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Performance of the MEG detector to search for $\mu^+ \to e^+\gamma$ decays at PSI

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The MEG experiment, which searches for a rare μ decay, $\mu \to e\gamma$, to explore supersymmetric grand unification, has started physics run since 2008 at Paul Scherrer Institute, Switzerland. Its innovative detector system, which consists of 900 liters of liquid xenon scintillation photon detector and a e^+ spectrometer with a superconducting magnet, drift chamber, and timing counter, enables orders of magnitude better sensitivity than previous experiments. The detector performance of the MEG experiment mainly at physics run in 2009 is described here in detail together with the detector calibration and monitoring methods.

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1. Introduction

In the neutral lepton sector, lepton flavor is already known to be violated through the discovery of neutrino oscillation. However in the charged lepton sector, the lepton flavor violation (LFV) has not been observed yet. In the Standard model with taking into account the neutrino oscillation effects, a branching ratio of LFV decay like $\mu \to e\gamma$ is still tiny and is not possible to reach by the current detector resolution. On the other hand, new physics like supersymmetry, grand unified theories, or seesaw mechanisms predicts measurable LFV such as $10^{-11} - 10^{-14}$ level. Therefore, the discovery of charged LFV would be a clear evidence of physics beyond the standard model. A goal of the MEG experiment is to reach branching ratio of $\mu \to e\gamma$ to 10^{-13} level, which is more than an order of magnitude better sensitivity than the current experimental limit ($\mathscr{B}(\mu \to e\gamma) < 1.2 \times 10^{-11}$ set by MEGA experiment in 1999[1]), and which enables us to have a real chance to discover new physics. In 2008, three months physics data were taken and the first result was published[2]. In this paper, the detector performance during two months physics data taken in 2009 is described.

2. MEG Experiment

The MEG experiment is done at Paul Scherrer Institute (PSI) in Switzerland. PSI has the most intense 1.3MW proton cyclotron accelerator that produces the most intense DC μ beam (more than $10^8 \mu^+/s$), which is essential to reach 10^{-13} level sensitivity for $\mu \to e\gamma$ search. DC μ beam is suitable to reduce an accidental background. Since $\mu^+ \to e^+\gamma$ decay is a clear two body kinematics, these features, such as back-to-back, monochromatic 52.8 MeV, and time coincident, are used to identify the signal. There are mainly two kinds of background sources to mimic the signal, radiative μ^+ decays $\mu^+ \to e^+\nu\bar{\nu}\gamma$ (RMD), and an accidental coincidence of an Michel e$^+$ with a random γ. Random γ is coming from RMD, bremsstrahlung, or annihilation-in-flight. The accidental background is the dominant background for this experiment. Michel decay energy spectrum is almost flat at around the 52.8 MeV signal region, e^+ spectrometer should be operational under high rate environment. The γ-ray energy spectrum is decreasing exponentially near the 52.8 MeV signal region. It means that the photon detector resolution is crucial to reduce the background events although the accidental background rate is related with all the detector resolutions. To fulfill such requirements, we have developed high precision low mass e^+ spectrometer and high performance photon detector. e^+ spectrometer consists of superconducting magnet(COBRA), drift chamber(DC), and timing counter(TC). γ-ray is detected by photon detector with 900 liters of liquid xenon(LXe) viewed by 846 PMTs which are immersed directly in LXe. Waveforms of all detectors are recorded by waveform digitizer which are necessary to deal with intense μ beam and to identify pileup events. A more detailed description of the MEG detector is given in [2].

In 2008, a discharge problem happened for many DC modules, and the 70% of the detection efficiency was lost, and the momentum and angle resolutions were also affected. It turned out that HV lines were affected by the long term exposure of helium atmosphere. These problems were reproduced at the laboratory, and fixed before 2009. In 2009 physics runs, all chambers were working fine, and the e^+ efficiency including TC hits reached to be $\sim$40% and the resolutions were improved. In 2008, gaseous purification was performed for LXe detector during physics run

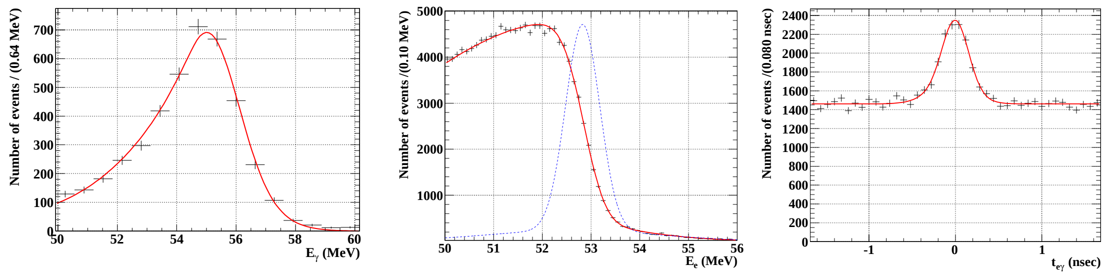

Figure 1: Left figure shows the energy spectrum of monochromatic 55 MeV γ-ray measured by the photon detector. Asymmetric shape especially at the lower energy tail is coming from the γ-ray interaction at the material in front of the photon detector or the shower leakage from the incident face. Middle figure shows the e^+ energy spectra for signal and background. Data points show the Michel spectrum data, and the line is the fitting result. Dashed line shows the signal response extracted from two turn events. Right figure shows the $T_{e\gamma}$ spectrum which has a clear RMD peak with a constant acidental background.

and after. Then, the light yield was increased by 45% in 2009, and the purification during the physics run was no longer necessary, which enabled the detector to be more stable. In order to monitor this light yield change (or absolute γ-ray energy scale), several calibration methods have been developed, Cockcroft-Walton (CW) proton accelerator, cosmic ray events, and AmBe source etc. The light yield was successfully monitored with 1% precision by these calibrations, especially by this CW calibration which makes use of 17.6 MeV γ-ray via Li(p,γ)Be reaction.

3. Detector Performance

We have evaluated detector performance using many calibration methods from physics runs and dedicated calibration runs. Almost monochromatic γ-rays with the energies of 55, 83 MeV are available once back-to-back γ-rays are selected via $\pi^- p \to \pi^0 n$, $\pi^0 \to \gamma\gamma$ charge exchange reaction (CEX). Since the 55 MeV γ-ray is close to our signal energy(52.8 MeV), this is a suitable and ideal calibration method at around signal region for photon detector. To select back-to-back events, tagging detector which consists of NaI array with APD readout is put on the opposite side of the xenon detector. Left of Figure1 shows the photon detector response to 55 MeV γ-ray. We can estimate energy, timing, and position resolutions at different incident positions by moving NaI from this CEX calibration as well as the signal response and the detection efficiency. The results were 2.1% for γ-ray energy resolution with depth>2 cm, >67 ps for timing resolution, 5$\sim$6mm for position resolution, and 58% for detection efficiency. In order to estimate e^+ detector performance, those events which have two turn tracks are used. Two turns are independently reconstructed, and the residuals of the crossing point are regarded as resolutions of momentum, θ, and ϕ angles. The results are 0.74% of momentum resolution, 11.2 mrad of θ, and 7.1 mrad of ϕ angle resolutions in 2009 analysis. e^+ background spectrum is obtained by the Michel decay spectrum in physics data itself, which is evaluated by fitting the theoretical Michel spectrum to Michel decay data smeared by detector momentum resolution. From this method, we can extract the momentum resolution, too. Middle of Figure1 shows the e^+ energy spectra for signal and background. The resolution of relative angle between e^+ and γ-ray is the combination of e^+ detector angle resolution, xenon detector position resolution, and vertex resolution on the target. In total, the resolution of $\theta_{e\gamma}$ is estimated to be 14.7 mrad, and that of $\phi_{e\gamma}$ is 12.7 mrad taking into account 3.3$\sim$3.4 mm resolution of the vertex resolution on the target. Relative timing between e^+ and γ-ray is estimated by RMD. Since this event has a coincident time between e^+ and γ-ray, it is suitable to study a relative timing resolution although γ-ray energy is lower than signal region and the decay direction is not back-to-back. Resolution of $T_{e\gamma}$ consists of each detector timing resolution, tracking ambiguity etc., and the obtained resolution is 142 ps in 2009 shown in the right of Figure1. This event is one of the background events for $\mu \to e\gamma$ search as explained already, but it's not serious, and can be a good test to detect $\mu \to e\gamma$ events, and can be used to estimate overall detection efficiency study, too.

We took physics run for about two months in 2009, which is shorter period than that in 2008, but the data statistics in 2009 became in total twice as much as that in 2008 thanks to the improved e^+ efficiency. Taking into account the detector performance described above, the sensitivity (which is defined as an average upper limit at 90% confidence level(C.L.) of many toy MC experiments) was found to be 6.1×10^{-12} for 2009 data, which is twice as good as the current experimental upper limit (1.2×10^{-11}). A likelihood analysis of the observed spectra yields an upper limit on the branching fraction $\mathscr{B}(\mu^+ \to e^+\gamma)/\mathscr{B}(\mu^+ \to e^+\nu\bar{\nu}) < 1.5\times10^{-11}$ at the 90% C.L. An analysis for 2009 physics data in detail is described in [3]. Since this result is still limited by statistics, we continue data taking at least for 2$\sim$3 years to reach our sensitivity to 10^{-13} level, which should depend on the detector performance. Several possibilities are already considered in order to improve our detector performance, such as a monochromatic e^+ beam calibration with Mott scattering, 9 MeV Nickel γ-ray calibration with beam on, and reconstruction algorithm improvements etc.

4. Summary

MEG experiment has started physics data taking since 2008. Many calibration and monitoring methods have been established to check MEG detector performance. Based on the evaluated detector performance, the branching fraction sensitivity of 2009 data was estimated to be 6.1×10^{-12} at 90% C.L., and the obtained upper limit of the branching fraction by a likelihood analysis was 1.5×10^{-11} at 90% C.L. All results about 2009 data are still preliminary. This result is still limited by statistics, and MEG detector is capable to reach 10^{-13} level branching fraction sensitivity within 2$\sim$3 years, and further improvement should be possible for resolutions of all detectors.

References

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