Coherent elastic neutrino-nucleus scattering at reactors and spallation sources: present constraints and future sensitivities

XXIst RENCONTRES DU VIETNAM

Gặp gỡ Việt Nam lần thứ 21

NEUTRINO PHYSICS VẬT LÝ NEUTRINOS

Anirban Majumdar

(In collaboration with A. Chattaraj, D. K. Papoulias and R. Srivastava)

PLB 864 (2025) 139438, JHEP 05 (2025) 064

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Overview of CEνNS

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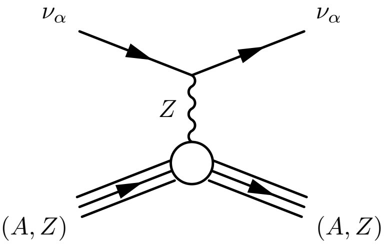
Freedman, 1974; Drukier and Stodolsky, 1984

$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}T_{\mathcal{N}}}\right]_{\mathrm{SM}} = \frac{G_F^2 m_{\mathcal{N}}}{\pi}\left[\mathcal{F}_W^2(\mathfrak{q}^2)\,(Q_W^V)^2\left(1-\frac{m_{\mathcal{N}}T_{\mathcal{N}}}{2E_\nu^2}-\frac{T_{\mathcal{N}}}{E_\nu}\right)\right.$$
$$\left.+\,\mathcal{F}_A(\mathfrak{q}^2)\left(1+\frac{m_{\mathcal{N}}T_{\mathcal{N}}}{2E_\nu^2}-\frac{T_{\mathcal{N}}}{E_\nu}\right)\right]$$



- Coherence condition: $\mathfrak{q} << \frac{1}{R}$
- CEνNS has the largest cross section among all electroweak processes involving neutrinos.
- Within SM at tree level it is a flavour blind neutral current process.
- Cross section enhanced for large N nuclei due to N^2 dependency.

- Extremely tiny nuclear recoil, hence difficult to detect
- Needs efficient cryogenic cooling system and background reduction strategy.

Overview of CEνNS

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PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany
(Received 21 November 1983)

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true "neutrino observatory." The recoil energy which must be detected is very small ($10-10^3$ eV), however. We examine a realization in terms of the superconducting-grain idea, which appears, in principle, to be feasible through extension and extrapolation of currently known techniques. Such a detector could permit determination of the neutrino energy spectrum and should be insensitive to neutrino oscillations since it detects all neutrino types. Various applications and tests are discussed, including spallation sources, reactors, supernovas, and solar and terrestrial neutrinos. A preliminary estimate of the most difficult backgrounds is attempted.

Small detectors

CEvNS is strong

CEvNS is tiny

experimental ideas

CEvNS is clean

Backgrounds (!)

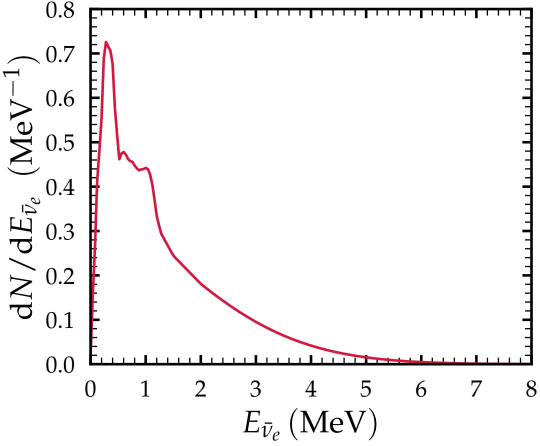
[Freedman, PRD 9 (1974) 1389]

Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering. We will discuss these problems at the end of this note, but first we wish to present the theoretical ideas relevant to the experiments.

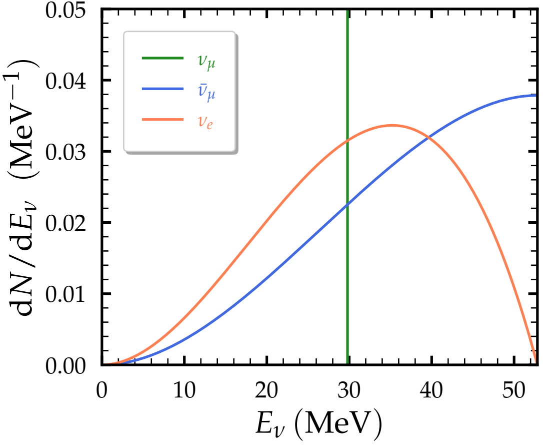
Experimentally the most conspicuous and most difficult feature of our process is that the only detectable reaction product is a recoil nucleus of low momentum. Ideally the apparatus should have sufficient resolution to identify and determine the momentum of the recoil nucleus and sufficient mass to achieve a reasonable interaction rate. Neutron background is a serious problem because elastic $n+A$ cross sections are generally large.

Reactor vs stopped-π ν sources

Reactors



π-DAR



Reactor vs stopped-π ν sources

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Reactors

Pros

- ✓ Low-energy neutrinos ensures small momentum transfer, offering access to near-complete coherence — ideal for CEνNS studies.
- ✓ Multiple reactor sources available globally.

Cons

- × Reactor environments have large backgrounds and detection requires extremely low recoil thresholds.
- × Systematic uncertainty on the reactor neutrino flux is large.
- × Reactor neutrino flux is purely $\bar{\nu}_e$, limiting sensitivity to flavor-dependent new physics parameters.

π-DAR

Pros

- ✓ Higher neutrino energies enable probing of nuclear structure.
- ✓ Powerful background rejection is achievable.
- ✓ Multiple neutrino flavors (ν_e, ν_μ, $\bar{\nu}_\mu$) allow probing of flavor-dependent new physics scenarios.

Cons

- × Limited number of facilities worldwide capable of producing stopped-pion neutrinos.
- × Higher neutrino energies reduce coherence, limiting CEνNS signal strength.

Experiments probing CEνNS

[Science 357 (2017) 6356, 1123-1126]

NEUTRINO PHYSICS

Observation of coherent elastic neutrino-nucleus scattering

D. Akimov,[1,2] J. B. Albert,[3] P. An,[4] C. Awe,[4,5] P. S. Barbeau,[4,5] B. Becker,[6] V. Belov,[1,2] A. Brown,[4,7] A. Bolozdynya,[2] B. Cabrera-Palmer,[8] M. Cervantes,[5] J. I. Collar,[9*] R. J. Cooper,[10] R. L. Cooper,[11,12] C. Cuesta,[13†] D. J. Dean,[14] J. A. Detwiler,[13] A. Eberhardt,[13] Y. Efremenko,[6,14] S. R. Elliott,[12] E. M. Erkela,[13] L. Fabris,[14] M. Febbraro,[14] N. E. Fields,[9‡] W. Fox,[3] Z. Fu,[13] A. Galindo-Uribarri,[14] M. P. Green,[4,14,15] M. Hai,[9§] M. R. Heath,[3] S. Hedges,[4,5] D. Hornback,[14] T. W. Hossbach,[16] E. B. Iverson,[14] L. J. Kaufman,[3||] S. Ki,[4,5] S. R. Klein,[10] A. Khromov,[2] A. Konovalov,[1,2,17] M. Kremer,[4] A. Kumpan,[2] C. Leadbetter,[4] L. Li,[4,5] W. Lu,[14] K. Mann,[4,15] D. M. Markoff,[4,7] K. Miller,[4,5] H. Moreno,[11] P. E. Mueller,[14] J. Newby,[14] J. L. Orrell,[16] C. T. Overman,[16] D. S. Parno,[13¶] S. Penttila,[14] G. Perumpilly,[9] H. Ray,[18] J. Raybern,[5] D. Reyna,[8] G. C. Rich,[4,14,19] D. Rimal,[18] D. Rudik,[1,2] K. Scholberg,[5] B. J. Scholz,[9] G. Sinev,[5] W. M. Snow,[3] V. Sosnovtsev,[2] A. Shakirov,[2] S. Suchyta,[10] B. Suh,[4,5,14] R. Tayloe,[3] R. T. Thornton,[3] I. Tolstukhin,[3] J. Vanderwerp,[3] R. L. Varner,[14] C. J. Virtue,[20] Z. Wan,[4] J. Yoo,[21] C.-H. Yu,[14] A. Zawada,[4] J. Zettlemoyer,[3] A. M. Zderic,[13] COHERENT Collaboration#

The coherent elastic scattering of neutrinos off nuclei has eluded detection for four decades, even though its predicted cross section is by far the largest of all low-energy neutrino couplings. This mode of interaction offers new opportunities to study neutrino properties and leads to a miniaturization of detector size, with potential technological applications. We observed this process at a 6.7σ confidence level, using a low-background, 14.6-kilogram CsI[Na] scintillator exposed to the neutrino emissions from the Spallation Neutron Source at Oak Ridge National Laboratory. Characteristic signatures in energy and time, predicted by the standard model for this process, were observed in high signal-to-background conditions. Improved constraints on nonstandard neutrino interactions with quarks are derived from this initial data set.

PHYSICAL REVIEW LETTERS **126,** 012002 (2021)

First Measurement of Coherent Elastic Neutrino-Nucleus Scattering on Argon

D. Akimov,[1,2] J. B. Albert,[3] P. An,[4,5] C. Awe,[4,5] P. S. Barbeau,[4,5] B. Becker,[6] V. Belov,[1,2] I. Bernardi,[6] M. A. Blackston,[7] L. Blokland,[6] A. Bolozdynya,[2] B. Cabrera-Palmer,[8] N. Chen,[9] D. Chernyak,[10] E. Conley,[4] R. L. Cooper,[11,12] J. Daughhetee,[6] M. del Valle Coello,[3] J. A. Detwiler,[9] M. R. Durand,[9] Y. Efremenko,[6,7] S. R. Elliott,[12] L. Fabris,[7] M. Febbraro,[7] W. Fox,[3] A. Galindo-Uribarri,[6,7] A. Gallo Rosso,[13] M. P. Green,[5,7,14] K. S. Hansen,[9] M. R. Heath,[7] S. Hedges,[4,5] M. Hughes,[3] T. Johnson,[4,5] M. Kaemingk,[11] L. J. Kaufman,[3,†] A. Khromov,[2] A. Konovalov,[1,2] E. Kozlova,[1,2] A. Kumpan,[2] L. Li,[4,5] J. T. Librande,[9] J. M. Link,[15] J. Liu,[10] K. Mann,[5,7] D. M. Markoff,[5,16] O. McGoldrick,[9] H. Moreno,[11] P. E. Mueller,[7] J. Newby,[7] D. S. Parno,[17] S. Penttila,[7] D. Pershey,[4] D. Radford,[7] R. Rapp,[17] H. Ray,[18] J. Raybern,[4] O. Razuvaeva,[1,2] D. Reyna,[8] G. C. Rich,[19] D. Rudik,[1,2] J. Runge,[4,5] D. J. Salvat,[3] K. Scholberg,[4] A. Shakirov,[2] G. Simakov,[1,2,20] G. Sinev,[4] W. M. Snow,[3] V. Sosnovtsev,[2] B. Suh,[3] R. Tayloe,[3,*] K. Tellez-Giron-Flores,[15] R. T. Thornton,[3,12] I. Tolstukhin,[3,‡] J. Vanderwerp,[3] R. L. Varner,[7] C. J. Virtue,[13] G. Visser,[3] C. Wiseman,[9] T. Wongjirad,[21] J. Yang,[21] Y.-R. Yen,[17] J. Yoo,[22,23] C.-H. Yu,[7] and J. Zettlemoyer[3]

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We report the first measurement of coherent elastic neutrino-nucleus scattering (CEvNS) on argon using a liquid argon detector at the Oak Ridge National Laboratory Spallation Neutron Source. Two independent analyses prefer CEvNS over the background-only null hypothesis with greater than 3σ significance. The measured cross section, averaged over the incident neutrino flux, is $(2.2 \pm 0.7) \times 10^{-39}$ cm^2—consistent with the standard model prediction. The neutron-number dependence of this result, together with that from our previous measurement on CsI, confirms the existence of the CEvNS process and provides improved constraints on nonstandard neutrino interactions.

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[arXiv:2406.13806]

First detection of coherent elastic neutrino-nucleus scattering on germanium

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(Dated: June 21, 2024)

We report the first detection of coherent elastic neutrino-nucleus scattering (CEvNS) on germanium, measured at the Spallation Neutron Source at Oak Ridge National Laboratory. The Ge-Mini detector of the COHERENT collaboration employs large-mass, low-noise, high-purity germanium spectrometers, enabling excellent energy resolution, and an analysis threshold of 1.5 keV electron-equivalent ionization energy. We observe a on-beam excess of $20.6^{-6.3}_{+7.1}$ counts with a total exposure of 10.22 GWhkg and we reject the no-CEvNS hypothesis with 3.9 σ significance. The result agrees

Experiments probing CEνNS

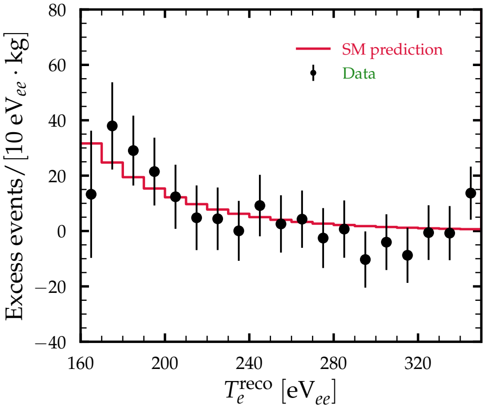
CONUS+ experiment

- **Location:** 20.7 m from the 3.9 GW_{th} reactor core at Leibstadt Nuclear Power Plant (KKL), Switzerland.
- **Neutrino Flux:** $\sim 1.5 \times 10^{13}\ \bar{\nu}_e/\text{cm}^2/\text{s}$.
- **Detector:** High-purity germanium (HPGe) arrays (C2, C3, C5) with ultra-low thresholds.

- **CEνNS Observation:** 3.7σ detection significance (327 kg·days exposure).
- **Thresholds:** Achieved recoil thresholds as low as:

  C3: 160 eV_{ee}, C5: 170 eV_{ee}, C2: 180 eV_{ee}
- **Quenching Model:** Data consistent with Lindhard theory ($k = 0.162$).

  $\Rightarrow$ Excludes deviations seen in earlier Dresden-II data [Colaresi et al., 2022].
- **Signal Modelling:** Includes both CEνNS and EνES contributions, as the latter enhances sensitivity to certain BSM scenarios.



GanESS program

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ESS (European Spallation Source) is a next-generation neutron spallation source research facility currently under development in Lund, Sweden, focused on producing the world's most intense neutron beams.

ESS CEvNS Highlights

- **Cutting-edge Neutrino Flux:** ESS will generate a large, pulsed neutrino flux, enabling high-statistics CEνNS measurements.
- **Record Proton Beam Power:** With a 5 MW proton beam, ESS will achieve up to 2.8×10^{23} protons-on-target annually, resulting in a neutrino flux of $9.3 \times 10^{7}/\mathrm{cm}^2/\mathrm{s}$–an improvement of almost an order of magnitude over the existing SNS facility.
- **Advanced Detector Technologies:** Six innovative detector types (CsI, Xe, Ge, Si, Ar, $\mathrm{C_3F_8}$) to achieve precise CEνNS measurements.

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Detector Technology	Detector	$m_{\rm det}$ (kg)	$T_{\mathcal{N}}^{\rm th}$ (keV$_{nr}$)	$T_{\mathcal{N}}^{\rm max}$ (keV$_{nr}$)	σ_0 (keV$_{nr}$)	Steady-state background
Cryogenic scintillator	CsI	22.5	1	46.1	0.3	10 counts/keV$_{nr}$/kg/day
High-pressure gaseous TPC	Xe	20	0.9	45.6	0.36	10 counts/keV$_{nr}$/kg/day
p-type point contact HPGe	Ge	7	0.6	78.9	0.09	3 counts/keV$_{nr}$/kg/day
CCD	Si	1	0.16	212.9	0.096	0.04375 counts/keV$_{nr}$/kg/day
Scintillating bubble chamber	Ar	10	0.1	150	0.04	0.1 counts/kg/day
Standard bubble chamber	C_3F_8	10	2	329.6	0.8	0.1 counts/kg/day

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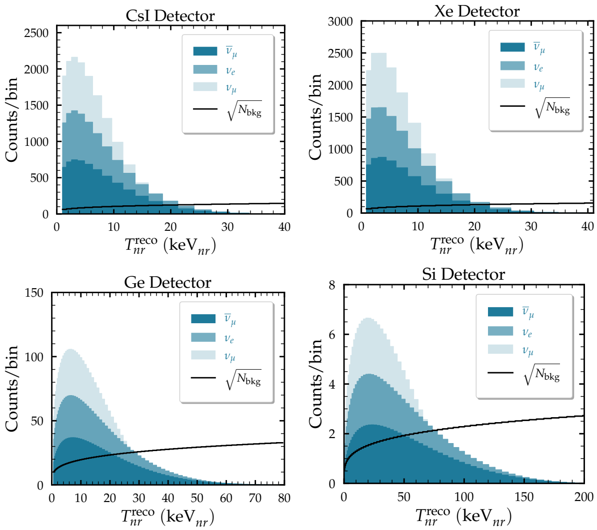


Phenomenological implications

Weak Mixing Angle

The CEνNS interaction rate is proportional to $Q_W^V = \left(\frac{1}{2} - 2\sin^2\theta_W\right) Z - \frac{1}{2}N$.

CONUS+:

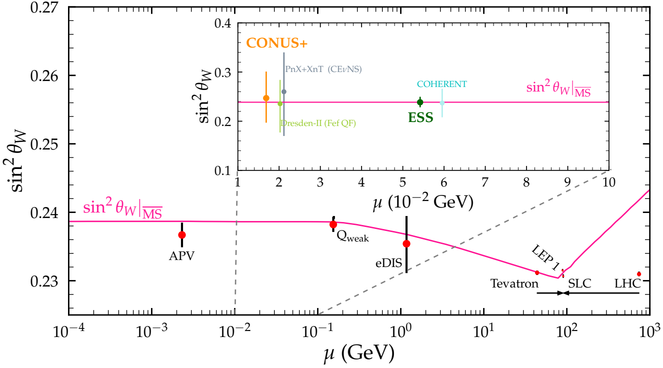
$\sin^2\theta_W = 0.247^{+0.050}_{-0.054}$

[PLB 864 (2025) 139438]

ESS (projected):

$\sin^2\theta_W = 0.239^{+0.011}_{-0.010}$

[JHEP 05 (2025) 064]



Nuclear Neutron RMS Radius

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The CEνNS interaction rate is proportional to:

$$\mathcal{F}_W(\mathfrak{q}^2)Q_W^V = \left(\frac{1}{2} - 2\sin^2\theta_w\right) Z\mathcal{F}_p(\mathfrak{q}^2) - \frac{1}{2}N\mathcal{F}_n(\mathfrak{q}^2)$$

ESS projected limits (at 1σ)

Detector	CsI	Xe	Ge	Si	Ar	C_3F_8
R_n (fm)	[4.79, 5.28]	[4.78, 5.27]	[3.65, 4.80]	[2.08, 4.25]	[2.47, 4.36]	[1.64, 3.88]

[JHEP 05 (2025) 064]

Nuclear Neutron RMS Radius

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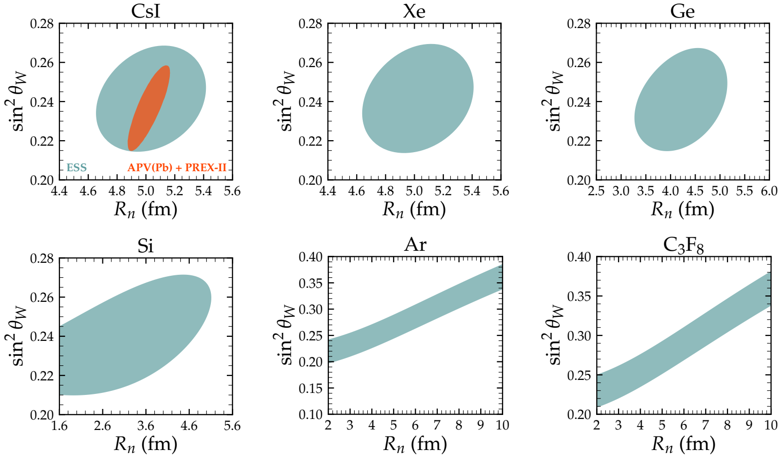
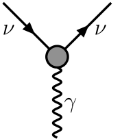


[JHEP 05 (2025) 064; M. Atzori Corona et al., 2024]

ν EM Properties

Parametrization and model-independent results derived by **[*Kayser PRD 26,1982 (1662) and Neves PRD 26, 1982 (3152)*]**



$$\mathscr{L}_{\nu}^{\mathrm{EM}} = (\bar{\nu}_{\ell}\Gamma^{\mu}\nu_{\ell'})\, A_{\mu}$$

$$\Gamma^{\mu} \equiv F_Q(\mathfrak{q}^2)_{\ell\ell'}\gamma^{\mu} + F_A(\mathfrak{q}^2)_{\ell\ell'}\left[\mathfrak{q}^2\gamma^{\mu} - \mathfrak{q}^{\mu}\not{\mathfrak{q}}\right]\gamma^5 + i\sigma^{\mu\nu}\mathfrak{q}_{\nu}\left[F_M(\mathfrak{q}^2)_{\ell\ell'} - iF_E(\mathfrak{q}^2)_{\ell\ell'}\gamma^5\right]$$

ν EM Properties

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- At $\mathfrak{q}^2 \to 0$, $\quad F_Q \to Q_\nu, \quad F_A \to a, \quad F_M \to \mu, \quad F_E \to \epsilon$
- Nuclear recoil experiments cannot differentiate between magnetic/electric moments or transition. So at effective level we define the effective parameter: $\left(\mu_\nu^{\mathrm{eff}}\right)^2 \propto |\mu - i\epsilon|^2$. The helicity-flipping neutrino magnetic moment contribution to the CEνNS cross sections adds incoherently to the SM contribution and is given by

$$\left[\frac{\mathrm{d}\sigma_{\nu_\ell}}{\mathrm{d}T_{\mathcal{N}}}\right]^{\mathrm{CE}\nu\mathrm{NS}}_{\mathrm{mag}} = \frac{\pi\alpha^2_{\mathrm{EM}}}{m_e^2}\left[\frac{1}{T_{\mathcal{N}}} - \frac{1}{E_\nu}\right] Z^2 \mathcal{F}_W^2(\mathfrak{q}^2)\left(\frac{\mu^{\mathrm{eff}}_{\nu_\ell}}{\mu_B}\right)^2 ,$$

- Helicity-preserving EM contributions from the millicharge ($Q_{\nu_{\ell\ell'}}$) and neutrino CR ($\langle r^2_{\nu_{\ell\ell'}}\rangle$) can be expressed through the following differential cross sections

$$\left[\frac{\mathrm{d}\sigma_{\nu_\ell}}{\mathrm{d}T_{\mathcal{N}}}\right]^{\mathrm{CE}\nu\mathrm{NS}}_{\mathrm{SM+EM}} = \frac{G_F^2 m_{\mathcal{N}}}{\pi}\left(1 - \frac{m_{\mathcal{N}} T_{\mathcal{N}}}{2E_\nu^2}\right)\mathcal{F}_W^2(\mathfrak{q}^2)\left\{\left[\left(\frac{1}{2} - 2\sin^2\theta_W - Q_{\ell\ell}\right) Z - \frac{N}{2}\right]^2 + Z^2 \sum_{\ell' \neq \ell} |Q_{\ell\ell'}|^2\right\} ,$$

with $Q_{\ell\ell'} = \sqrt{2}\pi\alpha_{\mathrm{EM}}/G_F\left(\langle r^2_{\nu_{\ell\ell'}}\rangle/3 - 2/\mathfrak{q}^2 \cdot (Q_{\nu_{\ell\ell'}}/e)\right)$

ν EM Properties

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Magnetic Moment $\lvert\mu_{\nu_e}\rvert$ $[10^{-11}\mu_B]$	**Millicharge** Q_{ν_e} $[10^{-12}e]$	**Charge Radius** $\langle r^2_{\nu_e}\rangle$ $[10^{-32}\ \mathrm{cm}^2]$
$\leq$ **11.2 (CONUS+)**	**[−1.8, 1.9] (CONUS+)**	**[−59.76, 8.33] (CONUS+)**
$\leq$ 420 (COHERENT)	[−500, 500] (COHERENT)	[−69, 14] (COHERENT)
$\leq$ 20.8 (Dresden-II)	[−8.6, 8.7] (Dresden-II)	[−57, 4] (Dresden-II)
$\leq$ 3.9 (Borexino)		
$\leq$ 7.4 (TEXONO)		[−4.2, 6.6] (TEXONO)
$\leq$ 0.9 (XENONnT)	[−0.1, 0.6] (XENONnT)	[−93.4, 9.5] (XENONnT)
$\leq$ 1.4 (LZ)	[−0.3, 0.6] (LZ)	[−121, 37.5] (LZ)

[PLB 864 (2025) 139438]

Neutrino generalized interactions

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NSI: Phenomenology of NSIs is discussed with a model independent parametrization.

Wolfenstein, 1978

$$\mathscr{L}_{\text{eff}}^{\text{NSI}} = -2\sqrt{2}\, G_F\, \varepsilon_{\alpha\beta}^{qC} \left(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right) \left(\bar{q}\gamma_\mu P_C q\right)$$

NGI: The conventional NSIs can be extended by incorporating all possible Lorentz-invariant interactions up to dimension 6 between neutrinos and other SM fermions—i.e., scalar, pseudoscalar, vector, axial vector, and tensor.

$$\boxed{\mathscr{L}_{\text{NGI}}^{\nu f} \supset -\sum_{\substack{X=S,P,V,A,T\\ f=e,\mathcal{N}}} \frac{C_X}{q^2 + M_X^2} \left[\bar{\nu}\Gamma^X \nu\right] \left[\bar{f}\Gamma_X f\right] \qquad \Gamma_X = \{\mathbb{I}, \gamma_5, \gamma_\mu, \gamma_\mu\gamma_5, \sigma_{\mu\nu}\}}$$

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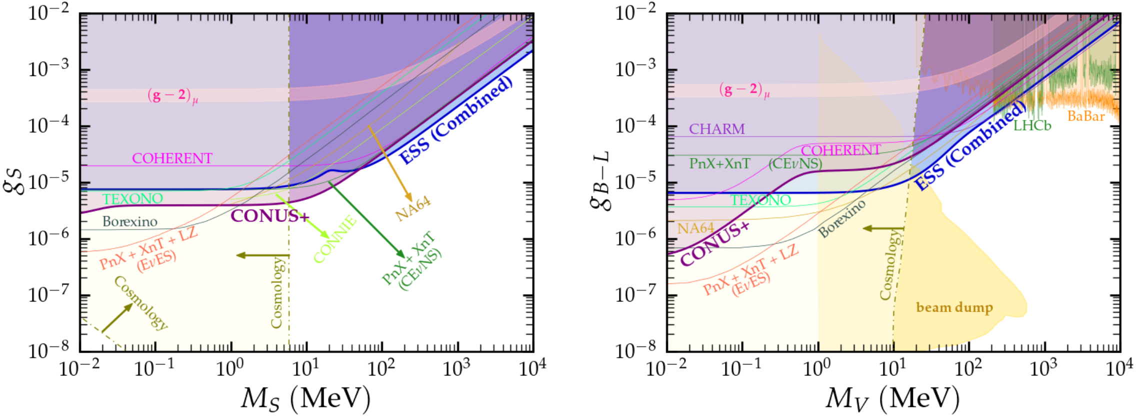

[PLB 864 (2025) 139438, JHEP 05 (2025) 064]

Sterile Neutrinos

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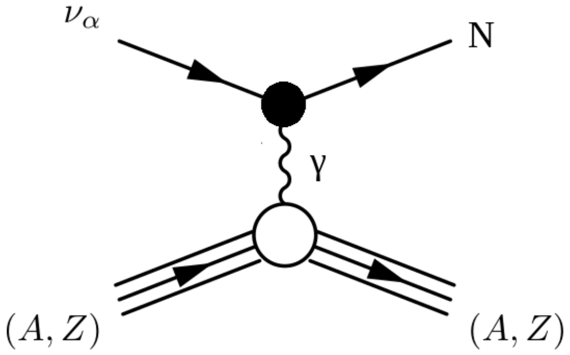
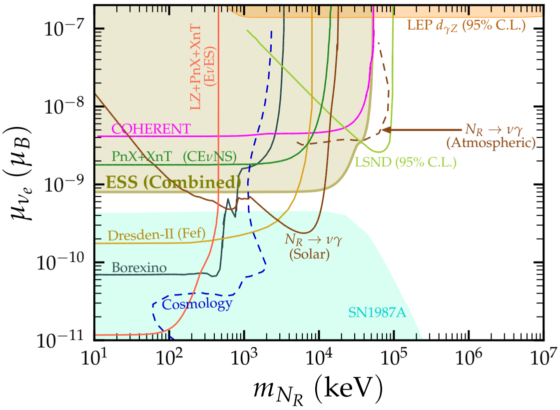
- In the SM, neutrinos are massless and only left-handed, with no right-handed isosinglet partners.
- A minimal and natural extension introducing neutrino masses is the seesaw mechanism, which adds right-handed sterile neutrinos as SM singlets.
- Some models allow sterile neutrino masses in the eV to MeV range, far below the typical seesaw scale.
- eV-scale sterile neutrinos can mix with active neutrinos, leading to active–sterile oscillations observable in short-baseline experiments.
- MeV or sub-MeV sterile neutrinos, though inaccessible via oscillations, can be produced via upscattering—where an active neutrino scatters off an electron or nucleus and transitions into a sterile state. Such transitions often arise via scalar mediators or loop-induced operators.
- These upscattering processes require physics beyond the SM, such as generalized neutrino interactions or electromagnetic portals like transition dipole moment.
- CEνNS experiments are sensitive to these interactions and offer a powerful probe for discovering light sterile neutrinos.

Sterile neutrino dipole portal

$$\mathscr{L} \subset F_M(\mathfrak{q}^2)\bar{\nu}_\alpha \sigma^{\mu\nu} N_R p_\mu A_\nu + eQ\bar{q}\gamma^\nu q A_\nu$$

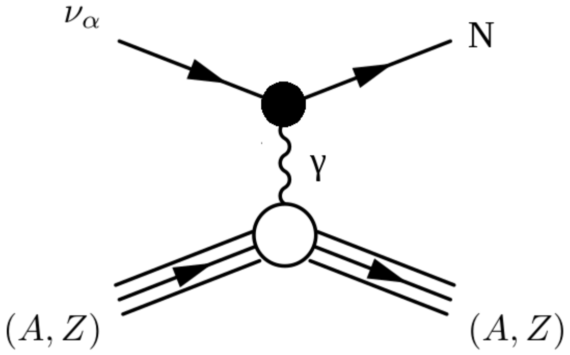


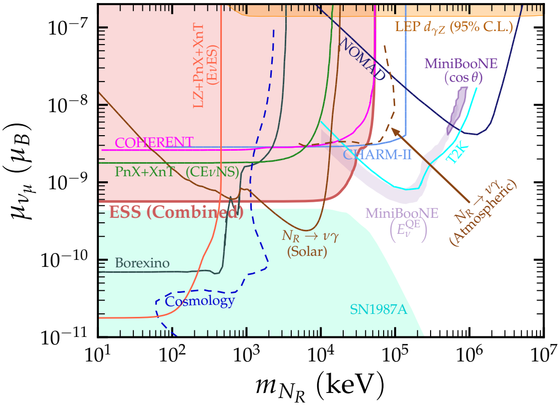


[JHEP 05 (2025) 064]

Sterile neutrino dipole portal

$$\mathscr{L} \subset F_M(q^2)\bar{\nu}_\alpha \sigma^{\mu\nu} N_R p_\mu A_\nu + eQ\bar{q}\gamma^\nu q A_\nu$$





[JHEP 05 (2025) 064]

Upscattering production of sterile ν through generalized interactions

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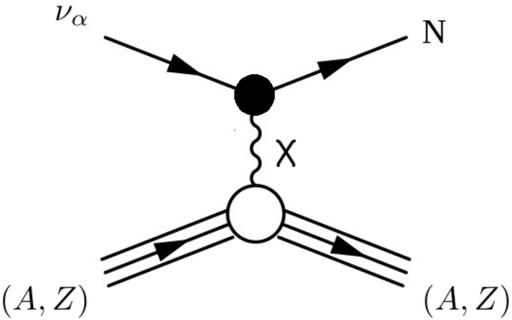
$$\mathscr{L}_{\nu_\alpha \mathcal{N} - N_R \mathcal{N}} \supset \sum_{\substack{X=S,P,V,A,T \\ \alpha=e,\mu,\tau}} \frac{C_X}{q^2 + M_X^2} \left[\bar{N_R} \Gamma^X \nu_\alpha \right] \left[\bar{\mathcal{N}} \Gamma_X \mathcal{N} \right]$$



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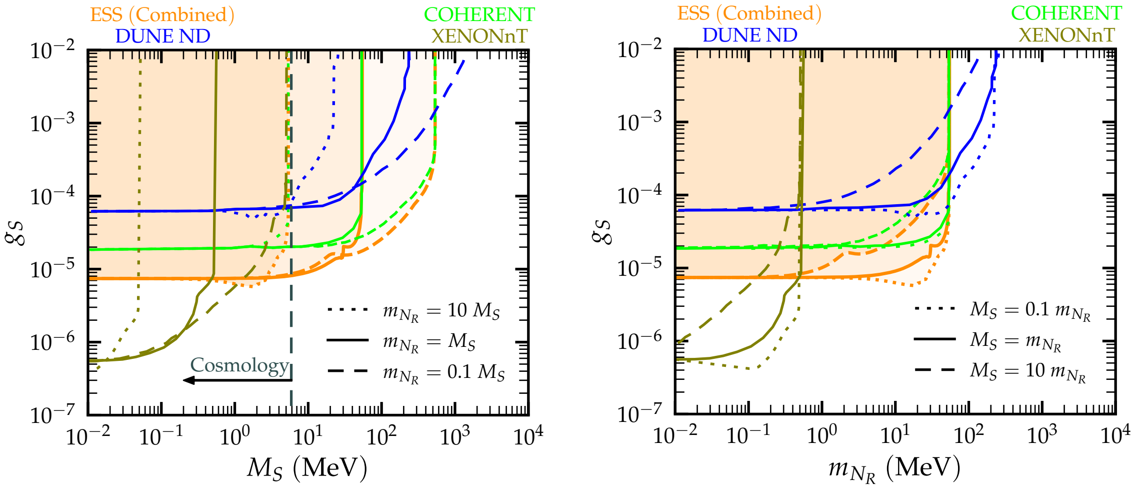

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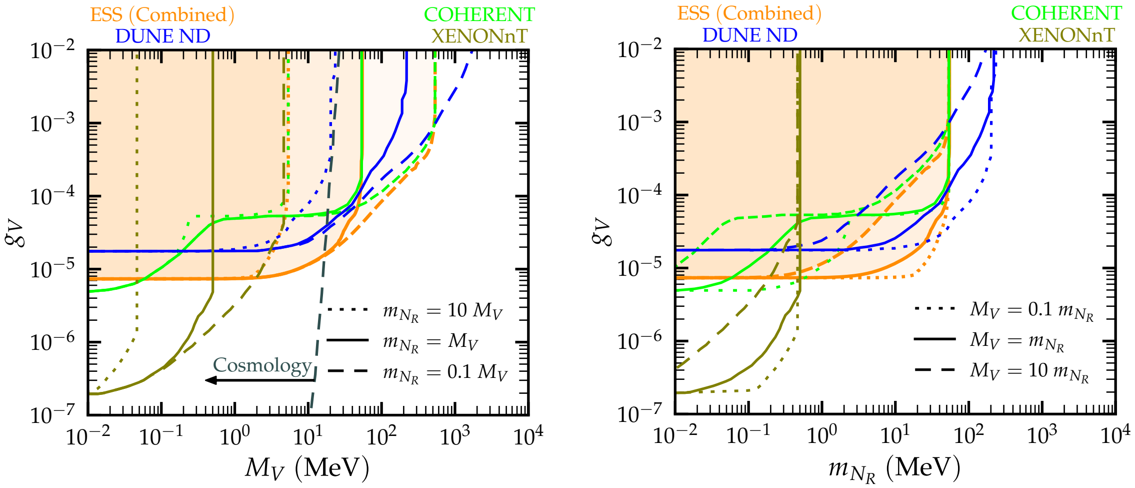

[JHEP 05 (2025) 064]

Conclusions

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- CEνNS is a precision frontier for neutrino physics, enabling tests of the Standard Model and sensitivity to several BSM scenarios.
- The recent CEνNS observation by CONUS+ using reactor antineutrinos marks a major milestone in low-energy neutrino detection, allowing for the extraction of SM and BSM parameters such as $\sin^2\theta_W$ and neutrino electromagnetic properties.
- The upcoming ESS experiment has profound phenomenological implications, thanks to its intense neutrino flux and state-of-the-art detector technology. ESS is expected to provide new insights into both the Standard Model and beyond, significantly improving sensitivity to a wide range of parameters.

THANK YOU

Extras

Vector vs axial vector contribution in CEνNS (SM)

$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}T_{\mathcal{N}}}\right]_{\mathrm{SM}} = \frac{G_F^2 m_{\mathcal{N}}}{\pi}\left[\mathcal{F}_W^2(\mathrm{q}^2)\,(Q_W^V)^2\left(1-\frac{m_{\mathcal{N}}T_{\mathcal{N}}}{2E_\nu^2}-\frac{T_{\mathcal{N}}}{E_\nu}\right)+\mathcal{F}_A(\mathrm{q}^2)\left(1+\frac{m_{\mathcal{N}}T_{\mathcal{N}}}{2E_\nu^2}-\frac{T_{\mathcal{N}}}{E_\nu}\right)\right]$$

- For reactor-based experiments like CONUS+, the weak vector nuclear form factor $\mathcal{F}_W(q^2) \approx 1$. However, for π-DAR sources, weak vector nuclear form factor effects become significant.
- The axial-vector term is spin-suppressed and typically negligible in CEνNS.

Detector	Events (Vector) (3 years)	Events (Axial) (3 years)
CsI	15867	3
Xe	14830	–
Si	181	–
Ge	3284	–
Ar	3012	–
C_3F_8	1283	46