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Cryogenics for the LUX detector

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Abstract—**In this paper, we describe results on R&D of an economical and efficient cryogenic system for the LUX detector containing 300 kg liquid xenon (LXe) and operating at a temperature of 175K in a new WIMP dark matter search experiment to be carried out at the Homestake (South Dakota) gold mine. The cooling system consist the cold head attached to the thermal screen surrounding the detector, three thermosyphons filled with nitrogen and the free-boiling liquid nitrogen bath used as a cooling machine. The most powerful thermosyphon mounted directly onto the cold head has demonstrated >1 kW cooling power and has been used for initial cooling of the detector and xenon condensation. The second thermosyphon with ~0.2kW cooling power is mounted to the cold head through thermal impedance designed for stable operation of the detector when the condensation is completed. The third thermosyphon similar to the second one is connected to the bottom of the thermal screen to control the temperature gradient along the detector. Results of the first cold test are presented.**

Index Terms—**Liquid xenon, emission detector, WIMP, thermosyphon, heat pipe, cooling system, cooling power, thermal conductivity, thermal impedanc**

I. Introduction

THE LUX (Large Underground Xenon Detector) detector belongs to the next generation of large emission liquid xenon (LXe) detectors which will search for cold dark matter in the form of weakly interacting massive particles (WIMPs). The relatively small LXe emission detector XENON10 containing only 26 kg LXe has recently delivered the best limit on the existence of WIMPs [1]. The LUX detector consists of a cylindrical vessel of 0.61-m diameter and 1.2-m depth containing 300 kg of liquid xenon (LXe) and enclosed in a copper thermal screen and vacuum jacket. The large size of the detector provides much efficient self-shielding from the natural radioactivity of surrounding materials that significantly increases the sensitivity of the experiment. The detector will be immersed ~2m inside a ~200-ton water shielding bath suppressing neutron and gamma ray background coming from walls of the deep underground cavern at the Homestake gold mine in South Dakota.

In the past, several different types of cooling systems have been used to support the operation of large LXe detectors. For example, LXe bubble chamber DIANA containing 800 kg LXe at -20^{o}C temperature and 3 MPa pressure was cooled with antifreeze circulating between a heat-exchanger embodied into the detector walls and an industrial Freon refrigerator [2]. In 130-kg LXe scintillation calorimeter LIDER, a combination of a cold nitrogen gas bath and several heaters have been used to operate the detector at normal pressure and temperature gradients <1 K [3]. In the recent dark matter experiment, XENON10, a 26-kg LXe detector, has been cooled with a cold head of the Pulse Tube Refrigerator engine directly installed into the detector vessel (see [1] and references therein).

In this paper, we describe results of R&D on economical and extremely efficient cryogenic system for the LUX detector. The system is compact, free from mechanical vibrations and can very effectively “pump out” heat from the detector located in the middle of the 5-m deep water bath. The LXe in the detector will be operated at temperatures of 170 - 185 K. The cooling power is a bath of free-boiling liquid nitrogen. Heat exchange between the detector and liquid nitrogen bath is provided with three thermosyphons.

II. Thermosyphon based cooling system

Tubular thermosyphons are devices with extremely high effective thermal conductivity that can be easily turned on or turned off by pressurizing or de-pressurizing with nitrogen gas. The two-phase liquid/gas nitrogen filling is used to transfer heat in closed loop inside the tube under pressure slightly exceeding atmospheric pressure.

A. Principle of Operation of Gravity-Assisted Heat Pipes

The thermosyphon or gravity-assisted heat pipe consists of three sections (Fig.1, [4,5]): the condenser section (1) located above the evaporator section (2) and the passive adiabatic section (3) connecting the two active sections. The nitrogen condensate generated in the condenser section falls down to the evaporator, where the liquid absorbing heat is boiling. During this phase transition, the fluid picks up the heat for vaporization (Table 1). Because the vapor is at higher temperature (and lower density) than the gas condensing in the condenser, the vapor rises to the top condenser section. In the condenser, the arriving relatively hot gas returns the latent heat of vaporization to the cooling machine and re-condenses, and the heat transfer cycle repeats. Since the operation of the thermosyphon relies upon the gravitational force, the evaporator must be located below the condenser. Alternatively, a wicking structure can be used to stimulate proper liquid circulation; this is termed a heat pipe. In this project, a

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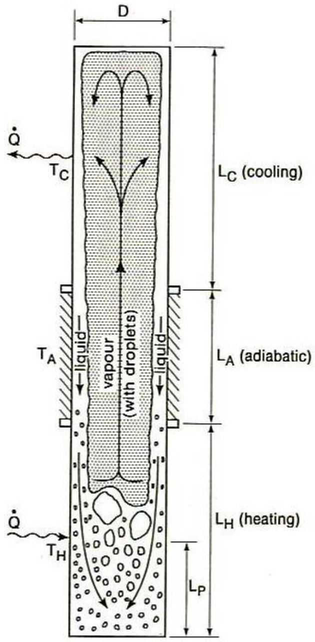


Fig. 1. Thermosyphon principle of operation [4]

separating tube has been installed inside the thermosyphon in order to p revent interaction between the returning gas flow and the liquid flow directed oppositely.

The thermosyphon has the advantage of low cost, compactness, short time required for cooling and heating, extremely high thermal conductivity, low heat capacity, and long-term stable operation. For cryogenic operations, a few normal gases can be chosen to fill thermosyphons depending on target temperature and preferable cooling technique. In our project, we have selected nitrogen due to its low cost, wide availability and non-flammability and a free-boiling liquid nitrogen bath, in which the condenser is immersed as a cooling machine. As seen from Table 1, nitrogen can be used in thermosyphons with the condenser section operating in the temperature range between 63.15K (78K with free-boiling liquid nitrogen cooling machine) and 126K.

TABLE I
CHARACTERISTIC DATA OF THE GASES FOR CRYOGENIC THERMOSYPHONS

Gas	Triple point			Critical point			*L*, J/g
	T, K	*p*, bar	d_{liquid}, g/cm^3	*T*, K	*p*, bar	*d*, g/cm^3	
H_2	13.95	0.072	0.0775	33	12.98	0.031	445.3
D_2	18.73	0.171	0.1732	35.2	16.65		303.9
N_2	63.15	0.125	0.858	126	34.00	0.314	198.4
CH_4	90.65	0.117	0.445	190.7	45.8	0.162	509.4

L - latent heat of vaporization at normal pressure

B. Requirements

The cryogenic system must efficiently and economically provide a stable ~180K environment free of temperature gradients and mechanical vibrations. These two requirements are important for effective light collection from bulk LXe samples and through the free liquid surface. The system must also have very low radioactivity burden near the detector.

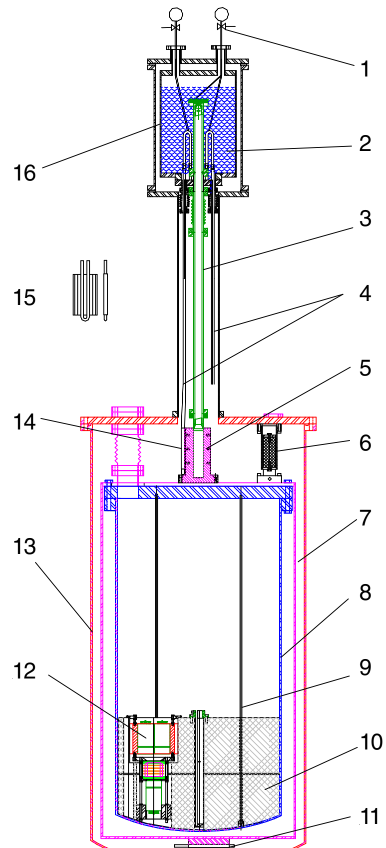
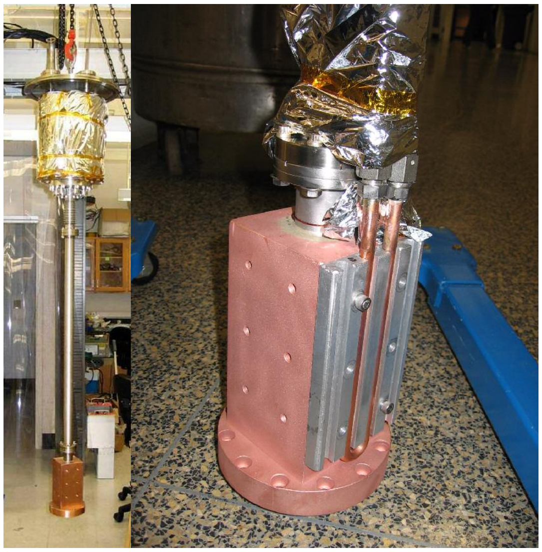


Fig. 2. LUX prototype cryostat with installed detector LUX-0.1 and thermosyphons: 1 – nitrogen gas supply line; 2 – liquid nitrogen bath; 3 – thermosyphon TS1; 4 – pipe-lines for thermosyphones TS2 and TS 3; 5 – cold head; 6 – support of the cold vessel inside the vaccum vassel; 7 – copper thermal screen; 8 – LXe cold vessel; 9 – support structure; 10 – aluminum filler; 11 – thermosyphon TS3; 12 – LUX_0.1 detector; 13 – vacuum vessel; 14 – thermosyphon TS2; 15 – cold plate; 16 – liquid nitrogen Dewar.

C. Architecture of Cooling System

The cooling system (Fig.2) consists of a massive cold head (5) made of oxygen-free copper and attached to the copper thermal screen (7) surrounding the detector vessel (8), two thermosyphons attached to the cold head (3, 14) and one thermosyphon (11) attached to the bottom of the thermal screen (7). The thermal load on the thermal screen from both radiation and gas is reduced by high-vacuum superinsulation (not shown in Fig.2). One of the thermosyphons (TS1 shown as 3, Fig.2) is a main cooling element used for initial cooling of the detector and condensation of xenon. TS1 is mounted directly into the cold head. Two additional thermosyphons (cold plates) TS2 and TS3 are attached with a thermal impedance and used as assisting cooling elements in order to support stable operation of the detector after LXe condensation is complete. The thermal impedance is a Teflon sheet with thickness of 6 mm selected so that the detector operates at its desired temperature when subjected to a modest ~50W heat load that results from radiation and gas heat loads from the outer vacuum can (13) and mechanical supports (6) and an additional electrically supplied control power. An



(a) (b)

Fig. 3. TS1 thermosyphon attached to the Dewar and to the cold head (a) and the cold head with TS1 installed and TS2 attached (b)

additional cold-plate thermosyphon TS3 and impedance are deployed at the bottom of the thermal screen allows us to set the temperature at the bottom of the thermal screen below the temperature at the top, aiding in establishing a stable thermal gradient in the liquid (with the coldest liquid at the bottom).

D. *Power Thermosyphon*

The power thermosyphon TS1 is a 3.8 cm diameter and 1.37 m long straight tube. The condenser section located inside the liquid nitrogen Dewar is 30-cm long; a half of this section is made of a bellow in order to improve the heat exchange between the condensing nitrogen gas inside the TS1 and the boiling liquid nitrogen in the Dewar. The adiabatic section is made of a stainless steel tube. The 18-cm long evaporator section is embodied into the cold head. Installed inside TS1 is a tube of 2.5 cm diameter with a nozzle on the bottom edge separating the falling liquid and the rising gas. A nitrogen gas feeding tube is connected to the TS1 through the Dewar (1, Fig.2). A general view of the TS1 attached to the Dewar (top) and the cold head (bottom) is shown Fig.3a. The cold head in assembly with TS1 main thermosyphon and the TS2 cold-plate thermosyphon is shown in Fig.3b.

E. *Assisting Thermosyphons*

TS2 and TS3 thermosyphons are both closed loops each made of a combination of 9.5-mm diameter stainless steel and copper tubes. Evaporator sections of TS2 and TS3 are commercially available cold plates (15, Fig.2) made of copper U-tubes impressed into the aluminum plates of 8.9x15x1.3 cm^3 overall dimensions (*CP10 2-pass cold plates* made by Lytron Inc.). The TS2 evaporator is attached to the cold head with a Teflon 6-mm thick plate playing a role of thermal impedance; the TS3 is attached with the same impedance to the bottom of the copper thermal screen. The condensers of these thermosyphons are 9.5 mm diameter copper U-tubes installed inside the Dewar (16, Fig.2). Nitrogen gas feeding tubes are passed to the TS1 and TS2 through the liquid nitrogen Dewar as shown in Fig.2.

III. Results and Discussions

The LUX cooling system has been tested to operate the full-scale LUX prototype cryostat installed at Case Western Reserve University. The cryostat is being used to test LUX-0.1, a two-phase emission prototype detector operating with 1 kg of LXe. The sample of LXe is viewed by three 50-mm diameter photomultipliers Hamamatsu R8778 placed in the gas phase above the liquid and one similar photomultiplier submersed into the liquid. Principle of the emission detector operation is described elsewhere [11]. The prototype detector was installed inside a massive (260 kg) aluminum displacer in order to mimic the mass of LXe working medium of the LUX detector (Fig.2).

A. *Thermal Conductivity*

The thermosyphon begins operating as soon as the condenser section is cooled down and the pressurized nitrogen gas is added. After stabilization, the gas pressure inside the thermosyphon depends mostly on the temperature of the evaporator section: the higher operating pressure responds to the higher temperature of the cold head. The cooling power of the power thermosyphon TS1 was measured with the cold head (decoupled from the rest of the detector assembly) and power provided by a 1-kW heater on the cold head. Fig. 5 shows the resulting stable operating temperature versus applied power. For example, at 880-W heat load, the temperature of the cold head was stabilized at 100K, and the pressure inside the thermosyphon was measured to be 0.81 MPa (117 psi). The pressure inside the thermosyphon is well correlated (roughly ~15% lower) with the vapor-liquid nitrogen equilibrium pressure associated with the cold head (evaporator) temperature as shown by the dashed line in Fig. 4.

The thermosyphon works as an efficient heat conductor. The rate of heat flow through the thermal conductor (cooling power) $\boldsymbol{W}$ is proportional to the cross section area of the conductor $\boldsymbol{A}$ and the temperature gradient $\Delta\boldsymbol{T}$ along the conductor length $\boldsymbol{L}$:

$$\boldsymbol{W = \Delta Q/\Delta t = k\cdot A\cdot(\Delta T/L)} \quad (1)$$

where proportionality factor $\boldsymbol{k}$ is the thermal conductivity of the thermosyphon. Taking into account the parasitic (passive) heat load through the cryostat, $\boldsymbol{W_0}$, we can define the thermal conductivity from (1) as

$$\boldsymbol{k = (W + W_0)\,(L/\Delta T\cdot A)} \quad (2)$$

Under the assumption that the thermal conductivity of the thermosyphon is temperature independent in the range of 80-100K, from Fig.4 we can derive $\boldsymbol{W_0}$ =100W and an effective thermal conductivity of $\boldsymbol{k}$ = 55 kW/K·m for TS1. The found value is much higher than the thermal conductivity of metal heat conductors such as copper and is comparable to the thermal conductivity of the carbon nanotubes at low temperatures (see Table II and references therein). In solid media the highest thermal conductivities are associated with the largest phonon mean free paths which achieve ~1μm in the best cases. By contrast, free-falling liquid and rising jets of the evaporated nitrogen provide effective heat transfer with a mean free path of about the smallest dimension (diameter) of the thermosyphon which is about 1cm.

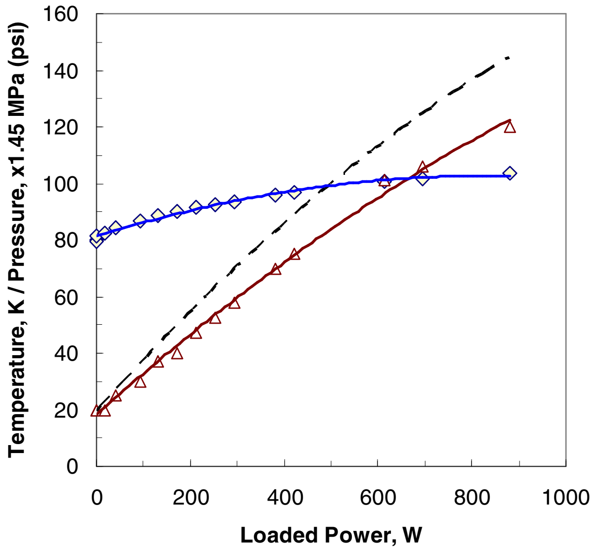


Fig. 4. Temperature (diamonds) of the cold head cooled by TS1 thermosyphon, the gas pressure (triangles) inside TS1 and the vapor-liquid equilibrium pressure for nitrogen (dashed line) at the temperature of the cold head, all as a function of the electrical power applied to the cold head

TABLE II
THERMAL CONDUCTIVITY OF SELECTED MATERIALS

Material/Device	Temperature, K	Thermal conductivity, W/K·m	Reference
Teflon	165	0.265	[10]
Aluminum (pure)	293	237	[9]
Copper (pure)	293	353-386	[9]
Diamond (synthetic)	293	2000-2500	[9]
Carbon nano-tubes	100	37000	[7]
TS1	80-100	55000	This work

B. *Temperature Stabilization*

The assisting thermosyphons TS2 and TS3 have demonstrated cooling powers of about 200 W under conditions similar to the TS1 test described above. The common cooling power of the thermosyphons is estimated to be sufficient to compensate the parasitic heat load from the cryostat to the detector when using with 6-mm thick Teflon thermal impedance. Fine-tuned temperature stability is provided by PID control of low-power (50W) heaters installed on the thermal screen in the vicinity of the cold plates.

C. *Testing the System*

The cooling system has been tested in the cooling of the LUX prototype cryostat with the LUX-0.1 detector installed. It was found that the thermosyphon cooling system can cool down the LUX cryostat itself for a few hours, with about 12 hours needed to cool the LUX-0.1 detector with 260 kg massive aluminum filler. Stability in the range of 168-170 K was achieved during two-weeks of non-stop operation.

IV. Conclusion

We have shown that the cooling system based on thermosyphon technology can support the operation of massive LXe detectors. The system provides condensation of a large mass of xenon and stable operation temperatures with minimum operation management. This system exhibits extremely high thermal conductivity comparable to that of carbon nanotubes. Further, the simple construction and remote cooling ability of this system is important for low background experiments such as LUX where the detector is operated remotely inside a shield, and the radioactivity of all materials near the detector must be minimized.

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