Nuclear Inst. and Methods in Physics Research, A 1047 (2023) 167877

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Commissioning of liquid xenon gamma-ray detector for MEG II experiment

Ayaka Matsushita [a,*], Sei Ban [a], Hicham Benmansour [b,c,d], Giovanni Dal Maso [d,f], Marco Francesconi [b,c], Luca Galli [b], Fumihito Ikeda [a], Toshiyuki Iwamoto [a], Satoru Kobayashi [a], Toshinori Mori [a], Donato Nicolo [b], Rina Onda [a], Wataru Ootani [a], Atsushi Oya [a], Shinji Ogawa [a,1], Angela Papa [b,c,d], Patrick Schwendimann [d,f,2], Yusuke Uchiyama [a], Bastiano Vitali [b,e], Kensuke Yamamoto [a], Taku Yonemoto [a], Keisuke Yoshida [a]

[a] *The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan*
[b] *Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, Polo Fibonacci Largo B. Pontecorvo 3, 56127, Pisa, Italy*
[c] *Dipartimento di Fisica, Universita di Pisa, Polo Fibonacci Largo B. Pontecorvo 3, 56127, Pisa, Italy*
[d] *Paul Scherrer Institute, Forschungsstrasse 111, Villigen PSI, 5232, Switzerland*
[e] *Universita degli Studi di Roma "La Sapienza", Piazzale Aldo Moro, 5, Roma, 00185, Italy*
[f] *Institute for Particle Physics and Astrophysics - ETH Zurich, Otto-Stern-Weg 5, Zurich, 8093, Switzerland*

ARTICLE INFO

Keywords:
Calorimetry
SiPM
Liquid xenon

ABSTRACT

The liquid xenon (LXe) gamma-ray detector in the MEG II experiment measures the energy, position and timing of the gamma-ray from $\mu^+ \to e^+\gamma$, and it is the key to the unprecedented sensitivity of the experiment. All the photo sensors of 4092 VUV MPPCs and 668 PMTs were read out for the first time and a physics data collection started in 2021. The detector response was monitored all through the beam time, and the LXe detector operated stably. The timing and energy resolution were measured using the gamma-rays from the π^0 decays after charge exchange reaction of charged pions in a liquid hydrogen target. The detector has been successfully commissioned and is ready for the long physics run.

1. Introduction

The MEG II experiment searches $\mu^+ \to e^+\gamma$ using the most intense μ^+ beam at Paul Scherrer Institute. $\mu^+ \to e^+\gamma$ is a charged lepton flavor violation decay. The observation would be evidence of new physics. In MEG experiment, an upper limit on the branching ratio of $\mathcal{B}(\mu \to e\gamma) < 4.2\times10^{-13}$(90% C.L.) was obtained. The goal of the MEG II experiment is to search for the decay with a 10 times better sensitivity using upgraded detectors.

A liquid xenon (LXe) detector measures the position, energy and timing of the gamma-ray. It consists of 900 liters of liquid xenon, 4092 VUV-sensitive MPPCs [1] on the entrance face and 668 PMTs on the other faces. The readout of all channels started in the 2021 engineering run.

2. Start of physics data taking

The condition of the photo sensors changes over the beam time. One of the significant factors is the photon detection efficiency (PDE) of the MPPCs. The PDE was found to decrease over beam time from the data of the previous run. Therefore, the calibration of PDE using α-ray emitted from ^{241}Am installed in the detector is important to obtain a stable energy scale. It is also found that the PDE can be recovered by annealing. All the MPPCs will be annealed every year before the physics run during the accelerator shutdown period.

Fig. 1 shows the energy scale history estimated with the gamma-rays from Li(p, γ)Be. The energy scale before the PDE calibration decreases, while that after the calibration is stable.

The physics run started after the calibration data taking for all detectors and the setting required for $\mu^+ \to e^+\gamma$ trigger. The gamma-ray and the positron are emitted at the same time in a radiative muon decay (RMD), so RMD events are useful to check the time coincidence. The RMD peak was observed (Fig. 2) and this means the $\mu^+ \to e^+\gamma$ trigger was fired correctly.

3. Timing resolution evaluation in CEX run

Charge exchange(CEX) reactions of π^- and a proton are used to evaluate the timing resolution. A π^- beam is injected into a liquid hydrogen target to generate π^0 via $\pi^- p \to \pi^0 n$. After that, two gamma

---

[*] Corresponding author.
E-mail address: ayaka@icepp.s.u-tokyo.ac.jp (A. Matsushita).
[1] Present address : Kyushu University, 744 Motooka, nishi-ku, Fukuoka-shi, Fukuoka, 819-0395, Japan.
[2] Present address : Department of Physics, University of Washington, Seattle, WA, Washington, 98195-1560, USA.

https://doi.org/10.1016/j.nima.2022.167877
Received 15 July 2022; Received in revised form 15 November 2022; Accepted 21 November 2022

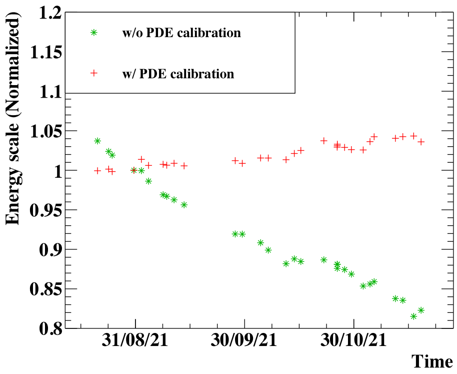

Fig. 1. Energy scale history estimated with the gamma-rays from Li(p, γ)Be The vertical axis corresponds to the sum of the charges detected by the sensors. The energy scale after PDE calibration is stable.

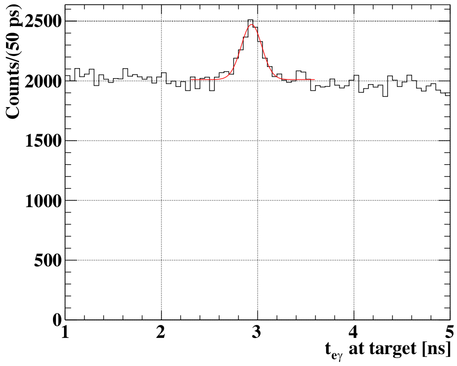

Fig. 2. Time difference between a gamma-ray and a positron.

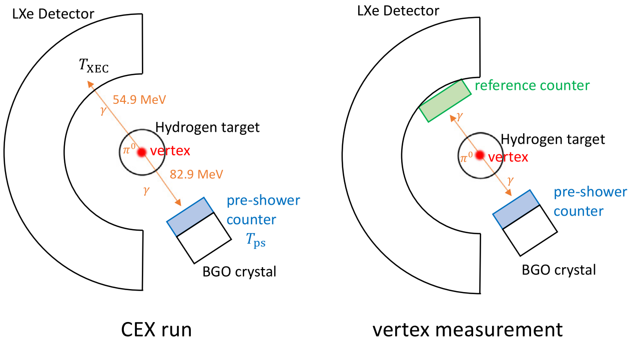

Fig. 3. The setup for the CEX run and the vertex measurement.

Table 1
The timing resolution of LXe.

	Measured	MC
σ_{abs} [ps]	85.4	57.3
σ_{int} [ps]	37.8	38.4

Table 2
The performance of LXe.

	MEG [3]	MEG II
Position [mm]	5	2.5 ± 0.2
Energy [%]	1.7–2.4	1.8 ± 0.1
Timing [ps]	64	85.4 ± 5.1

rays are emitted from $\pi^0 \rightarrow \gamma\gamma$. One of the gamma-ray energies emitted back-to-back is close to the energy of the signal events.

Two kinds of timing resolution are used for the estimation of the LXe detector timing resolution. One is the absolute timing resolution σ_{abs} and the other is the intrinsic timing resolution σ_{int}:

$$\sigma_{\mathrm{abs}} = \sigma\left(T_{\mathrm{LXe}} - T_{\mathrm{ps}} - T_{\mathrm{TOF}}\right) \ominus \sigma_{\mathrm{ps}} \ominus \sigma_{\mathrm{vertex}}, \tag{1}$$

$$\sigma_{\mathrm{int}} = \sigma\left(T_{\mathrm{PM,even}} - T_{\mathrm{PM,odd}}\right)/2. \tag{2}$$

The setup of CEX run is shown in Fig. 3. A pre-shower counter is used in CEX run, and the gamma-ray hit timing on the pre-shower counter [2] is used as a reference time. T_{LXe} is a reconstructed gamma-ray hit timing in the LXe detector, and T_{ps} and σ_{ps} are the gamma-ray hit timing in the pre-shower counter and the timing resolution. $\sigma\left(T_{\mathrm{LXe}} - T_{\mathrm{ps}} - T_{\mathrm{TOF}}\right)$ is smeared by the uncertainty of the $\pi^0 \rightarrow \gamma\gamma$ vertex position, so the effect of the vertex distribution has to be subtracted to estimate the timing resolution.

Two counters were installed, one on the LXe detector side and the other on the opposite side, to measure the vertex distribution (Fig. 3). σ_{vertex} was evaluated from the time difference between the two counters, whose resolutions are known by a prior measurement. The result is $\sigma_{\mathrm{vertex}} = 65.0 \pm 6.1$ ps (9.8 ± 0.9 mm). This measured vertex size is larger than the measured π^- beam size of 4 mm even after the effect of π^- spread is taken into account. The cause of the large measured vertex size is currently unknown.

The timing resolution of the LXe detector is evaluated with the measured σ_{vertex}. Table 1 summarizes the results together with those for a Monte Carlo (MC) simulation. The measured absolute timing resolution is worse than the result of MC; the cause of this difference needs to be investigated.

The energy resolution can also be evaluated in CEX run, and the analysis is in progress.

4. Performance of the LXe detector

The current estimation of the performance is summarized in Table 2. Improvements of the calibration and reconstruction methods are ongoing.

5. Conclusion

The LXe detector is ready for the long-term physics data taking, and the detector performance and stability will be improved furthermore.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work is supported by MEXT/JSPS KAKENHI, Japan Grant Numbers 20H00154, 21H04991, and JSPS, Japan Core-to-Core Program, A. Advanced Research Networks.

References

[1] K. Ieki, et al., Large-area MPPC with enhanced VUV sensitivity for liquid xenon scintillation detector, Nucl. Instrum. Method A 925 (2019) 148–155, http://dx.doi.org/10.1016/j.nima.2019.02.010.

[2] R. Onda, et al., Optimal design of plastic scintillator counter with multiple sipm readouts for best time resolution, Nucl. Instrum. Methods A 936 (2019) 563–564, Frontier Detectors for Frontier Physics: 14th Pisa Meeting on Advanced Detectors.

[3] A.M. Baldini, Y. Bao, E. Baracchini, et al., Search for the lepton flavour violating decay $\mu^+ \rightarrow e^+\gamma$ with the full dataset of the MEG experiment, Eur. Phys. J. C 76 (2016) 434, http://dx.doi.org/10.1140/epjc/s10052-016-4271-x.