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The MEG Experiment

Study of the Origin of m_ν by Searching for Lepton Flavor Violation in Charged Leptons[1]

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Abstract

The MEG Experiment[1], being prepared at the Paul Scherrer Institute, will search for lepton flavor violating decays of muons, $\mu \to e\gamma$, with more than two orders of magnitude better sensitivity than previous experiments. Discovery and subsequent measurement of such decays would provide undeniable evidence for new physics beyond the standard model and could lead to a deep insight into the mysteriously small neutrino masses. Here I describe the experiment and the current status of the preparation.

[1]Presented at the 5th Workshop on "Neutrino Oscillations and Their Origin" (NOON2004), Odaiba, Tokyo, Japan, February 11–15, 2004.

1 Neutrino Masses and $\mu \to e\gamma$ Decays

The mysteriously tiny neutrino masses that came to light by the discoveries of the neutrino oscillations[2] may be thought of as a possible sign of new physics beyond the Standard Model.

Such small masses may be naturally explained by the see-saw mechanism[3] assuming existence of ultra heavy right-handed neutrinos. In supersymmetric theories these heavy particles induce large lepton flavor violation (LFV) also in the charged lepton sector. It has been shown[4] that muon's LFV decays $\mu \to e\gamma$ then occur at a branching ratio as large as the current experimental limit (1.2×10^{-11} at 90% C.L.[5]), especially with the large solar neutrino mixing established recently by the SNO observations.[6] An experiment capable to detect $\mu \to e\gamma$ decays at a branching ratio of 10^{-11} – 10^{-14}, therefore, should play a crucial role in examining the origin of the neutrino masses.

2 MEG Experiment

The MEG experiment,[1] which will start searching for $\mu \to e\gamma$ decays in 2006 with an initial sensitivity of 10^{-13}, eventually down to 10^{-14}, was approved by the Paul Scherrer Institute (PSI), Switzerland, in 1999. The MEG collaboration consists of some 50 physicists from Japan, Switzerland, Italy and Russia. The experimental set-up is schematically shown in Fig. 1.

Such an unprecedented sensitivity has been made possible by three key components of the experiment:

- highest intensity DC muon beam available at PSI,
- special positron spectrometer with gradient magnetic field, and
- liquid xenon scintillation gamma ray detector.

In the following sections I will explain these components and their present status in turn.

3 Intense DC Muon Beam at PSI

The major background in a $\mu \to e\gamma$ search is accidental coincidence of a positron, coming from standard Michel decays, and a gamma ray, coming

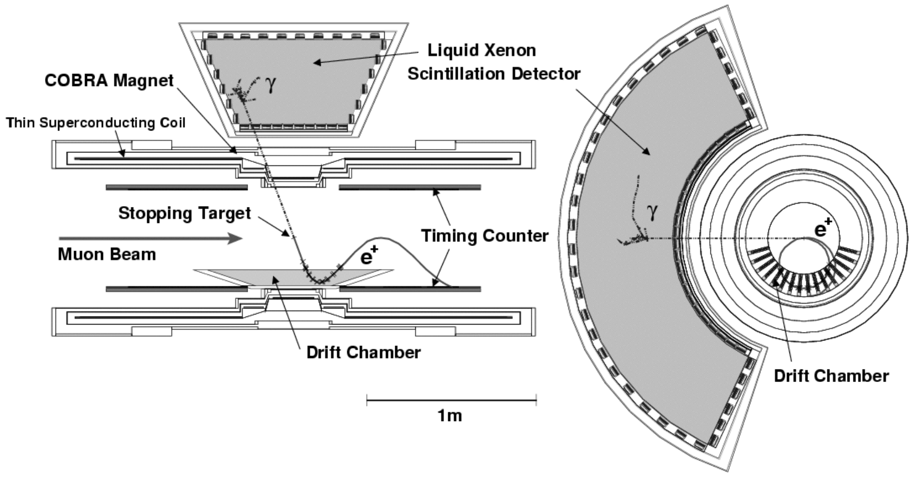

Figure 1: A schematic view of the MEG experiment.

from radiative decays or annihilation of positrons. Since this accidental background increases quadratically as the muon rate, a continuous, DC muon beam, rather than a pulsed beam, is best suited for a $\mu \to e\gamma$ search.

The 590MeV proton cyclotron at PSI, constantly operating with a beam current exceeding 1.8mA, provides the highest intensity DC muon beam in the world and thus is the best place for a $\mu \to e\gamma$ experiment.

A preliminary beam tuning carried out in 2003, at PSI's πE5 beam line, demonstrated that a muon stopping rate of 10^8/sec, i.e. more than 10^{15} stopped muons per year, is reasonably expected. This enables an experimental sensitivity of 10^{-14} assuming a detection efficiency of $\sim 10\%$.

Based on this study, final beam line elements such as a muon transport solenoid are currently being constructed. The beam tuning for the experiment is scheduled to start in the spring of 2005.

4 COBRA Positron Spectrometer Magnet

The COBRA (COnstant Bending RAdius) superconducting magnet is designed to form a special gradient magnetic field (1.27T at the center and 0.49T at the both ends), in which positrons with the same absolute momentum follow trajectories with a constant projected bending radius, independent of the emission angle over a wide angular range. This allows to sharply discriminate high momentum ($m_\mu/2 = 52.8\text{MeV}/c$) positrons out of

Figure 2: The COBRA magnet operating at PSI. The large Helmholtz coils seen in the figure are to compensate the magnetic field at the gamma ray detector down to below 50 Gauss.

10^8 Michel decay positrons emitted every second from the target. The gradient field also helps to sweep away curling tracks quickly out of the tracking volume, thereby reducing the accidental pile-up of the Michel positrons.

High strength Al stabilized conductor is used to make the magnet as thin as $0.197X_0$, so that 85% of 52.8MeV/c gamma rays traverse the magnet without any interaction before entering the gamma ray detector placed outside.

The COBRA magnet was successfully constructed and proved to show an excellent performance; it is now routinely operating at PSI (Fig. 2).

5 Liquid Xenon Gamma Ray Detector

An innovative liquid xenon scintillation detector is used to make a very precise measurement of energy, position and timing of gamma rays. The detector holds a 0.8m^3 volume of liquid xenon. Scintillation light emitted inside xenon are viewed from all sides by $\sim$800 photomultiplier tubes (PMTs).

High light yield of liquid xenon (roughly 75% of NaI) and its uniformity are necessary ingredients for good energy resolution. The scintillation pulse from xenon is very fast and has a short tail, thereby minimizing the pile-up

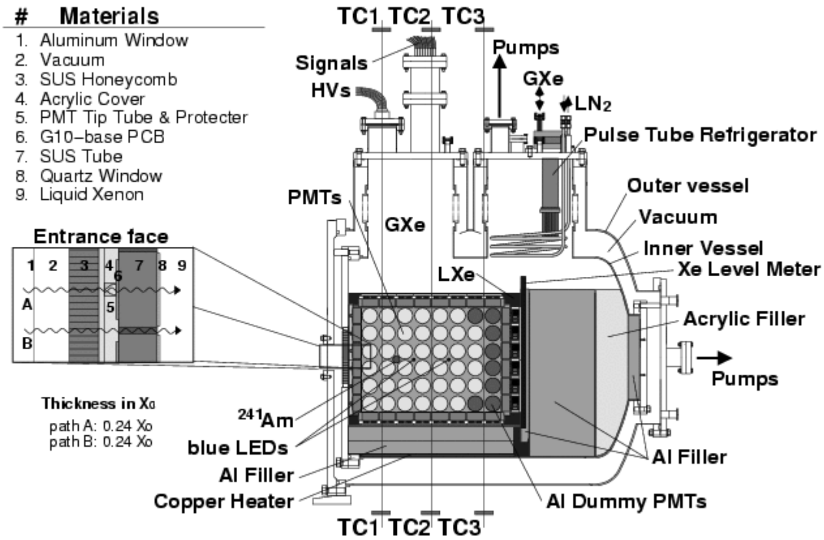

Figure 3: The 100 liter liquid xenon detector prototype.

problem. Distributions of the PMT outputs enable a measurement of the incident position of the gamma ray with a few mm accuracy. The position of the conversion point can be also estimated with an accuracy that corresponds to timing resolution of about 50psec.

The major ambiguity of this newly developed detector is absorption of the scintillation light ($\lambda = 178$nm) inside xenon. Impurities in xenon, such as water and oxygen, absorb UV light and could possibly degrade the detector performance.

A 100 liter prototype detector was built (Fig. 3). PMTs that are sensitive to the UV scintillation light and operate at low temperature (-100°C) inside liquid xenon have been developed in cooperation with Hamamatsu Photonics. A pulse tube refrigerator that maintains efficiently the liquid xenon temperature has been developed at KEK.

After successful start-up of the cryogenic system, cosmic rays and alpha sources placed inside the detector were measured. These measurements indicated clear light absorption as shown in Fig. 4. According to the subsequent mass spectrometer measurement, the main impurity was water. To remove the water contamination, a system to circulate and purify xenon was installed to the detector. Light absorption was monitored with cosmic rays and the alpha sources. After one month circulation, light absorption length improved to longer than 100cm (Fig. 4).

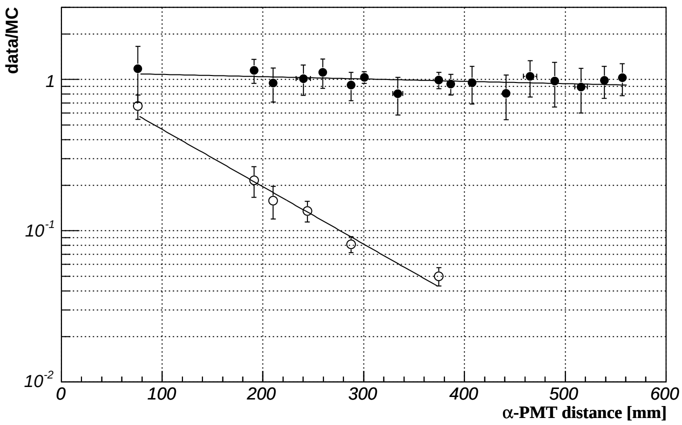

Figure 4: PMT outputs as a function of distance from the alpha sources before (open circles) and after (closed circles) purification. The data are normalized to simulations to correct for solid angles and effects of Rayleigh scattering and reflection.

To examine the performance the detector was irradiated with 10 – 129MeV gamma rays.

At the TERAS electron storage ring of the AIST laboratory, Tsukuba, Japan, gamma rays with upper edge energies of 10, 20 and 40MeV are available from the laser–electron Compton back-scattering. The left figure of Fig. 5 shows an example of the laser Compton gamma rays observed by the detector. Smearing of the Compton edge indicates the detector resolution.

At the Paul Scherrer Institute, Switzerland, π^0 decays in the charge exchange reactions, $\pi^- + p \to \pi^0 + n$, were used to obtain monochromatic energy gamma rays of 55 and 83MeV by tagging coincident gamma rays in the opposite direction. Another reaction, $\pi^- + p \to n + \gamma$, also provided monochromatic 129MeV gamma rays. An example of 55MeV gamma ray spectrum is shown in Fig. 5 (right). The lower tail of the spectrum is caused by shower leakage from the front side of the detector and gamma ray interactions in the material in front of liquid xenon. This tail only affects the detection efficiency. It is the upper side resolution that really discriminates the background, thus determines the sensitivity for $\mu \to \mathrm{e}\gamma$ events.

Preliminary energy resolutions obtained from these measurements are summarized in Fig. 6. The resolution scales according to $1/\sqrt{E}$ just as in-

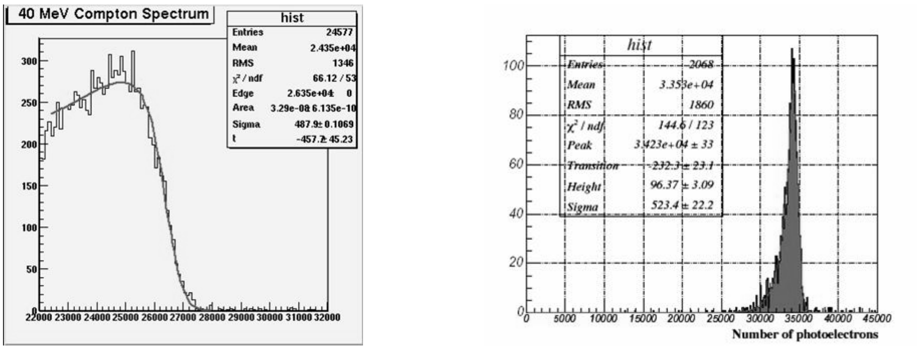

Figure 5: Left: The observed spectrum of the laser Compton gamma rays. The upper edge of the spectrum corresponds to 40MeV. Right: The spectrum of 55MeV monochromatic gamma rays from the π^- charge exchange reactions.

dicated by a straight line in the figure. For 52.8MeV gamma rays from $\mu \to e\gamma$ decays, an energy resolution is ~1.4% (σ). These measurements also provided position resolutions that vary from 2mm to 3.5mm, depending incident positions of gamma rays, and timing resolutions of better than 100psec. All together, the detector satisfies necessary resolutions to reach the initial goal of sensitivity of $\sim 10^{-13}$.

With recent development of PMTs, which has enabled an improvement of quantum efficiency by a factor of 2.5, we naturally anticipate further better performance of the final detector.

A design of the final xenon detector have been finalized and it should be ready after various tests by the summer of 2005.

6 Conclusion

With the large solar neutrino mixing, as well as supersymmetric grand unification of the forces,[7] the expectation for the MEG experiment is now higher than ever. The R&D and prototype studies indicate that the necessary performance for a possible discovery is in hand with a good change of further improvements. The detectors are currently under construction, and the experiment is expected to start in 2006.

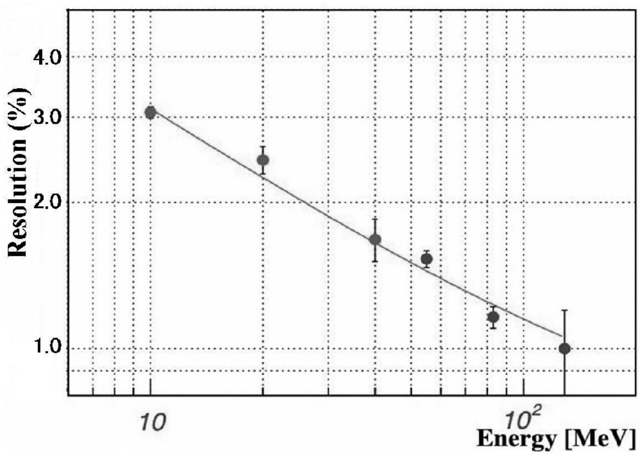

Figure 6: A preliminary result on energy resolution (upper side) as a function of gamma ray energies.

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