Standard and Non-Standard ν-nucleus Interactions

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INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS
36th Course
Nuclei in the Laboratory and in the Cosmos
Erice-Sicily: September 16-24, 2014

University of Ioannina

TECHNOLOGICAL EDUCATIONAL INSTITUTE OF
WESTERN MACEDONIA

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- NCSR Democritos, Greece: D. Bonatsos
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- Univ. of Tuebingen, Germany: Group of A. Faessler, K. Kokkotas
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- Univ. of Valencia, Spain: Group of J.W.F. Valle, F. Deppisch
- RCNP, Univ. of Osaka, Japan: H. Ejiri (MOON Experiment)

Overview

1. Introduction
   - Standard Model (SM) and exotic neutral-current processes
     - $\nu_\alpha + (A,Z) \to \nu_\alpha + (A,Z)$
     - $\nu_\alpha + (A,Z) \to \nu_\beta + (A,Z)$
     - $\mu^- + (A,Z) \to e^- + (A,Z)$
     - ν-nucleus coherent scattering experiments
     - muon to electron conversion in nuclei experiments
2. Description of the formalism
   - SM and exotic Lagrangians
   - SM and exotic nuclear cross sections
   - nuclear physics details (BCS method)
   - tensorial ν-nucleus interactions
   - transition neutrino magnetic moment
3. Results
   - Coherent cross sections and Simulated Signals
   - expected differential event rates and total counts
   - new limits on the lepton flavour violating parameters
4. Summary and Outlook

Lepton flavor non-conservation

1) Elementary LFV processes:

$$\mu \to e\gamma, \quad \tau \to e\gamma, \quad \tau \to \mu\gamma$$

$$\mu \to ee^+e^- \qquad (\mu \to 3e)$$

$$\tau \to ee^+e^-, \quad \tau \to \mu e^+e^-, \quad \tau \to e\mu^+\mu^-, \quad \tau \to \mu\mu^+\mu^-$$

$\nu_e \to \nu_\mu \ \ \nu_\mu \to \nu_\tau$ etc. (neutrino oscillations)

2) Neutrinoless LFV/L processes in Nuclei:

$$\mu_b^- + (A,Z) \to e^- + (A,Z)^* \qquad (\mu^- \to e^- \text{conversion})$$

$$\mu_b^- + (A,Z) \to e^+ + (A,Z-2)^* \qquad (\mu^- \to e^+ \text{conversion})$$

$$(A,Z) \to (A,Z\pm 2) + e^\mp e^\mp \qquad (0\nu\beta\beta - \text{decay})$$

$$e^- + (A,Z) \to (A,Z)^* + \mu^- \, (\text{high-energy } e^- \to \mu^- \text{ conversion})$$

3) Exotic neutrino-nucleus processes ($FCNC$ processes)

$$\nu_\alpha + (A,Z) \to \nu_\beta + (A,Z)^*$$

$$\tilde{\nu}_\alpha + (A,Z) \to \tilde{\nu}_\beta + (A,Z)^*$$

(α ≠ β)

Impact to Astrophysics

P. Amanik, Ph.D (2006) [UC San Diego, USA]

D.K. Papoulias, TSK, in preparation

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

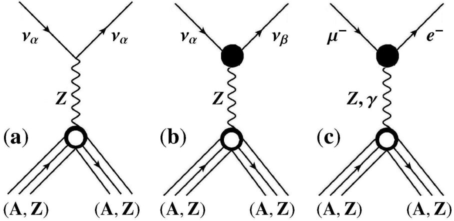
Charged Lepton Flavour Violating processes

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 NSI

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)

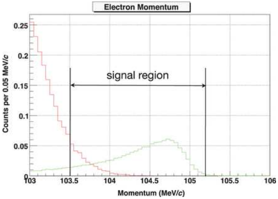
D.K. Papoulias and T.S. Kosmas, Phys. Lett. **B 728** 482 (2014)

Signals

For coherent ν-nucleus scattering

- the signal is the recoil of the nucleus
- cross sections are high but nuclear recoils are low
- high sensitivity required
- low background

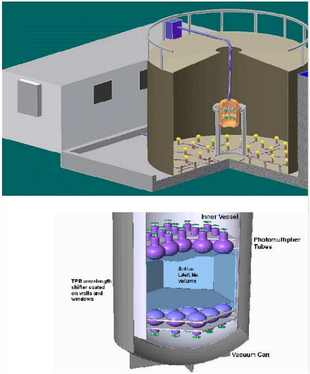
For $\mu^- \rightarrow e^-$ conversion

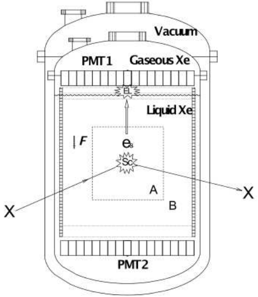


- high sensitivity required

Neutrinos from stopped-pion muon beam experiments

The Spallation Neutron Source (SNS) in Oak Ridge has excellent capabilities to measure ν-nucleus coherent scattering events





- very high fluxes about $\sim 10^7$ ν/s (see F.T. Avignone and Y.V. Efremenko, J. Phys. G29, (2003) 2615)
- energies up to $\sim$ 60 MeV
- however, nuclear effects at those energies become rather important

CLEAR Experiment: proposed nucl. detectors 456kg Liquid Ar and 491kg Liquid Ne

K.Scholberg, T.Wongjirad, E.Hungerford, A.Empl, D.Markoff, P.Mueller, Y.Efremenko, D.McKinsey, J.Nikkel, arXiv:0910.1989 [hep-ex]

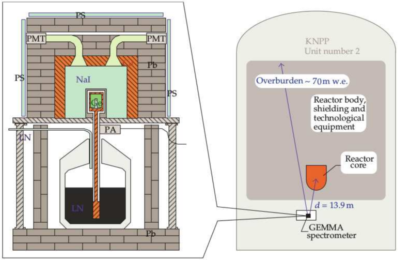
Neutrinos from reactor plants

TEXONO Colab.

$\mu_{\tilde{\nu}_e} < 7.4 \times 10^{-11} \mu_B \qquad (90\% \text{ C.L.})$

H.T. Wong et al., Phys. Rev. D75 (2007) 012001

GEMMA Colab.



Ge detector inside the active (NaI, PS) and passive (Cu, Pb) shielding.

$\mu_{\tilde{\nu}_e} < 2.9 \times 10^{-11} \mu_B \qquad (90\% \text{ C.L.})$

A.G. Beda et al., Adv. High Energy Phys. (2012) 350150

^{76}Ge detectors

extremely high fluxes ($\sim 10^{13}$ ν/s)

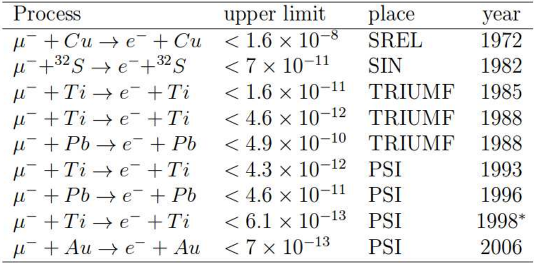
low neutrino energies up to $\sim$ 10 MeV

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

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

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

- current limits
- choice of nucleus



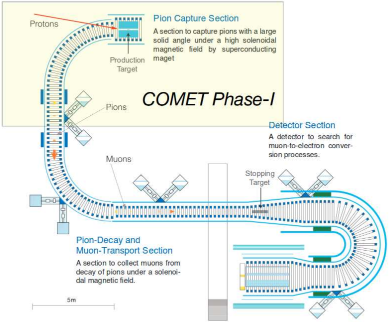
Process	upper limit	place	year
$\mu^- + Cu \to e^- + Cu$	$< 1.6 \times 10^{-8}$	SREL	1972
$\mu^- + {}^{32}S \to e^- + {}^{32}S$	$< 7 \times 10^{-11}$	SIN	1982
$\mu^- + Ti \to e^- + Ti$	$< 1.6 \times 10^{-11}$	TRIUMF	1985
$\mu^- + Ti \to e^- + Ti$	$< 4.6 \times 10^{-12}$	TRIUMF	1988
$\mu^- + Pb \to e^- + Pb$	$< 4.9 \times 10^{-10}$	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

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

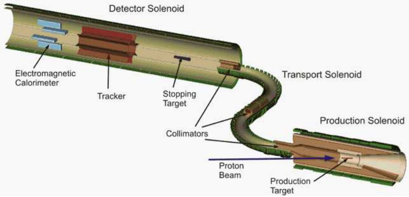
Recently planned $\mu^- \to e^-$ conversion experiments

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

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



Schematic layout of COMET and COMET Phase-I



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

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

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

SM Phenomenological description

Within the SM at the 4-fermion approximation (energies $\ll M_Z$) the Lagrangian takes the form

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

- 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)

NSI Phenomenological description

The non-standard Lagrangian takes the form

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

J. Barranco, O.G. Miranda, C.A. Moura and J.W.F. Valle, Phys. Rev. D 73 (2006) 113001

O.G. Miranda, M.A. Tortola and J.W.F. Valle, JHEP 0610 (2006) 008.

- *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

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

D.Z. Freedman, Phys. Rev. D 9 (1974) 1389
A. Drukier, L. Stodolsky, Phys. Rev. D 30 (1984) 2295

C.J. Horowitz, K.J. Coakley, D.N. McKinsey, Phys. Rev. D 68 (2003) 023005.

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

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

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

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 NSI ν-nucleus processes is written as

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

($\alpha = e, \mu, \tau$, denotes the flavour of incident neutrinos)

The NSI nuclear matrix element reads

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

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

Connection with experiments

From experimental physics perspectives 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.
- $T_N^{max} = \frac{2E_\nu^2}{M+2E_\nu}$

Experiments will measure nuclear recoils

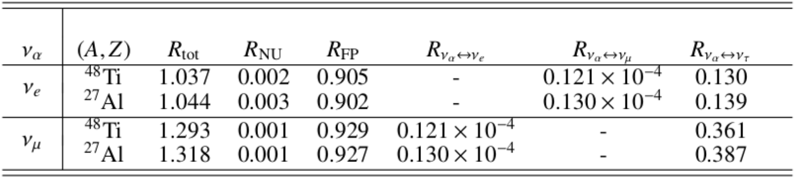
P. Vogel and J.Engel, Phys.Rev. **D 39** 3378 (1989)
J. Barranco, O.G. Miranda and T.I. Rashba, JHEP **0512** 021 (2005)
K. Scholberg, Phys. Rev. **D 73** 033005 (2006)

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

Branching ratios

It is interesting to to estimate the ratio of each of the individual cross sections, $\sigma_{\lambda,\nu_\alpha}$, with respect to the SM cross sections defined as

$$R_{\lambda,\nu_\alpha}(E_\nu) = \frac{\sigma_{\lambda,\nu_\alpha}(E_\nu)}{\sigma_{\rm SM}(E_\nu)}, \qquad \lambda = \rm tot, NU, FP, FC$$



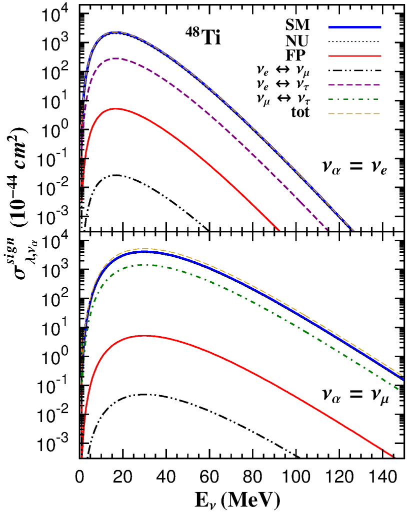
ν_α	(A,Z)	$R_{\rm tot}$	$R_{\rm NU}$	$R_{\rm FP}$	$R_{\nu_\alpha\leftrightarrow\nu_e}$	$R_{\nu_\alpha\leftrightarrow\nu_\mu}$	$R_{\nu_\alpha\leftrightarrow\nu_\tau}$
ν_e	^{48}Ti	1.037	0.002	0.905	-	0.121×10^{-4}	0.130
	^{27}Al	1.044	0.003	0.902	-	0.130×10^{-4}	0.139
ν_μ	^{48}Ti	1.293	0.001	0.929	0.121×10^{-4}	-	0.361
	^{27}Al	1.318	0.001	0.927	0.130×10^{-4}	-	0.387

The ratios R_{λ,ν_α} of all possible $\nu_\alpha + (A,Z) \rightarrow \nu_\beta + (A,Z)$ processes. They have been evaluated in their asymptotic values reached at $E_\nu \approx 120\,\mathrm{MeV}$

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

Convoluted Cross section calculations

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

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

C.J. Horowitz, K.J. Coakley, D.N. McKinsey, Phys. Rev. D 68 (2003) 023005

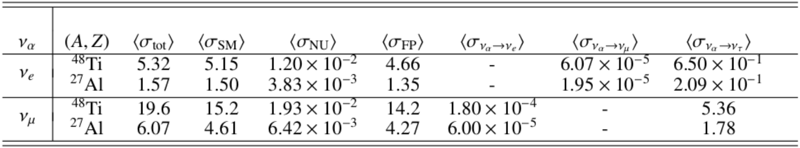
M. Biassoni, C. Martinez, Astropart. Phys. 36 (2012) 151.

Flux averaged cross section calculations

In supernova neutrino simulations, another useful quantity is the flux averaged cross section

$$\langle \sigma_{\lambda,\nu_\alpha} \rangle = \int \sigma_{\lambda,\nu_\alpha}(E_\nu)\, \eta^{\mathrm{SN}}_{\nu_\alpha}(E_\nu)\, dE_\nu$$

V. Tsakstara and T.S. Kosmas, Phys. Rev. C 83 (2011) 054612

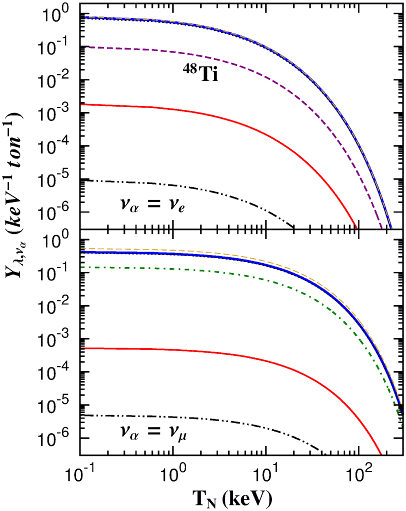


ν_α	(A,Z)	$\langle\sigma_{\mathrm{tot}}\rangle$	$\langle\sigma_{\mathrm{SM}}\rangle$	$\langle\sigma_{\mathrm{NU}}\rangle$	$\langle\sigma_{\mathrm{FP}}\rangle$	$\langle\sigma_{\nu_\alpha\to\nu_e}\rangle$	$\langle\sigma_{\nu_\alpha\to\nu_\mu}\rangle$	$\langle\sigma_{\nu_\alpha\to\nu_\tau}\rangle$
ν_e	^{48}Ti	5.32	5.15	1.20×10^{-2}	4.66	-	6.07×10^{-5}	6.50×10^{-1}
	^{27}Al	1.57	1.50	3.83×10^{-3}	1.35	-	1.95×10^{-5}	2.09×10^{-1}
ν_μ	^{48}Ti	19.6	15.2	1.93×10^{-2}	14.2	1.80×10^{-4}	-	5.36
	^{27}Al	6.07	4.61	6.42×10^{-3}	4.27	6.00×10^{-5}	-	1.78

Flux averaged cross sections (in $10^{-40}\mathrm{cm}^2$) for various SN ν-spectra parametrized by Maxwell-Boltzmann distributions

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

Expected Event Rates



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

$$Y_{\lambda,\nu_\alpha}(T_N) = N_t \int \Phi_{\nu_\alpha}\, dE_\nu$$

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

- N_t number of target nuclei

see also

C.J. Horowitz, K.J. Coakley, D.N. McKinsey, Phys. Rev. D 68 (2003) 023005

M. Biassoni, C. Martinez, Astropart. Phys. 36 (2012) 151.

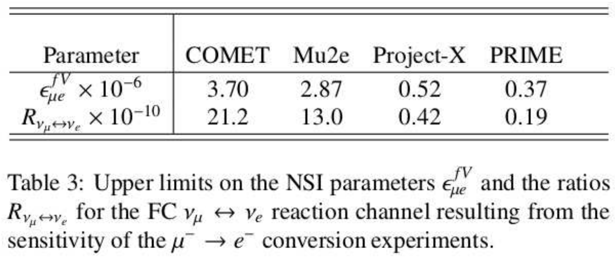
Limits from $\mu \to e$ conversion

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)

new upper limits expected to be set by the corresponding experiments

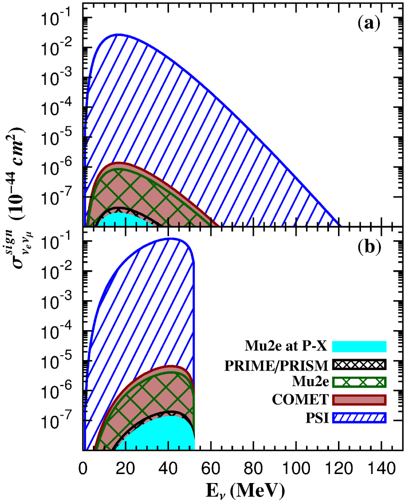


Parameter	COMET	Mu2e	Project-X	PRIME
$\epsilon_{\mu e}^{fV} \times 10^{-6}$	3.70	2.87	0.52	0.37
$R_{\nu_\mu \leftrightarrow \nu_e} \times 10^{-10}$	21.2	13.0	0.42	0.19

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.

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

Excluded region of observation for $\nu_\mu \to \nu_e$



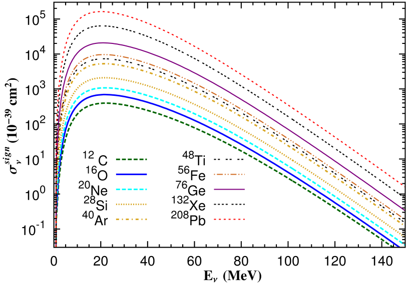
D.K. Papoulias and T.S. Kosmas, Phys. Lett. **B 728** 482 (2014)

Simulated signals

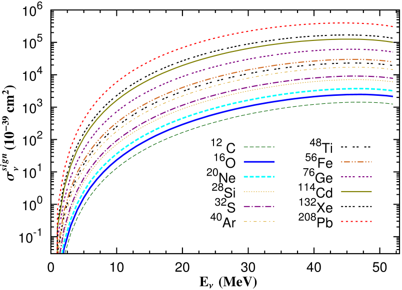
- **(a)** supernova neutrinos
- **(b)** stopped-pion muon neutrinos
- expected limits on NSI from next generation $\mu^- \to e^-$ conversion experiments is used

Expected signals for other interesting nuclei-targets

Supernova neutrinos



laboratory SNS neutrinos



Dark-matter detectors are also sensitive to Supernova neutrinos

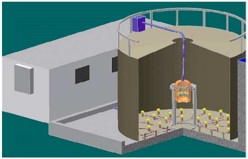
D.K. Papoulias and T.S. Kosmas, Advances in High Energy Physics, to appear

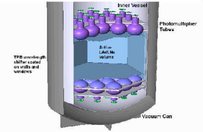
Neutrino detection by SNS facilities

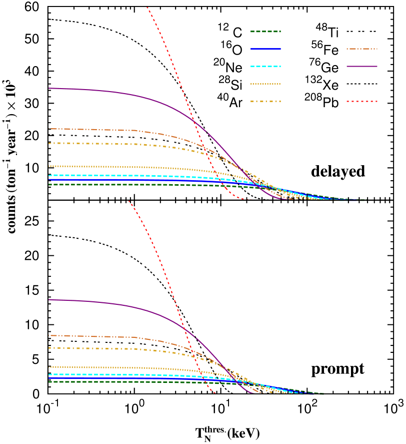
SM calculations for experimentally interesting nuclei (potential targets)

Particularly for the CLEAR experiment

- detector: liquid Ar/Ne
- expected events (in thousands for kg-scale detectors!)





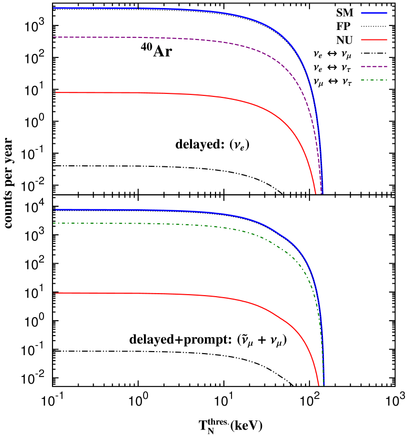


D.K. Papoulias and T.S. Kosmas, Advances in High Energy Physics, to appear

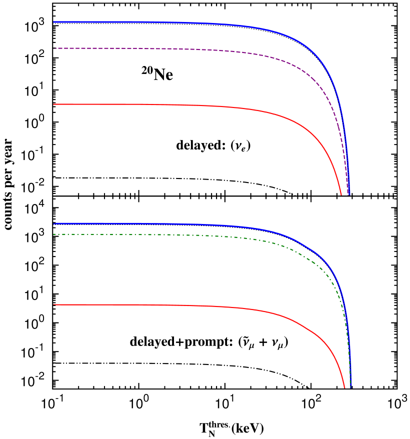
K.Scholberg, T.Wongjirad, E.Hungerford, A.Empl, D.Markoff, P.Mueller, Y.Efremenko, D.McKinsey, J.Nikkel, arXiv:0910.1989 [hep-ex]

Searching for NSI with the CLEAR experiment

calculation for 456 kg ^{40}Ar



calculation for 391 kg ^{20}Ne



Within the current limits on the NSI parameters, measurable rates are expected for NSI ν-nucleus events

D.K. Papoulias and T.S. Kosmas, Advances in High Energy Physics, to appear

Tensorial contribution to NSI neutrino-nucleus scattering

- The Lagrangian

$$\mathcal{L}^{T}_{\mathrm{NSI}} = -2\sqrt{2}G_F \sum_{\substack{f=u,d \\ \alpha,\beta=e,\mu,\tau}} \epsilon^{fT}_{\alpha\beta} \left[\bar{\nu}_\alpha \sigma^{\mu\nu} \nu_\beta\right] \left[\bar{f}\sigma_{\mu\nu} f\right]$$

J. Schechter, J. W. F. Valle (1981), Phys. Rev. D24 (1981) 1883

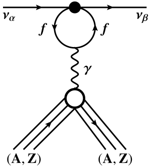
- Differential cross section

$$\frac{d\sigma_{\mathrm{NSI},\nu_\alpha}}{dT_N} = \frac{4G_F^2 M}{\pi}\left[\left(1-\frac{T_N}{2E_\nu}\right)^2 - \frac{MT_N}{4E_\nu^2}\right]\left|\langle gs||G^{\mathrm{NSI}}_{T,\nu_\alpha}(q)||gs\rangle\right|^2$$

J. Barranco, A. Bolanos, E.A. Garces, O.G. Miranda and T.I. Rashba, Int. J. Mod. Phys. A27 (2012) 1250147

- Nuclear matrix element

$$\left|\langle gs||G^{\mathrm{NSI}}_{T,\nu_\alpha}(q)||gs\rangle\right|^2 = \left[\left(2\epsilon^{uT}_{\alpha\beta} + \epsilon^{dT}_{\alpha\beta}\right) ZF_Z(q^2) + \left(\epsilon^{uT}_{\alpha\beta} + 2\epsilon^{dT}_{\alpha\beta}\right) NF_N(q^2)\right]^2$$



- neutrino electromagnetic effects
- NSI neutrino transition magnetic moments are generated at 1-loop level

D.K. Papoulias and T.S. Kosmas, Phys. Lett. **B** to be submitted

Neutrino NSI transition magnetic moment contribution to the cross section

- Neutrino magnetic moment contributes to the total cross section

$$\left(\frac{d\sigma}{dT_N}\right)_{tot} = \left(\frac{d\sigma}{dT_N}\right)_{SM} + \left(\frac{d\sigma}{dT_N}\right)_{magn}$$

P. Vogel, J. Engel, Phys. Rev. D39 (1989) 3378.

- In our NSI approximation the diff. cross section due to NSI transition NMM reads

$$\frac{d\sigma_{\mathrm{magn}}}{dT_N} = \frac{\pi a^2 \mu_{\alpha\beta}^2 Z^2}{m_e^2} \left(\frac{1 - T_N/E_\nu}{E_\nu} + \frac{T_N}{4\,E_\nu^2}\right) F_Z^2(q^2)$$

What is new in this cross section?

- $\mu_\nu \to \mu_{\alpha\beta}$ (NMM due to flavour transitions)
- Nuclear physics details enter the proton form factor

see also A.C. Dodd, E. Papageorgiu, S. Ranfone, Phys. Lett. B266 (1991) 434.

D.K. Papoulias and T.S. Kosmas, Phys. Lett. **B** to be submitted

Limits on the tensor NSI parameters

- The NSI transition neutrino magnetic moment reads

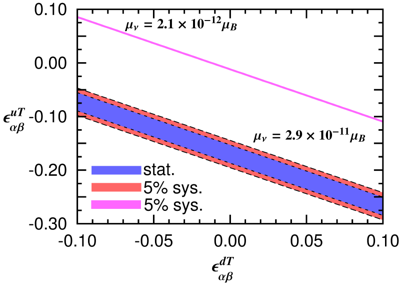
$$\mu_{\alpha\beta} = -\sum_q 2\sqrt{2} G_F \epsilon^{qT}_{\alpha\beta} \frac{N_c Q_q}{\pi^2} m_e m_q \ln\left(\frac{1}{2\sqrt{2} G_F m_q^2}\right) \mu_B$$

For other approximations see also K.J. Healey, A.A. Petrov, D. Zhuridov, Phys.Rev. D87 (2013) 11, 117301.

- The Gemma experiment upper limit on the NMM is used

Upper limits on the NSI parameters $\epsilon^{fT}_{\alpha\beta}$ from NMM

$\lvert\epsilon^{eT}_{\alpha\beta}\rvert$	1.3×10^{-1}	$\lvert\epsilon^{dT}_{\alpha\beta}\rvert$	1.7×10^{-2}	$\lvert\epsilon^{uT}_{\alpha\beta}\rvert$	1.7×10^{-2}
$\lvert\epsilon^{\mu T}_{\alpha\beta}\rvert$	1.1×10^{-3}	$\lvert\epsilon^{sT}_{\alpha\beta}\rvert$	1.2×10^{-3}	$\lvert\epsilon^{cT}_{\alpha\beta}\rvert$	6.9×10^{-5}
$\lvert\epsilon^{\tau T}_{\alpha\beta}\rvert$	1.1×10^{-4}	$\lvert\epsilon^{bT}_{\alpha\beta}\rvert$	5.6×10^{-5}	$\lvert\epsilon^{tT}_{\alpha\beta}\rvert$	4.0×10^{-4}



- Variation of the tensor NSI parameters

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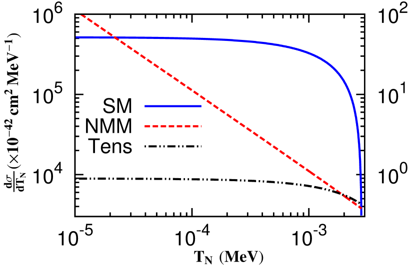
Comparison of the cross sections



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- The tensorial contribution is larger than the transition NMM one

Summary and Outlook

- After the construction of the formalism for the exotic ν-nucleus processes, we performed realistic cross sections calculations
- By exploiting the $\mu^- \to e^-$ conversion experimental sensitivity one can put severe limits to FCNC neutrino nucleus parameters
- predictions for the signals to be recorded by terrestrial detectors are obtained and for the expected event rates for the SM and exotic ν-reactions
- Detailed study for nuclear systems throughout the periodic table and for other ν-sources have been obtained.

We currently

- examine ν-magnetic moments induced via tensor NSI couplings and study the incoherent reaction channels within QRPA

Conclusions

What new physics can we gain SNS and reactor neutrino experiments?

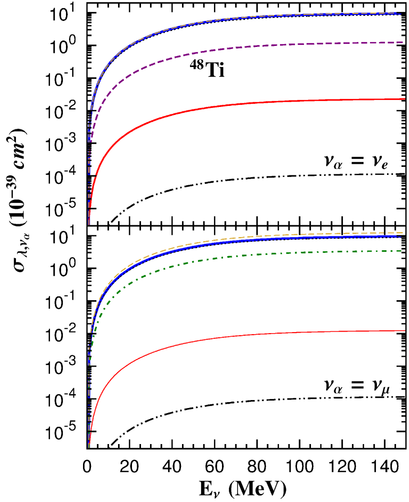
- detect coherent ν-nucleus event for the first time
- measure neutrino magnetic moment
- constrain non-standard neutrino interaction parameters (vector, tensor)
- SM precision tests (i.e. Weinberg-angle)

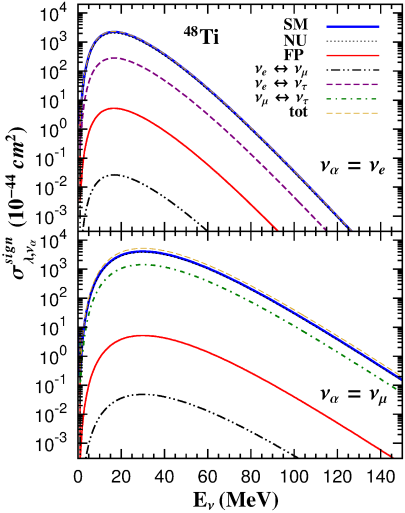
Thank you for your attention !

Extras

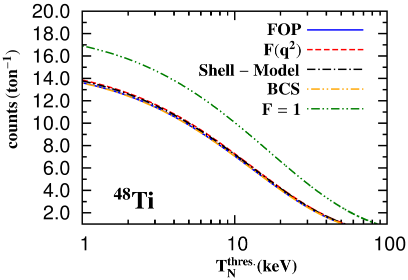
Coherent cross sections and Simulated Signals

Assuming a typical supernova at $d = 8.5$ kpc we may compute the cross section signal to be recorded on the $^{48}\mathrm{Ti}$ detector for all reaction channels





Total number of events



- several nuclear methods tested
- neglecting the nuclear physics details i.e. $F = 1$ could lead up to 30% more events

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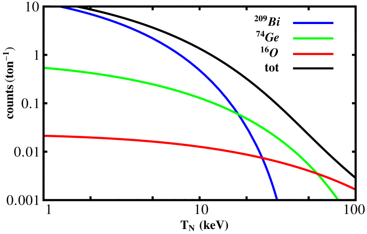
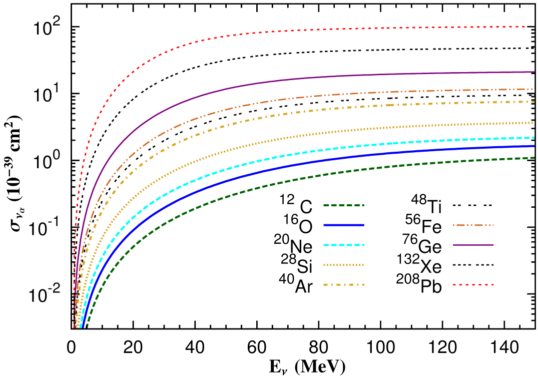
a combination of light and heavy nuclear target would be a more appropriate choice, i.e BGO scintillator ($Bi_4Ge_3O_{12}$)

- heavy nuclei → more events but low-energy recoils (due to large mass and form factor suppression)
- light nuclei → less events but high-energy (almost constant) recoils



Biassoni et. al. Astropart. Phys. 36 (2012) 151

SM ν-nucelus coherent cross sections



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