Development of a Liquid Xe Photon Detector for $\mu \rightarrow e\gamma$ Decay Search Experiment at PSI

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Abstract

We are developing a new type of photon detector for an experiment searching for muon decays to positron and gamma with the sensitivity of 10^{-14} branching ratio by using the world most intensive continuous muon beam provided at PSI. In this experiment the photon detector utilizes liquid xenon as scintillation material because of its fast response, large light output yield, and high density. Scintillation light emitted in liquid Xe is directly observed by photomultipliers (PMTs) located in liquid without any transmission window in order not to lose light yield. To study the detector response to gamma rays we constructed a prototype with an active volume of 2300 cm^3 surrounded by 32 PMTs. The PMT was newly developed so as to be operated even in liquid Xe at 165K. Energy, position, and timing resolutions have been evaluated with gamma-ray sources from 320keV to 1835keV. Performance of the prototype is presented in this article.

I. Introduction

A new experiment searching for $\mu \rightarrow e\gamma$ decay is planned at PSI aiming to achieve the sensitivity of 10^{-14} branching ratio[1]. Fundamental theories such as supersymmetric unification[2] seem to generically predict that $\mu \rightarrow e\gamma$ occurs with a decay branching ratio somewhere above 10^{-14}. We therefore consider that this experiment has a real chance of making a discovery, which will provide a stunning evidence for new physics beyond the standard model.

In this experiment muons are stopped at the target located at the center of the spectrometer and if $\mu \rightarrow e\gamma$ occurs, the signal will be observed as a back-to-back positron and gamma pair produced in time.

There are two main background sources to this process. One is the radiative muon decay with two neutrinos both carrying small energy which looks like a $\mu \rightarrow e\gamma$ decay. The other one is the accidental overlap of high-energy positrons close to the edge of the Michel decay spectrum and unexpected gamma(s) such as from annihiration in flight. For reducing these contributions it is required that the photon detector should have good energy, position, and timing resolutions for 52.8MeV gammas.

In this experiment, we employ a liquid Xe scintillation detector for gamma detection, which has a 0.8m^3 volume of liquid Xe viewed by arrays of 800 PMTs from all sides. The scintillation pulse from Xe is very fast and has a short tail[3], thereby minimizing the pile-up problem which could limit the sensitivity. To study the detector response to gamma rays, a prototype was constructed and tested with gamma-ray sources from 320keV to 1835keV.

II. Experimental Setup

The prototype detector has an active volume of $11.6 \times 11.6 \times 17.4 cm^3$ viewed by 32 UV-sensitive PMTs[4] assembled into a rectangular shape as shown in Figure 1(a).

The PMT has a silica window to transmit the ultra violet light, and can be stably operated at the liquid Xe temperature of 165K. The metal channel dynode structure is employed to reduce the length of the PMT. The properties of the PMT are summarized in Table 1.

Table 1.
Properties of R6041Q

PMT size	3.2cm x 5.7cmϕ
Photo-Cathode material	Rb-Cs-Sb
Size of effective area	4.6cmϕ
Quantum efficiency at normal temperature	10%-15%
Dynode type	Metal channel
Number of stages	12
Typical H.V.	1000V
Current amplification	9×10^6

In order to study the energy, position, and timing resolutions, several gamma-ray sources were located at one end of the detector as indicated in Figure 1(a). An α source of ^{241}Am was attached at the opposite end. Calibration and monitoring of PMTs were done using signals from α particles and LED light fed into the detector through optical fibers.

The detector was placed inside a large vessel filled with liquid Xe as shown in Figure 1(b). For accumulating sufficient amount of liquid Xe in the active volume before starting data taking, firstly the vessel was filled with gas Xe of 1.25 atom and then liquefaction was started with transferring liquid nitrogen inside the copper cooling pipe. It takes about 12 hours to fill the vessel with liquid Xe. After completing the liquefaction, the flow of liquid nitrogen was controlled to keep

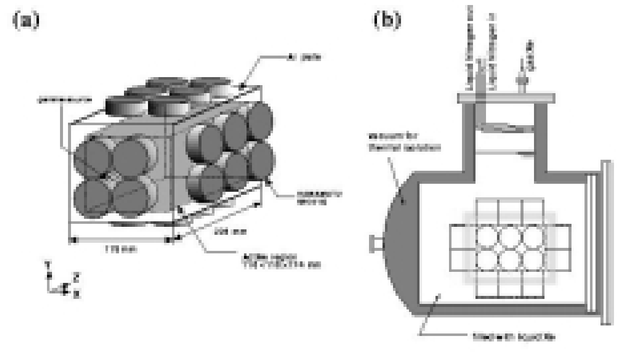

Figure 1: Experimental setup of the prototype. 32 PMTs assembled into a rectangular shape (shown in (a)) is installed in a cooling vessel (shown in (b)).

liquid Xe in stable condition with monitoring the vapor pressure in the vessel.

III. DATA TAKING

Signals from each PMTs were processed with charge sensitive ADCs, and high-resolution TDCs after descrimination. Figure 2 shows time dependence of a typical PMT output for α particles as a function of the time immediately after the vessel was filled with liquid Xe. After the initial gain change of a few percent, all 32 PMTs were found to be stable within +/-0.5% for many days.

After stabilization of PMTs, data taking was started. Events are triggered when any of the conditions on summed signals of 3 groups, each of which consists of 6 PMTs at the same z-coordinate on side plates, is satisfied. For example for gamma rays from ^{54}Mn, threshold levels were set at 300, 70, and 50 photoelectrons respectively for three individual groups along the z-direction.

The trigger condition required for gamma-ray events was loose enough that almost all events where the first interaction points were well inside the active volume could be triggered. The trigger efficiencies estimated with Monte Carlo simulation is larger than 98% for events where the first interaction points in –1cm<x,y,z<1cm. The simulation utilizes EGS4 code[5] and incorporates all important details of the prototype detector.

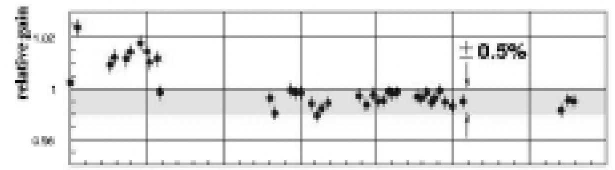

Figure 2: Time stability of PMT output monitored with scintillation light from liquid Xe activated by α particles as a function of time after the vessel was filled with liquid Xe. For the first stage of monitoring the output is unstable due to unstable temperature and pressure, although it is stabilized in +/-0.5% after 200 to 250 minutes.

Another trigger scheme is prepared for simultaneous data taking of α events to monitor the PMT outputs. LED runs were repeated once in two or three hours for calibration of PMT gains and pedestals of ADCs.

IV. ANALYSIS

In this section the performance of the prototype is described in points of

A. Energy resolution,

B. Position resolution, and

C. Timing resolution.

In the analysis, the position of gamma interaction was estimated by weighting positions of PMTs with their individual pulse heights.

A. ENERGY RESOLUTION

The energy resolution was evaluated for each of gamma-ray source energy after requiring that the interaction position should lie in a central volume (-1cm<x,y,z<1cm) of the detector. Energy spectra were fitted with asymmetric gaussian functions. The lower (left) part of the spectrum is affected by energy leakage although the upper (right) part is not. The sigma of the right part represents the energy resolution when all the gamma-ray energy was deposited in the active volume such in case of a large detector.

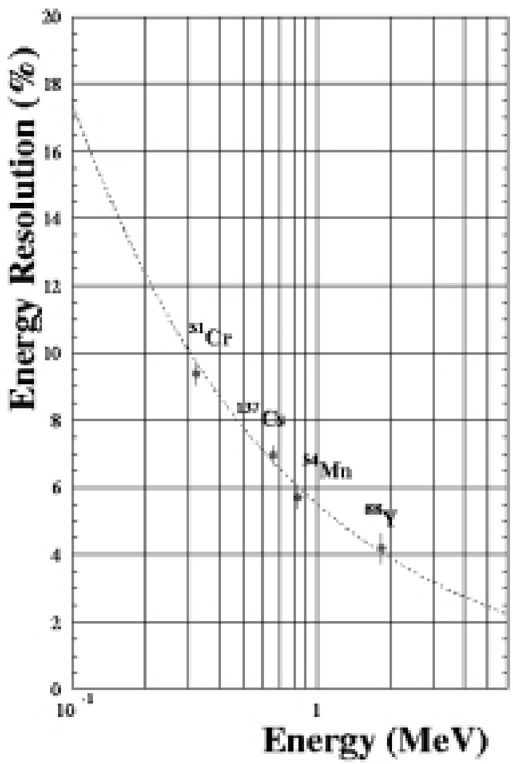

Figure 3: Energy resolution measured with gamma-ray sources as compared to the predictions (dashed line) by the simulation.

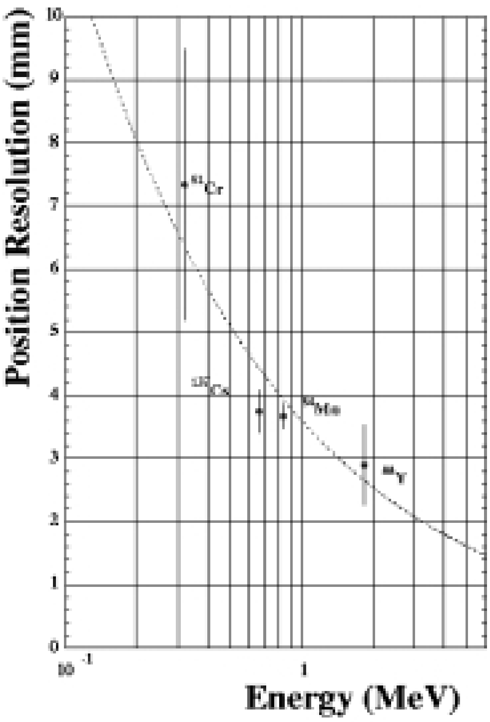

Figure 4: Position resolution measured with the prototype. The dashed line shows the prediction by the simulation.

Figure 3 shows the summary of energy resolutions together with the prediction of Monte Carlo simulation.

Simple extrapolation to higher energy suggests that 0.76% resolution in sigma can be obtained at 52.8MeV.

B. POSITION RESOLUTION

The position resolution was estimated by taking the difference between interaction positions evaluated in two groups in which half of PMTs (16 PMTs) were included after requiring the interaction position lie in the central volume.

The results are summarized in Figure 4 together with the Monte Carlo prediction. It can be seen that the resolution improves as a function of square root of $1/E_\gamma$, where E_γ means gamma-ray source energy.

More systematic should be taken into account when extrapolating this curve to higher energy, but simple extrapolation suggests that better than 3mm resolution will be obtained at 52.8MeV.

C. TIMING RESOLUTION

The timing resolution was evaluated in the same way as was done for the position resolution. The detector was divided into 2 groups and in each group mean of the arrival time was calculated after ADC slewing correction for each PMT.

Figure 4 shows the obtained timing resolution as a function of the number of observed photoelectrons.

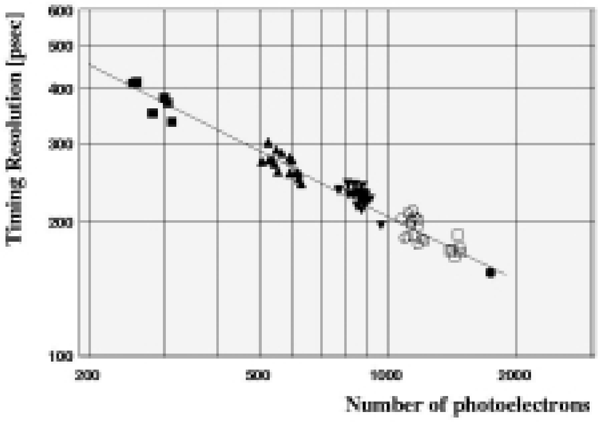

Figure 4: Timing resolution of the prototype as a function of number of observed photoelectrons.

For 52.8MeV gamma incident with a realistic configuration of the final photon detector, expected number of photoelectrons was estimated with Monte Carlo simulation incorporating GEANT3[6]. It is not straightforward to extrapolate to such higher energy since the signal distribution observed by each PMT is quite different, however 50psec resolution is reasonably expected for 52.8MeV gamma rays.

V. CONCLUSION

We are developing a liquid Xe scintillation detector for a new experiment to search for $\mu \rightarrow e\gamma$ down to 10^{-14} branching ratio using continuous muon beam at PSI. A prototype of the detector has been successfully constructed and tested with gamma-ray sources. The results show that it is feasible to achieve, for 52.8MeV gamma rays, resolutions of 0.76% for the energy-, better than 3mm for the position- and better than 50psec for the timing-measurement.

We are constructing another prototype as large as 1/3 of the final detector to investigate the detector response to higher energy gamma rays. The detector is large enough that it can fully contain high-energy gamma events around 50MeV. Tests will be performed in the year 2001 with gamma beam produced via inverse Compton scattering with relativistic electrons in the storage ring TERAS at Electrotechnical Laboratory in Tsukuba, Japan.

VI. REFERENCES

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