Cryogenic Large Liquid Xenon Detector for Dark Matter Searches

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Abstract. Observation of rotational curve of spiral galaxies shows that a large fraction (~23\%) of the mass density of the universe is unaccounted for. Such a significant percentage of missing dark matter suggests that the universe may consist of new types of elementary particles. A compelling explanation for the new particles is the existence of Weakly Interacting Massive Particles (WIMPs), which are non-baryonic particles characterized by particle physics theories beyond the Standard Model. WIMPs are believed to only interact through the weak force and gravity; hence the interaction cross section with ordinary matter is extremely small. Therefore, experimental techniques that combine low radioactivity, low energy thresholds, efficient discrimination against electronic recoil backgrounds, and scalability to large detector masses can only be performed at a deep underground environment where the interference of cosmic rays is obviated. In this paper, we report a cryogenic large liquid xenon detector for dark matter searches at Sanford Lab (Davis Cavern) in the Homestake Mine, USA. The goal of the large underground xenon (LUX) dual-phase detector is to clearly detect (or exclude) WIMPs with a spin independent cross-section per nucleon of $7 \times 10^{-46}$ cm$^2$, equivalent to ~0.5 events/100 kg/month in an inner 100 kg fiducial volume (FV) of a 300 kg LXe detector.
1. Introduction
Detecting Weakly Interacting Massive Particles (WIMPs), considered as the primary candidate for dark matter in the universe, is one of the most important programs in modern physical science. A phased-approach dark matter program at DUSEL is recommended by the nationwide dark matter group organized by DUSEL S1 committee in early November, 2007, at the DUSEL Town Meeting held by NSF in Washington D.C. Phase 1 is to build a few hundred-kg detector that will have potential of discovery WIMP with a sensitivity of $10^{-46}$ cm$^2$ of WIMP-Nucleon cross section at the DUSEL in five years. Phase 2 is to push to a greater sensitivity beyond $10^{-46}$ cm$^2$ for a detector with more than 10 tons of target mass at DUSEL. To carry out this dark matter program, the overall residual background level after application of various background rejection techniques in a multi-ton detector must be lower than one event per ton per year. It is extremely challenging to design a detector with multi-ton mass because ubiquitous radioactive impurities (such as $^{39}$Ar, $^{85}$Kr, $^{232}$Th, $^{238}$U and $^{40}$K) are proportional to the mass of the detector. Therefore, the development of purification and depletion techniques is the key to the development of large detectors. In addition, the capability of discriminating different types of events in the detector is also critical to the success of the detection of WIMPs. These two requirements make noble liquids the most promising targets [1, 2, 3, 4, 5].

Dual-phase liquid xenon detectors have been shown a powerful new technology for the detection of dark matter [2, 3]. Direct scintillation light ($S_1$) is generated in liquid target by a particle via ionization that creates ions and electrons, while electrons escaping recombination at the event site are drifted by electric filed to the liquid surface and extracted into the gas phase, where they create proportional scintillation light ($S_2$). Both $S_1$ and $S_2$ are measured by arrays of PMTs, located above and below the active liquid Xe region. The bottom PMT array measures the $S_1$ signal, as photons in the liquid are mostly trapped by total internal reflection. The top array of PMTs images the $x$-$y$ location of the $S_2$ signal, and the drift time gives the depth, hence this technique provides powerful 3D imaging of the event location. Xe is purified to a very low level of radioactivity (1 ppt of $^{238}$U and $^{232}$Th as well as 0.01 ppb of $^{40}$K), and external backgrounds is also minimized by the appropriate choice of detector materials and design of shielding. The remaining background is further reduced to levels allowing the detection of WIMPs using two powerful tools: (1) discrimination of electron recoils that are backgrounds gammas and betas from nuclear recoils that are possible WIMPs, based on the amount of charge recombination as measured by scintillation light ($S_1$) and charge ($S_2$); and (2) the strong self-shielding capability of the dense Xe liquid combined with precise 3-D event position determination.

The goal of the large underground xenon (LUX) [6, 7] dual-phase detector is to achieve a WIMP sensitivity that can clearly detect (or exclude) WIMPS with a spin independent cross section (normalized to a nucleon) of $7 \times 10^{-46}$ cm$^2$, equivalent to 0.5 events/100 kg/month in an inner 100 kg fiducial volume (FV) of a 300 kg liquid xenon (LXe) detector. The expected backgrounds are electron recoils, primarily from gamma rays, and nuclear recoils from neutrons. Based on the calibrations that have been performed in above ground laboratories [8], and comparison with data from the XENON100 experiment [3] we project that the detector will reject 99.9% of electron recoils with a 50% acceptance of nuclear recoil events in the energy range that is relevant to dark matter detection. This allows the low energy gamma background rate (using appropriate scaling factors for electron vs nuclear recoil quenching) is 1000 times higher than the nuclear recoil background rate.

The expected electronic-recoil event rate in LUX is less than $4 \times 10^{-4}$ events/keVee/kg/day at energy threshold within the fiducial volume of the detector. This can be achieved using both a charge ratio of $S_2$ to $S_1$ and a 3D imaging capabilities of the detector that powerfully eliminate the majority of the backgrounds in the outer portions of the detector hence the multiple-scattering events. The details of the effectiveness of this kind of cut are largely dependent on the specific
design/performance of a given detector. Extensive Monte Carlos have been performed for the large LUX detector, and show that the necessary suppression can readily be achieved.

A large volume of water reduces the external gamma rays to a negligible level and the internal radioactivity of the detector will be the dominant source of gamma background. Neutrons, like WIMPs deposit energy through nuclear recoils, thus neutrons must be reduced below the level of any possible WIMP signal. External neutrons are effectively reduced by the water shield. The inner neutrons from the PMT arrays are dominated source of background. However, neutrons unlike WIMPs, will undergo multiple scattering within the active volume of a detector. The LUX detector with a very good position resolution can identify these type of contributions from neutrons. Using low background PMTs, the Monte Carlo simulation has demonstrated that the neutron background is low enough so that the target sensitivity can be achieved. In this paper, we describe the detector, the background simulation, and the target sensitivity.

2. Cryogenic Detector

2.1. Muon veto

The designed LUX detector [9] consisting of the outer shield and inner vessel is shown in Figure 1. The large water shield instrumented with PMTs, and used as a Cherenkov veto for muons. The water also provides superior shielding of neutrons from cavern radioactivity and the very high-energy tail of neutrons from muon interactions in cavern walls. The water shield has a minimum shielding thickness of 2.5 m in any direction, and the cavern sources of γ and neutron activities will be reduced to a level where the internal radioactivity from detector components is the dominant source of background. The purified water with a level of 2 ppt/3 ppt/4 ppb U/Th/K is about 6 orders of magnitude lower than that of radioactivity in the surrounding rock. This level of impurities can be attained with a commercial purifier. A set of 20 eight-inch PMTs at the bottom of the tank are served as an active muon veto. With Tyvek reflector on the tank walls, a single downward-going muon will, on average, produce about 200 photoelectrons (phes). The amount of light collected from muons that produce a hadronic shower in the tank will be even greater. Thus, essentially all showering muons passing within two meters of the edge of the detector can be vetoed. This muon veto detector can be also used to ensure that any event associated with muons can be eliminated, and also demonstrate that any WIMP candidate is not correlated with muons.

2.2. Cryostat

The LUX detector cryostat vessels are made of 0.223 inches thick grade CP1 titanium sheet, machined and welded by Ability Engineering. The outer vessel holds a vacuum to insulate the inner vessel while the inner vessel contains the detector internals and liquid xenon. The inner vessel is a 39.75-inch tall, 24.25-inch diameter cylinder with a dome welded to the bottom and a 27.75-inch diameter flange welded to the upper rim. It hangs from the upper dome of the outer vessel, mechanically attached and thermally isolated via plastic in three hangers. To compensate for thermal contraction of the plastic in the hangers the instrumentation wiring and circulation plumbing lines penetrate through the outer vessel into the inner vessel via commercially available stainless steel flexible couplings; being thin-walled (0.006") stainless steel, these couplings have low thermal conductivity. The flanges of both vessels are designed to use Helicoflex gaskets.

2.3. Cryogenics

To efficiently and economically cool the LUX detector we use a unique cryogenic system, based on thermosyphon technology [10]. Each thermosyphon consists of a sealed tube, partially filled with a variable amount of gaseous nitrogen (N₂), 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 located vertically since it works with gravity, and is closed and pressurized with N$_2$. The N$_2$ condenses inside the condenser, trickles down the stainless steel lines to the copper cold heads (evaporators) that are securely fastened to various points on the detector’s inner can, syphons heat from the detector and evaporates, rising back up the lines to the LN bath. The pressure in the thermosyphons is close, but somewhat below the equilibrium pressure corresponding to the temperature of the evaporator. This condition allows for the highly efficient operation of the thermosyphon. Measurements of the thermosyphon thermal conductivity put it at $\sim 55$ kW/K $\cdot$ m, much higher than metals, such as copper, and comparable to carbon nanotubes at low temperatures (see [10]). This technology has demonstrated excellent efficiency in cooling.

Four thermosyphon cold heads are deployed in the LUX detector. One large capacity cold head is placed at the top of the inner vessel and thermally coupled to the top copper thermal and radiation shield. A smaller capacity cold head is placed at the bottom of the inner vessel and thermally coupled to the bottom copper thermal and radiation shield. These two cold heads will be used to cool the detector internals slowly and uniformly from room temperature to 175 K. The other two cold heads are attached to the copper thermal shield surrounding the inner vessel and are used to maintain a thermal gradient along the vertical dimension of the detector. The large capacity cold head at the top of the inner vessel can convey several hundred watts of cooling power, while the smaller cold heads can convey $\sim 200$ W of cooling power. Each head is instrumented with a 50-W heater and a thermometer as part of a Proportional-Integral-Derivative (PID) loop for fine temperature control. The top and bottom cold heads are additionally instrumented with a 750-W heater and a PID control thermometer to assist with warming the detector internals and LXe for recovery and opening of the inner vessel at the end of a run.

3. Underground background simulation
The geometry of the LUX detector is described above. We performed the GEANT4-based Monte Carlo simulation to evaluate the external and internal background for the LUX detector.
3.1. The sources of the external background

The water tank is dedicated to reduce $\gamma$ rays and neutrons from natural radioactivities in the surrounding rock. A $\gamma$-ray flux of $1.8 \text{ cm}^{-2} \text{s}^{-1}$ and a neutron flux of $2.3 \times 10^{-6} \text{ cm}^{-2} \text{s}^{-1}$ in Sanford Lab were predicted in Ref. [11] with known U/Th/K levels in the rock [12]. With a thickness of $2.5 \text{ m}$ water, the contributions to the region of interest (1.3 - 8.0 keVee) in the fiducial volume is predicted to be about 10 electronic recoil (ER) events per year before ER rejection and 0.003 nuclear recoil (NR) events.

Muon-induced neutrons come from the surrounding rock, the water tank, and the liquid xenon when muons transverse these materials. However, when the neutrons are produced in the xenon tank, the energy deposited by parent muon via ionization excess the energy region of interest. Therefore, those neutrons are vetoed by the energy rejection. Utilizing Mei & Hime’s paper [13], the muon-induced neutron flux at the Davis Cavern is obtained to be $5.3 \times 10^{-10} \text{ cm}^{-2} \text{s}^{-1}$ and the muon-induced neutron flux in the water tank is $7.3 \times 10^{-9} \text{ cm}^{-2} \text{s}^{-1}$. The simulation predicts 0.01 NR events per year for the neutrons originated in the Davis Cavern and 0.3 NR events per year for the neutron produced in the water tank with a muon veto efficient of 70%.

The radioactivity generated $\gamma$ rays and neutrons in the water tank are also evaluated by the simulation. The radio-purity level of U/Th/K in the water is targeted to be 2 ppt/3 ppt/3 ppb, respectively. The ($\alpha,n$) neutrons produced in the water is calculated to be about 80 per year [11]. We predict 17 ER events per year before ER rejection and 0.005 NR events per year.

3.2. The sources of internal background

Natural radioactivity induced $\gamma$ rays and neutrons in the PMTs are expected to be the majority of background events in the region of interest. There are 60 R8778 (Hamamatsu) PMTs severed as the photon detectors. The radioactivity levels of U/Th/K/$^{60}$Co are $9.5/2.7/66/2.6 \text{ mBq/PMT}$. Such radioactivity will generate $1.3 \text{ n/PMT}$ per year [11]. We expect 0.7 NR events and 80 ER events per year before ER rejection. Note that the branching ratio of the gamma-ray emission from $^{40}$K is only 10%.

The titanium vessel contains $\sim 1 \text{ ppb}$ of U/Th. With a total mass of about 15 kg, we predict 35 neutrons produced in the vessel per year. These neutrons would produce 0.14 NR events in the region of interest. The $\gamma$ rays from the vessel would contribute about 30 ER events per year to the region of interest before ER rejection.

Radioactive isotopes such as $^{85}$Kr, $^{220}$Rn, $^{222}$Rn, $^{124}$Xe, and $^{136}$Xe are important sources of background. The contaminations of $^{85}$Kr, $^{220}$Rn, and $^{222}$Rn depend largely on the purification requirements. The LUX Kr/Xe goal is $< \sim 5 \text{ ppt}$. The expected ER events corresponding to this contamination level is less than 50 per year before ER rejection. With a goal of 16 mBq/kg Rn decay rate, the simulated ER events are less than 10 before ER rejection. Natural xenon contains 0.1% $^{124}$Xe and 8.9% $^{136}$Xe. The former one is a double electron capture candidate and the latter one is a double decay candidate. Both have been yet observed. Using the upper limits obtained by Refs. [14, 15], we estimate 2 ER events from two isotopes before ER rejection.

Solar neutrinos induced background is a level of 3 ER events per year before ER rejection. This comes mainly from pp neutrinos. The NR events induced by solar neutrinos are calculated to be very small for the LUX detector.

3.3. Summary of the simulated background

We summarize the simulated background in Table 1. The energy deposition are both ER and NR events are simulated. The quenching factor $\eta_{\text{Xe}} = 0.18$ is used in the simulation. The single events are distinguished from multiple events with a position resolution of $\delta x, \delta y < 4 \text{ cm}$, $\delta z < 1 \text{ cm}$. Only single events are counted with an energy window of $E_{\text{th}} = 1.3 \text{ keV}$ to $E = 8 \text{ keV}$. Moreover, a 100 kg fiducial spheric volume is set in the middle of the LXe detector.
Table 1. Summary of NR and ER events in the region of interest (1.3-8 keV)

| Event type                          | LXe evts/year | Titanium evts/year | PMT evts/year | Water evts/year | Davis Cavern evts/year | Total Events (evts/year) |
|-------------------------------------|---------------|--------------------|---------------|-----------------|------------------------|--------------------------|
| ER before rej.                      | 65            | 35                 | 80            | 17              | 10                     | 202                      |
| ER after rej. (99.9%)               |               |                    |               |                 |                        |                          |
| Inherent NR                         | 0             | 0.14               | 0.7           | 0.003           | 0.005                  | 0.84                     |
| $\mu$-induced NR                    | 0             | 0                  | 0             | 0.3             | 0.01                   | 0.31                     |
| NR after NR acceptance (50%)        | 0.65          |                    |               |                 |                        |                          |

4. Target Sensitivity
The projected sensitivity of LUX is illustrated by the dashed curve in Fig. 2. After running for 100 days in dark-matter search mode (10,000 kg-days of exposure), LUX will achieve a WIMP spin-independent sensitivity at the 90% confidence level. Also plotted are currently existing limits from Zeplin III (solid, black), CDMS (solid, light grey), and XENON100 (solid, grey).

![Figure 2. LUX projected WIMP spin-independent sensitivity at the 90% confidence level (dashed, black) after an exposure of 10,000 kg-days. Also shown are current limits from Zeplin III (solid, black), CDMS (solid, light grey), and XENON100 (solid, grey). Plot generated using the software of Ref. [16]](image1.jpg)

In conclusion, we have demonstrated the LUX cryogenic dark matter detector that are being constructed at Davis Carven at the Sanford Lab. With hope that the detector will start to take data in 2012.
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