The LZ dark matter experiment

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Abstract. The LUX and ZEPLIN collaborations have merged to construct a 7 tonne two-phase Xe dark matter detector, known as LUX-ZEPLIN or LZ. Chosen as one of the Generation 2 suite of dark matter direct detection experiments, LZ will probe spin-independent WIMP-nucleon cross sections down to $2 \times 10^{-48}$ cm$^2$ at 50 GeV/c$^2$ within 3 years of operation, covering a substantial range of theoretically-motivated dark matter candidates. Along with dark matter interactions with Xe nuclei, LZ will also be sensitive to solar neutrinos emitted by the pp fusion process in the sun, neutrinos emitted by a nearby supernova and detected by coherent neutrino-nucleus scattering, certain classes of axions and axion-like particles, and neutrinoless double-beta decay of $^{136}$Xe. The design of LZ is presented, along with its expected backgrounds and projected sensitivity.

1. The LZ Experiment

The LZ detector [1] will be installed at the 4850 level of the Sanford Underground Research Facility (SURF) [2]. This detector will use the same infrastructure and 250-ton water tank that is currently used for LUX [3]. The size of the internal detector vessel was chosen to be the largest that can be fully assembled on the surface and transported intact to the Davis cavern. With a total liquid xenon mass of 10 tonnes, active mass of 7 tonnes, and fiducial mass of 5.6 tonnes, the LZ experiment will probe WIMP-nucleon cross sections down to $2 \times 10^{-48}$ cm$^2$ at 100 GeV within 3 years of operation, covering a substantial range of theoretically-motivated dark matter candidates.

The core of the LZ experiment is a two-phase xenon (Xe) time projection chamber (TPC). Scattering events in LXe create both a prompt scintillation signal (S1) and free electrons. Electric fields are employed to drift the electrons to the liquid surface, extract them into the gas phase above, and accelerate them to create a proportional scintillation signal (S2). Both signals are measured by arrays of photomultiplier tubes (PMTs) above and below the central region. The difference in time of arrival between the signals measures the position of the event in z, while the x, y position is determined from the pattern of S2 light in the top PMT array. Events with an S2 signal but no S1 are also recorded. Highly reflective polytetrafluoroethylene (PTFE) forms the inner wall of the TPC, so as to enable efficient S1 light collection. Self-shielding of LXe is highly effective in forcing gamma rays and neutrons to scatter multiple times, pushing events to higher total energy depositions and generating multiple S2 peaks. This is the primary means for achieving extremely low backgrounds in LZ, and the effectiveness of the self-shielding may be reliably modeled. An active LXe mass of 7 tonnes is enclosed by the cathode, liquid xenon-gaseous xenon interface, and PTFE walls. A schematic of the LZ detector detector is shown in Figure 1.
The LZ detector concept.

The LZ design is enhanced by several added capabilities beyond the successfully demonstrated LUX and ZEPLIN [4-5] designs. The most important addition is a hermetic liquid organic scintillator (gadolinium-loaded linear alkyl benzene [LAB]) outer detector, which surrounds the central cryostat vessels and TPC. The outer detector and the active Xe skin layer operate as an integrated veto system, which has several benefits. The first is rejecting gamma rays and neutrons generated internally (e.g., in the PMTs) that scatter a single time in the fully active region and would otherwise escape without detection; this could mimic a weakly interacting massive particle (WIMP) signal. As these internally generated backgrounds interact primarily at the outer regions of the detector, the veto thus allows an increase in the fiducial volume.

The LZ collaboration includes the current LUX collaboration and is attracting excellent new groups. LZ includes 32 institutions in the US, UK, China, Portugal, and Russia, and project management is in place. Cooldown and "first dark" are expected to occur by the start of 2019.

2. Backgrounds and WIMP sensitivity
LZ has a clear background-control strategy with optimal exploitation of self-shielding to pursue an unprecedented science reach. This strategy includes underground operation within an instrumented water tank to mitigate cosmogenic backgrounds, deployment of a target mass large enough to self-shield external radioactivity backgrounds, construction from low-activity materials and purification of the target medium to render intrinsic backgrounds subdominant, and rejection of the remaining ER backgrounds by S2/S1 discrimination.

The dominant radioactive backgrounds come from the Xe-space PMTs and their bases, field cage structures including the PTFE reflectors, and the cryostat vessels. Our goal is to self-shield those sources over the first few centimeters of active liquid and thereby be sensitive to a population of ERs caused by elastic scattering of solar pp neutrinos which can be further
discriminated by their S2/S1 ratio. An irreducible but very small background of NRs will also arise from coherent neutrino-nucleus scattering. To achieve this, any intrinsic ER backgrounds contained within the Xe itself must be made negligible, with $^{85}$Kr, $^{39}$Ar, and Rn progeny being a particular challenge. Electron recoils caused by the 2 decay of $^{136}$Xe are subdominant below about 20 $\text{keV}_{\text{ee}}$. Cosmogenic (muon-induced) backgrounds are not significant during operation due to the tagging capability of the instrumented water tank and the scintillator veto, but cosmogenic activation of detector materials prior to deployment (including the Xe) must be addressed. The solar pp neutrino scattering rate of $0.8 \times 10^{-5}$ events/keV$_{\text{ee}}$/day/kg is the benchmark against which other rates are assessed. The projected backgrounds in LZ are summarized in Table 1. All materials to be used in LZ will be subject to stringent constraints as part of a comprehensive screening campaign, with 10% of the solar pp neutrino scattering rate and a maximum of 0.2 NRs at 50% signal acceptance being the target for the total contribution from material radioactivity within the fiducial volume. The dominant rates come from the various PMT systems and the LZ cryostat, based on the large masses and close proximity to the active region of the detector.

| Item                          | Mass (kg) | U  | Th | $^{60}$Co | $^{40}$K | n/yr | ER cts | NR cts |
|-------------------------------|-----------|----|-----|-----------|---------|------|--------|--------|
| 11410 PMTs                    | 93.7      | 2.7| 2.0 | 3.9       | 62.1    | 373  | 1.24   | 0.20   |
| 11410 bases                   | 2.7       | 74.6| 29.1| 3.6       | 109.2   | 77   | 0.17   | 0.03   |
| Cryostat vessels              | 2,140     | 0.09| 0.23| ~0       | 0.54    | 213  | 0.86   | 0.02   |
| OD PMTs                      | 122       | 1,507| 1,065| ~0       | 3,900   | 20,850| 0.08   | 0.02   |
| Other components              | -         | -  | -   | -        | -       | 602  | 9.5    | 0.05   |
| **Total components**          |           |    |     |          |         |      | 11.9   | 0.32   |
| Dispersed radionuclides (Rn, Kr, Ar) |           |    |     |          |         |      | 11.9   | 0.32   |
| $^{136}$Xe$\nu\beta\beta$    |           |    |     |          |         |      | 54.8   | -      |
| Neutrinos ($\nu - e, \nu - A$)|           |    |     |          |         |      | 271    | 0.82   |
| **Total events**              |           |    |     |          |         |      | 391.5  | 15     |
| WIMP background events        |           |    |     |          |         |      | 1.96   | 0.41   |
| (99.5% ER discrimination, 50% NR acceptance) |           |    |     |          |         |      |        |        |
| **Total ER + NR background events** |           |    |     |          |         |      | 2.37   |        |
Figure 2. A compilation of WIMP-nucleon SI cross section sensitivity (solid curves), hints for WIMP signals (shaded closed contours), and projections (dot and dotdash curves) for direct detection experiments of the past and projected into the future. Also shown is an approximate band where the coherent nuclear scattering of neutrinos will limit the sensitivity of direct detection experiments to WIMPs. Finally, a suite of theoretical model predictions is indicated by the shaded regions, with model references included [6].

the decay electrons from two-neutrino double-beta decay $2\nu\beta\beta$ of $^{136}$Xe [9]. For ER energies between 1.5 and roughly 2 keV$_{ee}$, ERs from pp solar neutrinos dominate [10], and contribute 850 observable events through neutrino-electron scattering in the 5.6 tonne fiducial mass during a run of 1,000 days. We have neglected atomic effects that suppress the rate by of order 10% [11].

Should a core-collapse supernova occur in our galaxy during LZ operation, neutrinos emitted from the supernova would be detected via coherent neutrino-nucleus scattering, which is blind with respect to neutrino flavor. The energy spectrum of neutrinos emitted from a typical supernova peaks near 10 MeV, and has a tail that extends above 50 MeV, which causes NRs above the LZ threshold [12]. Coherent neutrino-nucleus scattering is mediated by the weak neutral current, and thus provides important information on the flux and spectrum of muon and tau neutrinos from supernovae, complementary to the signals that would be seen in other detectors. From a core-collapse supernova in our own galaxy at 10 kpc, LZ would see 50 NR events of energy greater than 6 keV$_{nr}$ in a rapid 10-sec burst [13,14]. The NR recoil spectrum increases as the recoil energy decreases; a threshold of 3 keV$_{nr}$ would allow detection of 100 supernova neutrino-induced NR events. The current world sample of 19 supernova neutrino-induced events were detected from supernova 1987a, 50 kpc from Earth, by detectors with total mass 1,200 times greater than LZ. A supernova 10 kpc from Earth would cause about 7,000 neutrino-induced events in the 32,000 tonnes of water in the Super-Kamiokande detector [12].

The sensitivity of LZ to neutrinoless double-beta decay of $^{136}$Xe (Q-value 2,458 keV) depends
strongly on the radioactivity levels achieved in detector materials and on the energy resolution of the combined S1+S2 signal. We have performed Monte Carlo simulations of various backgrounds for neutrinoless double-beta decay, and find that the most significant contributions are the 2,448-keV gamma line and the 2,614-keV gamma line, from $^{214}$Bi and $^{208}$Tl decay, respectively, which can penetrate deeply into the active region. These gamma-ray backgrounds can be accurately measured using the full detector active mass, and can be substantially reduced through self-shielding and multiple scattering cuts. Solar neutrino and 2-neutrino double beta decay backgrounds are found to be small in comparison. Energies are determined through an optimal linear combination of S1 and S2 signals, with a predicted 1-sigma energy resolution of 0.8 % at the 2,458-keV Q-value. With a natural Xe target and 1,000 live days, LZ should be sensitive to $^{136}$Xe half-lives from $2 \times 10^{25}$ years to $2 \times 10^{26}$ years, depending on achieved background, spatial, and energy resolution. The shorter value corresponds to an increase of 10 times over baseline radio purity, an energy resolution of 2%, and a spatial resolution of 6 mm. Enriching the Xe target would improve the sensitivity to perhaps $2 \times 10^{27}$ years.

There are long-standing anomalies arising from the study of antineutrinos from reactors, and from source-calibration of solar neutrino experiments. A recent study has evaluated the capabilities of deployment of a 5 MCi $^{51}$Cr electron neutrino source near to the LZ detector [15]. The excellent spatial resolution of the LXe TPC allows the spatial pattern of electron neutrino oscillation into a sterile neutrino to be detected. A neutrino source experiment with LZ would not be part of the principal LZ science goal, which is the WIMP search, and would constitute a distinct follow-on experiment after the WIMP search had achieved significant results.

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