Improving low-mass reach of xenon TPC dark matter searches by doping with light noble elements

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1 Introduction

I propose to increase the sensitivity of dual-phase xenon time projection chambers (LXe-TPC) used in dark matter (DM) direct detection searches to weakly-interacting massive particle (WIMP) masses down to $\mathcal{O}(100)$ MeV by doping the xenon with light noble elements. LXe-TPCs lead the way in the high-mass parameter space but lose sensitivity below WIMP masses of 5 GeV, due to the poor kinematic matching of xenon nuclei and light WIMPs. Helium and neon are better suited for these searches because, for the same momentum transfer, these nuclei have higher recoil energy than xenon. Additionally, recoils of these nuclei lose less energy to heat in liquid xenon (LXe) and thus make larger signals for the same recoil energy. The combination of these effects leads to a decrease in the energy threshold of these detectors as low as 100 eV for helium recoils. Doping an experiment like LUX-ZEPLIN (LZ) with helium or neon grants sensitivity to WIMPs with mass an order of magnitude smaller than can be probed by xenon alone.

This project consists of two phases: a research and development phase and a calibration phase. The focus of the R&D phase is to measure the solubility of helium and neon in liquid xenon (LXe) as a function of temperature and partial pressure of the doping agent above the LXe. This work will be performed in an existing xenon TPC at FNAL (the XELDA detector) after upgrading the photomultiplier tubes (PMT) to silicon photomultipliers (SiPM) due to their resistance to helium gas. This phase includes developing a technique to remove the doping agents, as well as preliminary electron recoil and high-energy nuclear recoil calibrations. The second phase of the proposal is focused on measuring the sensitivity of the doped xenon TPC to low-momentum transfer nuclear recoils. I will perform nuclear recoil calibrations using mono-energetic neutron sources to measure the charge and light yield of xenon and the doping agents as a function of recoil energy.

2 Motivation

Dark matter is an exciting topic, and important to high energy physics. The idea proposed here is a novel approach to detecting light dark matter that builds on the significant investment already made by HEP into LXe-TPCs to add sensitivity to new regions of interesting parameter space. At the same time, we will continue to develop expertise in vacuum ultraviolet-sensitive SiPMs, which have been proposed for use in dark matter and double beta decay experiments, potentially enabling a future generation three (G3) experiment.

The development of second generation (G2) dark matter direct detection experiments is currently underway. The LZ collaboration is projected to lead the search for WIMP masses greater than 10 GeV, with sensitivity down to $\sim$5 GeV. The projections for LZ show an increase in sensitivity by a factor of 50 over current limits, for a 40 GeV WIMP [2, 3]. As currently planned, a DM signal in low-mass sensitive experiments, such as SuperCDMS, cannot be confirmed in the xenon TPCs. The doping described in this proposal allows LZ to have reach complimentary to existing low mass WIMP searches, as well as probing new parameter space. Light nuclei targets at the scale

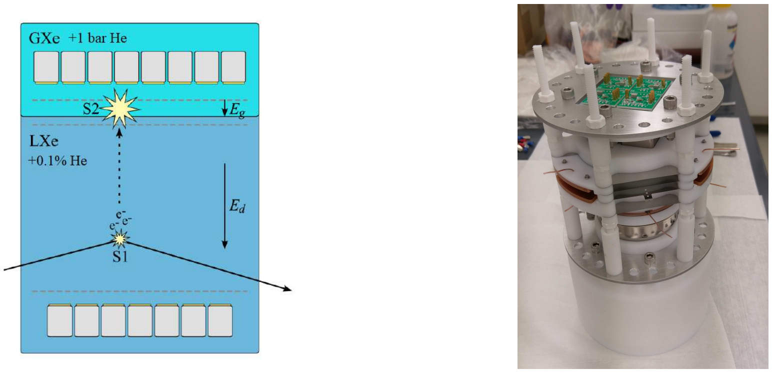

Figure 1: (Left) A schematic representation of a dual phase xenon time projection chamber doped with helium. A partial pressure of 1 bar results in a He concentration of 0.1%–0.3% by mass. Ionizing radiation produces scintillation light (S1) and free charge which drifts under the electric field E_d to the liquid surface where the electrons are extracted into the gas phase by a stronger field E_g. The acceleration through the gas phase produces a proportional scintillation signal (S2). The S2 pattern determines the xy position of the event, with the z position coming from the time difference of the signals. (Right) A photo of the XELDA detector which will be used to conduct the work in this proposal.

of tens of kilograms will carve out a significant portion of the low-mass parameter space, and in this implementation still benefit from the self-shielding and fiducialization of LXe-TPCs at the scale of LZ. Preliminary calculations suggest that helium in LZ could have sensitivity around 10^{-41} cm^2 at a WIMP mass of 1 GeV, with reach down to WIMP masses of roughly 500 MeV.

Work in evaluating the suitability of SiPMs for xenon TPCs is also proposed. Vacuum photomultiplier tubes are conventionally used in these detectors, but they are expensive and fragile. SiPMs are a relatively new technology, and have yet to be adopted by the particle physics community for large-scale experiments. There is ongoing R&D in the field [4, 5], but not for low-threshold TPCs such as LZ. A leading motivation for the use of SiPMs in this proposal is the introduction of helium into the xenon environment. Helium atoms can diffuse through the glass window of PMTs, leading to significant afterpulsing after prolonged exposure, rendering the tubes inoperable.

3 Technical Details

A dual-phase xenon time projection chamber uses the emission of secondary particles to reconstruct scatters from xenon atoms. Ionizing radiation passing through xenon liquid produces scintillation light and electron-ion pairs. The prompt scintillation signal (S1) is detected in the photomultipliers immediately, while the liberated electrons drift under an applied electric field to the liquid surface. Here they are extracted into the gas phase by a stronger electric field and create a proportional scintillation signal (S2). See the left panel of Fig. 1 for a schematic of a xenon TPC. Using the pattern of the S2 signal in the top PMT array and the time difference between S1 and S2, the 3D position of a point-like event can be determined to millimeter resolution. The energy of the recoiling particle is found by a linear combination of the S1 and S2 signal sizes.

The standard analysis uses both S1 and S2 signals and, for LZ, results in a 3 keV nuclear recoil threshold. In this mode, electron recoils (ER) can be rejected on an event-by-event basis due to

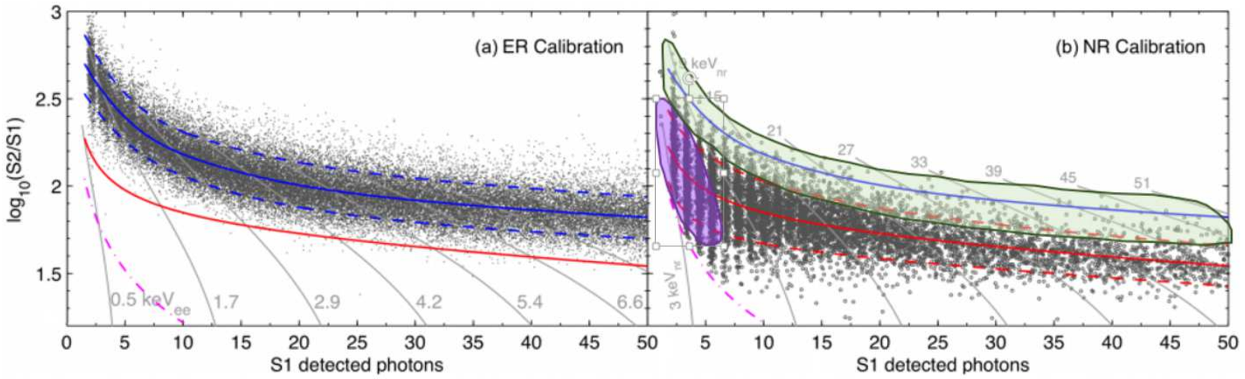

Figure 2: Discrimination parameter $\log_{10}$(S2/S1) from LUX calibration data [2]. The electron recoil spectrum (a) is obtained by calibration with a tritium source. The nuclear recoil band (b) is obtained from neutron sources. The solid lines are the medians of each band. LUX was able to achieve 99.6% rejection of ERs by maintaining a flat 50% acceptance of NRs, *i.e.*, below the median. The purple line shows the detector threshold, and appears in the same place in both panels. The green(purple) shaded regions are cartoons of where helium(neon) recoils from a SbBe low-energy neutron would appear, taking into account the S1+S2 threshold of 3 kev$_{\mathrm{nr}}$. Note xenon recoils from this neutron are too low energy to appear on these axes.

their higher charge-to-light ratio, which eliminates a significant source of background. However, a reduction in threshold can be attained by using an S2-only analysis, developed by the XENON10 experiment [7], which forgoes the discrimination (and z position) to take advantage of the large S2 gain (roughly a factor of 10) to see single electrons. The XENON100 collaboration was able to achieve thresholds as low as 700 keV$_{\mathrm{nr}}$ [8]. The same S2 analysis threshold would correspond to a helium recoil energy threshold of ~100 eV$_{\mathrm{He}}$ due to both reduced losses to heat and a higher charge-to-light ratio for helium recoils. A 700-eV xenon recoil threshold corresponds to a sensitivity to a minimum WIMP mass of 3.3 GeV, while a 100-eV helium recoil threshold corresponds to a mass of 300 MeV, more than an order of magnitude improvement.

Helium and neon both make attractive doping agents because they are light, inert, and have no naturally occurring radioactive isotopes. Doping with these elements at the sub-% level is not expected to significantly impact the scintillation and ionization signals produced by electron and xenon recoils. In particular, xenon doped with lighter noble elements is expected to produce scintillation at the same wavelength as pure xenon, so as to be detectable by the same photodetectors without the need for waveshifting. Any excitations of the lighter noble elements will effectively transfer to xenon and scintillation will be produced at the xenon wavelength [12]. Additionally, since only trace amounts of He/Ne will be added, the dynamics of electron drift through the bulk liquid will remain unchanged. The drift in the gas region may be affected due to the increased relative number density of the doping agents, but given the size of the S2 signals (dozens of photoelectrons), modest increases or decreases in gain can be accommodated, and any such shifts will be measured in this proposal.

Before any calibrations can be performed to determine the S1 and S2 yields of He/Ne in xenon, it must be understood exactly how much of the doping agents can be successfully dissolved in LXe. The amount of dissolved gas in a liquid is determined by the partial pressure of the gas above the liquid and the Henry coefficient for the gas/solvent pair. No published data exist on the Henry coefficients for helium or neon in liquid xenon, so this will be determined in the work proposed here. This measurement can be done by sampling gas and liquid regions with a residual gas analyzer, or by measuring neutron scattering rates on the lighter nuclei. The LUX collaboration showed that at 1 bar of partial pressure, helium can be dissolved into xenon at the level of 0.1-0.3% by mass. Argon dissolves neon 5 times more readily than helium [13], so given the design of the TPC, 0.2%(1.0%) of helium(neon) by mass is a reasonable target concentration. Additionally, once the doping agents are successfully mixed, the gas purification and xenon recovery systems must be modified to maintain or remove dopants as desired.

The final objective of the proposed work is to determine how nuclear recoils of these light atoms will partition their energy into S1, S2, and heat. Recoiling electrons lose their energy almost entirely to electronic excitation because losing their energy to heat is kinematically suppressed. Xenon recoils on the other hand lose ∼80% of their energy to heat via soft collisions with other xenon atoms, a ratio which should be unaffected by the trace amounts of He/Ne added. He/Ne recoils will lie between these two extremes, and TRIM simulations indicate ∼20%(70%) losses to heat for helium (neon) recoils [16]. The mechanism that determines the partition of electronic excitation into S1 and S2 for NR in liquid xenon is not fully understood, so where the He/Ne bands will appear remains unknown, though they should be bounded by the ER and xenon recoil bands (see Fig. 2).

All calibrations of He/Ne recoils will be made using mono-energetic neutron sources. At FNAL, a preliminary nuclear recoil calibration can be performed using a ^{124}Sb source on Be which produces a mono-energetic neutron of 23.47 keV [17]. The maximum recoil energy for a neutron with energy E_n is given by

$$E_{r,\max} = 4E_n \frac{m_n M_N}{(m_n + M_N)^2} \ , \tag{1}$$

where m_n is the neutron mass and M_N is the target nucleus mass. For the low-energy neutron of SbBe, this evaluates to a recoil energy of 0.7 keV (0.1 keVee) for xenon, 4.25 keV (1.0 keVee) for neon, and 15 keV (12.5 keVee) for helium. The regions in S1 vs $\log_{10}$(S2/S1) space where these recoils on helium(purple) and neon(green) would appear are shown in Fig. 2. This concept holds true for recoils from WIMPs: for the same momentum transfer, helium recoils will be more energetic than xenon recoils.

Once the preliminary calibration is done, the detector will be brought to the neutron beam at the Nuclear Science Laboratory at the University of Notre Dame. The Notre Dame tandem Van de Graaf produces a pulsed, variable energy, mono-energetic neutron source by firing protons on a lithium target, allowing for the investigation of low energy nuclear recoils. By employing neutron detectors at fixed angles from the beam, recoils of a known energy can be selected, due to the relationship between recoil energy and the angular dependence of the outgoing neutron. The first run in the beam will be pure xenon and will result in measurement of scintillation and ionization yields in pure xenon as a function of energy. The following runs will be the same calibration but using a target of doped xenon. Recoils of different nuclei are easily identifiable because, for the same solid angle of the outgoing neutron, helium and neon recoils are more energetic by factors of 20 and 6, respectively. Dr. Lippincott is familiar with this facility, and has done a similar measurement using an argon TPC [14, 15].

3.1 Project plan

The work laid out in this proposal is to be carried out in two phases: the first being a research and development phase measuring the solubility of He/Ne in xenon; the second is a calibration phase of a doped detector. The beginning of the first phase will be focused on outfitting an existing xenon TPC (the XELDA detector) with SiPMs as a replacement for the PMTs. Once these upgrades are completed, and the behavior of the TPC filled with pure xenon is well understood, I will begin tests to determine how much He/Ne can be dissolved. In addition to determining achievable concentrations, a method for reliably circulating doped xenon and removing the doping agents must be developed. The deliverables for the first phase are: (1) a functioning xenon TPC using SiPMs calibrated for electron and xenon recoils, (2) a measurement of the Henry coefficients for helium and neon in liquid xenon as a function of temperature, and (3) a method for the removal of light noble elements from xenon. This phase is expected to take two years to complete.

In the second phase, the light and charge yields of helium and neon nuclear recoils will be characterized. To do so, multiple calibrations will be performed with various neutron sources. A preliminary NR calibration will be performed using a SbBe at FNAL, followed by measurements with the mono-energetic neutron source at the University of Notre Dame. The calibration phase of the project is expected to take one year, depending on the availability of the neutron source. The deliverables for this phase would be: (1) a measurement of the S1 and S2 yields' dependence on recoil energy for Xe, Ne, and He, and (2) a study into the capabilities of a science run of LZ doped with 0.2%(1.0%) helium(neon) by mass.

4 Qualifications, Collaboration, and Resources

I am qualified to perform the work laid out in this proposal due to my experience working with xenon based TPCs, both on large and small scales. Over the past three years, I have worked on the LUX-ZEPLIN experiment, both on hardware and analysis. One of my main tasks has been the construction and operation of the xenon cryogenics and circulation system at the LZ System Test platform located at SLAC. In this capacity, I studied the effect of xenon circulation geometries and thermodynamics on the liquid-level stability in the TPC. Beyond this, I have been a participant in the LZ mock data challenges, and am familiar with the conventional calibrations and analyses done in these detectors.

I have also worked closely with Dr. Lippincott and Dr. Dahl, both experts in the field of noble element detectors, on the development of a small-scale xenon TPC at FNAL. Together, with another graduate student and an FNAL postdoctoral researcher, we designed and constructed the XELDA detector to study a possible discrepancy between ERs from the tritium beta decay and the ^{127}Xe L-shell electron capture, hinted at in observations by the LUX collaboration [18]. On this project, I was involved in the initial construction of the TPC (and subsequent repairs), the installation and operation of the various instrumentation components (PMTs, capacitive level sensors, thermometers, etc), gas and liquid operations, and data analysis.

Through my work on both of these projects, I have experienced the breadth and depth of xenon TPC experiments. The unique challenges of this proposal are well matched by my history with xenon detectors. In addition to their advisement, Dr. Lippincott and Dr. Dahl will both provide support for the hardware upgrades to the TPC through their groups at FNAL and Northwestern University. The mono-energetic neutron source at the Nuclear Science Laboratory of the University of Notre Dame is an ideal facility to test low energy nuclear recoils in the doped xenon. Dr. Lippincott is familiar with this facility through his work on argon detectors. In the far-term, I will have the support of the LZ collaboration to use the System Test to investigate the effects of doping agents on the xenon circulation system.

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