Snowmass2021 - Letter of Interest

Search for Muonium to Antimuonium Conversion

RF Topical Groups: (check all that apply □/■)

□ (RF1) Weak decays of b and c quarks
□ (RF2) Weak decays of strange and light quarks
□ (RF3) Fundamental Physics in Small Experiments
□ (RF4) Baryon and Lepton Number Violating Processes
■ (RF5) Charged Lepton Flavor Violation (electrons, muons and taus)
□ (RF6) Dark Sector Studies at High Intensities
□ (RF7) Hadron Spectroscopy
□ (Other) *[Please specify frontier/topical group(s)]*

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Abstract: It is puzzling whether there is any charged lepton flavor violation phenomenon beyond standard model. The upcoming Muonium (bound state of μ^+e^-) to Antimuonium (μ^-e^+) Conversion Experiment (MACE) will serve as a complementary experiment to search for charged lepton flavor violation processes, compared with other on-going experiments like Mu3e ($\mu^+ \to e^+e^-e^-$), MEG-II ($\mu^+ \to e^+\gamma$) and Mu2e/COMET ($\mu^-N \to e^-N$). MACE aims at a sensitivity of P($\mu^+e^- \to \mu^-e^+$) $\sim \mathcal{O}(10^{-13})$, about three orders of magnitude better than the best limit published two decades ago. It is desirable to optimize the slow and ultra-pure μ^+ beam, select high-efficiency muonium formation materials, develop Monte-Carlo simulation tools and design a new magnetic spectrometer to increase S/B.

Introduction: Neutrino oscillation is a neutral lepton flavor violation process, on one hand, pointing to the first direct evidence of new physics beyond standard model (BSM). There is no reason why charged lepton flavor violation (cLFV) phenomenon cannot happen. On the other hand, we have not clarified the origin of neutrino masses. One of the most natural interpretations is the so-called seesaw mechanism. A variety of neutrino mass models predict the charged lepton flavor violations[1]. For instance, the type-II seesaw model introduces a scalar triplet under a SU(2) symmetry. After spontaneous symmetry breaking, we will get the massive Higgs boson which can induce cLFV processes. Therefore, cLFV is one of the most interesting topics in BSM physics, offering an effective way of testing neutrino mass models. It is then well motivated to push forward the experimental efforts to search for BSM physics by cLFV.

Such cLFV experiments as **COMET**[3] in J-PARC and **Mu2e**[4] in FNAL to search for coherent muon to electron conversions ($\mu^- N \to e^- N$) are under construction. In addition, the accelerator muon beam experiments in PSI are searching for $\mu^+ \to e^+ e^- e^-$ by **Mu3e**[5] and $\mu^+ \to e^+ \gamma$ by **MEG-II**[6]. One of the most exceptional channels is to take the muonium atom as a probe of BSM physics and see whether there is a spontaneous conversion from muonium to antimuonium. Theoretical study of such a process in a model independent way was presented recently[2]. In a type-II seesaw model, the double-charged higgs particle predicts the muonium to antimuonium conversion even at the tree level. A history of searching for such a process is shown in Fig. 1. The latest upper limit for the probability of a muonium-to-antimuonium conversion was obtained as P$\lesssim 8.3 \times 10^{-11}$ at 90% confidence level by a PSI experiment in 1999. This channel has not been challenged in any experiment within the past two decades.

A 100 kW pulsed proton accelerator with the beam energy at 1.6 GeV and the repetition frequency at 25 Hz has been running at China Spallation Neutron Source (CSNS) in Guangdong province since 2018. Accompanied with an upgrade plan towards the beam power in 500 kW, we have proposed the experimental accelerator muon source (EMuS)[7] in China. It is still questionable to make use of the proton beam in the linac and build an independent muon beam ring, or extract the accelerated proton from rapid cyclotron storage ring in order to offer the requested muon beams more than $10^8 \mu^+$/s with the beam spread smaller than 5%. Anyway the new muon beamline will provide a platform to search for new physics. We intend to put efforts on muonium to antimuonium conversion experiment (MACE), aiming at more than two orders of magnitude improvement compared with the best limit obtained in 1999.

Search for $\mu^+ e^- \to \mu^- e^+$ by muonium atoms: Given that the required slow muon beamline is in place, we have to produce enough muonium atoms in vacuum to reach better sensitivities in experiments. It is expected to get much higher efficiency by means of new targets than the case in PSI experiment, where 61% of muons stopped in the target sample with the diffusion rate at 3.3%. New materials will be selected to increase the muonium formation efficiency and examined whether the muonium diffusion rate can meet the requirements in the detection system.

	Proton driver [MW]	Intensity [$\times 10^6$/s]	Polarization[%]	Spread [%]
PSI	1.30	420	90	10
ISIS	0.16	1.5	95	≤ 15
RIKEN/RAL	0.16	0.8	95	≤ 15
JPARC	1.00	100	95	15
TRIUMF	0.075	1.4	90	7
EMuS	0.025	83	50	10

Table 1: A comparison of accelerator muon sources around the world, including the proposed EMuS in China Spallation Neutron Source.

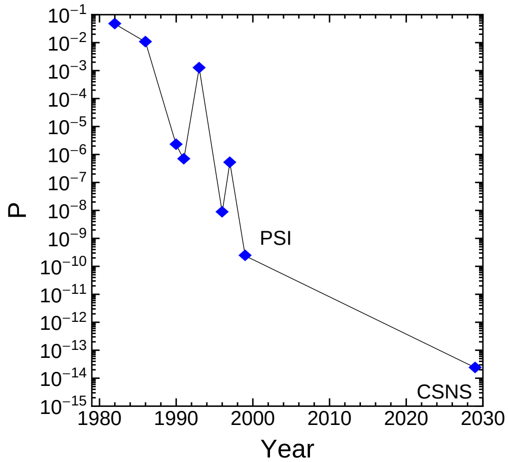

Figure 1: The history of searching for the spontaneous muonium to antimuonium conversion, including the expected sensitivity of the MACE experiment in CSNS.

There must be two signals to identify an antimuonium converted from the formed and diffused muonium in vacuum: one is the energetic electron from a μ^- decay in the magnetic spectrometer; the other is the atomic shell e^+. The magnetic spectrometer is the central detector component to fulfill the charge identification for final states. In addition, it is essential to identify the interaction vertex to suppress backgrounds. Both timing and position reconstruction have to be registered in an extremely high precision in the coincident detection techniques.

However, several backgrounds can lead to fake events. First, there might be accidental coincidence between an energetic e^- produced by Bhabha scattering of e^+ from an uncaptured μ^+ decay and a scattered e^+ in the uncaptured μ^+ beam. Cosmic ray muons might also make contributions to concident backgrounds. Second, apart from the dominant three-body decay from μ^+, we have to be confronted with the rare decay processes predicted by standard model:

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu + e^+ + e^- \, . \tag{1}$$

Based on the latest measurement in Particle Data Group[8], the branch ratio is $(3.4 \pm 0.4) \times 10^{-5}$. Both e^- and e^+ in such a rare process show up in continous energy spectra and can result intrinsic backgrounds. Part of them might also contribute to coincident backgrounds. Nevertheless, we cannot neglect the radioactive decay from the charge muon, either. In reality, it turns out to be a high precision measurement in the μ^+ beam experiment ahead of claiming any discovery in BSM physics. The detector components and their requirements are still under investigation by Monte-Carlo simulations, followed by a validation with sample tests and the previous PSI results. A conceptual design of the spectrometer is on the way to match the pulsed slow muon beamline in order to identify muonium to antimuonium conversion signals, where the time strucuture in the beam is feasible and can help with background suppression.

Summary: With an advent of intense and slow muon sources availabe and significant advance in modern particle detection technologies, we will have a chance to improve the present bound in muonium to antimuonium conversion by more than two orders of magnitude in the proposed MACE experiment. The high-efficency muonium formation target, the conceptual design of magnetic spectrometer and requirements in physics perforance are to be investigated along with a development of the first accelerator muon source in China.

References

[1] A. Ilakovac and A. Pilaftsis, “Flavor violating charged lepton decays in seesaw-type models,” Nucl. Phys. B **437**, 491 (1995) [arXiv:hep-ph/9403398 [hep-ph]].

[2] R. Conlin and A. A. Petrov, arXiv:2005.10276 [hep-ph].

[3] R. Abramishvili *et al.* [COMET], “COMET Phase-I Technical Design Report,” PTEP **2020**, no.3, 033C01 (2020) [arXiv:1812.09018 [physics.ins-det]].

[4] L. Bartoszek *et al.* [Mu2e], “Mu2e Technical Design Report,” [arXiv:1501.05241 [physics.ins-det]].

[5] N. Berger [Mu3e], “The Mu3e Experiment,” Nucl. Phys. B Proc. Suppl. **248-250**, 35-40 (2014)

[6] A. M. Baldini *et al.* [MEG II], “The design of the MEG II experiment,” Eur. Phys. J. C **78**, no.5, 380 (2018) [arXiv:1801.04688 [physics.ins-det]].

[7] Y. Bao, Y. Chen, Z. Hou, H. Jing, Y. Song, J. Tang, N. Vassilopoulos, Y. Yuan, G. Zhao and L. Zhou, “Beamline Design of EMuS - the First Experimental Muon Source in China,” J. Phys. Conf. Ser. **1067**, no.4, 042006 (2018)

[8] P. A. Zyla *et al.* [Particle Data Group], “Review of Particle Physics,” PTEP **2020**, no.8, 083C01 (2020)

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