PIN Diode Application for Nuclear Recoil Discrimination in the LZ Dark Matter Experiment

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The UC Davis DAX project is a testbed operation for the collaborative LZ direct dark matter detection experiment focused on developing detection and analysis techniques to provide increased sensitivity, effectively expanding the range of detectable WIMP energies. One focus of DAX is the use of Hamamatsu S3590-09 PIN diodes for discrimination of nuclear recoil (NR) sources. This device is designed to detect alpha particles that are correlated with ^{206}Pb NRs in LXe, characterizing a potential background to WIMP-induced nuclear recoils in LXe detectors [1]. Further tests were conducted to characterize the behavior of the PIN diode in approximate LZ conditions. This is a report of the work done for the summer 2015 REU program at UC Davis.

I. INTRODUCTION

A. Cosmological Background

Research in cosmology over the past few decades, particularly findings related to the Cosmic Microwave Background, has determined that dark matter accounts for 26.8% of the total mass-energy system of the universe, and that this matter must necessarily be non-relativistic (i.e. cold) and weakly interacting [2]. These findings led to the proposal of a class of particle known as WIMPs, or Weakly Interacting Massive Particles. The underlying idea behind the LUX dark matter experiment is that these WIMPs are measureable through their interactions with normal matter, specifically through collisions with liquid xenon nuclei [3].

B. LZ Experiment and DAX

LZ is the second generation of the LUX direct dark matter detection experiment in collaboration with ZEPLIN, consisting of a 7-ton active liquid-xenon (LXe) time projection chamber (TPC) to detect nuclear recoil (NR) scintillation prompted by WIMP-LXe collisions. A key goal of the new dark matter detection experiment is a distinct increase in sensitivity to greatly increase the range of detectable WIMP energies [1,3]. After the completion of the first phase of LUX, it was reported by Akerib et al. that the LUX data are in disagreement with low-mass WIMP signal interpretations of the results from several recent direct detection experiments,[3] which motivates the need for a greater degree of sensitivity in the LZ run.

The PIN diode project at DAX is developing analysis techniques to augment the effective sensitivity of LZ data. The aim of this project is to provide an experimental basis for discrimination between WIMP NR and extraneous NR induced by radioactive isotopes, particularly ^{210}Po, present in the experimental chamber. These isotopes are present naturally and cannot be readily removed, so their affects will be accounted for via analysis techniques developed at DAX.

C. Technical Background

PIN diodes are a class of semiconductor device that contain an undoped region of intrinsic semiconductor. An applied bias voltage pulls apart the doped regions of positive and negative charge, P+ and N- respectively, enlarging the intrinsic, or I region. This effect is shown in Figure 1, below.

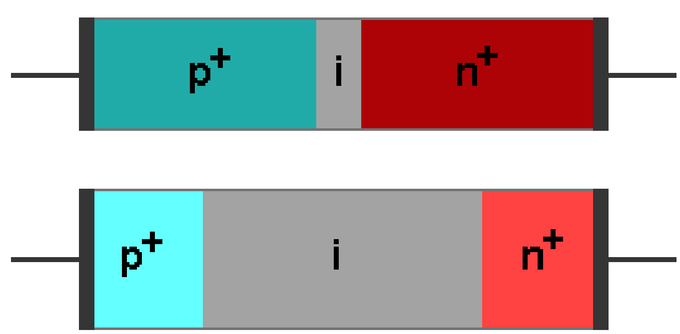

FIG. 1: TOP: Semiconductor region with no bias voltage
BOTTOM: enlarged "I" region under applied bias voltage

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The I region operates under high level injection when a voltage is applied; that is, the region is flooded with charge carriers from the P and N regions. This excess of charge carriers enables an electrical response to events in this region, such as the transfer of energy from an incident particle. The behavior of the diode can be characterized as a function of bias voltage, known as an IV curve.

The nuclear decay chain of ^{210}Po releases ^{206}Pb and an α-particle, and the ^{206}Pb can interact with the LXe in the TPC, causing unwanted nuclear recoil and subsequent scintillation. Since this is the same process by which WIMPs are detected, their responses must be discriminated. The PIN diode will be coated with a layer of ^{210}Po, allowing ^{206}Pb to rise into the LXe while sending α-particles incident upon the diode. When the diode detects an incident α-particle, it will necessarily be correlated with a ^{206}Pb event in the LXe. Counting and tagging the α-particles serves to determine the nuclear recoil events which are not caused by WIMPs.

II. EXPERIMENTAL METHODS

The experimental procedure conducted during this summer program was to characterize the behavior of the Hamamatsu S3590-09 PIN diodes under a variety of conditions approaching LZ conditions, and to refine the experimental apparatus.

A. Phase 1: General Characterization

The first phase of characterization was to understand the diode's behavior at room temperature with a controlled LED pulse to provide incident particles. This process mostly involved tweaking the overall circuit, eventually arriving at the design shown below in Figure 2.

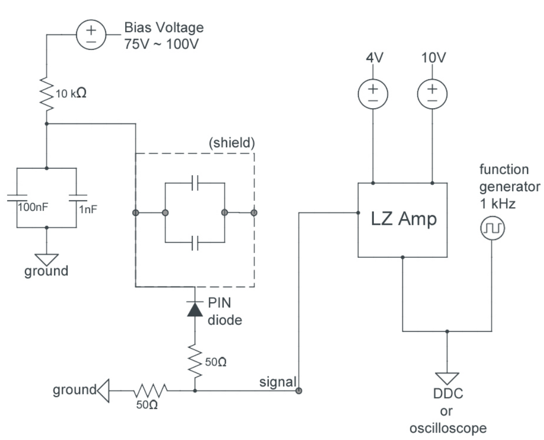

FIG. 2: Diagram of circuit design developed for PIN diode tests

Once the circuit was designed, an IV curve was taken. Due to the fact that the diode is only ever operated under reverse bias conditions, only the negative portion of the IV curve was measured. Figures 3 and 4, below, show the predicted IV curve for a PIN diode, and the measured one.

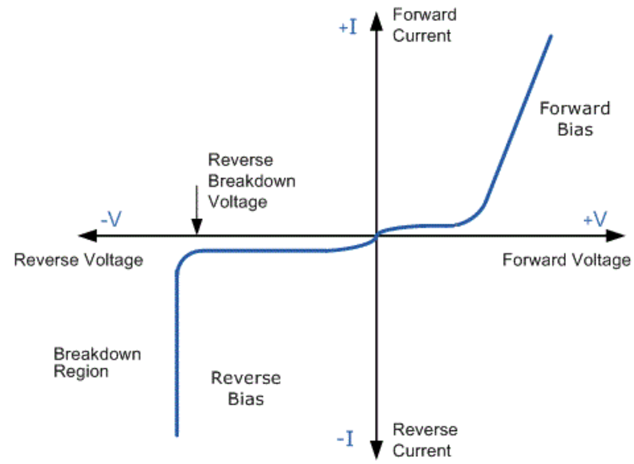

FIG. 3: Standard IV curve for PIN diodes [4]

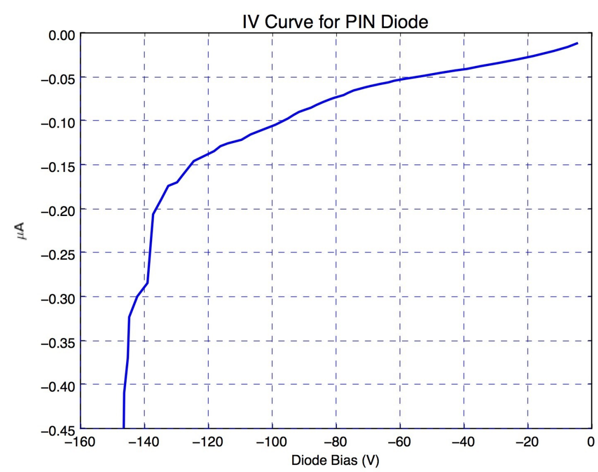

FIG. 4: Measured IV curve for Hamamatsu S3590-09 PIN diode

B. Phase 2: Alpha Source Tests

The second phase of experimentation involved characterizing the response of the PIN diode to alpha particles, produced by a source of radioactive ^{241}Am. This was an important phase as it allowed for a pulse-area spectrum analysis, which reveals exactly how the diode is responding to particles, roughly correlated with energy. This process employed a digital down-converter

(DDC) to digitize waveforms, implementing analog to digital conversion (ADC) of the waveform, in units of ADC counts. Data was recorded using 100ns, 1000 sample event windows randomly sampled at 1kHz using a squarewave function generator.

A pulse finding script was applied to the digitized waveforms to calculate pulse area for spectrum analysis. The algorithm sets a threshold at a user-specified value of ADC counts and determines baseline by averaging every sample below the threshold. Once the signal passes the threshold three samples ahead of current location, it begins summing the pulse height relative to the calculated baseline, adding additional samples for as long as the signal remains above threshold. A pulse-area spectrum was measured with variable threshold and is shown below in Figure 5.

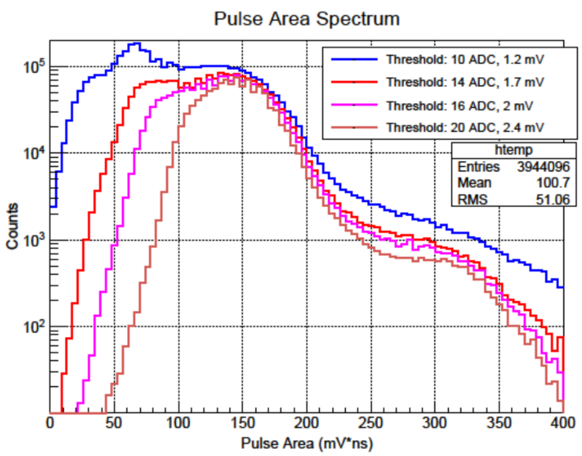

FIG. 5: Variable threshold pulse-area spectrum measured at room temperature using ^{241}Am α-source. α peak centered at 150 mV*ns.

C. Phase 3: Cold Dark Box

The final phase of experimentation was to apply near-LZ conditions to the setup and characterize the response, as well as negotiate complicating factors that arose with the addition of the cold dark box. A Cryo-Con PID heater control was used to achieve stable temperatures within the cold dark box, the cold temperature reservoir provided by liquid nitrogen (LN). The source and diode apparatus was fixed within a metal container within the cold dark box, providing thermal contact between the experimental environment and the rest of the chamber, while the heater was placed on the bottom surface of the metal container. A PT100 thermometer, used to provide feedback to the Cryo-Con, was placed in the metal container, suspended near the diode. The experimental setup can be seen below in Figures 6 and 7.

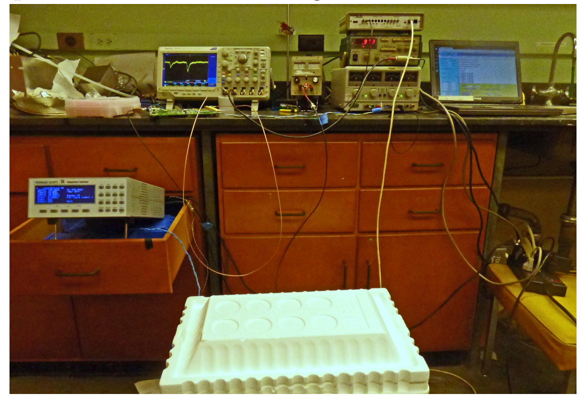

FIG. 6: Experimental setup, including cold dark box, Cryo-Con, and DDC.

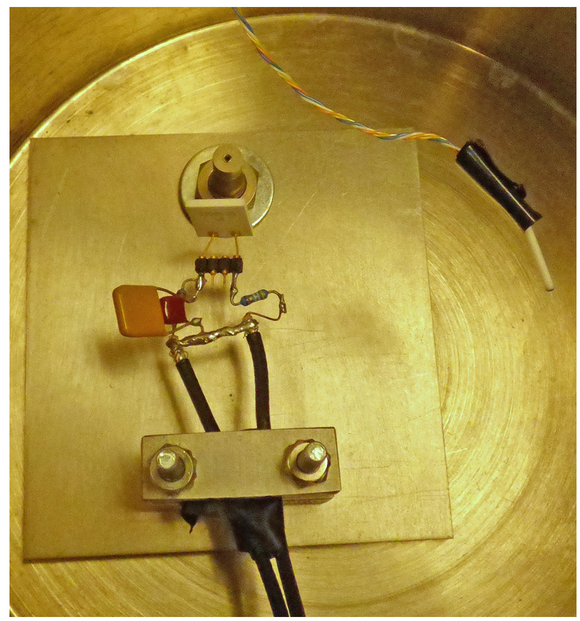

FIG. 7: Experimental setup, showing the PIN diode, ^{241}Am α-source, PT100 thermometer, and fixture.

A similar pulse-area spectrum was taken with a fixed threshold of 2.4 ADC counts across a variety of temperatures. After calibration, individual data sets were taken for approximately three minutes at 200K, 175K, and 150K. Recall that the temperature of LXe is 165K. These data should describe the behavior of the diode as a function of temperature over a useful range of temperatures. A script was written to record temperature and PID data as data were taken. Results are displayed in Figure 8 below.

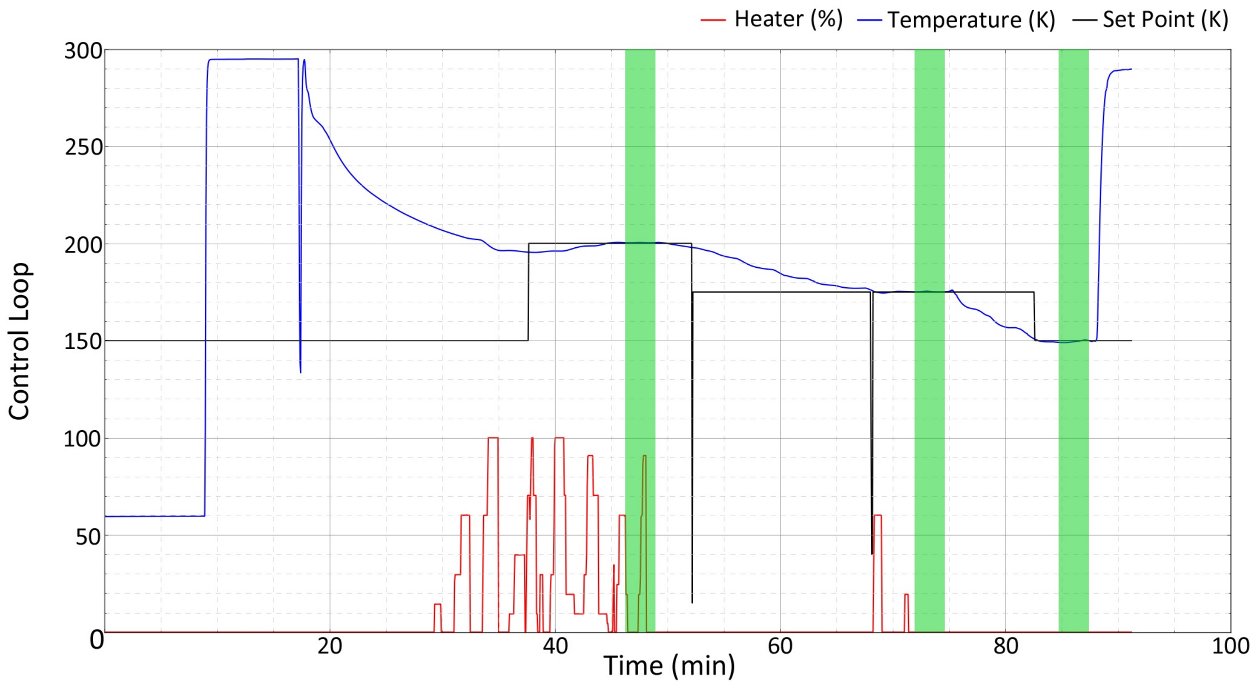

FIG. 8: Measured pulse-area spectrum at various precise temperatures. Vertical green bars indicate when data were recorded. Note that heater power is represented as a percentage of total output (unitless), while setpoint and temperature have units of Kelvin.

The data is displayed as a pulse-area spectrum in Figure 9 below.

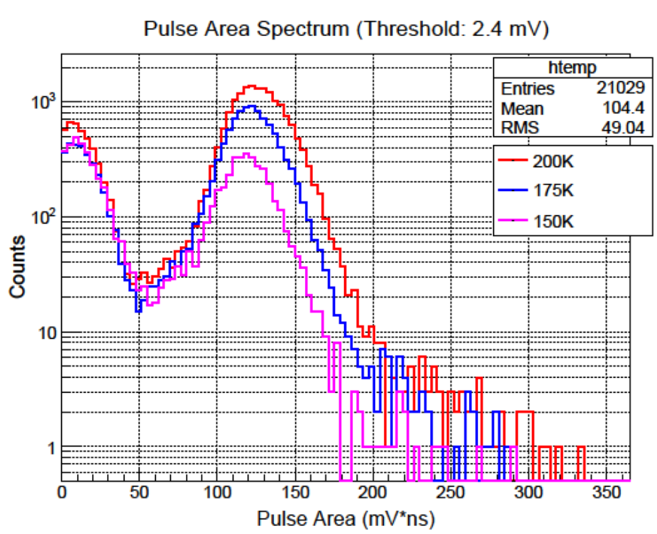

FIG. 9: Measured pulse-area spectrum at various precise temperatures. α peaks centered at roughly 125mV*ns.

III. RESULTS AND CONCLUSIONS

Note that the number of events registered during the fixed time window decreases as a function of temperature. The atmosphere within the experimental environment contains water vapor due to poor isolation, allowing a thin layer of frost to form on the surface of the diode as it cools. This frost could be a contributing factor to the observed signal loss. Other potential causes include the density of the surrounding gas or temperature-based effects on electronics in the signal chain.

Further tests under more isolated conditions must be done to determine if the observed shrinking of the distribution with temperature is indeed due to frost buildup and if there is any intrinsic response in the behavior of the diode due to the decreased temperature under which it is operating. This will allow us to be sure that the tracked α-particles are related to ^{206}Pb events and that no events will go uncorrelated.

The project has made significant development over this experimental process, now operating at more approximate LZ conditions. Further experimentation will include placing a charge amplifier in the signal chain to provide further separation of signal and noise and applying a ^{210}Po coating to the PIN diode to determine if the substance interacts with LXe.

More work will be done before this project can be applied to full LZ data analysis.

IV. REFERENCES

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