# Lepton Flavour Violating Muon Decay at MEG

H. Nishiguchi
*The University of Tokyo, 7-3-1 Hongo, Bunkyo 113-0033, Japan* [*]

The MEG Experiment searches for a lepton flavour violating decay, $\mu^+ \to e^+\gamma$ , with a branching-ratio sensitivity of $10^{-13}$ in order to explore the parameter region predicted by many theoretical models beyond the Standard Model. Detector construction and Engineering Run were completed in 2007, and the first Physics Run will be carried out in 2008. In this paper, the prospects of MEG Physics Run in 2008 is described in addition to the experimental overview.

## 1. Introduction

The Standard Model of elementary particle physics is one of the greatest success of modern science. Based on the principles of gauge symmetries and spontaneous symmetry breaking, everything had been consistently described until experimental evidence for neutrino oscillation was shown by SuperKamiokande for the first time.

Now, **Lepton Flavour Violation (LFV)** among charged leptons, which has never been observed while the quark mixing and the neutrino oscillations have been experimentally confirmed, is attracting a great deal of attention, since its observation is highly expected by many of well motivated theories beyond the Standard Model[1, 2]. Additionally, it would be a clear evidence of existence of new physics beyond the Standard Model because it is strongly suppressed in the Standard Model. Even if we assume a finite neutrino mass within the Standard Model, $\mu^+ \to e^+\gamma$ could occur with a negligible rate, $\approx 10^{-50}$. In consequence, recent reviews on flavour physics (see Ref.[1] for example) thus indicate high expectations for the next leading $\mu^+ \to e^+\gamma$ search experiment, **MEG** [3], which is just starting the physics-data taking in 2008.

The ambitious goal of the MEG experiment is to search for a $\mu^+ \to e^+\gamma$ decay with an improved sensitivity by at least two orders of magnitude over the current best limit of $\mathcal{B}(\mu^+ \to e^+\gamma) < 1.2 \times 10^{-11}$(90%C.L.) [4]. It is predicted that $\mu^+ \to e^+\gamma$ is naturally causable with a branching ratio just below the current upper limit,$10^{-11} \sim 10^{-14}$, by the leading theories for physics beyond the standard model, *eg.* the Supersymmetric theories of Grand Unification or Supersymmetric Standard Model with the *seesaw* mechanism (see Ref.[2] for a review).

The signal of $\mu^+ \to e^+\gamma$ decay is very simple and is characterized by a 2-body final state of a positron and $\gamma$-ray pair emitted in opposite directions with the same energy, 52.8MeV, which corresponds to half the muon mass. There are two major backgrounds in the search for $\mu^+ \to e^+\gamma$ . One is a physics (prompt) background from a radiative muon decay, $\mu^+ \to e^+\nu\nu_e\bar{\nu}_\mu\gamma$ , when the positron and the $\gamma$-ray are emitted back-to-back with the two neutrinos carrying off tiny energy. The other background is accidental coincidence of a positron from a normal Michel decay, $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ , with a high energy random photon. The source of high energy $\gamma$ ray is either a radiative decay $\mu^+ \to e^+\nu\nu_e\bar{\nu}_\mu\gamma$ , annihilation-in-flight or external bremsstrahlung of a positron. Both are schematically shown in Figure 1 in addition to the signal kinematics. The background is primarily dominated by accidental coincidence. Suppressing such an accidental overlap holds a key leading MEG to a successful conclusion.

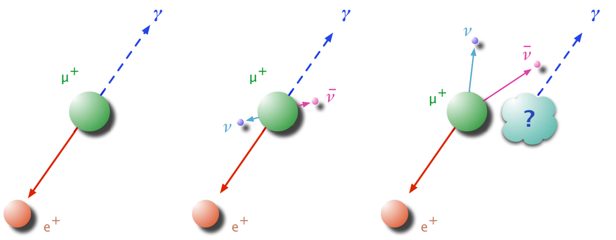

Figure 1: Schematic views of $\mu^+ \to e^+\gamma$ event signature and backgrounds; (Left) $\mu^+ \to e^+\gamma$ Signal, (Centre) Physics Background, (Right) Accidental Background

The excellent sensitivity of the MEG experiment is enabled by three key elements: (1) the world's most intense DC muon beam provided at Paul Scherrer Institute (PSI); (2) an innovative liquid xenon scintillation $\gamma$-ray detector [5]; (3) a specially designed positron spectrometer with a highly graded magnetic field [6].

The beam line and the detector construction have been completed in summer 2007, and Beam- and Detector-Engineering run has been carried out right after that. In this engineering run, all the detector-calibration procedures were established. In addition to the calibration, this engineering run provided a lot

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[*] Present Address: Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba 305-0801, Japan

of information, *eg.* detector performances, expected number of backgrounds, and what we have to maintain until the first physics data-taking in order to gain an experimental sensitivity as much as possible.

## 2. Beam and Detector

In order to fulfill the ambitious goal, the MEG experiment is designed carefully. The MEG detector apparatus consists of the muon beam transport system and the detector system; the Photon Detector and the Positron Spectrometer. A schematic view of the MEG apparatus is shown in Figure 2.

A DC muon beam is the best prove to search for $\mu^+ \to e^+\gamma$ since experimental sensitivity is mainly limited by accidental overlap of background events. The 590 MeV proton cyclotron at the Paul Scherrer Institute (PSI) delivers up to 2.2 mA proton beam, which is the world record for such proton cyclotrons at present (2008). This megawatt accelerator has played a role of *progenitor* of the most intense DC pion and muon beams and made it possible to measure the rare decays and the search for "classical" forbidden decay modes, *eg.* $\mu \to e\gamma$ . The MEG experiment employs this most intense DC muon beam.

The momentum and direction of positrons are measured precisely by a Positron Spectrometer, which consists of a superconducting solenoidal magnet specially designed to form a highly graded field, an ultimate low-mass drift chamber system, and a precise time measuring counter system [6]. The Positron Spectrometer has to satisfy several requirements. First, the spectrometer must cope in a stable way with a very high muon rate up to $3 \times 10^7$ s$^{-1}$. Second, a very-low-mass tracker is required since the momentum resolution is limited primarily by multiple Coulomb scattering. Furthermore, it is also important to minimize the amount of material from the point of view of background suppression in the photon detector. Additionally, excellent bidirectional spacial resolution of the tracker is necessary for both the transverse and longitudinal directions. Finally, excellent timing resolution is also necessary in order to suppress accidental overlap of events.

In order to attain such requirements, we adopted a specially designed solenoidal magnet with a highly graded field. The MEG solenoidal magnet is designed to change its radius between the centre and the outside. This provides a highly graded magnetic field (1.27 T at $z = 0$ and decreasing as $|z|$ increases, 0.49 T at $z = 1.25$ m, where $z$ is the coordinate along the beam axis) and allows to solve the problems inevitable in a normal uniform solenoidal field. In a uniform solenoidal field, positrons that emitted close to 90° undergo many turns in the tracker volume. However, the MEG solenoidal magnetic field can sweep such positrons out of the fiducial tracking volume quickly. In addition, this special magnetic field has yet another advantage. In this specially designed field, positrons with the same absolute momenta follow trajectories with a constant projected bending radius independent of the emission angles while in a uniform solenoidal field the bending radius depends on the emission angle. This allows us to discriminate sharply high momentum signal positrons from the tremendous Michel positron background originating from the muon-stopping target. The Positron Spectrometer therefore does not need to measure the positron trajectory in the small radius region. In other words, the drift chambers can be sensitive only to higher momentum positrons and blind to most of the Michel positrons that can cause accidental coincidences. Thanks to this benefit, this spectrometer can cope within such a highly-irradiated environment.

While all positrons are confined by the solenoid, the $\gamma$ ray pass through the thin superconducting coil of the spectrometer with ≈80% transmission probability, and are detected by an innovative liquid-xenon photon detector [5]. Scintillation light emitted inside liquid xenon are viewed from all sides by photo-multiplier tubes (PMT) that are immersed in liquid xenon in order to maximize direct light collection. Liquid-xenon scintillator has very high light yield (≈75% of NaI crystal) and fast response, which are the most essential ingredients for precise energy and timing resolutions required for this experiment. A scintillation pulse from xenon is very fast and has a short tail, thereby minimizing the pile-up problem. Distributions of the PMT outputs enable a measurement of the $\gamma$-ray incident position with a few mm accuracy.

Absorption of scintillation light by impurities inside liquid xenon, especially water and oxygen, could significantly degrade the detector performance, although there is no absorption by liquid xenon itself. In order to solve the absorption issue, a purification system that circulates and purifies xenon gas was developed [7]. Various studies were carried out using a 100 liter prototype detector with 238 PMTs in order to gain practical experiences in operating such a new device and to prove its excellent performances. The prototype detector was tested by using $\gamma$ rays from laser Compton scattering at National Institute of Advanced Industrial Science and Technology (AIST) in Tsukuba, Japan. Gamma rays with the Compton edge energy of 10, 20 and 40 MeV were generated via backward scattering of laser photons by 800 MeV electron beam in the storage ring of AIST. Another test was carried out at PSI by using the pion charge exchange reaction, $\pi^- p \to \pi^0 n$, which provides two $\gamma$ rays from the $\pi^0$ decay. By tagging back-to-back $\gamma$ rays, monochromatic $\gamma$ rays of 55 MeV and 83 MeV are selected. The energy resolution of 2 %, the timing

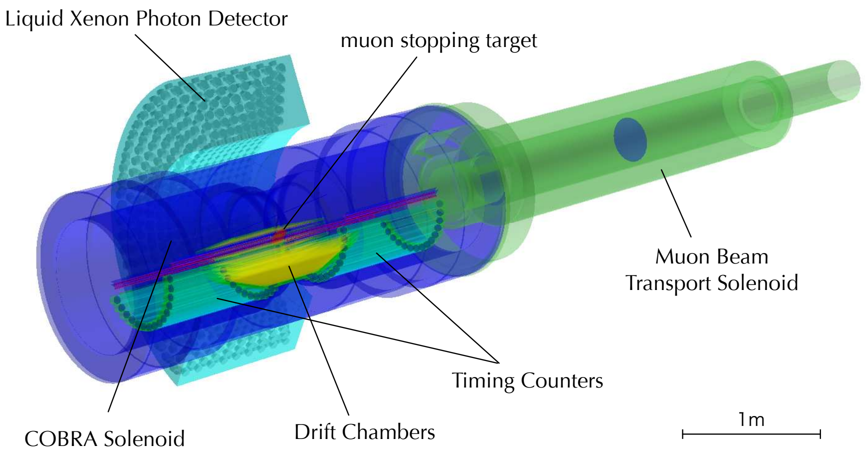

Figure 2: A schematic view of the MEG apparatus

resolution of 65 ps, and the position resolution of ≈4 mm depending on the incident position with respect to the PMT positions were obtained by these beam tests. In addition to the performance estimation, the purification method was established.

Based on the prototype works, the final MEG liquid-xenon photon detector, which is filled with ≈900 liter of liquid xenon incorporating 846 PMTs, was built. In order to speed up the purification process for the final detector, a liquid-phase purification system that uses a cryogenic centrifugal fluid pump capable to flow 100 liter of liquid xenon per hour was developed [8]. Currently(2008), this is the world's largest liquid-xenon photon detector.

All the signals, from PMTs and drift chambers, are individually recorded as digitized waveform by a custom chip called Domino Ring Sampler (DRS) [9]. The PMT signals are digitized at 1.6 GHz sampling speed to obtain a timing resolution of 50 ps by bin interpolation, and the drift chamber signals are digitized at 500 MHz in order to compensate wide drift time distributions. Recording all the waveform may cause difficulties concerning data size, data-acquisition (DAQ) flow speed *etc.*, however the rewards outweigh the works and difficulties, because waveform digitizing of all channels gives us an excellent handle to identify the pile-up event and to suppress noise that can worsen detector resolutions.

## 3. Run 2007 (Engineering Run)

In summer 2007, construction of all detector components was completed. Then we immediately started the detector operation in a phased manner.

We started several studies for the liquid-xenon photon detector, liquefaction test, liquid xenon transferring test, long term monitoring, stability checks, PMT gain calibrations, and liquid-xenon purification *etc.* In parallel with this, positron-spectrometer conditioning was performed, drift-chamber gas control test, high-voltage conditioning, wire alignment by using cosmic rays, position-measurement calibration, relative gain calibration *etc.* After such fundamental studies and conditioning, the muon-beam commissioning was performed with the final detector apparatus. Final focusing of the muon beam, beam profile measurement, and muon rate measurement, were carried out.

After the muon-beam commissioning has been completed, we started Engineering Run in October 2007. Figure 3 shows an typical example of accidental background events in the Engineering-Run. We successfully ran the whole program of the Engineering Run. All the detector components were operated over three months, trigger and DAQ electronics were integrated and data-taking worked at expected event rate, a full set of calibration has been performed. The physics data that has been taken at the Engineering Run was analyzed in the winter shutdown 2007-2008, and its results gave a certain feedback to the detector maintenance and also the offline-analysis development. One of the most important analysis of Engineering Run 2007 are to complete the reconstruction algorithm for all the detector, to evaluate the detector performances, and to estimate the feasible sensitivity of MEG.

By analyzing the data of engineering-run 2007, we could evaluate all the detector performances and verify the quality of Monte Calro (MC) simulation for the MEG detector apparatus. Unfortunately, the ob-

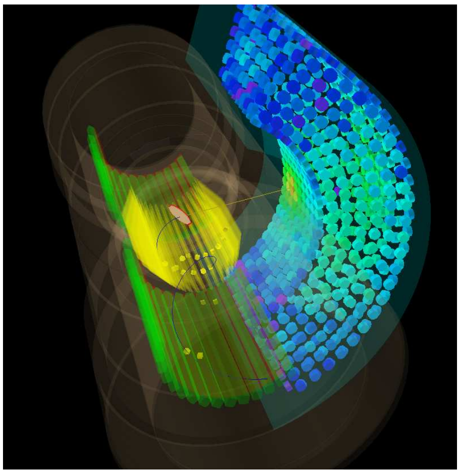

Figure 3: An example of event display of Engineering-Run 2007

tained performances were little worse than the design value due to several unsatisfactory conditioning of detectors, *eg.* approximately 27 % of dead channel of the drift-chamber system degraded the spectrometer resolutions, still remained impurity of liquid xenon deteriorated the photon-detector resolutions, and badly-fabricated internal clock circuit of DRS provided poor timing resolutions for all sub-detectors. Although such bad performances were obtained, we could figure out the sources of deterioration and reproduce phenomenon by MC incorporating artificially-degraded detector descriptions.

Table I summarize the obtained performances by the Engineering-Run 2007 and the expected performances for the MEG Physics-Run 2008. Expected values are obtained by assuming that all the deterioration clarified in 2007 could be fixed by the maintenance works during winter shutdown of 2007-2008. All resolutions are converted to Full-Width-at-Half-Maximum (FWHM).

Table I Detector Performances, Obtained(2007) and Expected(2008)

| Quantity | Run 2007 | Run 2008 |
|---|---|---|
| $\gamma$-Energy Resolution (%) | 6.5 | 5.0 |
| $\gamma$-Timing Resolution (ns) | 0.27 | 0.15 |
| $\gamma$-Spatial Resolution (mm) | 15 | 9.0 |
| $\gamma$-Detection Efficiency (%) | >40 | >40 |
| $e^+$-Momentum Resolution (%) | 2.1 | 1.1 |
| $e^+$-Timing Resolution (ns) | 0.12 | 0.12 |
| $e^+$-Angular Resolution (mrad) | 17 | 17 |
| $e^+$-Detection Efficiency (%) | 39 | 65 |

## 4. Run 2008 (Physics Run)

On the basis of the result of Engineering-Run 2007, we completed various maintenance on each sub-detectors during the winter-shutdown term 2007-2008, and now we are carrying out the final detector conditioning. The MEG Physics Run is being planned to start in summer 2008. We here discuss the feasible sensitivity of the MEG experiment by employing obtained performances and expected improvements.

We are planning to have 20 weeks of beam time in 2008. According to the PSI proton-accelerator operation procedure, 20-weeks beam time is corresponding to $8\times10^6$ sec. By employing these numbers with expected beam intensity, $3\times10^7$ sec$^{-1}$, the number of background event for the MEG physics run 2008 is expected to be 0.4.

Finally, let us evaluate the single event sensitivity and the feasible upper limit that will be determined by physics run 2008. By assuming 65 % of positron-detection efficiency, 40 % of $\gamma$-ray detection efficiency, 70 % of selection efficiency, $3\times10^7$ s$^{-1}$ of muon-beam intensity, $T = 8 \times 10^6$ s of experiment-running time, and $\Omega/4\pi = 0.09$ of detector solid angle that is calculated from the detector geometrical acceptance, the single event sensitivity for the MEG physics run 2008 can be evaluated as $\mathcal{B}^{2008}_{\rm S.E.S.}(\mu^+ \to e^+\gamma) = 2.6 \times 10^{-13}$. In case of no candidate observed, $2.6 \times 10^{-13}$ single event sensitivity implies the upper limit on $\mathcal{B}^{2008}(\mu^+ \to e^+\gamma)$ at the 90 % confidence level as $< 7.2 \times 10^{-13}$ for the MEG physics run 2008. This sensitivity will be eventually improved down to $1\times10^{-13}$ by the follow-up data-taking after next year.

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