CEvNS: Theory overview

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CEνNS occurs when the neutrino energy $E_\nu$ is such that nucleon amplitudes sum up coherently ⇒ cross section enhancement

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

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

$$E_\nu \lesssim 200 \text{ MeV}$$

Freedman, 1974

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

Form factor

$$Q_{SM}^2 = [N - (1 - s_{W}^2) Z]^2 \simeq N^2$$
Neutrino sources and CEvNS “regimes”

“Laboratory” sources: Reactor neutrinos, SNS neutrinos, LBNF (NuMI)

“Astrophysical” sources: Solar, DSNB, Atmospheric, SN burst

Entering the “high-energy” window requires a substantial amount of $\nu$'s in the low-energy tail

LBNF provides that!
CEvNS environments

Reactor neutrinos (CONUS, CONNIE...)

Fixed target neutrinos (COHERENT)

Solar+DSNB+Atm (DM detectors)
LBNF neutrino beamline low-energy tail

\( \nu_\mu \) fluxes at \( L_{\text{LBNF}} = 574 \) m

- On-axis
- Off-axis 9 m
- Off-axis 33 m

\[ \frac{d\phi_{\nu}}{dE} \left[ \text{10}^{-3} \text{GeV}^{-1} \text{cm}^{-2} \text{POT}^{-1} \right] \]

- Full spectrum \( \Rightarrow n_\nu \approx 10^{14} \text{/year/cm}^2 \)
- Available e.g for \( \nu - e \) scattering

Neutrino flux low-energy tail

- On-axis
- Off-axis 9 m
- Off-axis 33 m

\[ \frac{d\phi_{\nu}}{dE} \left[ \text{10}^{-3} \text{GeV}^{-1} \text{cm}^{-2} \text{POT}^{-1} \right] \]

- Low-energy tail: \( n_\nu \approx 10^{12} \text{/year/cm}^2 \)
- \( \sigma_{\text{CEvNS}} \sim N^2 \)
- Sizable number of events!
Physics opportunities

**Standard Physics**

- Determination of the root-mean-square radius of neutron distributions
  - Neutron skin ⇒ Neutron Stars EoS  
  - Improve understanding of EW parameters ⇒ Precise determination of the weak mixing angle at $\mu \simeq 1 \text{ MeV}$

**Non-standard physics**

- New dof ⇒ Light fermions (sterile $\nu$'s)
- New forces (for some reason) escaping observation at high intensity and/or high energy experiments

## Incomplete list!

- Giunti et al. 1710.02730, 2102.06153
- Miranda et al. 1806.01310, 2003.12050
- Aristizabal et al. 1902.07398
- Marfatia & Liao/Dutta, Liao & Strigari/Shoemaker
- Kosmas, Papoulias/Aristizabal, De Romeri & Rojas
- Valle et al., Giunti et al., Lindner et al...
Strategy

Select interactions: V+S (light+Eff)

Environment

SNS, DM direct detection detectors, reactors, LBNF

Diego Aristizabal, USM, August 23, 2021
What to expect

Each scenario comes along with distinctive features
signal degeneracies are expected!

COHERENT

Effective limit
Global enhancements

Light limit
Spectral distortions
NMM in multi-ton DM detectors
Neutrino EM current

\[
\langle \nu_i | j_\mu | \nu_j \rangle = f_Q(q^2)_{ij} \gamma_\mu + f_A(q^2)_{ij} (q^2 \gamma_\mu - q_\mu \not{\gamma}) + i \sigma_{\mu\nu} q^\nu [f_M(q^2)_{ij} - i f_E(q^2)_{ij} \gamma_5]
\]

\(\Rightarrow\) Diagonal EM FFs \((q^2 \to 0)\):
\[
\begin{align*}
    f_Q & \to Q_v \\
    f_M & \to \mu_v \\
    f_A & \to a_v \\
    f_E & \to e_v
\end{align*}
\]

\(\Rightarrow\) Diagonal EM FFs:
\[
\begin{align*}
    f_E(q^2)_{ii} & = 0 \text{ (CP conserved)} \\
    f_A(q^2)_{ii} & \neq 0
\end{align*}
\]

\(\Rightarrow\) Off-diagonal EM FFs:
\[
\text{Non-zero for } \nu_D \text{ and } \nu_M \Rightarrow \text{Transitions}
\]

Parametrization and model-independent results derived by Kayser PRD 26, 1982 (1662) and Nieves PRD, 26, 1982 (3152)
These couplings contribute to a variety of processes

The most widely considered: $\mu_\nu$

**Astrophysical bounds**


Spin-flip scattering in SN

$\nu$’s are trapped by EW int

$\mu_\nu \lesssim 3 \times 10^{-12} \mu_B$

Arceo et. al, arXiv:1910.10568

Globular cluster stars

$\omega^2 + |\vec{k}|^2 \geq 0$

$\mu_\nu \lesssim 2.2 \times 10^{-12} \mu_B$

My view/understanding:

These bounds should be understood as order of magnitude estimations
Laboratory limits

More robust than astrophysical bounds. Follow from $\nu - e$ scattering using solar and reactor neutrino fluxes.

90% CL laboratory limits

- Borexino
- TEXONO
- GEMMA
- KamLAND

$\mu_\nu/\mu_B$
Nuclear recoils

Sensitivities in multi-ton DM detectors

D.A, Branada, Miranda, Sanchez, JHEP 12 (2020) 178

Best sensitivities found for

\[ E_r = 0.3 \text{ keV and Bckg-2 hypothesis} \]

Worse sensitivities found for

\[ E_r = 1 \text{ keV and Bckg-1 hypothesis} \]
Sensitivities enter the region not constrained by astrophysical arguments... Region where some TeV-related new physics predicts $\mu_v \neq 0$
CPV at COHERENT
**Remarks**

- Axial quark current neglected ⇒ Leads to (spin) suppressed effects

\[ \mathcal{L} = \bar{\nu} \gamma_{\mu} (f_V + i f_A \gamma_5) \nu V^\mu + \sum_{q=u,d} \bar{q} \gamma_{\mu} h^q_V q V^\mu \]

The 9-parameter problem reduces to 3 parameters

\[ \mathcal{P} = \{ m_V, |H_V|, \phi \} \]
Dips CPV effects in $^{23}\text{Na}$

Departures from a dip in $N_{\text{counts}}$

“measure” the amount of CP violation

The structure of the dip gives info on CPV!

Run a pseudoexperiment with a dip and see what are the limits on $\phi$

Observation of a dip in the spectrum will not rule out CPV interactions

... But will set tight bounds
CEvNS with the $\nu$BDX-DRIFT detector
BDX-DRIFT: Sketch


- Directional low pressure TPC detector
- Operates with CS$_2$ (other gases possible CF$_4$, C$_8$H$_{20}$Pb...)

 NRs mainly in sulfur induce ionization
- CS$_2$ ions used to transport the ionization to the readout planes (MWPCs)
Signals in $\text{CS}_2$ and $\text{CF}_4$

**Carbon disulfide**

- Signal peaks at 400 Torr
- Expected signal: 370 events

**Carbon tetrafluoride**

- 100% filled with $\text{CF}_4$
- Expected signal: 880 events
Neutron density distributions

High-energy nature of the flux
⇒ Moderate dependence on the FF
⇒ Accounted for in signal uncertainty ~ 10%

Approximation: $r_{\text{rms}}^n|_C = r_{\text{rms}}^n|_F$
C and F determined with a 3% accuracy
Neutrino NSI

\[ \mathcal{L}_{\text{NSI}} \sim G_F \bar{\nu}_a \gamma_\mu (1 - \gamma_5) \nu_b q \gamma^\mu \epsilon_{ab}^q q \]

Initial state flavor, \( \nu_\mu \): Only \( \epsilon_{\mu b} \) parameters are testable

Region I: Deviations are small, \( \epsilon_{\mu \mu}^a \rightarrow 0 \)
Region II: NSI exceeds SM by \( \sim 2 \)  
⇒ Destructive interference

\[
\begin{array}{|c|c|}
\hline
\text{\( \nu \text{BDX-DRIFT} \text{ CS}_2 \) (7-years)} & \text{COHERENT CsI (1-year)} \\
\hline
\epsilon_{\mu \mu}^a & [-0.013, 0.011] \oplus [0.30, 0.32] \quad \epsilon_{\mu \mu}^a & [-0.06, 0.03] \oplus [0.37, 0.44] \\
\hline
\epsilon_{e \mu}^a & [-0.064, 0.064] \quad \epsilon_{e \mu}^a & [-0.13, 0.13] \\
\hline
\end{array}
\]
Final remarks
Conclusions

CEvNS offers a rich neutrino program, complementarity with CEvNS related agendas: v-cleus, CONUS, CONNIE, DM detectors, COHERENT (SNS), vBDX-DRIFT...

SM measurements include: Weak mixing angle at different low-energy scales neutron density distributions for Na, Ge, C, F, S, Pb

BSM searches include: Neutrino NSI, NGI and light vector and scalar mediators, NMM

vBDX-DRIFT combined with a high-energy neutrino beam (e.g. LBNF) is suitable for CEvNS measurements in

CS₂, CF₄, C₈H₂₀Pb...

Directionality improves background rejection

CEvNS is a powerful tool for SM measurements and BSM searches

Upcoming experiments provide a great deal of physics opportunities