Search of charged Lepton Flavor Violation decay $\mu \to e\gamma$: the MEG experiment

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The MEG experiment searches for the decay $\mu^+ \to e^+\gamma$, which is strictly forbidden in the Standard model, while new theories, such as supersymmetric grand unified theory and seesaw model of neutrinos, predict observable branching ratio just below the current upper limit.

The data taking for this search was started in 2008, and the physics run was performed for three months this year. Analysis of this 2008 data gives an upper limit BR($\mu^+ \to e^+\gamma$) $\leq 2.8 \times 10^{-11}(90\%C.L.)$.

1. Introduction

Recent observations of neutrino oscillations show that neutrinos have non-zero masses[1]. This induces lepton flavour violation (LFV) also in the charged lepton sector, but in the frame work of the Standard Model (SM), the prediction of it is far below the experimental reach even if we take the neutrino oscillations into acount.

While the SM has been a great success so far, scientists do not believe that this provides complete answers to all our questions about matter, and there have been discussed many theories beyond the SM. Most of such new theories predict a big enhancement in the charged LFV, such as $\mu \to e\gamma$. Predicted rate for this decay differs depending on the models of theories and some models predict the branching ratio[2][3] to be accessible experimentally, while it is strongly suppressed under the frame work of the SM. Hence, searches for cLFV is a promising probes for a new physics.

The current limit for the branching ratio BR($\mu^+ \to e^+\gamma$) $\leq 1.2 \times 10^{-11}$ is set by MEGA experiment[4].

2. Experimental principle

The decay $\mu^+ \to e^+\gamma$ is characterized by a simple 2-body final state. In the rest frame of μ^+, positron and γ are emitted coincident in time, back to back and each with an energy equal to half the muon mass.

In the experiment, two kinds of phenomena can be recognized as if a signal $\mu^+ \to e^+\gamma$. First is radiative muon decay (RMD) $\mu^+ \to e^+\nu_e\bar{\nu}_\mu\gamma$. Second is an accidental coincidence of a positron from normal muon decay $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ (Michel decay) and a γ from RMD, e^+ bremsstrahlung or annihilation in flight. In both the cases, positrons and γs coming from the muon stopping target can have energy smaller than that of the signal $\mu^+ \to e^+\gamma$ event. And for the rate of these two, it can be shown[5] that the accidental one dominates taking into account the muon rate, acceptances and resolutions.

To find $\mu^+ \to e^+\gamma$ out of these backgrounds, it is important to precisely measure energies, directions, and timing of both the positrons and γs.

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3. The MEG detector and performance

The MEG detector is shown schematically in Fig.1. It is composed of a liquid xenon(LXe) gamma ray detector and a positron magnetic spectrometer. A high intensity continuous beam of surface muons brought to the πE5 beam channel at PSI is stopped by polyethylene/polyester sandwich target with the thickness of 205μm. Stop rate on target is $\sim 3 \times 10^7 \mu^+/\mathrm{s}$.

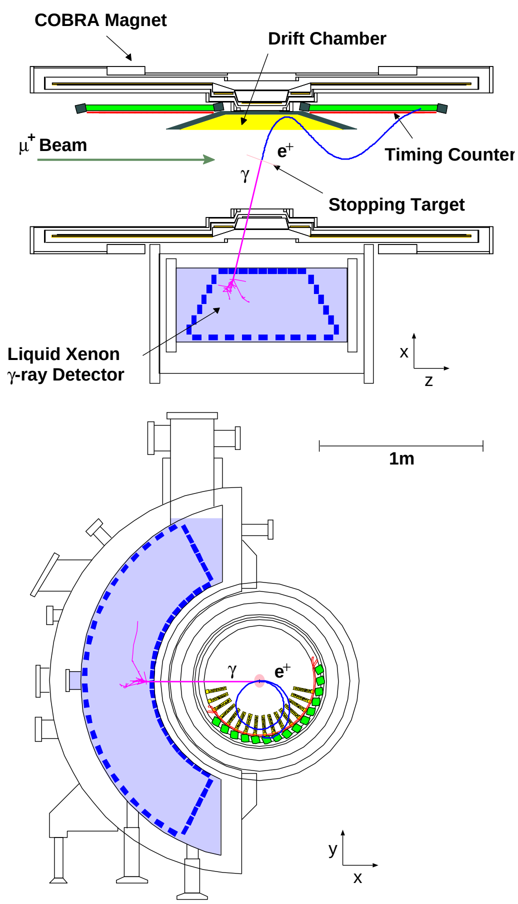

Figure 1. Schematic of the MEG detector

The gamma-ray detector is composed of 900ℓ LXe and 846 photomultiplier tubes (PMTs).

The position and time of the γ first interaction in the detector is reconstructed using the light distribution in space and time respectively, and energy using the sum of detected charges. Spectrum of this detector for 54.9 MeV gamma ray from π^0 decays ($\pi^0 \rightarrow \gamma\gamma$) produced in the charge-exchange process ($\pi^- + p \rightarrow \pi^0 + n$) is shown in Fig2.

Energy resolution of upper tail was estimated to be $\sigma(E_\gamma)_{up} = 2.0\%$ (depth $>$ 2cm),3.0%(1 cm $<$ depth $<$ 2cm), 4.2%(depth $<$ 1cm). The average position resolutions along the front-face sides of the LXe detector were $\sim$ 5 mm and in the depth $\sim$ 6 mm.

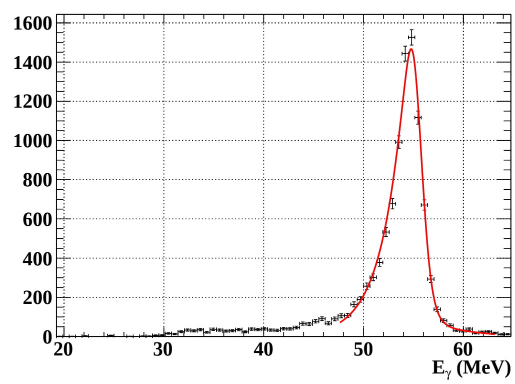

Figure 2. Measured energy spectrum for 54.9 MeV γ rays

Positrons emitted from muon decays are detected by the magnetic spectrometer composed of superconducting solenoidal coil with gradient magnetic field, drift chambers and plastic scintillator timing counter bars.

Decay point of muon and energy and direction of positron are estimated reconstructing the trajectory of positron. Time of positron is estimated using the information of timing counter with a correction for the path length of the trajectory. Energy spectrum of michel e^+ measured in 2008 run is shown in Fig.3.

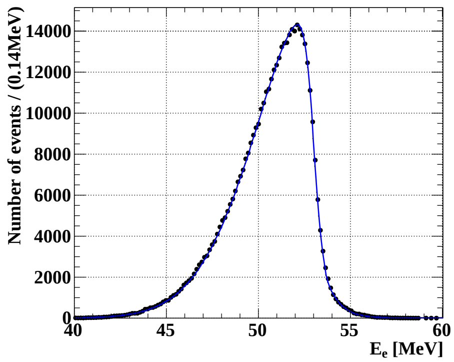

Figure 3. Measured michel e^+ energy spectrum

The energy resolutions extracted from data were $\sigma(\mathrm{E}_{e^+}) = 0.708\%$, 2.01%, 3.79% in sigma for the core component and the two tails, with fractions of 60%, 33%, 7% respectively. The e^+ angular resolutions were $\sigma(\theta_{e^+}) = 18$ mrad, $\sigma(\phi_{e^+})$ = 10 mrad.

Relative time between γ and e^+ was measured using RMD events(Fig.4). After correcting the energy dependence, relative time resolution for $\mu^+ \rightarrow e^+\gamma$ decay was estimated to be $\sigma(t_{e\gamma})$ = 148 ± 17 psec

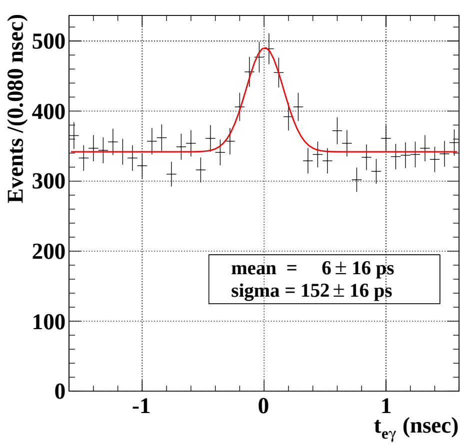

Figure 4. The relative time distribution with RMD peak obtained during physics runs

4. The 2008 run

We started the first physics data taking in 2008. We successfully took muon decay events for three months in 2008 corresponding to $\sim 9.5 \times 10^{13} \mu^+$ stops in the target. During data taking, a number of drift chambers suffering from discharge was increasing and it decreased positron detection efficiency to one third of expectation on average, and made the resolutions worse.

5. Data analysis

The data in the 2008 run were analyzed by means of blind-box likelihood analysis. For the background study and optimization of the analysis, events outside the blinding box were used. The probability density functions(PDFs) for signal $\mu^+ \rightarrow e^+\gamma$, RMD and accidental background were prepared using this sideband data and calibration data, in some cases complemented with Monte Carlo simulation.

The 90% confidence intervals on N_{sig} and N_{RMD} are determined by the FeldmanCousins approach[6]. A contour of 90 % C.L. on the (N_{sig}, N_{RMD})-plane is con-structed by means of a toy Monte Carlo simulation. The obtained upper limit at 90% C.L. is $N_{\mathrm{sig}} < 14.7$, where the systematic error is included.

We took Michel positrons data simultaneously with the signal, and used the number of the positrons selected with the same analysis cut as that for the signal to normalize the upper limit on N_{sig}, and calculated the upper limit on BR($\mu^+ \rightarrow e^+\gamma$). This technique has an advantage of being independent of the instantaneous beam rate and is nearly in- sensitive to positron acceptance and efficiency factors associated with the positron detectors.

The limit on the branching ratio of the decay $\mu^+ \rightarrow e^+\gamma$ is

$$BR(\mu^+ \rightarrow e^+\gamma) \leq 2.8 \times 10^{-11} (90\% C.L.)$$

where the systematic uncertainty on the normalization is taken into account.

The sensitivity of the experiment with this data statistic and the same number of accidental and RMD background events, assuming null signal is calculated to be 1.3×10^{-11} by means of toy Monte Carlo simulation. The probability to obtain an upper limit greater than this result is ∼5%.

6. Conclusion and prospects

The MEG experiment started to take physics data for searching the cLFV decay $\mu^+ \to e^+\gamma$ in 2008. We performed data taking successfully for three months in 2008 with a branching ratio sensitivity of 1.3×10^{-11}, which is comparable with the current branching ratio limit set by the MEGA experiment[4].

A blind likelihood analysis for this data yields an upper limit on the branching ratio of $\mathrm{BR}(\mu^+ \to e^+\gamma) \leq 2.8 \times 10^{-11}$. The result was good enough to show that we will be able to search for the decay $\mu^+ \to e^+\gamma$ with better sensitivity than the past experiments soon.

The problem of low e^+ detection efficiency, due to the drift chamber discharge, has been solved and we could get data in a stabler condition with higher efficiency in 2009 run. We will continue data taking to reach our goal sensitivity $\sim 10^{-13}$ to find $\mu^+ \to e^+\gamma$.

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