XENON1T Cryogenics and Vacuum
Report for 2015 Columbia REU Program

Name: Cameo Lance
University of Florida
Department of Physics
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Abstract
XENON1T is a third generation direct dark matter detector which is expected to begin taking data in January 2016. The method of detection utilizes a dual phase time projection chamber with an applied electric field in order to measure scintillation and ionization. The xenon will be cooled to 180K which will cause the xenon to be liquefied to achieve a higher density in order to increase sensitivity. To efficiently keep the xenon cooled, it is contained in a double-walled cryostat in which the outer region is under vacuum to minimize heat transfer via convection. My role during this REU program was to be a cryogenic and vacuum technician. During my summer I assisted in detecting and resolving a leak in the cryostat. I also designed, and began the assembly of, a portable pumping station to be used primarily for facilitating the pumping of a vessel dense with out-gassing electrical wires. The portable pumping station will also be used during leak testing and on other subsystems of XENON1T.

1 Dark Matter
The world as we know it is made out of matter that interacts with the electromagnetic force, strong force, and weak force. This enables, for example, photons, the force carrier of the electromagnetic force, to reflect off an object into our retinas giving the ability for humans, and other animals, to see the world around us.

In 2013 the ESAs Plank Satellite (Planck Collaboration, 2014) measured the matter which interacts in this manner contributes only 4.9 percent to
the total constituents of the universe. Dark matter, the other kind of matter which does not interact with the electromagnetic force, contributes 26.8 percent! The remaining 68.3 percent is attributed to dark energy, a wholly mysterious energy which is responsible for the current expansion of the universe and theorized to pervade all of space.

Short of knowing dark matter exist, humans know very little about it and are going to great lengths to discover it. Two types of dark matter candidates are Weakly Interacting Massive Particles (WIMPs) and MAssive Compact Halo Objects (MACHOs). The former is a more popular explanation and is what this paper will be focused on.

The name weakly interacting is misleading and does not imply that dark matter interacts only through the weak force, rather that dark matter interacts weakly with matter. We say this because if it were to interact in a stronger manner with visible matter scientist would have detected it by now. The WIMP is also a massive particle, we know the WIMP has mass because we have detected its gravitational effects.

1.1 Empirical Proof of Existence

In 1933 a swiss astronomer, Fritz Zwicky, noticed that the Coma Cluster had a larger kinetic energy than the visible matter could account for, from this he inferred the existence of ‘dunkle Materie’, and the concept of dark matter was born.(Springer, 2007) The idea was ignored for nearly 40 years until the early 1970’s when Vera Rubin, using optical rotation curves of spiral galaxies, noted that mass of the galaxy continues to rise linearly with its radius to a distance several times that of the disk isophotal (luminous) radius (see figure 2) despite the decreasing luminous mass observed.(Rubin, 1987)

Rubin became the first person to measure the galactic rotation curves, notice the velocity curve did not taper off as expected from the amount of luminous matter measured, and attribute this to the existence of an unseen matter. This was the first strong evidence of the existence of dark matter.

There are two methods of dark matter detection, indirect and direct detection. Indirect detection is a method which infers the existence of dark matter via missing energy in particle colliders such as the LHC, or observation of secondary particles from annihilation in the Sun or galactic center. Direct detection employs methods which utilize the weakly interacting nature of the supposed dark matter particle, the WIMP, by measuring WIMP nucleon collisions producing scintillation, ionization, heat, or any combination thereof. Several direct detection experiments, such as superCDMS,
Figure 1: This rotation curve plots the rotation velocity of six galaxies of similar morphology against the distance from the center of their respective centers. (Rubin, 1987)

Figure 2: This plot shows that the rotational velocity of this spiral galaxy remains constant near the edges and the regions far beyond the isophotal radius also rotate. This implies either, there exist an unseen matter near the edges holding the galaxy together and extended far beyond the luminous matter, or Newtonian gravity is wrong for large distances, though this hypothesis is not popular among current physicists. (Carroll, 2005)
LUX, and XENON100, are currently operational and have ruled out cross sections of $10^{-45} \text{cm}^2$ and larger. (S.E.A. Orrigo, for the XENON Collaboration), (Lang, 2013)

2 XENON1T

With 1 tonne of xenon in the fiducial volume, XENON1T is our latest and greatest attempt at directly detecting dark matter. After XENON10 and XENON100, scientists in the collaboration learned how to properly scale this detection method efficiently. Construction of XENON1T began in 2013 and continues today with a projected operation date of January 2016. The XENON experiment is located at LNGS in Italy, 1400m under Gran Sasso Mountain, shielded from alpha particles, beta particles, gamma particles, and most importantly cosmic rays. In fact, the detector (principal describes in figure 5) is located in a cylindrical water tank, about 10m high with a diameter of 9.6m, to add an additional shielding against muons (a cosmic ray) as shown in figure 4. These particles and their secondaries are undesirable because they interact in a similar manner as dark matter is predicted to and would constitute backgrounds.

Figure 3: Cross section of the XEON1T experiment located in LNGS. Left: Water tank with detector situated inside. Right: Operations building which houses a vessel for the recovery and storage of xenon (ReStox) and krypton column on the ground floor, Data Acquisition (DAQ) System on the middle floor and cryogenics and purification system on top floor.

3 Cryogenics System

The cryogenics infrastructure consists of 6 subsystems: the Xe cooling system, a Xe recovery and storage system (ReStox), a Xe purification system, a Radon removal column, a Krypton removal column, and control and
Figure 4: This schematic pictorially describes the method in which XENON aims to detect dark matter. Initially the WIMP will scatter off a xenon nuclei, the resulting energy will knock an electron free, ionizing the atom, and produce a burst of light referred to as primary scintillation (S1) which will be detected by the PMTs (photomultiplier tubes) at the top and bottom of the detector. Next an applied electric field will drift the electron up to the gas phase where an anode provides sufficient energy to extract the electrons which results in electroluminescent, this provides the light for the secondary scintillation (S2). The resulting light enters the PMTs, which utilize the photoelectric effect to generate photoelectrons, which are amplified and read out.
monitoring systems. Several of the cryogenics systems have an inner and outer region, the inner region or inner vessel, through which Xe cooled to 180K will travel, and the outer region or outer vessel which, under normal operating conditions, will be under vacuum of $\times 10^{-6}$ mbar in order to reduce heat transfer by convection.

### 3.1 Existence of a Leak

Just prior to my arrival a leak was detected in the cryogenics system. The conditions of the system were such that Xe was contained in the inner vessel whilst the outer vessel was under vacuum. Xe was detected in the outer vessel via the use of a residual gas analyzer (RGA) as the inner vessel was being filled with xenon. See figure 7.

The RGA is an instrument which attaches to a vacuum vessel and monitors the type and partial pressures of gases present in a system using mass spectrometry.

My first task was to help evacuate the cryostat into bottles on the ground floor in order to minimize the loss of Xe. This task included refilling our liquid nitrogen dewar then placing empty bottles in a chamber of liquid nitrogen to create a pressure differential so Xe would flow into the bottles.
Figure 6: This schematic represents some of the cryogenics system for Xenon1t, namely 3 cooling towers, a heat exchanger and the cryostat, which houses the detector. The gray lines indicate the outer vessel. The bold black lines indicate the inner vessel.

Figure 7: Here we see an increase of partial pressure due to xenon in the outer vessel upon filling the inner vessel with Xe. This rise in pressure contaminated with xenon indicates a leak.
3.2 Characterizing the leak

The first task in fixing a leak is to characterize the leak. To do this we first note that an increase of pressure in a region under vacuum indicates a leak. By pressurizing the inner vessel with $N_2$ and the outer vessel to vacuum, then pressurizing the inner vessel to vacuum and the outer vessel with $N_2$, we found the leak was mono directional. That is, the leak occurred when the inner vessel was pressurized to 0.5 bar with $N_2$ and the outer vessel at $5.3 \times 10^{-6}$ mbar. See figure 8.

![Graph showing pressure increase](image)

Figure 8: This graph shows an increase in outer pressure, which is under vacuum, occurs as the inner pressure rises past .4 bar indicating a leak.

A mono-directional leak rules out holes, for the leak should be present in both directions in this case.

The leak occurred when the inner vessel is under a pressure of at least 0.5 bar with a leak rate of $3 \times 10^{-3}$ mbar*L/s. This very large leak rate ruled out a leak in the smaller systems such as purification and the cooling towers. It was reasoned that the leak was due to a lack of sufficient torque on the 54 bolts in the inner vessel flange in the cryostat, see figure 9. The reasoning followed from the large area of the cryostat flange, relative to the smaller flanges of other parts of the system, would cause larger differences in force against the flange seal. (Eq 1).

3.3 Solution

The elastic torque equation (Eq 2) describes the amount of clamping force for a given nut torque. It includes a nut factor ($\kappa$) which attempts to
include frictional forces.

\[ F = PA. \]  

\[ \tau = \kappa DF. \]  

However real life is not a textbook scenario and there are uncertainties relating to friction, such as what the actual friction between the two surfaces is. A torque wrench is used to measure the torque applied to a bolt.

The solution is to tighten these bolts from 65 Nm, the torque which the bolt providers suggested, to 120 Nm, near the maximum torque the bolts could handle in the elastic regime.

### 3.4 Methods

In order to tighten the bolts on the inner vessel, the outer vessel needs to be removed. To remove the outer vessel, first the bolts need to be removed then the temporary floor is opened so the shell of the outer vessel can be lowered using 3 mechanical winches, then the outer vessel is temporarily stored in a cradle on the ground. Next the exposed mylar dressing of the inner vessel was covered with sanitary plastic as to reduce contamination. The bolts were tightened in 20 Nm increments from 65 Nm to 120 Nm. The interface of the flange, both top and bottom, was cleaned with alcohol, the 3 winches manually cranked the outer vessel into position, and finally the outer vessel bolts were lubricated and tightened to 50 Nm.
Figure 10: Outer pressure dependence on inner pressure before (in red) and after (in black) tightening the bolts on the inner vessel. The leak rate decreased as well as the inner pressure at which the leak began. The rise in the y position of the black line relative to the red is a negligible, relative to the inner pressure, effect from starting of the leak test at a higher baseline.

3.5 Results

Another leak test was performed. The results showed (see figure 10) that the leak rate decreased by 2 orders of magnitude and began occurring at twice the pressure.

Evidently tightening the bolts helped, but not enough. It seemed the bolts needed to be tightened more. Concerns about deforming the bolts under a large load were raised, so a load cell test was performed to measure the applied force. This entailed a mock set up of of the cryostat flange and bolts. A strain gauge load cell was placed between the flange components, and the bolt placed through them similarly to the flange of the cryostat. The force applied when we put the nominal torque was true however it was only achieved if we turned the bolt on the flange and held the nut fixed. This was due to the differences of materials used.

The bolt, nut, and flange of the cryostat are stainless steel where as the head of the bolt is silver plated. Two materials which are the same produce more friction than two materials which are different, so when the stainless steel nut is tightened on the stainless steel flange the friction is higher than the silver plated bolt on the stainless steel flange.

It was also noticed during the load cell test that tightening the bolts in increments reduces the final load. This is due to an increase of force lost to friction.
Figure 11: Outer pressure dependence on inner pressure for the final leak test. An increase in inner pressure does not cause an increase in outer pressure, this indicates there is no leak. The test was performed over a two day period in which during the night there was no decrease in inner pressure, i.e. we were not testing the system and the inner vessel pressure remained at 1.5 bar, however the outer pressure continued to decrease through the night from $7.94 \times 10^{-6}$ mbar to $7.8 \times 10^{-6}$ mbar.

Once again we removed the outer vessel, this time we flipped and tightened the inner vessel bolts in one motion via the head of the bolt. A final leak test was performed and the leak was no longer detected.

4 Portable Pumping Station

4.1 Motivation/Process

A Portable Pumping Station (PPS) is a system of vacuum pumps which includes a roots pump, to rough a system, and a turbo pump to obtain and maintain a high vacuum. The existing PPS is bulky, heavy, and used
primarily on the ground floor. In circumstances, such as leak checking, for which the top floor needs a PPS, it is difficult and dangerous to carry the existing unit up 2 flights of stairs. This also limits the availability of doing more than one activity which requires vacuum.

Further-more the porcupine, the interface between the TPCs and the electronics, houses densely packed cables made of Teflon and copper in the inner vessel. This device makes for a region that is difficult to pump and a large source of out-gassing. To reach a good vacuum and reduce the out-gassing from this region it is preferable to have a pump acting in close proximity to the porcupine.

I designed a more compact portable pumping station, which will be easier to maneuver and store, to be used for the porcupine and other tasks during the commissioning of XENON1T. To increase effectiveness for this task I learned how to use SolidWorks, a computer assisted design (CAD) program. This allowed me to make many renderings in order to assess different configurations of components.

### 4.2 Parts/Purposes

Two main designs came out of the process, first came a tall design which served as inadequate primarily due to the placement of the turbo pump. See figure 11. The turbo pump is a sensitive device and should not be vulnerable to environmental vibrations of any sort. To account for this, as seen in the middle and right most design, the turbo pump is supported by two struts which serve as shock absorbers.

![Figure 12: Several iterations of the PPS as designed with SolidWorks.](image-url)
The main components include a roots pump, a turbo pump and a controller. The purpose of the roots pump is to rough the system, from 1 atm to $10^{-3}$ mbar, as to not overload the turbo pump, which pressurizes the system from 3 mbar to $10^{-6}$ mbar.

Beginning with the top of the system, in red is an elbow which will connect to the system desired to be pumped. This elbow will have several options for size (not shown), the smaller inside the larger, for the accommodation of many ports.

The next item, in gray, is a CF100-KF40 flange with 4 (or two for later designs) radial ports which serves as a reducer from a CF100, e.g. the gate valve, to a KF40 which accommodates other desired systems, e.g. a pressure gauge or RGA. One of these ports is occupied by a manual angle valve as shown in darker gray. This angle valve will attach to a tee via a 2 in-diameter hose used to bypass the turbo pump during roughing. The tee connects to an emergency valve (yellow) which is connected to the roots pump (purple). Also connected to the tee is a 1.5 in-diameter hose which makes its way to the turbo pump. In bronze, attached to the turbo pump is a manual gate valve in order close the turbo pump.

A calculation of the deflection of the turbo struts under the 147.56 N of force from the gate valve, turbo pump and connecting mechanism lead me to choose 3 mm aluminum, because it is a light weight material with a high Young’s modulus.

After designing the system I chose parts to order and made a spreadsheet to organize prices and availability of components. Next I began assembling the PPS, however unfortunately the program ended before the assembly was finished.

5 Conclusion

The leak detected from the inner vessel into the outer vessel began at an inner vessel pressure of 0.5 bar and occurred in the cryostat. The solution to the leak was to tighten the inner vessel bolts, via the silver plated head of the bolt, from 65 Nm to 120 Nm in one motion as to decrease force loss to friction.

In the near future, the assembly of the PPS will be completed by a cryogenics and vacuum technician.
6 References


Rafael F. Lang, Department of Physics, Purdue University, West Lafayette, IN 47907, USA
