Analysis of Dark Matter Searching Based on Liquid Xenon: XENON, LUX-ZEPLIN and DARWIN

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Abstract. This paper delves into the ongoing quest to uncover the mysteries of dark matter, an endeavor that has captivated the scientific community for nearly a century. Focusing on the utilization of liquid xenon scintillators, specifically in the XENONnT and LZ experiments, it explores the remarkable properties of liquid xenon that make it a prime candidate for detecting Weakly Interacting Massive Particles (WIMPs), a leading dark matter candidate. These experiments have achieved significant milestones, placing stringent constraints on the WIMP-nucleon interaction cross section, yet face the challenge of the "neutrino fog" at lower energies, necessitating innovative solutions like advanced statistical methods and machine learning. The paper also highlights the promising future of dark matter detection through projects like DARWIN and the XLZD Consortium, which aim to construct next-generation liquid xenon detectors with increased target masses. These endeavors hold the potential to significantly enhance sensitivity, potentially unraveling the nature of dark matter. Furthermore, the versatility of liquid xenon detectors extends to the study of neutrinos, encompassing neutrinoless double-beta decays and solar pp neutrinos. These results shed light on guiding further exploration of dark matter searching.

Keywords: Dark matter; liquid xenon scintillators; WIMPs; direct detection.

1. Introduction

Although the search for dark matter has amassed large amounts of interest in the present day, its history spans the entirety of the last century [1]. As early as 1933, Swiss astronomer Fritz Zwicky noted the discrepancy between the large velocity dispersion of the Coma cluster and its low mass density, which resulted in a debate that lasted for the next couple of decades [2]. Papers published in the early 1970s studying the rotation curves of galaxies, which describe a relationship between the orbital velocity of its contents and their galactic radii, found them to be flat [3]. This is in direct contradiction to the widely accepted Keplerian model of galaxies, which predicted declining rotation curves, and as such hints at the notion of an invisible mass [1]. During the same period of time, theoretical astrophysicists were also searching for a source of additional mass such that the mass density of the universe is able to exceed the critical mass needed for the philosophically ideal closed universe. With this aesthetic belief of a closed universe as an impetus, the above-described enigmas of the mass discrepancy of galaxy clusters and flat rotation curves served as evidence for the existence of a mysterious, undetectable type of matter, which is what one knows today as "dark matter" [1]. Since then, there has only been an increasing amount of evidence in support of the existence of dark matter, yet there nonetheless lacks unequivocal observational proofs.

Aside from attempting to directly produce dark matter particles via particle accelerators, the contemporary search for dark matter can be loosely categorized into two broad categories: indirect and direct detection [4]. Models of dark matter predict it to undergo processes of self-annihilation, the products of which indirect methods of detection hope to identify and observe. Likely candidates for the byproduct of dark matter self-annihilation include gamma rays, antiprotons, and positrons [5]. Indirect methods of detection seek to observe byproducts of annihilation that originate from the center of galaxies, due to the hypothesized high density of dark matter that interacts with the large stellar content and supermassive black holes found there [5]. However, challenges arise from differentiating between these particles' origins and other astrophysical processes that can produce similar signals [4].

More significant to this paper are the methods of direct detection. Where indirect detection hopes to observe other particles that may point towards the existence of dark matter, direct detection hopes to observe dark matter particles themselves. The difficulty of direct dark matter detection lies in the vast theoretical range for the possible mass of dark matter particles, and as such, a wide variety of experiments are needed in order to examine every possibility [6]. Bosonic dark matter, such as axions, may be detected by resonant microwave cavities such as those employed in the Axion Dark Matter Experiment. Fermionic dark matter, such as weakly interacting massive particles (WIMPs), may be detected by cryogenic crystal detectors or by scintillators. Composite dark matter, such as primordial black holes, may be detected by observing gravitational waves through LIGO, for example.

The primary focus of this paper is to assess the effectiveness of WIMP detection based on the usage of liquid xenon scintillators, and possibly the detection of dark matter in other forms. To that end, this paper will be evaluating three collaborative projects at the forefront of building liquid xenon dark matter detectors: XENON, LUX-ZEPLIN (LZ), and DARWIN. Scintillators, specifically those based on liquid xenon, are amongst one of the most promising instruments of dark matter detection, with the U.S. Department of Energy even designating the LZ project as one of the flagship “second generation” projects for direct detection. In this case, this avenue of dark matter detection warrants great levels of interest and thusly serves as the motivation for the remainder of this paper. Firstly, the basic theory behind WIMPs as well as the principles on which liquid xenon detectors operate shall be introduced. Next, the structure and operational components of each of the aforementioned projects shall be illustrated, as well as the results of each and the limitations and future aspects of liquid xenon as a viable method of dark matter detection as a whole.

2. WIMPs & Liquid Xenon Scintillators

As its name naturally suggests, WIMPs are a broad category of theoretical particles that do not readily interact with the three forces currently described by the Standard Model (SM) of quantum physics, yet is still able to interact with baryonic matter via the gravitational force. As a result of this, WIMPs must be massive particles (to participate in gravitational interactions) that carry no electric charge (to abstain from electromagnetic interactions). Within the SM, the only particle that conforms to these requirements is the neutrino. However, cosmological surveys have shown that the neutrino mass density of the universe falls short of the theoretical mass density of dark matter [7]. Additionally, dark matter that shares the relativistic nature of neutrinos would result in a universe with a structure vastly different than what is observed [7]. Hence, many contemporary theorists have opted to search for a candidate that is beyond our understanding of the SM.

Supersymmetry (SUSY) is a proposed extension of the SM that doubles the amount of fundamental particles needed to describe the universe. SUSY theorizes a violation of certain symmetries that the SM assumes (hence the name). In particular, SUSY provides a framework that is able to maneuver around the laws of conservation of charge and lepton number and allows the conversion between fermions and bosons. Through this conversion, it posits the existence of a supersymmetrical counterpart to each particle in the SM, which is dubbed aptly as a “superpartner”; a fermion would have a boson superpartner, and vice versa [7]. With SUSY in consideration, there emerges an additional three particles that fulfill the criteria of being a massive particle that is electrically neutral: the sneutrino, the gravitino, and the neutralino. The theoretical properties of the sneutrino and the gravitino do not correspond well with the theoretical properties of dark matter. As a result, this leaves neutralinos as the sole suitable candidate for a dark-matter-like WIMP under SUSY [7]. Neutralinos are the fermionic result of the superposition of the higgsino, the wino, and the bino, which themselves are the fermionic superpartners of the Higgs boson, the W boson, and the B boson, respectively [8]. The neutralino has four mass eigenstates, the lightest of which is stable, and thus is able to theoretically exist as dark matter [8].

The principle behind the direct detection of these theoretically WIMPS is the premise that, if the universe is truly filled with dark matter, certainly, there is a large density of dark matter impacting and traveling through the Earth at any given moment [4]. Though WIMPs are electrically neutral and hence largely do not interact with most particles, on rare occasions, WIMPs theoretically have a chance to directly strike and deposit a portion of its energy onto the nucleus of an atom. Highly sensitive particle detectors may be employed to measure and observe these nuclear recoils and thus deduce the properties of the WIMP. However, due to the rarity of such nuclear interactions, it is extremely difficult to isolate a potential WIMP detection from the deluge of background radiation. As a result, these facilities that aim to detect dark matter directly must be situated deep underground to minimize the amount of background noise. An apparatus commonly used for particle detection is the scintillator. Scintillators utilize materials that are able to emit photons after an impact from a particle or radiation. The properties of the resultant photons can be measured and analyzed to deduce the properties of the incident particle. Scintillators designed for the purpose of WIMP detection should consist of materials that readily produce photons following a nuclear recoil event.

Xenon exhibits a multitude of properties that makes it the ideal material to detect WIMPs. Noble gases in general are good materials for particle detection as they have high stopping power and exhibit high densities [9]. Xenon is simultaneously the heaviest out of the noble gases, as well as extremely compressible, making it the easiest to achieve high densities [9]. Highly compact materials are ideal for scintillators as it increases the chances of an interaction with the target particle. Furthermore, liquid xenon is easy to purify, and its inert nature as a noble gas allows it to stay chemically and structurally nonreactive [9, 10]. Liquid xenon also has excellent scintillation efficiency, and produces scintillation photons with wavelengths that are transparent within its own medium [10].

Nuclear recoils of liquid xenon result in scintillation through two mechanisms: excitation and ionization [11]. Excitation results in direct scintillation through the following process,

$$\mathrm{Xe}\ast\ +\mathrm{Xe}+\mathrm{Xe}\rightarrow\mathrm{Xe}\ast 2+\mathrm{Xe} \tag{1}$$

$$\mathrm{Xe}\ast 2\rightarrow 2\mathrm{Xe}+h\nu \tag{2}$$

where * represents an excited state [11]. The above process illustrates that the source of the scintillation photon is in fact molecular xenon in its excited state. A photon with an energy hν within the ultraviolet range can then be picked up by photomultiplier tubes (PMT), which detect and convert photons into electric signals [10]. Nuclear recoils can also result in ionization, as the rapid motion of the recoiling nucleus can disturb the electron cloud surrounding the nucleus, hence producing an ion-electron pair. Through a process known as recombination, the ion-electron pair can also form an excited molecule of xenon and produce scintillation. This is shown as follows,

$$\mathrm{Xe}+\ +\mathrm{Xe}+\mathrm{Xe}\rightarrow\mathrm{Xe}+2+\mathrm{Xe} \tag{3}$$

$$\mathrm{Xe}+2+\mathrm{e}-\rightarrow\mathrm{Xe}\ast\ast\ +\mathrm{Xe} \tag{4}$$

$$\mathrm{Xe}\ast\ast\ \rightarrow\mathrm{Xe}\ast\ +\text{heat} \tag{5}$$

$$\mathrm{Xe}\ast\ +\mathrm{Xe}+\mathrm{Xe}\rightarrow\mathrm{Xe}\ast 2+\mathrm{Xe} \tag{6}$$

Where the resultant $\mathrm{Xe}\ast 2$ produces a photon in the same manner as before [11]. However, recombination in a liquid xenon scintillator is largely inhibited by the application of an electric field, which removes the free electron from the liquid xenon. Instead, it leads it to an area with gaseous xenon at the top of the apparatus. Here, a strong electric field induces a secondary scintillation that produces a signal that is distinct from the primary [9]. On this basis, the scintillator is able to isolate the processes of excitation and ionization, which would lead to the production of the primary and secondary scintillations, respectively. Doing so has two benefits. Firstly, nuclear recoil events caused by the scattering of WIMPs is known to have a small charge-to-light ratio, i.e. one should expect to see signals as a result of excitation than ionization [9]. This allows the discrimination of nuclear recoil against other background interactions, which mainly result in electron recoil and thus ionization. Secondly, the measurement of the secondary scintillation signal allows for a 3D reconstruction of the impact event. With the drift velocity of the electron in liquid xenon known, the depth (z-coordinate) at which the impact occurred can be found by calculating the time difference between the primary and secondary scintillation signals. The impact's location on the x-y plane can be found as the impact location should be directly underneath the PMTs that detect the highest number of photons [12]. The above-described apparatus that holds the PMTs and the xenon in both the liquid and gas phases is called a time projection chamber (TPC).

3. Xenon

The XENON project is based 1,400 meter underground in the Gran Sasso National Laboratory, located 120 kilometers away from Rome [13]. With XENON10 being their first prototype, the XENON project has been in operation since 2006 and has gone through multiple iterations. Their current detector is the XENONnT, and is a direct upgrade from its predecessor, XENON1T, and adopted much of its infrastructure. Within XENONnT is 8.6 tons of xenon, 5.9 of which is liquid xenon within the TPC serving as the active detection volume [13]. The rest of which would be within the purification process. The TPC itself is a cylindrical container with a diameter of 134 cm and height of 148 cm. On the top and the bottom are two arrays that include 253 and 241 PMTs, respectively, for a total of 494 PMTs [13]. The PMTs used are 3 inch Hamamatsu R11410-21, which exhibit properties of low radioactivity, high quantum efficiency, and high sensitivity to photons [14]. A dual gas and liquid phase purification system is used to remove electronegative impurities in the xenon content. It is important that the xenon is free of such impurities such that the electrons freed by ionization do not get captured. The gas purification system is borrowed directly from XENON1T, which evaporates liquid xenon and passes it through a zirconium alloy onto which the impurities bind. New to XENONnT is the liquid-phase purification system, which runs in parallel to the gaseous purifiers [15]. The system works by pumping liquid xenon through cryogenic sorbent beds made of copper that remove oxygen desorbed into liquid content from the equipment. The liquid phase purification system is more scalable compared to gaseous purification [15].

XENONnT also employs multiple methods to reduce sources of radioactivity in the experiment in an effort to reduce background radiation. To reduce radiation induced by radon, XENONnT utilizes a high-flow radon removal system, which takes advantage of the difference in the volatility of xenon and radon to separate the two elements [16]. The materials of the detector are also carefully selected to increase material radiopurity. The background radiation of the XENONnT experiment is approximately 17% that of the XENON1T experiment [17]. To further reduce background activity, neutron and muon vetos are in place to tag neutrons and muons by using PMTs that detect radiation emitted by these particles as they travel through water [13, 18]. It allows for the rejection of neutron-nucleus and muon scatter event by studying signals coincident with the TPC [18].

Over the course of a little bit more than a year, the XENONnT experiment has found no significant excess signal between the ranges of 3.3 keV and 60.5 keV [13]. Through this, the experiment was able to apply constraints on the maximum WIMP-nucleon cross section as a function of WIMP mass. The cross section is related to scattering, and is a representation of the likelihood of a scattering event occurring, which is directly related to the possible strength at which WIMPs can interact with normal matter. Particularly, the experiment has obtained that the lowest maximum value for the cross sectional area of WIMP-nucleon interactions to be 2.58×10^{-47} cm^2 for a WIMP mass of 28 GeV/c^2, which is a upper limit that is lower than the one obtained by XENON1T by 37% for a similar WIMP mass [19].

4. Lux-Zeplin

The LUX-ZEPLIN (LZ) experiment is located nearly a mile underground in the American Sanford Underground Research Facility in the state of South Dakota, across the pond from the XENON project. The LZ experiment borrows heavily from its predecessors: the LUX and ZEPLIN-III experiments [20]. The TPC contains 7 tons of liquid xenon that is actively being used for WIMP detection. The TPC itself is measures to be around 1.5 m in both its diameter and height [20]. Similar to XENONnT, the TPC in the LZ experiment features two arrays of PMTs, 253 on the top and 241 on the bottom for a total of 494 PMTs. Such a circular and hexagonal pattern is used to facilitate the 3D reconstruction of the impact event, especially in regions at the edge of the TPC [20]. The PMTs used are 3 inch Hamamatsu R11410-22, which is an iteration newer than the ones utilized in XENONnT. There is an observed flaw in previous variants of the Hamamatsu R11410 which can cause it to spontaneously emit photons. The Hamamatsu R11410-22, compared to previous variants, emits lower levels of radioactivity and is less likely to undergo spontaneous light emission [21].

The methods used by the LZ experiment to shield the TPC from external radiation differ to that of XENONnT. Where XENONnt employs neutron and muon vetos, the LZ experiment utilizes a socalled Xe Skin detector, which contains approximately 2 tons of liquid xenon. The skin not only serves to act as a dielectric insulator between the TPC and the electrodes in charge of conducting the electric field, but also takes advantage of the self-shielding property of liquid xenon [20]. The skin shields the TPC from gamma rays and acts as a scintillation-only veto for such incident rays. As such, the skin is also equipped with PMTs to be able to detect and successfully reject photon-induced events.

For the purification of xenon, the LZ experiment uses only a gas-phase filtration system. The system involves pumping xenon gas through a hot zirconium getter, operating at 400°C, which efficiently removes electronegative impurities [20]. The getter also serves as a repository for tritium and radiolabeled methane species used for calibration. Radon is also removed from the xenon by means of a 10 kg synthetic charcoal column which serves as an adsorbent, attracting and trapping radon atoms. This technique is known as gas chromatography, and 90% of the radon is allowed to decay over a 2.7-day sequestration period [20]. The entire xenon content of the experiment is also purged of krypton impurities prior to the experiment. To remove trace krypton from the xenon gas in the LZ experiment, activated charcoal columns are used. The xenon gas is mixed with helium carrier gas and circulated through the columns. The charcoal selectively traps the krypton, allowing purified xenon to be separated and stored for use in the detector. This process is repeated in batches to achieve the required krypton concentration reduction [20].

Throughout the exposure period of 60 days, the LZ experiment was not able to detect significant excess signals [22]. As a result, the experiment was able to obtain limits for WIMP-nucleon, WIMPneutron, and WIMP-proton cross sections as a function of WIMP mass. The lowest maximum value for the cross sectional area for a WIMP-neutron interaction is 1.49×10^{-42} cm^2 for a WIMP mass 30 GeV/c^2; the lowest maximum value for the cross sectional area for a WIMP-proton interaction is 4.2×10^{-41} cm^2 for a WIMP mass 32 GeV/c^2. The most stringent constraint obtained is that of the WIMP-nucleon interaction, with lowest maximum value for the cross sectional area for a WIMPnucleon interaction being 9.2×10^{-48} cm^2 for a WIMP mass 36 GeV/c^2 [22].

5. Limitations and Prospects

The XENON and LZ collaborations were able to successfully obtain stringent constraints for the cross section of a WIMP interaction as a function of mass during the course of their operations. However, the technology of liquid xenon scintillator can be furthered. Methods of increasing the average lifetime of the drift electrons that are produced as a result of ionization can allow for larger drift lengths, facilitating the construction of larger TPCs. Larger TPCs would be able to contain larger volumes of liquid xenon, increasing the target size and hence increasing the likelihoods of a nuclear recoil event. Additionally, the sensitivity to low-energy interactions can be improved by furthering removing sources of background radiation. WIMP search with liquid xenoN (DARWIN) project, since its conception in 2016, has aimed to achieve the construction of such a “third-generation” liquid xenon scintillator [23]. To this end, the DARWIN collaboration has since united with the XENON and LZ collaborations to form the XLZD Consortium to facilitate an avenue for communication of the technologies the various projects have developed over their decades of experimentation with liquid xenon detectors. The proposed liquid xenon detector would contain 50 tons of liquid xenon, massively amplifying the active xenon target size. DARWIN projects that such a detector would be able to probe interactions with a cross section of only a few $\times10^{-48}$ cm^2 for WIMPs with mass comparable to the previously discussed experiments [23]. Despite its ambitiously large xenon content, the project is envisioned to nonetheless be compact, with a diameter and height of around 3 m [24].

Despite this, there are fundamental limitations to the usage of direct detection methods of WIMP detection such as liquid xenon scintillators. As apparatus becomes more and more sensitive, a phenomenon known as neutrino fog becomes apparent, and presents a theoretical lower limit for dark matter detection. Below a certain point, the detectable signal of a WIMP will become increasingly similar to that of neutrino-nucleus scattering events [25]. As such, at low energy levels, the difficulty in distinguishing a WIMP-induced nuclear recoil from one that is neutrino-induced would increase dramatically. Unlike the various types of background discussed above, neutrino backgrounds cannot be shielded and hence inevitable [24]. However, through significant statistical data, one is still able to “penetrate” the neutrino fog, since the nuclear recoil spectra for WIMPs and neutrinos are not exactly the same [25]. Machine learning techniques have been predicted to be able to distinguish and classify different types of signals obtained by TPC of the LZ experiment with an accuracy of more than 99.0% [26]. As a consequence, perhaps machine learning can be utilized to create algorithms that are able to effectively distinguish between the nuclear recoil spectra of WIMPs and neutrinos. Furthermore, the neutrino fog can be effectively lowered by reducing neutrino flux uncertainties, which are directly correlated to the intensity of the neutrino background [25]. The phenomenon of the neutrino fog is a result the sensitivity of liquid xenon detectors to nuclear recoils of not only WIMPs, but also neutrinos [24]. As a result, liquid xenon detectors developed for the use of dark matter detection can easily be pivoted and repurposed for the study of neutrinos and aid in the detection of neutrinoless double-beta decays and solar pp neutrinos [24].

6. Conclusion

To sum up, the pursuit of dark matter, spanning nearly a century, has been characterized by intriguing observations, from Fritz Zwicky’s early work on galaxy cluster velocities to the flat rotation curves of galaxies. While mounting evidence strongly suggests its existence, definitive proof remains elusive, driving the need for innovative experiments. This paper has focused on cutting-edge dark matter detection techniques, particularly the use of liquid xenon scintillators in projects like XENONnT and LZ. Liquid xenon’s favorable properties, including high density and scintillation efficiency, make it an ideal medium for WIMP detection. These experiments have achieved remarkable results, constrained the WIMP-nucleon cross section, and set stringent limits on potential dark matter interactions. Exciting developments are on the horizon with projects like DARWIN and the XLZD Consortium. These collaborations aim to construct third-generation liquid xenon detectors with substantially larger target masses, enhancing sensitivity. By pooling expertise and resources from XENON, LZ, and DARWIN, these endeavors are poised to reshape dark matter research and potentially unveil its nature. Furthermore, liquid xenon detectors hold promise in neutrino research, enabling the study of neutrinoless double-beta decays and solar pp neutrinos. This versatility underscores the importance of liquid xenon scintillators in advancing our understanding of fundamental particles and forces. However, challenges persist, notably the so-called neutrino fog, which imposes a lower limit on WIMP-like dark matter detectability. Below this limit, distinguishing dark matter interactions from background neutrino-nucleus scattering becomes increasingly complex. Innovative solutions, such as advanced statistical techniques and machine learning algorithms, though, may offer hope in mitigating this challenge. In conclusion, the quest for dark matter, though challenging, is marked by recent advancements in liquid xenon detectors and collaborative efforts. As scholars continue to push boundaries, the mysteries of dark matter may soon yield, ushering in a new era of cosmic understanding

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