論文の内容の要旨

Liquid xenon detector with highly granular scintillation readout to search for $\mu^+ \to e^+\gamma$ with sensitivity of 5×10^{-14} in MEG II experiment

（MEG II 実験における感度 5×10^{-14} での $\mu^+ \to e^+\gamma$ 探索のためのシンチレーション光を高精細に読み出す液体キセノン検出器）

氏名：小川　真治

MEG II experiment

The Standard Model is a fundamental model in the particle physics validated by many experiments up to the electroweak energy scale. Even with its success, it is thought to be a low energy approximation of more fundamental physics due to the existence of some unexplained phenomena and theoretical difficulties. Therefore, physics beyond the Standard Model is actively searched.

A charged lepton flavor violating decay of a muon, $\mu \to e\gamma$, is an interesting probe in the search of the new physics. Experimentally reachable branching ratio of this decay is predicted by many extensions of the Standard Model, while this decay is prohibited in the Standard Model by the lepton flavor conservation law. Since this decay emits a coincident pair of monochromatic e and γ in the back-to-back direction, a signal event is efficiently distinguishable from the many other background events by searching for an event satisfying this criteria. The current upper limit on the branching ratio of this decay is set to 4.2×10^{-13} (90% confidence level) by the MEG experiment.

An upgrade of the MEG experiment called MEG II experiment is planned for a further improvement of the sensitivity by another one order of magnitude. In the MEG II experiment, the resolutions of all the detectors are improved because the sensitivity in MEG was limited by the number of the accidental background events.

Detector design

In the MEG experiment, the liquid xenon (LXe) γ-ray detector was used. It measured the hit position, timing, and energy of the 52.8 MeV γ-rays from the signal decay, by detecting the scintilation light from the LXe on the photomultiplier tubes (PMT).

In order to improve the γ-ray resolutions, the liquid xenon detector has been upgraded for MEG II in this thesis. The major upgrade is to replace the 216 PMTs on the γ-ray entrance face with 4092 multi-pixel photon counters (MPPC) as shown in Fig. 1(a) and 1(b). A high granularity and a good uniformity of the scintillation readout realized by the MPPCs enable us to achieve a good position and energy resolution, especially for the shallow events near the entrance face. This improvement is important because roughly half of the signal γ-rays hit this shallow region. The layout of the PMTs on the side faces is also modified to achieve a good uniformity of the readout for the events hitting near them.

Development of the VUV-MPPC and detector construction

The MPPC used for this detector has to be sensitive to the xenon scintillation light, centered at λ = 175 nm, in the vacuum ultraviolet (VUV) range. Because there was no commercial MPPCs sensitive to it, a new VUV-sensitive MPPC shown in Fig. 1(c) has been developed in collaboration with Hamamatsu Photonics K.K. Its sufficient performance was confirmed in the lab test, including a photon detection efficiency (PDE) above 15% for the xenon scintilation light.

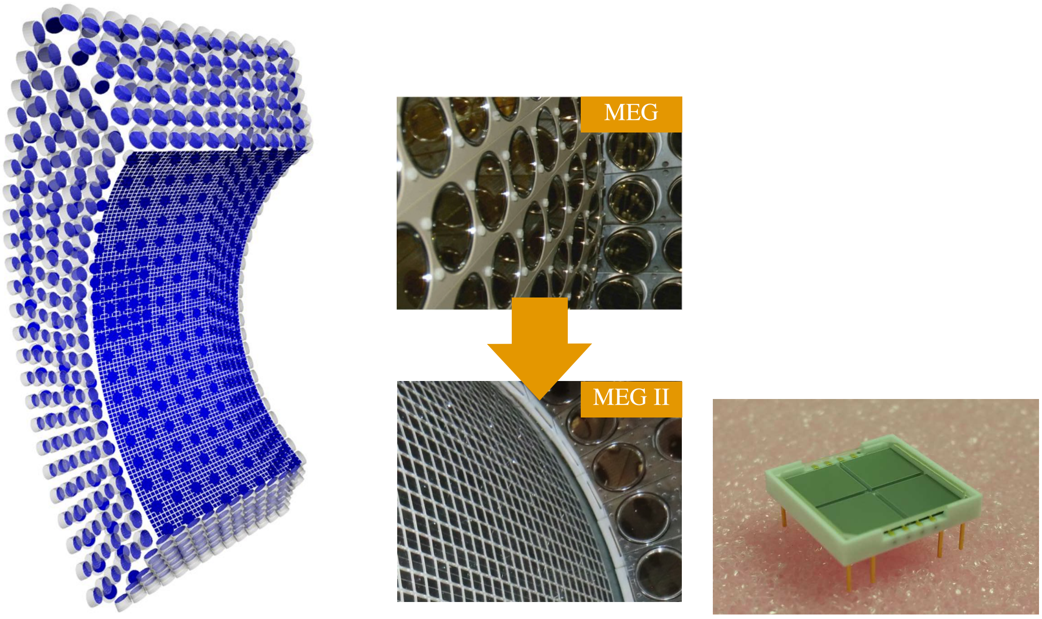
The 4092 MPPCs were successfully installed into the detector after a quality check. The bad PMTs found in MEG were also replaced with a good surplus one. The MPPCs were aligned by two independent measurements; a measurement by a laser scanner and that by a collimated γ-rays. By comparing the results of both measurements, a sufficient alignment precision was confirmed.

Evaluation of the detector performance

Commissioning of the LXe detector was carried out. A series of pilot runs was performed from 2017 to 2019 by using the MEG II intensity muon beam in order to evaluate the detector performance.

The position resolution was measured by placing a lead collimator in front of the detector. The resolution is estimated from the width of the slit on the reconstructed hit distribution. An improvement in the position resolution for the shallow events is confirmed. Even though a slightly worse resolution than expected is observed for the deep events, its effect on the sensitivity is found to be limitted due to a small number of the deep events.

The timing resolution was evaluated by applying an even-odd analysis for the signal-like energy γ-rays from the radiative muon decays. Thanks to an optimization of an analysis parameter newly introduced in this thesis, an improvement of the timing resolution is achieved. The estimated timing resolution becomes 55 ps for the signal γ-ray, which is much better than the



(a) (b) (c)

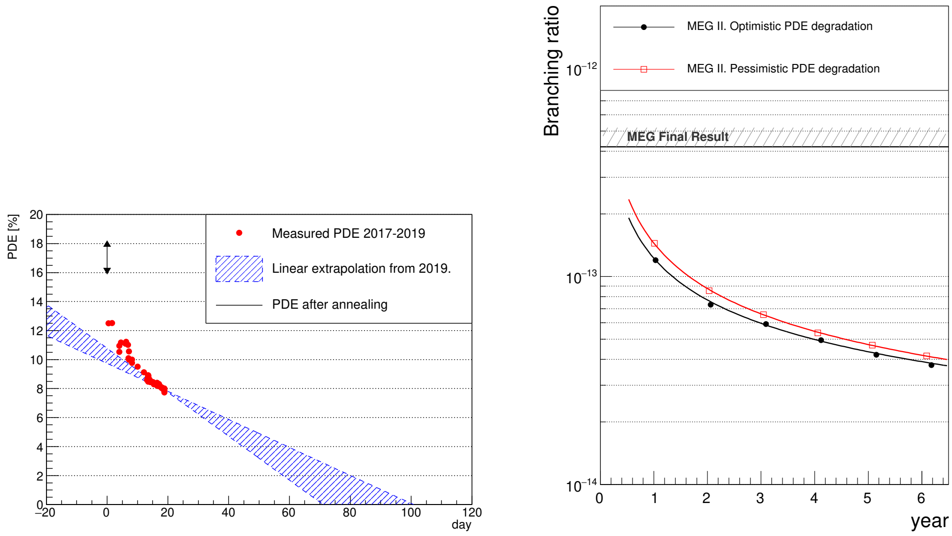
Figure 1 (a) The LXe γ-ray detector developed for MEG II. (b) Replacement of 216 PMTs on the γ entrance face with 4092 MPPCs. (c) A VUV-sensitive MPPC newly developed.

design value of 76 ps.

The energy resolution for the signal-like energy γ-ray was evaluated by fitting the energy spectrum of the background γ-rays. Thanks to the good uniformity of the readout realized by the MPPCs, the energy resolution for the shallow events is found to be improved from MEG. On the other hand, the resolution for the deep events is measured to be worse than expected, and the worse resolution is also confirmed for the 17.6 MeV γ-ray. A similar degradation was also observed in the MEG LXe detector, and is probably caused by the same reason. Though the cause of the degradation cannot be identified, this thesis reveals that the degradation is not due to a stochastic process on the photosensors by focusing on an even-odd energy resolution.

In addition to the worse energy resolution, another issue was found in the pilot run. A degradation of the PDE of the MPPCs to the xenon scintilation light was found during the MEG II beam usage (Fig. 2(a)). A response to the visible light also shows a little degradation at the same time. Since the degradation is correlated with the beam usage, this should be a radiation damage, while any damage was neither reported nor expected on the MPPCs at the radiation level of our experiment. It is also found that an annealing, where the MPPCs are kept at about 70°C for two days, can almost fully recover the degradation.

Though the cause of the degradation is not able to be identified in this thesis, a surface damage on the MPPC is the most suspicious cause. In the surface damage, stationary charges are accumulated near the sensor surface, which can distort the electric field nearby. Because the VUV photons convert near the sensor surface compared to the visible light, the VUV PDE can be deteriorated by the distortion, while the visible PDE is hardly affected.



(a) (b)

Figure 2 (a) History of the measured MPPC PDE. The x-axis is the MEG II beam usage time. Blue band shows a linear extrapolation of the degradation. (b) Sensitivity of MEG II as a function of the data-taking time. Each line shows the sensitivity assuming the most optimistic scenario and the most pessimistic scenario for the PDE degradation speed in the future, respectively.

Expected MEG II sensitivity with the LXe detector

The effect of the PDE degradation on the branching ratio sensitivity of MEG II is discussed. If we assume the most pessimistic scenario for the PDE degradation in the future, the PDE will become too small to operate the detector only after the 60 days of the data-taking. Even though the MPPCs can be annealed once per year during an annual accelerator maintenance period, the original MEG II data-taking plan is not possible since it assumes 120 days continuous data-taking for each year. As an alternative plan, a reduction of the beam rate is proposed. By halving the beam rate, the MPPCs and the detector can be operated for the given 120 days beam time. Comparing to a simple reduction of the data-taking period, the number of the accidental backgrounds becomes smaller and the degradation of the sensitivity can be mitigated.

The branching ratio sensitivity of MEG II with this LXe detector is estimated to be $6.0–6.6 \times 10^{-14}$ with three years of data-taking (Fig. 2(b)) based on the measured detector performance. The ambiguity of the sensitivity comes from that of the PDE degradation speed in the future. This is worse than the planned sensitivity of 5×10^{-14} mainly due to the worse energy resolution and the MPPC PDE degradation. Nonetheless, the planned sensitivity is found to be still achievable by a realistic extension of the beam time up to 4.6 years. Therefore, it is concluded that the LXe detector has a sufficient performance to search for the $\mu \to e\gamma$ decay with a sensitivity of 5×10^{-14}.