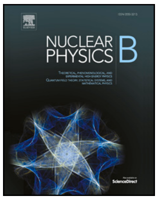
Nucl. Phys. B 1003 (2024) 116437

Contents lists available at ScienceDirect

Nuclear Physics, Section B

journal homepage: www.elsevier.com/locate/nuclphysb



High Energy Physics – Phenomenology

LUX, ZEPLIN and LUX-ZEPLIN: Developments in liquid xenon detectors and the search for WIMP dark matter

Daniel S. Akerib [a,b,*]

[a] SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94205-7015, USA
[b] Kavli Institute for Particle Astrophysics and Cosmology (KIPAC), Stanford University, 452 Lomita Mall, Stanford, CA 94309-4008, USA

ARTICLE INFO

Editor: Tommy Ohlsson

ABSTRACT

The search for dark matter in the form of Weakly Interacting Massive Particles (WIMPs) remains one of the enduring scientific and technical challenges in physics despite four decades of research. A discovery would have broad implications for particle physics, astrophysics, and cosmology. Over the last 15 years, liquid xenon time projection chambers have been on the forefront of this search, starting with detector masses on the 10-kg scale and now reaching the 10-tonne scale. Advances in a number of technical areas across xenon-detector collaborations worldwide, along with progress in related techniques in low-background and liquid noble detectors, have led to significant and steady improvements in sensitivity. In this contribution to Nobel Symposium 182, I highlight several of the contributions made by the LUX, ZEPLIN, and LUX-ZEPLIN (LZ) collaborations, and members thereof. I also discuss briefly the status of the currently-operating and world-leading LZ experiment.

1. Introduction

The search for dark matter in the form of Weakly Interacting Massive Particles, or WIMPs, in the 10-GeV to 10-TeV mass range has improved nearly 4 orders of magnitude in sensitivity over the last 15 years due to experiments based on liquid xenon (LXe) Time Projection Chambers (TPCs). The early years of WIMP searching began with solid detectors, including germanium diode detectors, originally configured to search for neutrinoless double beta decay. These experiments emphasized low radioactive backgrounds, underground siting, and good energy resolution at the 2-MeV beta spectrum endpoint. By reconfiguring them to search for events at low energy threshold to search for events at the 10-keV energy scale characteristic of WIMP-nucleus scatters, the search for dark matter particles in the galactic halo got underway. In time, these experiments were limited by irreducible radioactive backgrounds in the detectors and surrounding materials. These backgrounds were dominated by electron recoil (ER) events from gamma rays, whereas WIMPs give rise to nuclear recoil (NR) events. Thus, new approaches were developed to reject backgrounds by discriminating between these two event classes. Predominant among these approaches was the simultaneous measurement of an ionization signal and a thermal or phonon-mediated signal in germanium and silicon substrates, which takes advantage of the relatively larger thermal signal for NR versus ER events. With this new technique came the challenge of keeping backgrounds low in these more complex detectors while fabricating and deploying larger mass arrays. Many of these technical challenges were met by the CDMS, EDELWEISS

---

* Correspondence to: SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94205-7015, USA.
E-mail address: akerib@slac.stanford.edu.

https://doi.org/10.1016/j.nuclphysb.2024.116437
Received 21 December 2023; Accepted 3 January 2024

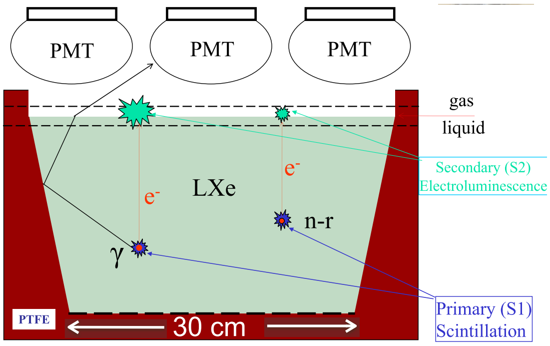


Fig. 1. The ZEPLIN-II detector, shown here in cross-section, is comprised of 31 kg of liquid xenon in a PTFE-lined cryogenic vessel read out with an array of seven PMTs. The two main event classes, an electron recoil due to gamma scattering and a nuclear recoil due to neutron or WIMP scattering, are illustrated. In both cases, primary and secondary scintillation occur, the latter from electrons drifted upward and extracted into the gas phase. Note the relatively larger S2 signal for the gamma-induced electron recoil as suggested by the size of the flashes. (Courtesy of the ZEPLIN-II collaboration.)

and CRESST collaborations, with world-leading sensitivity based on total target masses up to the multi-kilogram range. Eventually, this approach was eclipsed by the LXe TPCs starting in the mid-2010's.

Several successful LXe programs were launched, led initially by the XENON and ZEPLIN collaborations, and later expanding to include the LUX and PandaX collaborations. Different architectures were explored to map out performance, and different approaches to support systems and background mitigations were employed as larger detectors were developed. Essentially, the approach was to take advantage of xenon as an intrinsically clean target material and detector medium, and to "simply" instrument it in increasingly larger vessels to obtain larger exposures. In order for the sensitivity to improve, many technical challenges had to be met to instrument, calibrate, shield, purify, model and stably operate these detectors, as well as introduce active outer detectors to monitor and veto residual backgrounds. In what follows, I will review some of the key developments made within the LUX and ZEPLIN programs to advance the state of the art, and conclude with a description of the LUX-ZEPLIN (LZ) experiment and its current status as the world-leader in the search for WIMPs.

2. A larger bucket: LUX, ZEPLIN and LZ detector development

Xenon is an excellent detector medium for WIMP detection. With its large mass number, xenon is a good target for WIMP-nucleus scattering since it takes advantage of the coherent scattering of the nucleons at low momentum transfer for spin independent couplings. Naturally occurring xenon includes isotopes with an unpaired neutron, enhancing its coupling to spin-dependent interactions in some models. All of the isotopes in naturally occurring xenon are essentially stable so when sufficiently purified of non-xenon contaminants, an intrinsically low-radioactivity target results. Xenon permits the discrimination of ER and NR events through the measurement of scintillation and ionization signals. Finally, its large atomic number and density in the liquid phase give it good stopping power for external ambient gamma ray backgrounds, preventing them from reaching the interior of the detector once the linear dimension approaches the half-meter scale.

Given these favorable intrinsic properties, meeting the challenges of fielding larger "buckets" of liquid xenon has been highly impactful in advancing the search for WIMPs. Many of these technical challenges were met by the LUX and ZEPLIN collaborations, first working independently and then merging to form LZ.

2.1. Position measurement and self shielding

A critical benefit in taking advantage of the intrinsically radiopure xenon target comes from isolating an interior fiducial region in a detector sufficiently large to benefit from self-shielding. Accomplishing this isolation without an internal physical barrier (with the potential to introduce new background sources) relies on the TPC approach, which provides the position of individual events. The first such detector to demonstrate sufficient position resolution to establish a clean fiducial region was the ZEPLIN-II detector. In what is now the standard architecture of a dual-phase TPC, as shown in Fig. 1, an array of seven photo-multiplier tubes (PMTs) in the gas phase faces the liquid surface to collect scintillation light. When an event deposits energy in the bulk liquid, prompt primary scintillation light (S1) results from short-lived dimers and is collected by the PMTs. Some of the deposited energy results in ionization of xenon atoms at the event site, liberating free electrons which are drifted upward and extracted into the gas phase by a set of electrodes. In the gas phase, the electrons are accelerated by the field and cause electroluminescence, resulting in secondary proportional scintillation light (S2). Owing to a well-defined drift velocity for electrons in the LXe, the time difference between S1 and S2 pulse pairs determines the depth of the event below the liquid surface, as shown in Fig. 2. The weighted average of the S2 pulse size across the seven PMT determines the lateral position. With a total mass of 31 kg of xenon in the active region defined by the drift and extraction field electrodes, a fiducial mass of 7 kg was established [11], for a fiducial fraction of 23%. Notably, ZEPLIN-II also achieved the first detection of single electrons in a LXe 2-phase TPC [17].

By scaling up further in detector volume and instrumented mass, the fiducial fraction increases approximately with the linear dimension of the detector. The fraction of the detector excluded from the WIMP search, that is, the region used to define and shield

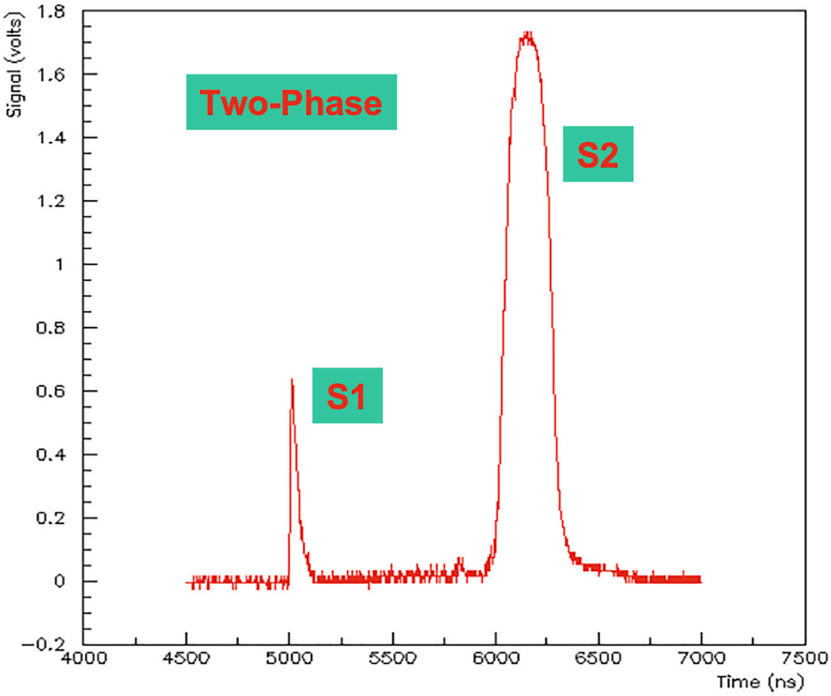


Fig. 2. Pulses from the ZEPLIN-II detector show sharp rise and short duration of the S1 pulse and the wide S2 electroluminescence pulse characteristic of electrons traversing the gas gap and exciting xenon atoms along the way. (Courtesy of the ZEPLIN-II collaboration.)

the fiducial volume, grows with the square of the linear dimension, whereas the volume grows with the cube. Thus by growing the detector, we obtain not just more mass total but a larger fiducial fraction. In the next-generation LUX detector, 250 kg of xenon was deployed in the TPC active region measuring 50 cm in diameter by 50 cm in height. The TPC was instrumented with 122 PMTs, half facing down from the gas phase as in ZEPLIN-II and half at the bottom of the TPC facing upward in the liquid phase, as shown in Fig. 3. With this geometry, LUX achieved a fiducial mass of 120 kg, or nearly 50% of the instrumented mass. This geometry also improves the overall light collection by increasing the efficiency for collecting S1 light with better PMT coverage and thus a low energy threshold.

2.2. Scaling up electric fields

Scaling up in linear dimension leads to technical challenges in establishing the required electric fields to develop the S1 and S2 signals, several of which were first addressed in a dark matter detector by LZ, which has linear dimensions of approximately 1.5 meters and is the largest LXe TPC in operation. First, the drift field in the bulk of the detector is defined by a cathodic electrode near the bottom of the TPC together with a so-called gate electrode just below the gas-liquid interface. To maintain the required electric field as the detector height increases requires a proportionately larger high voltage at the cathode. In LZ, this was achieved with a monolithic cable that entered through a side port at the bottom of the detector. Second, the extraction field is defined by the gate together with an anodic electrode in the gas phase, where a higher field is required to extract the electrons to create S2 light. At the required fields, the gate electrode is also cathodic and a concern for both the gate and the cathode are emission of electrons, thought to occur at imperfections on electrode surfaces that create high-field points well in excess of the average surface fields. Finally, because the gate and anode are in close proximity, there is a significant attractive force between them and so maintaining stiffness to prevent deflection is an important design criterion. However, in order to maintain high optical transparency for light collection the stiffness must be accomplished with a minimum of material. To meet these demands, LZ designed a custom loom to weave wire mesh grids from stainless steel wires epoxied to a stainless steel ring assembly, as shown in Fig. 4 [21]. Further, in order to reduce electron emission, LZ developed a process of chemical passivation using citric acid on the completed gate grid, which has the highest fields. (Schedule constraints prevented passivation of the cathode.) Studies of small prototype grids demonstrated substantial reduction in the electron emission rate versus voltage as shown in Fig. 5 [18].

2.3. Calibrations with self shielding

The development of LXe TPCs that were large enough to benefit from self shielding brought with it the new challenge of calibrating the interior of the detector, that is, the region to be used for physics analysis. The conventional approach of external radioactive sources becomes impractical. For example, the energy and rate of an external gamma source that would be needed to generate

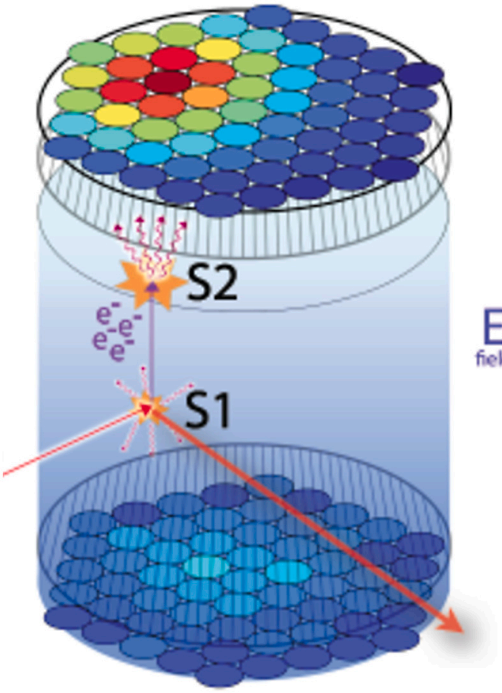


Fig. 3. The LUX TPC shows the now "standard" geometry for a dual-phase LXe TPC, with PMT arrays in the liquid looking up and in the gas looking down. A cathode electrode at the bottom with the gate at the top creates a drift field, while the gate and anode straddle the liquid-gas gap to create the electron extraction field and S2 electroluminescence region. (Image by C.H. Faham, Brown University.)

a spectrum of low-energy ER single scatters throughout the detector volume to model the detector response to ER backgrounds would lead to extreme pileup of events and be unusable. The solution to this problem lay in taking advantage of the LXe target requiring continuous circulation through a getter to remove electronegative impurities that would otherwise capture the S2 electrons before they could reach the liquid surface. By introducing appropriate gaseous radioactive sources into the circulating xenon stream, calibration events are generated throughout the detector volume.

The LUX collaboration developed tritiated methane (CH_3T) for calibrating the low-energy ER response [4] by taking advantage of tritium beta decay, which has a continuous energy spectrum that is well matched to the WIMP recoil region of interest. While CH_3T offers the advantage of a long half-life and is thus straightforward to inject into the detector, its use absolutely requires that it can be reliably removed. Otherwise, it would permanently contaminate the experiment with a potentially overwhelming background. Following the source development and removal in a dedicated test setup, a careful set of staged deployments was made in the LUX detector. First, the detector was dosed with ordinary methane, CH_4, and through precise measurements of its concentration, it was verified that it was removed by the getter. Second, a very low dose of CH_3T was injected, just enough to give a measurable rate, and it was also removed. Finally, increasingly large doses were added to generate high statistics calibration runs, producing the spectrum shown in Fig. 6 [6]. That figure illustrates the utility of the calibration by plotting the S2/S1 discrimination parameter used to separate ER from NR events versus S1, a proxy for the event energy. Fig. 7 shows the uniform position distribution of the tritium events.

Additionally, krypton-83m, with its short half-life, was developed as an alternative calibration source by LUX collaboration members [19]. It produces electrons at discrete energies at 32.1 and 9.4 keV and has a 1.8-hour half-life, so it conveniently decays in the detector, leaving no residual activity. With discrete energies above the WIMP recoil region of interest, the source was of great utility since its presence at a modest level throughout the WIMP exposures was a good real-time monitor and calibrator of detector performance, position-dependent corrections, electron lifetime, and other performance parameters.

2.4. Xenon handling

As detectors were scaled up, management of the liquid xenon became increasingly challenging, prompting a number of innovations. As the detector diameter grew, maintaining stability and uniformity of the liquid level and surface at the gas-liquid interface in the S2 extraction region became increasingly important. In the LUX and LZ detectors, stability was achieved by engineering a fixed-height spillover feature, or "weir," at the edge of the extraction region. The purified xenon returning from the getter is introduced at the bottom of the detector, causing excess xenon to flow over the weir, where it is withdrawn through heat exchangers out to the external circulation circuit. The returning purified warm gas from the getter provides the heat to warm and vaporize the exiting liquid. This heat exchange allows the circuit to function at about 95% thermodynamic efficiency, with the balance of cooling power coming from liquid-nitrogen thermosyphons sourced from an external LN reservoir to provide stable cooling. This cooling source also

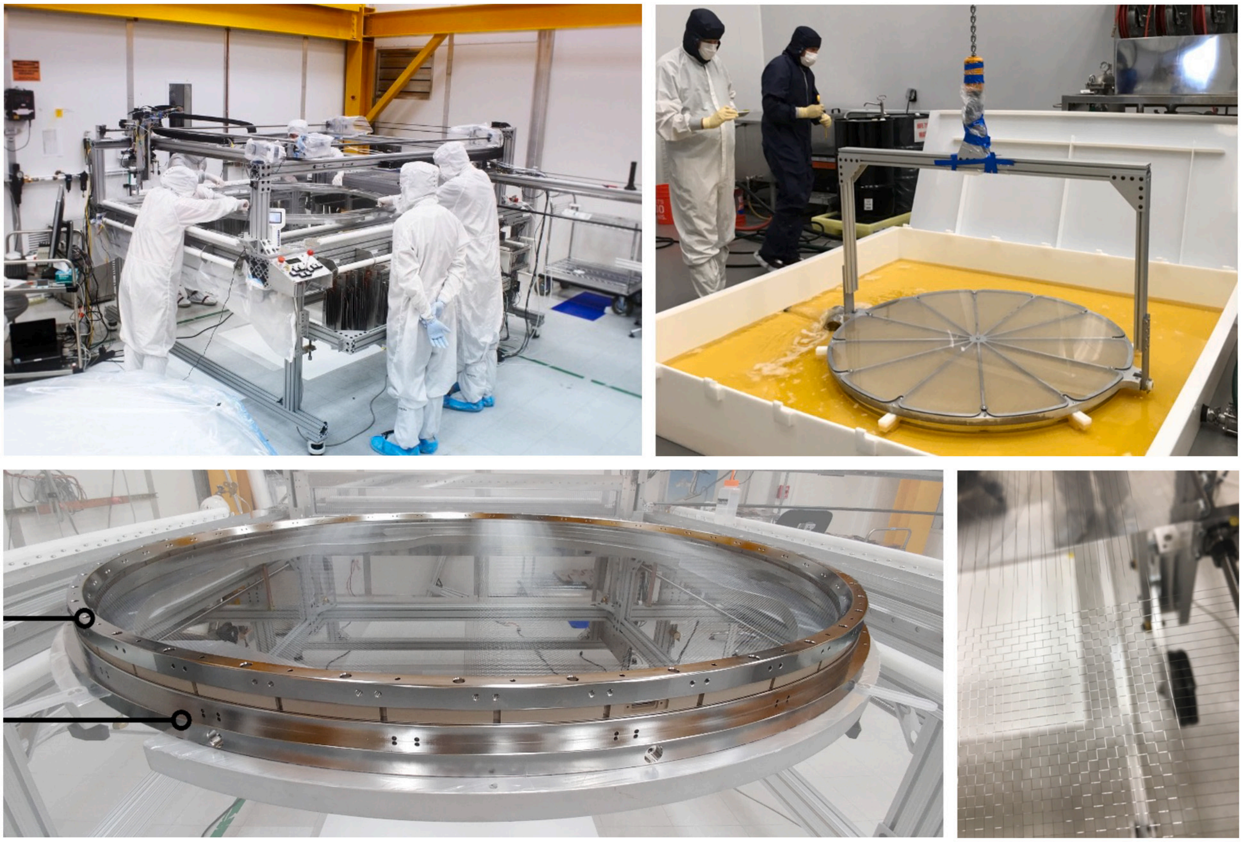


Fig. 4. Fabrication and treatment of LZ grid electrodes, counterclockwise from top left: custom loop to weave stainless steel wires at 5-mm or 2.5-mm pitch; a completed grid of wires epoxied between circular stainless steel frames; a close up of wire during weaving; and citric acid pickling as part of the passivation process [21].

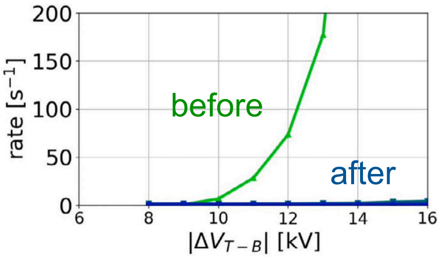


Fig. 5. Measurements of the single-electron emission rate are shown for a 20-cm pair of grids under voltage in xenon gas versus the voltage across the grid pair, before and after citric acid passivation (from [18]).

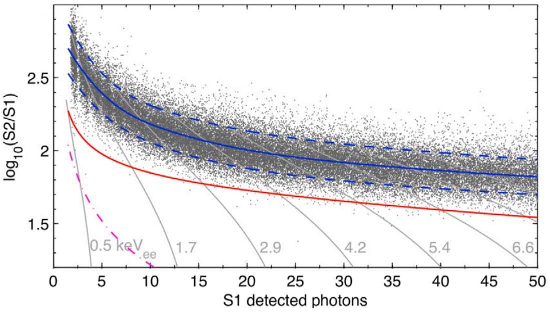


Fig. 6. A high statistics run of the LUX tritium calibration data (see [6] for details).

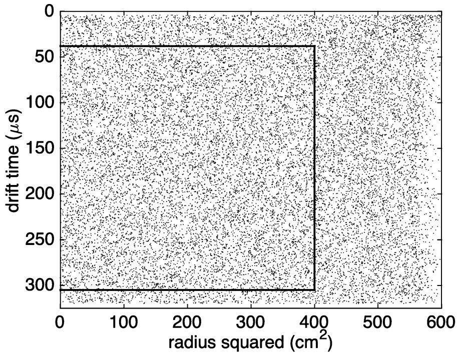


Fig. 7. LUX tritium calibration positions: this scatter plot of drift time (correlated with the depth of the event in the TPC) versus radius-squared based on the position measurement of the S2 signal shows the uniform distribution of events throughout the detector volume. The black square indicates the fiducial volume used in LUX physics analyses. (Taken from [4]).

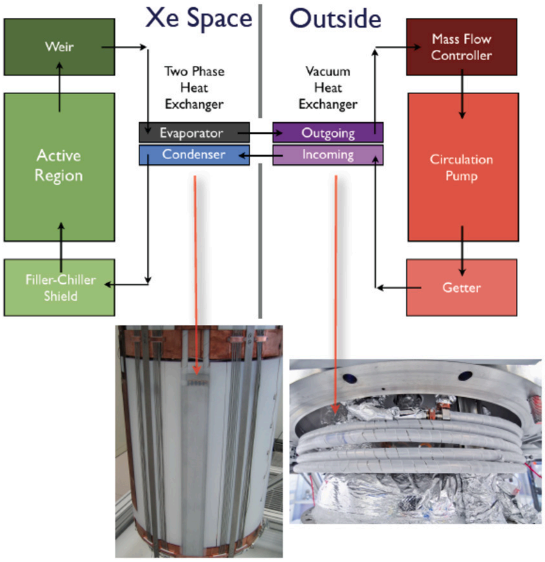


Fig. 8. The LUX circulation system: xenon gas circulates through a mass flow controller, circulation pump and getter on the room temperature side of the circuit. The purified xenon is returned to the detector through counter-flow (lower right photo) and tube-in-shell two-phase heat exchangers (lower left photo). Liquid xenon that is leaving the detector draws heat from the returning gas on the evaporator side of the two-phase heat exchanger and continues to warm towards room temperature in the counter-flow heat exchanger. Makeup cooling power is brought to the main detector through liquid nitrogen thermosyphons. (Image by P. Phelps, Case Western Reserve University).

provides a stable cryogenic platform that maintains cooling through power interruptions in the remote underground environments in which the experiments are operated [15]. Stable and reliable cooling is essential for extended detector operations, as well as for protecting the xenon target, which is a high-value asset. This approach to xenon circulation was first demonstrated in the LUX detector, as shown in Fig. 8 [15,14,24].

2.5. Controlling backgrounds

As detector mass is scaled up, the ever-present issue of backgrounds from radioactivity and instrumental sources must be brought down proportionately. The LUX and LZ teams developed several advances on this front, including low-background titanium vessels, loss-less separation of trace krypton from xenon using gas charcoal chromatography, and a cold-trap assisted residual gas analyzer (RGA) to monitor trace contamination.

Dual-phase liquid xenon TPCs operate on the liquid-vapor phase boundary typified by 2 bar of absolute pressure at 170 K, which requires the uses of a double-wall cryogenic pressure vessel. While stainless steel is a standard industrial solution for high-purity vessels and vacuum chambers, this material typically incorporates significant radionuclides that would generate gamma backgrounds in a low-background experiment. The LUX collaboration obtained and radioassayed samples of titanium metal of the two general classes of industrial grades rated for chemical purity, finding that “CP1” grade had significantly less radioactivity than “CP2,” and was suitable for use in the experiment [3]. The LUX vessels were the first titanium vessels developed for use in a dark matter experiment and in turn led to a further search for samples of CP1 titanium in sufficient quantity for the larger LZ experiment [5]. While the intrinsic contribution to the ER background was anticipated to be subdominant, i.e., relative to the rate from neutrino-electron scattering from solar neutrinos, radon emanation studies of the final vessel including non-titanium internal components showed a rate higher than anticipated [1]. While titanium remains a promising solution for low-background cryostats, further research is needed to realize its full potential.

While xenon has no long-lived radioisotopes, vendor-supplied research-grade xenon typically has concentrations of krypton as high as 100 parts per billion (ppb), which includes the radionuclide ^{85}Kr. Although this isotope occurs at minute concentrations as a fraction of atmospheric krypton, its beta activity and 10-year half-life require that it be significantly reduced from the xenon prior to use in a dark matter search. As an alternative solution to distillation to separate noble gases, members of the XENON [13], LUX [7], and LZ [12] collaborations developed a process of gas charcoal chromatography to separate and trap trace krypton from bulk xenon to render it a subdominant background. The xenon purified for XENON-10 and LUX were reduced to the few ppt (parts per trillion) level at the 30-kg and 400-kg scales, respectively. Most recently, the LZ system was used to purify 10 tonnes of xenon to an average concentration 0.1 ppt with individual 1-tonne batches as clean as 0.02 ppt at a processing rate of approximately 100 kg/d. At a concentration of 0.1 ppt, the ER rate from residual krypton is subdominant relative to the irreducible rate of ERs from *pp* solar neutrinos.

The cold-trap-assisted residual gas analyzer (RGA) to monitor trace contamination of volatile components in bulk xenon was developed to monitor detector conditions beyond the electron-lifetime purity monitors which address only the aggregate effect of electronegative impurities. The technique, developed by LUX and LZ collaborators [20,16], uses a liquid-nitrogen-cooled "U tube" to reduce the fraction of xenon reaching a commercial RGA by a factor of 10^6 by forming xenon ice on the interior surfaces but only minimally suppressing the trace components. By enhancing the relative fraction of these components by a similar factor, measurements as low as 0.07 ppt of krypton in bulk xenon have been obtained [23]. A system for the LZ krypton removal system [12] allowed for multiple measurements per day to provide tight feedback to the production process. Similar systems were critical in assessing trace methane, both natural and tritiated, in developing and deploying that calibration technique.

3. The LZ experiment

The LZ Experiment is the current world leader in sensitivity to search for WIMP-nuclear recoils in the 10 GeV range and above [2]. It has benefited from many of the technical developments detailed above. The experiment has been extensively described in a series of design reports [22,23], detector papers [9] and sensitivity studies [8]. Here, I give some highlights of the experiment and the ongoing science program.

LZ instruments 7 tonnes of liquid xenon in the active region of a standard dual-phase TPC with PMT readout top and bottom, surrounded by a PMT-instrumented 5-cm xenon skin within the main pressure vessel, an external gadolinium-loaded scintillator detector, and a water shield. The skin and scintillator form a powerful outer-detector (OD) system to veto events in the TPC that are coincident with events in the OD. Importantly, the OD provides an in situ monitor of ambient neutron and gamma backgrounds that will inform detailed modeling to support any future claim of dark matter signal. To suppress cosmic-ray induced backgrounds the experiment is installed in the Davis Cavern at a depth of 4850 feet in the Sanford Underground Research Facility, the site of the former Homestake Gold Mine in Lead, South Dakota, USA.

To date, the LZ collaboration has published the best upper limits on the WIMP-nucleon cross section using 60 live days of data. The experimental program aims to acquire a full exposure of 1000 live days, as discussed in [8]. Along the way, we expect to have sufficient sensitivity to observe coherent nuclear scatters from boron-8 solar neutrinos, as well as a range of other potential physics signals that scatter from electrons [10].

4. Summary

The search for dark matter in the form of Weakly Interacting Massive Particles (WIMPs) remains one of the enduring scientific and technical challenges in physics despite four decades of research. The last 15 years has seen major developments in liquid xenon TPCs, which have led the search for WIMPs since they first came into operation. In this paper, I've highlighted some of the developments in instrumentation that have enabled this progress, in particular those carried out by members of the LUX, ZEPLIN, and LZ collaborations. The culmination of this work underlies much of the success enjoyed by the currently-operating LZ experiment.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

I wish to thank my fellow members of the LUX and LUX-ZEPLIN Collaborations for years of fruitful collaboration and countless interesting science and technical conversations. Any errors in this manuscript are of course my own responsibility. This work is supported by the U.S. Department of Energy under contract number DE-AC02-76SF00515.

References

[1] J. Aalbers, et al., The LUX-ZEPLIN (LZ) Collaboration, Background determination for the LUX-ZEPLIN dark matter experiment, Phys. Rev. D 108 (2023).
[2] J. Aalbers, et al., The LUX-ZEPLIN (LZ) Collaboration, First dark matter search results from the LUX-ZEPLIN (LZ) experiment, Phys. Rev. Lett. 131 (2023).
[3] D.S. Akerib, et al., The LUX Collaboration, Radio-assay of titanium samples for the LUX experiment, arXiv:1112.1376, 2012.
[4] D.S. Akerib, et al., The LUX Collaboration, Tritium calibration of the LUX dark matter experiment, Phys. Rev. D 93 (2016).
[5] D.S. Akerib, et al., The LUX-ZEPLIN (LZ) Collaboration, Identification of radiopure titanium for the LZ dark matter experiment and future rare event searches, Astropart. Phys. 96 (2017) 1–10.
[6] D.S. Akerib, et al., The LUX Collaboration, Calibration, event reconstruction, data analysis, and limit calculation for the LUX dark matter experiment, Phys. Rev. D 97 (2018).
[7] D.S. Akerib, et al., The LUX Collaboration, Chromatographic separation of radioactive noble gases from xenon, Astropart. Phys. 97 (2018) 80–87.
[8] D.S. Akerib, et al., The LUX-ZEPLIN (LZ) Collaboration, Projected WIMP sensitivity of the LUX-ZEPLIN dark matter experiment, Phys. Rev. D 101 (2020).
[9] D.S. Akerib, et al., The LUX-ZEPLIN (LZ) Collaboration, The LUX-ZEPLIN (LZ) experiment, Nucl. Instrum. Methods Phys. Res., Sect. A, Accel. Spectrom. Detect. Assoc. Equip. 953 (2020) 163047.
[10] D.S. Akerib, et al., The LUX-ZEPLIN (LZ) Collaboration, Projected sensitivities of the LUX-ZEPLIN experiment to new physics via low-energy electron recoils, Phys. Rev. D 104 (2021).
[11] G.J. Alner, et al., The ZEPLIN-II Collaboration, First limits on WIMP nuclear recoil signals in ZEPLIN-II: a two-phase xenon detector for dark matter detection, Astropart. Phys. 28 (2007) 287–302.
[12] A. Ames, The LUX-ZEPLIN (LZ) Collaboration, Krypton removal via gas chromatography for the LZ experiment, AIP Conf. Proc. 2908 (2023) 070001.
[13] A.I. Bolozdynya, P.P. Brusov, T. Shutt, C.E. Dahl, J. Kwong, A chromatographic system for removal of radioactive ^{85}Kr from xenon, in: Proceedings of the 11th Symposium on Radiation Measurements and Applications, Nucl. Instrum. Methods Phys. Res., Sect. A, Accel. Spectrom. Detect. Assoc. Equip. 579 (2007) 50–53.
[14] A.W. Bradley, LUX Thermosyphon Cryogenics and Radon-Related Backgrounds for the First Wimp Result, Ph.D. thesis, Case Western Reserve University, 2014.
[15] A.W. Bradley, et al., Lux cryogenics and circulation, Phys. Proc. 37 (2012) 1122–1130.
[16] A. Dobi, C. Davis, C. Hall, T. Langford, S. Slutsky, Y.R. Yen, Detection of krypton in xenon for dark matter applications, Nucl. Instrum. Methods Phys. Res., Sect. A, Accel. Spectrom. Detect. Assoc. Equip. 665 (2011) 1–6.
[17] B. Edwards, et al., The ZEPLIN-II Collaboration, Measurement of single electron emission in two-phase xenon, Astropart. Phys. 30 (2008) 54–57.
[18] W. Ji, The LZ Dark Matter Search and Development of a New Gas Phase Technique to Characterize Low Level Electron Emission from Electrode Grids, Ph.D. thesis, Stanford University, 2019.
[19] L.W. Kastens, S.B. Cahn, A. Manzur, D.N. McKinsey, Calibration of a liquid xenon detector with ^{83m}kr, Phys. Rev. C 80 (2009).
[20] D.S. Leonard, A. Dobi, C. Hall, L. Kaufman, T. Langford, S. Slutsky, Y.R. Yen, A simple high-sensitivity technique for purity analysis of xenon gas, Nucl. Instrum. Methods Phys. Res., Sect. A, Accel. Spectrom. Detect. Assoc. Equip. 621 (2010) 678–684.
[21] R. Linehan, R.L. Mannino, A. Fan, C.M. Ignarra, S. Luitz, K. Skarpaas, T. Shutt, et al., Design and production of the high voltage electrode grids and electron extraction region for the LZ dual-phase xenon time projection chamber, Nucl. Instrum. Methods Phys. Res., Sect. A, Accel. Spectrom. Detect. Assoc. Equip. 1031 (2022) 165955.
[22] LZ Collaboration, LUX-ZEPLIN (LZ) conceptual design report, arXiv:1509.02910, 2015.
[23] B.J. Mount, et al., The LUX-ZEPLIN (LZ) Collaboration, LUX-ZEPLIN (LZ), Technical Design Report 2017, arXiv:1703.09144.
[24] P. Phelps, The LUX dark matter experiment: detector performance and energy calibration, Ph.D. thesis, Case Western Reserve University, 2014.