Exotic neutrino physics issues and nuclear theory

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Overview

1 Introduction

- SM and exotic neutral-current processes
  - $\nu_\alpha + (A, Z) \rightarrow \nu_\alpha + (A, Z)$
  - $\nu_\alpha + (A, Z) \rightarrow \nu_\beta + (A, Z)$
  - $\mu^- + (A, Z) \rightarrow e^- + (A, Z)$
  - muon to electron conversion in nuclei experiments

2 Mathematical Description

- SM and NSI Lagrangians
- SM and NSI cross sections
- nuclear physics details (BCS method)

3 Results

- simulated cross sections Supernova neutrinos
- expected differential event rates
- new limits on the lepton flavour violating parameters

4 Summary and Outlook

SM and Lepton Flavour Violating neutral-current processes

SM ν-nucleus reaction

$$\nu_\alpha + (A,Z) \rightarrow \nu_\alpha + (A,Z)$$

- Well-studied process theoretically.
- Any event has not been found yet experimentally.
- Very high experimental sensitivity is required.

LFV NSI ν-nucleus reaction

$$\nu_\alpha + (A,Z) \rightarrow \nu_\beta + (A,Z), \quad \alpha \neq \beta = (e,\mu,\tau)$$

- Not allowed in the SM due to violation of the lepton number
- Excellent probe to search for new physics

Charged Lepton Flavour Violating processes

CLFV muon to electron conversion in nuclei

$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$

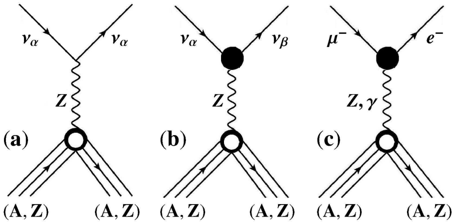
- Probably the best probe to search for lepton flavour violation
- New extremely sensitive experiments are in preparation at Fermilab and J-PARC
- Branching ratio down to $R_{\mu e}^{(A,Z)} \sim 10^{-16} - 10^{-18}$
- It can be studied under the same particle physics models (Seesaw, left-right symmetric models, etc.) with the exotic ν-reactions

R.H. Bernstein and P.S. Cooper, Phys. Rept. **532** 27 (2013).

PA. Kurup, Nucl. Phys. B Proc. Suppl. **218** 38 (2011).

R.J. Barlow, Nucl. Phys. B Proc. Suppl. **218** 44 (2011).

Feynman diagrams contributing to LFV



- *(a)* SM Z-exchange neutral current ν-nucleus reactions
- *(b)* non-standard Z-exchange ν-nucleus reactions
- *(c)* Z-exchange and photon-exchange $\mu^- \to e^-$ in the presence of a nucleus (muon-to-electron conversion)

T.S. Kosmas and J.D. Vergados, Phys. Rep. **264** 251 (1996).

F. Deppisch, T.S. Kosmas and J.W.F. Valle, Nucl. Phys. **B 752** 80 (2006).

D.K. Papoulias and T.S. Kosmas, J. Phys. Conf. Ser. **410** 012123 (2013).

D.K. Papoulias and T.S. Kosmas, Phys. Lett. **B 728** 482 (2014)

Past $\mu^- \to e^-$ conversion experiments

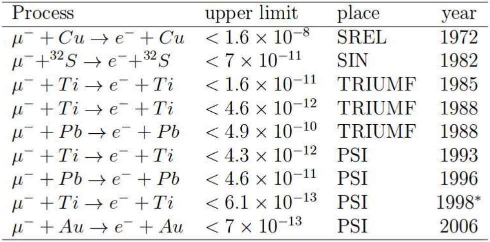
We are mainly interested for the branching ratio of the $\mu^- \to e^-$ process

$$R_{\mu e}^{(A,Z)} = \frac{\Gamma(\mu^- \to e^-)}{\Gamma(\mu^- \to \text{capture})}$$

T.S. Kosmas et. al., Nucl. Phys. **A 570** 637 (1994).

T.S. Kosmas, Nucl. Phys. **A 683** 443 (2001).

- current limits



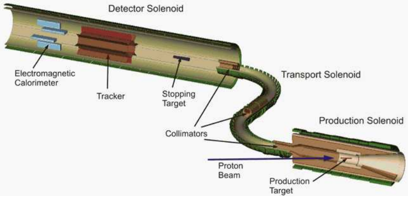
Process	upper limit	place	year
$\mu^- + Cu \to e^- + Cu$	$< 1.6 \times 10^{-8}$	SREL	1972
$\mu^- + {}^{32}S \to e^- + {}^{32}S$	$< 7 \times 10^{-11}$	SIN	1982
$\mu^- + Ti \to e^- + Ti$	$< 1.6 \times 10^{-11}$	TRIUMF	1985
$\mu^- + Ti \to e^- + Ti$	$< 4.6 \times 10^{-12}$	TRIUMF	1988
$\mu^- + Pb \to e^- + Pb$	$< 4.9 \times 10^{-10}$	TRIUMF	1988
$\mu^- + Ti \to e^- + Ti$	$< 4.3 \times 10^{-12}$	PSI	1993
$\mu^- + Pb \to e^- + Pb$	$< 4.6 \times 10^{-11}$	PSI	1996
$\mu^- + Ti \to e^- + Ti$	$< 6.1 \times 10^{-13}$	PSI	1998*
$\mu^- + Au \to e^- + Au$	$< 7 \times 10^{-13}$	PSI	2006

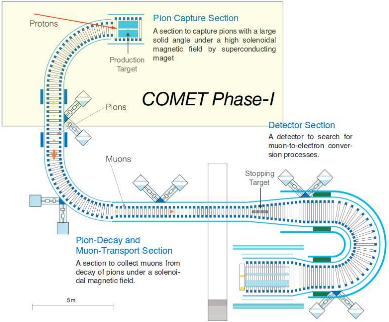
Y. Kuno and Y. Okada, Rev. Mod. Phys. **73** 151 (2001).

Recently planned $\mu^- \to e^-$ conversion experiments

- Mu2e experiment Fermilab
  $R_{\mu e}^{\mathrm{Al}} < 6 \times 10^{-17}$
- Next generation Mu2e-PX experiment aims
  $R_{\mu e}^{\mathrm{Al}} < 2 \times 10^{-18}$

- COMET at J-PARC
  $R_{\mu e}^{\mathrm{Al}} < 10^{-16}$
- Next generation PRIME/PRISM aims
  $R_{\mu e}^{\mathrm{Ti}} < 10^{-18}$





Schematic layout of COMET and COMET Phase-I

Conventional Phenomenological Lagrangian

Within the SM at the four fermion approximation (energies $\ll M_Z$) the Lagrangian takes the form

$$\mathcal{L}_{\mathrm{SM}} = -2\sqrt{2}G_F \sum_{\substack{f=u,d \\ \alpha=e,\mu,\tau}} g_P^f \left[\bar{\nu}_\alpha \gamma_\rho L \nu_\alpha\right] \left[\bar{f}\gamma^\rho P f\right] ,$$

- g_P^f are the P-handed SM couplings of f-quarks ($f = u, d$) to the Z-boson in terms of the Weinberg mixing angle θ_W.

- $g_L^u = \frac{1}{2} - \frac{2}{3}\sin^2\theta_W$ and $g_R^u = -\frac{2}{3}\sin^2\theta_W$
- $g_L^d = -\frac{1}{2} + \frac{1}{3}\sin^2\theta_W$ and $g_R^d = \frac{1}{3}\sin^2\theta_W$

S. Davidson et. al., JHEP **03** 011 (2003).

J. Barranco, O.G. Miranda and T.I. Rashba, JHEP **0512** 021 (2005).

Exotic Phenomenological Lagrangian

The non-standard Lagrangian takes the form

$$\mathcal{L}_{\mathrm{NSI}} = -2\sqrt{2}G_F \sum_{\substack{f=u,d \\ \alpha,\beta=e,\mu,\tau}} \epsilon_{\alpha\beta}^{fP} \left[\bar{\nu}_\alpha \gamma_\rho L \nu_\beta\right] \left[\bar{f}\gamma^\rho P f\right]$$

- flavour preserving non-universal (NU) terms proportional to $\epsilon_{\alpha\alpha}^{fP}$.
- flavour-changing (FC) terms proportional to $\epsilon_{\alpha\beta}^{fP}$, $\alpha \neq \beta$.

These couplings are taken with respect to the strength of the Fermi coupling constant G_F.

- polar-vector couplings: $\epsilon_{\alpha\beta}^{fV} = \epsilon_{\alpha\beta}^{fL} + \epsilon_{\alpha\beta}^{fR}$
- axial-vector couplings: $\epsilon_{\alpha\beta}^{fA} = \epsilon_{\alpha\beta}^{fL} - \epsilon_{\alpha\beta}^{fR}$

S. Davidson et. al., JHEP **03** 011 (2003).

J. Barranco, O.G. Miranda and T.I. Rashba, JHEP **0512** 021 (2005).

K. Scholberg, Phys. Rev. **D 73** 033005 (2006).

SM Cross sections and Nuclear Transition Matrix Elements

At nuclear level the coherent SM dif. cross-section with respect to the scattering angle θ becomes

$$\frac{d\sigma_{\mathrm{SM},\nu_\alpha}}{d\cos\theta} = \frac{G_F^2}{2\pi} E_\nu^2 \left(1+\cos\theta\right) \left| \langle gs || G_{V,\nu_\alpha}^{\mathrm{SM}}(q) || gs \rangle \right|^2$$

- E_ν is the incident neutrino energy
- the 3-momentum transfer $q^2 = 4E_\nu^2 \sin^2 \frac{\theta}{2}$
- $|gs\rangle = |J^\pi\rangle \equiv |0^+\rangle$ is the nuclear ground state (for even-even nuclei) constructed explicitly by solving the BCS equations
- $g_V^{p(n)}$ polar-vector coupling of proton (neutron) to the Z boson

The nuclear matrix element is given in terms of the electromagnetic form factors $F_{Z(N)}$ (CVC theory)

$$\left| \mathcal{M}_{V,\nu_\alpha}^{\mathrm{SM}} \right|^2 \equiv \left| \langle gs || \hat{\mathcal{M}}_0 || gs \rangle \right|^2 = \left[g_V^p Z F_Z(q^2) + g_V^n N F_N(q^2) \right]^2 .$$

D.K. Papoulias and T.S. Kosmas, Phys. Lett. **B 728** 482 (2014)

NSI Cross sections and Nuclear Transition Matrix Elements

The coherent differential cross section with respect to the scattering angle θ for the exotic ν-nucleus processes is written as

$$\frac{d\sigma_{\mathrm{NSI},\nu_\alpha}}{d\cos\theta} = \frac{G_F^2}{2\pi} E_\nu^2 \left(1+\cos\theta\right) \left| \langle gs || G_{V,\nu_\alpha}^{\mathrm{NSI}}(q) || gs \rangle \right|^2 , \qquad (1)$$

($\alpha = e, \mu, \tau$, denotes the flavour of incident neutrinos).
The NSI nuclear matrix element,

$$\begin{aligned} &\left| \mathcal{M}_{V,\nu_\alpha}^{\mathrm{NSI}} \right|^2 \equiv \left| \langle gs || G_{V,\nu_\alpha}^{\mathrm{NSI}}(q) || gs \rangle \right|^2 = \\ &\left[\left(2\epsilon_{\alpha\alpha}^{uV} + \epsilon_{\alpha\alpha}^{dV} \right) Z F_Z(q^2) + \left(\epsilon_{\alpha\alpha}^{uV} + 2\epsilon_{\alpha\alpha}^{dV} \right) N F_N(q^2) \right]^2 \\ &+ \sum_{\beta\neq\alpha} \left[\left(2\epsilon_{\alpha\beta}^{uV} + \epsilon_{\alpha\beta}^{dV} \right) Z F_Z(q^2) + \left(\epsilon_{\alpha\beta}^{uV} + 2\epsilon_{\alpha\beta}^{dV} \right) N F_N(q^2) \right]^2 \end{aligned}$$

D.K. Papoulias and T.S. Kosmas, Phys. Lett. **B 728** 482 (2014)

Connection with experiments

From experimental perspective it is important to compute the dif. cross section with respect to the nuclear recoil energy T_N

$$\frac{d\sigma_{\mathrm{NSI},\nu_\alpha}}{dT_N} = \frac{G_F^2\, M}{\pi}\left(1 - \frac{M\, T_N}{2E_\nu^2}\right)\left|\langle gs||G_{V,\nu_\alpha}^{\mathrm{NSI}}(q)||gs\rangle\right|^2 .$$

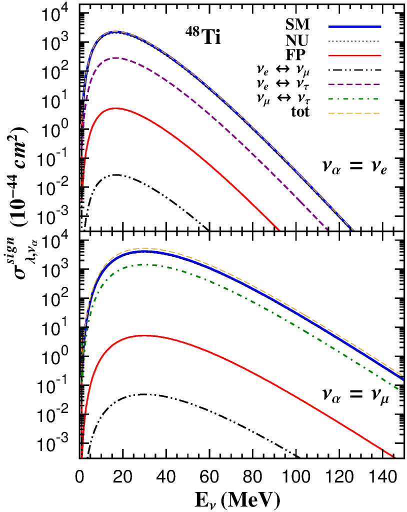
- 3-momentum transfer $q^2 = 2MT_N$
- M is the nuclear mass.
- $T_N^{max} = \frac{2E_\nu^2}{M+2E_\nu}$

P. Vogel and J.Engel, Phys.Rev. **D 39** 3378 (1989).

D.K. Papoulias and T.S. Kosmas, Phys. Lett. **B 728** 482 (2014)

Simulated Signals

Assuming a typical supernova at $d = 10$ kpc we may compute the cross section signal to be recorded on the $^{48}\mathrm{Ti}$ detector



- Supernova neutrino flux

$$\Phi(E_\nu) = \sum_\alpha \frac{N_{\nu_\alpha}}{4\pi\, d^2}\, \eta^{\mathrm{SN}}_{\nu_\alpha}(E_\nu)$$

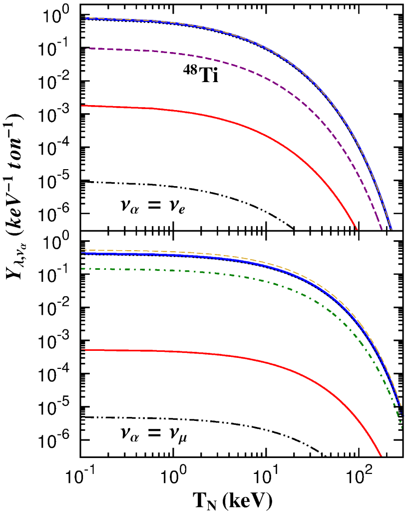
- Maxwell-Boltzmann distributions

$$\eta^{\mathrm{SN}}_{\nu_\alpha}(E_\nu) = \frac{E_\nu^2}{2\,T^3_{\nu_\alpha}}\, e^{-E_\nu/T_{\nu_\alpha}}$$

- convoluted cross sections

$$\sigma^{sign}_{\lambda,\nu_\alpha}(E_\nu) = \sigma_{\lambda,\nu_\alpha}(E_\nu)\, \eta^{\mathrm{SN}}_{\nu_\alpha}(E_\nu)$$

Expected Event Rates



Differential Yield in events assuming one tone of $^{48}\mathrm{Ti}$ detector material as function of the nuclear recoil energy

$$Y_{\lambda,\nu_\alpha}(T_N) = N_t \int \Phi_{\nu_\alpha}\, dE_\nu \times \int \frac{d\sigma_{\lambda,\nu_\alpha}}{d\cos\theta}\, \delta\left(T_N - \frac{q^2}{2M}\right) d\cos\theta$$

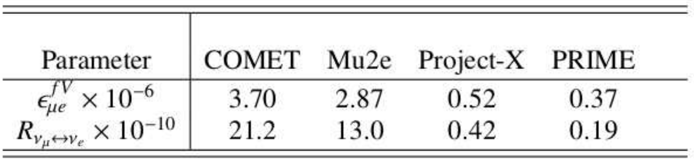
New limits from $\mu \to e$ conversion experiments

The $\nu_\mu \leftrightarrow \nu_e$ transition the NSI parameters are related with the experimental upper limits of $\mu^- \to e^-$ conversion as

$$\epsilon_{\mu e}^{fP} = C^{-1}\sqrt{R_{\mu e}^{(A,Z)}}\,.$$

S. Davidson et. al., JHEP **03** 011 (2003).

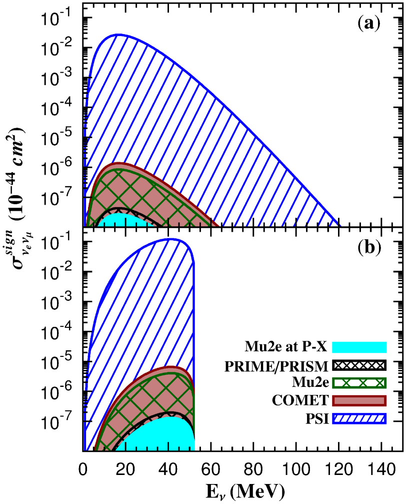
We obtained the following new upper limits to be set by the corresponding experiments



Parameter	COMET	Mu2e	Project-X	PRIME
$\epsilon_{\mu e}^{fV} \times 10^{-6}$	3.70	2.87	0.52	0.37
$R_{\nu_\mu \leftrightarrow \nu_e} \times 10^{-10}$	21.2	13.0	0.42	0.19

Table 3: Upper limits on the NSI parameters $\epsilon_{\mu e}^{fV}$ and the ratios $R_{\nu_\mu \leftrightarrow \nu_e}$ for the FC $\nu_\mu \leftrightarrow \nu_e$ reaction channel resulting from the sensitivity of the $\mu^- \to e^-$ conversion experiments.

Excluding Simulated Cross section Signals



Simulation for Supernova neutrinos (above) and stopped-pion muon neutrinos (below) using the upper limits obtained from the extremely high sensitivity of the next generation $\mu^- \to e^-$ conversion experiments

Summary and Outlook

Up to now

- construction of the formalism for the exotic ν-nucleus processes
- performed realistic cross sections calculations
- exploit the $\mu^- \rightarrow e^-$ conversion experimental sensitivity and put severe limits to FCNC neutrino nucleus parameters
- predictions for the signals to be recorded by terrestrial detectors
- obtained the expected event rates for the SM and exotic ν-reactions

Future work

- detailed study for nuclear systems throughout the periodic table and for other ν-sources (DKP and TSK, to be submitted)
- examine ν magnetic moments induced via tensor NSI couplings (in progress)
- study the incoherent reaction channels within QRPA

The End

Thank you for your attention !