Lepton Flavor Violating Decays -- Review & Outlook

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Here I review the status and prospects of experimental investigations into lepton flavor violation (LFV) in charged leptons. Rare LFV processes are naturally expected to occur through loops of TeV scale particles predicted by supersymmetric theories or other models beyond the Standard Model. In contrast to physics of quark flavors that is dominated by the Cabibbo-Kobayashi-Maskawa matrix, LFV in charged leptons is a definitive signal of new physics. Currently active researches are rare tau decay searches at the B factories. The MEG experiment will soon start a sensitive search for the LFV muon decay, $\mu \rightarrow$ eγ. Prospects for searches at the LHC, a possibility of a fixed target LFV experiment with high energy muons, and a sensitivity of leptonic kaon decays to LFV are also briefly discussed.

1. Why Lepton Flavor Violation?

Flavor violation or mixing among quarks has been known for many years and is beautifully described by the Cabibbo-Kobayashi-Maskawa matrix in the Standard Model. On the other hand, the discovery of flavor violation or oscillation among neutrinos came as a big surprise and provides a possible hint of new physics beyond the Standard Model. Now lepton flavor violation (LFV) among charged leptons, which has never been observed, is attracting a great deal of attention, because its observation is highly expected by many of the well motivated theories and would undisputedly establish a breakdown of the Standard Model.

An example of such LFV processes is schematically indicated in Figure 1. LFV is expected to occur in the loops of new physics processes at TeV scale such as supersymmetry or extra dimensions. Therefore the discovery of such a LFV process is of similar significance to that of the LHC.
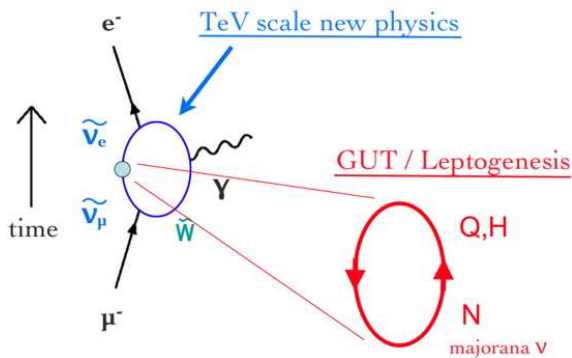

Figure 1: A possible origin of LFV processes ($\mu \rightarrow$ eγ in this example).

On the other hand, the source of LFV originates from much higher energy scale governed by grand unification theories (GUT) [1] or seesaw models that predict heavy majorana neutrinos to derive tiny neutrino masses [2], as indicated by the red loop in the Figure. Therefore the discovery and measurement of LFV pro-

cesses could also provide hints of physics at extremely high energy scale, which would not be accessible even at the LHC.

In this article the present and future *experimental* researches on LFV in charged leptons are reviewed.

2. LFV Tau Decays

Currently most actively studied LFV processes are the rare τ decays. τ-pairs are abundantly produced at the B factories where the τ-pair production cross section is as large as that of $B\bar{B}$. The two B factory experiments, Belle and BaBar, have accumulated more than 7.5×10^8 τ-pairs altogether. τ-pair events are selected and tagged by one of the τs that decayed in the normal way and the τs on the other side are searched for LFV decays. A result of such analyses is shown in Figure 2. As can be seen from this Figure, many of the searches are already beginning to be limited by background events. A more detailed description of various searches for LFV τ decays is given by Dr. H. Kakuno in this conference [3]. They have made an impressive improvement on most of the LFV modes of the τ decays, though any of them has not been discovered yet. The 90% C.L. upper limits on their branching ratios are now in the order of 10^{-7}, an order of magnitude improvement over the previous experiments (mostly by CLEO) [4].

These limits strongly constrain new physics models such as supersymmetry, especially for a large $\tan\beta$ region and also for Higgs-mediated LFV vertices.

For the future these limits should improve as the B factories continue to accumulate more data, but the improvements would be slow due to the background especially for some modes such as $\tau \rightarrow \mu\gamma/e\gamma$, $\tau \rightarrow \mu\eta$, etc. A Super B Factory with 5–10 ab^{-1} would bring them into the 10^{-8} region, possibly even to 10^{-9} for some modes, but claiming a discovery would be much harder with the existing background events.

Preparatory studies on LFV τ decays are being conducted by the LHC experiments [5]. During their ini-
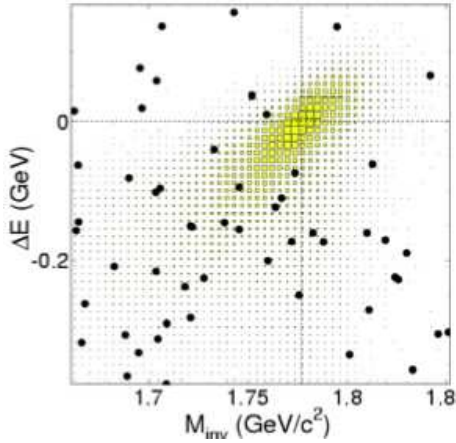
Figure 2: A result of $\tau \to \mu\gamma$ search by Belle for 86.7 fb^{-1} data, giving a 90% C.L. limit of 3.9×10^{-7}. Shown in yellow is the expected distribution for the signal while the points are the data. The background events are mostly τ-pair events with large initial state radiation.

tial low luminosity runs (10–30 fb^{-1}/year) for 2008–2009, a search for $\tau \to 3\mu$ may be possible. τs are produced by the decays of W and Z (an order of 10^8 τs per year) and B (10^{11} τs). In order to be competitive, more abundant τs coming from D_s decays (10^{12} τs/year) are being investigated. A preliminary study indicates that efficient triggering of these τs would be very difficult because of the low p_t (less than a few GeV) of the decay muons.

3. Muon to Tau Conversion

In a model independent approach, although many of the effective LFV four-fermion couplings involving τs are already strongly constrained by the LFV τ decay searches, there are some couplings that are still only loosely constrained [6]. For example, couplings involving heavy quarks cannot be studied by the τ decays, because τs cannot decay into heavy flavor hadrons. Such couplings may be studied by using high intensity muon beam on a fixed target and looking for a conversion from muons to τs [7].

In SUSY models such a muon to τ conversion could be enhanced by Higgs mediation [8]. With the present limits on $\tau \to \mu\eta$, 3μ, a maximum of $\approx 100\rho$ conversion events are possible for 10^{20} incident 50 GeV muons with a target thickness of ρ g/cm^3, and more events for higher energy muons. In fact, above 60 GeV, subprocesses involving b-quark component inside the target dominate and significantly increase the cross section. Such a high intensity, high energy beam may be available in the future at a neutrino factory or a muon collider, or, for an electron to τ conversion, the International Linear Collider (ILC).

A preliminary study with a conceptual experimen-

tal design indicates that designing an experiment for a muon rate of 3×10^{11}/sec/m^2 would not be totally unfeasible but challenging and expensive [7].

4. Leptonic Kaon Decays

As Dr.A. Ceccucci also pointed out in this conference [9], the ratio of the leptonic decays of kaons, $R_K = (K \to e\nu)/(K \to \mu\nu)$, with theoretical uncertainties canceling in the ratio, was recently shown to be very sensitive to LFV couplings [10]. In SUSY models the LFV decay of kaon into an electron or a muon with a τ neutrino can be strongly enhanced by charged Higgs mediation, while LF conserving SUSY effects do not contribute much. In fact a measurement with a 1% precision will lead to strong constraints on LFV vertices corresponding to upper limits on the LFV τ decays, $Br(\tau \to e\eta) < 10^{-10}$ or $Br(\tau \to e\gamma) < 10^{-11}$, i.e. exceeding even the Super B Factory sensitivity.

The NA48/2 experiment at CERN recently presented their preliminary result of $R_K = 2.416\pm0.043\pm0.024$ using their data taken in 2003 [11] for the Standard Model prediction of $R_K = 2.472\pm0.001$, indicating a possible one-sigma deviation. The data statistics will be at least doubled with their 2004 data. The NA48/2 collaboration now plans to take more data in 2007 to improve their measurements.

The leptonic π decay ratio, $R_\pi = (\pi \to e\nu)/(\pi \to \mu\nu)$, also has a LFV sensitivity which is much smaller than R_K by $(m_\pi/m_K)^4$. Two experimental programs, one at TRIUMF and the other at PSI, have been approved to investigate possibilities to improve the present precision of 0.3%.

5. LFV Muon Decays

Well motivated theories of supersymmetric grand unification (SUSY GUT) are very strongly constrained by the upper limits of the branching ratios of the LFV muon decays, $\mu \to e\gamma$, and $\mu \to e$ conversion on a nucleus. Therefore any improvement in experimental sensitivities to these decays could possibly lead to a discovery of SUSY GUT signals.

Assuming the standard Gauge (photon) mediated couplings, physics sensitivity of $\mu \to e\gamma$ is 300–400 times higher than that of $\mu \to e$ conversion, depending on the conversion target nuclei. Thus a branching ratio sensitivity of 10^{-13} for $\mu \to e\gamma$ corresponds to a $\approx 3 \times 10^{-16}$ $\mu \to e$ conversion sensitivity.

While an experimental search for $\mu \to e\gamma$ is mainly limited by accidental coincidence of background events, prompt backgrounds from muon beams are major obstacles in a $\mu \to e$ conversion experiment. Consequently a DC muon beam is best suited to a $\mu \to e\gamma$ search to minimize accidental overlap. On

the other hand, a pulsed beam is utilized to reduce prompt background in a $\mu \to e$ conversion search.

There is another interesting decay mode, $\mu \to 3e$, which, assuming the Gauge-mediated couplings, has a roughly 100 times smaller branching ratio than $\mu \to e\gamma$. Its major experimental limits come from accidental overlaps of background events. At the moment there is no experimental program, present or planned, for this decay mode.

In the following the status and prospects of the experimental programs to search for $\mu \to e\gamma$ and $\mu \to e$ conversion are briefly summarized.

5.1. Conversion to Electron on Nucleus

The present best limit on the $\mu \to e$ conversion is given by the SINDRUM-II experiment at PSI. Figure 3 shows their final result on gold target, giving a 90% C.L. limit of 7×10^{-13} [12]. As seen in the bottom figure, a class of events in coincidence with the 20 nsec beam pulse contain a lot more background.
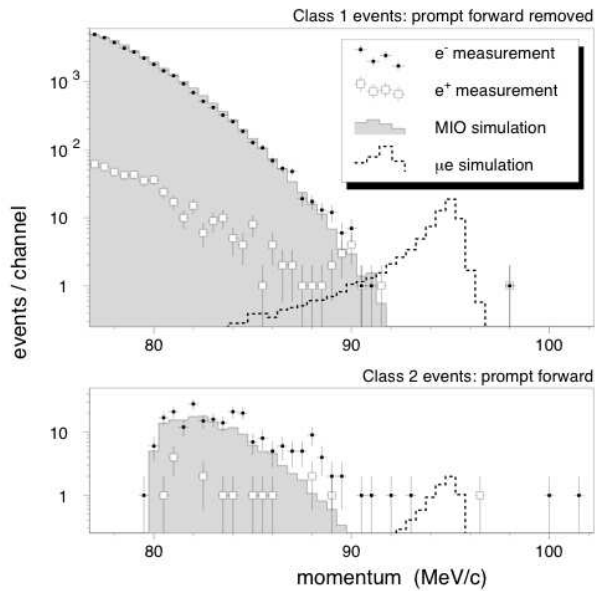

Figure 3: The final result of the SINDRUN-II experiment for the gold target.

The MECO experiment, proposed at BNL to achieve a 10^{-16} sensitivity by using a graded field solenoid to collect as much pions as possible at the production target, was unfortunately cancelled by the U.S. funding agency in 2005.

PRISM (Phase-Rotated Intense Slow Muons) is an ambitious project to produce high intensity negative muon beam with narrow energy spread and much less π contamination, proposed to be built at the J-PARC 50 GeV proton ring that is currently under construction at Tokai, Japan [13]. Its schematic layout is shown, together with the proposed $\mu \to e$ conversion

experiment PRIME, in Figure 4. A Fixed-Field Alternating Gradient synchrotron (FFAG) is used to carry out "phase rotation," i.e. a conversion of an original short pulse beam with wide momentum spread (± 30 %) into a long pulse beam with narrow momentum spread (± 3 %) by strong RF field. After 5 turns in the FFAG ring for the phase rotation, pions in the beam all decay out. Given 10^{14} protons/sec from the J-PARC ring, the PRISM facility should be able to provide 10^{11} - 10^{12} muons/sec, which might enable a $\mu \to e$ conversion sensitivity down to 10^{-18}. There are still several R&D items to study: for example, low energy pion production and capture system, and injection/extraction of muons into/from the FFAG ring. A real-size FFAG ring is being constructed at Osaka University for R&D studies. The schedule of the project is unknown as it is not funded yet.
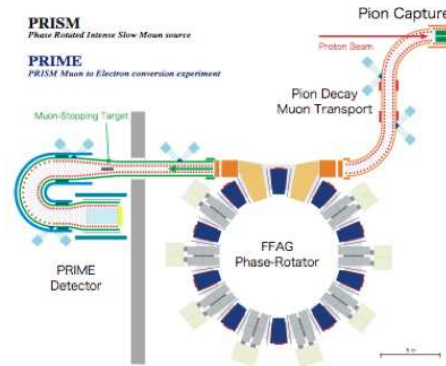

Figure 4: A possible layout of the PRISM/PRIME facility proposed at the J-PARC 50 GeV proton ring.

In conclusion there is no active or approved experiment for a $\mu \to e$ conversion search at the moment.

5.2. MEG Experiment

The MEG experiment [14], a $\mu \to e\gamma$ search experiment, currently being prepared at the Paul Scherrer Institute (PSI) in Switzerland, was proposed by the Japanese physicists and has since evolved to an international collaboration among Japan, Italy, Switzerland, Russia, and the U.S.A. The experiment is scheduled to be ready for physics run towards the end of 2006 and aims at a sensitivity of 10^{-13}, two orders of magnitude below the present limit of 1.2×10^{-11} [15].

The experimental set-up is schematically shown in Fig. 5. A DC surface muon beam of a few times 10^7/sec is focused and stopped in a thin plastic target. Gamma rays from $\mu \to e\gamma$ decays are measured by liquid xenon scintillation detector located just outside a very thin solenoidal magnet called COBRA. Positrons are tracked by low material drift chambers inside COBRA which provides specially graded magnetic field. Their timings are measured by plastic scin-
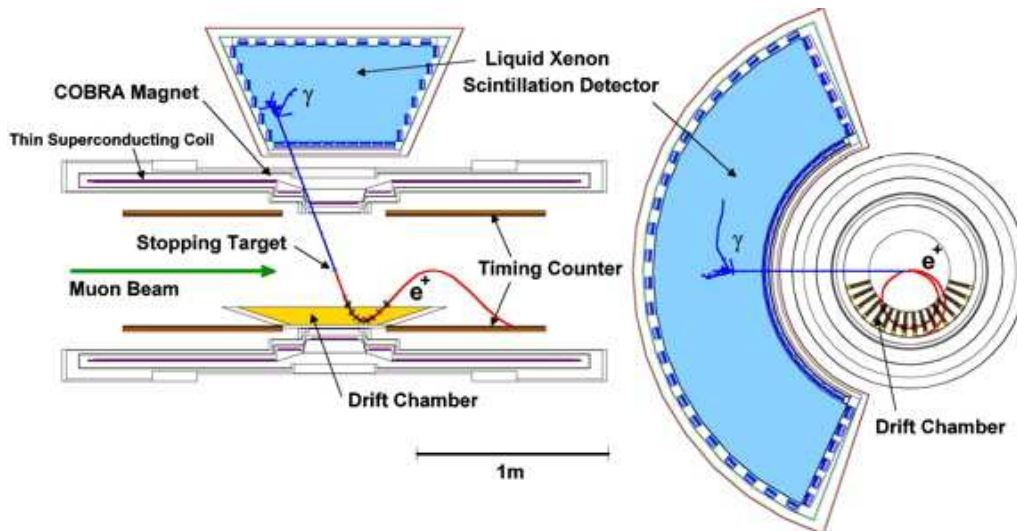
Figure 5: A schematic view of the MEG experiment.

tillation counters in the second turn of their trajectories.

The unprecedented sensitivity of the MEG experiment has been made possible by the three key components: (1) the highest intensity DC surface muon beam available at PSI; (2) a specially designed CO-BRA positron spectrometer with graded magnetic field; and (3) an innovative liquid xenon scintillation gamma ray detector. These key components are described in some detail in the following.

The 590MeV proton cyclotron at PSI, constantly operating with a beam current exceeding 1.8mA and a total beam power of more than 1 MW, is able to produce the highest intensity DC muon beam in the world. This is the best and only place suitable for a $\mu \to e\gamma$ experiment.

The πE5 beam line for the MEG experiment is shown in Figure 6. The superconducting solenoidal magnet is used to transport and focus the beam onto a small target (a few cmϕ). A DC separator is placed to reject unwanted positrons in the beam. A muon rate of 10^8/sec has been already demonstrated so that more than 10^{15} stopped muons per year is reasonably expected.

The COBRA (COnstant Bending RAdius) positron spectrometer [16] consists of a superconducting solenoidal magnet designed to form a special graded magnetic field (1.27 T at the center and 0.49 T at the both ends), in which positrons with the same absolute momenta follow trajectories with a constant projected bending radius, independent of the emission angles over a wide angular range. This allows to sharply discriminate high momentum signal positrons ($p = m_\mu/2 = 52.8$MeV/c) out of 10^7–10^8 Michel positrons emitted every second from the target. Only high momentum positrons enter the drift chamber volumes. The graded field also helps to sweep away curling tracks quickly out of the tracking volume, thereby reducing 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
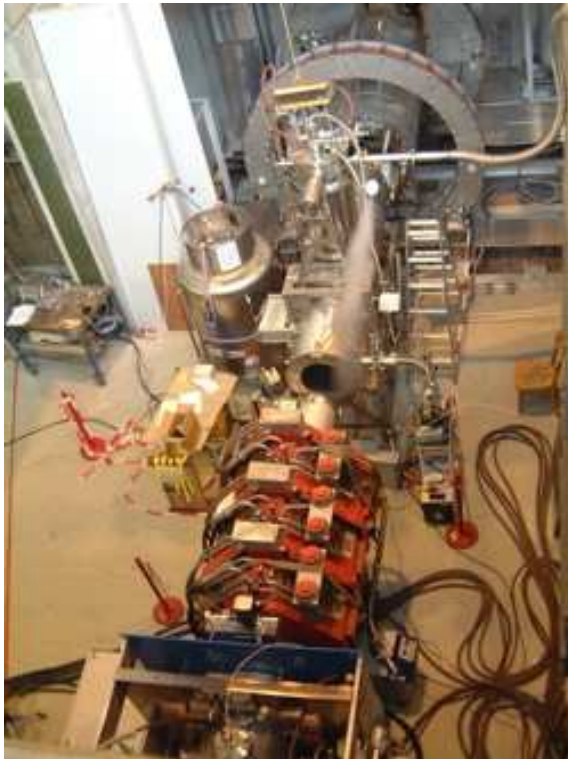

Figure 6: The πE5 beam line at PSI. From upstream (bottom) to downstream (top) are the DC separator, the quadrupole magnets (red), the superconducting muon transport magnet, and the COBRA magnet with ring-shaped compensation coils.

52.8MeV/c gamma rays traverse the magnet without interaction before entering the γ ray detector placed outside the magnet. A He-free, simple and easy operation of the magnet is realized with a GM refrigerator. As the COBRA magnet does not have a return yoke, a pair of compensation coils (seen as large rings in Figure 6) suppress the stray magnetic field below 50 Gauss in the vicinity of the gamma ray detector, so that the photomultiplier tubes can operate.
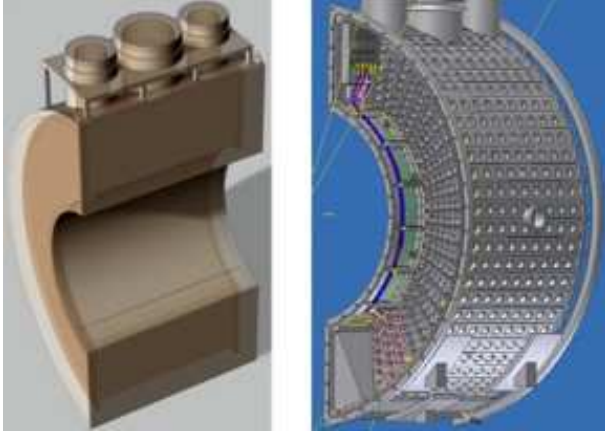

Figure 7: The liquid xenon γ ray detector. The cryostat (left) and the support structure for the photomultiplier tubes inside the cryostat (right).

An innovative liquid xenon (LXe) scintillation detector was specially devised for this experiment to make very precise measurements of energy, position and timing of gamma rays. The detector holds an active LXe volume of 800 ℓ. Scintillation light emitted inside LXe are viewed from all sides by approximately 850 photomultiplier tubes (PMTs) that are immersed in LXe in order to maximize direct light collection.

High light yield of LXe (roughly 75% of NaI) and its uniformity are necessary ingredients for good energy resolution. A scintillation pulse from xenon is very fast and has a short tail, thereby minimizing the pile-up 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 is also estimated with an accuracy that corresponds to a timing resolution of about 50 psec.

Various studies were carried out using a 100 ℓ prototype detector in order to gain practical experiences in operating such a new device and to prove its excellent performance. PMTs that work at the LXe temperature (-110°C), high power pulse tube refrigerators for LXe, a liquid phase purification method to remove possible impurities that absorb scintillation light, a calibration method using wire α sources, etc. have been developed [17]. Several gamma ray beam tests demonstrated its excellent performance which is necessary to achieve the sensitivity goal of the experiment.

The MEG detectors are currently being constructed and are scheduled to be ready later in the year 2006. It is expected to take ≈ 2 years with a muon beam of a few$\times 10^7$/sec to reach a 90% C.L. sensitivity of 1×10^{-13} with an expected background of 0.5 events.

6. Conclusion

LFV in charged leptons is a clean and clear signal of new physics beyond the Standard Model. It not only evidences new physics at TeV scale, such as supersymmetry or extra dimensions, but also provides hints of physics at extremely high energies, such as grand unification of forces that might have triggered inflation of the universe, or heavy majorana neutrinos that might be the origin of matter.

The B factory experiments have greatly improved and will further improve the limits on the LFV τ decays but are now starting to suffer background events. In parallel interesting limits may be provided by the measurement of the leptonic kaon decays and the LHC experiments could also contribute in their initial low luminosity phase.

In the absence of funded projects for $\mu \to e$ conversion searches, it is hoped that a sensible experiment be designed and started by international collaboration, before the ambitious PRISM facility may be eventually realized.
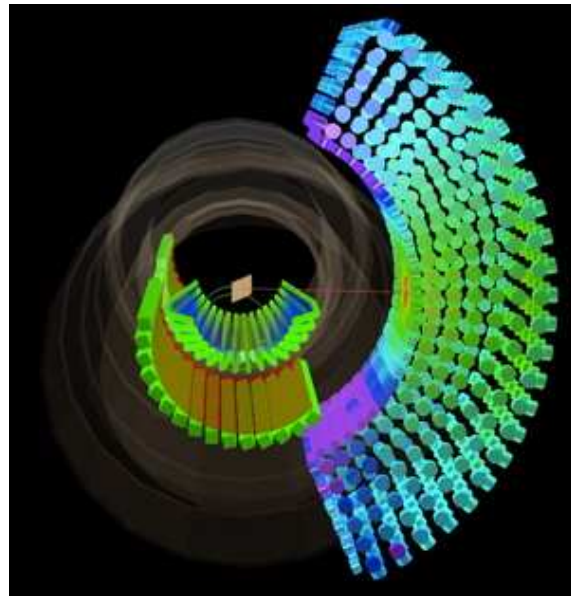

Figure 8: A simulated $\mu \to e\gamma$ event detected by the MEG detector.

Finally, the MEG experiment is expected to be ready toward the end of 2006 and could come across such a charming event as shown in Figure 8 at any time during the next few years. So stay tuned.

Acknowledgments

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