Search for the decay $\mu \rightarrow e\gamma$ in the MEG experiment

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Abstract. The MEG experiment is currently searching for the lepton-flavor-changing decay $\mu \rightarrow e\gamma$. The Standard Model implies the $\mu \rightarrow e\gamma$ by neutrino oscillations but it cannot be observed in experiments because of too small branching ratio. Many extensions of the Standard Model, however, predict the decay within a reach of the MEG experiment and it is a clear evidence of new physics. A liquid xenon gamma-ray detector and a positron spectrometer with a gradient magnetic field enables better sensitivity than the current limit by two orders of magnitude. The physics data taking started in 2008 and then upgrades of the detector brought a stable operation in 2009-year run. We report the preliminary result on the 2009 data together with a current status and a future of the experiment. The obtained upper limit of the branching ratio is $\text{Br}(\mu^+ \rightarrow e^+\gamma) < 1.5 \times 10^{-11}$ at 90% confidence level (C.L.).

1. Search for the Decay, $\mu \rightarrow e\gamma$

In particle physics the Standard Model (SM) can clearly explain a large number of particle phenomena but an extended theory is desired to overcome the artificial features of the SM. One of the observations to imply a scenario of new physics is the $\mu \rightarrow e\gamma$.

Currently there are three generations of quarks and leptons are known. The SM describes mixing of flavors in the quark sector by the Cabibbo-Kobayashi-Maskawa (CKM or KM) matrix and in the lepton sector by the Pontecorvo-Maki-Nakagawa-Sakaga (PMNS or MNS) matrix. Currently there is no observation of flavor violation only in the charged lepton sector. The search for the rare muon decay, $\mu \rightarrow e\gamma$, is sensitive to many models of the SM extensions because they predict the branching ratio around the current upper limit, $\text{Br}(\mu^+ \rightarrow e^+\gamma) < 1.2 \times 10^{-11}$ (90% C.L.) given by the MEGA experiment in 1999 [1]. Even without help of the extensions, the $\mu \rightarrow e\gamma$ decay occurs by the neutrino oscillation but the branching ratio is too small, $\text{Br}(\mu \rightarrow e\gamma) \approx (\alpha/128\pi) \sin^2 2\theta_{12} (\Delta m_{21}^2/M_W^2)^2 < 10^{-54}$, where $\Delta m_{21}$ is the mass difference of a muon neutrino and an electron neutrino and $M_W$ is a W boson mass, and $\sin^2 2\theta_{12} = 0.86$ and $\Delta m_{21}^2 = 8 \times 10^{-5}$ eV$^2$ are assumed. Therefore the $\mu \rightarrow e\gamma$ is a clear signal of the charged-lepton-flavor violation (cLFV) if it is observed in experiments.

The $\mu \rightarrow e\gamma$ signal is a two-body decay with 52.8 MeV energy corresponding to a half mass of a muon. Experiments that search for the $\mu^+ \rightarrow e^+\gamma$ are confronted with two types of backgrounds: an accidental background and a radiative decay background. The former is the most dominant background, and is due to the accidental pileup of positrons from Michel decays, $\mu^+ \rightarrow e^+\nu_e\nu_\mu$, with gamma-rays that originate from radiative muon decays (RD), $\mu^+ \rightarrow e^+\nu_e\nu_\mu\gamma$, or from the annihilation of positrons in flight. The radiative muon decays

1 On behalf of the MEG Collaboration
themselves make up the second type of background as well, when the energies and the opening angle of the positron and the gamma-ray occasionally end up around the signal region. The signal and the two backgrounds have different distributions of observables, which is taken into account in a likelihood function for the $\mu^+ \rightarrow e^+ \gamma$ analysis.

A low muon-beam rate and good detector resolutions, especially for the gamma-ray energy, are essential to suppress the backgrounds, as well as a large number of muons and a sufficient detection efficiency. Intense muon beam at Paul Sherrer Institut (PSI) in Switzerland is suitable for the MEG experiment because provided DC surface muons are preferred to avoid pileups rather than AC beam. We developed a large liquid xenon (LXe) detector to detect gamma rays in a high resolution with an excellent performance of a rare-gas scintillator. The COBRA (COnstant-Bending-RAdius) magnet with a special gradient magnetic field enables to sweep positrons away quickly with hitting low-mass drift chambers, then finally timing counters measure the precise timing at the end of the track.

2. Detector
The overview of the detectors is shown in Figure 1. Detectors consist of the positron detector inside the COBRA magnet and the LXe gamma-ray detector outside the magnet. The positron detectors, which consist of a drift chamber (DCH) and a scintillation timing counter (TIC), are mounted around a lower part from a muon stopping target. Two sets of TIC are located at the upstream and downstream side, each of which consists of two layers of arrays along the beam axis ($z$) and the azimuthal axis ($\phi$). The muon stopping target is a sheet of polyethylene and polyester with a 205 $\mu$m thickness corresponding to 18 mg/cm$^2$ on plane and gives 82% stopping efficiency thanks to a slanted angle with 20.5° relative to the beam axis.

![Figure 1. Layout of detectors in the MEG experiment.](image)

2.1. Positron Spectrometer
The COBRA magnet has an excellent performance to select a momentum by a radius thanks to the gradient magnetic field, where tracks of the same momentum have the same radius irrelevant to emission angles. Furthermore, a non-zero radial component of the magnetic field forces to sweep positrons away quickly. As a result pileups of positrons reduce compared to those in a normal solenoidal magnet. Total thickness of the magnet including its cryostat is 0.197 $X_0$.
and its light and thin structure enables gamma rays to pass through the magnet toward to the Lx detector with a good transmission efficiency of 85%. The thin structure can hold a strong magnetic field such that the central field is 1.27 T at $z = 0$ and slowly decreasing to 0.49 T at edge as $|z|$ increases.

The drift chambers consist of 16 modules that are radially aligned with 10.5° intervals in the azimuthal angle. The radius is from 19.3 cm to 27.9 cm in order to select only positrons around the signal region. Timing counter array detects a positron in the angular range of $0.08 < |\cos \theta| < 0.35$. The array consists of two layers of different plastic scintillators along $z$ direction and $\phi$ direction. A timing $\phi$-counter is an array of 15 plastic scintillation bars with a $4 \times 4 \times 80 \text{ cm}^3$ dimension. It covers $160^\circ \phi$-acceptance between $-150^\circ$ and $10^\circ$. A timing $z$-counter can tag hits of positrons although it is under preparation.

2.2. The Liquid Xenon $\gamma$-Ray Detector

The 900-liter LXe detector is designed to detect a gamma ray around 52.8 MeV signal after penetrating the COBRA magnet and the detector vessel. Liquid xenon has an excellent performance as a scintillator such as a high density of 2.95 g/cm$^3$ corresponding to $X_0 = 2.77$ (cm), a high light yield (80% of NaI(Tl)), a fast response of a 45-ns decay time for gamma rays, no absorption of the scintillation light, an uniform response of the scintillation light because of liquid and a particle discrimination by injecting particle thanks to different scintillation process. Although there are some difficulties to treat the liquid xenon, we developed a photo-multiplier tube (PMT) for the liquid xenon to detect high-rate vacuum-ultraviolet (VUV) photons ($\lambda \sim 178$ nm), a pulse-tube refrigerator to keep xenon liquid stably and two purification systems for liquid and gaseous xenon. The LXe detector equips 846 PMTs immersed in xenon and attached on six faces with recording waveforms from all PMTs. The spatial distribution of the scintillation light allows energy, timing and position measurement.

To calibrate and monitor the LXe detector, many apparatus are equipped. In order to calibrate gains and quantum efficiencies of PMTs blue-light LEDs on the wall and alpha sources of $^{241}$Am stretched on wires are immersed in the liquid xenon. For a constant light-yield monitor a Cockcroft-Walton (CW) proton accelerator provides gamma rays of 4.4 MeV, 12.0 MeV and 17.7 MeV energies after a nuclear reaction of $^6$Be($\alpha$, n)$^{12}$C and $^7$Li(p,$\gamma$)$^8$Be at a proton target. In addition, even without a special setup of a beam line, Am/Be source for a 4.8 MeV gamma ray enables the monitor. Meanwhile, the $\pi^-$ beam from the same beam line as muons brings a charge exchange (CEX) reaction at a liquid hydrogen target, $\pi^- p \rightarrow \pi^0 n$. It produces two gamma rays in a $\pi^0$ decay at the energy range from 54.9 MeV to 82.9 MeV and gamma rays get monochromatic after selecting a back-to-back decay by a tagging counter opposite to the LXe detector. The $3 \times 3$ NaI(Tl) array with avalanche photo diodes allows the selection of two-gamma-rays opening angle and is mounted on a mover system in order to scan the whole acceptance of the LXe detector. The CEX calibration is the most important method because the 54.9 MeV gamma ray is near to the signal 52.8 MeV energy. It is suitable for a determination of the energy scale and a performance evaluation of the energy, timing and position at arbitrary position on the detector.

2.3. Data Acquisition

Trigger, waveform sampling and data acquisition (DAQ) systems have been developed for the MEG. Trigger logic is programmable on FPGA (Field-Programmable Gate Array) chips and signals from the detectors are arranged in triple layers, which enables a complicated physical selection and custom triggers for each event type. Domino ring sampler (DRS) chips allow a fast waveform sampling up to 6 GHz with 1024 cells and 11-bit resolution. It reads out at 800 MHz for the drift chamber and 1.6 GHz for the LXe detector and the positron timing counter. The DAQ system, MIDAS (Maximum Integration Data Acquisition System), collects and records
data from all electronics and ROME (Root based Object oriented Midas Extension) framework offers an event display. ROME also performs an analysis for detector calibrations, an event reconstruction and a calculation for the final result.

3. Reconstruction and Performance

3.1. Reconstruction
Reconstructions of the positron and the gamma ray are separately performed in each detector after analyzing waveforms, then a vertex information can be acquired by extracting the positron track.

The reconstruction has different performances for the $z$ and $r$ positions because wires are stretched only along beam direction ($z$) in the drift chamber. Due to this difference, the relative angle is separately treated as two components of $\theta_{e\gamma} = \theta_e - (\pi - \theta_\gamma)$ and $\phi_{e\gamma} = \phi_e - (\pi - \phi_\gamma)$ on the analysis. In the radially aligned timing counter, $z$ position is determined by a charge ratio of two PMTs at both ends of the scintillator. After hit clusters and track candidates are found in drift chambers, the positron track is reconstructed by using the Kalman filter that can include the multiple Coulomb scattering, the energy losses and the magnetic field effectively [2].

Time and position of gamma rays are obtained by least squares fitting. Defined $\chi^2$ for the timing considers a time of flight and charge statistics. The reconstruction of the position uses local PMTs only on the detection face with taking solid angles into account. The energy is converted from the total number of scintillation photons in all PMTs weighted with the reciprocal of the coverage of the photo-cathode. Intrinsically non-uniform response of the energy scale arises from the reconstruction, though it is corrected by a measurement.

3.2. Run
In the previous run in 2008, some parts of the drift chamber had suffered from a discharge problem and the light yield of the LXe detector had been increasing by the purification. Throughout the 2009 run, the detector was quite stable for both the drift chamber and the LXe detector. The run consists of the physics run and dedicated periodic or long-term calibration runs. Twelve types of the trigger are mixed in the physics run. The signal candidate is taken at 5 Hz rate and totally 6.5 Hz with including triggers for a pedestal, positrons from Michel decays, LED flashing, cosmic rays and so on. Before the physics run started we had the CEX run to calibrate the LXe detector for twelve days. During physics data taking the gains of the PMTs were calibrated for times a week by dedicated runs using LEDs and alpha sources. The light yield was monitored by the 17.7 MeV gamma rays from the CW accelerator as well.

3.3. Event Selection
The event candidates of $\mu^+ \rightarrow e^+ \gamma$ is finally analyzed in an analysis region. The region is blinded until the calibration and the analysis are fixed. As soon as physics data is taken, a first analysis is performed and discards unnecessary events by using only timing information. Simultaneously the blind region is selected by the gamma-ray energy ($|E_\gamma - m_\mu/2| < 4.8$ MeV) and the relative timing ($|t_{e\gamma}| < 1$ ns) as shown in Figure 2. In addition, we defined the analysis region as 50 MeV $< E_e < 56$ MeV, 48 MeV $< E_\gamma < 58$ MeV, $|\phi_{e\gamma}| < 50$ mrad, $|\theta_{e\gamma}| < 50$ mrad and $|t_{e\gamma}| < 0.7$ ns. The time window corresponds to ten-sigma window in detector resolutions. Sideband data beside the blind region is useful to calibrate the detectors and to estimate backgrounds and sensitivities. The $E_\gamma$ sideband of the lower gamma-ray energy region contains radiative muon decays, therefore the gamma ray and the positron coincidently make a peak on the $t_{e\gamma}$ distribution. On the other hand the signal and the radiative muon decay are absent in two $t_{e\gamma}$ sidebands, where only accidental background forms a flat $t_{e\gamma}$ distribution.
3.4. Performance Evaluation

The $\mu^+ \rightarrow e^+ \gamma$ analysis needs the likelihood function, which is based on probability density functions (PDFs) of the signal, the RD background and the accidental background. It is important to measure resolutions and distributions in order to construct the PDFs and determine the likelihood on the events.

The timing resolution is evaluated by the peak from the radiative muon decay in $E_\gamma$ sideband outside the blind region at the range of 40 MeV to 47 MeV. Figure 3 shows the peak fitted with double Gaussian function and the timing resolution resulted in $149 \pm 10$ ps in 70% fraction as core sigma and 250 ps sigma in tail. The timing resolution at the signal energy is estimated to be 142 ps in sigma by correcting for the small energy dependence.

Figure 4 shows the 54.9 MeV gamma-ray peak obtained from the $\pi^0$ decay in CEX run. The peak of the energy has a low-end tail because of interactions before reaching liquid xenon and leakage around the face, therefore a combined function of Gaussian and exponential function is
used for the fitting. The high-end energy resolution is essential to identify the signal because the background gamma-ray energy of the radiative decay has an upper edge and is lower than the signal energy. We construct the position-dependent resolution map by scanning the whole detection face, then the typical energy resolutions are estimated by depths ($w$) to be 2.1% (2 cm ≤ $w$ < 38 cm), 2.8% (1 cm ≤ $w$ < 2 cm) and 3.3% (0 cm ≤ $w$ < 1 cm). To evaluate the position resolution, collimators made of lead with 1 cm slits are put on the vessel of the LXe detector to project gamma rays from the $\pi^0$ decay. By means of a Monte Carlo (MC) simulation, the depth resolution and a position dependence of the resolution is considered by taking the difference between true and reconstruction. The resolutions of the position reconstruction are evaluated to be 5 mm and 6 mm along the direction orthogonal to the LXe front face and for the depth, respectively.

In Figure 5 the background energy distribution of positrons from the Michel decays is fitted with a theoretical function, that is due to the kinematics of the decay, but smeared by a double Gaussian to account for the detector resolution. The resolution component of the function is separately shown in dashed line. The energy and position resolution for the signal PDF is estimated to tracks with two full turns in the drift chambers such that two turns are separately reconstructed as independent one turn and then a difference of each reconstruction indicates a resolution. The energy resolution is described with double Gaussian function, estimated to be 0.39 MeV as the core resolution in 79% fraction with 1.71 MeV sigma as a tail in 21%. The positron angular resolutions are also evaluated along two directions to be $\sigma_{\theta_e} = 11.2$ mrad and $\sigma_{\phi_e} = 7.1$ mrad, where $\sigma_{\phi_e}$ is an 85% component of double Gaussian.

4. Analysis for the $\mu \rightarrow e \gamma$

4.1. Likelihood Analysis

The goal of the maximum likelihood analysis is to obtain the best fit value of the number of the $\mu^+ \rightarrow e^+\gamma$ signal ($N_{\text{sig}}$), as well as the RD background ($N_{RD}$) and the accidental background ($N_{BG}$). Based on the measured performance or background distributions, three types of PDFs are defined for the signal ($S$), the RD background ($R$) and the accidental background ($B$) as a function of observables. Main observables are the following set, $\vec{x}_i = (E_e, E_\gamma, \theta_{e\gamma}, \phi_{e\gamma}, t_{e\gamma}, \delta E_e, \delta E_\gamma, \delta \theta_{e\gamma}, \delta \phi_{e\gamma}, \delta t_{e\gamma}$), accordingly PDFs are separated for each independent observable. The variables with $\delta$ indicate resolutions of the detectors used in the
construction of the PDFs. The likelihood function is then defined in Equation 1,
\[
L(N_{\text{sig}}, N_{\text{RD}}, N_{\text{BG}}) = \frac{N_{\text{obs}}!}{N_{\text{obs}}} \prod_{i=1}^{N_{\text{obs}}} \left( \frac{N_{\text{sig}}}{N} \cdot S(\bar{x}_i) + \frac{N_{\text{RD}}}{N} \cdot R(\bar{x}_i) + \frac{N_{\text{BG}}}{N} \cdot B(\bar{x}_i) \right),
\]
where \( N_{\text{obs}} \) is the observed number of events in the analysis region and \( N \) is the sum, \( N = N_{\text{sig}} + N_{\text{RD}} + N_{\text{BG}} \).

The best way to convert the number of signals to the branching ratio is to count the Michel decays instead of the decayed muons because instability of the beam and uncertainty of the muon stopping efficiency can be ignored and the detection efficiency of positrons is cancelled out. Relatively the signal is normalized as described in Equation 2,
\[
\frac{\text{Br}(\mu^+ \to e^+\gamma)}{\text{Br}(\mu^+ \to e^+\nu_e\bar{\nu}_\mu(\gamma))} = \frac{N_{\text{sig}}}{N_{\text{e}\text{e}}} \times \frac{f_{e\text{e}d}}{P_{e\text{e}d}} \times \frac{\epsilon_{\text{trig}}}{\epsilon_{\text{trig}} \epsilon_{\gamma\gamma}} \times \frac{A_{\text{TIC}}}{A_{\text{TIC}}} \times \frac{A_{\text{DCH}}}{A_{\text{DCH}}} \times \frac{\epsilon_{\text{DCH}}}{\epsilon_{\text{DCH}}} \times \frac{1}{\epsilon_{e\gamma}} \times \frac{1}{A_{\text{e}\text{e}}},
\]
where \( N_{\text{e}\text{e}} = 18,096 \) is the number of observed Michel decays, \( f_{e\text{e}d} = 0.114 \pm 0.002 \) is the fraction of Michel spectrum after the analysis cuts, \( P_{e\text{e}d} \) is a 10^{-5} pre-scale factor for the trigger, \( \epsilon_{\gamma\gamma}/\epsilon_{\text{e}\text{e}} \) = 0.84 \pm 0.02 is the trigger efficiency of a direction match for positrons, \( A_{\text{TIC}}/A_{\text{TIC}} \times \epsilon_{\text{DCH}}/\epsilon_{\text{DCH}} = 1.12 \pm 0.06 \) is the signal-to-Michel ratio of an acceptance at the timing counter and the reconstruction efficiency, \( \epsilon_{\text{LXe}} = 0.58 \pm 0.02 \) is the efficiency for the detection of gamma rays and \( A_{\text{LXe}} = 0.99 \pm 0.01 \) is the acceptance of the LXe detector after detecting the positron. As a result the branching ratio is obtained from the number of signal events by the formula: \( \text{Br}(\mu^+ \to e^+\gamma) = N_{\text{sig}} \times (1.01 \pm 0.08) \times 10^{-12}, \) which corresponds to the decays of \( 6 \times 10^{13} \) muons yields.

4.2. Result
The sensitivity in the MEG 2009 run is evaluated by means of the averaged results in the toy-MC simulation such that many toy experiments are generated based on the PDFs and data set in 2009, as well as the fit in the \( t_{e\gamma} \) sideband for a consistency check. With using the likelihood ratio ordering principle [3], the expected 90% C.L. branching-ratio upper limit is calculated to be
\[
S_{2009} = 6.1 \times 10^{-12}.
\]
The obtained sensitivity improves from the previous 2008 result, \( S_{2008} = 1.3 \times 10^{-11} \) [4].

The analysis region was opened and no strange reconstruction was found by checking each event in detail. The event distribution is plotted on the \( E_{\gamma} - E_e \) plane in Figure 6 (a) and on the \( t_{e\gamma} - \cos \Theta_{e\gamma} \) plane in Figure 6 (b).

In total, 370 events are observed in the analysis region. The best fit value of the signal is calculated to be 3.0 events, and that of the RD background is \( N_{RD} = 35^{+24}_{-22} \). The 90% C.L. upper limit of the \( N_{sig} \) is estimated to be 14.5, while \( N_{sig} = 0 \) is inside the confidence interval of 90%. In this calculation the systematic uncertainties are included, but the result is still preliminary. The upper limit of the branching ratio is finally obtained as
\[
\text{Br}(\mu^+ \to e^+\gamma) < 1.5 \times 10^{-11} \text{ at 90% C.L.}
\]

5. Update and Plan
After the analysis for the 2009 data, we have improved the reconstruction and understood several uncertainties, which is involved in the next result. Detector alignment had a large uncertainty for opening angles, therefore it was investigated in detail. Gamma rays from Am/Be source scanning
on the detector or collimated gamma rays from the nuclear reactions of protons by the CW suggest the actual position of PMTs of the LXe detector. Globally cosmic-ray muons through both the LXe detector and the drift chamber allow a relative alignment. These alignments reduced systematic uncertainties of opening angles by a factor of 0.4-0.5.

In addition, the magnetic field mapping, that is used for the positron tracking, was reconsidered to identify and resolve uncertainties previously unknown. Intrinsic bias in the Kalman filter was also studied in the MC simulation and is now well understood. In the reconstruction, a magnetic-field component along \( \phi \) direction had previously been neglected because it is tiny and much less than 1% of that of \( z \) direction, however, it is now taken into account. Accordingly the positron resolution of the energy and the angles improved as well as the uncertainties.

After the unblinding, we observe that the backgrounds estimated from the sidebands are in good agreement with the number of background events extracted by the fit in the analysis region. Given the larger background statistics in the sidebands, we decide to use the sideband data to determine the amount of background in the analysis region. Therefore, in the calculation of the branching ratio, we apply the constraints from the side-band background information to the fitting and the profile likelihood method is adopted for the toy-MC generation.

After the 2009 run new calibration systems were installed such as a neutron generator for the 9-MeV gamma ray, a target dedicated to Mott scattering for monochromatic positrons. For three months in 2010 we have accumulated twice as many muon decays as the events in 2009 with stable conditions. Performance of triggers and DAQ improved especially on \( \mu^+ \rightarrow e^+\gamma \) direction matching. Thus our next result will include 2010 data and will appear with the combined statistics of the years.

In 2011 a long run for four months is planned with an upgrade of high-voltage module with less noise and a more efficient live time by a buffer readout. Additionally BGO crystals instead of NaI arrays for the CEX run and the timing \( z \)-counter will be installed to make data taking more efficient. For a few years a long and stable run will be expected toward to the \( \mu^+ \rightarrow e^+\gamma \) observation.

**Figure 6.** Distribution in analysis region. The signal PDFs are superimposed as contours at 1, 1.64 and 2 sigma as blue solid, dot-dashed, and dashed lines respectively. The number shows the rank given by \( S/(0.1R+0.9B) \).
6. Summary
The MEG experiment reported the upper limit of the $\mu^+ \rightarrow e^+ \gamma$ branching ratio on the 2009 run. With the improved analysis, next result will be presented by combining the 2009 run with the 2010 run, corresponding to three times larger statistics than 2009 data. Currently the statistics limit the sensitivity and the physics data taking will be going on for the next few years. The performance of the detector and analysis are still improving toward to the branching ratio of $10^{-13}$.

References
[1] Brooks M L et al 1999 Phys. Rev. Lett. 83 1521-1524
[2] Kalman R E 1985 Transaction of the AMSE-J, Basic Engineering D 82 35-45
[3] Feldman G J and Cousins R D 1998 Phys. Rev. D 57 3873-3889
[4] Adam J et al 2010 Nucl. Phys. B 834 1-12