UT-ICEPP 2002-03
March 2002

Status and Future of $\mu \to e\gamma$ the PSI Experiment*

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* Presented at the 5th KEK Topical Conference, November, 2001.

Status and Future of $\mu \to e\gamma$: the PSI Experiment

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Searches for muon's decays that violate lepton flavors are the key to unveiling new physics underlying the neutrino oscillation phenomenology and an apparent unification of the coupling constants at extremely high energies. A new experiment [1] approved at the Paul Scherrer Institut to search for $\mu \to e\gamma$ decays is expected to be sensitive to such new physics. The design and the status of this experiment are briefly described.

1. Introduction

After a long successful history of the Standard Model, we are finally beginning to see possible signs of new physics beyond the Standard Model during the last several years.

One of such signs is an apparent unification of the three coupling constants of the strong and electroweak interactions at extremely high energy of 10^{16}GeV with the help of supersymmetry. The precision measurements of these coupling constants made at the Z^0 resonance have proven it a realistic possibility. This idea of supersymmetric grand unification (SUSY GUT) is also in good accordance with the recent observation that the Higgs boson may be as light as 114–200GeV [2].

It has been shown [3] that SUSY GUT generically predicts rather large lepton flavor violation (LFV) in the charged lepton sector that might be experimentally accessible. In particular, muon's LFV decays $\mu \to e\gamma$ are predicted to occur at a branching ratio of 10^{-11} – 10^{-14}, i.e. just below the current experimental limit of 1.2×10^{-11} (90% C.L.) by the MEGA experiment [4].

Another sign of new physics is the neutrino oscillations observed by the SuperKamiokande Experiment [5]. The apparent tiny masses of the neutrinos might be explained by the see-saw mechanism [6] induced by extremely heavy right-handed neutrinos. In supersymmetric theories these ultra heavy particles are expected to induce large LFV in the charged leptons, making muon's $\mu \to e\gamma$ decays occur at a branching ratio above 10^{-14}, especially if the solar neutrino deficit is due to the MSW large mixing [7]. Now the available solar neutrino data including the new SNO measurement [8] seem to strongly support the MSW large mixing scenario.

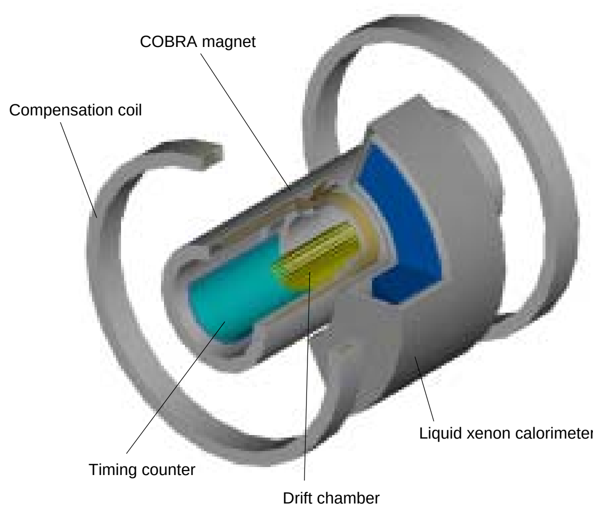

Figure 1. An experimental set-up of the new PSI experiment

Recently a new experimental proposal to search for $\mu \to e\gamma$ decays down to 10^{-14} [1] was approved by the Paul Scherrer Institut (PSI), Switzerland. Its experimental set-up is shown in Fig. 1. In this note the challenges and the prospects for the

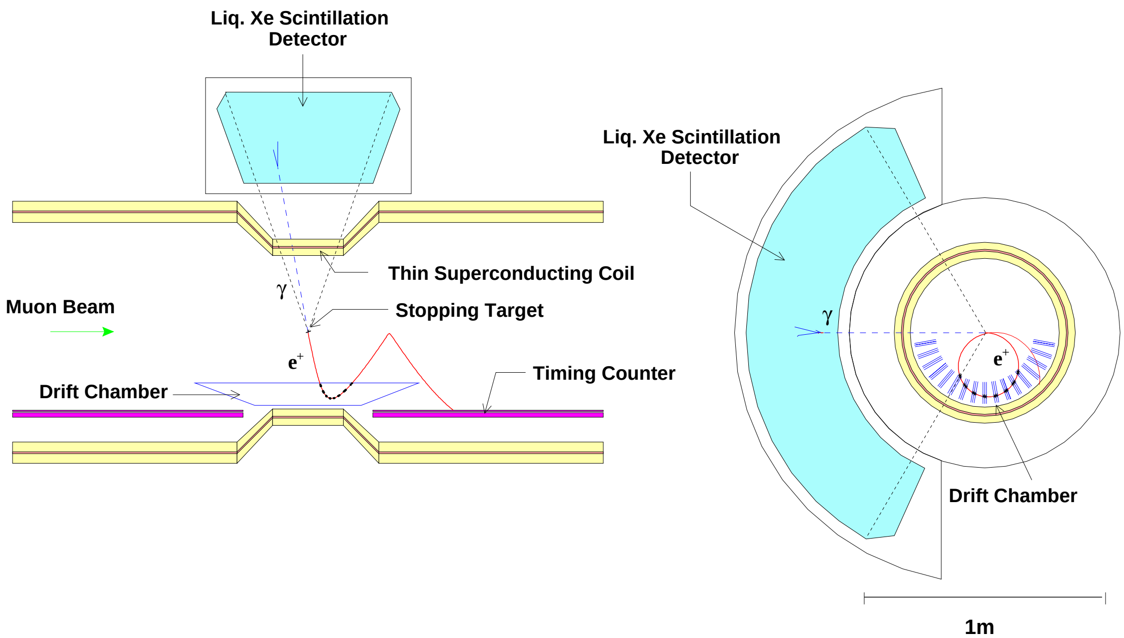

Figure 2. Detection of a $\mu \to e\gamma$ event in the PSI experiment

future of this experiment are briefly described.

2. Detection of $\mu \to e\gamma$ Decays

Since it is a simple two-body decay, in contrast to the usual Michel decays of muons, the $\mu \to e\gamma$ decays seem easy to identify: it consists of simultaneous, back-to-back emissions of a positron and a gamma ray from the muon stopping target[1].

But the reality is not that simple. A muon may decay radiatively, emitting a high energy gamma ray, possibly mimicking the $\mu \to e\gamma$ decay. However, with two neutrinos emitted at the same time, such a radiative decay can never be completely identical to the $\mu \to e\gamma$ decay. Thus, detectors with reasonably good energy resolutions for both positrons and gamma rays can eliminate such radiative decays down to a rate much smaller than 10^{-14}.

The real challenge to the experiment is accidental coincidences of the Michel decay positrons with high energy gamma rays that may come from radiative decays and positrons' annihilations in material. Such accidental coincidences inevitably occur, since the experiment has to deal with high muon rate of order of 10^8 muons/sec to achieve a 10^{-14} sensitivity within a reasonably short time ($\sim$ a year).

Because high energy gamma rays are much rarer than high momentum positrons that are abundant from the Michel decays, precise measurements of energy, position and timing of the gamma rays are important in discriminating the accidental coincidences against the signal.

To minimize the accidental coincidences the experiment should be designed to realize the following:

- continuous muon beam, rather than pulsed beam, to minimize the instantaneous muon rate;
- good tracking environment, to minimize possible tracking failures that could fake high energy tracks; and

[1]Positive muons are used to avoid formation of muonic atoms which destroys the simple two-body kinematics.

- an ultimate high resolution gamma ray detector that sustains high rate.

In what follows I describe how the PSI experiment tries to satisfy these requirements.

3. Surface Muon Beam at PSI

High rate ($\sim 10^8 \mu$/sec), continuous, low energy muon beam that satisfies our requirement is available at the πE5 beam line of the 590 MeV Proton Cyclotron at PSI, and not anywhere else.

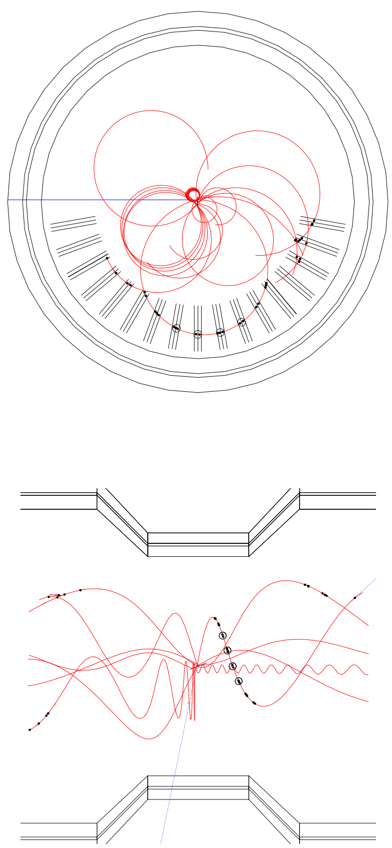

Figure 3. A simulated $\mu \to e\gamma$ event with several pile-up Michel positrons

Here pulsed proton beam with very short intervals (20ns) and high current (1.8mA or higher) is bombarded onto thick graphite targets. Positive pions produced in the hadronic interactions may stop inside the targets and decay to muons which may escape from the target with peak kinetic energy of about 4 MeV. These so-called "surface muons" are collected and transported into the beam line. With the pion lifetime and through the transportation, the muon beam becomes almost completely continuous.

With the DC muon beam, the instantaneous beam rate for the PSI experiment becomes a factor of 2.5 lower than the MEGA experiment which used pulsed muon beam.

The muon beam is then degraded, transported and focused by a combination of degraders, collimators and a long solenoid to stop in a slanted thin target. The beam size at the target is expected to be 1 cm in full width.

4. COBRA Spectrometer

The COBRA (COnstant Bending RAdius) positron spectrometer, schematically shown in Fig. 2, consists of a solenoidal magnet specially designed to form a gradient field, a drift chamber system to measure the positron momentum, and scintillation counters to measure the timing of the positron.

The field of the magnet is arranged such that monochromatic positrons from the target follow trajectories with constant projected bending radius, independent of the emission angle over a wide angular range. This allows us to sharply define the absolute momentum window to be detected by drift chamber cells at outermost radii, thereby reducing the accidental pile-up of the Michel positrons. This feature, together with the special staggered cell arrangement of the drift chamber, make the pattern recognition very secure against the pile-up tracks.

The drift chambers use He based gas to minimize multiple Coulomb scattering that finally limits tracking resolutions. They are equipped with vernier cathode pads that allow to determine 3D hit positions with 200–500μm accuracy.

In Fig. 3 a typical simulated $\mu \to e\gamma$ event with

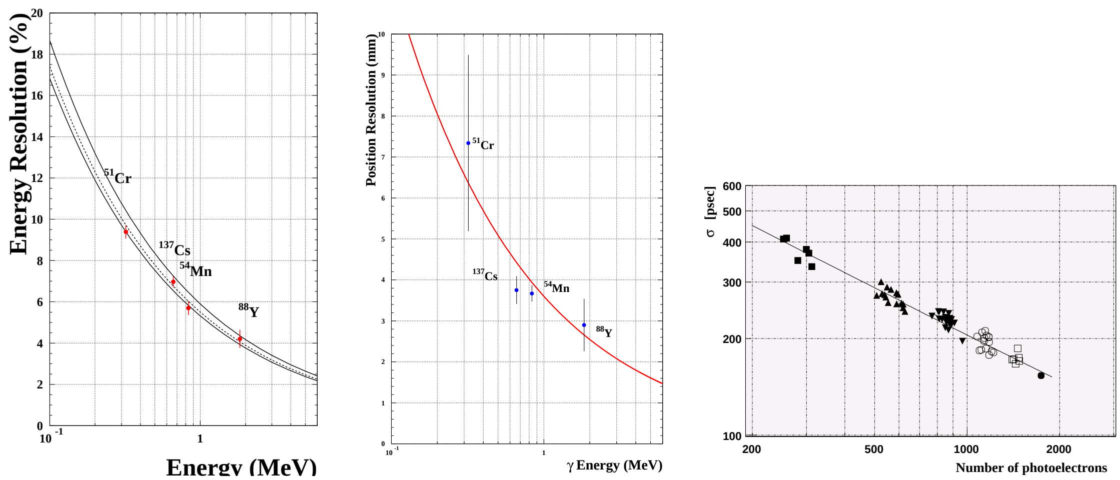

Figure 4. Energy, position, and timing resolutions (from left to right) as a function of energy or photoelectron statistics, obtained by the small prototype.

accidental pile-up of Michel positrons is shown. Starting from the outermost hit pairs that satisfy timing condition (indicated by small circles), 3D reconstruction of the 52.8MeV positron track can be unambiguously carried out.

After passing through the drift chambers, only high momentum positrons will hit a hodoscope array of plastic scintillators, the timing counters, placed at each side of the spectrometer, which measure the precise timing of the positrons. The timing counters also measure the the impact positions to provide redundant tracking information.

A prototype drift chamber was constructed and tested with beam at the πM1 beam line at PSI with and without magnetic field. Its low material mechanical design may be readily applicable to the final detector. Vernier pad measurements were also tested with a β ray source.

Several prototype timing counters were constructed and tested with beams at KEK, Japan, and also with cosmic rays at Pisa, Italy. From these tests the necessary timing resolution of less than 50psec was shown to be achievable.

All the superconducting cables for the magnet were produced. After the assembly planned in 2002, the magnet will be ready in early 2003 after initial tests.

5. Liquid Xenon Photon Detector

While the positrons are confined inside the magnet, the gamma rays penetrate through the COBRA magnet. Very thin superconducting coils have been developed at KEK to make the magnet transparent to the gamma rays.

A newly developed liquid xenon scintillation detector of "mini-Kamiokande" type, placed outside the magnet, detects the penetrating gamma rays. The detector holds a 0.8m^3 volume of liquid xenon. Scintillation light emitted by the gamma rays are viewed from all sides by arrays of $\sim$800 photomultiplier tubes (PMTs) facing the liquid volume.

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

A 52.8MeV gamma ray entering the liquid xenon loses most of its energy typically within 2–10cm from the xenon surface, resulting in a distribution of the PMT outputs peaked at the entry position. This enables a measurement of gamma ray position with a few mm accuracy.

The distribution of the PMT outputs becomes broader when the gamma ray conversion occurs deeper inside the xenon volume. Using the broadness of the distribution, the position of the conversion point can be estimated with an accuracy that corresponds to timing resolution of about 50psec.

In order to be confident that such an innovative detector should really work as the Monte Carlo simulation, two prototype detectors have been built. Along with the construction and the tests of the prototype detectors, necessary detector component R&D have been also carried out. In particular, a PMT that is sensitive to the UV scintillation light of xenon (a wave length of 175nm) under the low temperature (~ -100C°) and the pressure of liquid xenon has been developed in cooperation with Hamamatsu Photonics [9]. Also, a pulse-tube refrigerator that operates efficiently at the liquid xenon temperature has been developed at KEK to enable a long, stable operation of the detector.

5.1. Small Prototype

The first prototype detector has an active volume of $116 \times 116 \times 174$mm^3, viewed by 32 PMTs immersed in liquid xenon. α sources (^{241}Am) and various gamma ray sources of energy of 0.3–2MeV were used to test the principles of the operation of the liquid xenon detector.

The PMTs operated stably with $\pm 0.5\%$ gain stability during the whole running period of about one week.

The obtained resolutions of energy, position, and timing as a function of energy (or photoelectron statistics) are shown in Fig. 4. They all exhibit an anticipated tendency of being better for higher gamma ray energy. Simply extrapolating these results to 52.8MeV, the necessary resolutions for the experiment seems reasonably attainable.

5.2. Large Prototype

The aim of the second, larger prototype detector is two-fold:

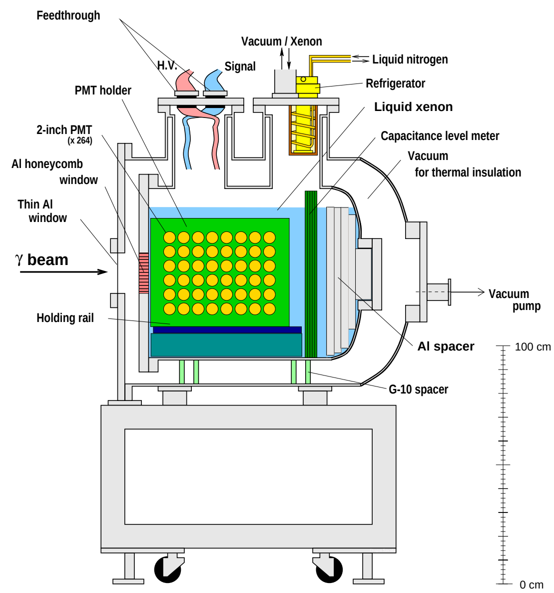

Figure 5. Large Prototype Xenon Detector

- It should serve as an engineering model to test various practical details necessary to be fixed before starting to construct the full-size detector;
- With a large active volume to absorb 52.8MeV gamma rays, the resolutions can be directly demonstrated.

It may also be used later to test and calibrate hundreds of PMTs to be installed in the final detector.

The design of the large prototype detector is shown in Fig. 5. It has an active volume of $40 \times 40 \times 50$cm^3 with 224 PMTs surrounding it.

Essentially all the components to be used in the final detector can be tested with this prototype: the honeycomb gamma ray window, the feedthrough connectors for signals and HV, the cables, the pulse-tube refrigerator, the PMTs and their bleeder circuits, the alpha sources and the LEDs for PMT calibration, the PMT holders, thermal insulation, and more.

The thermal inflow by radiation and along the cables and the heat dissipation by the PMTs were measured and agreed with calculations. Feedthrough connectors developed for the ATLAS liquid Ar calorimeter [10] were adopted for PMT signals and HVs. They worked with no serious problem. The pulse-tube refrigerator operated successfully and stably kept the liquid xenon temperature without interruption for a few weeks.

After these initial successful operations, cosmic rays were measured with trigger scintillators placed above and below the detector.

To demonstrate its performance for high energy ($\sim$ tens of MeV) gamma rays, the detector will be irradiated with 10–40MeV gamma rays at the laser Compton back-scattering facility at the TERAS storage ring at the AIST laboratory, Tsukuba, Japan. Preliminary measurements were already carried out and some problems with the PMT arrangement were sorted out. Details of the PMT gain matching using the LEDs and the sources are also being worked out.

6. Conclusion

The preparations of the new PSI experiment for $\mu \to e\gamma$ search are currently well in progress. While the R&D work will still continue in 2002, it is foreseen that the magnet will be ready in early 2003 and the assembly of the detectors will begin accordingly, so that the first commissioning run may start in late 2003 – early 2004. For most updated information take a look at the web site: `http://meg.psi.ch` or `http://meg.icepp.s.u-tokyo.ac.jp`.

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