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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 $\mu^+ \to e^+\gamma$. 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., $\mu^+ \to e^+\gamma$ 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.

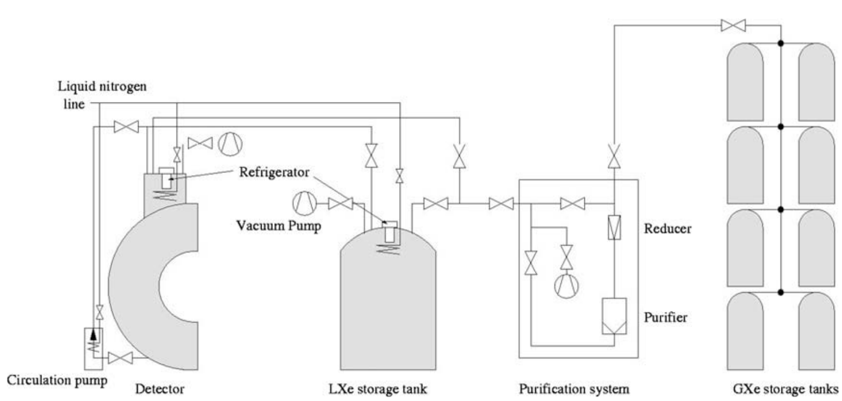

Fig. 1. Xenon storage system.