LIQUID XE DETECTOR FOR MU E GAMMA SEARCH

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A new type of liquid Xe detector has been developed for an experiment searching for $\mu^+ \rightarrow e^+\gamma$ at Paul Scherrer Institute(PSI). The detector utilizes liquid xenon as a scintillation material. The scintillation light are observed by photomultiplier tubes(PMTs) immersed in liquid xenon. The performance of the detector has been investigated with two prototypes. The first prototype with an active volume of 2.3 liter viewed by 32 PMTs was tested by using radioactive γ-ray sources of 0.3 MeV to 1.8 MeV. From the first prototype results, it is expected that ~1 %(r.m.s.) for energy resolution for 52.8-MeV γ, a few mm for position, and 50 psec for time will be obtained. The second larger prototype has already constructed, which has an active volume of 68.6 liter viewed by 228 PMTs. The second prototype is now undergoing all the necessary tests for construction of a final detector using Compton backscattered γ-rays up to 40 MeV.

1 Introduction

Fundamental theories such as SUSY-GUT seem to generically predict that $\mu \rightarrow e\gamma$ occurs with a decay branching ratio somewhere above 10^{-14} [1, 2]. The latest upper limit of the branching ratio for $\mu \rightarrow e\gamma$ decay is 1.2×10^{-11} at the 90% confidence level measured by the MEGA collaboration at LAMPF [3]. A new $\mu \rightarrow e\gamma$ experiment is planned at Paul Sherrer Institute (PSI) in Switzerland and detector development is undergoing, aiming to improve the sensitivity by 3 orders of magnitude compared with current world limit [4]. The experimental setup consists of a liquid Xe photon detector and a positron spectrometer with a superconducting solenoid magnet [5], as shown in Fig. 1. In this experiment, surface μ^+ beam with an intensity of 10^8/s is stopped in a target located at the center of the spectrometer. If the $\mu^+ \rightarrow e^+\gamma$ decay occurs, a back-to-back e^+ and γ will be observed with respective energy of 52.8 MeV in time. In the $\mu \rightarrow e\gamma$ search there are two major backgrounds. One is the radiative muon decay of $\mu \rightarrow e\,\overline{\nu_e}\,\nu_\mu\gamma$. It looks like the $\mu \rightarrow e\gamma$ signal when the two neutrinos take away with small amount of momenta. The other is an accidental overlap of positrons around the energy edge of the Michel decay and unexpected γ(s) such as from annihilation in flight. The liquid Xe detector is the key to suppress such big amount of backgrounds, and we are now researching and developing it.

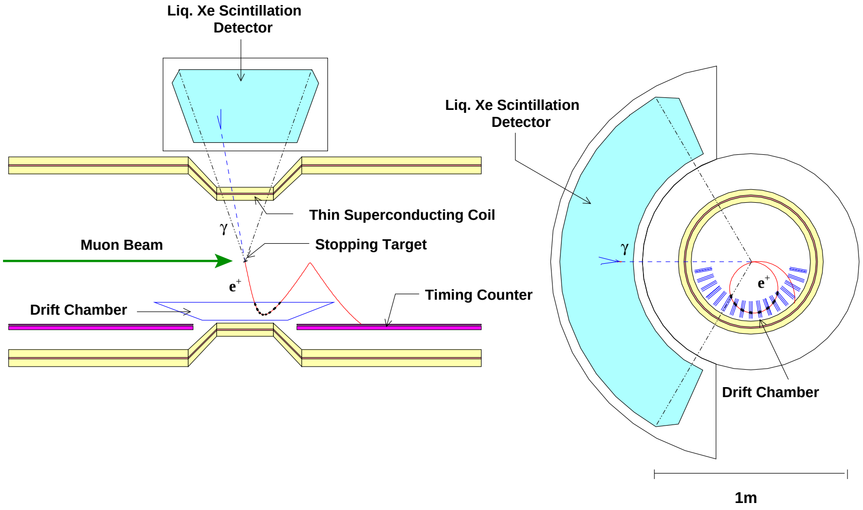

Figure 1. A schematic view of the $\mu \to e\gamma$ detector along the beam axis(left) and perpendicular to beam axis(right).

2 Liquid Xe Detector

Liquid xenon has several advantages as a scintillator material. It has large light yield ($W_{ph} = 24$ eV [6]), and its scintillation pulse has a fast response and short decay time which minimizes pile-ups under such high rate condition. Additionally it is free from a problem of non-uniformity which crystal scintillation detectors ought to have.

A schematic view of the liquid Xe detector for the $\mu \to e\gamma$ search is shown in Fig. 2. Similar to the Kamiokande detector, liquid xenon volume is surrounded with arrays of about 800 PMTs [7] for detecting scintillation light emitted inside. The PMT was specially developed for this experiment in cooperation with Hamamatsu Photonics K. K, so that all the PMTs can be immersed in liquid xenon. Properties of the PMT are summarized in Table 1.

In order to study performance of the detector for 52.8-MeV γ, two kinds of prototypes has been constructed and their performance has been tested. One is a small prototype and studies with this detector were successfully completed. The other is a large prototype and studies on it are now in advance.

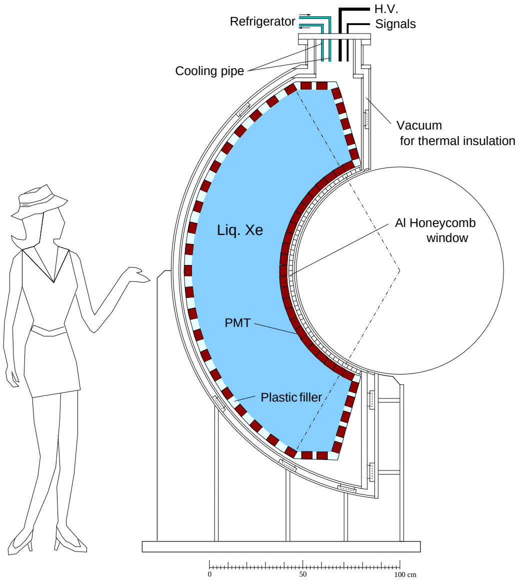

Figure 2. Cross sectional view of liquid Xe detector for $\mu \rightarrow e\gamma$ search.

Table 1. Properties of the PMT for the liquid Xe detector(in liquid xenon).

PMT size	57 mm ϕ
Photo-Cathode material	Rb-Cs-Sb
Size of effective area	46 mm ϕ
Typical Q.E.	5 %
Dynode Type	Metal channel
Number of stages	12
Typical H.V.	900 V
Typical gain	3×10^6

3 Small Prototype

The first prototype has an active volume of $116 \times 116 \times 174$ mm^3 (2.3 liter) viewed by 32 PMTs as shown in Fig. 3(left). The PMTs were placed inside double-layer vessels for thermal insulation as illustrated in Fig. 3(right). Liquid nitrogen was used for liquefaction of xenon. It took ~ 12 hours to fill the vessel with sufficient liquid xenon. After completing the liquefaction, the flow of liquid nitrogen in copper cooling pipe was controlled to keep liquid xenon stable.

LEDs were equipped on the corners of the holder for calibration of the PMT outputs. An α souce ^{241}Am was attached on one side for monitoring stability of PMTs because it can be regarded as point-like light source in liquid xenon. The PMT output was stabilized within an accuracy of 0.5% in 5 hours after liquefaction as described in [4]. One of γ-ray sources (^{51}Cr,^{137}Cs,^{54}Mn,^{88}Y) ranging from 0.3 MeV to 1.8 MeV were placed on the other side to study the energy, position, and timing resolution.

Weighted mean with their individual number of observed photoelectrons was used for evaluating the interaction point. All the resolutions were calculated after requiring that the interaction point should lie in a central volume (-1 cm$< x, y, z < 1$ cm) of the detector. All the results were compared with the predictions from Monte Carlo simulation which incorporated with EGS4 [8]. The same analysis was applied for the experimental data and the simulated data.

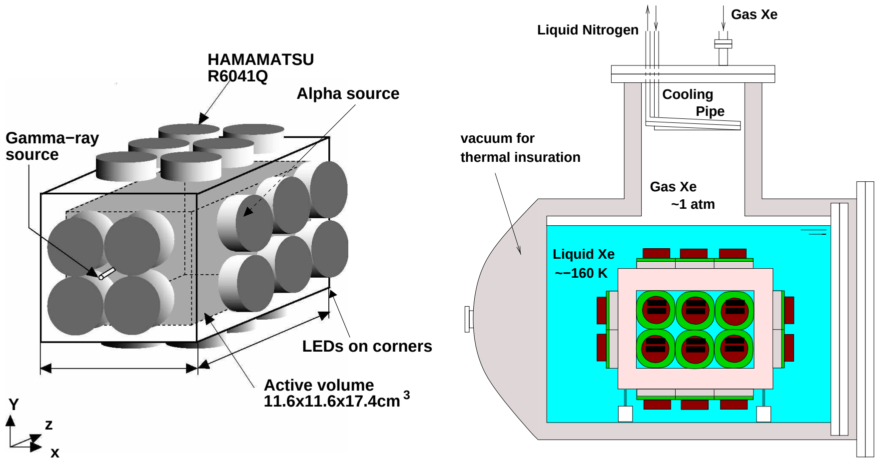

Figure 3. Experimental setup of the small prototype and its cooling vessel.

3.1 Energy resolution

The energy resolution was evaluated after selecting events with the estimated interaction point described above. Energy spectra for each of γ-ray source were fitted with asymmetric Gaussian functions. The right part of the Gaussian peak included the fully-contained events while the left part was affected by energy leakage. This is why the sigma of the right part represented the energy resolution.

Fig. 4(a) shows the summary of energy resolutions. It is also found that the prediction by the simulation (dashed line) is in good agreement with the experimental data.

For evaluating the liquid Xe detector performance for 52.8-MeV γ, these results are extrapolated to higher energy. It is suggested that about 1% resolution in sigma will be obtained at 52.8 MeV.

3.2 Position resolution

The position resolution was estimated in the following way. Firstly, the 32 PMTs were divided into two groups at the middle height (x-z plane) of the detector, and then interaction points were evaluated in each of the groups. From the distribution of the difference between them, the position resolution could be evaluated.

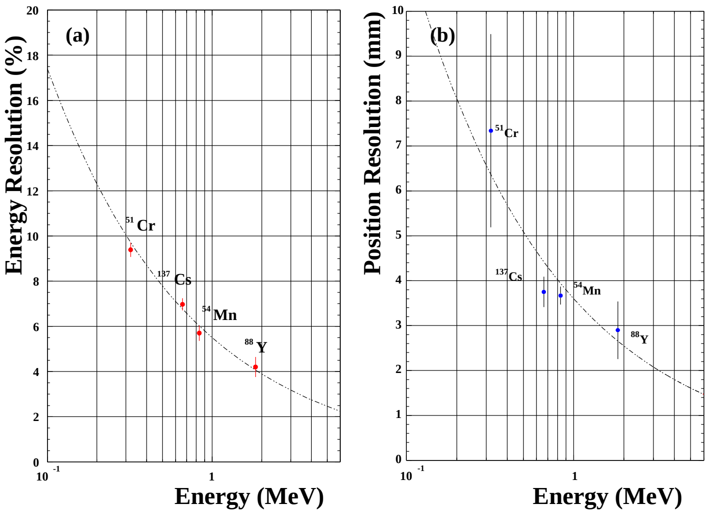

Figure 4. Energy(a) and position(b) resolutions with the small prototype, as compared to the predictions (dashed lines) by the simulation.

The results are summarized in Fig. 4(b) together with the prediction by the simulation. It indicates that the position resolution tends to improve as a function of $1/\sqrt{E}$, where E represents energy of γ-ray sources. As for position resolution, simple extrapolation is not always adequate and more systematics should be taken into account. However, we can safely conclude that the resolution for 52.8-MeV γ will be a few mm.

3.3 Timing resolution

In the similar way as done for evaluating the position resolution, the timing resolution was calculated. The 32 PMTs were divided into two groups again and mean of arrival time in each group was calculated after ADC slewing correction for each of the PMTs with a qualification that the number of observed photoelectrons is over 100. The obtained timing resolution is summarized in Fig. 5 as a function of the total number of observed photoelectrons.

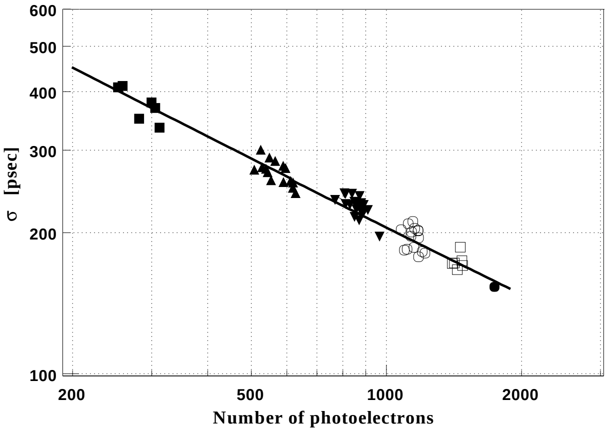

Figure 5. Timing resolution of the small prototype as a function of the total number of observed photoelectrons.

According to the simulation by GEANT3 [9], the final detector will observe about $20,000$ photoelectrons for 52.8-MeV γ. It is not straightforward to extrapolate to such high energy since the distribution of PMT outputs observed by the final detector is quite different. The timing resolution of 50 psec is, however, reasonably expected for 52.8-MeV γ.

4 Large Prototype

The first small prototype was constructed so as to examine performance of the liquid Xe detector for low energy γ-rays, because such a large liquid Xe scintillation detector had not been constructed. The next step was to construct a larger prototype to proof the detector performance for higher energy γ-rays. The large prototype can be regarded as a minimal part of the final detector, and indeed includes various components of the final detector such as feedthrough connectors, temperature and pressure monitors, and a xenon liquefaction system including refrigerators. It is also important to examine them.

A schema of the large prototype is shown in Fig. 6. The second prototype has an active volume of $372 \times 372 \times 496$ mm^3 (68.6 liter). The 228 PMTs were assembled into a rectangular shape to be inserted into the vessel. Instead of copper cooling pipe as used in the small prototype, a pulse tube refrigerator [10] was employed to keep liquid xenon stable. Stability of the PMTs was monitored with α sources and blue LEDs equipped on the PMT holder.

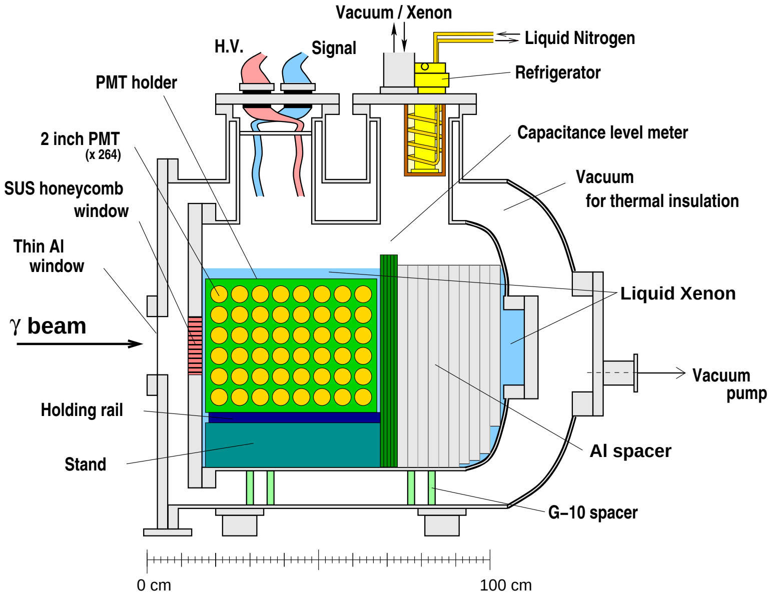

Figure 6. A schematic view of the second large prototype.

Compton backscattered γ-rays will be used to investigate the detector performance in the TERAS electron storage ring [11] at the National Institute of Advanced Industrial Science and Technology (AIST). Photons from Nd:YFL laser are led to a head-on collision point at TERAS to deliver γ-rays of energies up to 40 MeV. Energy resolution of the detector will be derived by means of 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 be also evaluated with a proper collimator setup.

The tests with this prototype have just started. In fact, the preliminary test for the large prototype was performed at AIST in 2001 in order to examine the whole system of the large prototype. In this test it was verified that all components of the large prototype worked well. Now the large prototype is ready for the next test, and more extensive studies will continue until the summer of 2002.

5 Summary

Research and development works on the liquid Xe detector is in progress for the $\mu^+ \to e^+\gamma$ search experiment at PSI. The first prototype with an active volume of 2.3 liter was successfully constructed and various tests were performed using γ-ray sources up to 1.8 MeV. The results show that it is feasible to achieve the required resolutions for the experiment. The second prototype with an active volume of 69 liter was constructed to verify the detector performance for higher energy γ-ray. Extensive studies with the large prototype will continue using γ-ray provided at AIST, cosmic rays, and α source.

Acknowledgments

We would like to thank Dr. H. Ohgaki and Dr. H. Toyokawa at AIST, who supported and helped us during the second prototype test.

This work is supported in part by Grant-in-Aid for Scientific Research on Priority Areas (A) provided by the Ministry of Education, Culture, Sports, Science and Technology of Japan.

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