New Process for Charged Lepton Flavor Violation Searches: $\mu^- e^- \to e^- e^-$ in a Muonic Atom

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We propose a new process of $\mu^- e^- \to e^- e^-$ in a muonic atom for a quest of charged lepton flavor violation. The Coulomb attraction from the nucleus in a heavy muonic atom leads to significant enhancement in its rate, compared to $\mu^+ e^- \to e^+ e^-$. The upper limit of the branching ratio is estimated to be of the orders of $O(10^{-17}\text{–}10^{-18})$ for the photonic and the four-fermion interactions from the present experimental constraints. The search for this process could serve complementarily with the other relevant processes to shed light upon the nature of charged lepton flavor violation.

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Charged lepton flavor violation (CLFV) is known to be one of the important rare processes to search for new physics beyond the standard model (SM). Various theoretical models predict sizable rates of CLFV processes, which are just below the present experimental upper limits. The ongoing and future experiments for CLFV searches might reach sensitivities in a range of predictions by many theoretical models. At this moment, the CLFV searches with muons have presented the best experimental limits owing to a large number of muons available for measurements [1]. Typical CLFV processes with muons include $\mu^+ \to e^+\gamma$, $\mu^+ \to e^+e^+e^-$, and μ^--e^- conversion in a muonic atom ($\mu^- N \to e^- N$). However, even if a CLFV process is discovered in future, many other different CLFV processes should be studied to shed light upon the understanding of the nature of the CLFV interactions and develop insights into new physics responsible for CLFV.

In this Letter, we propose a new CLFV reaction process of a bound μ^- in a muonic atom, which is

$$\mu^- e^- \to e^- e^-, \tag{1}$$

where μ^- and e^- in the initial state of Eq. (1) are the muon and the atomic $1S$ electron(s) bound in a Coulomb field of the nucleus in a muonic atom, respectively.

This $\mu^- e^- \to e^- e^-$ process in a muonic atom has various significant advantages. First of all, this process could have not only the photonic dipole interaction but also the four-fermion contact interaction, as in the processes of $\mu^+ \to e^+e^-e^-$ and $\mu^- N \to e^- N$, but in contrast to $\mu^+ \to e^+\gamma$ that has only the former. This would allow us potentially to investigate the full structure of new physics beyond the SM. Second, this process has a two-body final state, in which a sum of the energies of the two signal electrons would be equal to $m_\mu + m_e - B_\mu$, where B_μ is a binding energy of the muon in a muonic atom. This would provide a cleaner experimental signature as well as a larger final-state phase space than $\mu^+ \to e^+e^+e^-$ decay. Also, in comparison with the $\mu^+ \to e^+\gamma$ search, the measurement of this process would be relatively easier since no photon detection is involved. Third, one can consider a similar reaction process with a muonium, such as $\mu^+ e^- \to e^+ e^-$. However, the rate of this $\mu^+ e^- \to e^+ e^-$ process cannot be large because of small overlap between the μ^+ and e^- wave functions. However, in a muonic atom of atomic number Z, we can increase the overlap between the μ^- and e^- wave functions if an atom of large Z is chosen. The enhancement occurs owing to the Coulomb interaction from the nucleus which attracts the $1S$ state electron wave function towards the μ^- and the nucleus. The expected rate would increase by a factor of $(Z-1)^3$. For example, the rate for a lead ($Z = 82$) is 5×10^5 times that of the $\mu^+ e^- \to e^+ e^-$ reaction. However, in a muonic atom, nuclear muon capture occurs in addition to the normal Michel muon decay in the $1S$ state. But since a lifetime of a muonic atom changes from 2.2 μs for a hydrogen to $\sim$80 ns for a lead, the branching ratio of $\mu^- e^- \to e^- e^-$ is reduced by a factor of at most only 20. Therefore, a net increase of the branching ratio would become significant for a large atomic number Z. A potential disadvantage is that the rates of reaction processes like this might not be large enough compared to rare CLFV muon decays. Therefore, in this Letter we will evaluate the rate of $\mu^- e^- \to e^- e^-$ and discuss its upper limit that is allowed from the present experimental limits of other CLFV processes.

We describe the process of $\mu^- e^- \to e^- e^-$ in a muonic atom by an effective Lagrangian at the energy scale of the muon mass m_μ. Following Ref. [1], we define

$$\begin{aligned}\mathcal{L}_{\mu^- e^- \to e^- e^-} = -\frac{4G_F}{\sqrt{2}}[&m_\mu A_R \bar{\mu}_R \sigma^{\mu\nu} e_L F_{\mu\nu} + m_\mu A_L \bar{\mu}_L \sigma^{\mu\nu} e_R F_{\mu\nu} + g_1(\bar{\mu}_R e_L)(\bar{e}_R e_L) + g_2(\bar{\mu}_L e_R)(\bar{e}_L e_R) + g_3(\bar{\mu}_R \gamma^\mu e_R)\\ &\times (\bar{e}_R \gamma_\mu e_R) + g_4(\bar{\mu}_L \gamma^\mu e_L)(\bar{e}_L \gamma_\mu e_L) + g_5(\bar{\mu}_R \gamma^\mu e_R)(\bar{e}_L \gamma_\mu e_L) + g_6(\bar{\mu}_L \gamma^\mu e_L)(\bar{e}_R \gamma_\mu e_R) + (\text{H.c.})].\end{aligned} \tag{2}$$

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The first two terms in the brackets are the photonic interaction contributing to $\mu^- e^- \to e^- e^-$ (Fig. 1). The remaining terms are for the direct four-fermion contact interaction. The initial state of the process of Eq. (1) has the muon and the electron in their $1S$ ground state of the atomic orbits. For simplicity, the three-momenta of their initial bound states are ignored. The final state has the two electrons, which are treated as monochromatic plane waves that propagate with opposite momentum vectors, and it is assumed that each of the two signal electrons in the final-state takes an energy of about $m_\mu/2$.

We will estimate the branching ratio of $\mu^- e^- \to e^- e^-$ in two extreme cases. The first is the case where the four-fermion contact interaction is dominant and no contribution of the photonic interaction exists. The cross section of $\mu^- e^- \to e^- e^-$ is calculated to be

$$\sigma v_{\mathrm{rel}} = \frac{1}{m_\mu^2} \frac{(G_F m_\mu^2)^2}{16\pi} G, \tag{3}$$

where $G \equiv G_{12} + 16G_{34} + 4G_{56} + 8G'_{14} + 8G'_{23} - 8G'_{56}$ with $G_{ij} \equiv |g_i|^2 + |g_j|^2$ and $G'_{ij} \equiv \mathrm{Re}(g_i^* g_j)$. The transition rate is then given by

$$\begin{aligned}\Gamma(\mu^- e^- \to e^- e^-) &= 2\sigma v_{\mathrm{rel}} |\psi_{1S}^{(e)}(0; Z-1)|^2 \\ &= m_\mu \frac{1}{8\pi}(Z-1)^3 \alpha^3 (G_F m_\mu^2)^2 \left(\frac{m_e}{m_\mu}\right)^3 G.\end{aligned} \tag{4}$$

Here we took into account the facts that the $1S$ state can accommodate two electrons, and that the nuclear charge is shielded by the negative muon. We used the nonrelativistic wave functions given by

$$\psi_{1S}^{(e)}(r; Z-1) = \frac{[(Z-1)\alpha m_e]^{3/2}}{\sqrt{\pi}} e^{-(Z-1)\alpha m_e r}, \tag{5}$$

where r is the radial coordinate, so that $\psi_{1S}^{(e)}(0; Z-1) = [(Z-1)\alpha m_e]^{3/2}/\sqrt{\pi}$. The rate of Eq. (4) is enhanced for a larger atomic number Z by a factor of $(Z-1)^3$, giving a notable advantage for heavy nuclei. This enhancement comes from the factor of $|\psi_{1S}^{(e)}(0; Z-1)|^2$, and the large positive charge of a heavy nucleus strongly attracts the $1S$ wave functions of the leptons toward the nucleus position, rendering the overlap of the two wave functions large, and enhances the transition of the process of Eq. (1). We normalize the rate of Eq. (4) by the lifetime of a muonic atom $\tilde{\tau}_\mu$ to define the branching ratio of this process as

$$\begin{aligned}\mathrm{Br}(\mu^- e^- \to e^- e^-) &\equiv \tilde{\tau}_\mu \Gamma(\mu^- e^- \to e^- e^-) \\ &= 24\pi(Z-1)^3 \alpha^3 \left(\frac{m_e}{m_\mu}\right)^3 \frac{\tilde{\tau}_\mu}{\tau_\mu} G \\ &= (3.31 \times 10^{-12})(Z-1)^3 (\tilde{\tau}_\mu/\tau_\mu) G.\end{aligned} \tag{6}$$

The value of $\tilde{\tau}_\mu$ ranges from $\tilde{\tau}_\mu = 2.19 \times 10^{-6}$ s for ^{1}H to $\tilde{\tau}_\mu = (7\text{–}8) \times 10^{-8}$ s for ^{238}U as listed in Ref. [2]. This is shorter than the lifetime of free muons, $\tau_\mu = 2.197 \times 10^{-6}$ s [3], which is equal to $192\pi^3/(G_F^2 m_\mu^5)$ at the lowest order. To estimate the branching ratio that is experimentally allowed for Eq. (6), $\mu^+ \to e^+ e^+ e^-$ is used since it arises from elementary processes similar to $\mu^- e^- \to e^- e^-$ and its experimental upper limit is available. The branching ratio of $\mu^+ \to e^+ e^+ e^-$ with only the four-fermion interaction is given by [4]

$$\mathrm{Br}(\mu^+ \to e^+ e^+ e^-) = \tfrac{1}{8}(G_{12} + 16G_{34} + 8G_{56}). \tag{7}$$

The contributions from the interference among the four-fermion interactions are not present in Eq. (7), whereas it is found to be present in Eq. (6) as the terms of G'_{ij}'s. The absence of the interference in Eq. (7) is due to the large momenta of the final electrons. The search for $\mu^- e^- \to e^- e^-$ will thereby serve complementarily with that for $\mu^+ \to e^+ e^+ e^-$.

To evaluate the branching ratio of $\mu^- e^- \to e^- e^-$, a ratio of the two branching ratios of

$$\frac{\mathrm{Br}(\mu^- e^- \to e^- e^-)}{\mathrm{Br}(\mu^+ \to e^+ e^+ e^-)} \lesssim 192\pi(Z-1)^3 \alpha^3 \left(\frac{m_e}{m_\mu}\right)^3 \frac{\tilde{\tau}_\mu}{\tau_\mu}, \tag{8}$$

is obtained once $G/(G_{12} + 16G_{34} + 8G_{56}) \sim O(1)$ is assumed. Hence, $\mathrm{Br}(\mu^- e^- \to e^- e^-)$ is constrained by the existing limit of $\mathrm{Br}(\mu^+ \to e^+ e^+ e^-) < B_{\max}$ as

$$\mathrm{Br}(\mu^- e^- \to e^- e^-) < 192\pi(Z-1)^3 \alpha^3 \left(\frac{m_e}{m_\mu}\right)^3 \frac{\tilde{\tau}_\mu}{\tau_\mu} B_{\max}, \tag{9}$$

where $B_{\max} = 1.0 \times 10^{-12}$ is the present experimental upper limit from the SINDRUM experiment [5]. Figure 2 shows these upper limits as a function of an atomic number Z by a dotted curve. The light-shaded region in Fig. 2 is excluded. The reciprocal of the shown limit gives an estimation of the number of muons that is required to detect events of the process of Eq. (1). Let us take an example of the gold atom ($Z = 79$): our estimation on the branching ratio of $\mathrm{Br} < 4.21 \times 10^{-19}$ requires a collection of $(4.21 \times 10^{-19})^{-1} = 2.38 \times 10^{18}$ muon events. Assuming the detection efficiency of $O(10\%)$, the required number of muons amounts to a few times 10^{19}. Compared to this number is the muon intensity of $O(10^{18}\text{–}10^{19})$ that is

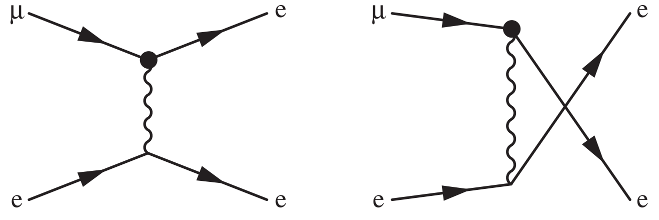

FIG. 1. The process $\mu^- e^- \to e^- e^-$ induced from the photonic interactions. The black dot indicates the effective interaction that is absent from the standard model.

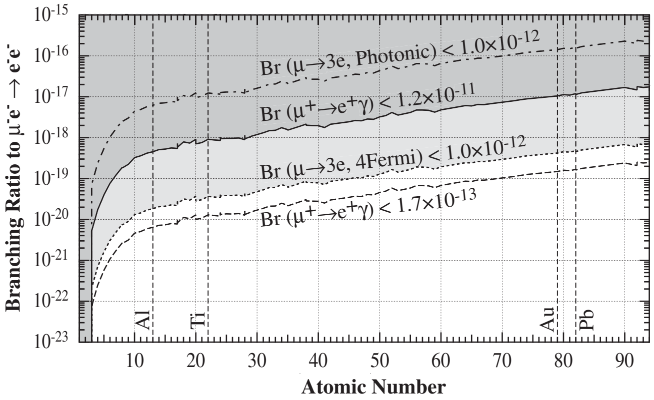

FIG. 2. Upper limits on $\mathrm{Br}(\mu^- e^- \to e^- e^-)$ imposed by the experimental upper limits of $\mathrm{Br}(\mu^+ \to e^+ \gamma)$ and $\mathrm{Br}(\mu^+ \to e^+ e^+ e^-)$. The light-shaded region is excluded for the four-fermion contact interaction, whereas the dark-shaded region is excluded for the photonic interaction.

the goal of the highly intense muon beams planned in the near-future searches for CLFV [6–8]. We thereby find that the current limits could be within the reach by these new muon sources.

The second is the case where the photonic interaction is present and dominates over the four-fermion interactions. In this case, the cross section, transition rate, and branching ratio of $\mu^- e^- \to e^- e^-$ are calculated to be

$$\sigma v_{\mathrm{rel}} = [4\alpha (G_F m_\mu^2)^2 / m_e^2](|A_L|^2 + |A_R|^2), \tag{10}$$

$$\begin{aligned}\Gamma(\mu^- e^- \to e^- e^-) &= 2\sigma v_{\mathrm{rel}} |\psi_{1S}^{(e)}(0; Z-1)|^2 \\ &= (8m_e/\pi)(Z-1)^3 \alpha^4 (G_F m_\mu^2)^2 (|A_R|^2 \\ &\quad + |A_L|^2),\end{aligned} \tag{11}$$

and

$$\begin{aligned}\mathrm{Br}(\mu^- e^- \to e^- e^-) &= 1536\pi^2 (Z-1)^3 \alpha^4 (|A_R|^2 \\ &\quad + |A_L|^2) \frac{m_e}{m_\mu} \frac{\tilde{\tau}_\mu}{\tau_\mu} \\ &= 2.08 \times 10^{-9} (Z-1)^3 (|A_R|^2 \\ &\quad + |A_L|^2)(\tilde{\tau}_\mu / \tau_\mu),\end{aligned} \tag{12}$$

respectively. On the other hand, the branching ratio of $\mu^+ \to e^+ e^+ e^-$ with only the photonic interaction is given by [4]

$$\begin{aligned}\mathrm{Br}(\mu^+ \to e^+ e^+ e^-) &= 128\pi\alpha (A_R|^2 + |A_L|^2) \\ &\quad \times \left[\log\left(\frac{m_\mu}{m_e}\right)^2 - \frac{11}{4}\right].\end{aligned} \tag{13}$$

We then have a ratio of these branching ratios as

$$\begin{aligned}\frac{\mathrm{Br}(\mu^- e^- \to e^- e^-)}{\mathrm{Br}(\mu^+ \to e^+ e^+ e^-)} &= 12\pi (Z-1)^3 \alpha^3 \frac{m_e}{m_\mu} \frac{\tilde{\tau}_\mu}{\tau_\mu} \\ &\quad \times \left[\log\left(\frac{m_\mu}{m_e}\right)^2 - \frac{11}{4}\right]^{-1}.\end{aligned} \tag{14}$$

Then, we could estimate the experimentally allowed upper limit by

$$\begin{aligned}\mathrm{Br}(\mu^- e^- \to e^- e^-) &< 12\pi (Z-1)^3 \alpha^3 \frac{m_e}{m_\mu} \frac{\tilde{\tau}_\mu}{\tau_\mu} \\ &\quad \times \left[\log\left(\frac{m_\mu}{m_e}\right)^2 - \frac{11}{4}\right]^{-1} B_{\max}.\end{aligned} \tag{15}$$

This upper limit is overlaid in Fig. 2 by a dash-dotted curve, according to the aforementioned SINDRUM limit.

When the photonic interaction exists, another CLFV process such as $\mu^+ \to e^+ \gamma$ would occur as well. The searches for this process also put an upper limit to $\mathrm{Br}(\mu^- e^- \to e^- e^-)$. The branching ratio of $\mu^+ \to e^+ \gamma$ decay is given by

$$\begin{aligned}\mathrm{Br}(\mu^+ \to e^+ \gamma) &= \frac{\Gamma(\mu^+ \to e^+ \gamma)}{\Gamma(\mu^+ \to e^+ \nu_e \bar{\nu}_\mu)} \\ &= 384\pi^2 (|A_R|^2 + |A_L|^2).\end{aligned} \tag{16}$$

Then, the upper limit on $\mathrm{Br}(\mu^- e^- \to e^- e^-)$ is estimated from $\mathrm{Br}(\mu^+ \to e^+ \gamma) < B_{\max}$ as

$$\begin{aligned}\mathrm{Br}(\mu^- e^- \to e^- e^-) &< \frac{\mathrm{Br}(\mu^- e^- \to e^- e^-)}{\mathrm{Br}(\mu^+ \to e^+ \gamma)} B_{\max} \\ &= 4(Z-1)^3 \alpha^4 \frac{m_e}{m_\mu} \frac{\tilde{\tau}_\mu}{\tau_\mu} B_{\max}.\end{aligned} \tag{17}$$

A solid curve in Fig. 2 presents the upper limits given in Eq. (17) with $B_{\max} = 1.2 \times 10^{-11}$, which is the current upper limit from the MEGA experiment [9]. A dashed curve in Fig. 2 also shows the limits with the $B_{\max} = 1.7 \times 10^{-13}$, which is the future goal value of the MEG experiment [10]. It is seen that even the current limit on $\mathrm{Br}(\mu^+ \to e^+ \gamma)$ overwhelms the limits on $\mathrm{Br}(\mu^- e^- \to e^- e^-)$ when the photonic interaction is dominant. Accordingly, the presently excluded region is above the current MEGA limit. Let us estimate, as we did earlier, the required number of muons to detect the $\mu^- e^- \to e^- e^-$ events, taking an example of the gold atom ($Z = 79$): to surpass the sensitivity of the MEGA ($B_{\max} = 1.2 \times 10^{-11}$), from the estimated $\mathrm{Br}(\mu^- e^- \to e^- e^-) < 1.04 \times 10^{-17}$, a net number of muon events of $(1.04 \times 10^{-17})^{-1} = 9.58 \times 10^{16}$ is needed. And similarly, to exceed that of the MEG goal, from the estimated $\mathrm{Br}(\mu^- e^- \to e^- e^-) < 1.48 \times 10^{-19}$, a number of muon events of $(1.480 \times 10^{-19})^{-1} = 6.76 \times 10^{18}$ is necessary. The required intensity of muon beams is estimated to be from 10^{18} to a few of 10^{19}/year, assuming the $O(10\%)$ of the detection efficiency again. Such beams are not available now, but could be possible in the future at one of the proposed highly intense muon sources.

We note here that the interferences between the four-fermion and photonic contributions is always subleading in terms of the powers of (m_e/m_μ); thus we do not estimate their contributions in this Letter.

The expected magnitudes of the branching ratio of the process of $\mu^- e^- \to e^- e^-$ are found to be not significantly large. Thus, this would not be the process to cultivate the discovery frontier of the CLFV searches. However, thanks to the enhancement of $(Z-1)^3$, this process can be accessible in the future by next-generation high-intensity muon beams to produce muons of an order of $O(10^{18}\text{–}10^{19})$ per year. On the other hand, the search for $\mu^+ e^- \rightarrow e^+ e^-$ would not be possible even with such beam intensities. Even higher beam intensities of $O(10^{21})$ muons per year are envisioned in future accelerator projects such as muon colliders, neutrino factories, and Higgs factories [11].

Several issues, which will be considered in the future, are listed as follows. (i) The bound effects in a muonic atom, which is known to be large for heavy atoms [12], might change the event signature such as energies of the two signal electrons. For instance, for lead, based on the energy spectrum of an electron of bound muon decays (BMD) [12], it is speculated that one of the two signal electrons may have an average energy of about 30 MeV. However, a sum of the energies of the two signal electrons should be $m_\mu + m_e - B_\mu$, since a kinetic energy of the recoil nucleus is small due to its large mass. Therefore, the other electron would have an average energy of about 65 MeV, where $B_\mu \sim 10$ MeV for lead. The energy of the latter, which is above the average energy of the BMD electrons, might benefit the experimental search. Since the process of $\mu^- e^- \rightarrow e^- e^-$ is quite different from that of BMD, to make precise evaluation of the bound effects, full detailed calculations are needed. (ii) The lepton wave functions should take account of the nuclear charge distribution and relativistic effects. (iii) The interaction among the muon and the two $1S$ electrons in the initial state needs detailed treatments. For instance, the transition rate may depend on the initial spin state, and its dependence may give a hint of new physics behind the CLFV processes. (iv) Possible contributions from the $2S$, $3S$,… electrons should also be considered. A simple estimation gives an additional enhancement factor of $\zeta(3) \simeq 1.20$ to the rates of Eqs. (4) and (11). But, the electronic shielding might diminish this factor. (v) An important experimental issue is the estimation of backgrounds, including the SM physics backgrounds from the $\mu^- e^- \rightarrow e^- e^- \nu \bar{\nu}$ decay and accidental backgrounds that are known to be detector dependent. These issues will be discussed in our future works.

In summary, the new CLFV process $\mu^- e^- \rightarrow e^- e^-$ in a muonic atom is proposed. This process has the rate enhancement of $(Z-1)^3$ over the $\mu^+ e^- \rightarrow e^+ e^-$ owing to the Coulomb attraction from the nucleus in a muonic atom. This process has a final state of two electrons, which would be an experimentally clean signature. The experimentally allowed upper limits of the branching ratio in the orders of $O(10^{-17}\text{–}10^{-18})$ are estimated separately for the four-fermion and photonic interactions from the present CLFV experimental results. Once this process is observed, CP violation might be also studied by comparing this process with $\mu^+ \rightarrow e^+ e^+ e^-$ decay.

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