SnowMass2021 - Letter of Interest

Search for Muon to Positron Conversion in $\mu^- \to e^-$ Conversion Experiments

Thematic Areas:

☐ (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]*

Contact Information: (authors listed after the text)
Submitter Name/Institution: MyeongJae Lee
Collaboration (optional): COMET collaboration
Contact Email: myeongjaelee@ibs.re.kr

Abstract:

The feasibility of searching for muon to positron ($\mu^- \to e^+$) conversion in a muonic atom by utilizing the current $\mu^- \to e^-$ conversion experiments, such as COMET and Mu2e, are discussed. The muon target made of aluminum, which will be employed in these experiments to search for $\mu^- \to e^-$ conversion, may not be optimal for $\mu^- \to e^+$ conversion. New muon target materials such as sulfur, titanium and calcium are proposed, based on the consideration of the separation of the signals from backgrounds of radiative muon capture. The expected experimental sensitivities for $\mu^- \to e^+$ conversion with these target materials can be $\mathcal{O}(10^{-15})$ or more. A possible strategy for the measurement of $\mu^- \to e^+$ conversion is also mentioned.

Introduction Muon to positron conversion in a muonic atom, $\mu^- + N(A, Z) \to e^+ + N'(A, Z-2)$, (referred to $\mu^- \to e^+$ conversion hereafter) is an exotic rare process of both lepton flavour violation (LFV) *and* lepton number violation (LNV) with the change of lepton number by two units ($\Delta L = 2$). The current experimental limits were obtained by the SINDRUM-II collaboration and are $\mathrm{Br}(\mu^- + \mathrm{Ti} \to e^+ + \mathrm{Ca}) < 1.7 \times 10^{-12}$ (3.6×10^{-11}) with 90% C.L. to the ground (excited) state of Calcium respectively[1]. The search and possibly discovery of such a LNV process is relevant to the presence of Majorana mediators in the scenario of new physics beyond the Standard Model (BSM) that may be responsible for the violation of total lepton number and baryon asymmetry of the Universe via leptogenesis. Recently $\mu^- \to e^+$ conversion attracted increasing attention: (1) its rate can increase if the LNV process is more likely to occur in the flavor off-diagonal sectors (like the μe sector), as suggested by some BSM constructions[2–7]; (2) in principle, the experimental sensitivity of $\mu^- \to e^+$ conversion can significantly increase with the coming $\mu^- \to e^-$ conversion experiments because the event signatures of the both physics processes are similar, and the difference is that the emitted lepton is either an electron or a positron, giving the expected experimental sensitivities at similar levels.

For $\mu^- \to e^+$ conversion, the nucleus in the final state can be the ground state or excited states. From now on, we will discuss only the transition to the ground state since it has less backgrounds. Then, the signal positron is mono-energetic with an energy ($E_{\mu^- e^+}$) given by:

$$E_{\mu^- e^+} = m_\mu + M(A, Z) - M(A, Z-2) - B_\mu - E_{\mathrm{recoil}} \,, \tag{1}$$

where m_μ is the muon mass. $M(A, Z)$ is the mass of the nucleus $N(A, Z)$. B_μ and E_{recoil} are the binding energy of a muonic atom and the recoil energy of the nucleus, respectively.

One of the major background source of $\mu^- \to e^+$ conversion comes from radiative muon capture (RMC), followed by photon pair production, where the e^+ in the pair is misidentified as a signal. The photon energy spectrum of RMC, in particular in the energy endpoint region, is only poorly known experimentally[8]. But the endpoint energy ($E^{\mathrm{end}}_{\mathrm{RMC}}$) can be kinematically determined:

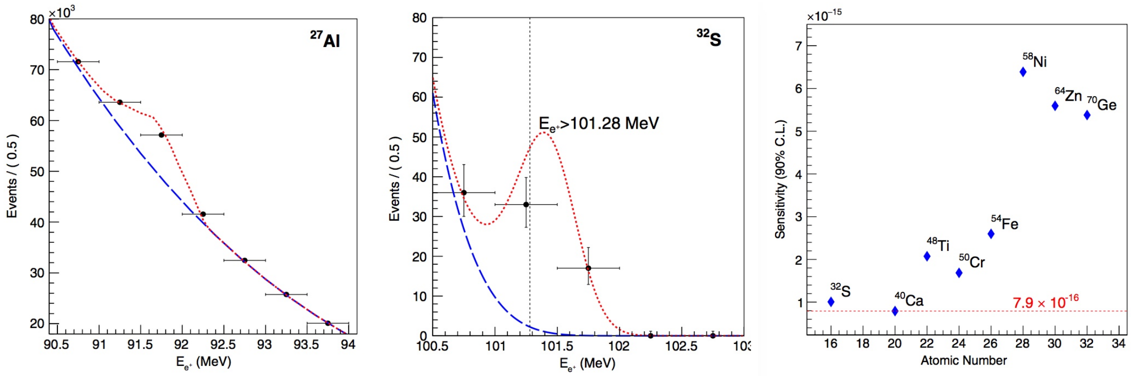
$$E^{\mathrm{end}}_{\mathrm{RMC}} = m_\mu + M(A, Z) - M(A, Z-1) - B_\mu - E_{\mathrm{recoil}} \,. \tag{2}$$

The nucleus in the final state may not be $N(A, Z-1)$ once nucleon emission occurs. For this case, the RMC endpoint energy is smaller than that of Eq.(2). It might be noted that COMET Phase-I aims of measuring the RMC photon spectrum in its endpoint region. In order to eliminate the RMC background, its endpoint energy should be smaller than the signal energy, $E^{\mathrm{end}}_{\mathrm{RMC}} < E_{\mu^- e^+}$. This yields the requirement for the target material:

$$M(A, Z-2) < M(A, Z-1) \,. \tag{3}$$

Another serious background is cosmic-ray induced events[9]. They will be removed by the cosmic ray veto system. Muon decay-in-orbit (DIO), which is one of the major background sources for $\mu^- \to e^-$ conversion, is not a serious background as long as the charge identification can be sufficiently achieved.

Target Selection The current $\mu^- \to e^-$ conversion experiments, COMET[10] and Mu2e[11] are both capable to measure precisely the momenta of electrons or positrons, where the charges of signal tracks can be determined by the direction of curvature of the tracks. Both the COMET and Mu2e experiments will be using aluminum as the muon target material, in their baseline plans. The requirement on the target material for $\mu^- \to e^+$ conversion described above, however, does not favor an aluminum target, as $E_{\mu^- e^+}(\mathrm{Al}) = 92.3\,\mathrm{MeV}$ and $E^{\mathrm{end}}_{\mathrm{RMC}}(\mathrm{Al}) = 101.34\,\mathrm{MeV}$. A simulation study on the $\mu^- \to e^+$ conversion spectrum of an aluminum muon target was made with the use of theoretical RMC spectrum shape. The result is shown in the left plot in Figure. It indicates large RMC backgrounds under the $\mu^- \to e^+$ conversion signals, as expected.



Left*: Energy distribution expectation of $\mu^- \to e^+$ conversion experiment with a $^{27}\mathrm{Al}$ muon target (black points) with the signal (dashed red line) and the RMC background (blue dashed line), assuming $\mathrm{Br}(\mu^- - \mathrm{e}^+) = 1.7 \times 10^{-12}$ and $N_{\mu stop} = 10^{18}$;* Middle*: the same plot for a $^{32}\mathrm{S}$ muon target when $\mathrm{Br}(\mu^- - \mathrm{e}^+) = 1.0 \times 10^{-14}$ and $N_{\mu stop} = 10^{18}$;* Right*: experimental sensitivities of 90% C.L. for various target candidates. The red dotted line and the number in red above the line indicate the sensitivity of $^{40}\mathrm{Ca}$, which is the best among the target nucleus candidates. All plots are from the reference*[12].

Possible muon target candidates for $\mu^- \to e^+$ conversion were thoroughly studied[9;12]. The nuclei which meet the requirement with reasonable natural abundance are not many in the low Z material region. From a kinematical point of view, Calcium ($^{40}\mathrm{Ca}$) is the best muon target material, although it remains challenging to use since its fast oxidation limits pure target foil construction. Sulfur ($^{32}\mathrm{S}$) can be another feasible choice, which was already used before[13]. A simulation study for a sulfur target for $\mathrm{Br}(\mu^- + \mathrm{S} \to \mathrm{e}^+ + \mathrm{Si}) = 1.0 \times 10^{-14}$ is shown in the middle plot in Figure. A better separation between the $\mu^- \to e^+$ conversion signals and the RMC backgrounds can be seen.

The right plot in Figure summarizes the foreseen experimental sensitivities for the candidate target materials with 10^{18} stopped muons. This plot shows all the candidates satisfying the requirement in Eq.(3) with an atomic number less or equal to 70. Heavier materials are not considered because of short lifetimes of their muonic atoms. They are $^{32}\mathrm{S}$, $^{40}\mathrm{Ca}$, $^{48}\mathrm{Ti}$, $^{50}\mathrm{Cr}$, $^{54}\mathrm{Fe}$, $^{58}\mathrm{Ni}$, $^{64}\mathrm{Zn}$ and $^{70}\mathrm{Ge}$. From this plot, it can be seen that with 10^{18} stopped muons expected in COMET Phase-II or Mu2e, the sensitivities of $\mu^- \to e^+$ conversion down to 10^{-15} can be expected. For sulfur, it is an $\mathcal{O}(10^6)$ improvement over the previous measurement[13], and also the best for $\mu^- \to e^+$ conversion. It should be noted that $^{48}\mathrm{Ti}$ is another good candidate for $\mu^- \to e^+$ conversion experiments, although the expected sensitivity is worse by factor of two than that of of the best candidate ($^{40}\mathrm{Ca}$). It is known that the titanium target is also favored for the $\mu^- \to e^-$ conversion experiment. Therefore, in order to do the searches for both $\mu^- \to e^-$ conversion and $\mu^- \to e^+$ conversion at the same time, titanium is one good candidate. It should be mentioned that COMET Phase-II cannot make the searches for $\mu^- \to e^+$ and $\mu^- \to e^-$ conversion at the same time, and a dedicated measurement can be arranged with the best target material. In case of COMET Phase-I, where the measurement of $\mu^- \to e^+$ conversion may be carried out at the same time of $\mu^- \to e^-$ conversions, it may require more consideration on the target material selection, and also keeping large acceptance for the both measurements[9].

Summary This LoI describes the possibility of searches for $\mu^- \to e^+$ conversion in the coming $\mu^- \to e^-$ conversion experiments and the corresponding target selection. Aluminum may not be optimal for $\mu^- \to e^+$ conversion. For a dedicated search for $\mu^- \to e^+$ conversion, sulfur is the mostly favored. For a combined search for $\mu^- \to e^-$ and $\mu^- \to e^+$ conversions at the same time, titanium can be considered. However, for the final target selection, a precise measurement of the RMC photon spectrum towards the endpoint region is highly required.

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Authors:

Masaharu Aoki, Department of Physics, Graduate School of Science, Osaka University, Japan.

Dmitry N. Grigoriev, Budker Institute of Nuclear Physics (BINP), Russia.

Yoshitaka Kuno, Department of Physics, Graduate School of Science, and Research Center of Nuclear Physics (RCNP), Osaka University, Japan.

MyeongJae Lee, Center for Axion and Precision Physics Research, Institute for Basic Science (IBS), Republic of Korea.

Akira Sato, Department of Physics, Graduate School of Science, Osaka University, Japan.

Jian Tang, School of Physics, Sun Yat-sen University, China.

Ana M. Teixeira, Laboratoire de Physique de Clermont (LPC), CNRS-IN2P3 and Université Clermont Auvergne, France.

Yoshi Uchida, Imperial College London, UK.

Beomki Yeo, Department of Physics, Korea Advanced Institute of Science and Technology (KAIST), Republic of Korea.

Kai Zuber, Institute for Nuclear and Particle Physics, Technische Universität Dresden. Germany.