Dark Matter Searches with the LUX Experiment

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DOI: http://dx.doi.org/10.3204/DESY-PROC-2015-02/beltrame_paolo

The Large Underground Xenon (LUX) experiment is a 350 kg liquid xenon time projection chamber (TPC) whose primary goal is to directly detect galactic Dark Matter in form of Weakly Interacting Massive Particles (WIMPs). The first LUX science search results based on 85.3 day of data (Run3) collected in 2013 has set the best limit on spin-independent WIMP-nucleon cross section, reaching a minimum of 7.6×10^{-46} cm^2 90% CL for WIMP mass of 33 GeV/c^2. While presently collecting a 300-day data set (Run4), the LUX collaboration is also performing the re-analysis of the Run3 sample with new calibration measurements for nuclear and electronic recoil events, and additional improvements of the analysis methods. Dual phase xenon based TPCs, although optimised to observe WIMPs, are particularly suitable for exploration of alternative Dark Matter scenarios, such as axions and axion-like particles. The present status of the ongoing searches in LUX is also described.

1 Introduction and LUX Experiment

Consistent evidence from multiple astrophysical observations suggests that cold Dark Matter is the dominant form of matter in our galaxy [1]. Weakly interacting massive particles (WIMPs) are a generic class of particle candidates, arising from extensions to the Standard Model of particle physics. They could be detected via Weak-force-mediated nuclear recoils (NR) in detectors on Earth [2, 3]. Direct search experiments look for the low NR energy expected when WIMPs scatter elastically off target nuclei in the active detector material. The small interaction cross sections and low velocities of galactic WIMPs impose the detectors to be sensitive to few keV and at the same time to exploit large exposures of many kg·years.

The Large Underground Xenon (LUX) experiments is a 350 kg dual-phase xenon time-projection chamber (TPC) located 4850 feet underground at the Sanford Underground Research Facility (SURF) in Lead, South Dakota. Energy deposited from the particle interaction in the xenon creates a primary scintillation signal ($S1$) and ionization charge which is drifted by an 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 ($S2$). Both signals are read out by two arrays of photomultipler tubes (PMTs): 61 viewing the TPC from above, and 61 from below. The precise (few mm) 3D position reconstruction of the particle scattering point enables to exploit the self-shielding capability of the liquid xenon selecting for the Dark Matter search only inner radioactively-quiet fiducial volume. The $S1$ and $S2$ signals are also used to estimate the deposited energy and their ratio is exploited as particle identification to discriminate WIMP-like NR from background electron recoils (ER) at the 99.6% level at a 50% NR acceptance in the energy range of the LUX analysis. Description of the detector technology, underground laboratory and deployment can be found in [4].

2 WIMP search

LUX completed its first physics run in 2013, collecting a total of 85.3 day of WIMP search data. During this period the ER background rate inside the 118 kg selected fiducial volume was 3.6 ± 0.3 mDRU (mDRU $= 10^{-3}$ counts/day/kg/keV) between $2 - 30$ photoelectrons $S1$, the energy range of interest. 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 preceding a single $S2$ were selected for further analysis. In total 160 events were observed, being consistent with the predicted background of ER. Confidence intervals on the spin-independent WIMP-nucleon cross section were set using a Profile Likelihood Ratio analysis (PLR), based on distributions in radius, depth and $S1$ and $S2$. The 90% upper CL is shown in Fig. 1 with a minimum of 7.6×10^{-46} cm^2 at a WIMP mass of 33 GeV/c^2. These remain the strongest constraints over a wide range of WIMP mass [5]. However, the analysis was performed under the conservative assumption of zero efficiency for NR events below the 3 keV, corresponding to the minimum energy of previous liquid xenon calibrations.

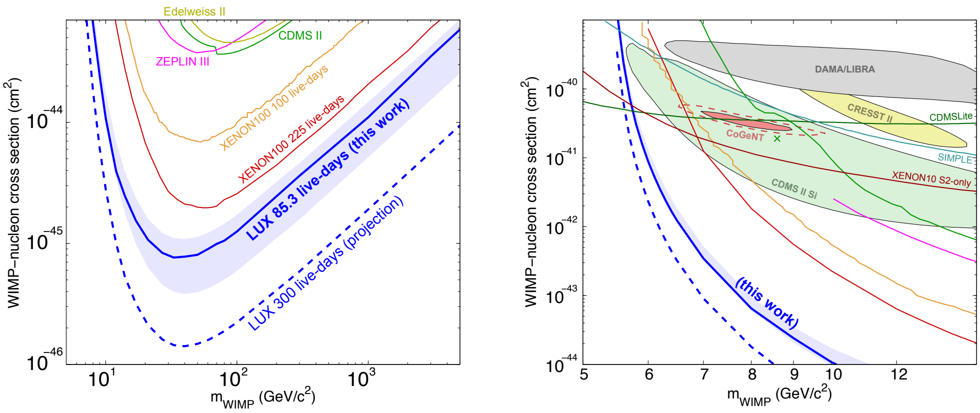

Figure 1: *Left*: The LUX 90% confidence limit on the spin-independent elastic WIMP-nucleon cross section for the 85.3-day exposure (blue) and projected limit for the upcoming 300-day run (dashed blue). *Right*: Close-up of the low mass region. The results use the conservative assumption of zero efficiency for NR events below the 3 keV.

2.1 Electron and nuclear recoil calibrations

The detector has been extensively calibrated with internal sources (for ER) and both external sources and DD neutron generator (for NR).
The internal sources, ^{83m}Kr and tritiated methane (CH_3T), injected into the xenon circulation stream, have the advantage of spreading evenly throughout the active volume, providing a homogeneous calibration. The mono-energetic 9.4 keV and 32.1 keV energy depositions of

^{83m}Kr were used to constantly monitor the electron drift attenuation length, the light yield and the corrections in x, y, z for detector effects. The novel CH$_3$T (β^- source with endpoint of ~18 keV) provided the ER response of the detector at low energies and information on the background shape. This also enabled to study the light and charge yields down to ~1 keV. The precise determination of ER events "leaking" down into NR $S2/S1$ region has been also evaluated between 0.2 and 5 keV, as a function of $S1$. A combined study with ^{83m}Kr and CH$_3$T enabled for a precise estimation of the fiducial volume.
To estimate the detector response to NR, in addition to AmBe and ^{252}Cf, a DD neutron generator was employed. This generates an almost monochromatic neutron beam, enabling through an analysis of multiple-scatter events to perform calibration down to 0.8 keV for the NR ionization and to 1.2 keV for the scintillation channels.

2.2 Re-analysis and Run4

Following the first WIMP-search results LUX underwent a period of 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. While collecting new data, the collaboration is also re-analysing the Run3 sample. The improved detector response calibration at very low energy, the better modelling of the background, a more accurate event position reconstruction for events close to the radial edge of the TPC, the updated fiducial volume (with an increased mass up to ~140 kg), and the more advanced PLR analysis (with the inclusion of nuisance parameters and an update energy scale), all this will lead to a considerable improved results, in particular in the low WIMP mass region, already in the re-analysis. As for the Run4, the increased exposure and the reduced background (because of the ^{127}Xe decaying away) will improve the sensitivity by more then a factor of 4 compared to the current limit.

3 Axion and Axion Like Particle searches

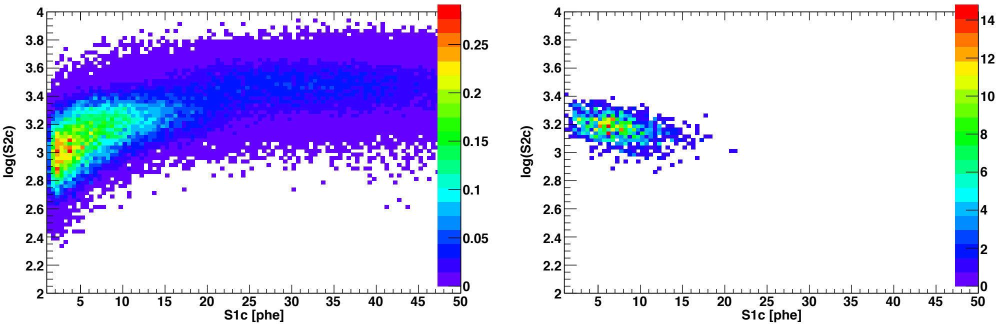

Figure 2: *Left*: Expected event rate in the LUX discrimination phase space from solar axions, assuming the axio-electric effect with coupling $g_{Ae} = 1.5 \times 10^{-12}$. *Right*: Expected signal from 2 keV ALPs and $g_{Ae} = 1.5 \times 10^{-13}$. The "c" subscript denotes that the $S1$ and $S2$ variables have been corrected by the detector effects at the position of the interaction point.

Astrophysical observations are thought to be the most sensitive technique for detecting axions and Axion Like Particles (ALPs) [7]. The Sun would constitute an intense source and searches can be conducted for ALPs. The latter may have been generated via a non-thermal production mechanism in the early universe, in which case they would be now slowly moving within our galaxy, and might constitute the Dark Matter.

Axions and ALPs may give rise to observable signatures in liquid xenon TPCs through their coupling to electrons (g_{Ae}), scattering off the electrons of an atom target, through the axio-electric effect [8, 9, 10]. This process is the analogue of the photo-electric effect with the absorption of an axion instead of a photon.

LUX is currently performing two specific analyses for axions and ALPs, based on the Run3 data sample. LUX is expected to surpass the current best limit on g_{Ae} set by the XENON100 collaboration [11] because of the very low ER background rate at low recoil energies, and the low energy threshold. Figure 2 shows the expected signal event rate in the LUX discrimination phase space for Solar axion (left) and ALPs (right). A dedicated PLR test statistic has been developed, exploiting the re-analysis background and detector response model implemented with the new ER calibrations data.

4 Conclusion and Outlook

During an 85.3 live-day (Run3) commissioning run with a 118 kg of fiducial xenon mass, the LUX experiment has achieved the most sensitive spin-independent WIMP exclusion limits over a wide range of masses. LUX commenced a 300-day data taking (Run4) in 2014 that will further improve the WIMP sensitivity by a factor of 4. A re-analysis of the Run3 data is ongoing, exploiting the new calibration campaign and various improvements which will significantly enhance the sensitivity at low mass. Publications will come soon.

Along with the standard WIMP searches, exploiting the low ER background rate and energy threshold of the LUX detector, the collaboration is conducting dedicated searches for alternative signals, primarily for axions and axion-like particles.

Acknowledgments

This work was partially supported by the U.S. Department of Energy (DOE) under award numbers DE-FG02-08ER41549, DE-FG02-91ER40688, DE-FG02-95ER40917, DE-FG02-91ER40674, DE-NA0000979, DE-FG02-11ER41738, DE-SC0006605, DE-AC02-05CH11231, DE-AC52-07NA 27344, and DE-FG01-91ER40618; the U.S. National Science Foundation under award numbers PHYS-0750671, PHY-0801536, PHY-1004661, PHY-1102470, PHY-1003660, PHY-1312561, PHY-1347449; the Research Corporation grant RA0350; the Center for Ultra-low Background Experiments in the Dakotas (CUBED); and the South Dakota School of Mines and Technology (SDSMT). LIP-Coimbra acknowledges funding from Fundao para a Cincia e Tecnologia (FCT) through the project-grant CERN/FP/123610/2011. Imperial College and Brown University thank the UK Royal Society for travel funds under the International Exchange Scheme (IE120804). The UK groups acknowledge institutional support from Imperial College London, University College London and Edinburgh University, and from the Science & Technology Facilities Council for PhD studentship ST/K502042/1 (AB). The University of Edinburgh is a charitable body, registered in Scotland, with registration number SC005336.

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