Liquid Xenon Detectors for Dark Matter Searches

Mathi Raja, Gabriel Orebi Gann
University of California, Berkeley

This article provides an overview of the notable progress and persistent challenges in the advancement of liquid xenon-based detectors for the purpose of investigating dark matter, a crucial field in astrophysics and particle physics. These detectors exploit the distinctive characteristics of xenon to identify the enigmatic weakly interacting massive particles (WIMPs) that are postulated to constitute dark matter. Through advancements in detector technology, such as refined xenon purification techniques and improved photodetection systems, the sensitivity of these detectors has been significantly enhanced while background noise has been reduced. Consequently, this has facilitated more accurate measurements and analysis. This comprehensive review encompasses the historical evolution, operational principles, and future prospects of xenon-based detection technology in its pursuit of unraveling some of the most profound mysteries of the universe.

I. INTRODUCTION

Dark matter, which accounts for approximately 85% of the mass in the universe and is inferred from its gravitational influence on visible matter, continues to be a mysterious subject in the field of physics. Scientists are employing liquid xenon-based detectors, known for their sensitivity to potential dark matter particles like Weakly Interacting Massive Particles (WIMPs), in their research endeavors. These detectors are capable of identifying scintillation and ionization signals resulting from interactions with particles, utilizing xenon's high atomic mass and self-shielding properties to reduce background noise and improve signal detection.

The development of this technology has progressed from initial prototypes to advanced large-scale detectors utilized in experiments such as XENON, LUX, and PandaX. These detectors are typically situated deep underground to minimize interference from cosmic rays, thereby enhancing their capacity to detect faint signals of dark matter. This investigation delves into the operational mechanisms, advancements, and obstacles associated with these detectors, underscoring their significance in the quest for dark matter [1].

II. HISTORY AND CHANGES OF DARK MATTER DETECTORS

The inception of dark matter detection devices can be traced back to the emphasis on Weakly Interacting Massive Particles (WIMPs), which were initially deemed as the most plausible candidates owing to their alignment with observed phenomena. This instigated the advancement of technologies geared towards identifying their subtle interactions with regular matter. As investigations progressed, liquid xenon emerged as the favored medium for detection due to its density, lack of reactivity (creating this "radio quiet" environment), and self-shielding properties, rendering it well-suited for capturing infrequent particle interactions and minimizing undesired responses [2].

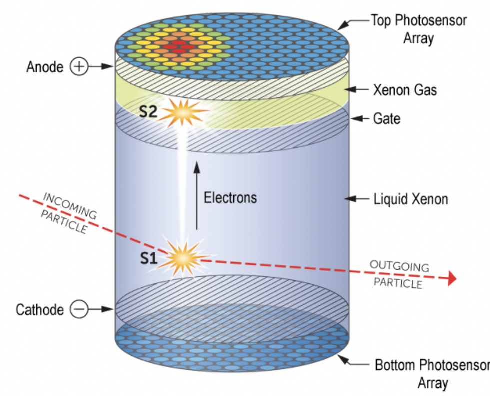

FIG. 1. Illustration of how the Time Projection Chamber detects events. [3]

Commencing in the late 1990s and early 2000s, the transition to liquid xenon detectors represented a notable shift in strategies employed in dark matter research. These detectors, leveraging xenon's elevated atomic number and mass, heightened the likelihood of engaging with dark matter particles, thereby enhancing detection capabilities. Opting for liquid xenon also served to diminish background noise, a critical factor in discerning authentic dark matter signals within an interference-free setting. This progression mirrors broader collider trends towards more intricate, sensitive experimental configurations.

III. DETECTOR MECHANISMS

The liquid xenon Time Projection Chamber (TPC), as seen in Figure 1, utilizes scintillation and ionization processes for the detection of dark matter. Interaction of dark matter particles with xenon results in the emission of ultraviolet light (scintillation) and the ionization of electrons. These electrons, under the influence of an electric field directed towards an anode, generate a secondary light signal in the gas phase, aiding in the determination of the interaction's position within the detector. The TPC's dual-phase (liquid and gas) configuration enables accurate 3D reconstruction of these interactions. The efficiency of the system relies on maintaining xenon purity to prevent absorption of light and electrons, requiring continuous purification and robust shielding against background radiation to ensure optimal functionality [4].

IV. MAJOR EXPERIMENTS

The XENON10 and XENON100 experiments, followed by LUX and ZEPLIN-III, were at the forefront of the development of xenon-based dark matter detection technologies. These experiments played a crucial role in demonstrating the viability of using liquid xenon as a sensitive medium for detecting interactions with dark matter. Among them, XENON100 was particularly significant in establishing strict limits on the cross-sections between Weakly Interacting Massive Particles (WIMPs) and nucleons, thereby expanding the boundaries of detectable dark matter particle masses and interaction strengths.

PandaX-II and its successor, PandaX-4T, as well as XENON1T and the more recent XENONnT, represent notable advancements in this field. These experiments utilize larger quantities of liquid xenon to enhance sensitivity to potential signals from dark matter. By increasing the target mass, these experiments are able to explore a wider range of WIMP masses, spanning from lighter to heavier candidates, thereby improving the chances of detecting rare interactions.

LUX-ZEPLIN (LZ), currently one of the largest-scale experiments, and the anticipated DARWIN/G3 project aim to further expand the target mass and minimize background noise to unprecedented levels. These endeavors underscore the ongoing pursuit of detectors with multi-ton xenon targets, which are expected to significantly enhance sensitivity to sub-GeV WIMP candidates and potentially detect interactions from other rare events, such as axion-like particles and neutrinoless double-beta decay [2].

The significance of these experiments extends beyond their individual contributions to dark matter detection. They collectively contribute to the refinement of detection technology and methodologies. Each experiment builds upon the knowledge gained from its predecessors, progressively reducing background levels and enhancing sensitivity as seen in Figure 2. As a result, the entire field is propelled closer to the potential discovery of dark matter particles.

V. ADVANCEMENTS AND LIMITATIONS

One of the primary advancements in liquid xenon detectors involves the improvement of xenon purity. The

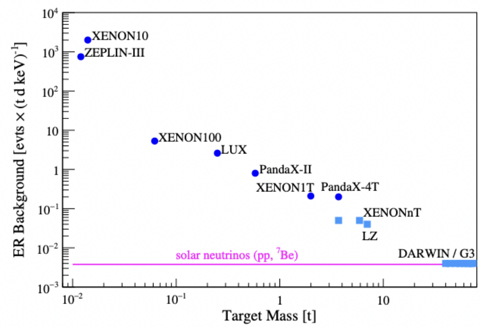

FIG. 2. Evolution of detectors over time and how they have improved with scale. [3]

elimination of impurities like krypton, which can interfere with signals from dark matter particles, has been a crucial area of focus. Methods such as gas charcoal chromatography have been devised to effectively purify xenon, utilizing helium to remove less adhesive krypton atoms from xenon. This heightened purity of xenon decreases background noise, thereby boosting the detectors' sensitivity to interactions with dark matter [3].

Photodetection technologies have also undergone significant enhancements. The optimization of high-voltage grids in detectors, which aid in capturing signals produced by particle interactions, has been perfected to decrease the emission of extraneous electrons from the grid materials themselves. This process is further improved by techniques like passivation, which involves coating materials to make them resistant to corrosion. These advancements contribute to obtaining clearer and more dependable data from the light signals generated within the xenon [3].

Detectors also employ timing strategies to distinguish between surface and bulk events. Events that take place near the detector walls are more likely to be background noise, while interactions within the central, or "fiducial" volume, are more likely to be authentic dark matter signals. Consequently, scalability has emerged as a significant area of interest. Through various experiments, it has been observed that by increasing the total mass of xenon utilized, such as by transitioning to larger detectors, the occurrence of background noise events can be further reduced.

Finally in the field of software, the data analysis methods utilized in these studies have grown more complex, integrating cutting-edge statistical approaches and machine learning algorithms to distinguish background noise from authentic signals.

The endeavor to diminish background noise has been pivotal in enhancing detector sensitivity. This encompasses both physical alterations to the detector environment and procedural innovations aimed at lessening the influence of cosmic rays and other sources of radiation on the detector readings.

In the future, there is great anticipation for the possibility of optimizing detectors to decrease the interference caused by solar neutrinos. By having knowledge of the trajectory of incoming solar neutrinos, upcoming detectors might have the capability to trace the movement of xenon atoms after they collide. If the path of these atoms aligns with the anticipated path of solar neutrinos, these interactions can be classified separately, resulting in a reduction of unwanted disturbances and enabling a more concentrated focus on signals that are more likely to originate from dark matter.

VI. CONCLUSION

The progress made in liquid xenon-based detectors has greatly advanced both theoretical and applied physics, contributing to our comprehension of the cosmos and its fundamental particles. These detectors have revolutionized experimental physics, particularly in the study of dark matter and the investigation of other uncommon phenomena. Through enhancements in xenon purification, photodetection, and data analysis, these systems have significantly improved their capacity to distinguish authentic dark matter signals from background interference. In the future, the utilization of directional data to eliminate known sources of noise, such as solar neutrinos, could further enhance the capabilities of these detectors. This continuous advancement not only deepens our understanding of dark matter but also enriches various fields within physics, propelling our exploration of the most elusive components of the universe.

[1] J. Howlett, *Liquid-phase purification for multi-ton xenon detectors and a search for dark matter and neutrinos in XENON1T*, Ph.D. thesis, Columbia University (2022).

[2] G. Bertone and D. Hooper, History of dark matter, Reviews of Modern Physics **90**, 045002 (2018).

[3] D. Akerib *et al.*, A next-generation liquid xenon observatory for dark matter and neutrino physics, arXiv (2022), arXiv:2203.02309 [astro-ph.IM].

[4] Phys.org, Researchers use purified liquid xenon to search for mysterious dark matter particles (2022).