

Non-Standard Interactions in Nuclear Physics

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AHEP Group Seminar



1 Introduction

- Standard Model (SM) and exotic neutral-current processes
 - $\nu_\alpha + (A, Z) \rightarrow \nu_\alpha + (A, Z)$
 - $\nu_\alpha + (A, Z) \rightarrow \nu_\beta + (A, Z)$
 - $\mu^- + (A, Z) \rightarrow e^- + (A, Z)$
 - 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
- description of the nuclear method

3 Results

- Coherent cross sections and Simulated Signals
- expected differential event rates and total counts
- new limits on the lepton flavour violating parameters

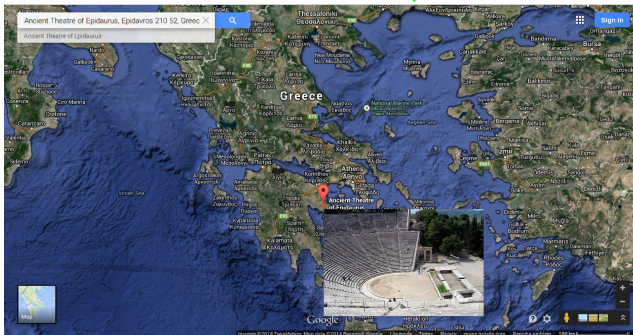
4 Summary and Outlook

Before starting, let me first introduce myself...

You may call me Dimitri (in greek: Δημήτρης)

- BSc. 2006-2010, Univ. of Ioannina, Greece
- MSc. 2010-2011, Univ. of Sussex, UK
(Thesis: Neutrino phenomenology and leptogenesis)
- PhD 2011-present, Univ. of Ioannina, Greece (Supervisor Prof. T.S. Kosmas)
(Thesis: exotic lepton flavour violating processes in nuclei)

I come from Ancient Epidaurus



Acknowledgements

Special thanks to:

- Prof. Valle for offering me such an advantageous opportunity to visit IFIC
- Dr. Tortola for her generous help during the application procedures
- Mr. Dorame for his great help my first day here

I wish also to thank the other members of the AHEP group for the warm hospitality and for making me feel welcome

Lepton flavor non-conservation

1) Elementary LFV processes:

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

$$\mu \rightarrow ee^+e^- \quad (\mu \rightarrow 3e)$$

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

$$\nu_e \rightarrow \nu_\mu \quad \nu_\mu \rightarrow \nu_\tau \quad \text{etc.} \quad (\text{neutrino oscillations})$$

2) Neutrinoless LFV/L processes in Nuclei:

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

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

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


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

3) Exotic neutrino-nucleus processes (FCNC processes)

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

$$(\alpha \neq \beta)$$

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

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

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

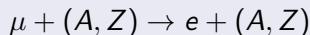
- Well-studied process theoretically.
- Any event has not been found yet experimentally.
- Very high experimental sensitivity is required.

LFV NSI ν -nucleus reaction

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

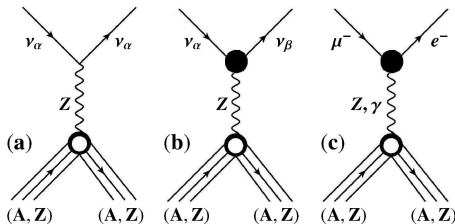
- Not allowed in the SM due to violation of the lepton number
- Excellent probe to search for new physics

CLFV muon to electron conversion in nuclei



- 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 ν -nucleus 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 $\mu^- \rightarrow e^-$ 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, J. Phys. Conf. Ser. **410** 012123 (2013)

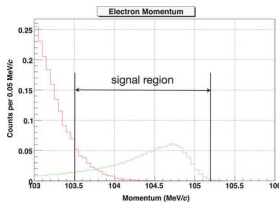
D.K. Papoulias and T.S. Kosmas, Phys. Lett. **B 728** 482 (2014)

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

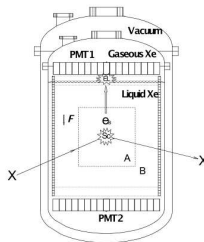
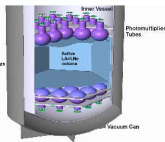
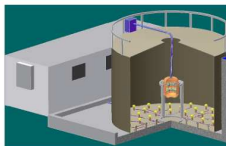


- high sensitivity required

Neutrinos from stopped-pion muon beam experiments

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

replacement of **CLEAR Experiment**: (proposed nucl. detectors **456kg Liquid Ar** and **491kg Liquid Ne**) K.Scholberg, et. al. arXiv:0910.1989 [hep-ex]

Neutrinos from reactor plants

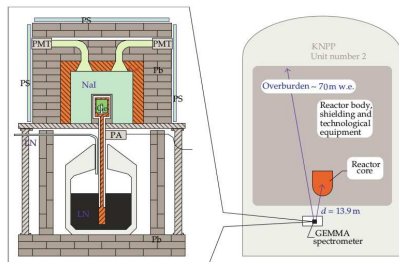
TEXONO Colab.



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

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

GEMMA Colab.



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

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

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

^{76}Ge detectors
extremely high fluxes ($\sim 10^{13} \nu/\text{s}$)
low neutrino energies up to $\sim 10 \text{ MeV}$

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

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

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

- current limits
- the choice of nucleus plays key role

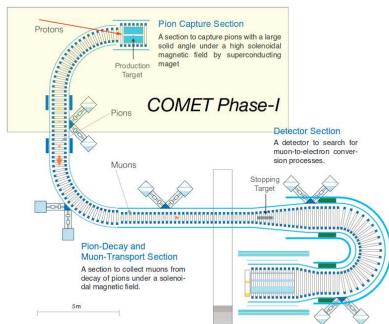
Process	upper limit	place	year
$\mu^- + Cu \rightarrow e^- + Cu$	$< 1.6 \times 10^{-8}$	SREL	1972
$\mu^- + {}^{32}S \rightarrow e^- + {}^{32}S$	$< 7 \times 10^{-11}$	SIN	1982
$\mu^- + Ti \rightarrow e^- + Ti$	$< 1.6 \times 10^{-11}$	TRIUMF	1985
$\mu^- + Ti \rightarrow e^- + Ti$	$< 4.6 \times 10^{-12}$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

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

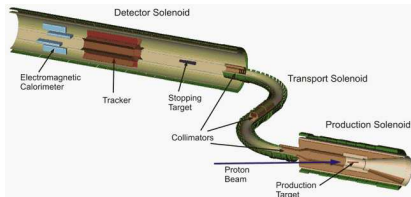
Recently planned $\mu^- \rightarrow e^-$ conversion experiments

- Mu2e experiment Fermilab
 $R_{\mu e}^{A1} < 6 \times 10^{-17}$
- Next generation Mu2e-PX
experiment aims $R_{\mu e}^{A1} < 2 \times 10^{-18}$

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



Schematic layout of COMET and COMET Phase-I



- COMET at J-PARC
 $R_{\mu e}^{A1} < 10^{-16}$
- Next generation PRIME/PRISM
aims $R_{\mu e}^{Ti} < 10^{-18}$

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

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

- 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

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

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

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

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 proton(neutron) form factors $F_{Z(N)}$ (CVC theory) more on nucl. ME at the end of the talk

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

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

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

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

The NSI nuclear matrix element reads

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

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**

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

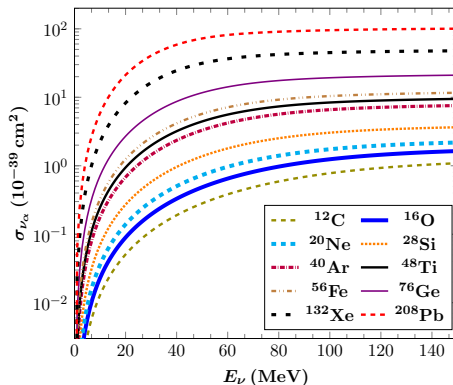
- 3-momentum transfer $q^2 = 2MT_N$
- M is the nuclear mass.
- $T_N^{\text{max}} = \frac{2E_\nu^2}{M+2E_\nu}$

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)

SM ν -nucleus coherent cross sections

Our research involves realistic cross sections calculations for a set of interesting nuclei throughout the periodic table



For heavier isotopes the form factor suppression to the coherent cross section is more important [D.K. Papoulias and T.S. Kosmas, Advances in High Energy Physics, in press](#)

Branching ratios

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

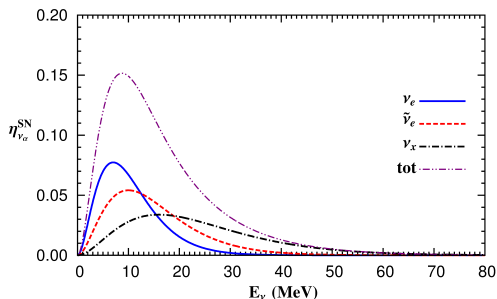
$$R_{\lambda,\nu_\alpha}(E_\nu) = \frac{\sigma_{\lambda,\nu_\alpha}(E_\nu)}{\sigma_{\text{SM}}(E_\nu)}, \quad \lambda = \text{tot, NU, FP, FC}$$

ν_α	(A,Z)	R_{tot}	R_{NU}	R_{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 $E_\nu \approx 120 \text{ MeV}$

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

Supernova (SN) neutrino fluxes



The maximum energy of a typical supernova explosion is released by high energy neutrino emission (every ~ 30 y)

- Supernova neutrino flux

$$\Phi(E_\nu) = \sum_{\alpha} \frac{N_{\nu_{\alpha}}}{4\pi d^2} \eta_{\nu_{\alpha}}^{\text{SN}}(E_\nu)$$

- Maxwell-Boltzmann distributions

$$\eta_{\nu_{\alpha}}^{\text{SN}}(E_\nu) = \frac{E_\nu^2}{2T_{\nu_{\alpha}}^3} e^{-E_\nu/T_{\nu_{\alpha}}}$$

- weighted cross sections

$$\sigma_{\lambda, \nu_{\alpha}}^{\text{sign.}}(E_\nu) = \sigma_{\lambda, \nu_{\alpha}}(E_\nu) \eta_{\nu_{\alpha}}^{\text{SN}}(E_\nu)$$

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

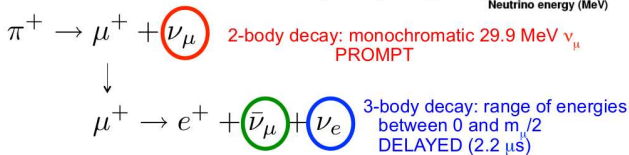
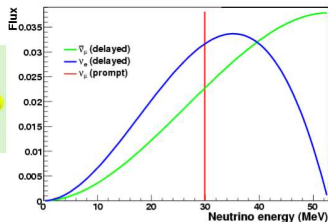
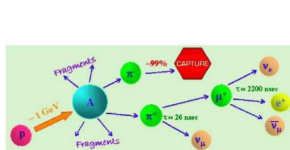
M. Biassoni, C. Martinez, *Astropart. Phys.* 36 (2012) 151.

Neutrino fluxes from Spallation neutron sources (SNS)

Neutrinos for free!

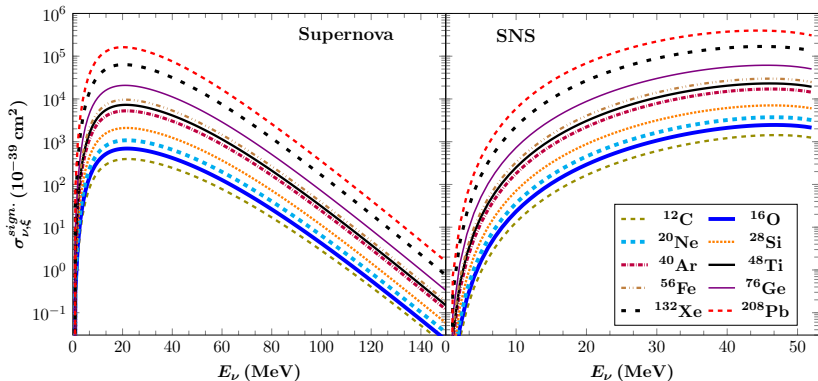
figure from Prof. K. Scholberg (talk at NuInt 2014, May 22, 2014)

Stopped-Pion (DAR) Neutrinos



Expected signals for other interesting nuclei-targets

SM-predicted signals for supernova (SN) and laboratory neutrinos (SNS)



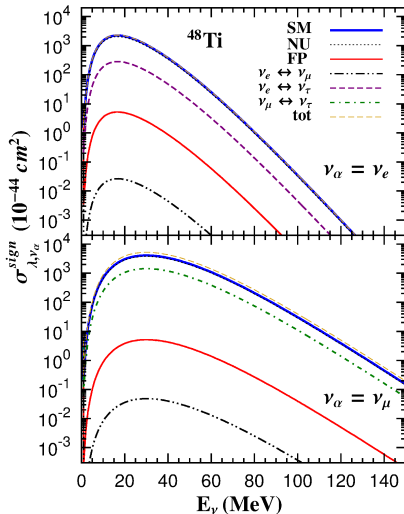
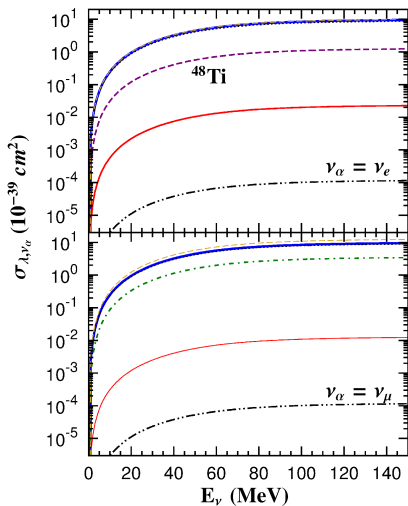
good overlap between SN and SNS neutrinos!

Dark-matter detectors are also sensitive to Supernova neutrinos (background to dark matter searches)

D.K. Papoulias and T.S. Kosmas, *Advances in High Energy Physics*, in press

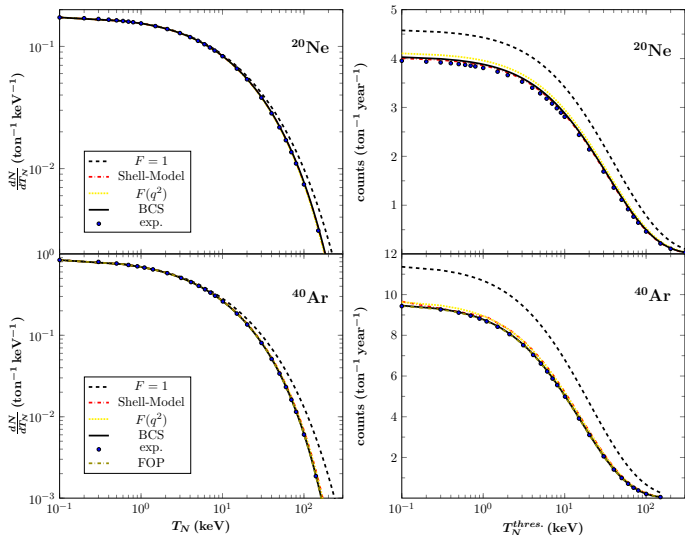
NSI cross sections and Simulated Signals for SN- ν'_s

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



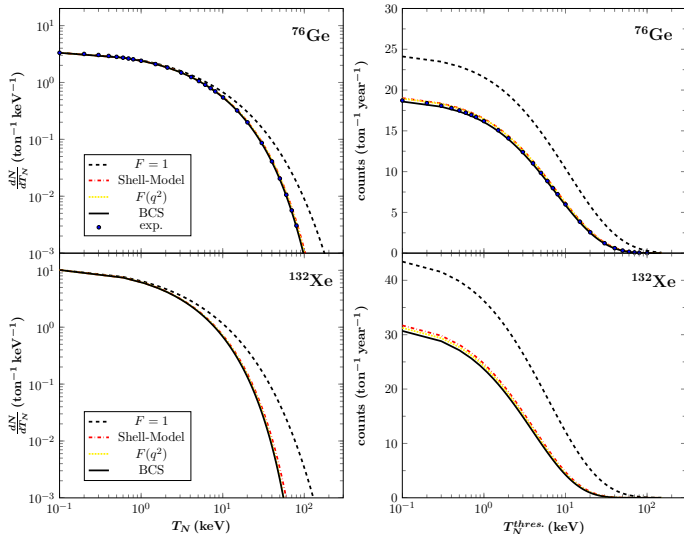
SM Event rates for supernova neutrinos

Various nuclear methods tested [D.K. Papoulias and T.S. Kosmas, Advances in High Energy Physics, in press](#)



SM Event rates for supernova neutrinos (continued)

Various nuclear methods tested [D.K. Papoulias and T.S. Kosmas, Advances in High Energy Physics, in press](#)



SM+NSI Flux averaged cross section calculations

In supernova neutrino simulations, another useful quantity is the flux averaged cross section [V. Tsakstara and T.S. Kosmas, Phys. Rev. C 83 \(2011\) 054612](#)

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

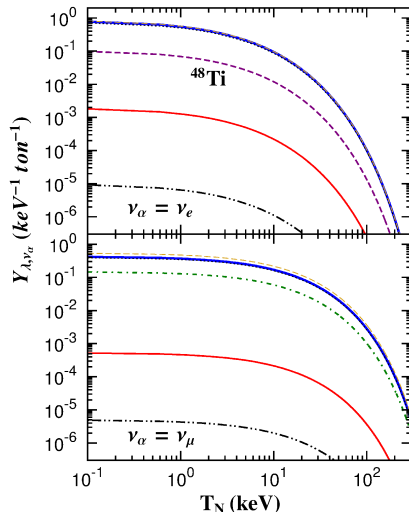
ν_α	(A, Z)	$\langle \sigma_{\text{tot}} \rangle$	$\langle \sigma_{\text{SM}} \rangle$	$\langle \sigma_{\text{NU}} \rangle$	$\langle \sigma_{\text{FP}} \rangle$	$\langle \sigma_{\nu_\alpha \rightarrow \nu_e} \rangle$	$\langle \sigma_{\nu_\alpha \rightarrow \nu_\mu} \rangle$	$\langle \sigma_{\nu_\alpha \rightarrow \nu_\tau} \rangle$
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}cm^2) for various SN ν -spectra parametrized by Maxwell-Boltzmann distributions

estimation of the response of the nuclear-detector to the energy distribution of the observed neutrinos.

[D.K. Papoulias and T.S. Kosmas, Phys. Lett. B 728 482 \(2014\)](#)

SM+NSI Expected Event Rates for supernova neutrinos



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.

Differential Yield in events assuming one ton of ^{48}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

Limits from $\mu \rightarrow e$ conversion

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

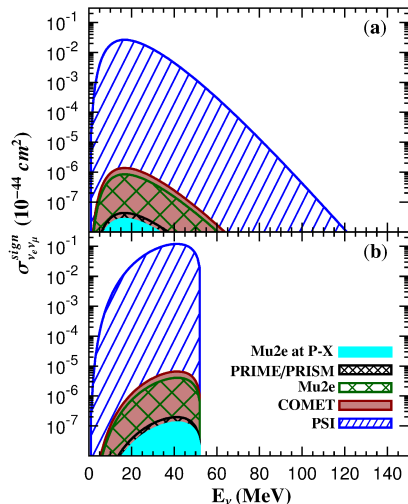
$$\epsilon_{\mu e}^{fP} = C^{-1} \sqrt{R_{\mu e}^{(A,Z)}}.$$

S. Davidson et. al., JHEP **03** 011 (2003) (current limit from PSI: $\epsilon_{\mu e}^{fP} = 7.7 \times 10^{-4}$)
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 $\mu^- \rightarrow e^-$ conversion experiments.

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

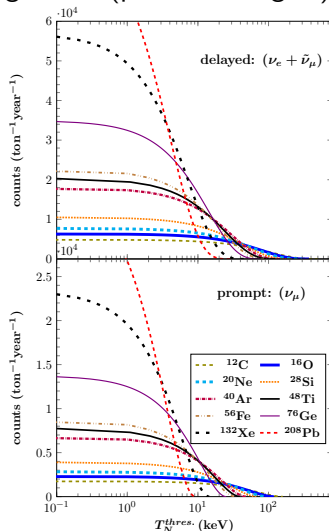
- (a) supernova neutrinos
- (b) stopped-pion muon neutrinos
- expected limits on NSI from next generation $\mu^- \rightarrow e^-$ conversion experiments is used

Neutrino detection by SNS facilities

SM calculations for experimentally interesting nuclei (potential targets)

Useful for the COHERENT exp.

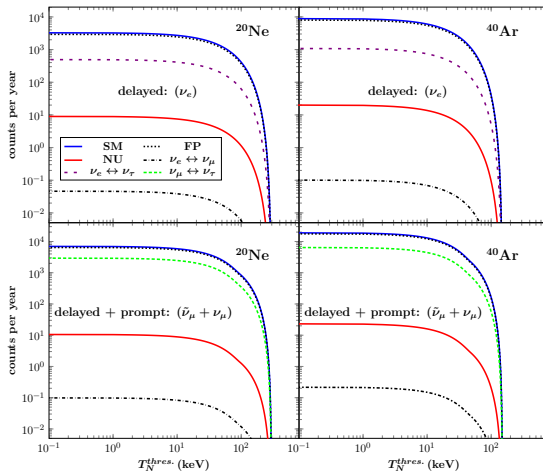
- detectors: liquid Ar/Ne, Ge, Xe, CsI[Na]
- expected no. of events
(thousands for kg-scale detectors!)
- for pulsed beams statistics are better (compared i.e. to reactor neutrinos)
- independent measurements for the prompt and delayed fluxes



D.K. Papoulias and T.S. Kosmas, *Advances in High Energy Physics*, in press

Searching for NSI with the COHERENT experiment

NSI events for ^{20}Ne (391 kg) and ^{40}Ar (456 kg) at 20 m from the source

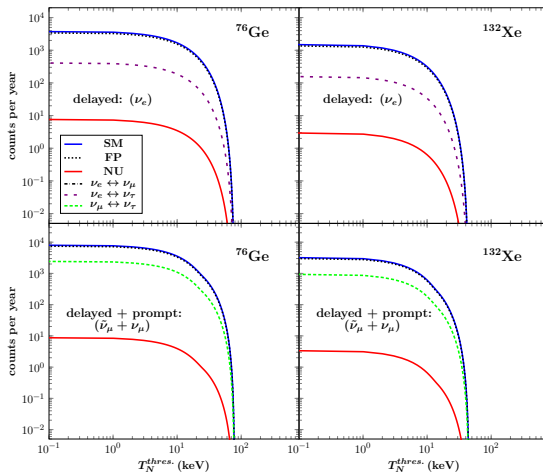


Within the current limits on the NSI parameters, measurable rates are expected for NSI

ν -nucleus events D.K. Papoulias and T.S. Kosmas, *Advances in High Energy Physics*, in press

Searching for NSI with the COHERENT experiment

NSI events for ^{76}Ge (100 kg) at 20 m and ^{132}Xe (100 kg) at 40 m from the source



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, in press](#)

Nuclear theory for neutrino scattering I

- At low and intermediate energies, any semileptonic process is described by an effective interaction Hamiltonian, written in terms of the **leptonic** j_μ^{lept} and **hadronic** $\mathcal{J}_\mu$ currents as

P.G. Giannaka, T.S. Kosmas, J. Phys. Conf. Ser. 410 (2013) 012124

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} j_\mu^{\text{lept}}(x) \mathcal{J}^\mu(x),$$

where G_F is the well-known Fermi constant.

- In the Donnelly-Walecka multipole decomposition method, the neutral-current, double differential SM cross section from an initial $|J_i\rangle$ to a final $|J_f\rangle$ nuclear state reads (**we construct them explicitly through realistic nuclear structure calculations**)

$$\frac{d^2\sigma_{i\rightarrow f}}{d\Omega d\omega} = \frac{G_F^2}{\pi} \frac{\epsilon_i \epsilon_f}{(2J_i + 1)} \left(\sum_{J=0}^{\infty} \sigma_{\text{CL}}^J + \sum_{J=1}^{\infty} \sigma_{\text{T}}^J \right),$$

where ϵ_i (ϵ_f) is the initial (final) neutrino energy and ω is the nucleus excitation energy.

T.W. Donnelly and J.D.Walecka, Nucl. Phys. A 274 (1976) 368.

Nuclear theory for neutrino scattering II

The cross sections σ_{CL}^J (for the Coulomb-longitudinal operators) and σ_{T}^J (for the tensor operators) are written in terms of the reduced matrix elements (ME) of eight basic irreducible tensor operators, as function of the weak nucleon form factors

F_x , $x = 1, 2, A, P$

$$\langle j_1 || T_i^J || j_2 \rangle = e^{-y} y^{\beta/2} \sum_{\mu=0}^{n_{\max}} \mathcal{P}_{\mu}^{i,J} y^{\mu}, \quad i = 1, \dots, 7. \quad (2)$$

V.Ch. Chasioti and T.S. Kosmas, Nucl. Phys. A 829 (2009) 234.

P.G. Giannaka, D.K. Papoulias, T.S. Kosmas, unpublished (for any configuration $(j_1, j_2)J$)

$$M_{JM}^{\text{Coul}}(qr) = F_1 M_M^J(qr), \quad iM_{JM}^{\text{Coul}^5}(qr) = \frac{q}{M} \left[F_A \Omega_M^J(qr) + \frac{1}{2} (F_A + \omega F_P) \Sigma_M^{\prime\prime J}(qr) \right], \quad (3)$$

$$L_{JM}(qr) = \frac{\omega}{q} M_{JM}^{\text{Coul}}(qr), \quad -iL_{JM}^5(qr) = \left[F_A - \frac{q^2}{2M} F_P \right] \Sigma_M^{\prime\prime J}(qr), \quad (4)$$

$$T_{JM}^{\text{el}}(qr) = \frac{q}{M} \left[F_1 \Delta_M^{\prime\prime J}(qr) + \frac{1}{2} (F_1 + 2MF_2) \Sigma_M^J(qr) \right], \quad -iT_{JM}^{\text{el}^5}(qr) = F_A \Sigma_M^{\prime\prime J}(qr), \quad (5)$$

$$iT_{JM}^{\text{mag}}(qr) = \frac{q}{M} \left[F_1 \Delta_M^J(qr) - \frac{1}{2} (F_1 + 2MF_2) \Sigma_M^{\prime\prime J}(qr) \right], \quad T_{JM}^{\text{mag}^5}(qr) = F_A \Sigma_M^J(qr). \quad (6)$$

T.W. Donnelly and J.D. Walecka, Nucl. Phys. A 274 (1976) 368.

SM + Non-standard nuclear Matrix elements (ME)

For **SM $gs \rightarrow gs$ transitions** (i.e. $|0^+\rangle \rightarrow |0^+\rangle$) only the Coulomb operator survives and the diff. cross section is proportional to the ME

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

where, the **polar-vector couplings** of protons g_V^p and neutrons g_V^n with the Z boson are written as $g_V^p = 2(g_L^u + g_R^u) + (g_L^d + g_R^d) = \frac{1}{2} - 2\sin^2\theta_W \sim 0.04$ and $g_V^n = (g_L^u + g_R^u) + 2(g_L^d + g_R^d) = -\frac{1}{2}$.

The **flavour preserving (FP)** part of the Lagrangian $\mathcal{L}_{\text{FP}} \equiv \mathcal{L}_{\text{NU}} + \mathcal{L}_{\text{SM}}$, yields the ME

$$\left| \mathcal{M}_{V,\nu_\alpha}^{\text{FP}} \right|^2 = \left| \mathcal{M}_{V,\nu_\alpha}^{\text{SM}} + \mathcal{M}_{V,\nu_\alpha}^{\text{NU}} \right|^2.$$

Subsequently, the **total** coherent cross section may be computed on the basis of the ME

$$\left| \mathcal{M}_{V,\nu_\alpha}^{\text{tot}} \right|^2 = \left| \mathcal{M}_V^{\text{FP}} \right|^2 + \left| \mathcal{M}_{V,\nu_\alpha}^{\text{FC}} \right|^2.$$

D.K. Papoulias and T.S. Kosmas, *Advances in High Energy Physics*, in press

Important conclusion: *The cross section is mostly sensitive to the neutron charge distribution*

Evaluation of the form factors I (BCS)

Within the context of the **quasi-particle random phase approximation (QRPA)** method the form factors for protons (neutrons) are

$$F_{N_n} = \frac{1}{N_n} \sum_j [j] \langle g.s. || j_0(qr) || g.s. \rangle \left(V_j^{p(n)} \right)^2$$

where $[j] = \sqrt{2j+1}$, $N_n = Z$ (or N), $V_j^{p(n)}$ are the BCS probability amplitudes, determined by solving iteratively the **BCS equations**.

T.S. Kosmas, J.D. Vergados, O. Civitarese and A. Faessler, Nucl. Phys. A 570 (1994) 637

Important parameters:

- the chosen active model space
- the harmonic oscillator (h.o.) parameter b
- the properly adjusted values of the two parameters $g_{\text{pair}}^{p(n)}$ for proton (neutron) pairs that renormalise the monopole (pairing) residual interaction (obtained from the Bonn C-D two-body potential describing the **strong two-nucleon forces**).

P.G. Giannaka, T.S. Kosmas, J. Phys. Conf. Ser. 410 (2013) 012124

The BCS method provides realistic proton and neutron form factors

Evaluation of the form factors II (experimental data)

- The proton charge density distribution $\rho_p(r)$ is well constrained by electron scattering experiments and in our case is evaluated from a model independent Fourier-Bessel analysis.

H. De Vries, C.W. De Jager and C. De Vries, *At. Data and Nucl. Data Tables* 36 (1987) 495536

- The proton nuclear form factor is the Fourier transform of the proton charge density distribution and takes the form

$$F_Z(q^2) = \frac{4\pi}{Z} \int \rho_p(r) j_0(qr) r^2 dr ,$$

with j_0 being the zero order spherical Bessel function.

- this method assumes $F_N(q^2) = F_Z(q^2)$ (not always a good approximation)

D.K. Papoulias and T.S. Kosmas, *Advances in High Energy Physics*, in press

Evaluation of the form factors III (Shell-Model)

The form factor $F_Z(q^2)$, for h.o. wavefunctions reads

$$F_Z(q^2) = \frac{1}{Z} e^{-(qb)^2/4} \Phi(qb, Z), \quad \Phi(qb, Z) = \sum_{\lambda=0}^{N_{\max}} \theta_{\lambda}(qb)^{2\lambda}.$$

The radial nuclear charge density distribution $\rho_p(r)$ is written in the following compact form

$$\rho_p(r) = \frac{1}{\pi^{3/2} b^3} e^{-(r/b)^2} \Pi\left(\frac{r}{b}, Z\right), \quad \Pi(\chi, Z) = \sum_{\lambda=0}^{N_{\max}} f_{\lambda} \chi^{2\lambda}$$

The coefficients f_{λ} are expressed as

$$f_{\lambda} = \sum_{(n,\ell)j} \frac{\pi^{1/2} (2j+1) n! C_{n\ell}^{\lambda-\ell}}{2\Gamma\left(n+\ell+\frac{3}{2}\right)}$$

T.S. Kosmas and J.D. Vergados, Nucl. Phys. A 536 (1992) 72

Evaluation of the form factors IV (Fractional occupation probabilities)

- Shell model assumes that the proton occupation probabilities equal to unity(zero) for the states below(above) the Fermi surface.
- Introduce depletion and occupation numbers, to parametrise the partially occupied levels of the states that satisfy the relation $\sum_{\text{all}} \alpha_{n\ell j} (2j+1) = N_n$.

T.S. Kosmas and J.D. Vergados, Nucl. Phys. A 536 (1992) 72

- In this approximation we have a number of active surface nucleons

$$\begin{aligned} \Pi(\chi, Z, \alpha_i) = & \Pi(\chi, Z_2) \frac{\alpha_1}{Z_1 - Z_2} + \Pi(\chi, Z_1) \left[\frac{\alpha_2}{Z_c - Z_1} - \frac{\alpha_1}{Z_1 - Z_2} \right] \\ & + \Pi(\chi, Z_c) \left[\frac{Z' - Z}{Z' - Z_c} - \frac{\alpha_2}{Z_c - Z_1} - \frac{\alpha_3}{Z' - Z_c} \right] \\ & + \Pi(\chi, Z') \left[\frac{Z - Z_c}{Z' - Z_c} + \frac{\alpha_3}{Z' - Z_c} - \frac{\alpha_4}{Z'' - Z'} \right] \\ & + \Pi(\chi, Z'') \left[\frac{\alpha_4}{Z'' - Z'} - \frac{\lambda}{Z''' - Z''} \right] + \Pi(\chi, Z''') \frac{\lambda}{Z''' - Z''}, \end{aligned}$$

with $\lambda = \alpha_1 + \alpha_2 - \alpha_3 - \alpha_4$ D.K. Papoulias and T.S. Kosmas, Advances in High Energy Physics, in press

- fit the parameters to reproduce the proton charge density distribution

Evaluation of the form factors V (Other effective methods)

The form factor is effectively represented by

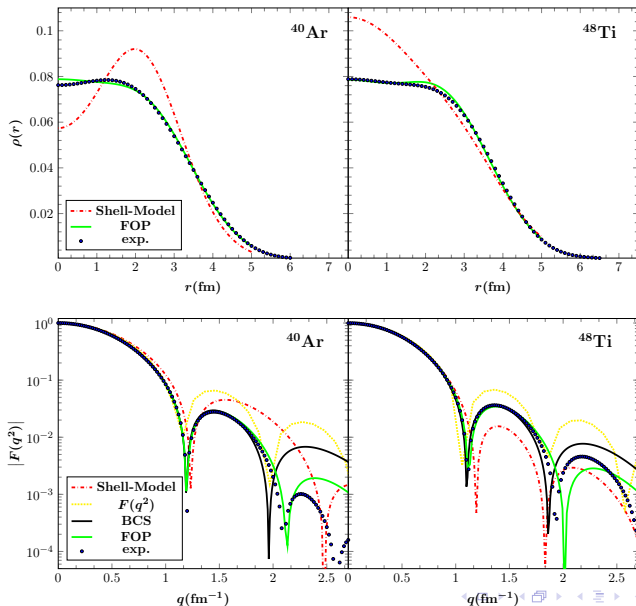
$$F_Z(q^2) = \frac{3j_1(qR_0)}{qR_0} \exp \left[-\frac{1}{2}(qs)^2 \right],$$

J. Engel, Phys. Lett. B 264 (1991) 114

- $j_1(x)$ is the known first-order Spherical-Bessel function and $R_0^2 = R^2 - 5s^2$,
- R and radius of the nucleus
- s surface thickness of the nucleus respectively.

The radius parameter is usually given from the semi-empirical form $R = 1.2A^{1/3}$ fm while s is of the order of 0.5 fm.

Comparison of the nuclear methods



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
- detailed study for nuclear systems throughout the periodic table (for several ν -sources)
- tested various nuclear methods for high reliability of results

Work in progress and future work

- examine ν -magnetic moments induced via tensor NSI couplings (in progress, last stage)
- study the incoherent reaction channels within QRPA

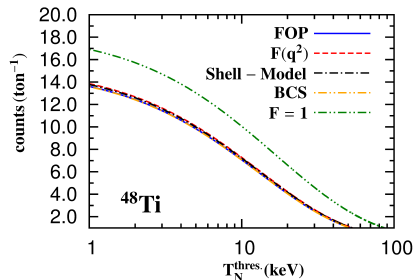
What new physics can we gain SNS and reactor neutrino experiments?

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

Gracias por su atencion !

Extras

Total number of events



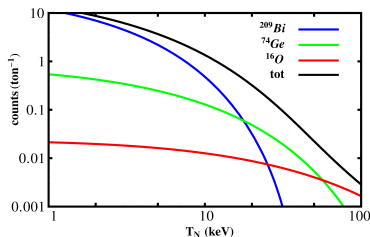
- several nuclear methods tested
- neglecting the nuclear physics details i.e. $F = 1$ could lead up to 30% more events

D.K. Papoulias and T.S. Kosmas, *Advances in*

High Energy Physics, in press

a combination of light and heavy nuclear targets would be a more appropriate choice, i.e. **BGO scintillator ($\text{Bi}_4\text{Ge}_3\text{O}_{12}$)**

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



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