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Effects of vector NSI in elastic neutrino–atom scattering

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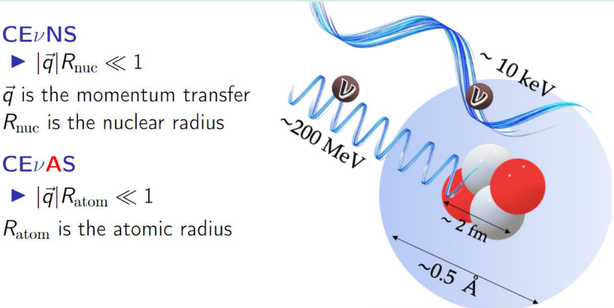
Motivation

- Neutrino oscillations have established that the Standard Model is incomplete. The neutrino sector is sensitive probes of physics beyond the SM.
- Non-standard interactions (NSI) of neutrinos with matter fermions form a natural class of BSM effects sourced, for example, by new mediators.
- NSI manifest themselves in two complementary regimes:
  - *neutrino oscillations*;
  - *neutrino scattering*.
- Within the scientific programme of the National Centre for Physics and Mathematics (NCPHM), the SATURNE project is currently being implemented. It is aimed at the first-in-the-world detection of coherent elastic scattering of tritium electron antineutrinos on the ^{4}He atom (CEνAS) and at a record-level constraint on the neutrino magnetic moment of order $10^{-13}\,\mu_B$.
- *In this talk*, an analytical description of CEνAS is presented, accounting for the contribution of vector NSI.

The processes CEνNS and CEνAS



Coherent elastic neutrino scattering — the neutrino interacts with a composite system (nucleus, atom) as a whole.

CEνNS: Coherent Elastic ν–Nucleus Scattering. First observed by COHERENT in 2017.

CEνAS: Coherent Elastic ν–Atom Scattering. Predicted by Gaponov & Tikhonov (1977). *Not yet observed.*

The SATURNE experiment will provide the first opportunity to observe this process.

- Gaponov & Tikhonov, Yad. Fiz. **26** (1977) 594
- COHERENT, Akimov et al., Science **357** (2017) 1123
- Cadeddu, Dordei, Giunti, Kouzakov, Picciau, Studenikin, PRD **100** (2019) 073014

Non-standard interactions (NSI)

NSI are interactions whose mediators are absent from the Standard Model but arise naturally in many of its extensions. A canonical example is the Z' boson; other possibilities include heavy scalars ϕ, leptoquarks, and similar mediators.

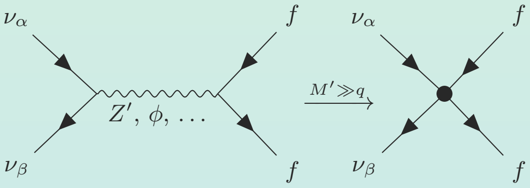


Fig. 1. NSI of neutrinos with a matter fermion f: heavy-mediator exchange (left) and its contact limit (right) for $M' \gg q$.

Since M' is much larger than the typical momentum transfer q, the heavy mediator can be integrated out and the interaction reduces to an effective four-fermion contact operator.

- J. B. Dent et al. (2017), Phys. Rev. D **96**(9): 095007.

Lorentz decomposition of the interaction vertex

The interaction vertex is a Dirac bilinear $\bar{\psi}\,\Gamma\,\psi$, where Γ is a 4×4 matrix in spinor space. A complete basis is provided by five Lorentz-covariant structures:

$$\Gamma \in \Big\{ \underbrace{\mathbb{1}}_{S},\ \underbrace{\gamma_5}_{P},\ \underbrace{\gamma^\mu}_{V},\ \underbrace{\gamma^\mu\gamma_5}_{A},\ \underbrace{\sigma^{\mu\nu}}_{T} \Big\}, \qquad \sigma^{\mu\nu} \equiv \tfrac{i}{2}\big[\gamma^\mu, \gamma^\nu\big].$$

In the SM neutrinos couple only via $V-A$: $\bar{\nu}\,\gamma^\mu P_L\,\nu$. New physics can generate any of the five structures. The most general NSI effective Lagrangian therefore reads

$$\mathcal{L}_{\mathsf{NSI}} = -\frac{G_F}{\sqrt{2}} \sum_{X=S,P,V,A,T} \varepsilon^{X}_{\alpha\beta}\,(\bar{\nu}_\alpha\,\Gamma_X\,\nu_\beta)\,(\bar{f}\,\Gamma_X\,f).$$

In what follows we focus on the vector ($X=V$) NSI structures.

Structure of vector and axial-vector NSI

To obtain analytical expressions for the differential cross section of neutrino scattering as a function of the recoil energy, we start the calculation from the elementary neutrino–nucleon scattering process.

The effective NSI Lagrangian for neutrino–nucleon interaction reads

$$\mathcal{L}_{\text{NSI}}^{\nu N} = -\frac{G_F}{\sqrt{2}} \sum_{\alpha,\beta=e,\mu,\tau} \left(\overline{\psi}_{\nu}^{\beta} \gamma^{\mu} (1-\gamma_5) \psi_{\nu}^{\alpha}\right) \left(\overline{\psi}_N \gamma_{\mu} (\varepsilon_{\alpha\beta}^{NV} - \varepsilon_{\alpha\beta}^{NA} \gamma_5) \psi_N\right),$$

where $N \in \{p, n\}$, and nucleon-level NSI relate to quark-level couplings as

$$\varepsilon_{\alpha\beta}^{pX} = 2\varepsilon_{\alpha\beta}^{uX} + \varepsilon_{\alpha\beta}^{dX}, \qquad \varepsilon_{\alpha\beta}^{nX} = \varepsilon_{\alpha\beta}^{uX} + 2\varepsilon_{\alpha\beta}^{dX}, \qquad X = V,\ A.$$

• P. Coloma, M. Gonzalez-Garcia, M. Maltoni, J. Pinheiro, S. Urrea, “Global constraints on non-standard neutrino interactions with quarks and electrons”, JHEP **08** (2023) 032.

NSI contribution to the scattering process

To incorporate NSI into the neutrino–nucleon scattering process, the NSI Lagrangian must be combined with the SM weak-interaction Lagrangian for the neutrino. The SM neutral-current Lagrangian reads

$$\mathcal{L}_{\text{SM}}^{\nu N} = -\frac{G_F}{\sqrt{2}} \left(\overline{\psi}_\nu \gamma^\mu (1-\gamma_5) \psi_\nu\right) \left(\overline{\psi}_N \gamma_\mu (g_V^N - g_A^N \gamma_5) \psi_N\right) .$$

Adding NSI yields a single neutral-current operator with *effective couplings*:

$$\mathcal{L}_{\nu N}^{NC} = -\frac{G_F}{\sqrt{2}} \sum_{\alpha,\beta} \left(\overline{\psi}_\nu^\beta \gamma^\mu (1-\gamma_5) \psi_\nu^\alpha\right) \left(\overline{\psi}_N \left(f_{\alpha\beta}^{NV} \gamma_\mu - f_{\alpha\beta}^{NA} \gamma_\mu \gamma_5\right) \psi_N\right) ,$$

$$f_{\alpha\beta}^{NV} = g_V^N \, \delta_{\alpha\beta} + \varepsilon_{\alpha\beta}^{NV} , \qquad f_{\alpha\beta}^{NA} = g_A^N \, \delta_{\alpha\beta} + \varepsilon_{\alpha\beta}^{NA} .$$

NSI shift the SM couplings by $\varepsilon_{\alpha\beta}^{NX}$ and introduce flavor-changing ($\alpha \neq \beta$) processes absent in the SM.

CEνAS on ^{4}He with NSI: cross section and form factors

To generalise to the atomic case, we introduce form factors that account for the spatial distribution of nucleons in the nucleus and electrons in the atomic shell. The expressions below give the differential cross section of neutrino scattering on the ^{4}He atom including vector NSI together with neutrino mixing and oscillation effects.

$$\left(\frac{d\sigma}{dT}\right)_{\text{Atom}} = \frac{G_F^2\, M_{\text{Atom}}}{\pi}\left(1 - \frac{M_{\text{Atom}}\, T}{2E_\nu^2}\right)\mathcal{C}_V^{\text{Atom}}(\alpha),$$

$$\mathcal{C}_V^{\text{Atom}}(\alpha) = \sum_{j=1}^{3}\left|\sum_{i=1}^{3} U_{\alpha i}^*\, e^{-i\frac{m_i^2}{2E_\nu}L}\, \mathcal{F}_{ji}^{\text{Atom},V}\right|^2, \quad \mathcal{F}_{ji}^{\text{Atom},V} = \mathcal{F}_{ji}^{\text{Nucl},V}(0) + \mathcal{F}_{ji}^{\text{el},V}(\vec{q}).$$

The nuclear and electronic form factors:

$$\mathcal{F}_{ji}^{\text{Nucl},V}(0) = Z f_{ji}^{pV} + N f_{ji}^{nV}, \quad \mathcal{F}_{ji}^{\text{el},V}(\vec{q}) = \int d^3r\, e^{i\vec{q}\cdot\vec{r}}\, \langle 1s^2 | \sum_{k=1,2}\left(f_{ji}^{eV} + U_{ej}U_{ei}^*\right)_k \delta^{(3)}(\vec{r}-\vec{r}_k)\, |1s^2\rangle,$$

$$f_{ji}^{\mathcal{K}V} = g_V^{\mathcal{K}}\,\delta_{ji} + \varepsilon_{ji}^{\mathcal{K}V}, \quad \mathcal{K} \in \{e, p, n\}.$$

For ^{4}He the axial nuclear contribution vanishes since the nuclear spin is zero; the extra $U_{ej}U_{ei}^*$ term encodes the W-exchange contribution present only for ν_e.

Compact analytical form for ^{4}He

Setting $L = 0$ (oscillation phases negligible on the detector baseline) and using PMNS unitarity, $\sum_i U^*_{\alpha i} U_{\beta i} = \delta_{\alpha\beta}$, the quantity $\mathcal{C}_V(\alpha)$ can be cleanly decomposed into nuclear and electronic NSI contributions and written in three transparent pieces:

$$\mathcal{C}_V(\alpha) = \underbrace{\left(g^{\text{Atom},V}_{\alpha\alpha}\right)^2}_{\text{SM}^2} + \underbrace{\sum_\gamma \left|\varepsilon^{\text{Atom},V}_{\alpha\gamma}\right|^2}_{\text{quadratic NSI }(\geq 0)} + \underbrace{2\, g^{\text{Atom},V}_{\alpha\alpha}\, \varepsilon^{\text{Atom},V}_{\alpha\alpha}}_{\text{linear interference}},$$

where the SM and NSI matrices in flavor space read

$$g^{\text{Atom},V}_{\alpha\beta} = g^{\text{Nucl}}_V\, \delta_{\alpha\beta} + Z F_e(q)\, g^e_V\, \delta_{\alpha\beta} + Z F_e(q)\, \delta_{\alpha e}\delta_{e\beta}, \quad \varepsilon^{\text{Atom},V}_{\alpha\beta} = \varepsilon^{\text{Nucl}}_{\alpha\beta} + Z F_e(q)\, \varepsilon^e_{\alpha\beta},$$

with $g^{\text{Nucl}}_V = Z\, g^p_V + N\, g^n_V$, $\varepsilon^{\text{Nucl}}_{\alpha\beta} = Z\, \varepsilon^{pV}_{\alpha\beta} + N\, \varepsilon^{nV}_{\alpha\beta}$, and the atomic form factor (with $F_e(0) = 1$) parametrised for the ^{4}He ground state as

$$F_e(q) = \frac{1}{Z}\left[\sum_{i=1}^{6} a_i\, e^{-b_i q^2} + a_0\right],$$

where $\{a_i, b_i\}$ are obtained from a fit to the electron density of a 26-parameter correlated Hylleraas-type wave function.

- Diagonal $\varepsilon_{\alpha\alpha}$: linear SM–NSI interference, enhances *or* suppresses the cross section.
- Off-diagonal $\varepsilon_{\alpha\gamma}$ $(\alpha \neq \gamma)$: only quadratic, always increases the cross section.

• S. Diallo, I. G. Faye, L. Gomis, M. S. Tall, I. Diédhiou, “Atomic Form Factor Calculations of S-states of Helium”, Am. J. Mod. Phys. **8**(4) (2019) 66.

Standard Model prediction

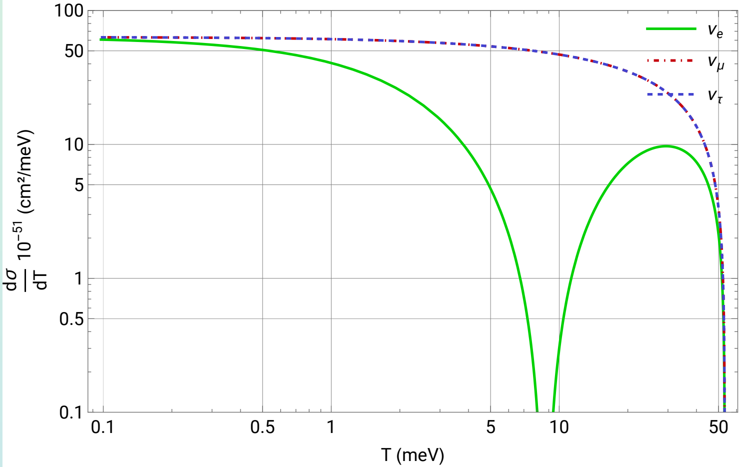


Fig. 2. SM CEνAS cross section on ^{4}He for three flavors.

A Wolfram Mathematica code was developed to perform the numerical computation of the differential cross section of neutrino scattering on the ^{4}He atom, taking into account vector non-standard interactions together with neutrino mixing and oscillation effects.

As a validation step, the cross section was evaluated for the three neutrino flavors on ^{4}He with all NSI parameters set to zero. The resulting curve reproduces the characteristic Standard Model behaviour: a dip appears in the spectrum, present only for the initial electron neutrino.

ν_e channel: diagonal NSI ε_{ee}

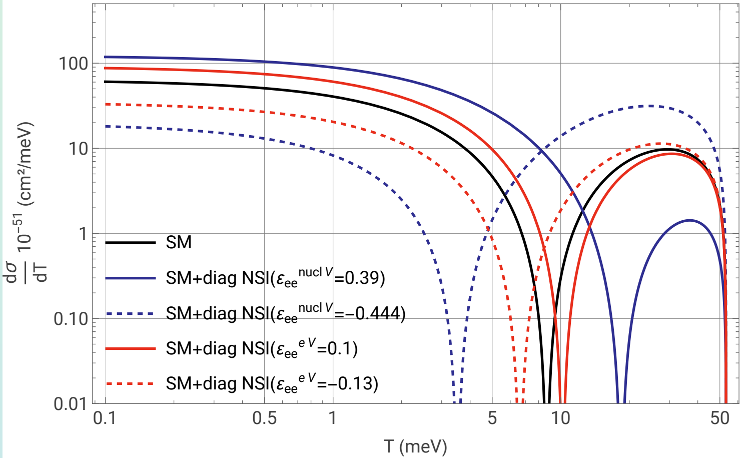


Fig. 3. Diagonal NSI: *Blue* nuclear $\varepsilon_{ee}^{\text{nucl},V}=[-0.444;+0.39]$; *Red* electronic $\varepsilon_{ee}^{e,V}=[-0.13;+0.1]$; vs. SM (black).

The diagonal NSI coupling ε_{ee} is now introduced for the electron neutrino, with values taken at the boundaries of its current global allowed range.

Being diagonal, ε_{ee} interferes linearly with the SM amplitude, so the cross section can be either enhanced or suppressed depending on the sign of the coupling.

ν_e channel: off-diagonal NSI $\varepsilon_{e\mu}$

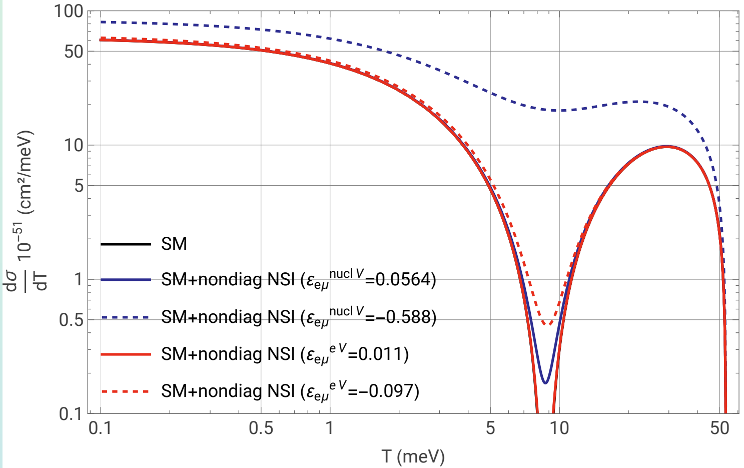


Fig. 4. Off-diagonal $\varepsilon_{e\mu}$: *Blue* nuclear $\varepsilon_{e\mu}^{\text{nucl},V} = [-0.588; +0.0564]$; *Red* electronic $\varepsilon_{e\mu}^{e,V} = [-0.097; +0.011]$ vs. SM (black).

Next, the off-diagonal coupling $\varepsilon_{e\mu}$ is considered, which represents a flavor-changing operator with no SM counterpart.

Off-diagonal couplings enter the cross section only quadratically, so they can only increase it relative to the SM.

ν_e channel: off-diagonal NSI $\varepsilon_{e\tau}$

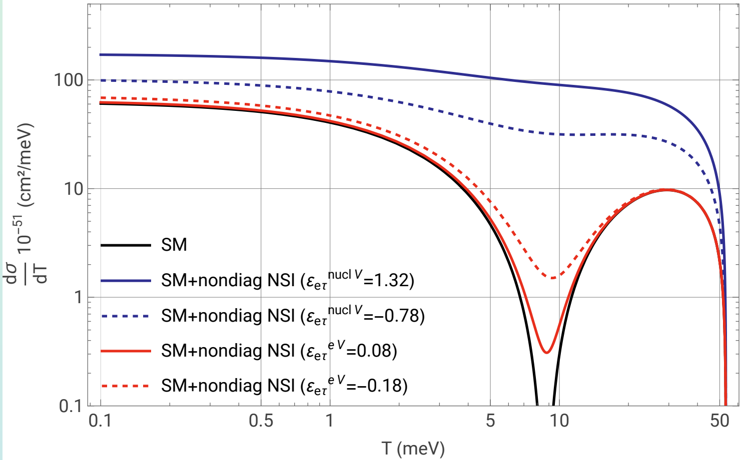


Fig. 5. Off-diagonal $\varepsilon_{e\tau}$ vs. SM (black). Blue: nuclear $\varepsilon_{e\tau}^{\text{nucl},V}=[-0.78;+1.32]$; red: electronic $\varepsilon_{e\tau}^{e,V}=[-0.18;+0.08]$.

Finally, the off-diagonal coupling $\varepsilon_{e\tau}$.

As a consequence, this channel produces the largest deviation from the SM among all ν_e channels considered. The nuclear coupling alone can enhance the cross section by a factor of several across the entire recoil-energy range.

Summary and outlook

- Compact analytical form of the CEνAS cross section on ^{4}He including vector NSI, with three-neutrino mixing and oscillations was obtained.
- The NSI contribution has been separated into nuclear and electronic parts. The characteristic CEνAS screening dip shifts once NSI are included, which provides a handle to constrain or measure the NSI parameters.
- *Ongoing and planned work:*
  - the SATURNE projected sensitivities to the vector NSI parameters are currently being computed;
  - the remaining NSI contributions are planned for investigation, with the axial-vector and scalar channels already being studied.

Thank you for your attention!

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Backup: SATURNE project

Differential event rate due to neutrinos as a function of ^{4}He recoil energy:

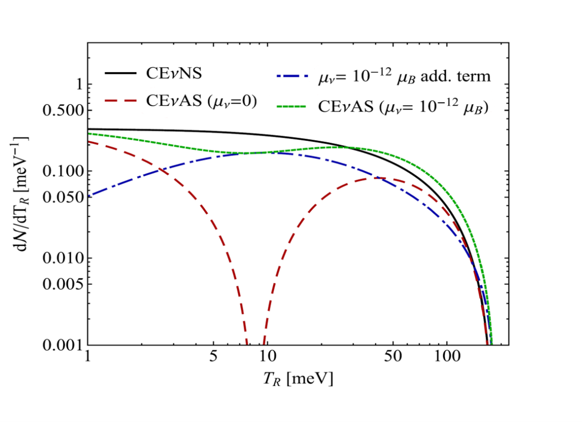

Fig. B1. Recoil-energy spectrum of ^{4}He atoms in the SATURNE project.

- M. Cadeddu et al., Phys. Rev. D **100** (2019) 073014.

Backup: Formfactors

Next analytical results was obtained:

$$\frac{d\sigma}{dT} = \frac{G_F^2 M_A}{2\pi}\left(2 - \frac{M_A T}{E_\nu^2}\right)\mathbb{C}_V, \tag{1}$$

where

$$\mathbb{C}_V = \sum_{j=1}^{3}\left|\sum_{i=1}^{3} U_{\alpha i}^{*} e^{-i\frac{m_i^2}{2E_\nu}L}\mathcal{F}_{At,ji}^{V}\right|^2, \quad \mathcal{F}_{At,ji}^{V} = \mathcal{F}_{Nucl,ji}^{V}(0) + \mathcal{F}_{el,ji}^{V}(\vec{q}), \tag{2}$$

and formfactors are:

$$\begin{gathered}\mathcal{F}_{Nucl,ji}^{V}(\vec{q}) = \frac{1}{(2\pi)^3}\int d^3r\, e^{i\vec{q}\vec{r}}\left\langle n, J, M_J'\right|\sum_{k=1}^{Z+N} f_{ji}^{n_{(k)}V}\delta^{(3)}(\vec{r}-\vec{r}_k)\left|n, J, M_J\right\rangle, \\ \mathcal{F}_{Nucl,ji}^{V}(0) = Z\cdot f_{ji}^{pV} + N\cdot f_{ji}^{nV}, \\ \mathcal{F}_{el,ji}^{V}(\vec{q}) = \frac{1}{(2\pi)^3}\int d^3r\, e^{i\vec{q}\vec{r}}\left\langle 1s\right|\sum_{k=1}^{Z}\left(f_{ji}^{eV} + U_{ej}U_{ei}^{*}\right)_k\delta^{(3)}(\vec{r}-\vec{r}_k)\left|1s\right\rangle,\end{gathered} \tag{3}$$

$$f_{ji}^{kV} = g_V^k\delta_{ji} + \varepsilon_{ji}^{kV}, k = \{e, p, n\} \tag{4}$$