Phenomenological description of Standard and non-Standard neutrino-nucleus Interactions

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Overview

- Introduction
- Standard and and non-standard NC ν-nucleus processes
  - $\nu_\alpha + (A, Z) \rightarrow \nu_\alpha + (A, Z)^\star$ (Standard Model ν-nucleus reactions)
  - $\nu_\alpha + (A, Z) \rightarrow \nu_\beta + (A, Z)^\star$ (Non-Standard ν-nucleus reactions)
- Description of the formalism
  - SM and exotic Lagrangians
  - SM and exotic nuclear cross sections
- Constraints on the NSI parameters
  - Vector ν-nucleus interactions
  - Tensorial ν-nucleus interactions
  - Transition neutrino magnetic moment
- Concluding remarks

SM and Lepton Flavour Violating neutral-current processes

SM ν-nucleus reaction

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

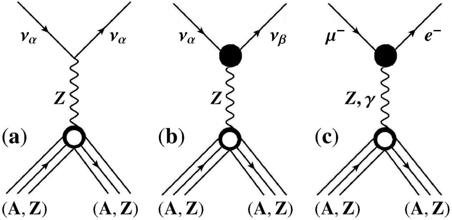
- Well-studied process theoretically.
- No events have been measured yet
- Very high experimental sensitivity is required.

LFV NSI ν-nucleus reaction

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

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

Feynman diagrams contributing to LFV



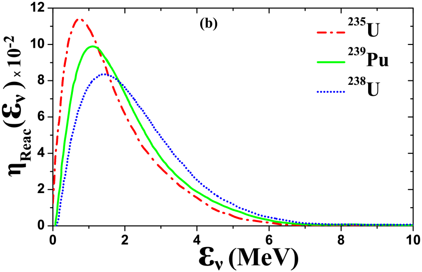
- *(a)* SM Z-exchange neutral current ν-nucleus reactions
- *(b)* non-standard Z-exchange ν-nucleus reactions
- *(c)* Z-exchange and photon-exchange $\mu^- \rightarrow e^-$ in the presence of a nucleus (muon-to-electron conversion)

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, Phys. Lett. **B 728** 482 (2014)

Reactor neutrinos

Nuclear reactors have been used as intense ν_e sources in many experiments. In the fission of ^{235}U, ^{239}Pu, and ^{238}U, neutron rich nuclei are produced and $\widetilde{\nu}_e$ anti-neutrinos are subsequently emitted via β decay.



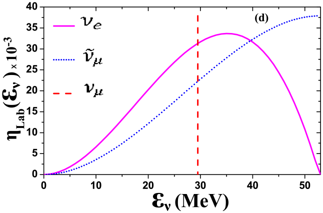
Nuclear reactors, are sources of $\widetilde{\nu}_e$ These antineutrinos have an energy spectrum peaked at very low energies ($\sim$ 0.3 MeV) and extending up to $\sim$ 10 MeV, characteristic of the β^- decay of the fission products.

Pion-muon decay at rest neutrino energy distributions

The slow pion and muon decay neutrinos have energy: $\varepsilon_\nu \preceq 52.8\text{MeV}$

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_\mu(\widetilde{\nu_\mu}) \qquad \mu^{+} \rightarrow e^{+} + \nu_e + \widetilde{\nu}_\mu$$

$$\pi^{\pm} \rightarrow e^{\pm} + \nu_e(\widetilde{\nu}_e) \qquad \mu^{-} \rightarrow e^{-} + \widetilde{\nu}_e + \nu_\mu$$

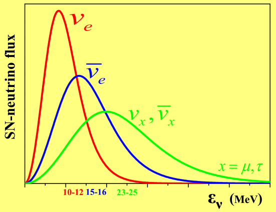


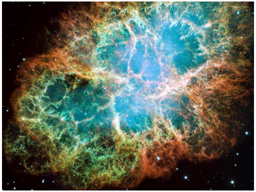
$$f_{\nu_e}(\varepsilon_{\nu_e}) = 96\varepsilon_{\nu_e}^2\, m_\mu^{-4}\, (m_\mu - 2\varepsilon_{\nu_e})$$

$$f_{\tilde{\nu}_\mu}(\varepsilon_{\tilde{\nu}_\mu}) = 16\varepsilon_{\tilde{\nu}_\mu}^2\, m_\mu^{-4}\, \left(3m_\mu - 4\varepsilon_{\tilde{\nu}_\mu}\right)$$

The f_{ν_e}, $f_{\tilde{\nu}_\mu}$ were used in the parametrization of *SN*-ν (non realistic in low energies ε_ν)

Supernova neutrinos





Mean Energies: $\langle \varepsilon_{\nu_e} \rangle < \langle \varepsilon_{\tilde{\nu}_e} \rangle < \langle \varepsilon_{\nu_x} \rangle$

- Elementary charged current (CC) neutrino reactions

$$\nu_e + n \longrightarrow e^- + p \qquad \tilde{\nu}_e + p \longrightarrow e^+ + n$$

- Elementary neutral current (NC) neutrino reactions

$$\nu(\tilde{\nu}) + e^{\pm} \longrightarrow \nu(\widetilde{\nu}) + e^{\pm} \qquad \nu(\tilde{\nu}) + (A, Z) \longrightarrow \nu(\widetilde{\nu}) + (A, Z)$$

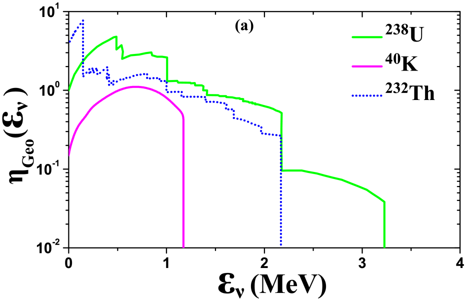
Geoneutrinos

Geo-neutrinos are mainly ($\widetilde{\nu}_e$) generated upon transmutation of β-decay nuclei, accompanied by emission of an electron (e^-) and release of decay-energy (Q_β)

$$(A, Z) \rightarrow (A, Z+1) + e^- + \widetilde{\nu}_e + Q_\beta \; , \qquad (1)$$

- The abundant radioactive isotopes that are in the present Earth are classified into three groups: (i) isotopes in the ^{238}U decay series, (ii) isotopes in ^{232}Th decay series, and ^{40}K isotope.
- The most recent measurements from KamLAND [**?**] and Borexino [**?**] are reaching the precision where they can start to constrain Earth models.

Geoneutrinos

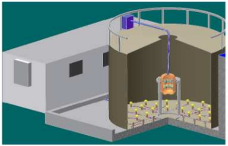


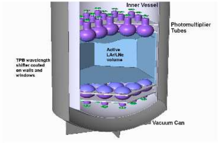
- Spectra of the U-Series, Th-Series and ^{40}K Geo-Neutrinos. Neutrinos from ^{40}K electron capture are also shown.
- neutrino energy distribution $\widetilde{\nu}_e$ coming from 82 beta decays in the U series and 70 beta decays in the Th series are included.
- Antineutrinos are generated by β-decays of all intermediate radioactive isotopes

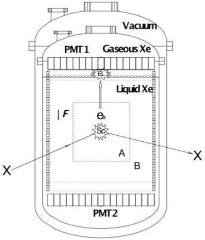
Neutrinos from stopped-pion muon beam experiments

The new COHERENT experiment: at the Spallation Neutron Source (SNS), Oak Ridge has excellent capabilities to measure ν-nucleus coherent scattering events

D.Akimov et al. (COHERENT collaboration), arXiv:1310.0125







Proposed detectors

- Liquid Ar/Ne
- Germanium
- Xenon
- CsI[Na]

- very intense fluxes about $\sim 10^7$ ν/s
- energies up to $\sim$ 60 MeV (important nuclear effects)

Proposed nuclear detectors: 456kg Liquid Ar and 491kg Liquid Ne

F.T. Avignone and Y.V. Efremenko, J. Phys. G29, (2003) 2615

K.Scholberg, et. al. arXiv:0910.1989 [hep-ex]

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

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

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)

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

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 NSI ν-nucleus processes is written as

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

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

The NSI nuclear matrix element reads

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

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

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

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

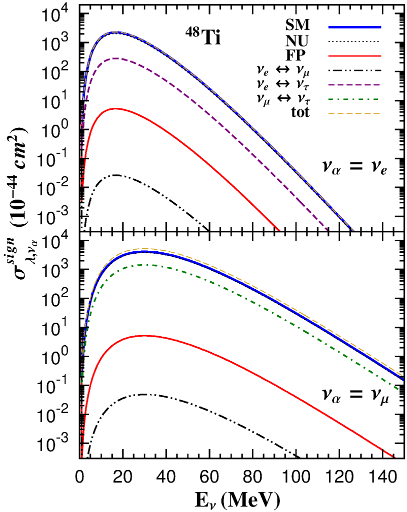
Experiments will measure nuclear recoils

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)

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

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

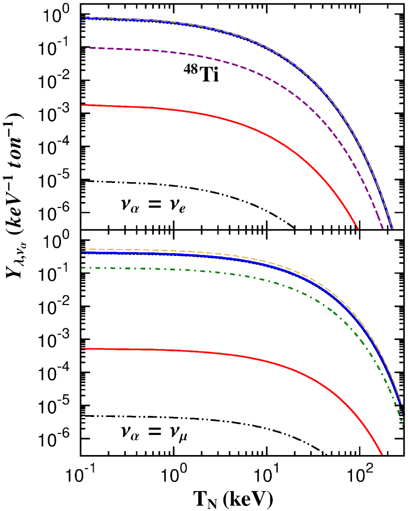
V. Tsakstara and T.S. Kosmas, Phys. Rev. C 83 (2011) 054612

ν_α	(A,Z)	$\langle\sigma_{\rm tot}\rangle$	$\langle\sigma_{\rm SM}\rangle$	$\langle\sigma_{\rm NU}\rangle$	$\langle\sigma_{\rm FP}\rangle$	$\langle\sigma_{\nu_\alpha\to\nu_e}\rangle$	$\langle\sigma_{\nu_\alpha\to\nu_\mu}\rangle$	$\langle\sigma_{\nu_\alpha\to\nu_\tau}\rangle$
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)

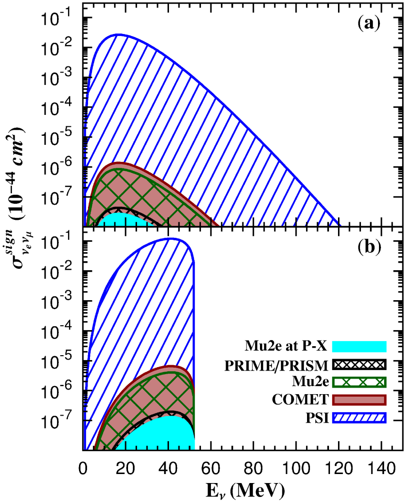
new upper limits expected to be set by the corresponding experiments

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 $\nu_\mu \rightarrow \nu_e$



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 $\mu^- \rightarrow e^-$ conversion experiments is used

Tensorial contribution to NSI neutrino-nucleus scattering

- The Lagrangian

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

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

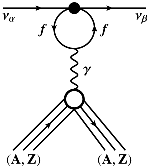
- Differential cross section

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

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

- Nuclear matrix element

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



- 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

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

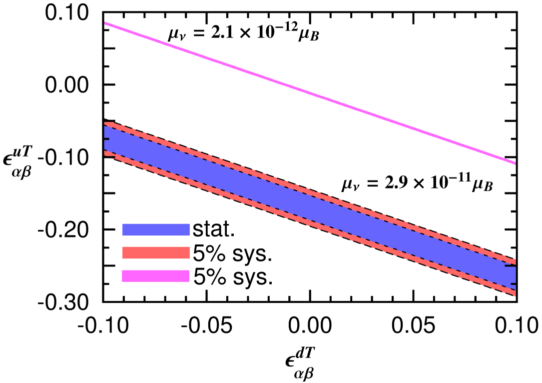
What is new in this cross section?

- $\mu_\nu \rightarrow \mu_{\alpha\beta}$ (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

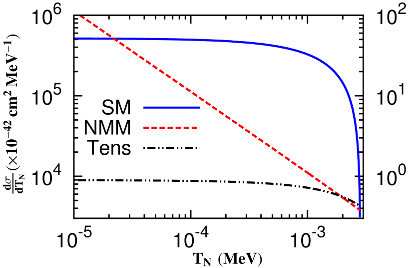
Constraining tensorial neutrino NSI parameters

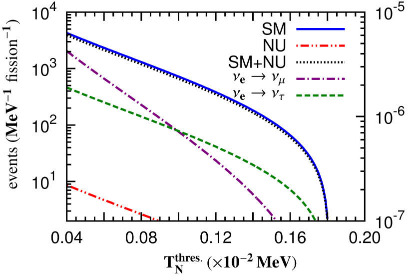


- exploit limits to further constrain neutrino magnetic moment
- Variation of the tensor NSI parameters

D.K. Papoulias and T.S. Kosmas, Phys. Lett. **B 747**(2015)454

Comparison of the cross sections at TEXONO





D.K. Papoulias and T.S. Kosmas, Phys. Lett. **B 747**(2015)454

- The tensorial contribution is larger than the transition NMM one

- events over threshold
- vector couplings (SM or NSI)
- 400 eV threshold
- 1 kg of ^{76}Ge detector material

Summary and Outlook

In view of the detection, for the first time, coherent NC ν-nucleus scattering events at SNS and reactor neutrino beams, predictions for the signals and expected event rates in several nuclear ν-detectors are required

- for the SM and exotic ν-reactions
- examine ν-magnetic moments induced via tensor NSI couplings

New physics is also expected to come out from SNS and reactor neutrino experiments (COHERENT, TEXONO, etc.) for the open problems

- neutrino magnetic moment
- SM precision tests (i.e. Weinberg-angle)

To this aim, we provided QRPA calculations and extracted constrains for non-standard neutrino interaction parameters (vector and tensor)

Collaborators:

- University of Ioannina, Greece: J.D. Vergados, G.K. Leontaris V. Tsakstara, T. Smponias, P. Giannaka, D.K. Papoulias
- T.E.I. of Western Macedonia, Greece: J. Sinatkas
- NCSR Democritos, Greece: D. Bonatsos
- Univ. of Valencia, Spain: Group of J.W.F. Valle
- RCNP, Univ. of Osaka, Japan: H. Ejiri
- Univ. of Tuebingen, Germany: Group of A. Faessler, K. Kokkotas
- Univ. of Jyvaskyla, Finland: Group of J. Suhonen
- UCL. London, UK: Frank Deppisch

Thank you for your attention !