Constraints on neutrino generalized interactions from COHERENT data

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Magnificent CEvNS Workshop

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Coherent Elastic Neutrino-Nucleus Scattering

Sensitivity to new physics

Summary
CE$_\nu$NS occurs when the neutrino energy $E_\nu$ is such that nucleon amplitudes sum up coherently $\Rightarrow$ cross section enhancement

$$\lambda \gtrsim R_N \Rightarrow q \lesssim 200 \text{ MeV}$$

$$E_R = q^2 / 2m_N \Rightarrow E_\nu \approx \sqrt{E_R^{\max} m_N / 2}$$

$$E_\nu \lesssim 100 \text{ MeV}$$

Freedman, 1974

$$\frac{d\sigma_\nu}{dE_R} = \frac{G_F^2}{4\pi} Q_{SM}^2 m_N \left( 1 - \frac{E_r m_N}{2E_\nu^2} \right) F^2(E_r)$$

Form factor

$$Q_{SM}^2 = [N - (1 - s_W^2)Z]^2 \approx N^2$$

Helm, 1956

![Graph showing the relationship between $E_r$ and $F^2(E_r)$ for Ge and Xe isotopes.](image)
Relevant neutrino sources

“Astrophysical” sources

Reactor Neutrinos

Fixed target

Solar+Atm: $\nu$ backgrounds DM detectors
Reactor: Basis for CONUS, $\nu$-CLEUS
Fixed target: COHERENT experiment
COHERENT

CEνNS observed by COHERENT more than 40 years after its prediction

COHERENT uses neutrinos produced in SNS
@ Oak Ridge National Laboratory in the collision $p - Hg$

\[
\pi^+ \rightarrow \mu^+ + \nu_\mu \\
\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu
\]

Presence of CEνNS favored @ the 6.7σ level. Data consistent with SM @ the 1σ

DAS, De Romeri, Rojas, 2018

\[ n_{PE} = 1.17 \left(\frac{E_R}{\text{keV}}\right) \]

There is still some room for NEW PHYSICS!
Sensitivity to new physics
The case of NSI

Non-standard interactions parametrized in a model-independent and phenomenological way

\[ \mathcal{L} \sim G_F \sum_{q=u,d} \bar{\nu}_i (1 - \gamma_5) \gamma_\mu \nu_j \bar{q} \left( \epsilon^{qV}_{i,j} - \epsilon^{qA}_{i,j} \gamma_5 \right) \gamma^\mu q \]

Wolfenstein, 1978

Phenomenological constraints from forward coherent scattering (matter potentials) DIS and COHERENT data

Scenarios

- For \( m_X^2 \ll q^2 \) contributions of NSI to DIS are suppressed, \( q_{\text{DIS}}^2 \gtrsim (10 \, \text{GeV})^2 \)

- Light mediator scenarios: \( M_X \subset [10, 10^3] \, \text{MeV} \Rightarrow \) DIS constraints evaded

- Heavy mediator scenarios: \( M_X \subset [1, 10^3] \, \text{GeV} \) all constraints apply

COHERENT constraints are particularly relevant for light mediators
COHERENT data has been used to constraint NSI contributions to the CEνNS

- Gonzalez-Garcia et al., 2017
- J. Liao & D. Marfatia, 2017
- Kosmas et al., 2018
- Billard et al., 2018
The NGI case

NSI are a subset of a larger set of neutrino-quark interactions: Neutrino Generalized Interactions (NGI)

\[
\mathcal{L} \sim G_F \sum_{q=u,d} (\bar{\nu} \Gamma_A \nu) \left[ \bar{q} \Gamma_A \left( C_A^q + i D_A^q \gamma_5 \right) q \right]
\]

\[
\Gamma_A = \{\emptyset, i \gamma_5, \gamma \mu, \gamma_5 \gamma \mu, \sigma \mu \nu\}
\]

Diagonal and non-diagonal LS

\[
\Gamma_P : \mathcal{L} \sim \bar{\nu} \gamma_5 \nu \bar{q} \left( \gamma_5 C_P^q + i D_P^q \right) q
\]

\[P\] and \[A\] quark currents are nuclear spin-dependent \(\Rightarrow Z_{\uparrow} - Z_{\downarrow}, N_{\uparrow} - N_{\downarrow}\)

\[
\mathcal{L}_S \sim (\bar{\nu} \nu) \left[ \bar{q} \left( C_S^q + i \gamma_5 D_S^q \right) q \right]
\]

\[
\mathcal{L}_P \sim (\bar{\nu} \gamma_5 \nu) \left[ \bar{q} \left( \gamma_5 C_P^q + i D_P^q \right) q \right]
\]

\[
\mathcal{L}_V \sim (\bar{\nu} \gamma^\mu \nu) \left[ \bar{q} \left( \gamma^\mu C_V^q + i \gamma_5 D_V^q \right) q \right]
\]

\[
\mathcal{L}_A \sim (\bar{\nu} \gamma^\mu \gamma_5 \nu) \left[ \bar{q} \left( \gamma_5 \gamma^\mu C_A^q + i \gamma_5 D_A^q \right) q \right]
\]

\[
\mathcal{L}_T \sim (\bar{\nu} \sigma^{\mu \nu} \nu) \left[ \bar{q} \left( \sigma^{\mu \nu} C_T^q + i \sigma^{\mu \nu} \gamma_5 D_T^q \right) q \right]
\]

\[\mathcal{P}_1 = \{C_S^q, D_S^q, C_P^q, D_P^q, C_V^q \} \checkmark\]

\[\mathcal{P}_2 = \{C_P^q, D_S^q, C_A^q, D_V^q, D_T^q \} \times\]

Constraints on \[\mathcal{P}_2\] are weak!
Constraints from oscillations

Constraints from forward coherent scattering are only relevant for vector interactions

Matter potentials

\[ \mathcal{L}_{\text{int}} \sim \sum_{a,f} (\bar{\nu} \Gamma^a \nu) \left( V_a \right) \]

\[ V_{S,P} \sim G_F n_f g_{S,P} \left( \frac{m_f}{E_f} \right) \]

\[ V_V \sim G_F n_f + \cdots \]

\[ V_{A,T} \sim G_F n_f g_{A,T} \left( \frac{\sigma_f p_f}{E_f} \right) + \cdots \]

Scalar & Pseudoscalar: Helicity suppressed
Axial & Tensor: Relevant only in polarized media

Only vector NGI are constrained by forward coherent scattering
### Cross section parameterized in terms of nuclear currents: **Scalar, Vector and Tensor**

\[
\frac{d\sigma^a(q^2=0)}{dE_r} = \frac{G_F^2}{4\pi} m_N a N^2 \left[ \xi_S^2 \frac{E_r}{E_r^{\max}} + \xi_V^2 \left( 1 - \frac{E_r}{E_r^{\max}} - \frac{E_r}{E_v} \right) + \xi_T^2 \left( 1 - \frac{E_r}{2E_r^{\max}} - \frac{E_r}{E_v} \right) - R \frac{E_r}{E_v} \right]
\]

**Scenarios**

- **Single parameter case**: Only one nuclear current present at a time
- **Two parameter case**: Two nuclear currents are simultaneously present

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*Linndner, Rodejohann, Xu, 2016*

*DAS, De Romeri, Rojas, 2018*
One-parameter analysis

<table>
<thead>
<tr>
<th>Param</th>
<th>BFP value</th>
<th>90% CL</th>
<th>99% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\xi_S$</td>
<td>0</td>
<td>$[-0.62, 0.62]$</td>
<td>$[-1.065, 1.065]$</td>
</tr>
<tr>
<td>$\xi_V$</td>
<td>$-0.113$</td>
<td>$[-0.324, 0.224]$</td>
<td>$[-0.436, 0.67]$</td>
</tr>
<tr>
<td>$\xi_T$</td>
<td>0</td>
<td>$[-2.102, -1.554]$</td>
<td>$[-2.545, -1.442]$</td>
</tr>
</tbody>
</table>

\[
\xi^2_S = \frac{C^2_S + D^2_P}{N^2}
\]

\[
C_S = Z \sum_q u, d \ C_S^{(q)} \frac{m_p}{m_q} f_T^p + (A - Z) \sum_q u, d \ C_S^{(q)} \frac{m_n}{m_q} f_T^n
\]
The presence of NGI can indeed improve the data fit... In particular for the vector NGI

If such trend persist with further data... Is there BSM physics hidden in CEνNS [??]
Summary
Résumé

- COHERENT data and forthcoming data from CONUS and e.g. $\nu$-CLEUS will allow unraveling the presence of new physics

- Good understanding of the SM contribution including the axial piece, nuclear physics form factors...

- NGI are the most general set of effective interactions. Using current data we have derived constraints: **NGI can still be fairly large**

- If new interactions are present in the neutrino sector, forthcoming data might allow their discovery