Gamma ray reconstruction with liquid xenon calorimeter for the MEG experiment

Y. Uchiyama*

The University of Tokyo, 7-3-1 Hongo, Bunkyo 113-0033, Japan

Abstract

An innovative gamma-ray detector with liquid xenon was constructed for the MEG experiment to search for the lepton-flavor violating muon decay, $\mu^+ \rightarrow e^+\gamma$. Excellent properties of liquid xenon enable us to measure the energy, timing and position of incident gamma ray with high resolutions. We have developed dedicated reconstruction algorithms for the new detector. Using calibration data with π^- charge exchange reaction taken before and after the physics data taking, performance of the detector during the run in 2008 was studied in detail and good resolutions were demonstrated.

Key words: Liquid xenon scintillator, Lepton flavor violation

1. Introduction

The MEG experiment [1] searches for the lepton-flavor violating muon decay $\mu^+ \rightarrow e^+\gamma$, at Paul Sherrer Institut in Switzerland. Signature of the decay is very simple; a positron and a gamma ray emitted back-to-back, at the same time, with same momentum of 52.8 MeV/c. The background spectrum of gamma ray is highly suppressed at the signal energy while positrons at the signal region are abundant. Hence a precise measurement of gamma-ray energy is the most important point of the experiment. In addition, precise measurements of timing and position powerfully reduce the accidental background rate in a high rate environment. Liquid xenon (LXe) is a suitable choice for a material of gamma-ray detector since it has large atomic number, relatively high light yield and fast decay time. We developed a LXe scintillation detector and the construction was successfully completed in 2007. We started the physics data taking of MEG experiment in 2008.

2. Principle of the measurements

The detector consists of 900 liter LXe and 846 PMTs. PMTs are directly immersed in LXe surrounding the active volume to collect the scintillation light. It is designed such that a gamma ray around 50 MeV can deposit all its energy in LXe active volume. Therefore by efficiently collecting the scintillation light with the PMTs we can reconstruct the gamma ray energy with little influence by the fluctuation of shower development. A distribution of PMT outputs enable us to reconstruct not only the incident position but also the depth of interaction. High time resolution can be achieved by combining a lot of measurements by each PMT.

3. Waveform analysis

Outputs of PMTs are digitized with a fast waveform digitizer [2]. In 2008 run, we took data at 1.6 GHz sampling frequency. Waveform gives us information about pile-up events as well as charge and time. The analysis can be optimized in the offline process.

Compared to a conventional ADC, we can determine the integration window better since we know the pulse leading edge without any ambiguity of trigger time and optimize the signal-to-noise ratio. The baseline is estimated and subtracted event-by-event. A timing of the pulse is picked by the digital constant fraction method, which determines the pulse time as a time at which the signal reaches a given fraction (here 30%) of the full pulse height. We can determine the pulse timing independent of the amplitude.

4. Reconstruction methods

The interaction point is reconstructed by fitting the PMT output distribution. An expected light distribution is calculated so that each PMT output is proportional to solid angle of the photocathode viewed from the reconstructed position. The precision of this method will be limited by the fluctuation of shower developed behind the first interaction point since we assume here that scintillation light comes from a point-like source. To minimize the effect of shower fluctuation, fittings are performed twice only using PMTs in restricted region on the face where gamma ray entered. First fitting uses typically 50 PMTs around the maximum one. Second fitting is then performed with fewer PMTs, typically 16 PMTs, around the result of the first fitting. In addition the difference between the two results gives us the direction of the shower development. Thus it can be used to correct the remaining influence of the shower fluctuation.

With the reconstructed interaction point, we can reconstruct the timing by individual PMT, $t_{\mathrm{hit},i} = t_{\mathrm{PMT},i} - t_{\mathrm{prop},i} - t_{\mathrm{offset},i}$,

---

*On behalf of MEG collaboration

Email address: `uchiyama@icepp.s.u-tokyo.ac.jp` (Y. Uchiyama)

where $t_{\mathrm{PMT},i}$ is time of the i-th PMT measured by the constant-fraction method, $t_{\mathrm{prop},i}$ is time delay during the light propagation in LXe and $t_{\mathrm{offset},i}$ is a constant time offset of the channel. The propagation time is calculated with the distance and incident angle to the PMT. As the incident angle gets larger, the fraction of scattered or reflected photons in the observed light increases. It results in a longer effective path length and thus a longer delay. The hit time, T_{hit}, is then determined with PMTs collecting more than 50 photoelectrons to minimize,

$$\chi^2 = \sum_i \frac{(t_{\mathrm{hit},i} - T_{\mathrm{hit}})^2}{\sigma_i(N_{\mathrm{pe}})^2} \tag{1}$$

, where $\sigma_i(N_{\mathrm{pe}})$ is resolution of each PMT as a function of the number of photoelectrons. Typically about 150 PMTs are used. The fitting process is iterated with rejecting bad χ^2 channels to remove pileup effect.

The energy is reconstructed by summing up outputs of all PMTs after correcting gains and quantum efficiencies. In addition a correction factor is applied to each PMT to correct different coverage of photocathode according to the location on the detector wall. Small non uniformity is still observed in spite of these corrections because of the dependence of light collection efficiency and leakage on the interaction point. Therefore a global correction is applied as a function of the interaction position.

5. Performance

The performance is evaluated by using gamma rays from π^0 decay. π^0 is created by the charge exchange reaction of π^- in a hydrogen target. The π^- beam is supplied from the same beam line where μ^+ beam is extracted in MEG data taking. By selecting two gamma rays from the decay go back-to-back each other, we can get almost monochromatic gamma rays at 55 and 83 MeV. We put a tagging counter composed of two plastic scintillators and nine NaI crystals at the opposite side of the LXe detector. By selecting 83 MeV gamma at the tagging side, we can use 55 MeV gamma which is very close to the signal energy (52.8 MeV).

We measured the position resolutions in dedicated run with lead slits. A lead brick (18 mm thick) with three slits is placed just in front of the gamma ray entrance window of the detector. Shadow of the slits and edges are used to evaluate the resolution. The resolution is estimated to 4.5 – 5.5 mm.

The timing resolution is evaluated by the time difference between LXe detector and the tagging detector. With taking into account the timing resolution of the tagging detector (93 ps) and the target size effect (60 ps), the resolution is estimated to 78 ps with data taken in August. During the physics data taking in 2008 we conducted purification of LXe continuously and we succeeded in gaining the light yield. Thanks to the higher light yield, resolution was improved to 68 ps with data taken in December.

To evaluate energy resolution for 55 MeV gamma ray, we selected the events where 83 MeV gamma ray was detected in the NaI detector with an opening angle larger than 170 degree. The distribution of reconstructed energy is fitted with an asymmetric Gaussian with lower side tail convolved with the pedestal distribution (Fig 1). For the resolution we quote the sigma of higher energy side since it is the most important quantity for the background suppression of the MEG experiment, while the FWHM value is important when we think about the efficiency. The lower tail comes mainly from the interaction of gamma ray on the material in front of the LXe active volume. You also see higher tail in the distribution. It is particular to the π^0 data since in π^- beam much more background from electrons in beam and high energy gamma from π^0 decay are there. These effects are evaluated by comparing pedestal distribution with that in MEG normal data taking. The obtained energy resolution slightly depends on the position and the mean value is 1.75% in higher-side sigma and 5.5% in FWHM.

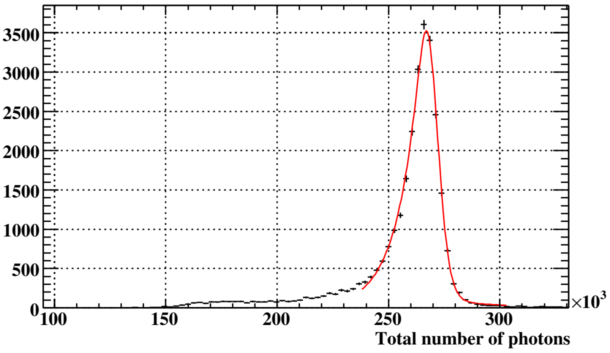

Figure 1: Reconstructed spectrum of 55 MeV gamma in total number of scintillation photons. Energy scale is also determined with this peak.

6. Summary

We successfully constructed a new LXe gamma ray detector and operated it stably during the MEG physics run in 2008. It is the first LXe detector in tons-scale size in use. We have developed reconstruction algorithms for the precise measurement of gamma ray. The performance was evaluated with high-energy gamma rays from π^0 decay, and the preliminary results are given in Table 1 together with our design goal. We confirm that our new algorithms can extract the excellent performance of our LXe detector and sufficiently good resolutions are achieved to improve the current experimental limit to the $\mu^+ \to e^+\gamma$ decay.

Table 1: Summary of current resolutions (in σ).

	Goal	Current resolution
Position (mm)	2–4	5
Timing (ps)	65	68
Energy (%)	1.2–1.5	1.75

References

[1] T. Mori et al., Research proposal to PSI R-9905 (1999).
[2] S. Ritt, Nucl. Instrum. Meth. A518 (2004) 470.