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R&D work on a liquid-xenon photon detector for the $\mu \rightarrow e\gamma$ experiment at PSI

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Abstract

The development of a liquid-xenon photon detector is in progress for an experiment searching for $\mu^+ \rightarrow e^+\gamma$ at Paul Scherrer Institut (PSI). The detector utilizes liquid xenon as a scintillation material. The scintillation light is observed by photomultiplier tubes (PMTs) immersed in a liquid. An energy resolution of 0.76% is reasonably expected for 52.8 MeVγ rays from results obtained with a first prototype, where the active volume of 2.3 l is viewed by 32 PMTs. Another prototype has been constructed with an active volume of 80 l and 228 PMTs. The performance of the detector will be tested using laser-induced compton backscattered γ rays up to 40 MeV.

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Keywords: Liquid xenon; Photon detector; $\mu \rightarrow e\gamma$

1. Introduction

Fundamental theories, such as Supersymmetric Unification, seem to generically predict that the neutrino-less lepton-flavor-violating μ decay to an e and γ should occur with a branching ratio somewhere above 10^{-14} [1]. A new experimental facility is to be built at PSI, aiming to detect $\mu^+ \rightarrow e^+\gamma$ decay with a sensitivity of 10^{-14} on the branching ratio by using advanced detector components [2]. In this experiment, a surface μ^+ beam with an intensity of 10^8/s is to be stopped in a target located at the center of the spectrometer. If the decay $\mu^+ \rightarrow e^+\gamma$ occurs, the signature will be observed as a back-to-back e^+ and γ, produced in time, with a respective energy of 52.8 MeV. The setup of the experiment consists of a positron spectrometer with a super-conducting solenoidal magnet and a photon detector. Details of the setup can be found in Ref. [3].

The photon detector utilizes liquid xenon as a scintillation material because of its large light yield

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and high density. In addition, the scintillation pulse from xenon is very fast and has a short decay constant ($\tau = 45$ ns) [4,5]. These features are the most essential ingredients for the precise energy and timing resolutions required for this experiment. Especially its short decay-time is necessary to minimize any pile-up of high rate γ rays. Liquid xenon is also free from a problem of non-uniformity, which limits the energy resolution of scintillation crystals. The properties of liquid xenon are summarized in Table 1. In order to observe scintillation light from liquid xenon, a simple "mini-Kamiokande" scheme is adopted, as shown in Fig. 1. The active volume is viewed from all sides by an array of 800 PMTs immersed in the liquid. The detector development will be done in the following two steps. The first step is to construct a small prototype of the detector to perform various test using γ-ray sources and to be confident of the photon detector. The second is to construct a larger prototype based on the obtained experience in the first prototype to demonstrate the detector performance for observing higher-energy γ rays around 52.8 MeV. It is also important to examine, in the second prototype, various components used in the final detector, such as feedthrough connectors, temperature and pressure probes, and refrigerators for the long-term stable operation of the detector.

Table 1
Properties of liquid xenon

Density	3.00 g/cm^3
Boiling and melting points	165, 161 K
Energy per scintillation photon	24 eV [4]
Radiation length	2.77 cm
Decay time	4.2, 22 ns
	45 ns (75%) [5]
Scintillation light wave length	175 nm
Scintillation absorption length	> 100 cm
Attenuation length (Rayleigh scattering)	30 cm
Refractive index	1.57

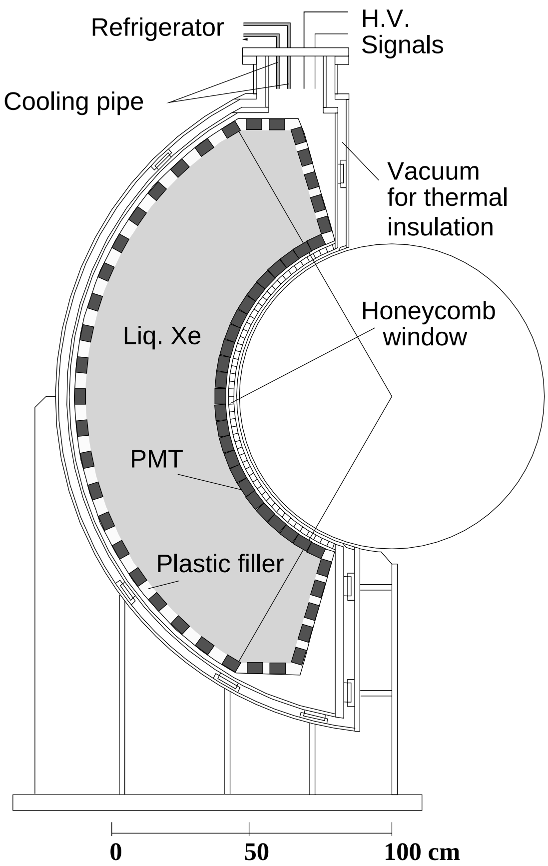

Fig. 1. Cut view of the 'mini-Kamiokande' detector.

2. The first prototype

In order to be confident of the photon detector, the first prototype was constructed and various tests were performed.

This prototype has an active volume of $11.6 \times 11.6 \times 17.4$ cm^3 viewed by 32 UV-sensitive PMTs. The PMT is a new development with a silica window to transmit the scintillation light from liquid xenon ($\lambda = 175$ nm), and can be stably operated at temperatures as low as liquid xenon (165 K). A schematic view of the prototype is shown in Fig. 2. The detector was placed inside a large vessel filled with liquid xenon. In order to study the energy, position, and timing resolutions, several γ-ray sources ranging from 0.32 to 1.8 MeV were located at the one end of the prototype, as indicated in Fig. 2. An α source ^{241}Am was attached at the opposite end for PMTs calibration.

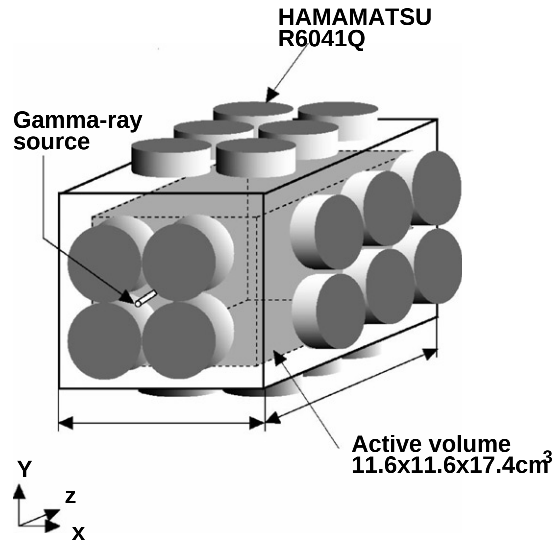

Fig. 2. Schematic view of the first prototype photon detector.

Fig. 3 shows the energy resolution measured for γ rays from ^{51}Cr, ^{137}Cs, ^{54}Mn, and ^{88}Y in comparison with the predictions from Monte Carlo simulation. The simulation utilizes EGS4 code [6] and incorporates all important details of the prototype module. The same off-line analysis was applied both for the real data and for the simulated data. The measured resolutions closely follow the line predicted by the simulation. This suggests that our basic understanding of the liquid-xenon photon detector is correct. The position and timing resolutions were estimated in the following way. In the off-line analysis, the 32 PMTs were divided into two groups in the middle x–z plane. In each group, the center position of the events (z_1, z_2) and the mean arrival time of output pulses (t_1, t_2) were calculated. In calculation of z_1 and z_2, the average of PMT positions weighted by the pulse heights were taken, and for t_1 and t_2, ADC slewing corrections were applied for each PMT before calculating the mean arrival times. From the distributions of the differences between two positions $(\Delta_z \equiv z_1 - z_2)$ and two mean arrival times $(\Delta_t \equiv t_1 - t_2)$, position and timing resolutions were estimated. The position resolutions estimated in this way are summarized in Table 2. It is about 3 mm above 1 MeV, and shows a tendency of improving with the energy. Fig. 4 shows the timing resolutions as a function of the number of photoelectrons. Several cases are shown for various numbers of PMTs used in the estimation. It can be seen that the timing resolution improves as $\sim 1/\sqrt{N_{pe}}$ as the observed number of photoelectrons (N_{pe}) increases.

For demonstrating the xenon photon detector performance for 52.8 MeV γ rays, these results are

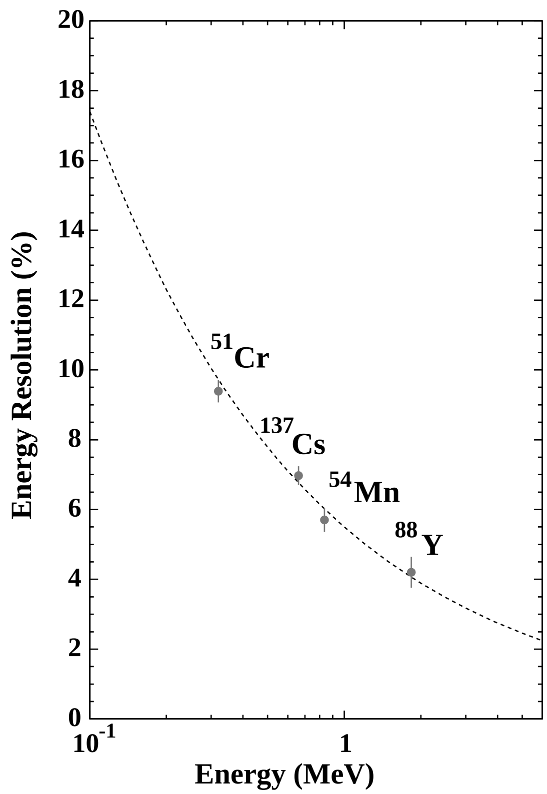

Fig. 3. Energy resolution measured with the first prototype, as compared to the predictions by the simulation.

Table 2
Position resolution for γ rays

Nuclide	γ energy (MeV)	$\sigma_{\Delta_z}/\sqrt{2}$(mm)
^{51}Cr	0.320	7.3 ± 0.15
^{137}Cs	0.662	4.3 ± 0.11
^{54}Mn	0.835	4.0 ± 0.13
^{88}Y	1.836	2.9 ± 0.04

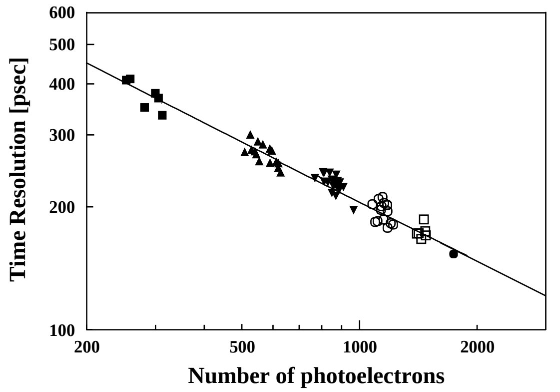

Fig. 4. Time resolution as a function of the observed number of photoelectrons.

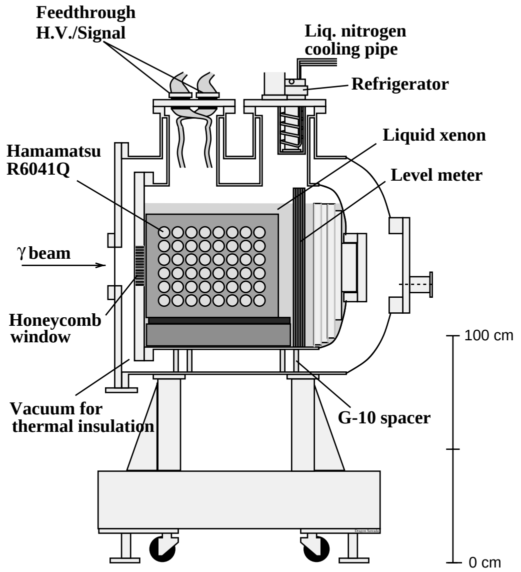

Fig. 5. Schematic of the second prototype photon detector.

extrapolated to higher energies. The extrapolation indicates that resolutions of 0.76% for energy and 45 ps for time measurements are reasonably expected. As for the position resolution, care must be taken when extrapolating to higher energies; however, we can safely conclude that a resolution of 3 mm or better should be obtained at 52.8 MeV, where more photoelectrons are expected to be observed.

3. The second prototype

Tests performed with the first prototype are limited to a low γ-ray energy region because of its limited volume. A second prototype of a larger size is necessary to prove the detector performance for higher-energy γ rays. It is also important to examine not only the performance of the xenon photon detector, but also various components necessary to build the final detector, such as feedthrough connectors, temperature and pressure probes, and a xenon liquefaction system including refrigerators.

A schematic view of the detector is shown in Fig. 5. Vessel construction has been successfully completed and the thermal inflow by conduction and radiation through vessel walls was measured at two different temperatures by filling liquid nitrogen (77 K) and liquid xenon (165 K). The thermal inflow was found to be 24 W at liquid-xenon temperature, which is consistent with the design value. In this prototype, we use 228 PMTs of the same type as used in the first prototype. The PMTs are constructed in a rectangular shape to be inserted into the vessel. A liquefaction test was performed and the detector response was examined with α sources and blue LED signals equipped on the PMT holder. A pulse tube refrigerator [7] has been introduced to this prototype to recondense xenon gas. The refrigerator is easier to handle than the cryogenic fluid and has no moving part in the low-temperature region. The vibration at the cold part is, therefore, negligibly small, making a long-term operation stable and reliable. The cooling power of the refrigerator was measured to be 70 W at liquid-xenon temperature, which is enough to cancel the total heat load from thermal inflow through the walls (24 W) and through the cables (10 W), and from the PMT bleeder circuits (18 W). During a liquefaction test for over 60 h the refrigerator could successfully recondense xenon and keep the liquid in a stable condition.

Extensive studies using this prototype will be continued during this year. Laser-induced compton backscattered γ rays will be used to investigate the detector performance in the TERAS electron storage ring [8] at the National Institute of Advanced Industrial Science and Technology (AIST) in Tsukuba, Japan. Nd:YFL laser photons are led to a head-on collision point at TERAS to deliver γ rays having energies of up to 40 MeV. The energy resolution of the detector will be derived by measuring the spread of the Compton edge. For evaluating the timing resolution, the signal from the master oscillator for the RF cavities in the storage ring will be employed as a reference of the timing. The position resolution will also be evaluated with a proper collimator setup.

4. Summary and prospects

Research and development work on a liquid-xenon photon detector is in progress for the $\mu^+ \rightarrow e^+\gamma$ decay search experiment at PSI. The first prototype with an active volume of 2.3 l was successfully constructed, and various tests using γ-ray sources were performed. The results show that it is feasible to achieve the required resolutions for the experiment. The second prototype with an active volume of 80 l has been constructed to verify the detector performance for higher-energy γ rays. Extensive studies will be continued during this year using γ rays provided at the electron storage ring TERAS in AIST.

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