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New physics searches with LUX and LZ

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Summary. — The frontier of experimental particle physics research, especially astroparticle physics, frequently involves the detection of signals that are both rare (fewer than an event per year per kilogram), and small (energy depositions at the keV scale). A prime example is the direct search for dark matter, although other signatures for new physics are also being sought, such as axions and various neutrino signals. The key technology that has evolved to meet this challenge is that of the ultra low background two-phase time projection chamber, deployed deep underground. The Large Underground Xenon (LUX) instrument was a leading device of this type. Now dismantled to make way for its successor, analysis of legacy data continues. The main scientific results of LUX are presented. With 50 times larger fiducial (usable) mass, and increased background rejection power, LUX-ZEPLIN (LZ) is presently under construction and is due to take first data in 2020. It will have a sensitivity at least two orders of magnitude beyond current best limits for the leading dark matter candidates. An overview of the LZ experiment is presented.

1. – Introduction

The Standard Model of particle physics, despite its great success, fails to provide explanations to a number of phenomena including dark matter, the absence of CP violation in strong interactions and the origin of matter–antimatter asymmetry. Low-background rare-event searches provide an experimental tool to investigate these areas. Here, key results of searches for new physics with the Large Underground Xenon (LUX) experiment are presented, together with an outline of the design, the current status of construction, and the expected science reach of its successor, LUX-ZEPLIN (LZ).

2. – LUX and LZ at Homestake

Both instruments have been sited at the Homestake Mine, South Dakota [1]. A depth of 1480 m (4300 m water equivalent), reduces the cosmic ray muon flux by a factor

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of $\approx 10^6$. The principle of operation for a two-phase xenon time projection chamber (TPC) is as follows. A vessel, fabricated from low background titanium, is partially filled with liquid xenon such that above the liquid a thin layer of gaseous xenon is maintained. A vertical electric field is established through an anode placed within the gas layer, and a cathode at the base of the liquid. Incident radiation scattering within the xenon generates electron and/or nuclear recoils, and their energy depositions lead to excitations, ionisation and heat. De-excitations and recombinations together produce primary scintillation (denoted 'S1'), while ionisation electrons that escape recombination are drifted by the electric field to the surface, where they are extracted into the gas phase by a strong electric field to produce electroluminescence leading to secondary scintillation in the gas ('S2'). Since ionised noble gas atoms react with surrounding atoms to produce molecules, their scintillation light originates in the decay of excited dimers. Consequently, they are highly transparent to their own scintillation light (λ=175 nm). Xenon has a high light yield, $\approx$60 ph/keV at zero electric field. Arrays of high quantum efficiency, vacuum ultraviolet(1) sensitive, low radioctivity PMTs are located both above and below the xenon volume. The primary S1 signal is relatively small, while the delayed secondary S2 is larger, with the ratio of S2/S1 greater for electron recoils (ER) than it is for nuclear recoils (NR). The horizontal location of an energy deposition may be reconstructed from the distribution of signal sizes in the PMTs, and the period of delay between the S1 and S2 then gives the vertical position. Calibrations [2], including the use of injected tritiated methane (CH_3T), ^{83m}Kr, and DD-generated neutrons, have been devised to provide accurate, internal and uniform calibrations of both light and charge yields for both ER and NR responses. Table 1 presents key parameters of the two instruments. Further technical details may be found in [3, 4].

The above features make the two-phase xenon TPC well suited to rare event searches, offering high light collection efficiency, low energy detection threshold, fiducialisation, active and passive shielding for a clean signal region, and the ability to discriminate NR and ER signals to boost sensitivity to particular signal types. In terms of weakly interacting massive particles (WIMPs) – the leading candidate for dark matter – the high mass number of xenon makes it well suited to a spin-independent cross section expected to scale as A^2, and its large natural abundance of the non-zero spin isotopes ^{129}Xe and ^{131}Xe allows a response to spin-dependent interactions.

TABLE I. – *Key parameters of LUX and LZ.*

	LUX	LZ
Active xenon mass [kg]	250	7000
Fiducial xenon mass [kg]	$\approx$100	5600
Main volume PMT type	Hamamatsu R8520	Hamamatsu R11410-22
# upper array PMTs	61	253
# lower array PMTs	61	241
Field in LXe [V/cm]	181	310
Max drift length [μs]	324	810
Active liquid Xe skin region	no	yes
Active Gd loaded outer detector	no	yes
7.62 m diameter water tank	yes	yes

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(1) 100-200 nm

3. – Science results from LUX.

The first scientific results from LUX concerned direct searches for WIMP-like dark matter, acquired from 118 kg of target over 85.3 live days during 2013. A profile likelihood ratio test explored whether the observed data were consistent with a background only hypothesis, or whether an additional NR component due to WIMP scatters was required. The data were consistent with no addtional contribution, allowing a 90% c.l. upper limit on the cross section for spin-independent WIMPs to be set. This had a minimum at 7.6×10^{-46} cm^2 for a WIMP mass of 33 GeV/c^2 [5]. Reanalysis of these data included improved calibrations, event reconstruction and background model, giving a new results from 145 kg–95 days of data with an equivalent minimum at 6.0×10^{-46} cm^2 [6], and greater improvement over previous results for lower masses. Results for spin-dependent scattering were published at the same time [7]. Both these results were then supreceded in 2016 by publication of the data from the complete scientific exposure of the instrument. Again, data were in good agreement with the background-only model, giving a 90% c.l. upper limit cross section for spin-independent WIMPs at 2.2×10^{-46} cm^2 [8] (at 50 GeV/c^2). It is noted that these results, together with those from the XENON and PANDAX Xe-based TPCs, have moved the field some 5 to 6 orders of magnitude in sensitivity over the past two decades, and the rate of progress is increasing.

In [9], the sensitivity of LUX to axions and axion-like particles (ALPs) was explored. An interesting feature here is that axions and ALPs interact via the axioelectric effect, analogous to the photoelectric effect. As such, this study required a search for excess events lying within the ER band. Strategies used to reduce terrestrial backgrounds (deep underground location, rigourous radiological screening and material selection, fiducialisation, single-site interaction requirement, cleanliness protocols during construction, etc.) result in essenitially no NR background, but invariably leaves a small rate of ERs. Hence the background model required for ER-band searches must be particularly accurate, or false-positive detections may be generated. World leading and competitive limits on the axioelectric coupling, g_{Ae} and allowed masses were determined for both axions and ALPs.

The well established annually-modulating signal in the DAMA/LIBRA experiment remains unexplained [10]. DAMA/LIBRA does not provide ER:NR discrimination (though it could, based on pulse shape) opening the possibility that the signal may be caused by leptophilic dark matter. In LUX, both annual and diurnal modulation searches for such a signal have been conducted. No significant annual modulation signature was observed between 2-26 keV in the LUX data, with the most stringent search so far between 2 and 6 keV and a best fit modulation parameter that is in tension with that reported by DAMA/LIBRA at the level of 9.2σ [11]. The diurnal modulation search disfavours any day-night or morning-evening asymmetry above 0.2 cpd/keV/tonne.

Even in the canonical WIMP dark matter scenario, ER signals may be present. One exciting possibility has been suggested (e.g. [12]) in which Bremsstrahlung and so-called Migdal effects lead to ER-generating atomic emissions. Since in Xe-based TPCs the ER threshold is lower that the NR threshold, these effects allow increased sensitivity to lower masses where NR signals fall below threshold. An initial search for such signals has been conducted by LUX and is presented in [13], improving sensitivity to low masses competitive to other more dedicated technologies. Other searches for new physics that are ongoing include dark matter searches within the effective field theory formalism, constraining operators that can produce novel responses such as angular-momentum-dependent and spin-orbit couplings, searches for neutrinoless double beta decay of ^{134,136}Xe isotopes, two-neutrino double electron capture of ^{124}Xe, lightly ionising particles, and much more.

Significant further progress in sensitivity beyond that achievable with LUX will require a bigger detector. LUX-ZEPLIN (LZ) will be such an instrument, with a proposed liquid xenon active mass of around 7 tons. This will require a scale up of about a factor of three in linear dimensions, but will offer an improvement by a factor of around 100 in sensitivity, driven by the larger fiducial volume, the substantially increased power of self-shielding, and improved screening and material selection. Another significant factor is that LZ includes a liquid xenon "skin-veto" (a separate region within the inner croystat instrumented with its own PMTs) and a gadolinium loaded liquid scintillator outer detector within the water and close to the main detector. The LZ TPC volume will include 494 ultra low background 3" PMTs and a 50 kV cathode. Online purification will mean electrons liberated by ionisation will have a minimum mean survival against capture by electronegatives of 850 μs, and natural Kr will be reduced to a level of 0.015 ppt g/g. Preparation of the Davis cavern is well underway, with cryostat installation imminent and first operation expected in 2020. A comprehensive study of the expected performance of the instrument, based on the latest background estimates and simulations of the detector, has been conducted, showing that for a 1000 live day run using a 5.6 tonne fiducial mass, the device will exclude at 90% c.l. spin-independent WIMP-nucleon cross sections above 1.6×10^{-48} cm^2 for a 40 GeV/c^2 mass WIMP. Additionally, a 5σ discovery potential is projected reaching cross sections below the existing and projected exclusion limits of similar experiments that are currently operating. For spin-dependent WIMP-neutron(-proton) scattering, a sensitivity of 2.7×10^{-43} cm^2 (8.1×10^{-42} cm^2) for a 40 GeV/c^2 mass WIMP is expected. Expected sensitivity to other signal types is presently being determined.

4. – Summary

Liquid xenon based TPCs have sensitivity to a number of interesting phenomena, including various particle dark matter candidates, axions and ALPs, neutrinoless double beta decay, ^{8}B solar neutrinos, two-neutrino double electron capture, lightly ionising particles, etc. LUX has delivered several world leading results and, having now ceased operations, analysis of legacy data is on-going. The LUX instrument itself has been relocated as a museum exhibit at the Sanford Laboratory Homestake Visitors Center. Its larger and more sensitive successor, LZ, is expected to start taking data in 2020.

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