Repairing the ^{3}He TPC Neutron Spectrometer

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The "Cyclon" detector is a gaseous TPC based on carbon tetrafluoride (CF_4) and ^{3}He developed by Dr. Hidefumi Tomita as a prototype dark matter experiment and as a potential radioactive material detector [1]. Over the last two years, a spark has developed inside of the apparatus, making data taking impossible. For that reason, we transfered the valuable ^{3}He to a storage vessel, opened up the chamber and diagnosed the issue. Specifically, we removed dust, clipped fibers that were potentially grounding the high voltage, cleaned the oxidized anode plate and ultimately found but were unable to replace a burn on the anode wire mesh. The result of this work, whether the spark is removed, is to be determined.

I. THEORY

Dark matter has been proven to exist and interact via the gravitational force from cosmological observations, but has yet to be seen directly by particle experiments. Dark Matter does not interact electromagnetically and can only be directly observed via weak interactions. Experiments search for this by looking for the nuclear recoil from a Dark Matter particle colliding with a nucleus.

A gaseous Time Projection Chamber (TPC) is well equipped to be a direct-detection Dark Matter experiment because of background suppression via fine tracking abilities. The Dark Matter signal would be a near point in space, while backgrounds like alpha particles or muon leave tracks that are easily reconstructed and rejected from signal.

The primary background left is from neutrons. Neutrons also do not interact electromagnetically and background neutrons can only be seen in a nuclear weak scatter, leaving only a point in 3D space. In practice, this would be suppressed by surrounding the detector in layers of low-background lead and steel.

The principals of the time projection chambers rely upon 1) triggering on scintillation light 2) drifting of ionized electrons created by charged particles and 3) collecting / amplifying the electrons as a function of time. When a neutral particle enters the chamber and interacts, it creates scintillation light [2]. This is collected by photo multiplier tubes (PMTs) to trigger the collection of signals created by ionized electrons. The electrons drift towards sensing / amplification wires due to an electric field, arriving O(milliseconds) after the triggering light. Timing difference is used to reconstruct a third spacial dimension - signals close to the mesh arrive sooner than signals further away. When the electrons arrive at the mesh, they are exposed to an extremely high electric potential, causing them to heavily ionize and scintillate. This amplified light is then captured on a camera.

II. APPARATUS

The apparatus, designed by Dr. Hidefumi Tomita, is called the Cyclon and uses 170 Torr of CF_4 as its medium, chosen for its scintillation properties [1]. A diagram of the Cyclon can be seen in Figure 1. The electric potential in the drift region is created by a series of copper rings of decreasing electric potential of -150 volts/cm. The electrons drift towards a copper mesh. On the opposite side of the mesh is a potential of +6000 volts/cm, large enough to greatly amplify the signal for the CCD camera operating above the apparatus.

For the sake of characterizing the neutron background, the TPC was filled with 40 Torr of ^{3}He. Under normal conditions in the lab, the ^{3}He captures a thermal neutron approximately every 5 seconds.

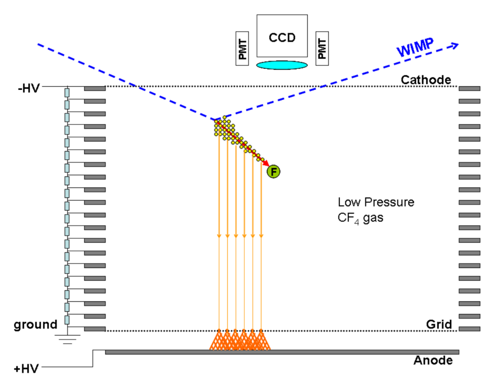

FIG. 1: TPC Apparatus, courtesy of Dr. Hidefumi Tomita's Thesis [1]

For data acquisition, the signals from the PMTs trigger the camera when there is greater than three PMTs in coincidence. A pictorial representation of the data acquisition system (DAQ) can be seen in Figure 2. The system is inside a NIM crate, allowing for the expansion of the DAQ in the future. The signals are 10x amplified, passed to a discriminator, passed through a Nim-to-TTL level adapter and end in a coincidence module. The discriminator is tuned to the single electron signal for each PMT. If coincidence is made, a trigger is sent both to the computer and camera to begin data acquisition.

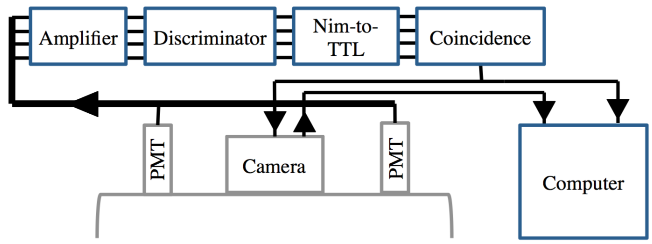

FIG. 2: Electronic setup.

The TPC is connected to a piping system to allow for the removal, storage and then replacement of the TPC gas with minimum loss. The diagram of the piping system can be seen in Figure 3. The oil rough pump brings the system, including the storage tank, down to O(1) Torr vacuum, while the Turbomolecular pump brings the system down to O(10^{-6}) Torr. The ^{4}He gas canister is used to purge the system, making any residual gas helium instead of a potentially destructive air mixture. The ^{4}He is also used for leak detection.

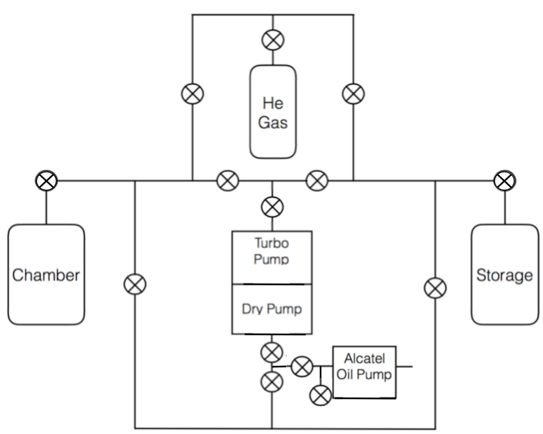

FIG. 3: Piping setup.

III. PROBLEM DIAGNOSTICS

The experimenters before us, Brandon Ling and Zachary Orent, noted that data collecting was impossible due to a large spark inside of the chamber when the anode and cathode are at operational voltages. An example event can be seen in Figure 4. This same spark was seen by further previous experimenters Shiyu Zhou and Emmanuel Fernandez in 2016, which required the team to open the TPC [3]. They temporally repaired the experiment by removing dust and cleaning the mesh. However, the spark has returned at approximately the same spot, tripping the high voltage supplies and making data acquisition impossible. This required us to open the vessel and make similar, hopefully more permanent, repairs.

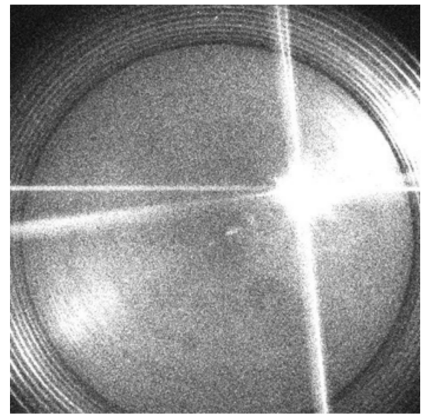

FIG. 4: Example event with large spark.

IV. TRANSPORTATION PROCESS

Due to the precious ^{3}He inside of the TPC, the gas needs to be stored before opening the vessel. The process is complex and careful. Instructions on how to do so can be founded at http://physics.bu.edu/˜sulak/AdLab17/. An abridged version of the process is the following:

1. Rough pump entire system, including storage tank.
2. Turbomolecular pump system to low vacuum.
3. Leak test with acetone over all joints in system.
4. Remove oil pump from system.
5. Open TPC valve and bring storage vessel to equilibrium pressure.
6. Pump from TPC to storage, down to ~ 2 Torr in the TPC.
7. Cork system and open chamber.

After opening the vessel, inspection, and closing again, the gas must be placed back into the TPC. The process is very similar to taking out the gas, except with pumping from the storage tank into the TPC instead of vice versa.

The vast majority of our time was spent in the 3^{rd} step of leak testing. It was important to make the system air-tight as to not vent helium to the atmosphere. In this process, we were forced to replace several couplings and were unable to use the ^{4}He system due to a large leak.

Due to step 6, there is a minimum loss of 2% of ^{3}He at each transfer. Since the transfer happens twice, we are losing approximately 4% per entire repair cycle.

V. VISUAL INSPECTION AND REPAIR

After the transfer, we used a lifting table and hand-operated crane to lift the lid off of the can to expose the anode and cathode.

We did several things to mitigate sparking:

- Remove dust. The TPC was last opened in an unclean environment, allowing dust to enter the chamber. Under voltage, the dust wedged itself into the fine mesh, leading to sharp points that could spark. We attempted to remove, with mixed results, the dust with tweezers and high pressure air.

- Clean the anode plate. Upon inspection, the polished plate had a visible layer of oxidation, which we removed with acetone and kim wipes.

- Clip supporting fiberglass fibers. These fibers, while an insulator, had the potential of touching high voltage and the grounded can, potentially causing a short circuit.

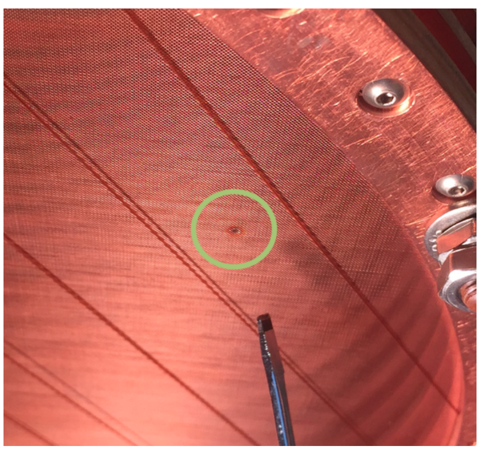

FIG. 5: Burn on the grounding mesh.

These steps may not be sufficient to solve the sparking issue. A visual inspection of the grounding mesh showed a 2 mm scorch mark where the spark had consistently occurred, seen in Figure 5. This spark site is most likely self sustaining - a random spark caused the area to deform, leading to more future sparks and only worsening the deformity. This can only be fixed by replacing the entire mesh. While this is not a difficult process, we did not have the replacement mesh, meaning that the work of replacing the mesh will have to be done by future experimenters.

VI. CONCLUSIONS

We successfully setup the DAQ system, recreated and diagnosed the spark issue. We then went through the process of leak testing the pipe system and transferring the ^{3}He gas into a storage tank. We also opened the TPC and made some improvements, but are unsure if we fully repaired the system. The next round of students will need to replace the grounding wire mesh and transfer the ^{3}He back into the TPC to complete the repair.

In regards to ways of improving the experiment, I would recommend that the TPC use ^{4}He instead of ^{3}He. The much cheaper gas would make the gas transfer process much easier and much less costly, but it would detect many fewer thermal neutrons. However, cosmic muons are still visible and perhaps a lightly radioactive source can be added inside of the chamber to see alpha particle tracks. Replacing the gas would make a repair process much quicker, as the ^{4}He can simply be vented to the atmosphere without the threat of losing thousands of dollars of a precious gas.

VII. REFERENCES

[1] H. Tomita, *Detector Development for Direction-Sensitive Dark Matter Research*, Boston Uni., 2010.

[2] C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016)

[3] E. J. Fernandez, *Repair of Time Projection Chamber*, Boston Uni., 2016.