cLFV on target at GeV scale electron/positron beam experiment

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Content:

- **status quo and theoretical aspect of cLFV**
- $e - \tau$ **conversion on nucleon/nucleus for GeV scale** $e^{\pm}$ **beam**
- **probing** $e\tau$ **magnetic vertex**
- **probing** $Ze\tau$ **vertex**
- **conclusion**

status quo for cLFV

Lepton flavor violation(LFV):

Processes with

- **lepton flavor number** L_e, L_μ, L_τ **not conserved**
- **total lepton number** $L = L_e + L_\mu + L_\tau$ **conserved**
- **e.g. LFV in neutral lepton: neutrino oscillation** $\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$ **violates lepton flavor but not total lepton number.**

charged LFV: $\mu - e$, $\tau - e$, $\tau - \mu$ **conversion**

status quo for cLFV

In SM, LFV of neutral/charged leptons all forbidden.

- ν **oscillation shows: there are new physics beyond SM**
- **A natural question to ask is**
  whether there are also LFV in charged lepton sector
- **Models behind neutrino masses and mixings are also possible to give rise to flavor mixings of charged leptons.**
- **e.g. , susy seesaw model, natural to give tiny neutrino masses and mixings, can lead to cLFV.**

LFV also possible in extension of Higgs sector.
Signal: $h \to e^{\mp}\mu^{\pm}$, $h \to e^{\mp}\tau^{\pm}$ **and** $h \to \mu^{\mp}\tau^{\pm}$.

status quo for cLFV

Some major cLFV processes

$$Br(\mu^- \to e^-\gamma) < 5.7 \times 10^{-13}$$
$$Br(\mu^- \to e^-e^+e^-) < 1.0 \times 10^{-12}$$
$$Br(\tau^- \to e^-\gamma) < 3.3 \times 10^{-8}$$
$$Br(\tau^- \to e^-e^+e^-) < 2.7 \times 10^{-8}$$
$$Br(\tau^- \to \mu^-\gamma) < 4.4 \times 10^{-8}$$
$$Br(\tau^- \to \mu^-e^+e^-) < 1.8 \times 10^{-8}$$
$$Br(\tau^- \to e^-\pi^+\pi^-) < 2.3 \times 10^{-8}$$
$$Br(\tau^- \to \mu^-\pi^+\pi^-) < 3.9 \times 10^{-8}$$

Constraints on $e-\tau, \mu-\tau$ conversion are considerably weaker

$\mu - e$ **conversion on target,** $\mu + N \to e + N$**, quite competitive.**

status quo for cLFV

Since

$$Br(\tau \to \nu_\tau e \bar{\nu}_e) \approx Br(\tau \to \nu_\tau \mu \bar{\nu}_\mu) \approx 0.17$$
$$Br(\tau \to \nu_\tau \pi^- \pi^0) \approx 0.25$$

The constraints on NC flavor changing coupling squared are at order

$$\frac{Br(\tau^- \to \mu^- e^+ e^-)}{Br(\tau \to \nu_\tau e \bar{\nu}_e)}, \frac{Br(\tau^- \to e^- \pi^+ \pi^-)}{Br(\tau \to \nu_\tau \pi^- \pi^0)},$$

which are around 10^{-7}(in unit of SM coupling squared)

status quo for cLFV

Constraints on flavor changing Z vertex are much weaker

$$Br(Z \to e^{\pm}\mu^{\mp}) < 1.7 \times 10^{-6}$$
$$Br(Z \to e^{\pm}\tau^{\mp}) < 9.8 \times 10^{-6}$$
$$Br(Z \to \mu^{\pm}\tau^{\mp}) < 1.2 \times 10^{-5}$$

$Br(Z \to 3\nu\bar{\nu}) = 0.20$
constraints on flavor changing Z coupling squared are at order

$$\frac{Br(Z \to e^{\pm}\tau^{\mp})}{Br(Z \to \nu_i\bar{\nu}_i)}$$

which is around 10^{-4}**(in unit of SM coupling squared for** ν**)**

Z factory in the future can probe this coupling squared to $< 10^{-10}$

For example, two types of effective operator for LFV:

Chirality flip:

$$\bar{\tau}_R i\sigma^{\mu\nu} e_L F_{\mu\nu}, \;\; \bar{\tau}_L i\sigma^{\mu\nu} e_R F_{\mu\nu}$$

A naive estimate of strength $\propto m_\tau$, so for $e-\mu$ conversion $\propto m_\mu$.

No chirality flip

$$\bar{\tau}_L \gamma^\mu e_L Z_\mu, \;\; \bar{\tau}_R \gamma^\mu e_R Z_\mu$$

In general, relative strength of $e-\mu$ and $e-\tau$ conversions is model dependent.

status quo for cLFV

Real situation is not simple

For example, if considering neutrino mixing in SM, cFLV can be induced by loop with light neutrino, chirality flip given by neutrino mass, amplitude extremely small

in models with gauge interaction
chirality flip given by different fermions in loop
and amplitude can be quite different

If given by Yukawa type interaction(e.g. LFV in Higgs sector transferred to gauge boson), strength of $e - \tau$ conversion stronger than $e - \mu$ conversion, but not always in power one of ratio m_τ/m_μ

status quo for cLFV

$e - \tau$ **conversion is of a lot of interests**

- **in general, we could expect (much) stronger conversion amplitude in** $e - \tau$ **channel**
- **the bound in** $e - \tau$ **sector is weaker than in** $e - \mu$ **sector**
- **the constraint in** $e - \mu$ **sector can not be directly translated into that in** $e - \tau$ **sector.**

Intense τ **source is needed for this research, difficult!**

Another option is to use intense electron/positron source.

$e - \tau$ conversion at GeV scale

high energy electron/positron beam can be used to probe LFV process.

- **it can probe $e - \tau$ conversion from electron/positron initial state**
- **the experiment can be done for wide range of energy(GeV-100GeV), for various targets(internal/fixed target), or on colliders**
- **electron/positron of a few GeV scale is economical, more clean than what very high energy beam can produce**

Consider

$$e(k) + T(P) \to \tau(k') + T^*(P')$$

T can be nucleon or nucleus. T^* can be

- **the same nucleon/nucleus(elastic),**
- **excited nucleus,**
- **two/three bodies states with no change in number of nucleon(QE)**
- **two/three bodies states with particle production.**

$e - \tau$ conversion at GeV scale

For T at rest, the energy E of the initial beam should satisfy

$$E > \frac{1}{2m_T}(m_\tau^2 + 2m_\tau m_{T^*} + m_{T^*}^2 - m_T^2) \geq m_\tau + \frac{m_\tau^2}{2m_T}$$

Threshold energy of $e + T \to \tau + T'$ process

Target	proton	deteuron	Helium-3	Helium-4	Lithium-7
E(GeV)	3.44	2.61	2.33	2.19	2.01

$e - \tau$ conversion at GeV scale

For target at rest,

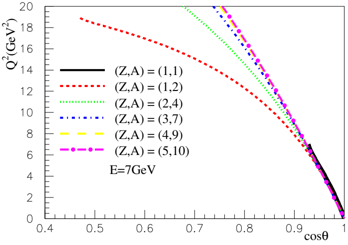
$$\begin{aligned} Q^2 &= 2P \cdot q - (m_{T*}^2 - m_T^2) \\ &= 2m_T \delta E - (m_{T*}^2 - m_T^2) \end{aligned}$$

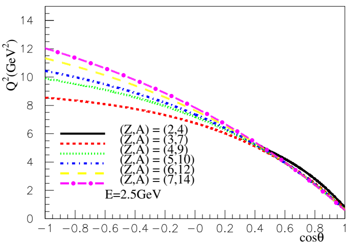
$\delta E = E_{T*} - E_T = E - E'$, **energy transfer to target**

Kinematics changed a lot by the final τ

$$Q^2 = -(k - k')^2 = 2k \cdot k' - m_\tau^2$$

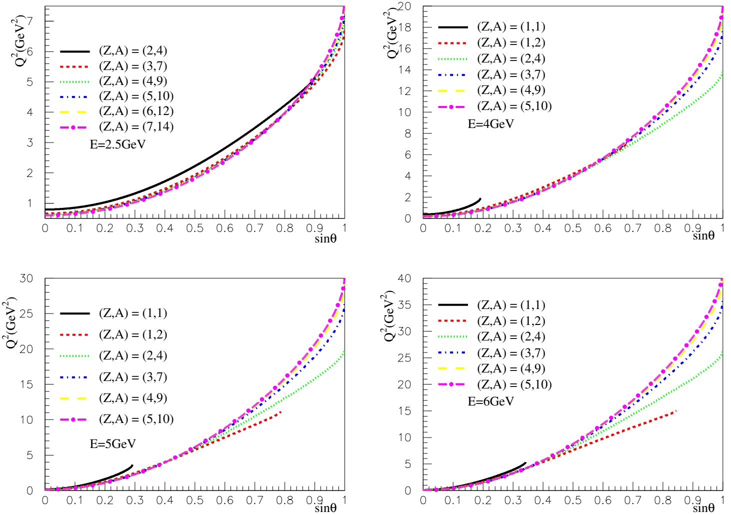
In elastic scattering, Q^2 versus $\cos\theta$ for elastic scattering $e + T \to \tau + T$:





Minimal Q^2 can not reach zero due to unavoidable momentum transfer to target.

Q^2 versus $\sin\theta$, events appear in forward direction



$e - \tau$ conversion at GeV scale

Minimal Q^2 for elastic scattering $e + T \to \tau + T$.

Target(Z,A)	(1,1)	(1,2)	(2,4)	(3,7)	(4,9)	(5,10)
Q^2_{min}(GeV^2) (E=2.5 GeV)	$\times$	$\times$	0.79	0.66	0.63	0.62
Q^2_{min}(GeV^2) (E=4 GeV)	0.37	0.23	0.20	0.19	0.18	0.18
Q^2_{min}(GeV^2) (E=5 GeV)	0.17	0.13	0.12	0.11	0.11	0.11
Q^2_{min}(GeV^2) (E=6 GeV)	0.10	0.085	0.078	0.076	0.075	0.075
Q^2_{min}(GeV^2) (E=7 GeV)	0.071	0.060	0.056	0.055	0.054	0.054

For larger energy, the Q^2 can reach smaller values

0.6GeV^2, equivalent to $\sim 4\ \mathrm{fm}^{-1}$

probing $\gamma e\tau$ vertex

$$\Delta L = em_\tau c_L \bar{\tau} i\sigma^{\mu\nu} e_L F_{\mu\nu} + em_\tau c_R \bar{\tau} i\sigma^{\mu\nu} e_R F_{\mu\nu} + h.c.$$

$c_{L,R}$, **the coupling strength**

$$Br(\tau \to e\gamma) = \tau_\tau \alpha(|c_L|^2 + |c_R|^2) m_\tau^5$$

τ_τ, **the** τ **lifetime. For** $Br < 3.3 \times 10^{-8}$

$$|c_L|^2 + |c_R|^2 < 5.7 \times 10^{-19}\ \mathbf{GeV}^{-4}$$

For one photon exchange processes, one can parametrize using nuclear(hadronic) tensor and leptonic tensor

$$\frac{d\sigma}{dQ^2} = \frac{\pi Z^2 \alpha^2}{Q^4 E^2} W_{\mu\nu} L^{\mu\nu}$$
$$W_{\mu\nu} = -(\eta_{\mu\nu} - q_\mu q_\nu / q^2) W_1 + \frac{1}{m_T^2}(P_\mu - q_\mu P \cdot q/q^2)(P_\nu - q_\nu P \cdot q/q^2) W_2$$

where

$$\text{spin } 0: \; W_1 = 0, \; W_2 = |F(Q^2)|^2,$$
$$\text{spin } \frac{1}{2}: \; W_1 = \frac{Q^2}{4m_T^2}(F_1 + F_2)^2, \; W_2 = F_1^2 + \frac{Q^2}{4m_T^2} F_2^2$$

$G_E = F_1 - \frac{Q^2}{4m_T^2} F_2$, $G_M = F_1 + F_2$.

probing $\gamma e \tau$ vertex

Form factors can be measured in $e + T \to e + T^*$ scattering. Dipole approximation can be used in calculation.

For Mott type scattering,

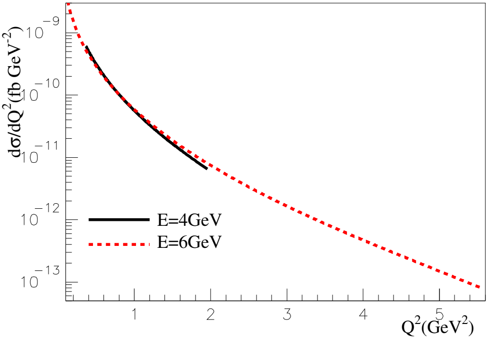
$$L^{\mu\nu} = 2(k^\mu k'^\nu + k^\nu k'^\mu - k \cdot k' \eta^{\mu\nu})$$

For $e \to \tau$ conversion

$$\begin{aligned} L^{\mu\nu} \quad &= -2(|c_L|^2 + |c_R|^2)[m_\tau^2(m_\tau^2 - q^2)(\eta^{\mu\nu} - q^\mu q^\nu / q^2) \\ &+4q^2(k^\mu - q^\mu k \cdot q/q^2)(k^\nu - q^\nu k \cdot q/q^2)] \end{aligned}$$

$q = k - k'$, $q^2 = -Q^2$

Differential cross section of $e + p \to \tau + p$ versus Q^2,
$Br(\tau \to e\gamma) < 3.3 \times 10^{-8}$



Total Xsec at 4 GeV and 6 GeV are about 1.5×10^{-10} fb and 5.4×10^{-10} fb respectively.

probing $\gamma e \tau$ vertex

For scattering with heavy nuclei:

He3 form factors, drop down very quickly:

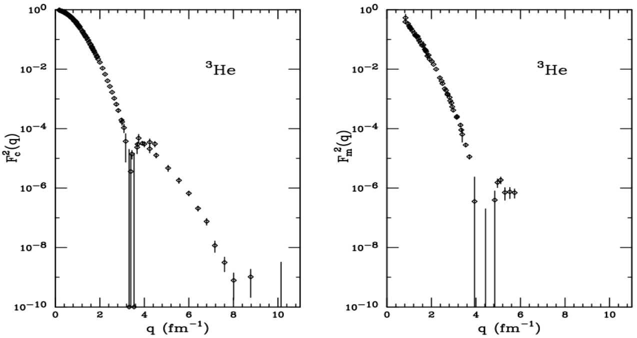


Figure 22: Charge and magnetic form factors of ^3He.

No hope to increase Xsec by the charge of nuclei

probing $\gamma e \tau$ vertex

He4 form factors(spin 0):

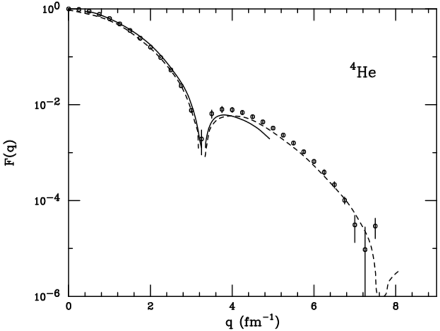


Figure 32: Experimental ^4He form factor together with early results from the exp(S)-calculation of Gari *et al.* [234] (solid curve) and the VMC calculation of Schiavilla *et al.* [223] performed using the V14 interaction (dashed).

probing $Ze\tau$ vertex

$$\Delta L = \frac{g}{\cos\theta_w}[C_L Z^\mu \bar{\tau}\gamma_\mu e_L + C_R Z^\mu \bar{\tau}\gamma_\mu e_R + h.c.]$$

$C_{L,R}$ **the coupling strength, normalized in unit of SM coupling**

$$\Gamma(Z \to e^\pm \tau^\mp) = \frac{g^2 m_Z}{12\pi \cos^2\theta_w}(|C_L|^2 + |C_R|^2)$$

Compared to SM coupling for ν**,** $C_\nu = 1/2$

$$\frac{|C_L|^2 + |C_R|^2}{|C_\nu|^2} = \frac{3}{2}\frac{Br(Z \to e^\pm\tau^\mp)}{Br(Z \to \textbf{invisible})}$$

For $Br < 9.8 \times 10^{-6}$**,** $|C_L|^2 + |C_R|^2 < 7.35 \times 10^{-5}|C_\nu|^2$

probing $Ze\tau$ vertex

$$Br(\tau \to 3e) = \tau_\tau \frac{G_F^2 m_\tau^5}{96\pi^3}(|C_L|^2 + |C_R|^2)[(-\frac{1}{2} + \sin^2\theta_W)^2 + \sin^4\theta_W]$$
$$= 0.125\ \tau_\tau \frac{G_F^2 m_\tau^5}{96\pi^3}(|C_L|^2 + |C_R|^2)$$

For $Br < 2.7 \times 10^{-8}$

$$|C_L|^2 + |C_R|^2 < 6 \times 10^{-7}$$

Stronger than that from $Z \to e^\pm \tau^\mp$ **by about a factor 30**

probing $Ze\tau$ vertex

For one Z exchange, one can parametrize using the hadronic tensor and leptonic tensor

$$\frac{d\sigma}{dQ^2} = \frac{G_F^2}{32\pi E^2} W_{\mu\nu} L^{\mu\nu}$$

where in general

$$\begin{aligned} W_{\mu\nu} \quad &= -\eta_{\mu\nu} W_1 + \frac{P_\mu P_\nu}{m_T^2} W_2 + \frac{i\epsilon_{\mu\nu\rho\sigma} P^\rho q^\sigma}{2m_T^2} W_3 \\ &+ \frac{q_\mu q_\nu}{m_T^2} W_4 + \frac{P_\mu q_\nu + P_\nu q_\mu}{2m_T^2} W_5 + i\frac{P_\mu q_\nu - P_\nu q_\mu}{2m_T^2} W_6 \end{aligned}$$

W_i **in terms of the EM vector form factors and axial-vector form factors can be obtained.**

probing $Ze\tau$ vertex

$W_{1,2,3}$ can be obtained in $\nu + T$ scattering

For $\nu + T \to \nu + T^*$

$$L^{\mu\nu} = 8(k^\mu k'^\nu + k^\nu k'^\mu - k \cdot k' \eta^{\mu\nu} + i\varepsilon^{\mu\nu\rho\sigma} k_\rho q_\sigma)$$

It gives cross section depending on $W_{1,2,3}$.

For $e + T \to \tau + T^*$

$$\begin{aligned} L^{\mu\nu} &= 16[(k^\mu k'^\nu + k^\nu k'^\mu - k \cdot k' \eta^{\mu\nu})(|C_L|^2 + |C_R|^2) \\ &\quad + i\varepsilon^{\mu\nu\rho\sigma} k_\rho q_\sigma (|C_L|^2 - |C_R|^2)] \end{aligned}$$

The cross section depends on $W_{1,2,3,4,5}(W_6 = 0)$

$W_{4,5}$ can be obtained from $W_{1,2,3}$ by enforcing current conservation on the hadronic part

probing $Ze\tau$ vertex

- **The order of magnitude of σ can be estimated as**

$$\frac{\sigma(e + T \to \tau + T^*)}{\sigma(\nu + T \to \nu + T^*)} \sim \frac{|C_L|^2 + |C_R|^2}{|C_\nu|^2}$$

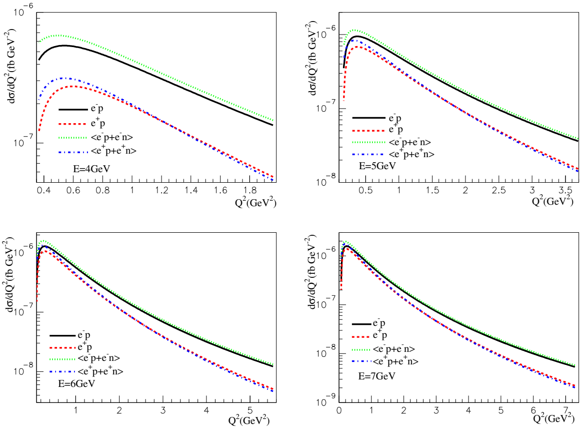
- **If neglecting m_τ, for $C_R = 0$ the cross section is directly proportional to $\sigma(\nu + T \to \nu + T^*)$**
- **If neglecting m_τ, for $C_L = 0$ the cross section is directly proportional to $\sigma(\bar{\nu} + T \to \bar{\nu} + T^*)$**

Elastic scattering with total nucleus(coherent scattering)

- **so-called coherent scattering in neutrino community, in which contribution of all nucleon in nucleus add coherently.**
- **in view of the recent observation of neutrino coherent scattering, a re-examination of this process is needed for $e - \tau$ conversion.**

probing $Ze\tau$ vertex

$d\sigma/dQ^2$ of $e+N \to \tau + N$ versus Q^2, $Br(\tau \to 3e) < 2.7 \times 10^{-8}$ used



Total Xsecs for 4-7GeV: $(0.63 - 1.6) \times 10^{-6}$ **fb,** $(0.28 - 1.2) \times 10^{-6}$ **fb,** $(0.71 - 1.8) \times 10^{-6}$ **fb, and** $(0.30 - 1.4) \times 10^{-6}$ **fb**

probing $Ze\tau$ vertex

exp can be done in quasi-elastic scattering with nuclei: elastic scattering with "free nucleon" in nuclei

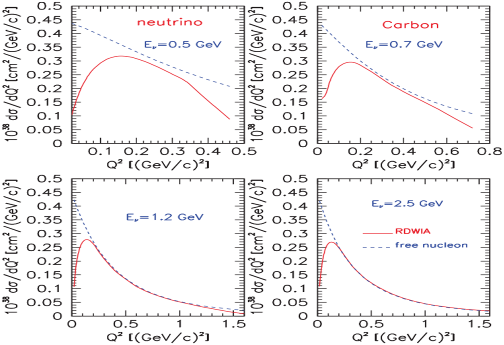


FIG. 4. (Color online) Inclusive NCE cross sections vs the four-momentum transfer Q^2 for neutrino scattering off ^{12}C (solid line) and a free nucleon (dashed line) and for the four values of incoming neutrino energy: ε = 0.5, 0.7, 1.2, and 2.5 GeV.

A good approximation for $Q^2 > 0.2$ GeV^2(PRC84, 015501)

probing $Ze\tau$ vertex

cLFV can be searched in elastic scattering of $e^{\mp}$ with nucleon or in quasi-elastic scattering of $e^{\mp}$ with nuclei

- **for 30 ab^{-1} luminosity, the bound on the vertex can compete that from LEP Z data**
- **for $\sim$ 1000 ab^{-1}, can compete the bound from $\tau \to 3e$ of $e\tau Z$ vertex .**
- **can not be done for 2.5 GeV beam, but can be done for $e^{\mp}$ beam with a bit higher energy, e.g. 4 -6 GeV**

For more detail, see arXiv: 1512.01951

Analysis for other flavor changing vertex should be analyzed

probing $Ze\tau$ vertex

Possible background:

- **one** τ **from** $D^{\pm}$ **or** $D_s^{\pm}$ **decay in** $e + N \to e + N + 2D(2D_s)$**, with other decay products lost in detection**
- **threshold energy for this background process**

$$E > 2m_D + 2\frac{m_D^2}{m_T}$$

For (QE)scattering on p/n(nuclei) it's about 11 GeV for electron beam, so this background can be avoided

Threshold energy of $e + T \to e + T + D^+ + D^-$ **process**

Target	proton	deteuron	Helium-3	Helium-4	Lithium-7
E(GeV)	11.1	7.40	6.18	5.56	4.78

Conclusion

- $e - \tau$ **conversion with GeV scale** $e^{\mp}$ **beam on target exp is a new way to probe cFLV.**
- **This exp with luminosity more than** 10^3 **ab**$^{-1}$ **can play leading role on the research of** $Z\bar{\tau}e$ **vertex.**
- $e^{\mp}$ **beam energy should be** $\gtrsim 3.5$ **GeV**
- **To avoid background from** D **meson decay, beam energy should be** $\lesssim 11$ **GeV**
- **This type of exp can be done at places with electron beam of appropriate energy, e.g. JLAB, injector linac of CEPC(7-10 GeV), Shanghai free electron laser facility(8 GeV), or other light source facilities such as SPring-8.**

A lot of experimental and theoretical works can be done.