Searching for Dark Matter with the LUX experiment

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The Large Underground Xenon (LUX) experiment completed its first physics run in 2013 and produced a world-leading limit for spin-independent scattering of Weakly Interacting Massive Particles using 85.3 live-days of data. After presenting these first results we discuss the detector development work and calibrations following the first physics run, the current status of LUX and plans for the future multi-ton LUX-ZEPLIN experiment.

1 Introduction

First postulated more than 80 years ago to address the missing mass of the Milky Way galaxy, dark matter remains one of the best motivations for physics beyond the Standard Model. The Λ-Cold Dark Matter standard model of Big Bang cosmology is now well established and presents a clear and consistent picture of a universe in which non-baryonic cold dark matter makes up around four fifths of the total matter content. The evidence in support of this is both abundant and varied and includes galactic rotation curves, precise measurements of the cosmic microwave background, weak lensing studies of galaxy clusters, primordial nucleosynthesis and the characteristics of large scale structure in the universe [1]. Despite considerable knowledge concerning the impact of dark matter on these astrophysical phenomena very little is known about its fundamental nature. Direct search experiments aim to change this by detecting individual interactions of particles of dark matter that are hypothesised to permeate our galaxy. Many experiments focus on the search for Weakly Interacting Massive Particles (WIMPs), the leading candidates for dark matter. They look for the low energy nuclear recoils expected when WIMPs scatter elastically off target nuclei in the experiment. The small interaction cross sections and low velocities expected for galactic WIMPs impose the challenging requirement that dark matter detectors need to be sensitive to ∼few keV recoiling nuclei and at the same time be capable of amassing exposures of many kg · years.

2 The LUX Experiment

The Large Underground Xenon (LUX) experiment [2] is a 370 kg dual-phase liquid xenon time projection chamber (TPC) located 4850 feet underground (4300 m w.e.) at the Sanford Underground Research Facility (SURF) in Lead, South Dakota. The active region of the TPC is 47 cm in diameter and 48 cm in height comprising 250 kg of xenon. Interactions in the liquid xenon produce both prompt scintillation light (S1) and ionisation electrons that drift in an applied electric field (181 V/cm) to the liquid-gas interface at the top of the detector. The electrons are then extracted into the gas phase (6.0 kV/cm), where they produce electroluminescence (S2). The S1 and S2 signals are used to reconstruct the deposited energy and their ratio is used to discriminate WIMP-like nuclear recoils (NR) from background electron recoils (ER) at the 99.6% level at a 50% NR acceptance in the energy range of the LUX analysis. The TPC is read out from the top and bottom by two arrays of 61 photomultiplier tubes (PMTs) which image the central liquid xenon region and record the S1 and S2 signals. The x-y position of an interaction is determined to better than 4–6 mm from the localisation of the hit pattern of S2 light in the top PMT array. The depth of the interaction is given—to similar precision—based on the measured drift speed of the electrons (1.51 ± 0.01 mm/μs) and the time interval between the S1 and S2 light. This knowledge of the precise 3D position of an interaction means the full self-shielding capability of the liquid xenon can be utilised by only considering interactions in an inner radioactively-quiet fiducial volume.

An extensive screening campaign imposed stringent requirements on the levels of radioactivity for materials used to build the detector. Before being used in LUX, the full contingent of research grade xenon was purified at a dedicated research facility using a novel technique based on chromatographic separation. In addition to shielding against cosmic rays provided by the rock overburden, the LUX detector sits within a 6.1 m tall and 7.6 m in diameter water tank, instrumented with 20 8-inch PMTs, which acts as both an active veto for any penetrating cosmic rays and as a further shield to any remaining γ-rays and neutrons. Backgrounds from these particles are thereby rendered subdominant to those from radioactivity of internal detector components. A full description of LUX can be found in [2].

3 First results from LUX

LUX completed its first physics run in 2013, collecting a total of 85.3 live-days of WIMP search data between late April and early August. During this period the ER background rate inside the 118 kg fiducial volume was measured to be 3.6 ± 0.3 mDRU (mDRU$= 10^{-3}$ counts/day/kg/keV) in the energy range of interest, to date the lowest achieved by any xenon TPC. Full details of the radiogenic and muon-induced backgrounds in LUX can be found in [3]. To reduce the scope for bias, a non-blind analysis was conducted in which only a minimal set of high-acceptance data quality cuts were used. Single scatter events containing exactly one S1 within the maximum drift time (324 μs) preceding a single S2 were selected for further analysis. The single scatter ER and NR acceptance was measured with dedicated tritium (β^-), AmBe, and ^{252}Cf (neutron) datasets. All the cuts and efficiencies combined to give an overall WIMP-detection efficiency of 17, 50 and $> 95\%$ at 3.0, 4.3 and 7.5 keV recoil energies respectively.

In total 160 events were observed in the energy range of interest for WIMPs, between 2–30 photoelectrons (phe) S1, with all observed events being consistent with the predicted background of electron recoils. The p-value for the background-only hypothesis was 0.35. Confidence intervals on the spin-independent WIMP-nucleon cross section were set using a profile likelihood ratio (PLR) test statistic which exploits the separation of signal and background distributions in radius, depth and S1 and S2. For the signal model we conservatively assumed no signal below 3 keV, the lowest energy for which direct light yield measurements in xenon existed. The 90% upper C.L. are shown in figure 1 (left) with a minimum of 7.6×10^{-46}cm^2 at a WIMP mass of 33 GeV/c^2, making LUX the first experiment to probe sub-zeptobarn WIMP-nucleon cross sections. We see in figure 1 (right) that the LUX limit fully excludes nearly all the anomalous results at low WIMP masses claimed by a number of experiments. Full details of the analysis can be found in [4].

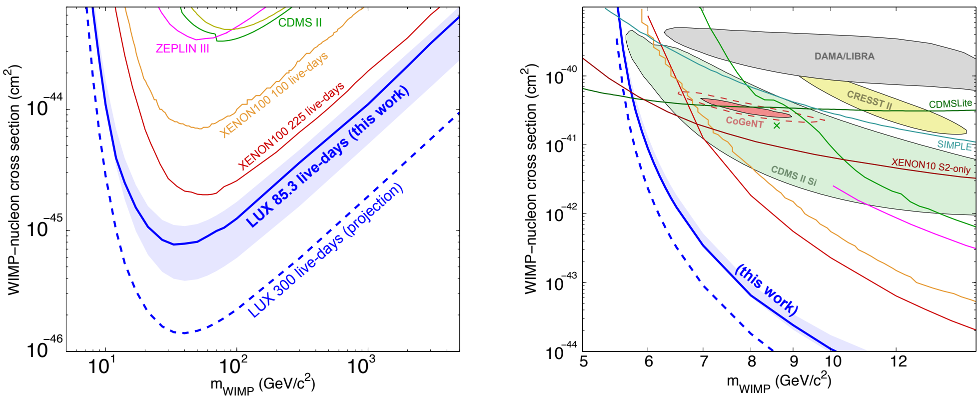

Figure 1: *Left:* The LUX 90% confidence limit on the spin-independent elastic WIMP-nucleon cross section for the 85.3 live-day exposure (blue) and projected limit for the upcoming 300-day run (dashed blue). *Right:* Close-up of low-mass region.

Following the first WIMP-search result LUX underwent a period of upgrades and maintenance in preparation for the final 300-day WIMP-search run. This included a campaign of cathode and grid wire conditioning aimed at increasing the applied drift and extraction fields and improvements to the krypton calibration system and the xenon controls and recovery system. Finally, a D-D neutron generator providing an almost monochromatic source of neutrons was used to make an in-situ calibration (down to 0.7 keV for the ionization channel) of the low-energy nuclear recoil response of LUX through an analysis of multiple-scatter events [5].

Final preparations for the 300-day run are now underway and it is expected to start before the end of 2014. The sensitivity for the 300-day run is expected to surpass that of the first WIMP-search result by a factor of around five and the sensitivity at low masses will benefit from the confirmation of the detector response to low-energy recoils.

4 LUX-ZEPLIN

Looking to the future, designs for the LUX-ZEPLIN (LZ) experiment are well underway. At the heart of LZ is a scaled up version of the LUX TPC with an active region containing about 7 tonnes (at least 5 tonnes fiducial). LZ will replace LUX on the 4850' level at SURF and will reuse the LUX water tank. Figure 2 shows the overall detector concept.

In addition to the considerable increase in target mass ($\sim$40 × LUX fiducial) LZ features a more sophisticated veto system which includes an optically separated and instrumented xenon *skin* layer between the inner TPC and the walls of the cryostat and an external liquid scintillator veto (gadolinium loaded linear alkyl benzene). The combination of skin readout and the outer detector creates a highly efficient integrated veto system providing powerful rejection of γ-rays and neutrons from internal sources (e.g. PMTs) that could otherwise scatter once in the TPC and then escape, thus potentially posing a problematic background.

With a projected sensitivity of 10^{-48}cm^2 for its full 1000-day exposure, LZ reaches faster and further than any competing experiment being proposed on a similar timescale, exploring a significant fraction of the parameter space remaining above the irreducible background from coherent scattering of neutrinos from astrophysical sources [6]. Earlier this year LZ was selected by the US Department of Energy as one of three approved *Generation 2* dark matter experiments and plans to begin its construction phase in 2015 with a projected start of physics data taking in 2018.

5 Conclusions

With its first WIMP search data LUX set the world's most stringent limit for spin-independent WIMP-nucleon elastic scattering, becoming the first direct search experiment to probe the sub-zeptobarn regime. The LUX 300-day run is due to start soon and will further increase this sensitivity by a factor of five with discovery still possible. In the longer term the LUX-ZEPLIN experiment will improve on the LUX 300-day sensitivity by almost two orders of magnitude, enabling significantly deeper probing of parameter space for discovery if necessary, or giving the capability to characterise a dark matter signal if found.

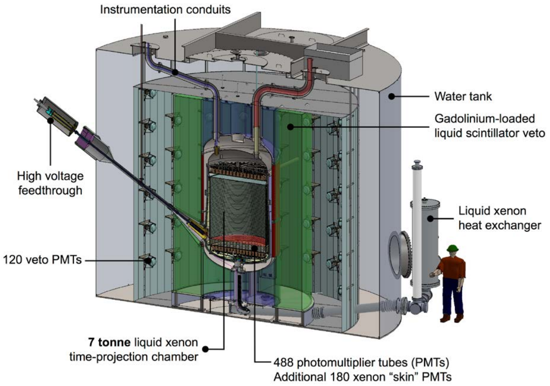

Figure 2: Schematic of the LZ experiment as housed in the reused LUX water-tank.

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