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DIRECT SEARCH FOR DARK MATTER WITH TWO-PHASE XENON DETECTORS: CURRENT STATUS OF LUX AND PLANS FOR LZ

The LUX Collaboration*

Abstract

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The search for dark matter reaches back generations and remains one of the most compelling endeavors in the hunt for physics beyond the Standard Model. Experiments attempting to directly detect WIMP dark matter have made remarkable progress in increasing sensitivity to elastic scattering of WIMPs on nuclei. The LUX experiment is a 370-kg, two-phase, xenon TPC currently running at SURF, 4850 feet below Lead, SD. LUX recently completed its first science run and was sensitive to spin independent WIMP scattering at cross sections below 10^{-45} cm^2 for WIMP masses of approximately 20 to 80 GeV. Preparations for the final science run of LUX are currently underway, with final results expected in 2015. We will present results from and current status of the LUX experiment, as well as plans for a follow-on, multi-ton-scale xenon experiment at SURF.

1 Introduction to WIMP Dark Matter

Astronomical evidence for the existence of non-luminous, heavy “dark matter” has been accumulating since Fritz Zwicky’s observations of the Coma Cluster [1, 2], and subsequent observations of spiral galaxy rotation curves [3]. The advent of ever higher resolution and sensitivity telescopes has allowed for numerous gravitational lensing surveys, which quantified the structure of the dark matter surrounding galaxies and clusters [4, 5]. High-precision measurements of the cosmic microwave background by WMAP [6] and then Planck [7] also strongly favor the existence of dark matter. Observations of cosmic isotope abundances strongly constrain the baryon mass of the Universe to be much less than the total mass fraction [8], leaving the balance to be comprised of some heavy, non-luminous, non-baryonic component. We assume that this part of the cosmic mass fraction is a gas of primordial relic particles, and give them the general name, “Weakly Interacting Massive Particle” (WIMP). WIMPs must be electrically neutral and only interact with baryons very rarely. As a result, most experiments endeavoring to detect WIMP dark matter look for recoiling nuclei, uncorrelated in time with any other event in the data stream. Such dark matter search experiments maximize their sensitivity with very low backgrounds (to remove events that might obscure rare signals) and very low energy thresholds (to remain sensitive to the smallest possible signatures in any individual event).

2 Design of the LUX Detector

The drive for lower backgrounds and lower thresholds has strongly informed the design of the LUX dark matter detector. Xenon was chosen as the target material for several reasons. Xenon has no long-lived radioactive isotopes, meaning that there are no background events intrinsic to the detector medium. Xenon's boiling temperature is fairly high (165 K), making the cryogenic engineering problem a more tractable one. Liquid xenon has a rather high density (~ 3 g/cm^3), meaning that with position reconstruction we can focus our search on the cleanest, quietest, most central volume of the detector. The high atomic mass of xenon means that the sensitivity for coherent WIMP scattering on nuclei (which scales roughly as A^2) is favorable for xenon compared to other targets. Xenon also has good material properties related to its dielectric breakdown (allowing for a high bias field) and chemical inactivity (which allows for the efficient removal of any electronegative impurities that will attenuate the ionization signal). Xenon has an extremely high scintillation yield, allowing for a much lower energy threshold than most detectors (the only complication is that the scintillation light from xenon is emitted at 175 nm, well into the vacuum ultraviolet).

The LUX detector itself (shown in Figure 1), is a two-phase time projection chamber (TPC) filled with 370 kg of liquid xenon, installed at the 4850-foot level of the Sanford Underground Research Facility (SURF). The TPC is read out by an array of 122 photomultiplier tubes (PMT). The windows of the LUX PMTs are made from synthetic quartz, making them directly sensitive to xenon scintillation light. The inside of the detector volume is lined with high-purity teflon (PTFE), which is an almost perfect diffuse reflector at 175 nm, allowing for even better light collection and therefore lower energy threshold.

There are two types of signals in the LUX detector. Primary scintillation (or "S1") comes from ionizing radiation depositing energy in the xenon. Such energy depositions can also ionize xenon atoms. Ionization electrons loosed from their parent atoms are drifted upward through the bulk of the detector in an external electric field. This field is created in the drift volume by a total of five wire grids. The top and bottom grids shield the PMTs from the drift field. The cathode and gate grids define the drift field in the liquid. The anode grid defines the extraction field (with the gate grid) for pulling ionization electrons out of the liquid, because the liquid-gas boundary is halfway between them.

Figure 1: *A cross section rendering of the LUX detector.*

The ionization signal ("S2") is read out with electroluminescent light in the gas region with the top PMT array.

Three-dimensional position of each energy deposition in the LUX detector is reconstructed event-by-event in a two step process. Position perpendicular to the drift field is defined by the pattern of hits in the top PMT array, and position along the drift field is defined by the time between the S1 and S2 light. Position reconstruction in LUX allows for a fiducialization cut and subsequent self shielding of the quietest inner region from the PMT arrays and construction materials, which are much more naturally radioactive than the xenon itself. LUX was designed to have a fiducial mass of 100 kg of xenon, and the first physics result was produced with a fiducial mass of 118 kg. The proportion of each signal in S1 and S2 allow for the discrimination between electron recoil events (which should all be backgrounds) and nuclear recoils (which is how WIMP scatters should be observed). In addition to the shielding against cosmic rays provided by the rock overburden underground, the LUX detector collects data from inside a water shield tank instrumented with twenty eight-inch Hamamatsu PMTs to serve as an active veto.

3 Previous LUX Science Output

There have been three separate runs in the LUX science program, and preparations are underway for a fourth. LUX runs 1 and 2 were engineering and commissioning runs on the surface [9]. Between the second and third LUX run, the detector was moved underground. LUX run 3 was the first WIMP search run for the LUX experiment, running from April to August of 2013. In October 2013, LUX published its first WIMP search limit based on run 3 data [10]. The LUX run 3 limit (see Figure 2) is the first one to place a spin independent WIMP nucleon scattering limit below a cross section level of 10^{-45} cm^2. This

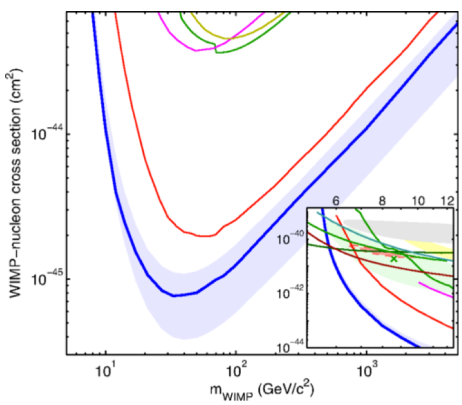

Figure 2: *90% Confidence limits on WIMP nucleon scattering from LUX Run 3 data, Blue (line and band) LUX 2013 result* [10]*. For comparison, we include limits from: XENON100 (red), ZEPLINIII (magenta), CDMSII (green) and EDELWEISSII (dark yellow). The inset shows limits and results for WIMP nucleon scattering at low mass. The low mass region also includes results (closed regions) from: CoGeNT (orange), CDMSII-Si (green), CRESSTII (yellow), and DAMA-LIBRA (grey).*

limit also excluded (at the 90% confidence level) nearly all of the anomalous results at low WIMP mass from several previous experiments. Much of this success was due to the extensive calibration program for the LUX experiment. For run 3, this included: external sources, internal ^{83m}Kr injections uniformly distributed throughout the xenon volume, and a tritiated methane injection.

4 Status of the LUX Experiment

At the conclusion of LUX run 3, LUX underwent a series of upgrades and maintenance in preparation for its fourth and final science run. Principally, this involved a wire grid conditioning campaign aimed at increasing the drift and extraction fields in the LUX detector to further enhance performance for run 4. Additionally, bias supplies for the veto PMTs and the process control for xenon circulation and recovery were upgraded. Finally, we included data from a D-D generator to calibrate the low-energy nuclear recoil response of LUX using double scatter events from this nearly monochromatic source of neutrons. The WIMP scattering sensitivity for LUX run 4 will surpass that of run 3 by almost an order of magnitude (to approximately 10^{-46} cm^2), and will conclude the LUX experiment.

5 Plans for the LZ Experiment

Design of a next-generation experiment based on the LUX design has been underway for some time. The collaboration began as a fusion of the LUX and ZEPLIN collaborations (making the new experiment's name "LZ"). A rendering of the LZ detector design is shown in Figure 3. The heart of the detector is a much larger version of the LUX detector, installed in the same water tank. The total mass will be approximately seven tons ($\sim 20\times$ LUX) and the fiducial mass will be five tons ($\sim 50\times$ LUX). In addition to building a larger TPC, several upgrades to the veto system will also be made. The xenon space outside of the TPC will be instrumented to collect scintillation light. There will also be a liquid scintillator veto (gadolinium loaded linear alkyl benzene) outside the xenon cryostat but inside the outer water shield. The larger xenon volume and mode sophisticated veto will increase any potential WIMP signal and lower the background, making LZ's WIMP-nucleon cross section sensitivity approach 10^{-48} cm^2. LZ was recently approved as one of the "Generation 2" dark matter searches by the Department of Energy.

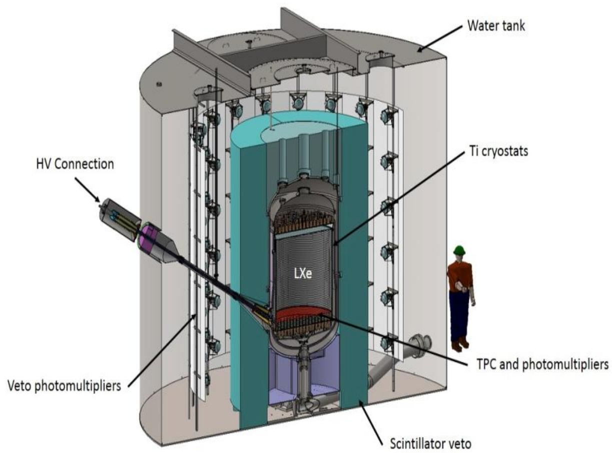

Figure 3: *A cross section rendering of the LZ detector including the TPC, veto, and grid bias feedthroughs.*

6 Conclusions and Discussion

Evidence for the existence of dark matter represents one of the currently most promising avenues for the discovery of physics beyond the Standard Model. While this evidence has been seen in astronomical observations for nearly a century, laboratory evidence continues to elude the scientific community. Two-phase xenon TPC detectors represent one of the most scientifically promising experimental techniques for filling this gap in our understanding of the Universe, and the LUX and LZ collaborations are well positioned to move forward in this endeavor over the next several years.

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