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LUX Cryogenics and Circulation

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Abstract

We report the efficiency of a thermosyphon-based cooling system for a liquid xenon (LXe) time projection chamber (TPC), as well as the efficiency of a unique internal heat exchanger with standard gas phase purification using a heated getter, which allows for very high flow purification without requiring large cooling power.

Keywords: LUX, dark matter, thermosyphon, cryogenics, noble gas circulation

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1. Dark Matter and Underground Science

The LUX (Large Underground Xenon) experiment is the latest in seven decades of observing, measuring, and searching for dark matter since Zwicky's 1933 paper on extragalactic nebulae [1]. While Vera Rubin's careful measurements of stellar motion [2] and recent observations of lensing centers and x-ray sources in the Bullet Cluster [3] have shown strong indirect evidence for the existence of dark matter, we still wait for direct detection as the search continues with larger detectors, better shielding, and greater background discrimination ability. The LUX Collaboration brings together over 60 scientists from 15 US and international academic institutions and national laboratories, with previous experience in ultra-low background experiments [4, 5, 6, 7] and dark matter searches [8, 9, 10] in addition to underground operation and water shield deployment. The collaboration was formed in 2007 and fully funded by DOE and NSF grants by 2008. Since then new groups from other institutions have joined the LUX effort as well as the growing LZ collaboration for a very-large scale underground dark matter search with new European collaborators.

The experiment is an outgrowth from previous, well-established xenon time projection chamber (TPC) technology [10, 8] designed to detect and measure recoil events of xenon atoms with WIMP particles, which are candidates for the dark matter. The TPC provides single electron and photon detection capability, as well as excellent 3D imaging of the event location with millimeter precision. This allows LUX to reject multiple scatter events as well as a portion of the liquid xenon volume to take advantage of xenon's self-shielding against gamma backgrounds. The LUX detector will contain 350 kg of liquid xenon (LXe) situated in an 8-m-tall, 6-m-diameter water shield in the Davis Campus of the Sanford Underground Research Facility at the Homestake Mine. The active region of the detector contains 300 kg LXe in a 59-cm-tall $\times$ 49-cm-diameter PTFE chamber viewed by 120 Hamamatsu R8778 2" PMTs. The PMTs have been shown to have quantum efficiencies surpassing 30%, and together with the PTFE reflective walls will permit a light collection efficiency in LUX at 10 phe/keVee (zero field). With this capability LUX will be competitive with other leading dark matter search experiments (see figure 1).

The LUX collaboration ran a prototype at Case Western Reserve University (CWRU), which is discussed below, and moved into a surface facility at the Sanford Lab in Lead, SD in Fall 2009. At this site the LUX detector was assembled and a first cooldown was carried out in May 2011, fully deployed into a two-story-tall water shield for these purposes. This first run of the detector was very successful and its results are also discussed in these proceedings.

2. Thermosyphon Cryogenics

To efficiently and economically cool the LUX detector we developed a unique cryogenic system based on thermosyphon technology [13]. Figure 2 shows drawings of the system. The thermosyphons consist of a sealed tube filled with a variable amount of gaseous nitrogen (N2), and are comprised of three regions: at the top a 15-cm-tall by 1.3-cm-diameter stainless steel (SS) cylindrical condenser which is immersed in a bath of liquid nitrogen (LN); at the bottom a 15-cm by 5-cm by 1.9-cm copper evaporator which is attached to the detector; and a passive adiabatic length made of meters of SS connecting the two active sections. Figure 2b shows a vertically-compressed draft of the LUX thermosyphon system, with the condenser sections immersed in the LN bath at the top, and the evaporators attached to the detector at the bottom. The whole system is located vertically since it works with gravity, and is closed and pressurized with N2. The N2 liquefies inside the condenser, trickles down the SS lines to the copper evaporators that are securely fastened to various points on the detector's inner can, syphons heat from the detector to boil and evaporate, rising back up the lines to the LN bath. As seen in the pressure data in red in figure 3, the pressure in the thermosyphons is below the equilibrium pressure just at the temperature of the evaporator. This condition and the large latent heat of the liquid nitrogen phase change allows for the highly efficient operation of the thermosyphon. The measured thermosyphon thermal conductivity is $55\ \mathrm{kW/K \cdot m}$, much higher than metals such as copper and comparable to carbon nanotubes at low temperatures (see [13] and references therein). This technology has demonstrated excellent efficiency in cooling as shown in blue in figure 3.

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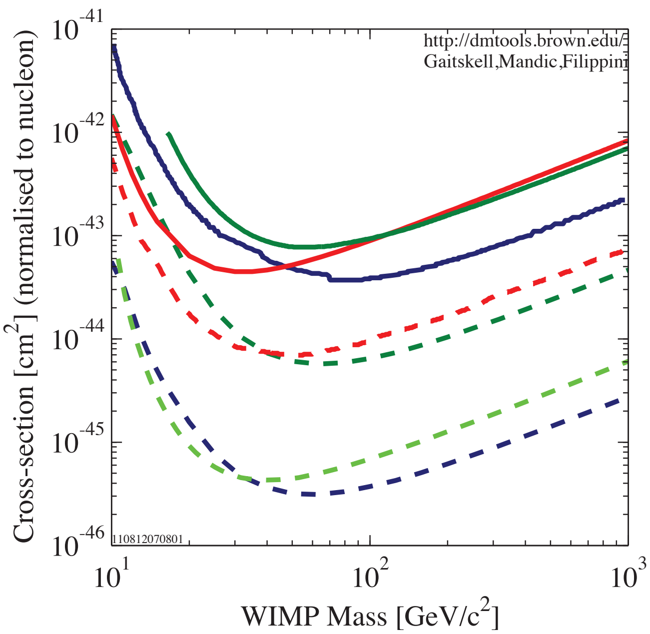
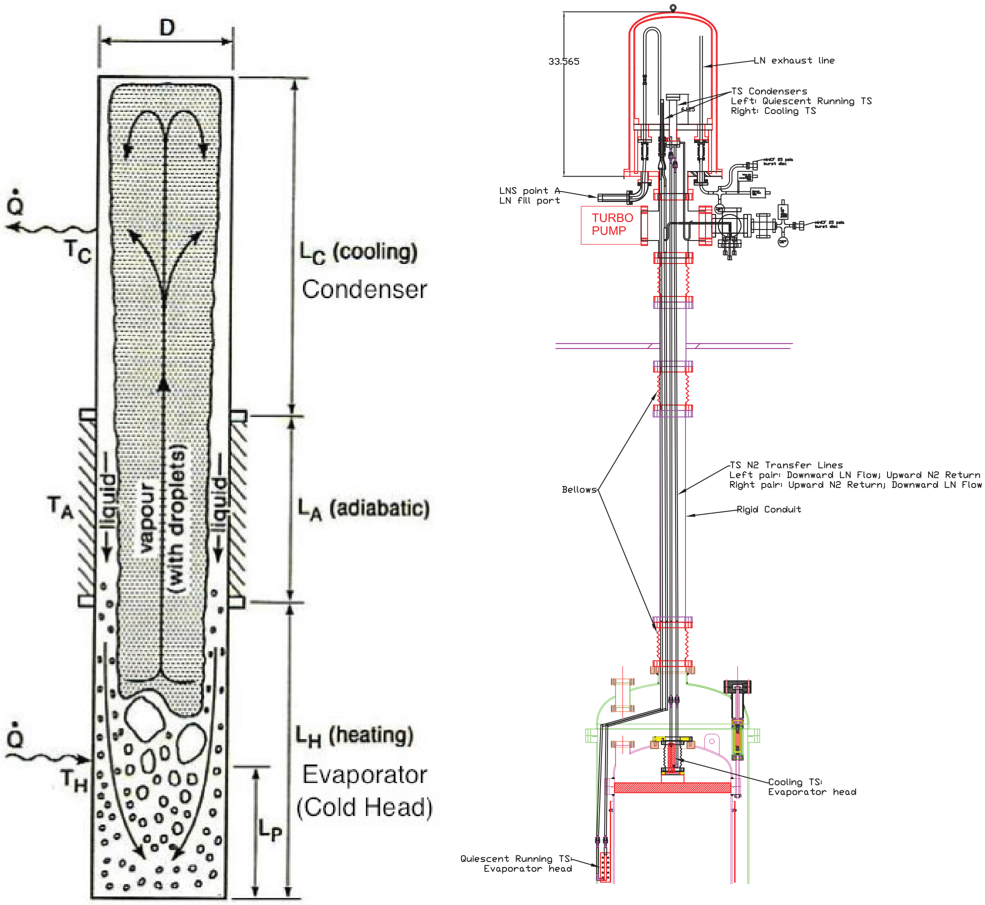


Fig. 1: The elastic scattering cross section for spin-independent couplings versus WIMP mass, showing leading experimental upper limits with solid curves reported by ZEPLIN-III (dark green) [10], CDMS-II (dark blue) [9], XENON10 (red) [8], and XENON100 (red dash) [11]. Experimental projections are shown for ZEPLIN-III yr. 3 (dark green dash) [12], SuperCDMS for seven super towers at SNOlab (dark blue dash), and LUX 300-kg for a 100-kg fiducial volume × 300 live days (green dash).



(a) Schematic of a thermosyphon. The condenser section is immersed in liquid nitrogen. The evaporator section is attached to the detector. The two are connected with a pair of meters of 3/8-inch-diameter stainless steel tubing. Taken from [14].

(b) A vertically-compressed sketch of the LUX thermosyphon cooling system.

Fig. 2: Concept sketch and construction draft of the LUX thermosyphon system.

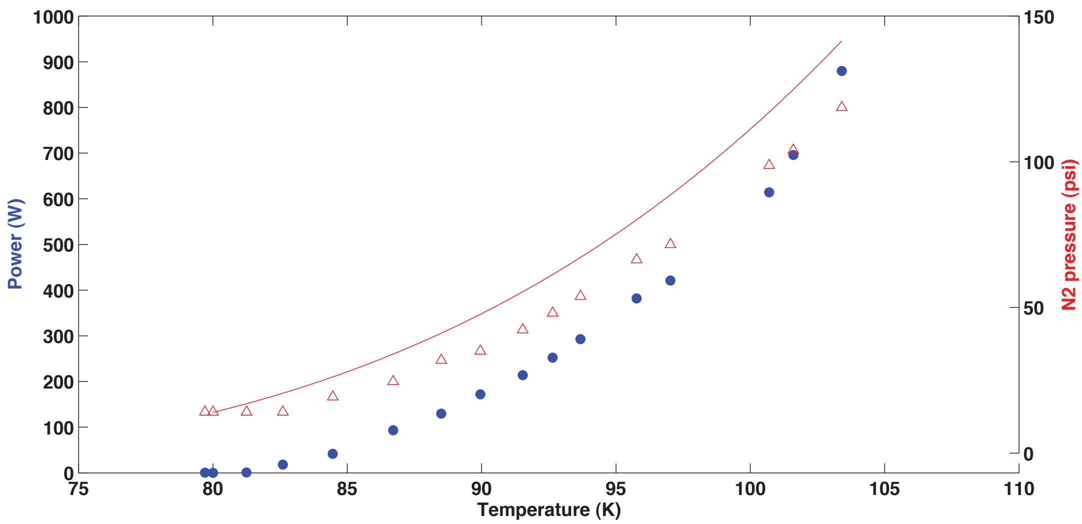


Fig. 3: The thermosyphon temperature (blue dots) and pressure (red triangles) are shown as a function of power applied to the evaporator. The vapor-liquid equilibrium pressure for nitrogen (red line) at the temperature of the evaporator is plotted for comparison. Data taken from [13].

The first surface run of the LUX detector in May 2011 successfully demonstrated the thermosyphon system as designed and implemented for LUX. Two individual thermosyphons are thermally connected to the detector internals via ports at the top and the bottom of the Xe can of the LUX cryostat. Using 20 liters of dry nitrogen gas to run each thermosyphon at a rate of 1 K/hr, the LUX detector was cooled to 180 K in one week. The cooling rate was limited by possible destructive thermal contraction of the large HDPE and PTFE panels in the detector, and the cooling rate used was well below the 500-W capability of the thermosyphon system. It is encouraging to see that our present system will be able to cool and stabilize the temperature of multi-ton xenon and scintillator detectors. During the cooling of LUX, the detector produced a 70-W heat load on the thermosyphon dewar liquid nitrogen supply. With the detector at180 K,the nitrogen in both thermosyphons was decreased and the 10-W PID heaters on each evaporator were turned on to provide a stable control of the detector temperature. Maintaining stable operation of the detector was a 10-W heat load on the thermosyphon dewar liquid nitrogen supply.

3. Circulation

The LXe in the detector needs to maintain high electron drift length so that WIMP interactions throughout the detector can be properly measured by the PMT arrays above and below the active volume of xenon. The need for this high purity requires constant circulation of the xenon through a heated getter. Economical purification technology only works in the gas phase, as does the mass flow controller (MFC) used to regulate the flow rate of the circulating xenon, and since liquid cryogen pumps are quite expensive, we circulate xenon through the detector, evaporating the outgoing LXe, purifying it in the gas phase, then recondensing it for use as the target medium. The simple circulation of LXe out of the detector and room-temperature gaseous xenon (GXe) back into the detector leads to a 9.8-W/slpm heat load, which at the target 50-slpm flow rate gives a 500-W heat load. This rate is necessary for a large scale experiment as the xenon in a 350-kg detector would be turned over in less than a day. As designed the LUX thermosyphons are able to match this heat load, but the liquid nitrogen costs would be prohibitive. To combat the heat load produced from

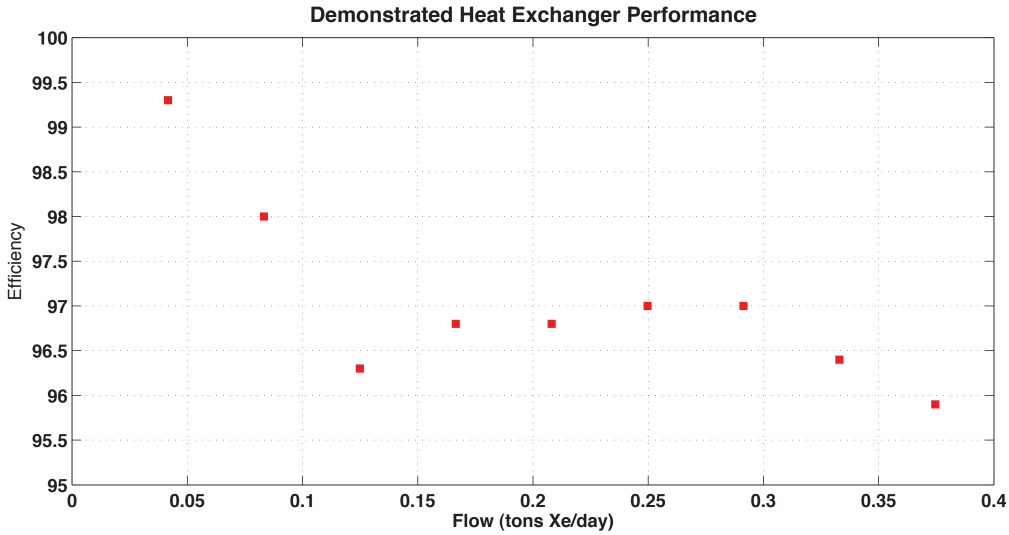


Fig. 4: LUX prototype heat exchanger efficiency as a function of flow rate in units of tons Xe/day (0.1 tons Xe/day = 12 slpm). Note that at all tested flow rates an efficiency > 95% was achieved.

maintaining this flow rate we designed a heat exchanger to allow the endothermic process of evaporation to pull heat from the exothermic process of condensation through a thin metal surface. After several iterations of heat exchangers we found a design that provided > 95% efficiency at high flow rates as seen in figure 4. Efficiency was calculated by measuring the heat load (change of rate of the temperature of the different parts of the detector mulitplied by their respective heat capacities) of the detector at a quiescent state, and then again at each flow rate up to 45 slpm once the change of rate of temperatures came to a stable equilibrium. A design based on the successful prototype is deployed in the LUX detector and will be used when a full LXe run of the detector take place at the Sanford Underground Research Facility. This design will be reported on in full detail in a forthcoming publication from LUX and is shown in schematic in figure 5.

4. Purity

The LUX prototype also tested ways to increase the speed and efficiency of purifying the xenon for use as a detector medium, especially for efficient charge drift over long distances [15]. We report the purity in terms of the exponential drift as the length ionized electrons drift from event sites in the LXe to the liquid-gas phase transition. The initial event creates a flash of primary scintillation light (called S1) of 175 nm. When electrons drift upward into the gas phase they cause a secondary light signal (called S2); purity is the exponential increase in the timing between these two signals as a function of the depth of the detector's active drift region. While xenon is a noble element and therefore incapable of conventional chemical interactions, its large size makes it easily polarizable and therefore is a rather strong solvent. Water vapor and O_2 are two possible impurities that can capture electrons drifting through the LXe. Organic solvents such as acetone and ethanol, which are used for parts cleaning, might also contribute to these impurities. To purify the LXe of these unwanted molecules, the LXe is pulled out of the active region of the detector, pumped through a heated getter (SAES MonoTorr), and reintroduced into the detector. The purity was measured by irradiating the active volume with radioactive sources via a SS 1.5"-diameter tube that came in from the outside to next

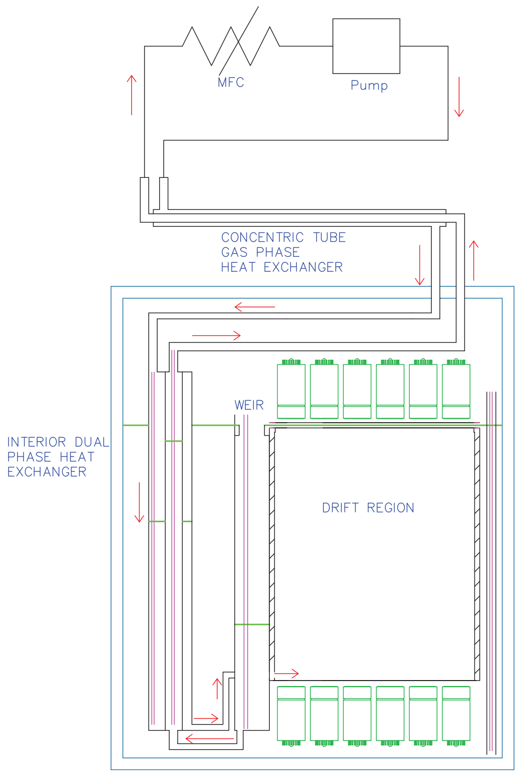


Fig. 5: Schematic of the LUX Xe circulation path including dual phase heat exchanger, gas-phase heat exchanger, and weir. The Xe liquid levels are in green; capacitive liquid level meters are in parallel pink lines; the Xe circulation path labeled with red arrows.

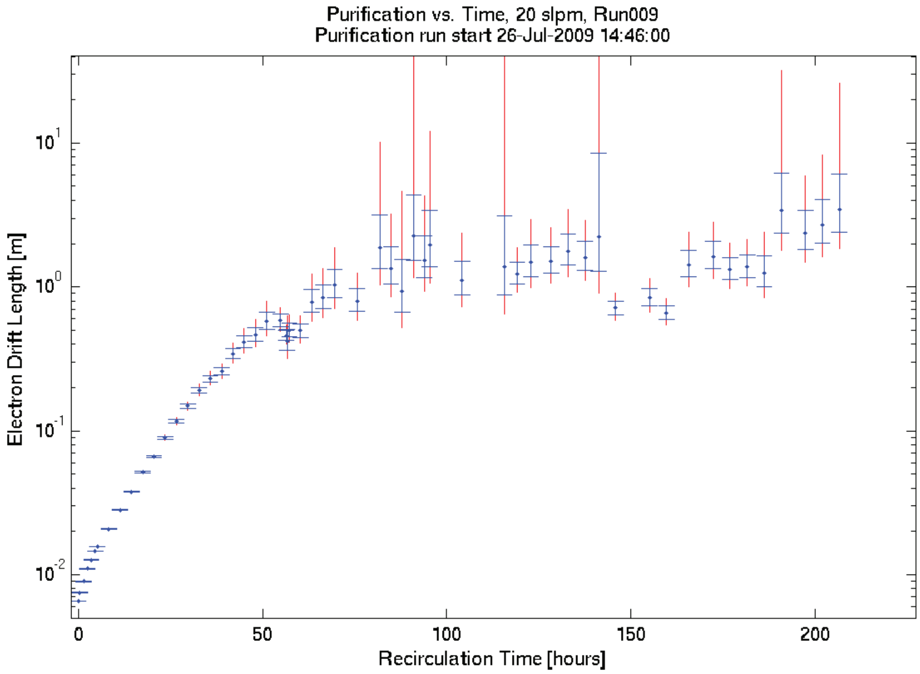


Fig. 6: Purity in LUX prototype. Blue error bars are 1-σ, red are 2-σ. After 200 hours of circulation through a heated getter there was an obvious plateau $\sim$ 2 m.

to the active region to allow sources to irradiate the active volume with minimum loss, as shown in figure 7. The closed circulation system, which includes the internal dual phase heat exchanger discussed above, circulated the xenon at 20 slpm and purified it to a drift length of over 1 m in just 200 hours of circulation, an unprecedented speed to achieve this purity level in a detector of this mass scale (see figure 6).

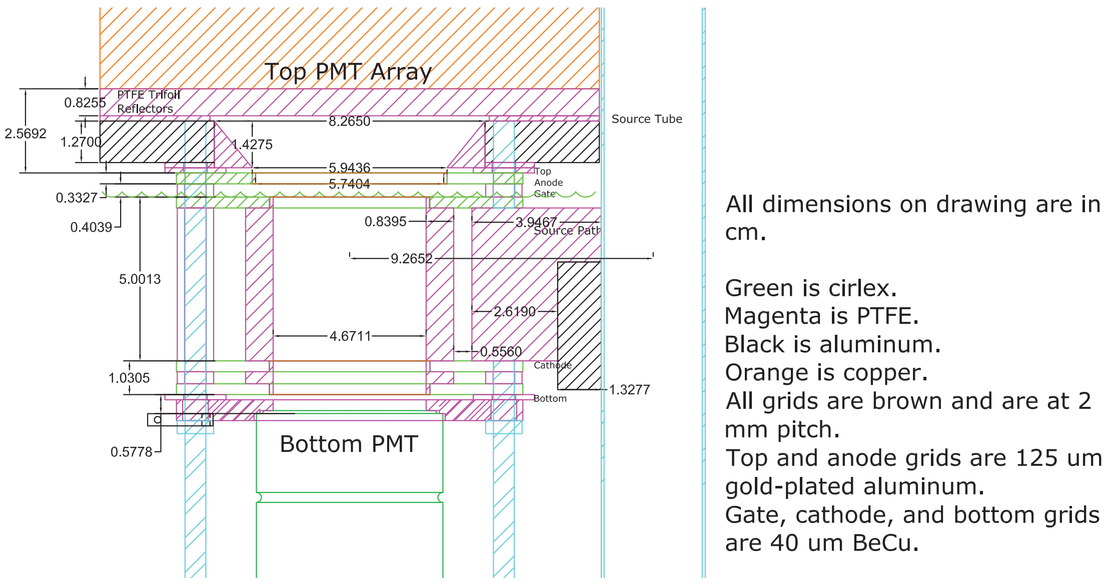


Fig. 7: A schematic of the LUX_0.1 active region. All dimensions in centimeters.

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