Upgrade of liquid xenon gamma-ray detector in MEG experiment

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Abstract

The MEG experiment is searching for the lepton flavor violating decay, \( \mu^+ \rightarrow e^+ + \gamma \), with the highest sensitivity. A major upgrade of the experiment is planned where an upgrade of the liquid xenon (LXe) gamma-ray detector is included. The current 2-inch photomultiplier tubes (PMT) on the gamma-ray incident face will be replaced with smaller photo-sensors such as multi-pixel photon counter (MPPC) in order to improve the resolutions and the efficiency. A UV-sensitive MPPC operational in LXe is under development in collaboration with Hamamatsu Photonics. A high photon detection efficiency of 17% to LXe scintillation light is achieved with a prototype of MPPC with an active area of 12 \( \times \) 12 mm\(^2\) and a single-photoelectron peak is clearly observed. The engineering design of the final detector is also described.

Keywords: MEG experiment, liquid xenon, MPPC(SiPM)

1. Introduction

We are searching for the rare muon decay, \( \mu^+ \rightarrow e^+ + \gamma \), with an unprecedented sensitivity in the MEG experiment at Paul Scherrer Institute (PSI) in Switzerland. The lepton flavor violating process is forbidden in the standard model. Even considering neutrino oscillation, it cannot be detected practically since its branching ratio is extremely low. A sizable branching ratio is however predicted in many promising theories beyond the standard model such as SUSY-GUT [1]. It has been searched for since 1940’s, but has not been found yet. The current most stringent experimental upper limit (5.7 \( \times \) 10\(^{-13}\) at 90% C.L.) was set by the MEG experiment from the data taken until year 2011 [2].

The signature of the decay is a pair of a \( \gamma \)-ray and a positron which have the same energy of 52.8MeV and are emitted back-to-back, simultaneously. There are two types of background events. One is the radiative muon decay (\( \mu^+ \rightarrow e^+ \bar{\nu}_e \gamma \)), and the other is caused by an accidental coincidence of positron from normal Michel decay (\( \mu^+ \rightarrow e^+ \bar{\nu}_e + \gamma \)) and \( \gamma \)-ray. In order to suppress backgrounds and thus to achieve a high sensitivity, the energy, position (emission angle) and timing resolutions are important.

In order to achieve a higher sensitivity, we plan to upgrade the experiment, which includes an upgrade of the 900 l LXe \( \gamma \)-ray detector. The LXe scintillation photons are collected by PMTs in the present detector. The basic idea of the upgrade is to increase the granularity at the gamma entrance face by replacing the PMTs with smaller sensors such as MPPC (the product name of silicon photomultipliers (SiPM) from Hamamatsu Photonics). However, commercial MPPCs are not sensitive to the scintillation light of LXe in vacuum ultra violet range (\( \lambda = 175 \pm 5\) nm).

MPPCs which can detect LXe scintillation light are under development in collaboration with Hamamatsu Photonics [3]. The design and the expected performance of the upgraded LXe detector and the R&D status of the UV-sensitive MPPC are presented herein.

2. Concept of LXe Detector Upgrade

We aim to accomplish a higher sensitivity by upgrading MEG detectors. The MEG upgrade proposal [4] was approved by PSI in Jan. 2013. The anticipated sensitivity of the upgraded experiment is one order of magnitude higher than that of current MEG, \( \sim 5 \times 10^{-14} \).

![Figure 1: Photon collection efficiency as a function of conversion depth.](image)

The current LXe detector is equipped with 846 PMTs and 216 out of them are arrayed on the inner face (where \( \gamma \)-rays enter the detector). The PMTs on the face are the most important because most \( \gamma \)-rays convert near the inner face, and the energy and position resolutions in this region are limited by the PMT size effect. Fig.1 shows the photon collection efficiency as a function of the conversion depth of \( \gamma \)-rays from the inner face. The energy and position resolutions are worse for the shallow...
events, because of the large dependence of the photon collection efficiency on the relative position from the PMT center.

A main idea of the upgrade is to reduce the non-uniform response by replacing the PMTs on the inner face with smaller photosensors such as MPPCs as shown in Fig.2. Fig.3 shows the difference in the light distribution. The identification of pileup event is expected to be improved as well as the resolutions.

PMTs on the other faces remain in the upgraded detector, but the layout will be changed as illustrated in Fig.4. By widening the incident face, the energy leakage near the lateral edge of the acceptance is reduced. The PMTs on the lateral faces will be rotated such that the photocathode are on the same plane for a more uniform response.

3. Expected Performance of Upgraded Detector

The performance of the upgraded detector is evaluated by Monte Carlo simulation. Fig.5 shows the energy spectra with the current and upgraded configuration for the signal $\gamma$ (52.8 MeV). The improvement of the energy resolution is remarkable especially in shallow part, from 2.4% to 1.1% in $\sigma$, while the improvement in deep part is from 1.7% to 1.0%. The tail at the lower energy side will be reduced because of the less energy leakage of the upgraded detector.

Fig.6 shows the position resolutions along the inner face in the present and upgraded detectors. The position resolution also improves in shallow part of the detector. The detection efficiency improves by 9% since MPPCs are much thinner than the PMTs, and thus the material in front of the LXe volume can be substantially reduced. The timing resolution is expected to be the same as the current detector.

4. Development of UV-sensitive MPPC

The SiPM is being actively developed and being applied in many fields, because of its excellent properties. However, there are mainly a few issues for using them for the MEG LXe detector. We are developing a new type of MPPC in collaboration with Hamamatsu Photonics.

The most important issue is the PDE for the LXe scintillation light in VUV range. The low PDE is due to the low transmission efficiency of the scintillation light in the insensitive layers on top of the sensitive layer of the MPPC. Most of scintillation light is absorbed in the protection coating made of epoxy resin and the contact layer on top of the sensitive layer, or reflected on the silicon surface. In order to improve the sensitivity, we develop several prototypes without the protection coating, with
a thinner contact layer or with an optimized surface material to suppress the reflection.

Another issue is the size of MPPC. The largest size of the commercially available single MPPC is $3 \times 3 \text{ mm}^2$, while we need a MPPC with an active area of $12 \times 12 \text{ mm}^2$ in order to suppress the number of read-out channels.

There are some possible issues for a large area MPPC. The dark count rate increases in proportion to the area of MPPC. The decay time of the signal is longer for the larger area MPPC due to its larger capacitance. It worsens the signal to noise ratio and increases pile-up of waveforms.

Performance of the prototypes of the UV sensitive MPPC is measured in a LXe test facility at PSI which can handle 2 \ell of liquid xenon. The setup in the LXe cryostat is shown in Fig.7.

**PDE measurement**

PDE is defined as the probability of detecting a photoelectron when one photon enters the active area of MPPC. It is measured as a ratio of the number of detected photons to that of expected photons reaching the MPPC in \alpha-ray events. The effects of optical crosstalk and afterpulses which are separately measured, are corrected in the PDE measurement.

Figure 7: Typical setup of the prototype test in the LXe cryostat

**Dark Count Rate**

SiPMs has a relatively high dark count rate. Since the dark count mostly comes from thermal noise, it can be suppressed at a low temperature. The dark count rate is measured to be about a few Hz/mm\(^2\) (Fig.9), which is five orders of magnitude lower than the rate at room temperature, and is low enough for the MEG LXe detector.

Figure 9: Dark count rates measured with $3 \times 3 \text{ mm}^2$ sample at at 165K, 205K and 290K.

**Single-photon counting**

It is difficult to count a single photon with a large area SiPM, because the waveform becomes wider due to the large sensor capacitance, which worsens the signal to noise ratio. Furthermore a high uniformity of the gain over pixels and low enough dark count rate are required. We succeeded in resolving single photoelectron peak with the $12 \times 12 \text{ mm}^2$ large area prototype as shown in Fig.10.

Figure 10: Charge spectrum of the dark noise measured with the $12 \times 12 \text{ mm}^2$ prototype of UV-sensitive MPPC.

**Temperature dependence of gain & PDE**

It is known that the gain and the PDE of SiPM depend on temperature, because of shifts of breakdown voltage. Fig.11 shows the measured temperature dependence of the gain and the PDE with the same bias voltages. The temperature coefficients of the gain and PDE are about 2 \%/K, and 5 \%/K, respectively. We are checking the LXe temperature stability in the detector cryostat.
5. Engineering Design

The engineering design of the upgraded detector is being progressed. A possible package design of MPPCs is shown in Fig. 12. A silicon crystal of $12 \times 12$ mm$^2$ is glue on a ceramic base and is covered by a thin quartz window for protection.

The MPPCs will be mounted on a specially designed PCB with coaxial-like signal line structure as shown in Fig. 12. Ninety six PCBs are arrayed along $\phi$-direction on the inner wall.

![Figure 12: Assembly of the MPPC on the inner wall of the cryostat.](image)

The total number of MPPCs is about 4000. The signal from each MPPC goes through the PCB internal line whose characteristic impedance is designed to be 50 $\Omega$, and then connected to a coaxial cable at the end of the PCB. In order to increase the channel density in the vacuum feedthrough, we are developing a new type of PCB-based high-density feedthrough. Several PCBs with a similar design to the PCB for the MPPC mounting are embedded with epoxy glue in a standard ICF vacuum flange. Prototype of the feedthrough was tested, and good vacuum tightness and no serious signal deterioration were confirmed.

At the outside of the LXe detector, the signal is transmitted on about 7 m-long coaxial cable to readout electronics without any signal amplification. Figure 13 shows the effect of the long coaxial cable on the signal transmission measured by using a signal from $3 \times 3$ mm$^2$ MPPC. No serious deterioration of the signal was observed.

6. Summary and Prospects

A UV-sensitive MPPC is under development for the upgraded LXe detector of the MEG experiment in collaboration with Hamamatsu Photonics. A reasonably high PDE (17% at an over-voltage of 1.5 V) is already achieved with a prototype. A further optimization of the MPPC parameters is in progress. We are also accomplishing the engineering design of the upgraded detector.

Hamamatsu Photonics recently announced a development of new technologies, which significantly improve the MPPC performance [5][6]. Since the afterpulses are highly suppressed in the new MPPC. It can be operated at higher bias voltage, which results in higher PDE and gain.

Metal quench resistor is used in the new MPPC instead of a conventional polysilicon quench resistors. Since the temperature coefficient of the metal quench resistor is much smaller than that of the polysilicon one, the resistance can be much smaller for the operation of the MPPC at the LXe temperature. That results in a shorter pulse. We plan to apply the new technologies to the UV-sensitive MPPC for the MEG experiment.

We plan to construct a prototype detector with about 600 MPPCs in year 2013 to demonstrate an improved performance of the proposed concept of the upgraded detector. The construction of the final LXe detector is planned to be started in year 2014.

References