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Development of a large volume zero boil-off liquid xenon storage system for muon rare decay experiment (MEG)

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ABSTRACT

We have developed a new type of photon detector for an experiment aimed at searching for the lepton flavor violating decay $\mu^+ \rightarrow e^+\gamma$. In this experiment, a total of 900 L of liquid xenon is used in order for the scintillation detector to detect γ-rays with an extremely high sensitivity, where the liquid xenon is viewed by an array of 846 photomultipliers from all sides. The entire amount of xenon should be stored in certain storage systems before the start of the experiment, during detector maintenance in the period of accelerator shutdown, etc. We have developed a new liquid xenon storage system by employing the zero boil-off condition by using a pulse tube cryocooler. The details of system and its performance results are described in this article.

1. Introduction

The MEG experiment is an experiment aimed at searching for a lepton flavor violating muon decay, i.e., $\mu^+ \rightarrow e^+\gamma$ decay [1]. Gamma rays are detected by a liquid xenon (LXe) scintillation detector, which has a good performance that is attributed to its high light output and fast response. We employ 900 L of LXe viewed by 846 photomultipliers (PMTs) from all sides. A xenon storage system requires a high level of cleanliness, which is directly correlated with detector performance; it is also required to be airtight in order to avoid any loss of expensive xenon during the entire experiment. A zero boil-off control system is highly desirable for satisfying such requirements.

Gaseous and liquid phase purification systems have been developed to remove water and oxygen contaminations that can cause the absorption of LXe scintillation light [2–4]. We have developed two types of storage systems for this experiment. One is a gaseous xenon (GXe) storage tank and the other is a LXe cryogenic tank. The GXe storage tank can store GXe at room temperature for a long period, without requiring any control. The LXe cryogenic tank is used for the purposes of a temporal transportation of LXe during detector maintenance, a quick recovery of LXe from the detector in the case of an emergency, and so on, because the transfer of LXe is considerably faster than that of GXe. Our group has specifically developed and optimized a cryocooler for the cooling of LXe in the LXe cryogenic tank [5,6]; this cryocooler can maintain xenon in the liquid state. The zero boil-off condition is imposed on stored LXe by means of the cryocooler and a simple well-insulated tank. Liquid transfer from the LXe cryogenic tank to the detector is achieved by making use of a pressure difference through vacuum-insulated pipes and that from the detector to the LXe cryogenic tank is achieved by making use of a cryogenic centrifugal pump [4]. The transfer of GXe from the GXe storage tank to the LXe cryogenic tank (liquefaction) is achieved by utilizing the pressure difference; GXe is continuously cooled by the cryocooler or liquid nitrogen (LN_2).

The construction of the LXe detector has been completed. Prior to the physics experiments, xenon gas was liquefied and stored in the LXe cryogenic tank; subsequently, for more than 6 months, LXe was maintained stable in the liquid state and was subjected to the zero boil-off condition. In this study, the entire xenon storage system is briefly summarized and recent results of the system operation are reported.

2. Purpose

Xenon gas can only be produced as the side product of an air separation plant. The concentration of xenon gas in air is 0.086 ppm.

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Therefore, the amount of liquid xenon produced annually is limited; consequently, it is very expensive.

In the MEG experiment, 900 L of LXe is required in a gamma detector. LXe temperature should be maintained at 165 K during normal operation. Two storage methods have been developed for the xenon operation in the MEG experiment. The first method involves the use of several GXe storage tanks, and the second involves the use of a cryogenic LXe cryogenic tank. The purpose of the GXe storage tanks, each of whose volume is 250 L, is to maintain GXe at room temperature without using any cooling system. This tank is mainly used during no detector operation, long-term shutdown of the accelerator, and so on. GXe is expected to be stored under a supercritical condition at a pressure of more than 6 MPa; under this condition, the pressure does not increase much even if the density increases, but it strongly depends on the temperature. We maintain the density of the GXe tank at up to a maximum value of 1.44 g/cm^3, with 360 kg of GXe (which is equivalent to 120 L of LXe) in each GXe tank. Eight tanks that can tolerate a high pressure of up to 8 MPa are prepared for this purpose. In total, 960 L of xenon can be stored in these GXe tanks.

The purpose of the LXe cryogenic tank is to maintain the entire amount of xenon gas (~900 L) in the liquid state at 165 K and 1 bar. This LXe cryogenic tank is used as a temporal storage tank during γ-ray detector maintenance and as a quick recovery tank in the case of an emergency in the detector. Ultrapure LXe is used in the γ-ray detector and for preventing the contamination of LXe by impurities. A high cleanliness should be maintained in the storage tanks; further, they should be airtight in order to prevent leakage.

Fig. 2. GXe storage tank.

Fig. 3. LXe cryogenic tank with gas purification system.

3. System

The entire xenon storage system consists of eight GXe storage tanks, a gas purification system, and an LXe cryogenic tank, as shown in Fig. 1. A purification system is installed between two storage systems in order to purify GXe when it is transferred from the GXe storage tanks to the LXe cryogenic tank or to the detector. Fig. 2 shows a photograph of the eight 250 L GXe storage tanks placed in the experimental area. Fig. 3 shows a photograph of the zero boil-off LXe cryogenic tank. The right-hand side of the photograph shows the purification system. The specifications of the LXe cryogenic tank are summarized in Table 1.

The LXe cryogenic tank is a usual double-walled vessel with a vacuum insulation. The volume of the inner vessel is 1110 L, and the maximum storage capacity is 1000 L. A pulse tube cryocooler and a LN_2 cooling pipe are mounted at the top of the tank flange for carrying out the liquefaction and recondensation of xenon gas. LN_2 cooling is employed when rapid liquefaction is required and in the case of an electric power failure. For measuring the level of LXe, a capacitance level meter is installed (AMI, model 185). The LXe temperatures can be measured by five Pt-100 sensors located at various heights of the LXe cryogenic tank.

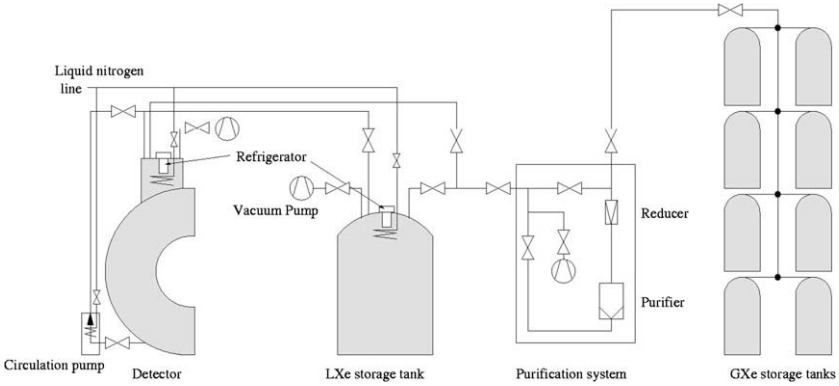

Fig. 1. Xenon storage system.

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Table 1
Specifications of LXe Dewar

Dimensions	∅1400 × 2570 mm^2
Volume	1110 L (max storage 1000 L)
Design pressure (DP)	0.6013 MPa
Hydrostatic test pressure	0.91 MPa (1.5 × DP)
Air test pressure	0.67 MPa (1.1 × DP)
Design temperature	77–313 K
Operation temperature	165 K
Material	SUS304
Designed incoming heat	<20 W
Inner surface treatment	Polishing

The pulse tube cryocooler is used to achieve the zero boil-off condition of the LXe cryogenic tank. The cryocooler is of the same type as that used in the LXe detector [5,6]. The cooling power is nearly 200 W at 165 K, obtained using a 6 kW Gifford–McMahon (GM)-type helium compressor. Since there is no mechanically moving part in the low-temperature stage, the vibrations induced by this cryocooler are small, and its long-term operation is highly reliable and free of any electrical noise that could affect the monitoring system or the experimental measurement. The cold head temperature is maintained constant at around 165 K by the use of a MINCO heater which is attached on the coldhead. Its heating power is controlled by the coldhead temperature or the pressure of inner vessel. The main role of another heater which is attached at the bottom of the LXe cryogenic tank is to assist in the vaporization of LXe for recovering the entire amount of LXe to the GXe storage tanks.

A high-temperature getter [7] is mounted in the purification system. The getter removes H_2O, O_2, CO, CO_2, H_2, N_2, and CH_4 from GXe, down to the level of parts per billion. A total of 100 L of xenon is purified by using a purifier similar to that used in Refs. [2,3]. It is confirmed that the impurity, which is mainly water, is successfully reduced by monitoring the absorption length of the liquid xenon, and an adequate performance of the MEG photon detector is achieved. To evaluate and monitor light absorption in LXe, cosmic ray muons as well as the α sources installed in the LXe detector were used [2,3].

The entire system is controlled by in-house electronics by using the MSCB [8] system. A control node connected to the MSCB bus has a microcontroller that incorporates DACs, ADCs, IO ports, and a relay, and the node controls the system by proportional–integral–derivative (PID) control, which is a generic control loop feedback mechanism widely used in industrial control systems. The control node handles the opening/closing of valves and the turning on/off of equipment, and it acquires the system status. Firmware has been specifically developed for this xenon storage system. Algorithms for controlling the cryocooler, heaters, and valves in PID loop are written in the microcontroller. The variables of the firmware can be written through an MSCB bus in order to permit the changing of control parameters for controlling the system without interrupting the operation.

The status of the system is monitored by using LabVIEW [9] panels running on a remote computer, as shown in Fig. 4. The panels are programmed to show the status graphically, to change the control parameters, and to use an alarm system. The control nodes are connected to a computer over Ethernet or by USB by using MSCB bus adapters. The system is not affected even if the computer on which the LabVIEW program is running has some problem, because the algorithms and all variables are written on the memory of the microcontroller in the control node and LabVIEW is only the interface to the control node. To prevent the freezing of LXe, refrigerator and LN_2 operation will be stopped when the pressure is under a certain limit. An alarm system is implemented

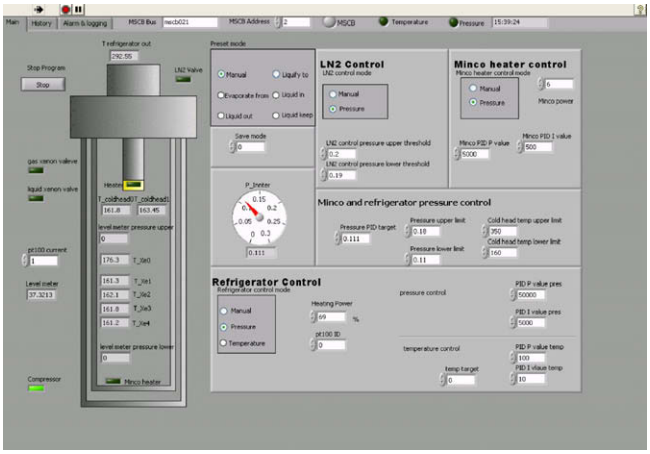

Fig. 4. LabVIEW panel for monitoring.

in the LabVIEW panels so that alerts are sent to mobile phones when the pressure of the LXe cryogenic tank or the temperature of LXe increases beyond a certain range or when the connection between the computer and the control nodes is lost. This function is available only when LabVIEW is running. The status of almost all valves can be changed through the panel; therefore, the storage system can be controlled fully and remotely even when the beam area is inaccessible.

The xenon gas in the GXe storage tanks can be transferred to the LXe cryogenic tank or to the detector by making use of the pressure difference. When GXe is transferred to the LXe cryogenic tank, GXe is continuously liquefied in the LXe cryogenic tank, and the pressure is maintained at around 0.1 MPa. Xenon can be transferred until equilibrium is achieved between the pressures of the LXe cryogenic tank and GXe storage tanks; approximately 1.5 kg GXe remains in the GXe storage tanks. The LXe cryogenic tank is connected to the detector by vacuum-insulated pipes in order to transfer LXe by making use of the pressure difference. The rate at which xenon is transferred in the gaseous state is limited by the cooling power required for the liquefaction of xenon. While the MEG experiment is in progress, xenon is stored in either the detector or the LXe cryogenic tank. However, when the experiment is paused for a long period, such as during a detector upgrade, xenon is stored in the GXe storage tanks because no control system or electric power is required. In order to recover xenon to the GXe storage tanks, they are cooled by filling LN_2 into the open Dewar surrounding the GXe tanks, and the LXe cryogenic tank is pressurized up to 0.18 MPa by using the heaters installed at the bottom. Then, evaporated xenon is transferred to the GXe storage tanks and solidified continuously. After recovering the entire amount of xenon from the LXe cryogenic tank and after the valves of the GXe storage tanks are closed, it is no longer necessary to cool the GXe storage tanks. Assuming that the temperature of the xenon gas inside the GXe storage tanks becomes sufficiently low (less than 100 K), the amount of xenon remaining in the LXe cryogenic tank can be expected to be negligible.

4. Results

This section summarizes the performance of the LXe cryogenic tank. All GXe storage tanks are connected to the LXe cryogenic tank, and the gas purification system, placed between these two storage systems, purified GXe prior to liquefaction. After all connections are established, each storage tank and its related pipes are evacuated up to 5×10^{-5} Pa. Then, 0.2 MPa GXe is transferred to the LXe cryogenic tank in order to start precooling the tank by using the cryocooler.

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First, we wanted to ensure the functioning of all sensors, the cryocooler, LN_2 line, and the heaters used for temperature control in the LXe cryogenic tank; we also wanted to ensure that some amount of LXe could be maintained stable by using our slow control system and that LXe could be successfully recovered to GXe storage tanks. To ensure that these conditions are satisfied and to gain practical experience, we attempted the liquefaction of 120 L of xenon in 2005. Gas purification was also carried out. Approximately 5 days were required to liquefy 120 L of xenon. The rate of liquefaction of GXe was 20–36 L/min, and the pressure of the tank was maintained at less than 0.2 MPa. Then, LXe was maintained stable by controlling the cryocooler and heaters. LXe was continuously evaporated by the incoming heat from the heaters, and the resultant xenon was recondensed by the cryocooler. We succeeded in maintaining a stable pressure for 3 days and with a variation of up to 0.1%, and achieved the zero boil-off condition.

The MEG experiment utilizes a COBRA magnet to measure positron momentum. This magnet induces a magnetic fringe field of the order of several tens of gauss at around the LXe cryogenic tank. We have confirmed the adequate performance of both the slow control system and the cryocooler under such a magnetic field.

We resumed the liquefaction of a large amount of LXe and the testing of the long-term stability of the LXe cryogenic tank. The procedure for carrying out liquefaction was the same as that employed previously. The flow rate was 25 L/min; therefore, LN_2 was supplied continuously. For safety reasons, at a time, the xenon gas stored in only one GXe storage tank was liquefied. The pressure buildup rate of the LXe cryogenic tank was measured each time following the completion of the liquefaction of the xenon gas in each GXe storage tank, by turning off the cryocooler. The pressure buildup rate for 100–900 L of LXe was constant in the range 0.002–0.003 MPa per hour. Fig. 5 shows the pressure buildup of the LXe cryogenic tank containing 900 L of LXe as a function of time when the cryocooler is turned off. After 43 h, the pressure increased to 0.2 MPa from 0.11 MPa, and the cryocooler was turned on. This result implied that the cryogenic tank could hold LXe for a certain period without requiring cooling. The LXe level in the LXe cryogenic tank was measured by three methods. The first method involved the use of the integrated flow rate of a GXe mass flow meter during liquefaction from GXe storage tank to LXe cryogenic tank, the second method involved the use of a commercial capacitance level meter installed inside the LXe cryogenic tank, and the third method involved the use of the Pt-100 temperature sensors installed at five different heights of the LXe cryogenic tank.

Fig. 6 shows the flow rate over the entire liquefaction period, together with a histogram; the LXe level variation in the LXe cryogenic tank is also shown. Since the commencement of the liquefaction process, for approximately a month, liquefaction was carried out at an almost constant flow rate (25 L/min), as mentioned previously. After a month, the flow rate was reduced to 10 L/min. Liquefaction was carried out during daytime and was paused at night. Overall, around 900 L of xenon from eight GXe storage tanks was liquefied to the LXe cryogenic tank in approximately 2 months. After the completion of liquefaction, LXe was maintained stable for more than 4 months. In order to measure the heat load of the cryogenic tank under this stable condition, we measured the increase in the LXe temperature by turning off the cryocooler. It was found that the temperature increase was in the range 3–5 K per 45 h, which corresponded to an incoming heat of 20–30 W. The design value of the incoming heat for this storage tank was 20 W, which was almost consistent with the test result.

Fig. 7 shows the temperature and pressure changes as a function of time. The five Pt-100 temperature sensors were installed at various heights in the LXe cryogenic tank (131.5, 100.3, 69.1, 37.9, and 4.1 cm from the bottom). The upper graph in Fig. 7 shows one example of temperature changes, which corresponds to the sensor at a height of 100.3 cm. The LXe temperature is around 160 K at around 0.11 MPa, and a temperature gradient can be observed in the gaseous phase region. The Pt-100 sensor at a height of 131.5 cm is still in the gaseous phase, whereas the others are already in the liquid phase. Once a Pt-100 sensor is immersed in the LXe, the temperature of the sensor drops immediately. Thus, the height of the liquid level can also be known. The bottom graph in Fig. 7 shows the pressure of the LXe cryogenic tank. The pressure is maintained in the range from 0.11 MPa to 0.2 MPa throughout the liquefaction process. There are several instances of rapid increases both in the tank pressure, and the temperature sensors; these changes occur when the cryocooler is turned off.

After liquefaction, we used two techniques to maintain stable LXe. The first technique was to maintain the pressure of the cryogenic tank constant to 0.11 MPa, and the second technique was to maintain the inner pressure in the range from 0.11 MPa to 0.2 MPa. The first technique was implemented by turning on the cryocooler normally and repeatedly turning on and turning off the heater surrounding the cryocooler. As a result, the variation in the pressure of the storage tank was less than 0.1%. The second technique was

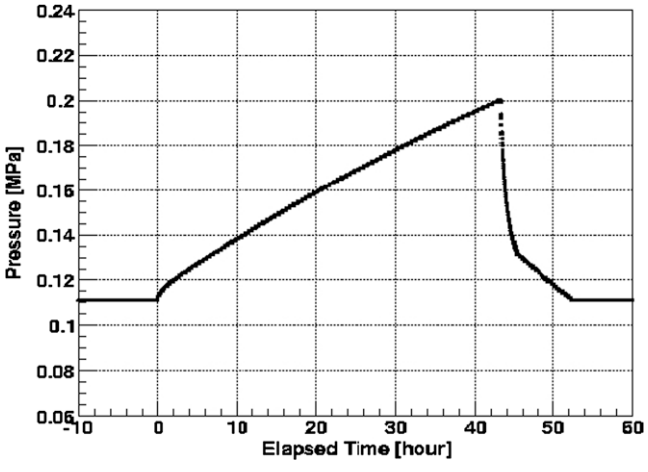

Fig. 5. Increase in pressure of cryogenic tank comprising 900 L of LXe after termination of operation of cryocooler.

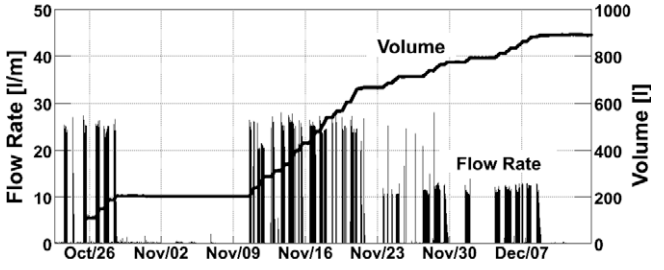

Fig. 6. Flow rates for each period during which liquefaction is carried out and volume of stored LXe.

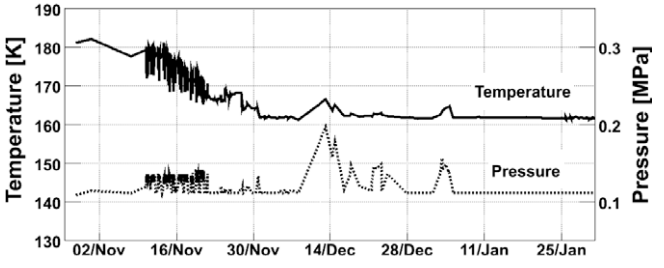

Fig. 7. Temperature and pressure profiles during zero boil-off test of LXe cryogenic tank.

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implemented by turning on and turning off the compressor without operating the heater. Both techniques were successfully tested and it was confirmed that 900 L of LXe could be maintained stable in the cryogenic tank for a period as long as 4 months, thereby verifying the effectiveness of the zero boil-off condition.

5. Summary

A xenon storage system has been developed and tested for being employed in the MEG experiment. This system consists of GXe tanks and the LXe cryogenic tank with a pulse tube cryocooler. The system can store up to 1000 L of xenon in both gaseous and liquid states. A total of 900 L of LXe is liquefied and maintained stable for several months under the zero boil-off condition.

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