PROCEEDINGS OF SCIENCE

A new concept of Mu – $\overline{\mathrm{Mu}}$ conversion search

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A new concept of experimental study for Mu – $\overline{\mathrm{Mu}}$ conversion search is proposed, which is strongly suppressed in the standard model of particle physics. The intrinsic beam-related background limits the current upper limit of the conversion rate obtained by previous studies, and thus, there are few possibilities for further improvement. In the proposed method, an $\overline{\mathrm{Mu}}$, which could be formed by conversion in the huge number of Mu generated by a pulsed μ^+, is ionized by a laser shot synchronized with the muon pulse, and the released μ^- is analyzed by a spectrometer with isolation ability from the background due to μ^+s and their related e^+/e^-. This enables more direct observation than the previous studies. This article introduces a new concept of Mu – $\overline{\mathrm{Mu}}$ conversion search and the result of a feasibility study performed in the muon facility (MUSE) Materials and Life Science Facility (MLF) J-PARC.

International Conference on Exotic Atoms and Related Topics and Conference on Low Energy Antiprotons (EXA-LEAP2024)
26-30 August 2024
Austrian Academy of Sciences, Vienna.

*Speaker

PoS(EXA-LEAP2024)074

1. Introduction

A muonium (Mu, μ^+e^-) is one of the simplest system described by the Standard Model (SM). This hydrogen-like atom is composed of only leptons, and is bounded only by the electroweak interaction. The conversion from muonium to anti-muonium ($\overline{\text{Mu}}$, μ^-e^+) is strongly suppressed in the standard model of particle physics because it violates conservation of the leptonic family number. To discover the evidence of new physics beyond the standard model (BSM), a lot of studies search the charged-lepton flavor violation processes like $\mu^+ \to e^+\gamma$, $\mu^- N \to e^- N$, in which the number of violation is 1, $\Delta L = 1$. Independent of such studies, some theoretical studies predict the $\Delta L = 2$ process like Mu – $\overline{\text{Mu}}$ conversion [1, 2], and the conversion rate can be just below the current experimental upper limit of 8.3×10^{-11} [3]. Although the search for the Mu – $\overline{\text{Mu}}$ conversion is attractive, a new experimental method is required to go beyond the current limit that is determined by the accidental coincidence of a scattered e^+ and an energetic e^- due to Bhabha scattering of e^+ from μ^+ decay.

We propose to search for the Mu – $\overline{\text{Mu}}$ conversion with a new method; Mu is produced in vacuum by injecting muon to a Mu production target such as silica aerogel [4, 5]. An intense laser with the energy to ionize Mu is directed at the cloud of Mu. If there is an $\overline{\text{Mu}}$, it is separated into μ^- and e^+, and then a μ^- is transported by a spectrometer composed of electrostatic and magnetic devices. This method is analogous to the technique of ultra slow muon beam generation [6], and the difference is the polarity of the beamline. Because there exists no source of μ^- in principle, this method is able to realize a background-free measurement. This method requires an intense pulsed muon beam and an intense laser, both of which will be available in MUSE.

2. Feasibility Study

To check the feasibility of this new concept, the background was investigated. The result was also reported in the conference proceedings paper [7]. Figure 1 shows the experimental setup assembled in MUSE. The laser-ablated aerogel target was adopted for efficient Mu production [5]. A sub-surface, 25 MeV/c, muon beam was injected into the target. A muon picked an electron to form a Mu in aerogel, and then a fraction of Mu was diffused out from the rear-surface of the target to the vacuum. The beam momentum was tuned to maximize the Mu yield in vacuum by setting half of the total muons to stop in the target. Namely, the center of the muon stopping region is set at around the edge of the rear surface. The number of stopping muon is counted by a plastic-scintillator telescope located beside the target chamber that is not appeared in Fig. 1. The Mu-emission efficiency to the incident muon was carefully examined to be about 0.3% in separated studies for the purpose of muon g-2/EDM measurement [8]. For the sake of feasibility check, the background level was measured without the ionization laser to $\overline{\text{Mu}}$, while the beamline is tuned to transport expected μ^-s. The tuning was done by transporting Mu$^-$ (μ^+e$^-$e$^-$) obtained by an aluminum target instead of the aerogel one, and the transmission efficiency was determined to be about 70% [9]. as explained in the next section. Namely, a negatively-charged particle with the mass of a muon was confirmed to be transported through beamline components shown in Fig. 1: an electrostatic extraction lens denoted as SOA lens; electrostatic quadrupoles, EQ's; an electrostatic deflector, ED; a bending magnet, MB. The energy and the momentum of the transported particles are selected by ED and

MB, respectively. Then, the particles are detected by two micro channel plates mounted at the end of the beam line, MCP1 and MCP2. A single anode MCP and an MCP with a phosphor screen were employed, and they were mounted at an either position alternatively. The MCP2 chamber is surrounded by plastic-scintillator telescopes, PS, to detect an electron originating from an expected μ^- decay.

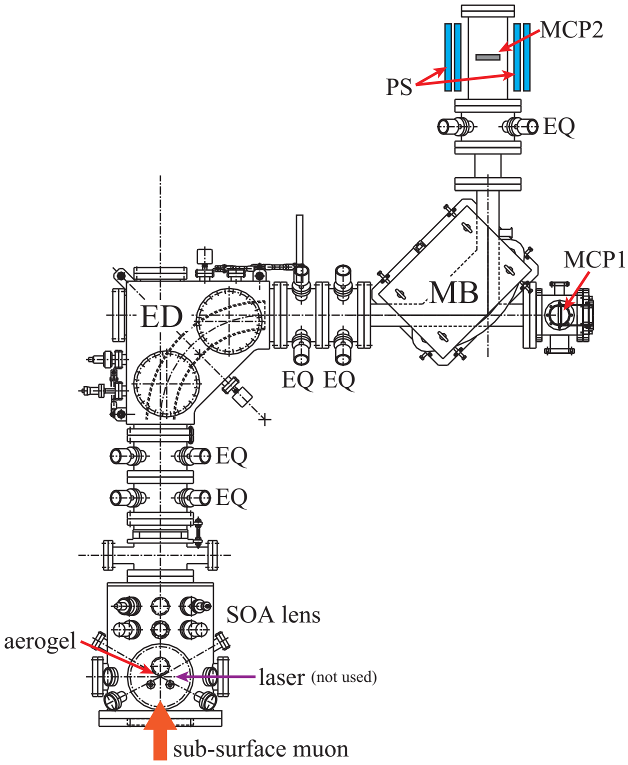

Figure 1: A top-view of the experimental setup for feasibility studies performed in D-line MUSE. EQ denotes an electrostatic quadrupole; ED, an electrostatic deflector; MB, a bending magnet.

3. Analysis Results

A huge background due to H^- sputtered by incident μ^+ and its secondary particles, which was observed by MCP1 that located at the position passing through MB as shown in Fig. 2 (A) and (C), was able to be eliminated by adopting MB. The Figures 2 (B) and (D) show typical results obtained at the downstream of MB. Although H^- background was rejected, there still existed a background with muon's life time of about 2.2 μs as shown in (B), which is explained by e^+ from μ^+-decay stopping at around the aerogel target and the beamline devices in the downstream. Namely, the shield between such background sources and the detector was insufficient.

Although the reinforcement of the shield is the most reliable way to suppress the muon-life background, the background can also be suppressed by requesting the coincident signal in PS with MCP2 hit. Figure 3 shows a typical result of MCP2 events requiring a coincident hit in PS. The dashed lines represent the pulse height threshold to cut e^+/e^- signals (horizontal line) and the expected time window of the background particle arrival (vertical lines), which is assumed to be

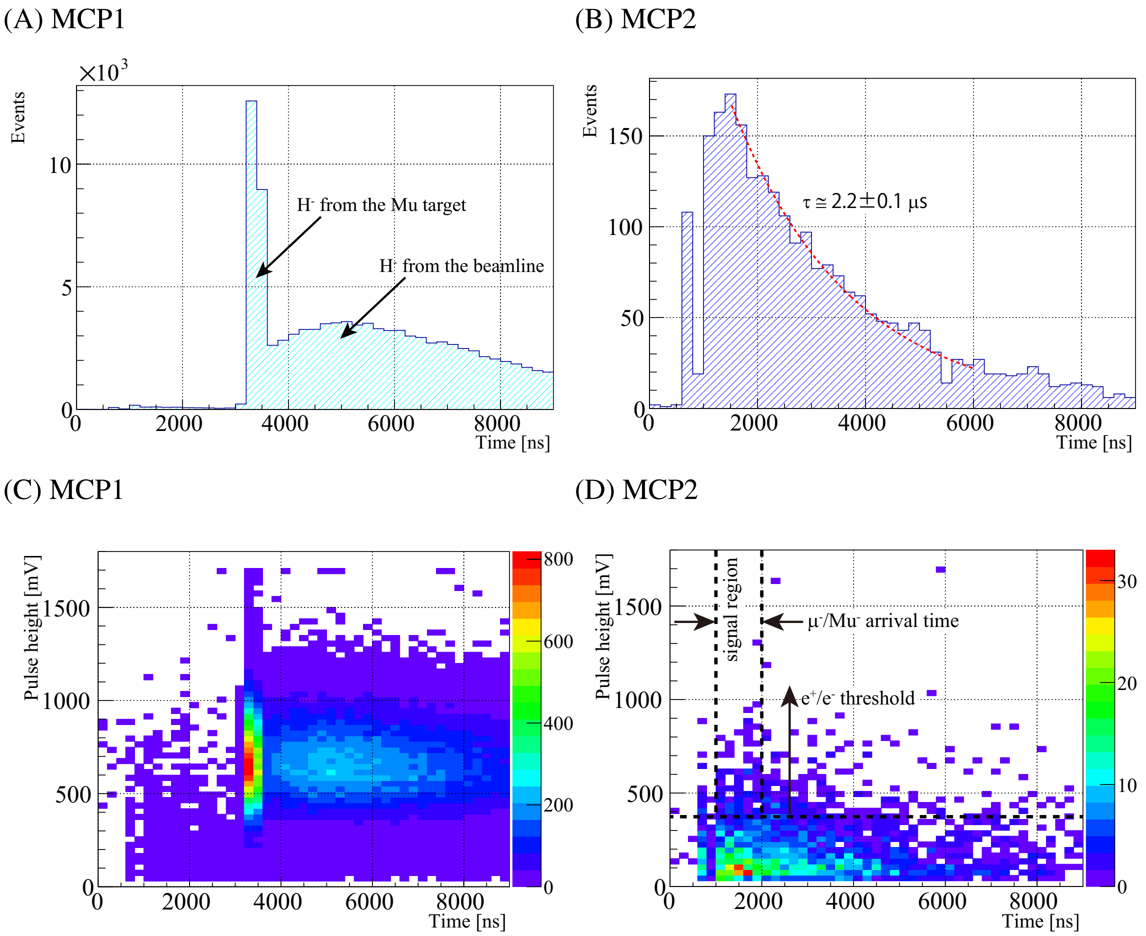

Figure 2: Typical TOF spectra obtained by (A) MCP1 located at the passing straight through MB and (B) MCP2 at the downstream of MB, and contour plots of TOF and pulse height in each MCP (C) and (D). The area surround with the dashed lines in (D) shows the expected region of μ^- appearance.

emitted from around the target with a negative element charge, the same mass as the muon, and almost zero energy. There still exist 4 background events in the signal region in half-a-day data accumulation period corresponding 10^{10} μ^+ incident. These 4 events satisfy all the μ^- conditions. However, no μ^- should be detected even if there would exist because the ionization laser was not used. These events are explained as Mu$^-$ ($\mu^+e^-e^-$) which are spattered by incident μ^+ beam from the metallic parts around the target like the electrode mesh, the target flame *etc*. Most of the devices around the target are made of metal like stainless steel, and they are known to produce Mu$^-$ [10]. Mu$^-$, which fakes a μ^-, is transported through the beamline along the same trajectory as μ^-, detected by MCP2 as a particle with the muon mass, and then decays to emit an e^+. Thus, to distinguish them, the ionization laser should shoot at the delayed timing after the muon beam injection. Coincidentally, the laser shot is expected to optimize to shoot at 2-3 μs after the muon beam incident which is determined to strike a balance between the Mu diffusion in vacuum and the conversion probability.

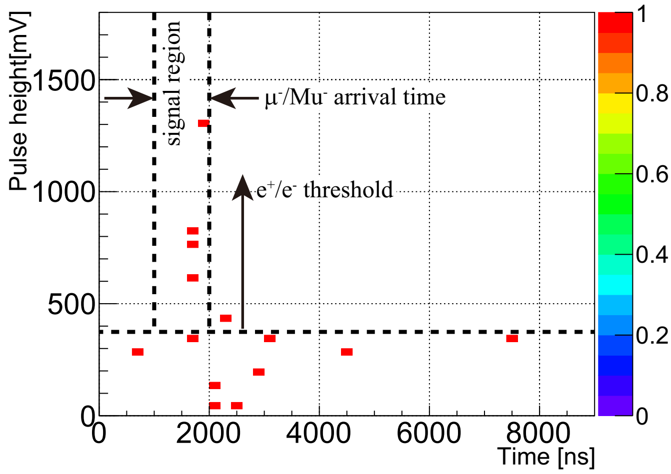

Figure 3: The remaining event in Fig. 2 (D) after requiring a coincident hit in PS telescopes during half-a-day beam time, 10^{10} μ^+ incident to the aerogel. The 4 events remaining in the signal region are explained to be due to Mu$^-$ spattered by incident μ^+ beam from the metallic parts around the target.

4. Discussion and Conclusions

We demonstrated a new concept of Mu – $\overline{\text{Mu}}$ conversion search that has no intrinsic beam-related background limiting the previous studies. We also examined background sources that were unintentionally added to this method.

The detection system will be designed to detect μ^- signals for physics data acquisition. A μ^- introduced into a material forms a muonic atom, and then decays into an electron and two neutrinos or is captured to a nucleus. For instance, more than 90% muons are captured to lead nuclei, the main composition of MCP, and don't emit electrons. Thus, a detector array composed of an MCP and PSs is inefficient in identifying μ^-. To solve this problem, an MCP should be surrounded by X-ray detectors that efficiently catch muonic X-rays emitted in the deexcitation processes of a muonic atom. The X-ray detection is also essential to reject an intrinsic background of Mu$^-$ which is spattered by incident μ^+ beam from the metallic parts around the aerogel target and the devices in the downstream. In the feasibility study, several Mu$^-$ events were observed during half-a-day data accumulation under 500 kW beam.

The incident time of the laser shot is important. The laser should be introduced as delayed as possible to accumulate the converted $\overline{\text{Mu}}$ as much as possible. This is also effective to reduce the Mu$^-$ background. On the other hand, Mu from aerogel has thermal energy and is diffused in a vacuum with time. The laser-shot timing must be determined to balance them. The laser stability is also important to keep the ionization efficiency constant, and Mu$^-$ can be used to monitor it.

In the proposed method, Mu is kept in the zero magnetic field unlike the previous studies. This is one of the advantages of this method because Mu – $\overline{\text{Mu}}$ conversion is expected to be suppressed in the magnetic field [12, 13]. Moreover, in principle, this method narrow down the SM extension models by sweeping and measuring the response to the field.

At the last, achievable sensitivity to the new physics by this scheme is discussed. The surface muon beam intensity in MUSE is estimated to 10^8 /sec under 1-MW operation. The optimum efficiency of Mu emission to the effective volume for the laser irradiation is about 4×10^{-3} at 1 μs after muon beam injection to the aerogel target [8], and will be the order of magnitude lower at a few μs, the optimized time for the conversion. The efficiencies of laser ionization and electrode-mesh transmission are also estimated to be 0.7 and 0.8, respectively [8]. A typical beamline transmission efficiency is about 0.7. The detection efficiency of the detector array including X-ray detectors can be reachable at 0.1. Multiplying all these values, the yield of the observable Mu is about 10^3 /sec. Therefore, the new scheme can reach at the current experimental limit of the order of 10^{-10} for 10^7 sec, about 100 days. This indicates that the proposed method can overcome the current experimental limit. No direct evidence of BSM has appeared in collider studies so far. Thus, a different approach like this scheme becomes meaningful.

Acknowledgment

The authors would like to acknowledge Drs. S. Bae, B. Kim, H. Choi, S. Choi, H. Ko, G. Razuvaev and other Muon g-2/EDM experiment at J-PARC collaborators for their support. This work is supported by JSPS KAKENHI Grant Numbers JP15H03666, JP16H03987, JP15H05742, JP16J07784, JP16K13810, and JP22H01237. The muon experiments at MLF J-PARC were performed under user programs (Proposal No. 2016A0162 and 2018B0313).

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