

Snowmass2021 - Letter of Interest

Possibility of Search for Bound $\mu^- \rightarrow e^- a$ Decay

Thematic Areas: (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*]

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Abstract: The upcoming $\mu \rightarrow e$ conversion experiments would open a new window to search for a light neutral invisible particle a in a bound $\mu^- \rightarrow e^- a$ decay. The particle a can be an axion-like particle (ALP), familon, or majoron with lepton flavour violating coupling to leptons. With a large number of muons available in these $\mu \rightarrow e$ conversion experiments, the search for bound $\mu^- \rightarrow e^- a$ decays will receive huge statistical advantage, providing great discovery potential to probe new physics beyond the Standard Model (SM). From our preliminary studies, with the data corresponding to the experimental sensitivity of $\mu \rightarrow e$ conversion of $\mathcal{O}(10^{-17})$, the search with the sensitivity of $B(\mu^- \rightarrow e^- a) \sim \mathcal{O}(10^{-8})$ is expected. However to make more reliable estimation of the sensitivity, several issues, such as uncertainties of the background spectrum shapes and the energy dependence of the detection acceptance, have to be carefully considered.

Introduction: The exotic rare decay of $\mu \rightarrow ea$ has attracted much attention recently, where a is a light invisible neutral particle with lepton flavour violating coupling to leptons¹. The candidates of a are scalar particles like an axion-like particle (ALP), familon, majoron. For instance, the interaction Lagrangian with ALP is given:

$$\mathcal{L} = \frac{\partial^\mu a}{f_a} (C_{ij}^V \bar{\ell}_i \gamma_\mu \ell_j + C_{ij}^A \bar{\ell}_i \gamma_\mu \gamma_5 \ell_j), \quad (1)$$

where f_a is a decay constant related to the energy scale of ALP. The branching ratio of the decay $\mu \rightarrow ea$ is given by

$$\Gamma(\ell_i \rightarrow \ell_j a) = \frac{1}{16\pi^2} \frac{m_{\ell_i}^3}{F_{ij}^2} \left(1 - \frac{m_a^2}{m_i^2}\right)^2, \quad (2)$$

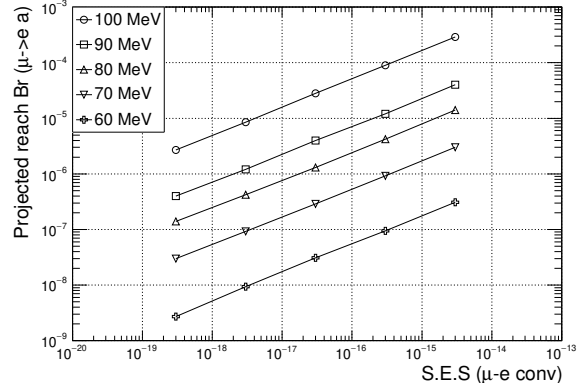
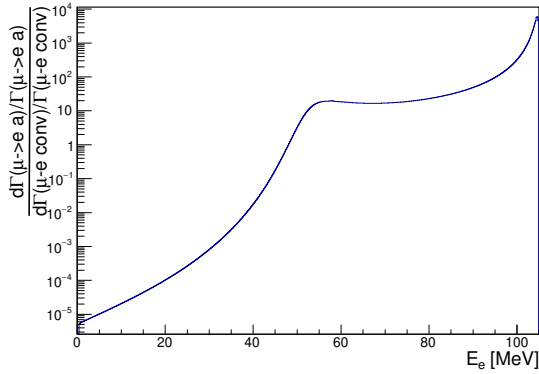
where $F_{ij} = 2f_a/\sqrt{|C_{ij}^V|^2 + |C_{ij}^A|^2}$. The mass of a and the chiral structure of the coupling are important factors for the search.

The experimental searches for the $\mu \rightarrow ea$ decay in the past were mostly made by using a free decay of a positive muon at rest, $\mu^+ \rightarrow e^+ a$. The signature can be identified by a mono-energetic positron. The best experimental limits were made at TRIUMF with the use of polarized muons to suppress the SM muon decay backgrounds, giving $B(\mu^+ \rightarrow e^+ a) < 2.6 \times 10^{-6}$ at 90% C.L. for the case of non-zero right-handed couplings and $m_a \sim 0$ ². The TWIST experiment at TRIUMF also determined $B(\mu^+ \rightarrow e^+ a) < 5.8 \times 10^{-5}$ at 90% C.L. with isotropic decay distribution³. In the future, the Mu3e Online at PSI⁴ is expecting high sensitivity of $B(\mu^+ \rightarrow e^+ a) \sim \mathcal{O}(10^{-8})$. Recently a new proposal of MEG II-fwd^{1,5} has been made to achieve $B(\mu^+ \rightarrow e^+ a) \sim \mathcal{O}(10^{-6} - 10^{-7})$.

Bound $\mu^- \rightarrow e^- a$ Decay Search: It was proposed⁶ to search for $\mu^- \rightarrow e^- a$ by using a bound muon decay in a muonic atom, namely $\mu^- + N(A, Z) \rightarrow e^- + a + N(A, Z)$, which will be referred to AEIO (ALP emission in orbit) in this report. The idea of using bound muon decays was based on statistical advantage of a large number of muons available in the coming $\mu \rightarrow e$ conversion experiments such as COMET at J-PARC⁷ and Mu2e at Fermilab⁸.

In the case of massless a , the emitted electron in the final state can have energy (E_e) up to the signal energy of $\mu \rightarrow e$ conversion, $E_{\mu e} = m_\mu - E_B - E_{rec}$, because of the nuclear recoil. Here, E_B and E_{rec} are the binding energy of the muon in a muonic atom and the recoil energy of the nucleus respectively. For a muonic atom of aluminium, $E_{\mu e}$ is 104.9 MeV. The main background is SM bound muon decays in orbit (DIO), whose energy spectrum also extends up to $E_{\mu e}$. The DIO electron spectrum has been calculated precisely, with the QCD corrections^{9,10}. The AEIO electron spectrum has a different E_e distribution than the DIO spectrum⁶ and therefore it can be discriminated by spectrum shape analysis; for instance, at the endpoint region towards E_e , the AEIO spectrum has $(E_{\mu e} - E_e)^3$ whereas the DIO has a quick drop, $(E_{\mu e} - E_e)^5$, in a simple approximation. The ratio of the AEIO spectrum¹¹ over the DIO spectrum (referred to the S/B ratio) for an aluminium case was calculated and is shown in the left plot in Figure below. It can be seen that the S/B ratio is large at the endpoint region (because of the reason mentioned above), making the analysis of this endpoint region more effective. However the AEIO spectrum fraction at the endpoint region is very small, in the order of $\mathcal{O}(10^{-10})$ for aluminium. Therefore, to improve the statistical significance, the wide energy region above 55 MeV up to $E_{\mu e}$, where the S/B ratio is still reasonably large, are considered for the spectrum shape analysis described below.

At first, a preliminary simulation study has been made to estimate the sensitivity of AEIO in the COMET Phase-I experiment. The energy range of analysis was from 75 MeV to 105 MeV, which is determined by the acceptance of the COMET Phase-I detector. With the consideration of the detection efficiency and the momentum resolution⁷, the projected reach of $B(\mu^- \rightarrow e^- a) < 3.9 \times 10^{-5}$ at 90% C.L. was obtained.



The ratio of AEIO rate¹¹ over the DIO rate is shown in the left plot. The projected sensitivity reach of $\mu^- \rightarrow e^- a$ as a function of the SES of $\mu \rightarrow e$ conversion is shown in the right plot, where the low boundary of the energy range of analysis are denoted in the legends, and the high boundary is fixed to be 105 MeV for all the cases. Here the acceptance of the electron detection was assumed as constant in the energy regions considered.

This result is comparable to the TWIST result. Here, the branching ratio is defined as $B(\mu^- \rightarrow e^- a) = \Gamma(\mu^- \rightarrow e^- a) / \Gamma(\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu)$.

In the near future experiments, the experimental sensitivity to $\mu \rightarrow e$ conversion will reach the order of $\mathcal{O}(10^{-17})$. In the first order approximation, the experimental sensitivity to AEIO can be proportional to a square root of the single event sensitivity (SES) of $\mu \rightarrow e$ conversion. A very preliminary study was carried out to investigate the sensitivity to AEIO, with the assumption of a constant acceptance of electron detection as a function of E_e . The five energy regions of analysis were selected, in which the lower boundary is changed from 60 MeV, 70 MeV, 80 MeV, 90 MeV, to 100 MeV whereas the the high boundary is fixed to be 105 MeV. The expected sensitivity of AEIO as a function of SES of $\mu \rightarrow e$ conversion is shown in the right plot in Figure, where the numbers in the legends denote the low boundary of the energy region of analysis. From this, it can be seen that, for the case of SES of $\mu \rightarrow e$ conversion of $\mathcal{O}(10^{-17})$, the AEIO sensitivity of $\mathcal{O}(10^{-8})$ (and $\mathcal{O}(10^{-7})$) can be achieved with the energy region from 60 MeV (and 70 MeV), respectively. They are comparable to the Mu3e online and the MEG II-fwd. In this case, a number of the DIO events of the order of $\mathcal{O}(10^{13})$ is collected. It should be noted that this preliminary analysis does not include the uncertainty of the DIO spectrum, and no contribution from radiative muon capture (RMC). Also the energy dependence of the electron acceptance should be taken into account. In our next studies, these issues will be addressed. Also it is worth to mention that the AEIO and DIO spectrum shapes are different for different muon target materials. Therefore, comparison with different target materials would provide additional controls of systematic uncertainties.

Summary The coming $\mu \rightarrow e$ conversion experiments with the expected sensitivity of $\mathcal{O}(10^{-17})$ would provide a great opportunity to search for the exotic bound $\mu^- \rightarrow e^- a$ decay. The preliminary study shows the spectrum analysis with a wide energy range would provide the sensitivity of $\mathcal{O}(10^{-8})$, which is comparable to those of Mu3e online and MEG II-fwd. However, the uncertainties from the DIO and RMC spectra have to be carefully examined to make reliable estimation of the AEIO sensitivity.

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