (See Figure 7). Students then were able to test the connection of the flanges and other ports by spraying a small amount of Helium gas into the small test ports in all of the connections (See Figure 8). This test is not something many physics students get to see a side of when taking part in experiments because they focused more heavily on data analysis. But this gave the students a great example of how experimental the construction of the test chambers are and how much care and testing is needed for the apparati before they’re given to scientists for their experimental usage.

Preliminary testing included the use of Nitrogen to test the vessel’s ability to remove heat from the connected system. If the system proves to have adequate cooling responses, Xenon can then be filled and the full range of the cryogenic capabilities of the camera chamber can be tested. On the final day of the program, we filled the vessel with Xenon and ran tests (see Figure 9). The large chamber in the back was
connected to the nitrogen which flowed in, cooling the system and removing heat from the vessel we connected it to. The two sensors inside allowed nitrogen to flow freely when the heat removed enough to fall below the lower sensor, then stop flowing once the level of nitrogen reached the top sensor. The main vessel was filled with Xenon gas which cooled significantly and increased in density causing the molecules to fall, then when they hit the warmer parts of the vessel near the bottom they increase in density and rise again in its own regulated cycle of convection. We found some issues in our system of removing the heat from the vessel which stopped us from seeing the expected pooling of liquid xenon in the bottom of the vessel once it reached the needed temperature. Roughly -108 degrees Celsius. In figure 9, the outputs from our temperature sensors show this issue:

- The Bottom of the vessel temperature was -6.43 degrees Celsius
- The top of the vessel temperature was -11.8 degrees Celsius
- The temperature of the copper cold finger in the cooling chamber is -103 degrees Celsius

Next steps would be to readdress the insulation of the heat removal chamber to find where we are losing cooling capabilities to heat flow.

This project is the first of many experiments testing the possibilities of using a cryogenic camera to record dark matter interactions inside the XENONnT and future versions. Further changes to the design and testing methods are expected and encouraged.

3. CONCLUSIONS

Based on the tests run to measure the capabilities of our constructed vessel, there is still a lot of work to
do in order for it to reach the cryogenic temperatures we desire. Future work on this project will include bringing on more sensitive cameras and personnel that understand them. The recent breakthroughs in cryoelectron microscopy shows promise for imaging of atoms and smaller particles, which could be tweaked for use in projects like this one. Similarly more sophisticated vessels could be used for testing at a more serious level. Given the constraints of the time this program ran, time needed for parts to arrive, and availability of the staff involved, the XENON group scientists did a lot of work and showed some great science.

This project stands out in the long list of previous XENON group REU years. This year students not only strengthened their knowledge of physics, but they also participated in uncharted experimental research as they would in future career positions. As physicists we often use the example conditions of a vacuum to produce desired outcomes, this project brought the vacuum use-age to real life and showed the applicability of teachings of physics in the classroom setting. Similarly, this project strengthened students understanding of electronics because of their work with wiring and electrical outputs. It also introduced students to the importance of thermodynamics and its effect on the testing of systems that require things like cryogenic temperatures. The ability to construct a vessel, test it, and continuously tweak and retest it also allowed students to gain confidence in their ability to apply their knowledge and explore the forward and backward steps involved in experimental physics.

When we explain positions of work in physics fields we often focus on data taking and analysis. This project goes to show that there is also a hands-on component of experimental physics. That is a great thing to share with undergraduate minds because of the inspirations it could give them to pursue more physics field careers. This project is the first of its kind to test using a cryogenic camera in the XENON experiment and it won’t be the last.

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REFERENCES