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Low Energy Backgrounds in Liquid Xenon Time Projection Chambers

Historical Background

The composition of the Universe is something that scientists strive to understand through theoretical and experimental studies. The matter that makes up everything we know and see is only 15% of the matter in the Universe. The other 85% is so called "dark matter". The existence of dark matter is evident from its many astrophysical and cosmological observations. These observations can be seen on all scales, from galaxies and galaxy clusters to the entire cosmos. From these observations we know that dark matter interacts gravitationally, but not electromagnetically. We also know the mass density of dark matter which is approximately 1/3 the mass of a proton per cubic centimeter. While knowing the mass density is a great step forward to understanding what dark matter is, we do not know much about the number or mass of dark matter particles. The Standard Model of Particle Physics is a theory that describes the building blocks of the Universe. Experimental results have shown that the Standard Model is able to describe most of the Universe, however there are a few aspects that it cannot explain. For example, it is unable to explain the presence of dark matter.

The list of dark matter candidates is quite vast with many detection techniques used to search for the various models. Liquid xenon time projection chambers currently lead the search for a dark matter candidate called Weakly Interacting Massive Particles (WIMPs) which has a theorized mass of approximately 100 times the mass of the proton. Particle detectors, such as XENON1T, aim to understand the fundamental particles of the Universe. XENON1T was a dark matter direct detection experiment looking for dark matter interactions with liquid xenon via a variety of dark matter models.

Delayed Electron Emissions in XENON1T

XENON1T was a dual-phase time projection chamber (TPC) dark matter direct detection experiment located at Gran Sasso National Laboratory in Italy. The active region of the TPC contained two tonnes of liquid xenon (LXe). When a particle enters the TPC, it can scatter off a xenon nucleus or an electron. These interactions produce a flash of light and free electrons in the LXe. The flash of light, called the S1, is detected promptly by two arrays of photomultiplier tubes (PMTs) located at the top and bottom of the TPC. An electric field is used to drift the free electrons from the event location up to the liquid-gas interface. A second, stronger electric field at the top of the detector extracts electrons into the gaseous xenon phase. This produces a secondary flash of light, called the S2, which is proportional to the number of extracted electrons. The localization of the S2 in the top PMTs can give the x-y position of the interaction and the time difference between the S1 and the S2 gives the z position of the interaction. The working principle of XENON1T can be seen in Figure 1.

To increase the sensitivity of XENON1T to search for various dark matter models, it is necessary to decrease backgrounds in the detector which mimic the signature of dark matter. One background that is specific to low-energy interactions comes from single- and few-electron signals. It is expected that all the free electrons produced in the interaction should be detected within the maximum drift time of about one millisecond. However, single- and few-electron signals continue to be observed for hundreds of times the maximum drift time, which inhibits low mass dark matter searches. An example event from XENON1T displaying these delayed electron signals is illustrated in Figure 2.

I led the analysis to understand what causes these delayed electron emissions in XENON1T by studying the effects of these backgrounds under various detector conditions [Aprile et al., 2021]. From this work, I concluded that delayed electron emissions are produced from interactions in the liquid region of the TPC. These backgrounds are not observed following interactions in the upper gas region. By studying these delayed electron backgrounds across many parameters, I found that the delayed electrons were correlated in time and position to large energy deposits in the TPC. There are two main hypotheses that developed to try and describe the cause of these delayed electron backgrounds. From XENON1T results, it was concluded that these backgrounds were not caused by imperfect extraction of electrons from the liquid to the gas (the first hypothesis). There was minimal correlation with the number of delayed electrons and the extraction electric field. Instead, we did see an increase of delayed electrons when the main interaction occurred deeper in the detector. As the electrons drift past more impurities, atoms and molecules which are not xenon, when produced deeper in the detector, it seemed likely that the cause of the delayed electron emissions resulted from trapping on impurities (the second hypothesis). By studying the effects of the delayed electron emissions with various detector conditions, I was able to develop cuts to remove these correlated backgrounds. By removing these backgrounds based on my data analysis, new limits on various low mass dark matter models were able to be placed using an analysis that looks at only the S2 signal. These new results are competitive with, or in some cases more sensitive than, other dark matter experiments for a variety of dark matter models.

While this work is able to cut away backgrounds on the data analysis side, it would be even better to remove these backgrounds from the detector all together. Here at Purdue University, I have been working on a parallel study using a small-scale TPC, called ASTERiX. The goal is to understand the cause of these delayed electrons from the source. A picture of ASTERiX is shown in Figure 3. With a team of undergraduate students, we have been trying to create ripples on the surface of the liquid xenon to see if slight changes the level of the liquid xenon has any impact on the delayed electron emissions. If the first hypothesis, electrons getting trapped at the liquid-gas interface, is correct, these ripples might help free the electrons on shorter timescales.

Applications in XENONnT

XENON1T was decommissioned in 2019 and XENONnT was built in its place. With four times the active volume, XENONnT has the same exposure as XENON1T with just a few months of data taking. The understanding of these delayed electron emissions is being directly transferred over to XENONnT in a variety of analyses; specifically to the S2-only analysis which I am currently conducting for XENONnT with a second team of undergraduates. The larger exposure and reduced backgrounds will aid in the improvement of the sensitivity to search for low mass dark matter models in combination with the cuts I developed from XENON1T.

XENONnT is also sensitive to neutrinos from various astrophysical sources. Specifically, XENONnT has detection capabilities for boron-8 (^{8}B) solar neutrinos and supernova neutrinos, which will a similar signal as low mass WIMPs. By reducing the backgrounds caused by delayed electron emissions, a search for ^{8}B solar neutrinos will be done at the same time as low mass dark matter searches. ^{8}B solar neutrinos come from solar nuclear fusion. Measuring the flux of ^{8}B solar neutrinos will provide insight to the composition and metallicity of the Sun. Current measurements of the ^{8}B neutrino flux lies between the high and low metallicity predictions in Standard Solar Model. More cross-check measurements are needed from different experiments, including those from XENONnT, to clear up this discrepancy.

Members of the multi-messenger astrophysics community are patiently awaiting the next galactic supernova. When a star dies and collapses, neutrinos from the explosion break out before the electromagnetic counterparts. This will allow neutrino and dark matter detectors to play an important role in understanding the physics of stellar deaths and neutrino propagation. In order to be prepared for the next supernova, the Supernova Early Warning System (SNEWS) was developed. SNEWS is an inter-experimental network prepared to provide an early warning to astronomers and observatories when a galactic supernova occurs. This is possible due to bursts of neutrinos that will arrive hours or days before electromagnetic signals. SNEWS is in the process of being revamped and amplified to SNEWS 2.0 which will have a larger physics reach.

In XENONnT, 100 neutrinos in 10 seconds are expected to be detectable from a supernova within the Milky Way galaxy. With the anticipation of a galactic supernova in the near future, I am using my knowledge of the single- and few-electron backgrounds to develop a real-time supernova trigger in XENONnT. This will allow XENONnT to be an active participant in the SNEWS. I have led key contributions to the modernization of the SNEWS server by implementing HOPSKOTCH, a new publish-subscribe software which will improve the networking infrastructure of SNEWS to a robust and reliable alert system. I worked with the Scalable Cyberinfrastructure for Multi-Messenger Astrophysics (SCiMMA) project to prototype the server which was later adopted by the SNEWS Collaboration [Baxter et al., 2021]. XENONnT was a trailblazing experiment in the SNEWS server prototype which has allowed me to gain insight on the requirements needed for an experiment to contribute to a supernova alert.

The characterization of delayed electron backgrounds conducted on XENON1T and XENONnT will allow XENONnT to be more sensitive to a variety of low mass dark matter particles and neutrinos from various astrophysical sources. Data taking is underway right now, and rare interactions occurring within XENONnT are waiting to be discovered!

[Aprile et al., 2021] Aprile, E., Baxter, A. L., et al. (2021). Emission of Single and Few Electrons in XENON1T and Limits on Light Dark Matter. *Submitted to Physical Review D.* arXiv:2112.12116 [hep-ex].

[Baxter et al., 2021] Baxter, A. L. et al. (2021). Agile scrum development in an ad hoc software collaboration. *Submitted to Journal of Software: Practices and Experiences.* arXiv:2101.07779 [cs.SE].

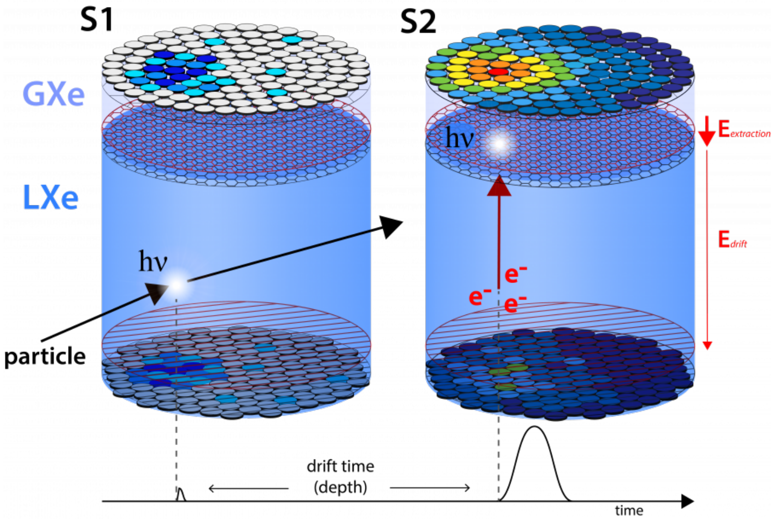

Figure 1: The working principle of the XENON1T experiment.

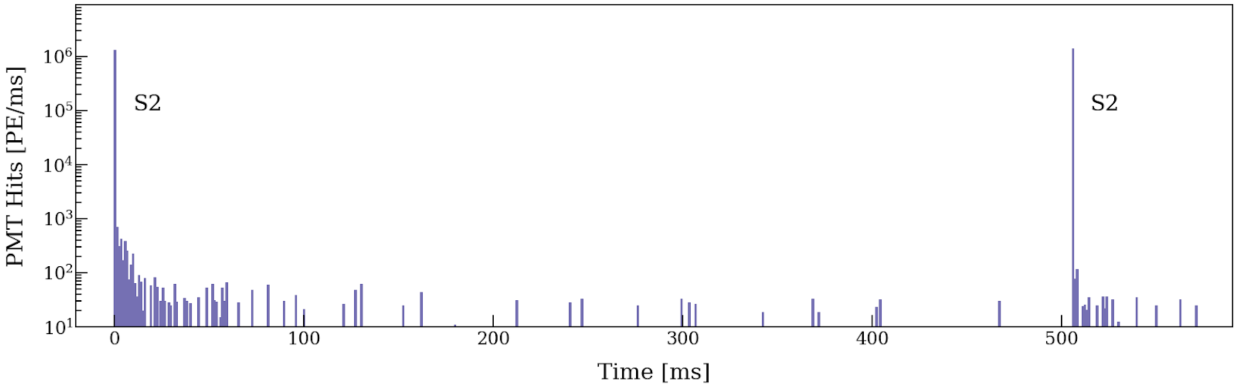

Figure 2: An illustrative event from XENON1T which demonstrates the number and time distribution of few-electron S2 signals following a large S2 signal.

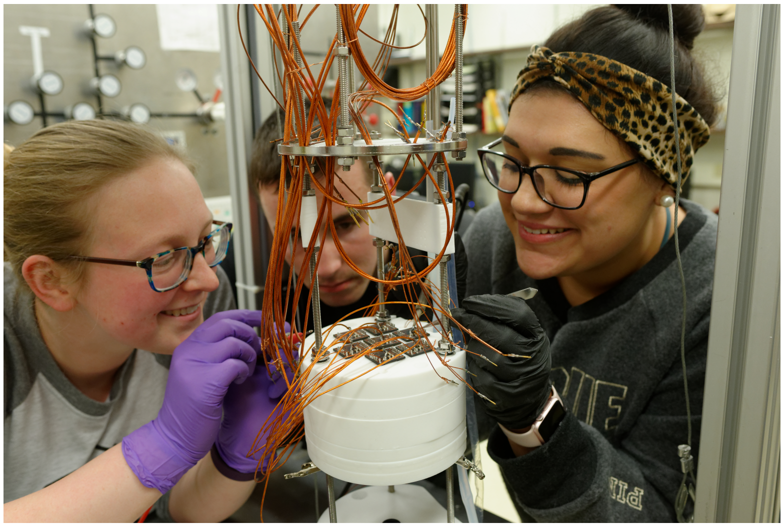

Figure 3: Picture of ASTERiX, the small TPC at Purdue University used to characterize delayed electron backgrounds. Photographed from left to right is Dr. Abigail Kopec, undergraduate Frank DiBartolomeo, and me (Amanda Depoian-Baxter).