

Scintillation of Xenon doped Liquid Argon in the BACON Detector

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Abstract

The BACON¹ liquid argon (LAr) scintillation² detector prototype will be used to measure intensity, promptness³, and decay behavior for pure LAr and xenon (Xe) doped LAr mixtures. The goal is to aid in planning, cost reduction, and improved detection for the Deep Underground Neutrino Experiment (DUNE) [6]. The scintillation of LAr is in the vacuum ultra-violet (VUV), requiring detectors to use a wavelength shifter to detect light. The typical wavelength shifter used is tetraphenyl butadiene (TPB), which re-emits in the blue. The goal with BACON is to determine if xenon doping at the ppm concentration level is a viable option for LAr detectors. I have preformed initial calibration measurements with our residual gas analyzer (RGA), an important step for characterizing the purity of the LAr in the BACON cryostat. I am currently constructing the auxiliary components for BACON and plan to take data in the Summer of 2016.

¹ There is a list of abbreviations in Appendix A.

² Scintillation is radiation emitted from a media due to energy deposition by high momentum particles. This is distinct from Cherenkov radiation, which is due to particles traveling faster than the media's local speed of light.

³ Promptness is the measurement of the time delay between the actual time an event occurs and the time the event is detected.

Contents

	Abstract	1
1	Introduction	2
2	Theory	3
2.1	Cryogenics	3
2.2	Scintillation	4
2.3	Xenon Doping	5
2.4	LAr Purity	6
3	Experiment	7
4	Data	11
5	Conclusion	12
	References	13
	Appendices	
A	Abbreviations	15
B	Time Projection Chambers	16

1. Introduction

The search for the properties of neutrinos, dark matter, and physics beyond the standard model has led to the development of the LAr time projection chamber (TPC) for use as detectors. Cross sections for these types of particle interactions has led to the proposed development and construction of multi-kiloton LAr detectors, notably the DUNE far detector. Argon purity, cryogenic temperature, and low interaction rates pose many challenges for the construction and operation LAr TPC detectors. A primary goal for the BACON project is to understand the problems faced in construction of LAr TPC detectors, and to propose and prototype solutions which optimize cost and efficiency without sacrificing data quality.

The LAr TPC was first proposed as a neutrino detector by Carlo Rubbia in 1977.[14] The primary neutrino interaction which can be observed in a LAr TPC is given by [1]:



The ${}^{40}\text{K}^*$ will decay to its ground state ${}^{40}\text{K}$ with a γ emission, which will produce a ${}^{40}\text{K}$ nuclear recoil. The nuclear recoil will result in an ionization track in the LAr. The ions will recombine with the ionization electrons and produce scintillation, an important part of energy reconstruction. Such phenomenon occurs in other noble gases, but argon, which composes $\sim 1\%$ of the atmosphere, is by far the most common and affordable. Noble gases such as argon are ideal for use in TPCs because of the effectively zero electronegativity. If there is a free floating electron in pure argon, the electron will remain free without being captured by the argon. If an electric field is applied to the argon, the electron will drift through the argon along the field. The BACON project does not have a TPC, but the projects it is prototyping for do. The majority

of the discussion on TPC theory and operation is located in appendix B. LAr detectors are also used for direct dark matter detection, such as mini-CLEAN, and to explore physics beyond the standard model, such as proton decay.

The challenge that BACON will address involves the light detection system in LAr detectors. Light detection in LAr TPC detectors plays the important role of triggering⁴ the data acquisition system (DAQ). For beam pulses the DAQ can be triggered off of when the beam fires, but for random events such as a supernova neutrinos or proton decay, scintillation is the best way to trigger. The promptness of the light detection system is an important part of data acquisition in liquid TPC detectors. Current designs rely on LAr scintillation to first interact with TPB. The TPB is coated on the inside wall of the detector or sometimes directly on light detecting photomultiplier tube (PMT). This method of wavelength shifting has several problems which will be addressed in the scintillation section. The goal with BACON is to explore an alternative method of wavelength shifting via Xe doping.

The goal with BACON is to measure both the intensity and decay time of Xe doped LAr using different Xe concentrations. Achieving this goal will require precise knowledge of the gas concentration, which will be done with an RGA. The RGA runs on proprietary software which only runs on Window XP, meaning I had to acquire and install this operating system on a separate computer. There is a reported increase in scintillation intensity due to Xe [19]. The BACON project will measure the increased intensity and characterize it for different Xe concentrations.

2 Theory

There are several necessary theoretical concepts that must be discussed in order to understand neutrino detection in LAr TPC's. LAr must be maintained in its liquid phase, which requires an understanding of cryogenic physics and engineering. LAr scintillation is the cornerstone of LAr detectors and needs to be discussed in some detail. Xe doping in LAr is the major focus of BACON. The effects of Xe doping could be beneficial, but has its own drawbacks. The purity of LAr must be properly controlled as it effects scintillation yields. Even ppm levels of contaminants can reduce photon yield by 10's of percent depending on the contaminant.

2.1 Cryogenics

Liquid argon detectors function due to cryogenic technology. To design and operate LAr detectors requires an understanding of cryogenic physics and experimental techniques. The cryostat is essential to the operation of a LAr scintillation detector. There are efficient methods of cooling and maintaining temperature which should be employed. Cryogenics has several unique safety considerations which need to be understood.

To use liquid argon as a scintillator requires an understanding of argon's chemical properties. At atmospheric pressure, argon condenses at 87.3 K and freezes at 83.8 K. Any LAr

⁴ Triggering refers to the light detection system communicating to the DAQ when data acquisition should start.

detector will have a narrow operational temperature band. In order to obtain and maintain LAr temperature, the detector requires a cooling method and insulation. Liquid nitrogen (LN2) has a boiling point of 77.3 K and can be used to condense argon and cool the detector. Another choice is a cryorefrigerator, an example being a helium compressor. A cryorefrigerator will be capable of much lower temperatures than LAr and therefore must be regulated. An effective method of insulation is to surround the detector with a vacuum, eliminating as much thermal contact as possible with the outside environment. This vacuum-jacket or dewar can be difficult to seal properly and requires continuous pump operation to be properly maintained. Other layers of insulation, such as highly reflective BoPET⁵, can be used to help decrease heat leaks.

It is possible to raise the condensation temperature by raising the pressure in the detector, but it is safer to run LAr detectors at ambient atmospheric pressure due to risk of a boiling liquid expanding vapor explosion (BLEVE). For the sake of safety, most LAr detectors are run at atmospheric pressure.

The cryostat assumes three primary roles. One role is thermal isolation of the system. By creating and maintaining a vacuum around the inner section of the dewar. Another role is chemical isolation. Again by creating a vacuum around the inner volume prevents contact with outside contaminants which seep into the system. The last role is light isolation. Sealing the fiducial volume against light leaks allows for the of detection of rare, low scintillation intensity events.

2.2 Scintillation

LAr has a strong scintillation peak at 128 nm. This peak results from two distinct decay mechanisms, which each have different expected decay times. The detection of 128 nm is quite difficult, as it does not penetrate most types of materials. The current detection technique is to use TPB, which shifts the wavelength from 128 nm to ~420 nm [17].

Current theory suggests the scintillation of LAr occurs through a multi-step process. After ionization occurs, the argon ion binds to an unionized argon atom. On the order of 900 ps after the argon dimer⁶ forms, it recombines with the ionization electron, splitting the dimer pair. The now recombined ion is in an excited state, Ar^{**}. The Ar^{**} excited state is forbidden to decay to the ground state directly, and so decays to a lower energy excited state, Ar^{*}, on the order of 4 ps. Both of these transitions release infrared that has not been characterized. The Ar^{*} form another dimer pair with an unexcited Ar atom. The dimer then decays into two unexcited Ar atoms and the 128 nm scintillation.

The final dimer has two states: a singlet state and triplet state. The singlet state has an expected decay time of 6 ns, and the triplet state has an expected decay time of 1600 ns. [12] Due to the 3 order of magnitude difference in decay times, the singlet state is sometimes referred to as the fast component and the triplet state as the slow component. The relative abundance of the singlet state is ~ 25% corresponding to a relative abundance of the triplet state of ~ 75%. The

⁵ BoPET has several marketing names such as Mylar.

⁶ A dimer is two bound molecules of the same type, in this case atomic argon.

ratio of the singlet to triplet intensity has a measurable difference between nuclear and electronic recoils⁷. The technique for measuring the ratio of singlet to triplet is called pulse shape discrimination (PSD). PSD is very important for LAr detectors which do not have a TPC. While BACON does not have a TPC, it is prototyping for detectors which do have TPCs. PSD is not a primary goal with BACON, but we may decide to implement it if needed. As PSD is a part of analysis, this technique can be implemented after data is taken.

Wavelength shifting is an essential process in the use of LAr detectors. TPB is typically applied to the inside of the the detector walls or directly to the surface of the PMTs, as with ICARUS [4]. TPB shifts LAr's 128 nm peak to a peak centered at 420 nm with $\sim 100\%$ efficiency but introduces a ~ 10 ns delay in the signal [17]. A 10 ns delay is not a large detriment to PSD, but needs to be accounted for.

2.3 Xenon Doping

Measuring the properties of Xenon doping is intended to help solve some of the problems faced when building kilo-tonne size LAr detectors. Xenon acts as a wavelength shifter when dissolved in small concentrations in LAr. The scintillation from Xenon doped LAr has been measured to have a longer attenuation length⁸ than LAr scintillation, although measurements from more recent experiments are in conflict. More accurate measurements for these attenuation lengths are required. There is also new research which has revealed new possibilities for Xe doping.

Xenon freezes at 162.6 K, so is solid at LAr temperatures. Because Xe and Ar have similar chemical properties, Xe can be dissolved into LAr. The Xe concentration saturates at 16% by mass [23], which is several orders of magnitude higher concentration than required. A problem experiments have encountered with concentrations on the order of 1% or greater is Xe freezing in the apparatus. At high Xe concentrations, even if it is known exactly how much Xe was put into the apparatus, it is difficult to know exactly how much is dissolved in the LAr [12,18]. It has been reported that very low concentrations of Xe, the freezing problem disappears [18]. When considering use of Xe for a project like DUNE, 2% Xe in 40 Kt of LAr is 800 tonnes of Xe. This amount of Xe is prohibitively expensive and possibly exceeds world supply. Several recent experiments have tested at the 1 to 10 ppm concentration level [8,16], which would correspond to 40 to 400 Kg of Xe for DUNE, an affordable, attainable amount.

The presence of xenon interrupts the normal scintillation process of LAr and causes the energy, which would be emitted as 128 nm scintillation, to instead be transferred to the Xe. The Xe scintillation is emitted at 175 nm. The 175 nm scintillation could allow for the use of new materials for use in detectors. If new detector materials are not used, TPB has the same wavelength shifting properties for Xe doped LAr as pure LAr. It may still be beneficial to use

⁷ Nuclear recoil indicate an incident particle has a imparted kinetic energy to the nucleus of an atom, causing it to recoil. Electronic recoil is when kinetic energy is imparted to an electron by an incident particle, typically resulting in ionization.

⁸ Attenuation length is the $1/e$ ($\sim 63\%$) expected length for a photon to travel before scattering, i.e. if a beam of light travels the distance of one attenuation length in a material, the beam is expected to be reduced in intensity by 63%.

Xe as a dopant because it increases total light yield [19]. The $\sim 25\%$ increase in light yield at ~ 10 ppm Xe concentration in LAr has the potential to be a measurable increase in energy resolution.

One of the major arguments for using xenon doping is the attenuation length of LAr scintillation in LAr. The long-time standard measurement of attenuation length is 66 ± 3 cm [5]. The same experiment measured 170 ± 23 cm and 118 ± 10 cm for 3% Xe in LAr [5]. The the given explanation for the discrepancy is xenon clumping⁹ [5]. The clumping phenomenon is difficult to quantify, but it appears to be avoidable if much lower concentration is used [16]. The most recent measurement of the attenuation length of LAr scintillation in LAr established a lower limit of 1.10 m [7,8]. This measurement is at odds with the established value, and the discrepancy need to be verified experimentally.

A recent experimental study discovered a new strong spectral emission line in the infrared, which maximizes near the 1 to 10 ppm Xe in LAr [9]. This line is in the near infrared (NIR) and occurs at a wavelength of 1.18 μm . The 1.18 μm emission has a total photon per MeV yield about half that of the 175 nm line. While a reduction in light yield is undesirable, direct detection of the NIR could eliminate the need for TPB. Another possibility is to detect both the VUV and NIR emissions for maximum light yield, although this would be a budget increase instead of savings. It has also been shown that at the same Xe concentration, $\sim 86\%$ of the argon excitation energy is transferred to the 175 nm spectral line [9]. It is possible the use of NIR detectors could supersede or be used in combination with VUV detectors in the near future.

2.4 LAr Purity

The entire premise of a LAr TPC detector operation rests upon the liquid being free of electronegative and light attenuating impurities. If there are residual contaminants, scintillation in the desired spectral range will be highly attenuated. In order to ensure the purity of BACON, an RGA will be employed. The purity also has a dramatic effect on the drift lifetime of electron in TPCs (see appendix B). By measuring the relative concentrations of gas in the cryostat, it is possible to obtain the concentration in the liquid through Henry's law.

To understand the problem that contamination poses, it is instructive to look at measurements. It has been shown that nitrogen concentrations of 40 ppm can attenuate 50% of scintillation in argon [20], and 2 ppm oxygen in LAr attenuates 80% of the scintillation intensity [21]. At 1 ppm, water will attenuate the scintillation signal by 45% [22]. All of these indicate that the LAr must be as pure as possible. BACON has a getter with a rated purity output of less than 1 ppb for most gases [15]. All of these contaminants are absorbed by the walls of the cryostat when exposed to atmosphere, and the contaminants will diffuse into the system. A common method to deal with the seeping contaminants is to bake the system in an oven or with heating tape. For the best results with baking, the system should be in a vacuum.

In order to understand the composition of the LAr, BACON will use an RGA. The RGA ionizes gas via thermionic emission. The ionized gas is accelerated in an electric field and analyzed by a spectrometer. In order for this method to work, the mean free path of the ions

⁹ The xenon clumps together into nanoparticles, altering the attenuation length and other properties.

must be fairly long. As such, an RGA requires medium to high vacuum in order to operate, below 10^{-6} Torr. The ion current at a particular mass is directly proportional to the concentration of that molecule. Identifying what ion corresponds to what molecule is a bit of a challenge. As an example, let us say the RGA has a reading at 84 amu. I go look up possible molecules with mass 84 amu on the NIST website and discover there are 245 possibilities. In the case of 84, krypton is the most likely candidate, but the RGA does not tell me if there are small concentrations of other 84 amu molecules in my system. Despite this, the RGA will work well for determining the concentrations of lower mass contaminants, and the most troubling contaminants are low mass.

Henry's law states that for a liquid and gas at chemical and thermal equilibrium, the concentration of a substance in a liquid, c_a , is proportional to the concentration of that substance in the gas, c_g , by a constant H^{cc} :

$$H^{cc} = c_a/c_g$$

H^{cc} is tabulated for different substances at stp, for example H^{cc} for argon is 3.4×10^{-2} . H^{cc} is not actually a constant and depends on temperature. The temperature dependence is given by:

$$\frac{d(\ln H)}{d(1/T)} = -\frac{\Delta \epsilon}{R} \quad (3)$$

Where $\Delta \epsilon$ is the change in enthalpy (normally denoted by ΔH), the ideal gas constant R , and temperature T . This equation is solved by:

$$H(T) = H_0 * \exp\left(-\frac{\Delta \epsilon}{R} \left(\frac{1}{T} - \frac{1}{T_0}\right)\right) \quad (4)$$

Where H_0 is H^{cc} at stp and T is 298.15 K. H^{cc} is convenient to use because it is a dimensionless quantity, but it can be written in terms of other quantities. H^{cc} can be formulated as H^{cp} , which relates the partial pressure, p , of the substance in the gas to the concentration in the liquid by replacing c_g with p and H^{cc} with H^{cp} in (2). H^{cp} for argon is 1.4×10^{-3} mol per L atm.

3 Experiment

Many components for BACON were provided by Los Alamos National Laboratory (LANL). Components provided by LANL are: the BACON cryostat, a gas purifier, an RGA, a cryorefrigerator and cold head, and electronics readouts for thermocouples and even sensor. Additional auxiliary components require for operation are: a condenser, a vacuum system, and the LN2 cooling system. The cryostat was built for LANL to prototype the mini-CAPTAIN and CAPTAIN detectors, all three of which are prototypes for DUNE. The purifier primarily consists of a getter, but the condenser will contribute to purity as well. The vacuum pump is designed to insulate the system, and also works in conjunction with the RGA as the purity detection system.

The LN2 cooling system is designed to cool BACON in a timely manner but not so fast (2) to damage the PMTs.

The BACON cryostat has several components. Auxiliary components are a Cryomech AL60 cryogenic cooler (cryocooler) with cold head, a MonoTorr PS4-MT3 getter, two PMT's with PMT mounts, a thermocouple readout with two thermocouples, and a liquid level sensor readout. The BACON cryostat is a cylindrical dewar, 0.82 m tall (without instrumentation) and 0.58 m in diameter. The inner volume can hold up to 100 L, although operational volume is not expected to exceed 60 L.

The argon gas purification system is comprised of a standard argon gas cylinder with a regulator, the getter, the argon condenser in combination with the cold head, and the cryocooler. The getter, which is a type of gas purifier, has pneumatically actuated valves and requires an external compressed air source in the form of a nitrogen gas cylinder. The getter is rated to remove oxygen, nitrogen, and water to less than 1 ppb [15]. The cold head is rated to remove 60

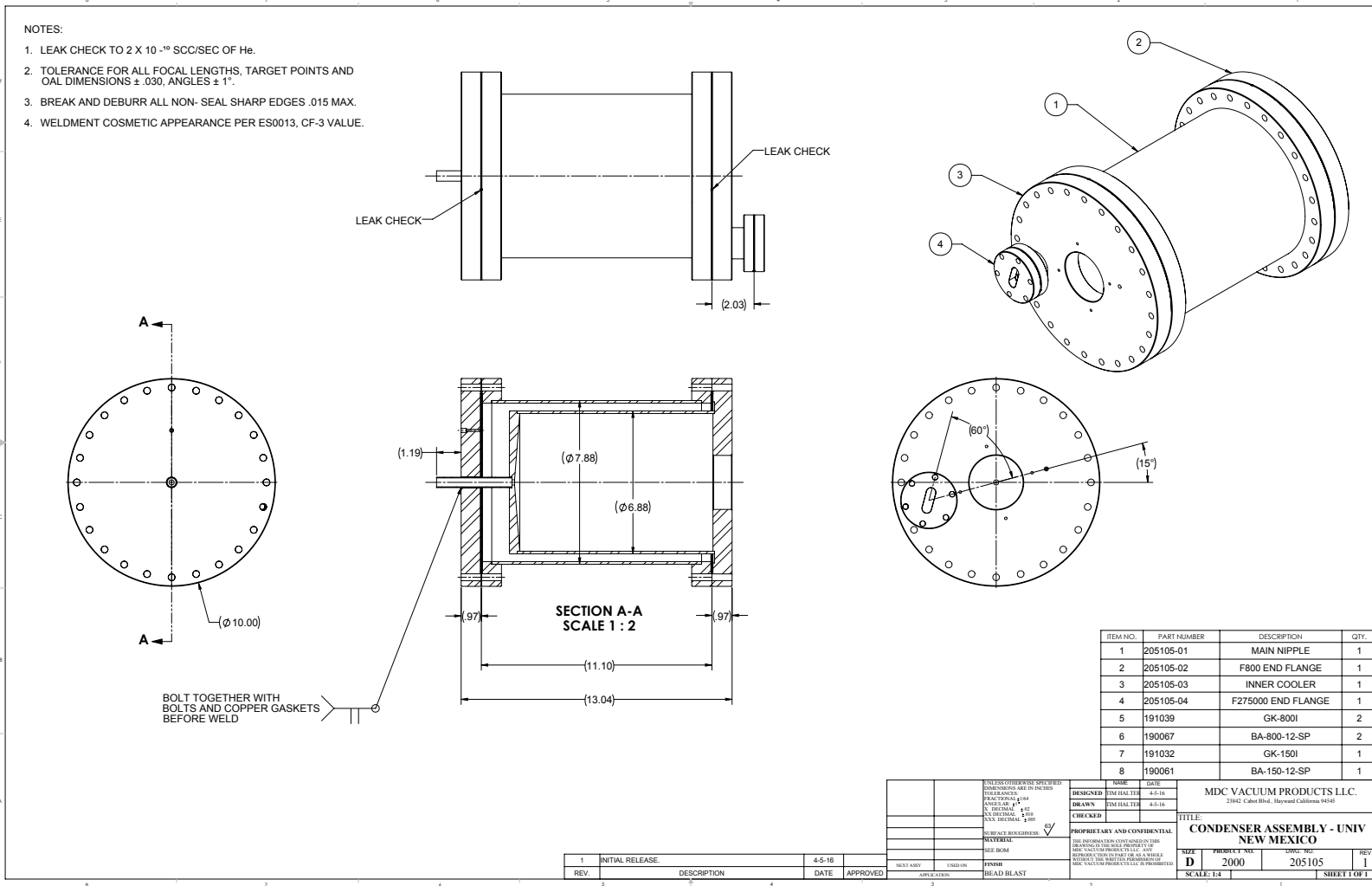


Figure 1 shows the technical schematic of the argon condenser. I designed it to accommodate the cold head provided by LANL. The protrusion with an oval slot will have an EB-9 connector which will act as a feedthrough for both thermocouples and the heater wire.

watts at 80 K and should cool to 80 K from room temperature in about 15 minutes [2]. If left unattended, the cold head will cool to 25 K and cause a severe argon freezing problem. Temperature regulation of the cold head will be done with nickel chromium wire (nichrome) purpose built for cryogenic heating and a thermocouple. Both the heating wire and the thermocouples will be adhered to the cold head, ideally with a very low contaminant material.



I used designs from the CAPTAIN project [1] (for which BACON is a prototype) as an initial model for the argon condenser. The mini-CAPTAIN detector has an argon recirculation unit. The recirculation unit takes argon gas in the cryostat, purifies the gas, condenses the gas, and deposits the liquid back into the cryostat. I examined the design of the mini-CAPTAIN condenser to get an idea of what properties condenser should have. The mini-CAPTAIN condenser is fully vacuum-jacketed and uses liquid nitrogen as a coolant.

Figure 2 shows the AL60 cold head. To make a fully vacuum-jacketed condenser would require two seals on the cold head. The flair at the end of the cold head prevents one of the seals from being on the stem (the cold head has fit into the condenser). Because the stem being an unsuitable sealing area, the inner seal must be on the flange at the center. Again as with the stem, if the flange is to be the inner seal, then it must fit through the outer seal, which would need to be on the square part of the instrumentation region, which is not feasible.

I designed the condenser to be semi vacuum-jacketed and be used in conjunction with the AL60 cold head. It would be preferable to have a fully vacuum-jacketed system for the best thermal isolation, but the use of the cold head makes such a design untenable as described in figure 2. The lid has ports for the cold head, argon gas, and a 9-pin connector for the thermocouples and heating wire. The interface between the cold head and the lid of the condenser will be sealed with pure indium wire, a commonly used low-leak cryogenic seal. The argon gas port is designed to be used with a VCO™¹⁰ to KF16¹¹ adapter. The inner volume is permanently fixed to the lid, and the LAr output tube from the inner volume is permanently fixed to the baseplate of the outer volume to minimize leaks and ensure purity. The baseplate of the inner volume has the shape of a low angle funnel to ensure condensed LAr flows into the BACON cryostat. The outer volume baseplate has ports for the vacuum system and the LAr. The vacuum port will use the same VCO™ to KF16 connector as the argon fill port, and the LAr port will connect with a mating VCR™¹² fixed to the lid of the BACON cryostat.

In order for the condenser to maintain its position above the cryostat, a scaffolding must be built. The scaffolding will be built from aluminum struts bound together with bolts and

¹⁰ VCO™ is a national pipe thread (npt) connector with an o-ring seated at the end to assist in sealing. Trademark owned by Swagelok®.

¹¹ KF16 stand for Klein Flange 16 mm and is a commonly used connector for vacuum and cryogenic systems.

¹² VCR™ incorporates a metal gasket to seal the connection. There is no connection to videocassette recorders. Trademark also owned by Swagelok®

winged washers. The scaffolding will be braced both on the ground and the lid of the BACON cryostat. Construction of the scaffolding can begin once the condenser arrives and length measurements can be finalized.

Many small scale experiments similar to BACON use argon condensed in an condenser to cool the cryostat. For BACON, I calculated the process will take weeks to months. As a solution, I designed the liquid nitrogen cooling system with some inspiration from the ICARUS T600 detector, a 600 tonne LAr TPC. The T600 is, in essence, surrounded by an aluminum heat sink which has LN2 pipes permeating it [4]. The LN2 pipes are pressurized to 2.7 bar, which raises the boiling point of nitrogen to 89 K [4]. BACON has been modified to have a copper pipe coiled around in thermal contact with its inner volume. The method is to use LN2 evaporation to cool the inner volume, which will be monitored by the thermocouples inside the cryostat. When the system is cold the nitrogen can either be removed or used as a thermal shield.

The vacuum system is comprised of a mechanical pump, a cryopump, and a vacuum chamber. The mechanical pump has a maximum operation of rough vacuum, $\sim 10^{-3}$ - 10^{-4} torr. The cryopump takes the system from rough vacuum to the high vacuum region, $\sim 10^{-5}$ - 10^{-6} torr. Vacuum system operation is a multi-step process beginning with cleaning the system. The mechanical pump is engaged to get the system rough vacuum. Once the system is at rough vacuum, the cryopump can be engaged to get the system to high vacuum. For the purposes of insulating BACON and the condenser 10^{-3} torr should be sufficient, but the RGA requires lower pressure.

The RGA requires at least 10^{-6} torr for operation. The RGA is connected to one of the ports on the vacuum chamber, and the background contaminants of the chamber has been measured. Our intention is to transfer gas samples from the BACON cryostat to the vacuum chamber and use the RGA to measure the chemical composition of the high purity argon environment. By subtracting the background from the added sample, the true composition of the LAr in the cryostat should be determinable via Henry's law. In this way we can monitor the contaminants in BACON, and manage the Xe doping concentration.

The RGA has proprietary software which only runs on Windows XP. I acquired a copy of the operating system and installed it on our lab computer, which was running Windows 7. Our lab computer is very old and does not have the capacity to have two partitions, so Windows 7 was overwritten with Windows XP. This causes some serious issues as the copy of XP I installed did not have any hardware drivers. After I resolved this issue (in short, by attaching a bit of wire to the wireless card as an antenna), I installed the RGA software. The RGA did not work right away as a part had gone missing when the RGA was transferred from LANL. We had to order the rather important missing power adapter, which is rated at 2.5 A, 12 V. The graphical interface for the software, while not intuitive, was not difficult to operate. I was finally able to successfully acquire data one gas concentration from the RGA. For reference, one of the reasons LANL gave us the RGA is a graduate student spent a summer unsuccessfully trying to get the RGA to operate.

One of the objectives of the BACON project is to acquire a fused silica PMT to be able compare scintillation intensity yields for pure LAr and Xe doped LAr. Fused silica is one of the alternate materials which can be used to detect 175 nm light but not 128 nm light. The goal would be to use a fused silica PMT and our current PMT in conjunction to measure scintillation

signals for different concentrations of Xe. By examining the same events with both PMTS, there will be a direct comparison of the efficiencies of the two detection methods.

4 Data

There several quantities that need to be recorded and monitored to make the BACON experiment a success: the temperature of the argon and condenser, the liquid level of the argon, the purity of the argon, and the PMT high voltage. BACON cannot operate without maintaining the proper temperature, which will be monitored with thermocouples. If the amount of LAr in the cryostat is too low, it may not be possible to make measurements. If the LAr is contaminated with even small concentrations of common components of the atmosphere, scintillation light will be highly attenuated. High LAr purity must be obtained and managed. The PMT signal is the crux of the BACON project. All relevant science, the scintillation intensity and decay time, depends on the PMTs.

BACON has a total of four thermocouples. All four thermocouples are connected to a single readout. Two thermocouples monitor the temperature of the top and bottom of the inner volume of the cryostat. These must be maintained below 87 K. If the LAr is boiling, it will attenuate the signal. The other two monitor the cold head and condenser wall temperatures. The

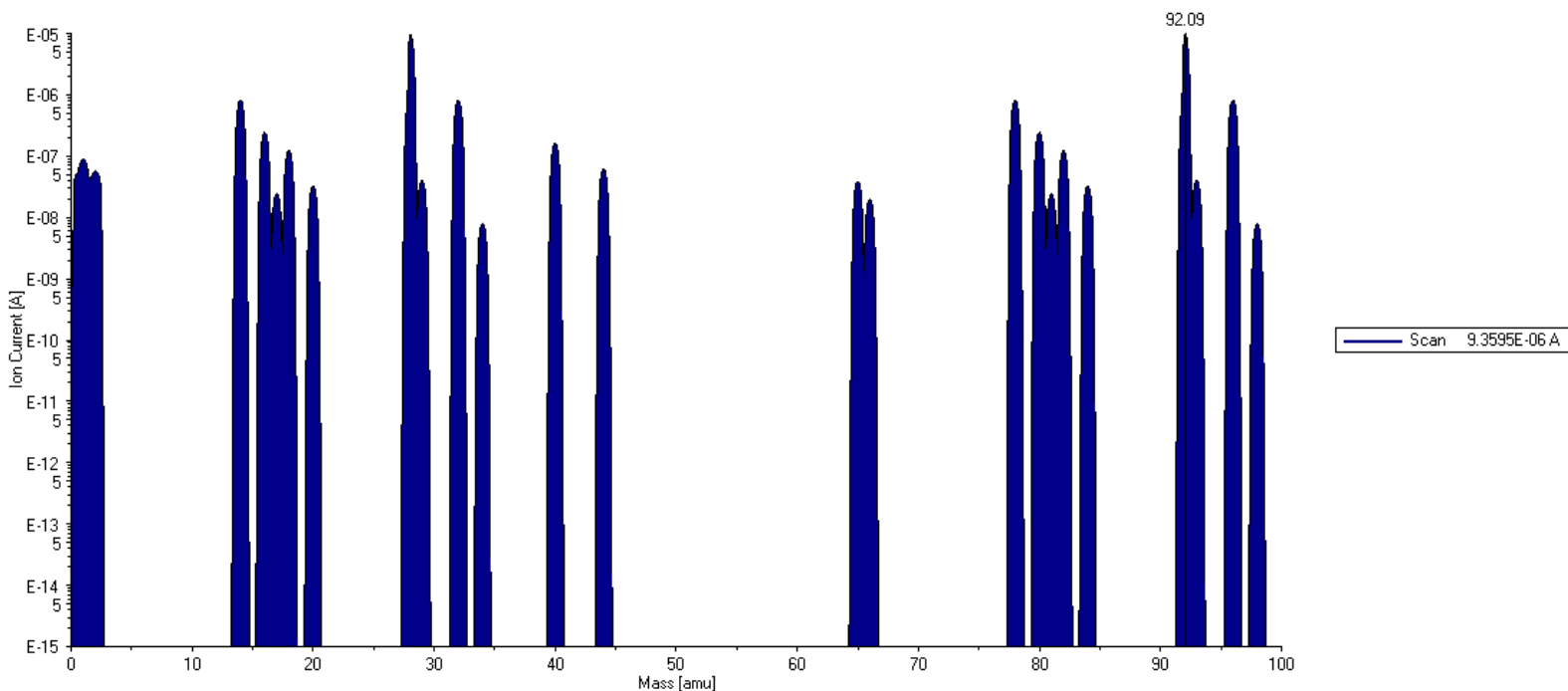


Figure 3 shows the RGA calibration data. On the X axis this is the atomic mass, and on the y axis is the ion current. The ion current is directly proportional to the concentration. The highlighted peak at 92 amu is possibly dimethoxysilane, a component of vacuum grease. It has an ion current the same magnitude as nitrogen N_2 . Such a high concentration contaminant is troublesome for gas transfer.

thermocouple on the cold finger will be connected to a PID controller to maintain proper condensation temperature for argon without freezing it.

I have used the RGA to measure the background of the vacuum chamber. I observed a large unexpected peak at 92 amu, the same order of magnitude as the nitrogen concentration. I determined the most likely candidate for this peak is dimethoxysilane, a common component of vacuum grease. There are many other contaminants which I will to reduce in magnitude by baking-out the chamber.

The known peaks are: 1 is mono-atomic hydrogen, 2 is H₂, 14 is mono-atomic nitrogen, 16 is mono-atomic oxygen, 17 is hydroxide, 18 is water, 20 is neon, 28 is N₂, 32 is O₂, 40 is Ar, 44 is CO₂, 84 is krypton, and 92 is dimethoxysilane. Unknown peaks are at 29, 34, 65, 66, 78, 80, 81, 85, 93, 96, and 98 amu. The unknown are accessible at the NIST website, but can have between 30 to more than 100 possible candidates. Identifying the unknown peaks is still in the process of being researched. Determining which chemical corresponds to which peak involves looking up each element and matching its properties to criterion. Criterion include: Is it possible for this substance to have gotten into the vacuum system? or: Can this substance be in the gas phase under the conditions in the vacuum cell? Each of these questions can take quite a bit of time to research, and it is not uncommon for information to simply not be available. Nevertheless, the RGA is a powerful tool for determining impurity concentration for the LAr in the cryostat.

The two PMTs each have a single coaxial cable supplying the high voltage. The PMT signal is capacitively coupled the the high voltage. Capacitive coupling is done to lower the number of holes in the inner volume to limit contamination.

The source for the LAr scintillation will either be cobalt-60 or cosmic muons. These sources will provide the necessary scintillation signal for the PMTs. The PMT signal for an event will be recorded in time as counts. Counts over time for an event will give allow for the calculation of the decay time. This is typically fit to at two or three component exponential [17]. The signal will provide a measure of intensity over time, which will allow the calculation of the decay time. Tests with pure LAr will provide baseline decay times and scintillation yields with which to compare the Xe doping results.

5 Conclusions

LAr scintillation detectors are the current future of rare event particle physics. Projects such as DUNE and ICARUS a pushing the size of the detectors to the extreme, which reveal certain physical limitations to LAr detection technology. These limitations are attenuation length and the difficulty of working with VUV scintillation. A proposed solution to these limitations is xenon doping. Xe doping has its own limitations, but they are not as well understood as they need to be. There has already been a great deal of research put into characterizing these limitations, but there is still a a few key points which are unknown. More needs to be done before the definitive decision whether pure LAr or Xe doped LAr is the better detector. Realistically, the pure LAr detector may be better for certain applications, and the Xe doped LAr detector for others.

Wavelength shifting is an integral part of any LAr detector. The purposes of Xe doping are to potentially remove the need for TPB coating, improve the attenuation length of the scintillation, and improve PSD for non-TPC experiments. There are a couple of paths made possible with Xe doping. Switching to a different PMT material, or perhaps to specialized diode detectors could eliminate the need for TPB. The newly discovered infrared scintillation signal offers a new spectral window into light detection. One possibility is to abandon the VUV scintillation in favor of the NIR emission. Another possibility is to detect both the NIR and VUV for in order to maximize photon yield. All cases require more research and development.

The attenuation length was a major contributing factor in deciding to investigate Xe doping. New measurements have overturned long standing standards, and the situation requires more experiments to be done. The long standing measurement for the attenuation length for Xe in LAr was done by the same experiment, which calls into question its accuracy. The measurement for the attenuation length for Xe in LAr was done with 3% Xe in LAr, which may not have the same value for concentrations in the ppm range. To better understand the interactions of Xe doping, it would be prudent to measure the attenuation length for Xe in LAr at the ppm concentration level. Although it cannot be done with BACON, an interesting measurement to make and a potential future project is the attenuation length of the new infrared signal.

The goal for the BACON project is to study ways to potentially improve LAr detector design with Xe doping. The important properties to be explored with BACON are scintillation intensity and decay time with a few ppm Xe in LAr concentration levels. I have done some initial calibrations with the residual gas analyzer, but more needs to be done. The LN2 cooling system and argon purification system need to be completed. I designed an argon condenser to be used with a cryogenic refrigeration system, which will provide BACON with the highest purity LAr we can produce. BACON is under construction and we plan to have it operational the Summer of 2016.

Xenon doping of liquid argon is an area of active field research. Some of the original reasons for its use may no longer be valid, but there is new evidence that it could be useful in different ways. More experiments must be done to determine if Xe doping can be used in DUNE or other future LAr detector experiments.

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Appendix A: Abbreviations

Abbreviations are shown where they are first mentioned in the text, but that is not always convenient for the reader. Here is a reference list for convenience, in alphabetical order.

amu - atomic mass unit

Ar - argon

BACON - Big can of liquid Argon for the detection Of Neutrinos

BLEVE - Boiling Liquid Expanding Vapor Explosion

BoPET - Biaxially-oriented Polyethylene Terephthalate (mylar)

CAPTAIN - Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrino

DAQ - Data Acquisition system

DUNE - Deep Underground Neutrino Experiment, formerly LBNE

GAr - Gaseous Argon

ICARUS - Imaging Cosmic And Rare Underground Signals

Kt - Kilotonne

LANL - Los Alamos National Laboratory

LAr - Liquid Argon

LN2 - Liquid Nitrogen

nichrome - 80% nickel, 20% chrome (this is not always the case, but true for this paper)

ppb - parts per billion (by mass)

ppm - parts per million (by mass)

stp - standard temperature and pressure, 101.325 Kpa and 298.15 K.

T600 - a 600 tonne LAr detector built at Gran Sasso, Italy as a part of the ICARUS program

TPB - TetraPhenyl Butadiene

TPC - Time Projection Chamber

Xe - xenon

Appendix B: The Time Projection chamber in Liquid Argon

Time projection chambers are an important part of DUNE. TPCs allow 3D reconstruction of events with exceptional resolution. BACON is prototyping for the DUNE project, but it does not have its own TPC. As such, the discussion of TPCs is included as appendix B.

The TPC is a wire cage with uniformly spaced parallel wires on two opposite sides and constructed such that there is a uniform electric field in the fiducial volume. The electric field pulls a percentage of the ionization electrons away from the cations, typically 66% to 75%, depending on the TPC voltage. The electrons drift along the electric field lines to collection wires, at which the electrons are detected as current in the wires. There is also one or more induction wire planes, usually perpendicular to the collection plane. None of the electric field lines end on the induction wire plane. The result is drifting electrons induce a mirror charge as they drift toward the induction wires, which then dissipates as the electrons move away. The result is a bipolar current in the detector. It is worth noting that scintillation and the charge collected are competing processes. Raising the TPC voltage corresponds to an increase in charge collection and a drop in scintillation intensity.

A key feature of the TPC is the electron drift velocity is approximately constant. The scintillation detection time provides an initial time for the event. The combination of the constant drift velocity, the initial event time, and the time the electrons arrive at the collection plane gives one spacial dimension. The orthogonal induction and collection planes give the other two spacial directions. All of this information results in a 3 dimensional reconstruction of the event. An additional important feature is different particles have unique energy deposition rates through LAr, allowing particle identification.

Argon has a full outer electron orbital, which is the operational principal for the TPC. The full outer orbital means that argon has a negligible electronegativity. Applying a uniform electric field to a volume of pure LAr will cause the electrons to drift without being absorbed. The important impurities oxygen, water, and nitrogen will absorb the drifting electrons at a high rate even at very low concentrations. As an example, 40 ppb oxygen yields a mean free path of 1.5 cm for an electric field of 500 V/cm [14], 2 orders of magnitude below what is proposed for DUNE [6].

An important feature of LAr for TPC operation is an opaqueness threshold for the kinetic energy of a drifting electrons. If the electrons are above the W value¹³ for LAr, 26.4 eV [], they will scatter off argon atoms creating more ionization and excitation. As the electrons deposit energy, they will eventually drop below the W value and become freely drifting. The resulting will be a drifting electron shower in the LAr, which results in a measurable current at the collection wires. Without this effect, the TPC would be unable to collect enough electrons for a measurable current.

¹³ The energy required for an electron to scatter.