Available online at www.sciencedirect.com

ScienceDirect

Nuclear Physics B Proceedings Supplement 00 (2014) 1–5

Nuclear Physics B Proceedings Supplement

First Results of the LUX Dark Matter Experiment

M.C. Carmona-Benitez[a,*],

on behalf of the LUX Collaboration:

D.S. Akerib[b], H.M. Araújo[c], X. Bai[d], A.J. Bailey[c], J. Balajthy[e], P. Beltrame[f], E. Bernard[g], A. Bernstein[h], A. Bradley[b], D. Byram[i], S.B. Cahn[g], C. Chan[j], J.J. Chapman[j], A.A. Chiller[i], C. Chiller[i], A. Currie[c], L. de Viveiros[k], A. Dobi[e], J. Dobson[f], E. Druszkiewicz[l], B. Edwards[g], C.H. Faham[m], S. Fiorucci[j], C. Flores[n], R.J. Gaitskell[j], V.M. Gehman[m], C. Ghag[o], K.R. Gibson[b], M.G.D. Gilchriese[m], C. Hall[e], M. Hanhardt[p], S. Haselschwardt[a], S.A. Hertel[g], M. Horn[g,1], D.Q. Huang[j], M. Ihm[q], R.G. Jacobsen[q], K. Kazkaz[h], R. Knoche[e], N.A. Larsen[g], C. Lee[b], B. Lenardo[n], K.T. Lesko[m], A. Lindote[k], M.I. Lopes[k], D.C. Malling[j], A. Manalaysay[n], R. Mannino[r], D.N. McKinsey[g], D.-M. Mei[i], J. Mock[n], M. Moongweluwan[l], J. Morad[n], A.St.J. Murphy[f], C. Nehrkorn[a], H. Nelson[a], F. Neves[k], R.A. Ott[n], M. Pangilinan[j], P.D. Parker[g], E.K. Pease[g], K. Pech[b], P. Phelps[b], L. Reichhart[o], T. Shutt[b], C. Silva[k], V.N. Solovov[k], P. Sorensen[h], K. O'Sullivan[g], T.J. Sumner[c], M. Szydagis[n], D. Taylor[p], B. Tennyson[g], D.R. Tiedt[d], M. Tripathi[n], L. Tvrznikova[g], S. Uvarov[n], J.R. Verbus[j], N. Walsh[n], R. Webb[r], J.T. White[r,**], M.S. Witherell[a], F.L.H. Wolfs[l], M. Woods[n], C. Zhang[i]

[a] *University of California Santa Barbara, Dept. of Physics, Santa Barbara, CA, USA*
[b] *Case Western Reserve University, Dept. of Physics, 10900 Euclid Ave, Cleveland OH 44106, USA*
[c] *Imperial College London, High Energy Physics, Blackett Laboratory, London SW7 2BZ, UK*
[d] *South Dakota School of Mines and Technology, 501 East St Joseph St., Rapid City SD 57701, USA*
[e] *University of Maryland, Dept. of Physics, College Park MD 20742, USA*
[f] *SUPA, School of Physics and Astronomy, University of Edinburgh, Edinburgh, EH9 3JZ, UK*
[g] *Yale University, Dept. of Physics, 217 Prospect St., New Haven CT 06511, USA*
[h] *Lawrence Livermore National Laboratory, 7000 East Ave., Livermore CA 94551, USA*
[i] *University of South Dakota, Dept. of Physics, 414E Clark St., Vermillion SD 57069, USA*
[j] *Brown University, Dept. of Physics, 182 Hope St., Providence RI 02912, USA*
[k] *LIP-Coimbra, Department of Physics, University of Coimbra, Rua Larga, 3004-516 Coimbra, Portugal*
[l] *University of Rochester, Dept. of Physics and Astronomy, Rochester NY 14627, USA*
[m] *Lawrence Berkeley National Laboratory, 1 Cyclotron Rd., Berkeley, CA 94720, USA*
[n] *University of California Davis, Dept. of Physics, One Shields Ave., Davis CA 95616, USA*
[o] *Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK*
[p] *South Dakota Science and Technology Authority, Sanford Underground Research Facility, Lead, SD 57754, USA*
[q] *University of California Berkeley, Department of Physics, Berkeley, CA 94720, USA*
[r] *Texas A & M University, Dept. of Physics, College Station TX 77843, USA*

Abstract

LUX (Large Underground Xenon) is a dark matter direct detection experiment deployed at the 4850' level of the Sanford Underground Research Facility (SURF) in Lead, SD, operating a 370 kg dual-phase xenon TPC. Results of the first WIMP search run were presented in late 2013, for the analysis of 85.3 live-days with a fiducial volume of 118 kg, taken during the period of April to August 2013. The experiment exhibited a sensitivity to spin-independent WIMP-nucleon elastic scattering with a minimum upper limit on the cross section of 7.6×10^{-46} cm^2 at a WIMP mass of 33 GeV/c^2, becoming the world's leading WIMP search result, in conflict with several previous claimed hints of discovery.

Keywords: dark matter, WIMP, liquid xenon, time projection chamber

1. Introduction

The observational evidence for the existence of dark matter is overwhelming, mainly due to its gravitational effects. A wide variety of cosmological observations support the existence of non-baryonic cold dark matter: galactic rotation curves, the precise measurements of the cosmic microwave background, the study of supernovae and the mapping of large scale structures [1]. Despite this progress, the identity of dark matter remains a mystery. One of the leading candidates for dark matter in the universe are Weakly Interacting Massive Particles (WIMPs), and there are currently many experiments attempting to detect them. Direct search detectors aim to observe nuclear recoils produced by dark matter particles scattering off target nuclei. Direct dark matter search experiments look for an excess of nuclear recoil signals in a low-background underground environment. The energy deposition associated with the nuclear recoil of WIMPs is on the ~keV scale, and massive detectors with low energy threshold and high background discrimination capabilities are vital. There are different methods that can be used to detect nuclear recoils, including collecting ionization, scintillation, or thermal energy deposition data. In this framework, dual-phase liquid xenon detectors are a powerful technology for the direct detection of dark matter [2, 3, 4].

2. The LUX detector

The LUX (Large Underground Xenon) detector is a two-phase xenon time-projection chamber (TPC), containing 370 kg of xenon, operating 1.5 km underground (4300 m.w.e.) in the Sanford Underground Research Facility (SURF) in Lead, South Dakota, USA [5]. The TPC is monitored by two arrays of 61 photomultiplier tubes (PMT) each, located above and below the active liquid xenon (LXe) region. Events in the LXe target produce direct scintillation light (S1), while electrons escaping recombination at the event site are drifted to the liquid surface and extracted into the gas phase by applied electric fields, where they create proportional scintillation light (S2). Both signals are measured by the arrays of PMTs. Most of the S1 signal is measured by the bottom PMT array, while the top array is used mainly to reconstruct the x-y position of the event. The drift time between the S1 and S2 signals gives the event depth, providing this technology with excellent 3D imaging capabilities. In this type of detector, the discrimination between electron recoils (ER) from background radioactivity and nuclear recoils (NR) from neutrons and the potential WIMP-nucleon interaction is based on the ratio of S2 to S1. The background rejection is also enhanced by the strong self-shielding capability of this dense liquid (LXe) combined with the precise 3D event position determination, and it has been demonstrated in LUX to be $\sim$ 99.6 % in the energy range of interest for the WIMP signal search.

The detector design is characterized by the use of low radioactivity detector materials, like PMTs and Ti cryostats [6, 7], and by very high light collection, which is crucial for the sensitivity to low-energy events. The photon detection efficiency for events at the center of LUX is measured to be 14% [8]. The active region is a dodecagonal structure with a maximum drift distance of 48 cm (height), and a diameter of 47 cm. The walls of the barrel consist of twelve reflector panels of polytetrafluoroethylene (PTFE), which has very high reflectivity in liquid xenon (>95%). This active region is observed by 122 Hamamatsu R8778 2-inch diameter PMTs that have an average quantum efficiency (QE) of 33% at the xenon scintillation wavelength of 175 nm.

A unique cryogenic system is used to efficiently and economically cool the LUX detector, based on thermosyphon technology [9]. Each thermosyphon consists of a sealed tube, filled with a variable amount of gaseous nitrogen, and comprised of three regions: at the top, a condenser which is immersed in a bath of liquid nitrogen (LN); at the bottom, an evaporator which is attached to the detector; and a passive length made of stainless steel connecting the two active sections. The whole system is oriented vertically since it works with gravity, and is closed and pressurized with N_2. The thermosyphon thermal conductivity was measured to be $\sim$ 55 kW/K $\cdot$ m, much higher than metals, such as copper.

The detector is housed in an 8 m diameter (300 tonne) water tank that shields it against the neutrons from cavern radioactivity and the very high-energy tail of neutrons from muon interactions in the cavern walls. The water tank provides a reduction of the external backgrounds to a level that is subdominant to the internal backgrounds from detector components. Also, the water shield is instrumented with a set of 20 eight-inch PMTs and can be used as a Cherenkov veto for muons.

*Corresponding author: carmona@physics.ucsb.edu
**Deceased

3. First LUX Dark Matter search results

A total of 85.3 live-days of WIMP search data were acquired starting in April 2013. During this first underground run, the background rate inside the fiducial volume in the energy range of interest (2-30 photoelectrons (phe) S1 signals) was measured to be 3.6 ± 0.4 mDRU (1 mDRU = 10^{-3} counts/keV/kg/day), which is the lowest rate achieved by any xenon TPC to date. Most of those background events are due to radioactivity of the detector materials, primarily the PMTs. Another source of background is residual ^{85}Kr in the xenon. Using chromatographic separation, LUX achieved a measured level of 3.5 ± 1ppt natural Kr before the start of the run [5]. During the run, an automatic in-line xenon sampling system allowed us to verify the Kr level in-situ to an accuracy of ∼ 0.5 ppt [10]. Other background sources are ^{214}Pb naked β^- from the ^{222}Rn chain and x-rays from the cosmogenically produced ^{127}Xe, which decayed throughout the WIMP search run ($T_{1/2}^{^{127}Xe}$ = 36.4 days). A detailed study of the radiogenic backgrounds in LUX and comparison to simulations can be found in Ref.[11].

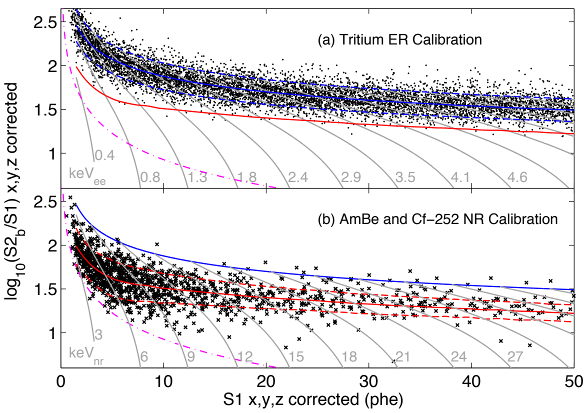

Figure 1: The LUX low-energy response inside the fiducial volume to tritium internal ER calibration source (panel *a*) and AmBe and ^{252}Cf external NR calibration sources (panel *b*) [5]. The ER band mean (solid blue) of the parametrized tritium distribution and the NR band mean (solid red) obtained from simulations are shown in both panels, together with ±1.28 σ contours (dashed lines). The 200 phe analysis threshold for S2 signals is shown as a dashed-dotted line (magenta) in both panels. Grey contours indicate constant energies in keV_{ee} and keV_{nr} respectively.

The LUX detector was calibrated extensively using internal and external sources. ^{83m}Kr was injected regularly to monitor the electron drift attenuation length, the light yield, and the x,y,z position reconstruction corrections. A novel technique of injecting tritiated methane into the xenon circulation system was used to perform low-energy ER calibrations. The tritiated methane was removed by the purification system using a hot getter. This allowed a high-statistics, homogenous distribution to be acquired for low-energy depositions from β^- events within the liquid xenon ($E_{max}^{H_3}$ = 18.6 keV). The detector response to these ER events, is shown in the top panel of Fig. 1, in $\log_{10}(S2_b/S1)$ vs. S1 space (the "b" subscript denotes that only the bottom PMT signals were used in order to eliminate systematics from two deactivated top PMTs). The mean (blue solid) and $\pm 1.28\sigma$ (blue dashed) contours used to characterize the ER band from this calibration are shown on top of the data. External neutron sources (AmBe and ^{252}Cf) were used to calibrate the NR response of the detector, shown in the lower panel of Fig. 1. The mean (red solid) and $\pm 1.28\sigma$ (red dashed) NR band parameterization was derived from the comprehensive NEST simulation model [12].

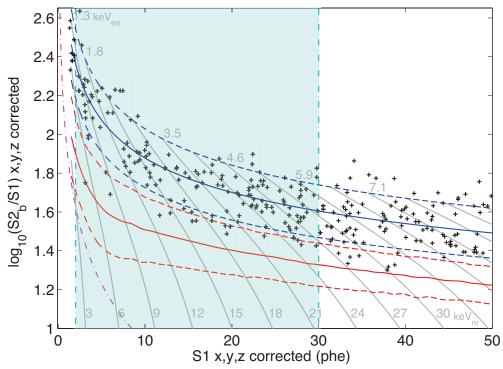

Figure 2: The LUX WIMP search data from the 85.3 live-days within the fiducial volume passing all cuts [5]. The shaded region indicates the selected analysis region from 2-30 phe in S1. The same parameterization of the mean ER and NR bands as in Fig. 1 is also shown. A Profile Likelihood Ratio analysis shows that all events are consistent with the ER background-only hypothesis.

LUX performed an unblind analysis on the WIMP search data with only minimal cuts, to maintain a high acceptance. Single scatter interactions (one S1 and one S2) in the liquid xenon volume with areas between 2-30 phe for the x, y, z corrected S1 signal were selected, corresponding to energies of about 3-25 keV_{nr} or 0.9-5.3 keV_{ee}, where the subscripts represent the energy scales for nuclear and electron recoils, respectively. In order to avoid contamination from the 5 keV x-rays from ^{127}Xe, an upper bound of 30 phe was chosen. An analysis threshold of 200 phe (∼8 extracted electrons) was used to exclude small S2 signals with poor x,y position reconstruction. The fiducial volume was defined

as the inner 18 cm in radius and approximately 40 cm in height corresponding to an electron drift length between 38 and 305 μs. These limits enclose a fiducial mass of 118.3 ± 6.5 kg. Despite the low NR scintillation light yield assumed (a conservative and unphysical cutoff at 3 keV_{nr} was applied), LUX achieved a very good WIMP detection efficiency of roughly 17% at 3 keV_{nr}, 50% at 4.3 keV_{nr}, and >95% above 7.5 keV_{nr}.
A total of 160 events passed the selection cuts, which are shown inside the shaded area in Fig. 2. A Profile Likelihood Ratio (PLR) analysis was used to attempt to set a one-sided exclusion limit of signal above background. The likelihood for both the signal and background is modeled as a function of radius, depth, S1, and S2/S1. The PLR result indicates that the observed data are consistent with the background-only prediction at the level of 35%. The resulting 90% C.L. upper limits of the PLR analysis on the spin-independent WIMP-nucleon interaction cross-sections are shown in Fig. 3, with a close-up view on low WIMP masses (below ∼15 GeV) on the bottom panel. The WIMP exclusion limits set by LUX provide a significant improvement in sensitivity over existing limits, and LUX is the first experiment to set a limit below a cross section level of 10^{-45} cm^2. In particular, the LUX low-mass WIMP sensitivity improves on the previous best limit set by XENON100 [13] by more than a factor of 20 above 6 GeV/c^2. These low-mass limits are also in disagreement with potential low-mass WIMP events suggested by earlier experiments such as DAMA/LIBRA[14, 15], CoGeNT [16], and CDMS-II Si [17].

4. Conclusions and outlook

LUX has achieved the most sensitive spin-independent WIMP exclusion limits to date over a wide range of masses, using 85.3 live-day of data from a first commissioning run, with a ∼118 kg of fiducial xenon mass. Under the assumption of isospin invariance, this result excludes the low-mass WIMP region where hints of signal have been published. This LUX sensitivity was accomplished mainly due its large mass, low background rate, high light collection efficiency, and very low energy threshold. The WIMP exclusion limit in LUX was obtained assuming a conservative xenon response to NR at low energies, which placed an unphysical cutoff in the signal yields for electrons and photons below 3 keVnr, the lowest calibration point available at the time of the limit calculation. New measurements carried out in the LUX detector using a D-D neutron generator show available signal below this imposed cutoff (measured

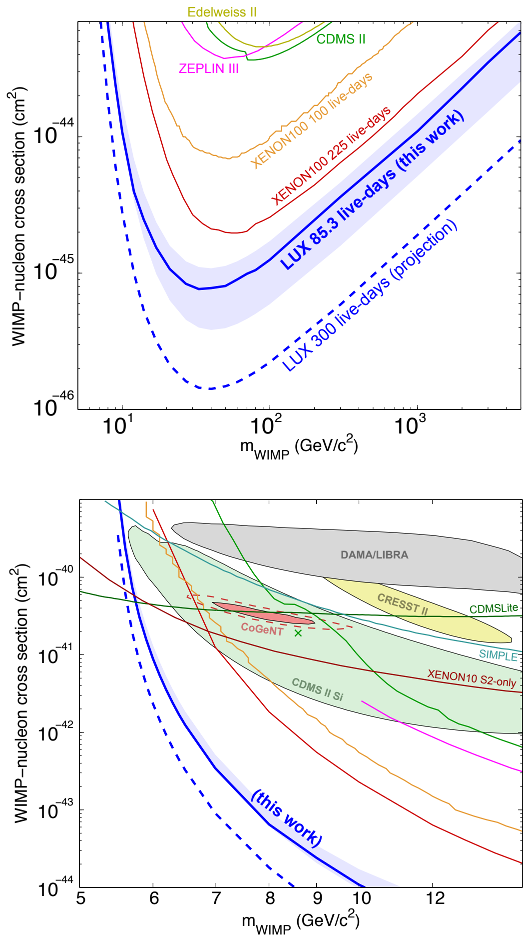

Figure 3: *Top:* The LUX 90% C.L. spin-independent WIMP exclusion limits for the 85.3 live-day result (solid blue) and a projected limit of the upcoming 300-day run (dashed blue). The blue shaded region indicates ±1 σ variation from repeated trials, where trials fluctuating below the expected number of background events are forced from zero to 2.3. *Bottom:* Close-up view at lower WIMP masses showing the tension between LUX result and previous hints of low-mass WIMP signals. LUX limits calculated assuming an artificial cut-off of light yield for nuclear recoils below 3 keV_{nr}, despite evidence of signals down to 0.7 keV_{nr}. See text for details.

down to 0.7 keVnr for the ionization channel) [18]. LUX will start a 300 live-day run in 2014 that will further improve the WIMP sensitivity by a factor of 5. The increased sensitivity factor is greater than the ratio of exposures due to lower radioactivity backgrounds from the decay of the cosmogenically activated ^{127}Xe. The sensitivity interpretation at low masses will also benefit from the novel calibration of the xenon response to nuclear recoils using the D-D generator. Designs and plans for a next generation experiment, called LZ (LUX-ZEPLIN), are already in place. The projected improvement in exposure will be a factor of 50 to achieve a WIMP-nucleon cross section sensitivity of 10^{-48}cm^2.

5. 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-AC52-07NA27344, 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 Fundação para a Cîencia 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. This research was conducted using computational resources and services at the Center for Computation and Visualization, Brown University.

References

[1] J. Beringer, et al., Review of Particle Physics, Phys. Rev. D 86 (2012) 010001.

[2] E. Aprile, et al., Liquid xenon detectors for particle physics and astrophysics, Reviews of Modern Physics 82 (2010) 2053.

[3] D. Y. Akimov, et al., The ZEPLIN-III dark matter detector: Instrument design, manufacture and commissionin, Astropart. Phys 27 (2007) 46.

[4] D. S. Akerib, et al., The Large Underground Xenon (LUX) experiment, Nucl. Instr. Meth. 704 (2013) 111–126.

[5] D. S. Akerib, et al., First Results from the LUX Dark Matter Experiment at the Sanford Underground Research Facility, Phys. Rev. Lett. 112 (9) (2014) 091303.

[6] D. S. Akerib, et al., An ultra-low background PMT for liquid xenon detectors, Nucl. Instr. Meth. 703 (2013) 1–6.

[7] D. S. Akerib, et al., Radio-assay of Titanium samples for the LUX Experiment.

[8] D. S. Akerib, et al., Technical results from the surface run of the LUX dark matter experiment, Astropart. Phys. 45 (2013) 34–43.

[9] A. I. Bolozdynya, et al., IEEE Trans. on Nucl. Sci.

[10] D. Leonard, et al., A simple high-sensitivity technique for purity analysis of xenon gas, Nucl. Instr. Meth. 621 (1-3) (2010) 678–684.

[11] D. S. Akerib, et al., Radiogenic and Muon-Induced Backgrounds in the LUX Dark Matter Detector, arXivarXiv:1403.1299v1.

[12] M. Szydagis, et al., Enhancement of NEST capabilities for simulating low-energy recoils in liquid xenon, JINST 8 (1).

[13] E. Aprile, et al., Dark Matter Results from 225 Live Days of XENON100 Data, Phys. Rev. Lett. 109 (18) (2012) 181301.

[14] R. Bernabei, et al., First results from DAMA/LIBRA and the combined results with DAMA/NaI, Eur. Phys. J. C 56 (3) (2008) 333–355.

[15] C. Savage, et al., Compatibility of DAMA/LIBRA dark matter detection with other searches, J. Cosm. Astrop. Phys. 04 (4).

[16] C. E. Aalseth, et al., CoGeNT: A search for low-mass dark matter using p-type point contact germanium detectors, Phys. Rev. D 88 (1) (2013) 012002.

[17] R. Agnese, et al., Silicon Detector Dark Matter Results from the Final Exposure of CDMS II, Phys. Rev. Lett. 111 (25) (2013) 251301.

[18] J. R. Verbus, Recent Results from the LUX Dark Matter Search, in: Lake Louise Winter Institute 2014, 16-22 February 2014, 2014.