Improved analysis of the CLFV decay of muonic atoms $\mu^- e^- \to e^- e^-$

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Search for Charged Lepton Flavor Violation (CLFV)

- CLFV is signal to search for new physics beyond the standard model
- High sensitivity for muonic CLFV due to high intensity muon beam
- Current upper limits of branching ratio for muonic CLFV processes

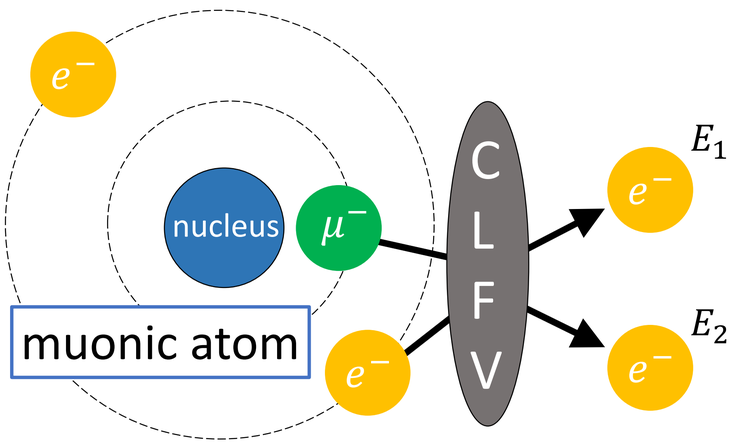
$Br(\mu^+ \to e^+\gamma) < 5.7 \times 10^{-13}$

$Br(\mu^+ \to e^+e^-e^+) < 1.0 \times 10^{-12}$

$Br(\mu^-\mathrm{Au} \to e^-\mathrm{Au}) < 7 \times 10^{-13}$

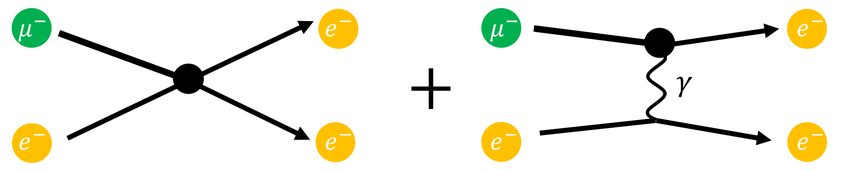
- New process for CLFV
  "$\mu^- e^- \to e^- e^-$ in a muonic atom"

  proposed by
  Koike *et al.* Phys. Rev. Lett. **105**, 121601(2010)



advantages

1. Capability to probe both short- and long-range CLFV interactions



contact interaction　　photonic interaction

2. Clear signal
   $E_1 + E_2 = m_\mu + m_e - B_\mu - B_e$
3. Enhancement of decay rate due to nuclear Coulomb attraction

Purpose The quantitative estimation for $\mu^- e^- \to e^- e^-$ in a muonic atom

Formalism

Effective Lagrangian : $\mathcal{L}_I = \mathcal{L}_{\mathrm{contact}} + \mathcal{L}_{\mathrm{photonic}}$

$$\mathcal{L}_{\mathrm{contact}} = -\frac{4G_F}{\sqrt{2}}\left[g_1(\overline{\mu_R}e_L)(\overline{e_R}e_L) + \cdots\right]$$

(In this presentation, we restrict ourselves to contact interactions.)

Previous work

Koike *et al.* Phys. Rev. Lett. **105**, 121601(2010)

$$\Gamma_{CLFV} = \sigma_{\mu e \to ee} v_{rel} |\psi_e(0)|^2$$

approximations

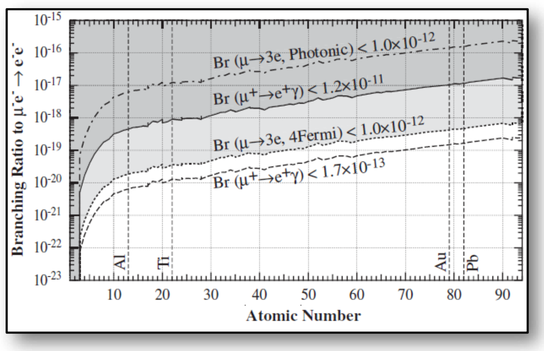
1. Bohr radius of bound μ^- >> wave length of emitted e^-
2. Emitted electrons : plane-wave
3. Bound leptons : non-relativistic
4. Nuclear Coulomb potential : point nuclear charge distribution

Result $\Gamma_{\mu^- e^- \to e^- e^-} \propto (Z-1)^3$

◆ estimation of $Br(\mu^- e^- \to e^- e^-) \equiv \Gamma_{CLFV}/\Gamma_{total}$ by current limit of $Br(\mu \to 3e) < 10^{-12}$

Γ_{total} : total decay width of a muonic atom

- required muonic atoms for ^{208}Pb
  $> (4.8 \times 10^{-19})^{-1} = 2.1 \times 10^{18}$
  for restricting $\mathcal{L}_{\mathrm{contact}}$ more tightly



This work

Improved treatment of lepton wave functions

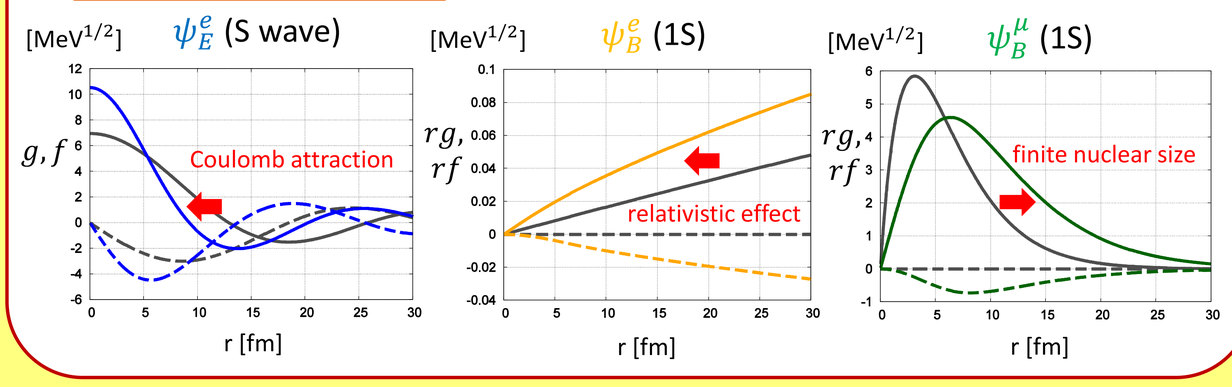
$$\Gamma_{CLFV} = \sum_{f,i} \delta(E_f - E_i)\left|\left\langle \psi^e_{E_1}\psi^e_{E_2}\middle|\mathcal{L}_I\middle|\psi^\mu_B\psi^e_B\right\rangle\right|^2$$

- $\psi^e_{E_1}, \psi^e_{E_2}$ → distorted by Coulomb potential
- ψ^μ_B, ψ^e_B → relativistic
- Nuclear Coulomb potential : uniform nuclear charge distribution

wave function (partial wave expansion)

$$\psi_\kappa(\vec{r}) = \begin{pmatrix} g_\kappa(r)\chi_\kappa(\hat{r}) \\ if_\kappa(r)\chi_{-\kappa}(\hat{r}) \end{pmatrix}$$

solid line : large component, g
dotted line : small component, f
(gray line : w.f. used in previous work)



Results to short-range CLFV interaction

Ratio of decay rate to Koike *et al.*'s (for g_1 term)

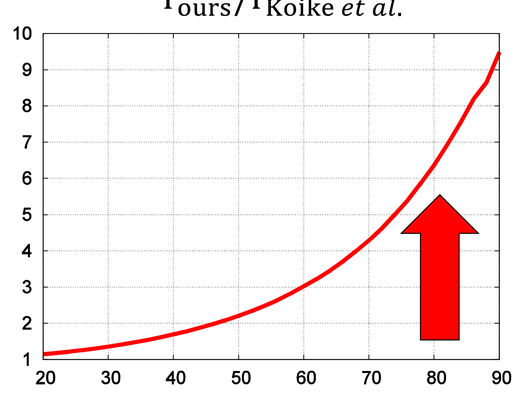
$\Gamma_{\mathrm{ours}}/\Gamma_{\mathrm{Koike\ et\ al.}}$ gets larger as atomic # is larger.

Enhancement factor ~7 for ^{208}Pb

◆ **the main reasons for enhancement**

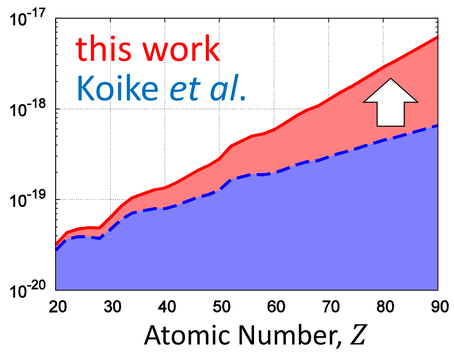
- Coulomb attraction on emitted electrons
- Relativistic effects on a bound electron

✓ Finite nuclear size is also impotant but reduce Γ.



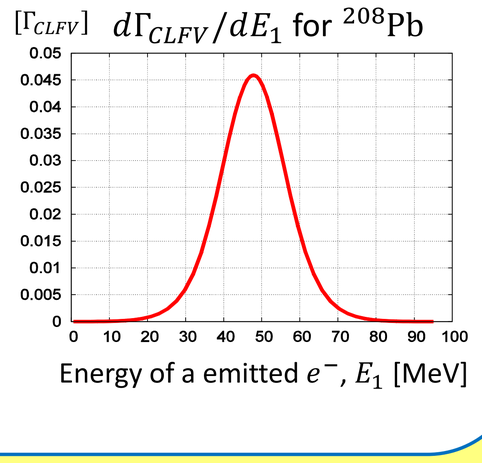
Branching Ratio

- required muonic atoms for ^{208}Pb
  $> (3.3 \times 10^{-18})^{-1} = 3.0 \times 10^{17}$



Energy distribution of a emitted electron

- symmetric for two emitted e^-s
- width ~ 20 MeV for ^{208}Pb due to momentum distribution of a bound muon



Summary

We estimated the decay rate of the contact CLFV interaction and showed that it gets larger than the previous estimation.

Important effects

- Distortion of emitted electrons
- Relativistic effects on a bound electron
- Finite nuclear charge distribution

Future work

- analysis of long-range photon exchange CLFV interaction
- find signal to discriminate CLFV interactions
  e.g. energy and angular distribution of emitted electrons