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Lepton Flavor Violation: Muon to electron conversion, COMET and PRISM/PRIME at J-PARC

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Physics motivation and phenomenology of $\mu - e$ conversion ($\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$) in a muonic atom, which is one the most important muon process to search for lepton flavor violation of charged leptons, are presented. Prospects for future experiments at J-PARC (Japan Proton Accelerator Complex) in Japan, such as the COMET experiment for sensitivity of less than 10^{-16} as the first stage and the PRISM/PRIME experiment for sensitivity of less than 10^{-18} as the ultimate stage, are discussed.

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1. Physics Motivation of Lepton Flavor Violation for Charged Leptons (cLFV)

After the observation of neutrino oscillation, it has been established that lepton flavor is not conserved in the Standard Model. However, processes of lepton flavor violation for charged leptons (cLFV) have not experimentally been observed yet. In the Standard Model with neutrino mixing, cLFV could occur through loop diagrams. However, those contributions are suppressed by the GIM mechanism and are proportional to $(\Delta m_\nu^2/m_W^2)^2$, which yields only very small branching ratio probability of the order of $O(10^{-52})$. Therefore, it is considered that search for cLFV would be very important and any evidence of cLFV would indicate without doubts new physics beyond the Standard Model [1].

Various theoretical models which predict sizable magnitudes of their branching ratios exist. Among them, most-well-motivated models are supersymmetric (SUSY) extension of the Standard Model, such as SUSY-GUT or SUSY-Seesaw models. For such theoretical models, cLFV would occur through slepton mixing which arises from quantum corrections (renormalization equation group) from the Planck scale to the weak energy scale. The predicted branching ratios are just a few orders of magnitude lower than the present experimental limits. Therefore, future experiments would have high potential for discovery.

Among charged leptons, the muons is the most promising, because the number of muons available at this moment for measurements is large ($\sim 10^8$ muons/sec), and will be much larger with the highly intense proton machines which are being constructed and planned ($\sim 10^{13-14}$ muons/sec).

2. What is a $\mu - e$ Conversion ?

When negative muons are stopped in matter and captured by atoms, they form muonic atoms and cascade down to their $1s$ ground state. The muons in the $1s$ state either decay in the muonic $1s$ orbit, or are captured by the nucleus by emitting a neutrino (nuclear muon capture), as in $\mu^- + N(A,Z) \rightarrow \nu_\mu + N(A,Z-1)$. When an electron is emitted instead of a neutrino, the process occurs as $\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$ and is called a "$\mu - e$ conversion". This process is lepton-flavor violating and is a coherent process which enhances the rate by a factor equal to the number of nucleons over the normal nuclear muon capture.

The experimental signature of $\mu - e$ conversion is a single mono-energetic electron whose energy is about the muon mass of about 105 MeV/c^2 minus the binding energy of the muonic atom. Potential background events are caused by several sources, such as muon-related, beam-related and others. The muon-related backgrounds are electrons from muon decay in orbit (DIO), radiative muon capture with photon conversion. The beam related backgrounds are radiative pion capture with photon conversion, beam electrons, muon decays in flight (DIF), and anti-protons. Other sources are cosmic ray and tracking failures in a high counting rate, and many others.

3. $\mu - e$ Conversion Experiments

The current published experimental limit of $\mu - e$ conversion, which is $B(\mu^- + Au \rightarrow e^- + Au) > 7 \times 10^{-13}$, is given by the SINDRUM-II experiment at PSI. They observed several background events above the signal region, which they suspected to come from either pions in a beam or cosmic rays. Based on the SINDRUM-II experiments, various experimental improvements have been considered for future searches for $\mu - e$ conversion. They are summarized as follows.

1. *Bean Pulsing* : To reduce beam-related backgrounds, beam pulsing is needed. And the measurement of $\mu - e$ conversion signals will be made between beam pulses.
2. *High Muon Beam Intensity* : To achieve high sensitivity, a large number of muons should be produced. For this purpose, large-solid angle pion capture by high magnetic-field solenoids surrounding a pion production target and the muon transport system by superconducting solenoids might be needed.
3. *Narrow Beam Energy Spread* : To eliminate electrons from DIO, good energy resolution of electron detection is critically important. To achieve this, a thin muon stopping target and a muon beam of narrow energy spread are needed.
4. *Reduction of Pions in a Muon Beam* : To eliminate pions which is one of the critical background, a long muon beam line where pions decay out is needed. One method of having more than 100 meter flight length is to use a muon storage ring.

Regarding the next-generation $\mu - e$ conversion experiments, for example in the US, the Mu2E experiment [2] which is aiming to search for $\mu - e$ conversion at a sensitivity of 10^{-16} at Fermi National Laboratory is being planned and proposed. It is a reincarnation of the MECO/MELC experiment that was cancelled due to budget problems in summer, 2005.

In Japan, a new proton accelerator complex called J-PARC (Japan Proton Accelerator Complex) at Tokai, Japan is being constructed and commissioned. It consists of a proton linac, a 3-GeV rapid synchrotron, and a 30-GeV main synchrotron ring (MR). The Japanese strategy to search for $\mu - e$ conversion is planned at two stage approaches. The first stage is to search at a sensitivity of less than 10^{-16}, and the second stage is to search at a sensitivity of less than 10^{-18}.

4. COMET for Sensitivity of less than 10^{-16}

The experiment at the first stage is called COMET (COherent Muon to Electron Transition), which is aiming to search for $\mu^- + Al \to e^- + Al$ at single sensitivity of 3×10^{-17}. It will use a pulsed proton beam with pulse separation of $\sim 1\mu$sec (a muon lifetime in a muonic atom of Al), which can be realized by slow extraction of proton bunches with every other RF buckets filled with protons in the J-PARC MR ring. The COMET experiment can be carried out in the J-PARC Hadron Experimental Hall.

The layout of the COMET experiment is shown in Fig.1. It is comprised of the pion capture section, the muon transport section, and the detector. The pion capture section has a proton target and superconducting magnets surrounding the target to capture pions in a high efficiency. And the muon transport section has a long solenoid magnets in which pions decay and muons are transported efficiently through the solenoids. The muon beam line and detector are similar to those of the MECO/MELC experiment with several differences.

One significant difference is to use a C-shape curved solenoid beam line, instead of a S-shape curved solenoid beam line. A curved solenoid is adopted to make a muon dispersive along the direction perpendicular to the curved plane and select the muon momentum of interest by applying a adjusted vertical magnetic field. In the COMET muon beam line, the vertical magnetic field can be produced by tilting thin solenoid coils. Then, the C-shape muon beam line (which has 180

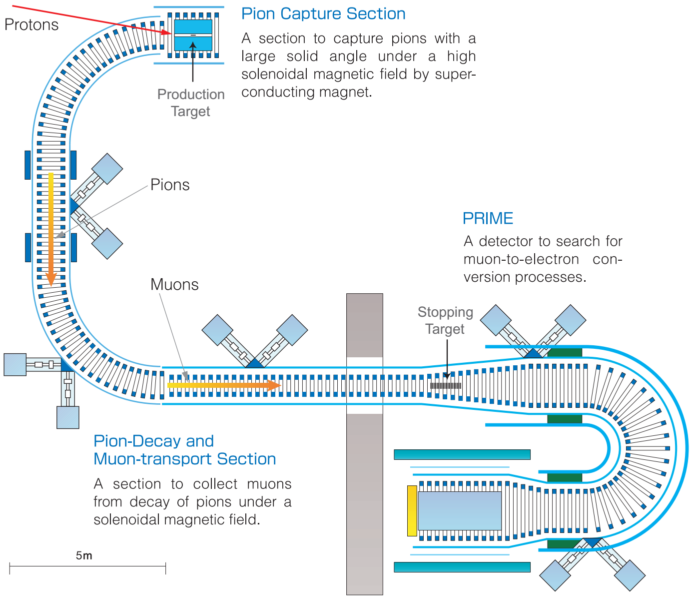

Figure 1: Schematic layout of the COMET experiment. It comprises of the pion capture section witht high-field superconducting solenoid magnets, the muon transport section with 180-degree toroid superconducting solenoids, and the detector with curved solenoid spectometer.

degree bending) has better momentum selection than the S-shape (which has 90 degree bending). It is critical to eliminate muons of momentum p_μ larger than 75 MeV/c, which would otherwise produce electrons of 100 MeV from muon DIF.

The second difference is to use a curved solenoid spectrometer in COMET, whereas a straight solenoid spectrometer in Mu2E. The major purpose of the curved solenoid spectrometer is to eliminate low energy electrons from muon DIO and reduce single rates of the electron tracking chambers and the electron calorimeter. Using a curved spectrometer, only about 1000 trackes come to the detector section, whereas the single rate of tracking chambers in Mu2E is in an order of 500 kHz per wire. It would reduce significantly fake tracking probability, which is one of the serious background events in a high rate.

The COMET will run with a 8-GeV proton beam of 7 μA (56 kW) for 2 SSC years (2×10^7 sec). A total of 1.5×10^{18} muons stopped in the muon stopping target. The estimated background of 0.4 events is expected at a single sensitivity of 3×10^{-17}. The proposal was submitted to the J-PARC PAC in January, 2008, and is evaluated as a would-be flagship experiments at J-PARC. The conceptual design report (CDR) of COMET, which was asked by the J-PARC PAC, is being prepared, with detail cost estimation.

5. PRISM for Sensitivity of 10^{-18}

PRISM, which is the second stage of our plan, is a highly intense muon source dedicated to a $\mu - e$ conversion experiment with a sensitivity of less than 10^{-18} [3]. PRISM stands for “Phase Rotated Intense Slow Muon source”. The schematic layout of PRISM is shown in Fig.2. The muon intensity of $10^{11} - 10^{12}$ muons/sec is aimed. The central momentum is about 68 MeV/c. In order to improve the resolution of electron energy detection, a thin muon stopping target and therefore narrow beam energy spread are needed. The narrow energy spread of ± 3 % from the original ± 30 % can be achieved by a phase rotation method, which is a technique to accelerate slow muons and decelerate fast muons by high rf fields. Phase rotation is performed in a muon storage ring to save a number of rf cavities and a total RF power. As another benefit, pions in the ring decay away. Their expected survival rate is less than 10^{-20}. As a muon storage ring, a fixed field alternating gradient (FFAG) synchrotron ring is chosen, which is called the PRISM-FFAG ring.

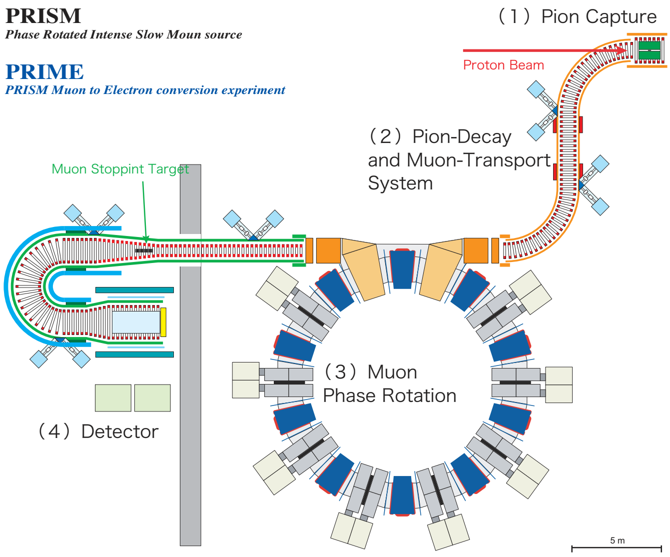

Figure 2: Schematic layout of PRISM that consists of pion capture, pion-decay and muon transport system, a muon storage ring (PRISM-FFAG ring), and the PRIME detector for search for $\mu - e$ conversion.

With the Grant-in-Aid for Creative Scientific Research in Japan, a section of the PRISM-FFAG ring is being constructed at Osaka University since year 2003. Experimental demonstration of phase rotation in the PRISM-FFAG ring is underway.

6. Summary

Search for cLFV is sensitive to new physics beyond the Standard Model. One of the important muon processes of charged lepton mixing is $\mu - e$ conversion. Their predictions of SUSY-GUT and SUSY-Seesaw models are just a few orders of magnitude smaller than the current limits. In Japan, as the first stage, the COMET experiment which is aiming at 10^{-16} sensitivity has been planned and proposed to J-PARC. As the second stage, the PRISM/PRIME project is being developed in Japan to aim for a sensitivity of 10^{-18}. The R&D of the PRISM FFAG ring is being undertaken at Osaka University.

References

[1] Y. Kuno and Y. Okada, Rev. Mod. Phys. **73** (2001) 151 - 202, and references therein.

[2] C. Dukes, *LFV: Muon to electron conversion, Mu2e at Fermilab*, in proceedings of *10th International Workshop on Neutrino Factories, Super beams and Beta beams (NuFact08)*, June 30 – July 5 2008, Valencia, Spain `PoS(NUFACT08)110`.

[3] Y. Kuno *et al.*, J-PARC Proposal P21 "An Experimental Search for Lepton Flavor Violating $\mu^- - e^-$ Conversion at Sensitivity of 10^{-16} with a Slow-Extracted Bunched Proton Beam". See in P21 in http://j-parc.jp/NuclPart/Proposal_e.html.

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