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Direct search for WIMP dark matter particles with the LUX-ZEPLIN (LZ) detector

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ABSTRACT

LZ is a second-generation Dark Matter experiment to conduct searches for weakly interacting massive particles. It is expected that the detector will reach a sensitivity for spin-independent elastic WIMP-nucleon cross-section of 1.6×10^{-48} cm^2 at a mass of 40 GeV/c^2 in 1000 days of operation. Aside from Dark Matter particle interactions, the detector will also be sensitive to solar and supernova neutrinos as well as neutrinoless double beta decay from ^{136}Xe. Background sources such as ^{222}Rn and ^{85}Kr must be significantly suppressed. This will be assured by radioactive screening of detector components and purification of xenon. The design of the LZ detector, radioactive background expectations and projected WIMP sensitivity are presented in this article.

Contents

1. Introduction

A large variety of cosmological observations such as galactic rotation curves, the accurate measurements of cosmic microwave background (CMB) and the gravitational lensing effect around galaxy clusters suggests the existence of non-baryonic cold Dark Matter (DM). However, the core nature of DM still remains a mystery. One of the favorite candidates for DM in the Universe is weakly interacting massive particles (WIMPs) [1].

The first results from the ZEPLIN and XENON collaborations [2,3] obtained almost a decade ago led to a new era in underground direct searches for DM significantly improving the sensitivity to this candidate particle. This was mainly made possible by the use of the dual-phase (liquid/gas) xenon time projection chambers (LXe TPC) developed at the end of 1960s [4]. Noble liquid TPCs combine several attractive features for DM searches such as identification of particles, 3-D event position reconstruction, excellent self-shielding from external radioactive backgrounds, and cost effective scalability compared to solid-state detectors. LXe is a very attractive target for WIMP detection due to its efficient conversion of energy from low energy nuclear recoils into observable scintillation and ionization signals. Unlike other noble gases, xenon offers several advantages such as an absence of long-lived activation products, high sensitivity to spin-independent (SI) WIMP interactions due to its large atomic weight and a coherent scattering enhancement ($\propto A^2$) for non-relativistic WIMPs, assuming isospin-conserving interactions, and sensitivity to spin-dependent (SD) interactions due to naturally-occurring odd-neutron isotopes.

LZ is an international collaboration which includes 37 institutions from the USA, UK, Portugal and Russia. LZ is constructing the next generation of a dual-phase LXe TPC aiming to probe spin-independent WIMP-nucleon cross-sections to reach the ultimate sensitivity of 1.6×10^{-48}cm^2 at a mass of 40 GeV/c^2 in 1000 days of operation [5].

The LZ apparatus, design, radioactive background expectations and projected WIMP sensitivity are presented.

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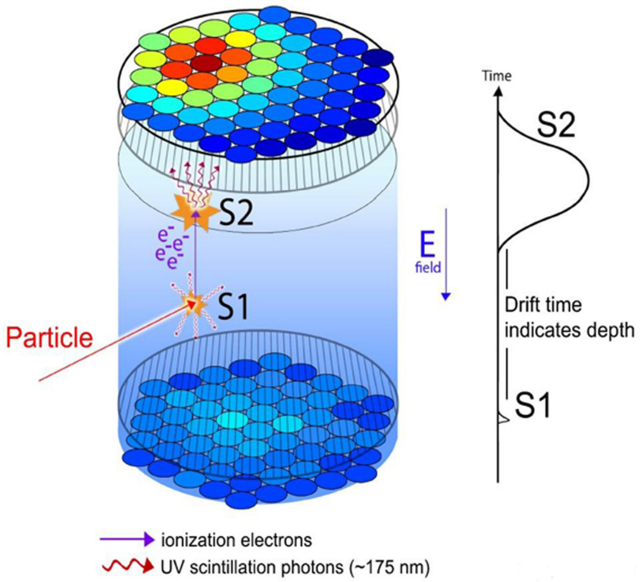

Fig. 1. Operating principle of the dual-phase LXe TPC featuring its two main signatures: Primary scintillation light (S1) and electroluminescence signal (S2), where the latter one is proportional to the initial number of the electrons.

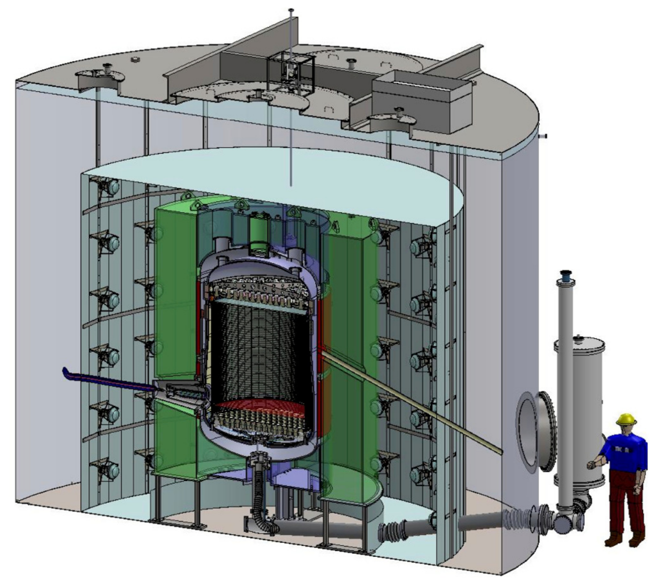

Fig. 2. A cutaway view of the LZ apparatus.

2. The LZ detector

The LZ experiment will have about 10 tons of LXe. The TPC is housed in a vacuum-insulated cryostat made from ultra-pure titanium. The cryostat is maintained at 175 K using a unique cryogenic system to efficiently and economically cool the detector based on thermosyphon technology. The cryostat is surrounded by an outer detector (OD) based on a liquid organic scintillator (gadolinium-loaded linear alkyl benzene [GdLAB]) maintained at room temperature. Both are located within a large water tank in the Davis Campus at the 4850-foot level (4300 m.w.e.) of the Sanford Underground Research Facility (SURF, South Dakota, USA). The active volume of the TPC is a cylinder with both diameter and height equal to 146 cm, containing about 7 tons of LXe.

When particles interact with xenon, they excite and ionize xenon atoms resulting in production of primary scintillation light with a wavelength of 175 nm due to excitation and recombination processes (S1). As the liberated electrons start drifting to the liquid–gas interface, toward the anode, they are extracted into the gaseous phase by strong electric field and produce electroluminescence signals (S2). Photons (S1 and S2) are detected by the top and bottom arrays of the photosensitive devices consisting of 494 Hamamatsu R11410-22, 3" diameter, photomultiplier tubes (PMTs) with low levels of radioactive contamination. The difference in time between S1 and S2 signals locate the events in the Z-axis, while the X and Y positions are determined from the pattern of S2 signals. Highly reflective polytetrafluoroethylene (PTFE) covers the inner walls of the detector and between the PMTs to collect scintillation light with high efficiency (> 97%) [6,7]. Fig. 1 indicates the operating principle of the dual-phase LXe TPC.

The strong self-shielding capability is based on dense LXe ($\approx$3 g/cm^3) and high atomic number (Z = 54) that shields the fiducial volume of the detector to produce an extremely low background. The LZ apparatus distinctly features a two-component veto system featuring several benefits. The innermost veto "skin" region contains about 2 tons of LXe which is optically separated from the TPC detector. Its region is viewed by 93 Hamamatsu R8520, 1", PMTs mounted near the xenon liquid level and additional 38 Hamamatsu R8778, 2", PMTs mounted near the bottom of the TPC. The principal role of the "skin" region is to detect scattered gamma-rays. The second veto of the LZ cryostat, the OD, consists of 17 tons of GdLAB contained in 10 acrylic tanks. The role of the OD is to tag neutrons emerging from the TPC mimicking WIMP signals. Scintillation light produced in the GdLAB is observed by 120 Hamamatsu R5912, 8", PMTs mounted in the water space outside of the acrylic tanks and surrounded by Tyvek diffuse reflectors. The volume outside the acrylic tanks is filled with ultra-pure distilled water, providing suppression of radioactive background from the surrounding rocks of the Davis Campus as Fig. 2 shows.

3. Radioactive background in the LZ detector

The strategy to mitigate radioactive backgrounds combines underground operation of the LZ detector within an instrumented water tank to detect cosmogenic backgrounds, deployment of a large enough detector target to self-shield from external radioactive background and construction of the internal detector assemblies from materials with extremely low radioactive levels. Table 1 summarizes all radioactive backgrounds expected in the LZ TPC for electronic recoil (ER) and nuclear recoil (NR) counts in the 5.6 ton fiducial mass during 1000 live days of operations. For the purposes of tracking material radioactivity throughout the design and construction of LZ, Table 1 is based on a restricted region of interest (ROI) relevant to a 40 GeV/c^2 WIMP spectrum, equivalent to approximately 1.5–6.5 keV for ERs and 6–30 keV for NRs. Table 1 gives values based on the baseline optical model described in details in the LZ TDR report [8]. The expected total from all ER(NR) background sources is 1195(1.03) counts in the full 1000 live day exposure. Applying discrimination against ER at 99.5% for an NR acceptance of 50% (met for all WIMP masses given the nominal drift electric field and light collection efficiency in LZ) suppresses the ER(NR) background to 5.98(0.51) counts. ^{222}Rn presents the largest contribution to the total number of events. Atmospheric neutrinos are the largest contributor to NR counts, showing that LZ is approaching the irreducible neutrino background. Fig. 3 (a and b) presents the spectral contributions to ER and NR backgrounds. This figure shows rates of unvetoed single scatter events in the fiducial volume with no energy ROI or detector efficiency cuts applied.

The primary isotopes occurring in radioactive materials are the gamma-emitting isotopes such as ^{238}U, ^{232}Th etc. LZ has undertaken a very thorough campaign on radioactive assay of the LZ TPC's components. Radioactive isotopes distributed throughout the LXe in the TPC produce background that cannot be mitigated through self-shielding. ^{222}Rn emanation from the detector components is problematic due to

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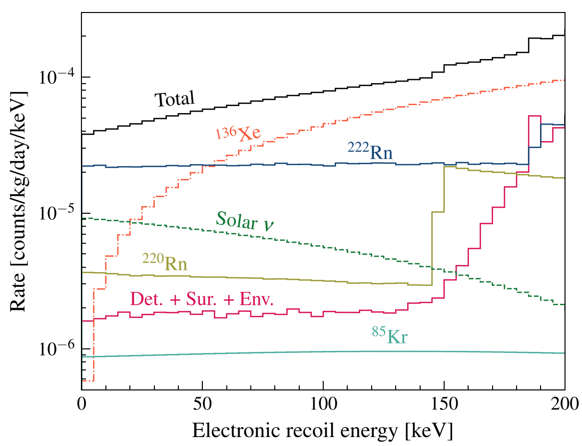
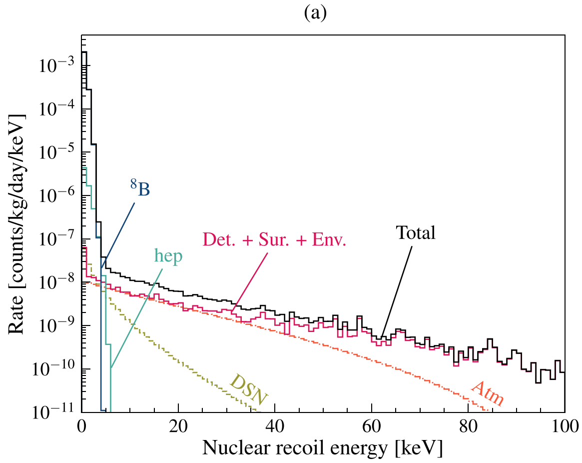
Table 1
Summary of radioactive backgrounds in the LZ detector showing radioactivity levels for some dominant components, their neutron emission rates and the total number of counts (6.49 events) expected in the 5.6 ton fiducial volume for 40 GeV/c^2 WIMP ROI.

LZ Radioactive Backgrounds		
Source	ER counts	NR counts
Detector components	9	0.07
Surface Contamination	40	0.39
Laboratory and Cosmogenics	5	0.06
Xenon Contaminants: Rn, Kr and Ar	819	0
Physics backgrounds: $2\nu\beta\beta$ and neutrinos	322	0.51
Total	1195	1.03



(a)



(b)

Fig. 3. (a) ER and (b) NR background spectra in the 5.6 ton fiducial volume of the LZ LXe TPC for single scatter events with neither a xenon skin nor an OD veto signal.

beta-decay of ^{214}Pb to the ground state of ^{214}Bi whose signal can end up in the WIMP ROI and survive a discrimination cut (S2/S1). ^{222}Rn gas, continually emanated from the warm detector components embedded in gaseous xenon such as the feedthrough flanges, the breakout boxes, and the PMT cables, can be reduced with the inline radon reduction system. For these components, the most recent R&D studies suggest that it will require about 5(7) kg of HNO_3 etched Saratech charcoal to reduce the estimated radon concentrations of 8.3(20) mBq, continually emanated from the LZ detector components, at a Xe flow rate of 0.5 standard liters per minute below 1 mBq in the return stream of the radon reduction system [9]. Natural xenon also includes trace levels of ^{85}Kr and ^{39}Ar, both of which dissolve in the liquid and are beta emitters that lead to ER events in the WIMP ROI. LZ has implemented significant purification of xenon gas using chromatography methods to control ^{85}Kr. In an R&D

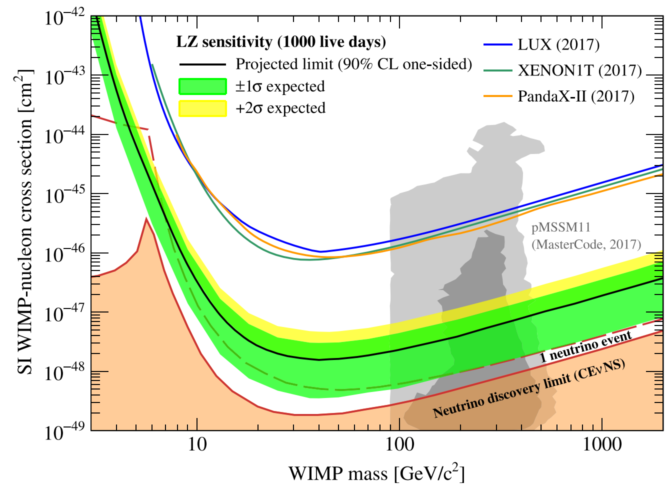


Fig. 4. LZ projected sensitivity for SI WIMP-nucleon elastic scattering from xenon nuclei for 1000 live days in the 5.6 tons fiducial volume.

phase, the chromatography system reduced the ^{84}Kr/Xe concentration to 0.075 ppt in terms of (g/g). Argon levels were also reduced during the purification with an expected concentration of ^{40}Ar/Xe below 0.45 ppb in terms of (g/g) [5].

4. The LZ projected WIMP sensitivity

The LZ projected sensitivity to SI WIMP-nucleon scattering from xenon nuclei is shown in Fig. 4.

A minimum sensitivity of 1.6×10^{-48} cm^2 is expected for 40 GeV/c^2 WIMPs which is an order of magnitude in sensitivity improvement compared to the currently running DM experiments using similar technology. With this sensitivity, LZ will probe a significant fraction of the parameter space remaining above the irreducible background from coherent scattering of neutrinos from astrophysical sources. Since ^{222}Rn is projected to be the largest source of events, a number of scenarios are presented based on current assessments for ^{222}Rn rates in LZ. The high and low scenarios correspond to all ^{222}Rn screening measurements being within at their $+1\sigma$ and -1σ expectations, respectively. Moreover, the highest scenario also assumes no reduction in emanation rate at LZ operating temperatures (175 K). Fig. 5 shows how the SI sensitivity to a 40 GeV/c^2 WIMP varies as a function of overall ^{222}Rn concentration in the 5.6 ton fiducial volume. Even for the highest estimate scenario the median sensitivity is better than 3×10^{-48}cm^2.

5. Summary and outlook

The LZ TPC will be the largest detector in the world optimized for a potential discovery of WIMP DM particles starting to run in 2020. The detector components are carefully selected and meticulously assayed for the presence of residual radioactive background, which is detrimental to WIMP searches. The outer detector and active xenon "skin" veto systems are critical and will provide both the rejection of neutrons and gamma rays from internal background sources. LZ is capable of excluding SI WIMP-nucleon cross-section of 1.6×10^{-48}cm^2 at 90% CL for 40 GeV/c^2 WIMPs which will represent an order of magnitude sensitivity improvement compared to the current DM experiments.

The LZ detector will be sufficiently sensitive to neutrino signals. Most events in LZ from solar neutrinos originating from the p-p-reaction will have ERs signature. Additional ER background will be contributed from double-beta decay ($2\nu\beta\beta$) from ^{136}Xe. In addition to direct interactions of DM particles, LZ will observe ^{8}B and "hep" (^{3}He-p) solar neutrinos, supernova, at a distance of 10 kpc, and atmospheric neutrinos interacting through coherent elastic neutrino-nucleus scattering. Moreover,

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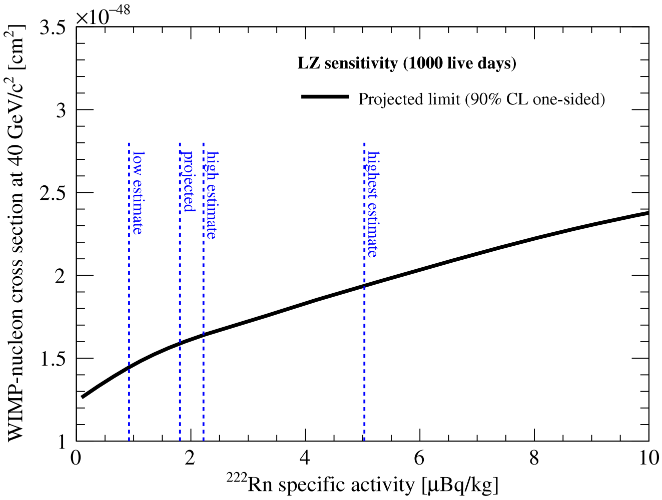

Fig. 5. LZ projected SI sensitivity for 40 GeV/c^2 WIMPs as a function of ^{222}Rn level, for a 5.6 ton fiducial volume measured during 1000 days of operation.

with natural xenon, LZ should be sensitive to neutrinoless-double beta decay ($0\nu\beta\beta$) from isotope ^{136}Xe with a half-life of 7.4×10^{25} years. The ultimate result will depend on the energy and spatial resolution of the detector (Q-value: 2.46 MeV) and radioactive background contamination levels.

Acknowledgments

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