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Development of a liquid xenon scintillation detector for a new experiment to search for $\mu \to e\gamma$ decays

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Abstract

A novel gamma-ray detector based on a liquid xenon scintillator is under development for a new experiment to search for the lepton flavor violating process $\mu^+ \to e^+\gamma$ at the Paul Scherrer Institute (PSI). The experiment is designed to have a sensitivity down to 10^{-14} branching ratio. We constructed a prototype detector with an active volume of 69 l to demonstrate the performance of the proposed detector for high-energy gamma rays of around 50 MeV. After a test of the cryogenic system for the prototype detector, we have begun studies with the prototype using a gamma-beam up to 40 MeV from the laser Compton backscattering facility at the TERAS electron storage ring of the National Institute of Advanced Industrial Science and Technology (AIST).

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1. Introduction

A new experiment is planned to search for the rare decay of the muon into an electron and a gamma ray which violates lepton flavor conservation [1]. We aim to search with a sensitivity down to 10^{-14} branching ratio by using the world's most intense DC muon beam at the Paul Scherrer Institute (PSI). This sensitivity is below the current experimental bound [2] by three orders of magnitude. Promising theories beyond the standard model, such as SUSY-GUT, naturally predict a branching ratio of $\mu \to e\gamma$ decays of above 10^{-14}. Therefore, this experiment could give us a chance to explore such new physics [3,4]. A sizable decay rate is also predicted in the SUSY model with the seesaw mechanism, which can explain the finite mass of neutrino. A branching ratio above 10^{-14}

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can be expected especially for the 'large mixing angle solution' in this model, which is favored by the recent results from the solar neutrino measurements at Super Kamiokande [5–7].

Fig. 1 shows the current design of the detector for the $\mu \rightarrow e\gamma$ search experiment at PSI. The positron and gamma ray from the $\mu \rightarrow e\gamma$ decay can be detected with a positron spectrometer and a gamma-ray detector placed just outside the positron spectrometer, respectively. We have been developing a new type of liquid xenon gamma-ray detector for this experiment. A gamma-ray detector with good energy, position, and timing resolutions is indispensable to minimize the accidental pileups that could be a major background source in this experiment. The proposed gamma-ray detector utilizes scintillation light from liquid xenon with a volume of around 800 l. The scintillation light is collected by an array of 800 photomultipliers (PMTs) immersed in the liquid xenon, so that the scintillation light can be collected efficiently. The fast response [8] and large light yield [9] of xenon also serve to realize the good energy, timing, and position-resolutions.

In a previous study, the response to gamma rays up to 2 MeV was measured using a small prototype detector with an active volume of 2.3 l and 32 PMTs [10]. Naive extrapolation form the results, and various simulation studies taking account of geometry of the full-scale detector imply the proposed detector could have resolutions (RMS) at 52.8 MeV of 0.7% for energy, less than 3 mm for position, and less than 50 ps for timing. In order to verify this estimate and test various elements to be used in the full-scale detector such as a refrigerator, cables, feedthroughs, etc., we constructed a larger prototype with an active volume of 69 l so that an event caused by a high-energy gamma-ray of around 50 MeV can be fully contained within the active volume.

2. Large prototype detector

Fig. 2 shows the schematic view of the constructed prototype detector. The active volume of the detector is 69 l ($37 \times 37 \times 50\,\mathrm{cm}^3$), which is large enough to fully contain an event caused by a gamma ray of around 50 MeV. This detector is the world's largest liquid xenon scintillation detector, although it is just a prototype.

A total of 228 PMTs are arrayed in a rectangular shape and installed in the liquid xenon. The front face of the detector should be transparent to 50 MeV gamma rays. A 100-μm-thick aluminum window and a stainless-steel honeycomb window are used on the front face in the inner and outer vessel, respectively, and the front face of the PMT holder is made of G10 and acrylic in order to minimize the material thickness. Light-emitting diodes and alpha sources (^{241}Am) are located on the holder for PMT calibration.

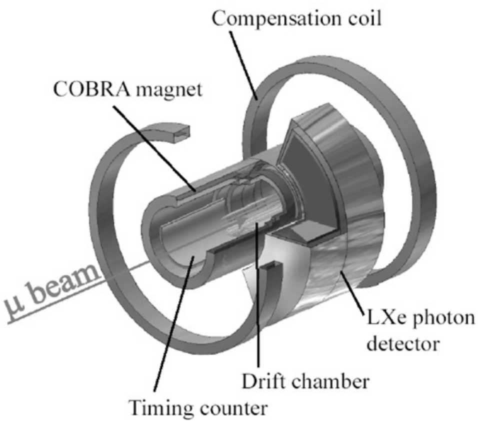

Fig. 1. Detector for a new $\mu \rightarrow e\gamma$ search experiment at PSI.

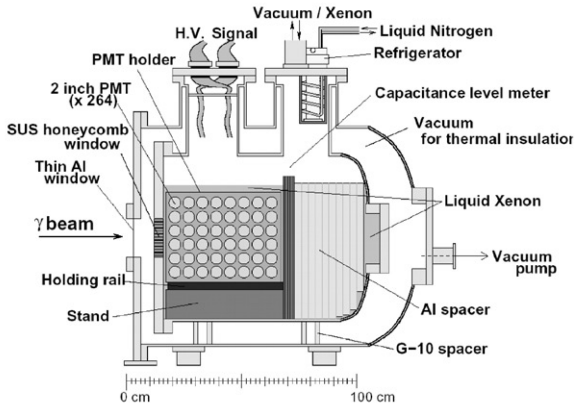

Fig. 2. Schematic view of the constructed prototype of the liquid xenon gamma-ray detector.

A powerful and reliable cryogenic system is required to liquefy the large amount of xenon (a total of 120 l in liquid form) and to keep it stable after the liquefaction for a long period of time. Gaseous xenon is liquefied by using a heat exchanger pipe cooled down with liquid nitrogen. After completion of the liquefaction, the liquid is maintained by using a pulse tube refrigerator. The pulse tube refrigerator is easy to handle and the vibration noise is much lower compared with a conventional GM refrigerator because there is no mechanical moving part in the low-temperature stage. The heat load into the liquid xenon is dominated by heat generation in the PMTs (18 W) and heat inflow through the cables (10 W). We measured the cooling power of the refrigerator prior to assembling of the prototype. Fig. 3 shows the measured cooling power as a function of the temperature of the cooling head in the refrigerator. The cooling power at liquid xenon temperature (165 K) was found to be around 70 W, which is sufficient to cover the heat load of the prototype detector.

In order to minimize the concentration of impurities in the liquid xenon, the detector chamber is evacuated for many days and then flushed by means of hot xenon gas circulation. The circulated xenon gas is purified by passing through a purification system and warmed up in a heat exchanger just before flowing into the chamber.

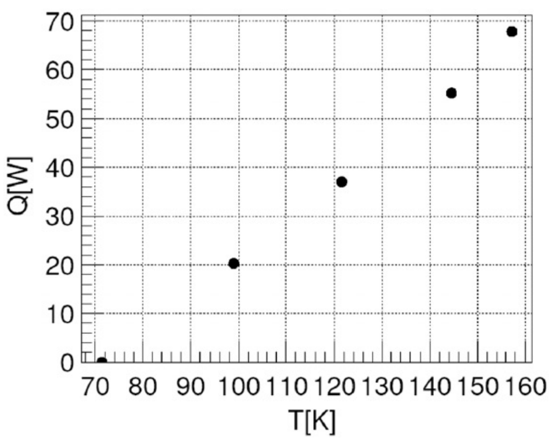

Fig. 3. Measured cooling power as a function of temperature of cooling head in the pulse tube refrigerator constructed for the prototype detector.

The purification system consists of two types of purification filters: an Oxisorb filter (Messer Griesheim GmbH) and a Zr–V–Fe getter (SAES getters MonoTorr PS15).

We successfully operated the prototype detector over a few weeks by keeping the liquid xenon at stable temperature with only the pulse tube refrigerator. We believe that performance of the cryogenic system based on the pulse tube refrigerator is sufficient for our purpose, and a similar system with larger cooling power is applicable to the full-scale detector.

3. Beam tests at the laser Compton backscattering facility at TERAS

To demonstrate the performance of the proposed liquid xenon detector for the 52.8 MeV gamma rays from the $\mu \rightarrow e\gamma$ decays, we have begun a study with the prototype detector using high-energy gamma rays. We are using high-energy gamma rays up to 40 MeV from the laser Compton backscattering facility at the TERAS electron storage ring of the National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Japan.

The energy resolution can be evaluated by the spread of Compton edge. The position resolution can be estimated by analyzing the distribution of the PMT outputs with a collimated gamma-ray beam. The timing resolution can be estimated by

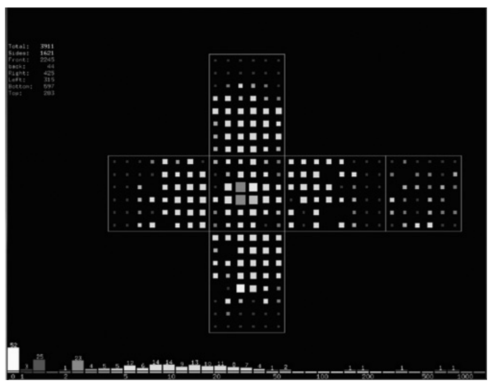

Fig. 4. Typical distribution of PMT outputs for the Compton backscattered gamma ray of around 40 MeV.

averaging the arrival times after proper ADC slewing collections.

We started a series of gamma-ray beam tests at AIST in June 2001. We successfully observed 40 MeV gamma ray and reconstructed the energy and position. Fig. 4 shows a typical distribution of the number of photolelectrons collected at the PMTs for a Compton backscattered gamma ray of around 40 MeV. Analysis of the data from the beam tests is still in progress since reliable evaluation of the energy, position, and timing resolutions requires some unmeasured parameters such as relative quantum efficiencies of the PMTs and attenuation length of the scintillation light in the liquid xenon. Separate experiments to measure such parameters are going on in parallel.

4. Summary and prospects

We constructed a prototype of the liquid xenon scintillation detector for the $\mu \rightarrow e\gamma$ search experiment at PSI. The prototype is large enough to demonstrate performance of the proposed detector for high-energy gamma rays of around 50 MeV. We successfully liquefied large amount of xenon ($\sim$120 l in liquid form) and operated the detector over a few weeks. We have started studies with gamma rays up to 40 MeV from laser Compton backscattering, where we successfully observed the 40 MeV gamma ray and reconstructed the energy and position. Analysis of the data from the beam tests is still in progress. In order to evaluate the detector resolutions reliably, separate experiments to measure some detector parameters are going on in parallel.

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