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System overview of liquid xenon calorimeter for the MEG experiment

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ABSTRACT

MEG experiment aims to search for lepton flavor violating $\mu^+ \to e^+\gamma$ decay with a sensitivity of 10^{-13} branching ratio. To detect 52.8 MeV γ's, we have been developing a new photon detector with 900 L of liquid xenon viewed by 8462 in. photomultiplier tubes. Construction of the detector was finished in 2007, and the methods to keep liquid xenon stably were confirmed during the engineering run. In 2008, a calibration was done by using 55 MeV $\gamma-$rays from π^0 decays to estimate the detector performance. In autumn, MEG experiment has started taking physics data. The detector stability had been monitored by using 17.6 MeV γ's from Li(p, γ)Be reaction, etc. I will summarize here the detector preparation, operation, calibration, and monitoring methods, mainly concentrating on the hardware related things.

1. Introduction

Taking into account tiny neutrino mass and mixing in the standard model, lepton flavor violating (LFV) processes in the charged lepton sector like $\mu \to e\gamma$ are negligibly small, and thus the discovery of such phenomena is a clear evidence of new physics beyond the standard model. Many scenarios like supersymmetric grand unified theories (SUSY-GUT), SUSY with right-handed neutrinos predict large branching ratio at a level of $10^{-11}-10^{-15}$.

Current best upper limit (90% C.L.) on this B($\mu \to e\gamma$) of 1.2×10^{-11} is obtained by the MEGA experiment at the Los Alamos Meson Physics Facility (LAMPF) [1].

MEG experiment [2] aims to search for lepton flavor violating $\mu^+ \to e^+\gamma$ decay with a sensitivity of 10^{-13} branching ratio. To achieve that in one year ($T = 10^7$ s), suppose the detector acceptance is 10%, μ rate $> 10^7$ μm/s is required.

2. MEG experiment

$\mu^+ \to e^+\gamma$ event is a simple two-body decay. A low energy muon stopping in a thin target will decay into a positron and gamma, which are back-to-back events with half the muon mass, 52.8 MeV, and simultaneous events. To avoid the formation of muonic atoms, positive muons are used.

There are two major backgrounds in a $\mu^+ \to e^+\gamma$ search. One is a physics background from radiative muon decays, $\mu \to e\nu\overline{\nu}\gamma$, and the other is an accidental coincidence of a positron from the standard Michel decays ($\mu \to e\nu\overline{\nu}$) and a gamma from radiative muon decays or annihilation in flight of positrons in material. The physics background is strongly suppressed by relatively good energy, angle, and timing measurements, and currently supposed the expected detector performance for MEG experiment, the accidental background is more dangerous for MEG experiment. The accidental background rate (B_{acc} is proportional to each detector resolution $\delta E_e \times \delta t_{e\gamma} \times (\delta E_\gamma)^2 \times (\delta\theta_{e\gamma})^2$, and good resolutions of all detectors are critical. Continuous DC muon beam is also important to reduce the accidental background rate.

A new experiment was approved by Paul Scherrer Institute (PSI) in 1999 to search for $\mu^+ \to e^+\gamma$ decays, called MEG (muon to electron and gamma) experiment. There is a 590 MeV ring cyclotron at PSI in Switzerland, which produces a proton beam with the highest power in the world. The most intense DC muon beam of more than 10^8 μm/s is available from this PSI proton accelerator, and the beam rate with 3×10^7 μm/s is used for the MEG experiment.

An experimental setup of the MEG experiment is shown in Fig. 1.

A positron spectrometer with a special graded magnetic field and an innovative 900-L liquid xenon $\gamma-$ray calorimeter had been developed. The momentum and the direction of emitted positron are measured precisely by a COBRA (Constant Bending Radius) spectrometer, whose field is designed to get a constant bending radius for the trajectory of 52.8 MeV positrons, independent of the positron emission angle, and which enables low momentum positrons swept away quickly. The positron tracking is done by a drift chamber system made of special low materials, and timing is measured by plastic scintillator bars with double sided readout by fine mesh PMTs [3]. A 900-L liquid xenon produces scintillation photons induced by incident $\gamma-$rays viewed from all sides by 846 2 in. photomultiplier tubes (PMTs), which measure precise conversion position, energy, and timing of the $\gamma-$rays.

In 2006, some engineering data were taken without xenon calorimeter because of some construction delay. MEG experiment took some physics data with all detectors for about three days in

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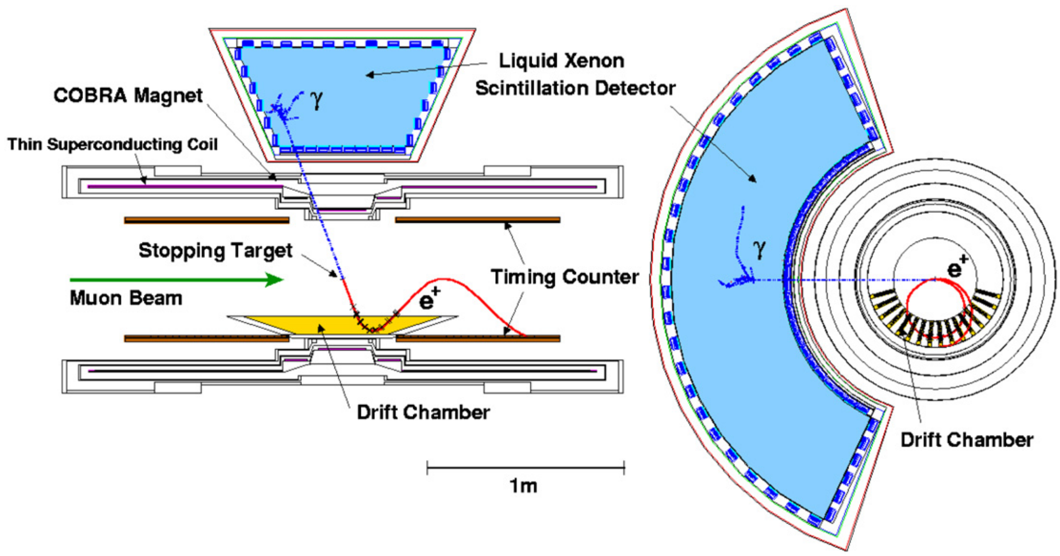

Fig. 1. An experimental setup of the MEG experiment.

2007. In 2008, MEG experiment had taken physics data for three months and full calibration data for xenon calorimeter by using $\pi^- p \to \pi^0 n$, $\pi^0 \to 2\gamma$ reaction had been taken for one month before the physics runs. If back-to-back two γ's from π^0 decay are selected, almost monochromatic 55 and 83 MeV γ's are available. Thanks to this 55 MeV energy close to our signal energy, we can estimate various parameters needed for physics analysis, such as energy resolution, energy scale, response function, timing resolution, and position resolution, etc. at 55 MeV.

Currently we are analyzing data in 2008, and 2009's data taking will be restarted in this September.

MEG Collaboration consists of approximately 60 physicists from Japan, Switzerland, Italy, Russia, and the United States.

3. Liquid xenon calorimeter

Liquid xenon scintillator has mainly two excellent characteristics, high light yield ($\sim 75\%$ of NaI(Tl)) and fast signals (decay time of 4.2, 22, and 45 ns), which are essential for precise energy, position and timing resolutions. Its short decay time helps minimizing pileup of high rate γ's. Moreover, it is possible to construct a large scale of detector homogeneously by using liquid scintillator. Waveforms of all PMTs are readout by fast waveform digitizers [4] to identify and remove pileup γ−rays. Properties of liquid xenon are summarized in Table 1.

A pulse tube cryocooler dedicated to this liquid xenon operation was developed by KEK [5], whose cooling power is about 200 W, to keep liquid xenon at 165 K.

All PMTs are directly immersed in liquid xenon to maximize the direct light collection. The 2 in. PMT(R9288)s are developed in cooperation with Hamamatsu Photonics especially for such a low temperature operation and short wavelength (~ 178 nm) of the scintillation lights. Two zener diodes are installed in the last two stages of their base to minimize a voltage drop under high rate background.

Impurities in the liquid xenon like water, oxygen, and nitrogen, etc. can absorb scintillation light, and deteriorate our detector performance. Two kinds of purification systems, gaseous and liquid purification, eliminate such impurities by circulating liquid xenon. A high temperature metal getter is installed into the gaseous purification system, which removes H_2O, O_2, CO, CO_2, H_2, N_2, CH_4, etc. from gas xenon [6]. Molecular sieves, which remove mainly water, and O_2 getter (which was installed in 2008), which removes electronegative impurities like O_2, are mounted in the liquid purification circuit [7].

Table 1
Properties of liquid Xe.

Density	3 g/cm^3
Boiling and melting points	165 K, 161 K
Energy per scintillation photon	24 eV
Radiation length	2.77 cm
Decay-time	4.2, 22, and 45 ns (75%)
Peak scintillation wavelength	178 nm
Scintillation absorption length	>100 cm
Refractive index	1.6–1.7

When the MEG proposal was presented to PSI in 1999, a small prototype detector with 2.3 L liquid xenon surrounded by 32 PMTs was used to check energy, timing, and position resolutions by radioactive sources. In 2001, a large prototype with 100 L liquid xenon and 240 PMTs are developed to confirm purification system, and PMT stability, etc., and the performance of the detector was checked by 10, 20, and 40 MeV inverse Compton γ beam, and 60 MeV electron beam. In 2003, a comprehensive calibration was done by using charge exchange (CEX) reaction, $\pi^- p \to \pi^0 n, \pi^0 \to \gamma\gamma$. If we select back-to-back γ events, we can obtain almost monochromatic 55 and 83 MeV γ's. Because this 55 MeV γ is close to our signal energy (52.8 MeV), and almost monochromatic, we can estimate our energy, timing, position resolution, and response function at around signal region. From this calibration, the resolutions of our detector are expected to be 1.2% in σ for energy, 65 ps for timing, and 4 mm for position. After that, the detector construction was started. All PMTs were tested in the liquid xenon by using the large prototype and a test station in PISA [8] before installation into the calorimeter.

4. Construction and operation

Detector system consists of five major components, liquid xenon calorimeter, gaseous purification system, liquid purification system, 1000 L liquid xenon storage system [9], and 250 L high pressure gas xenon storage tanks.