New physics with coherent elastic neutrino-nucleus scattering

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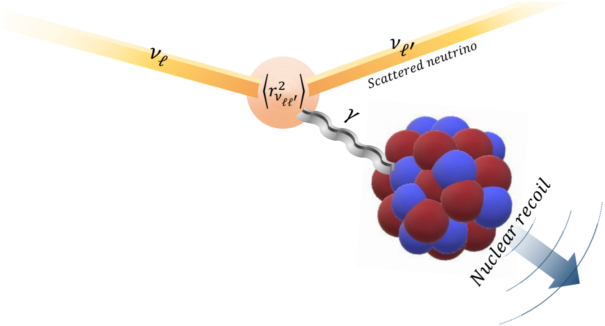


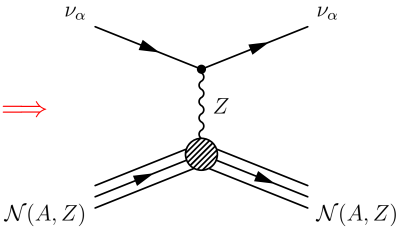
Coherent Elastic Neutrino-Nucleus Scattering

- CEνNS: pronounced "sevens"

- Neutral-Current (NC) interaction:

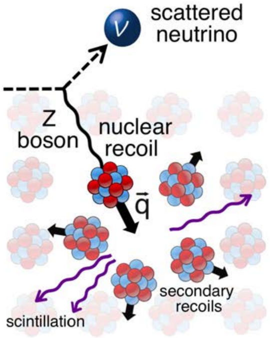
$$\boxed{\nu_\alpha + \mathcal{N}(A, Z) \to \nu_\alpha + \mathcal{N}(A, Z)}$$

Standard Model $\Longrightarrow$



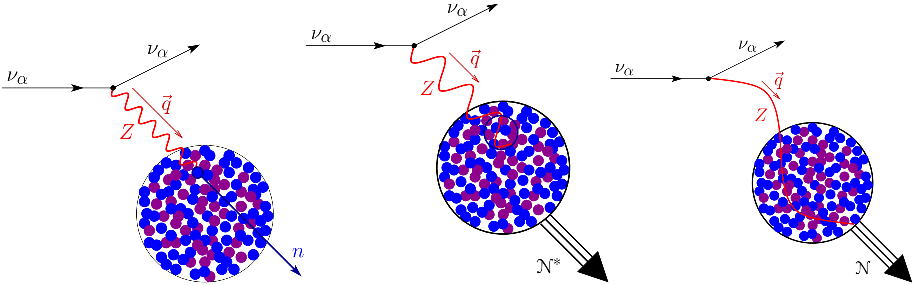
- The nucleus $\mathcal{N}(A, Z)$ recoils as a whole, without any internal change of state!

- So what?



- Big cross section enhancement for heavy nuclei $\mathcal{N}(A, Z)$ with large neutron numbers $N = A - Z$:
  - Incoherent NC scattering: $\sigma_{\text{NC}}(\nu\mathcal{N}) \sim \sum_i |\mathcal{A}(\nu n_i)|^2 \propto N_{\mathcal{N}}$
  - Coherent NC scattering: $\sigma_{\text{NC}}(\nu\mathcal{N}) \sim \left|\sum_i \mathcal{A}(\nu n_i)\right|^2 \propto N_{\mathcal{N}}^2$

Neutrino-Nucleus Scattering

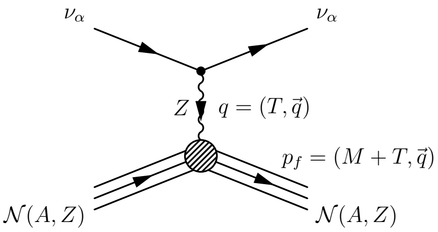


Inelastic Incoherent	Elastic Incoherent	Elastic Coherent
$\lambda_Z \ll R$	$\lambda_Z \lesssim R$	$\lambda_Z \gtrsim 2R$

$$\lambda_Z = 2\pi \frac{\hbar}{|\vec{q}|} \quad \Longrightarrow \quad \text{CE}\nu\text{NS for } |\vec{q}|\, R \lesssim \hbar$$

$$\boxed{|\vec{q}|\, R \lesssim 1} \quad \leftarrow \quad \text{Natural Units}$$

$$\boxed{|\vec{q}|\,R \lesssim 1}$$



- Heavy target nucleus $\mathcal{N}(A, Z)$:

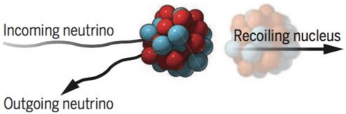
$$A \sim 100 \qquad M \sim 100\,\text{GeV}$$

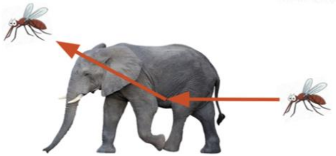
$$R \approx 1.2\,A^{1/3}\,\text{fm} \approx 5\,\text{fm}$$

- CEνNS for $|\vec{q}| \lesssim 40\,\text{MeV}$

- Non-Relativistic nuclear recoil:

$$|\vec{q}| \simeq \sqrt{2\,M\,T} \qquad\qquad q^0 = T \quad \leftarrow \quad \text{Kinetic Energy}$$





- Observable nuclear recoil kinetic energy:

$$T \simeq \frac{|\vec{q}|^2}{2\,M} \lesssim 10\,\text{keV} \quad \leftarrow \quad \text{Very Small!}$$

- CEνNS was predicted in 1974! [Freedman, PRD 9 (1974) 1389]

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

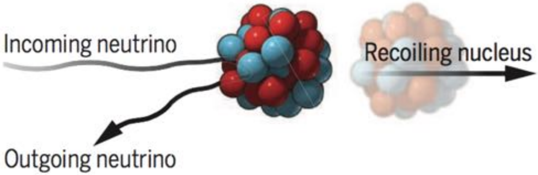
Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 1973)

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.

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.

- CEνNS was observed for the first time 43 years later, in 2017 by the COHERENT experiment at the Oak Ridge Spallation Neutron Source with CsI ($^{133}_{55}\mathrm{Cs}_{78}$, $^{127}_{53}\mathrm{I}_{74}$) and a threshold $T_{\mathrm{thr}} \simeq 5\,\mathrm{keV}$ [arXiv:1708.01294]



Maximum momentum transfer for $\vec{p}_{\nu_f} = -\vec{p}_{\nu_i}$

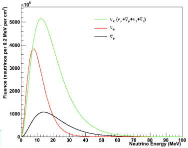
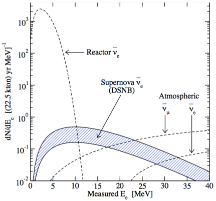
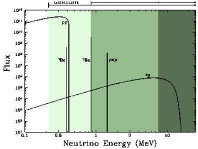
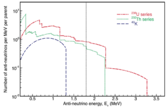
$$\vec{q} = \vec{p}_{\nu_i} - \vec{p}_{\nu_f} \Longrightarrow \underbrace{|\vec{q}|}_{\sqrt{2\,M\,T}} \leq 2\,|\vec{p}_{\nu_i}| = 2\,E_\nu$$

$$\boxed{T \leq \frac{2\,E_\nu^2}{M}}$$

Low-energy neutrinos are needed!

$$T \lesssim 10\,\text{keV} \quad \text{and} \quad M \sim 100\,\text{GeV} \quad \Longrightarrow \quad E_\nu \lesssim 30\,\text{MeV}$$

Natural sources of low-energy neutrinos

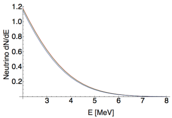
Supernova burst neutrinos		Every ~30 years in the Galaxy,~few 10's of sec burst, all flavors
Supernova relic neutrinos		All flavors, low flux
Atmospheric neutrinos		Some component at low energy
Solar neutrinos		Most flux below 1 MeV
Geoneutrinos		Very low energy

CEvNS eventually seen in DM expts

[Scholberg @ CNNP2017]

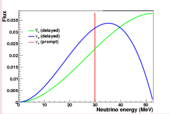
Artificial sources of low-energy neutrinos

Reactors



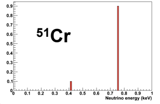
Low energy, but very high fluxes possible; ~continuous source, good bg rejection needed

Stopped pions (decay at rest)



High energy, pulsed beam possible for good background rejection; possible neutron backgrounds

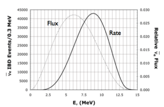
Radioactive sources (electron capture)



Portable; can get very short baseline, monochromatic

Low energy challenging

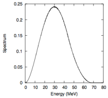
Beam-induced radioactive sources (IsoDAR)



Relatively compact, higher energy than reactor; time structure not sharp

Does not exist yet

Low-energy beta beams

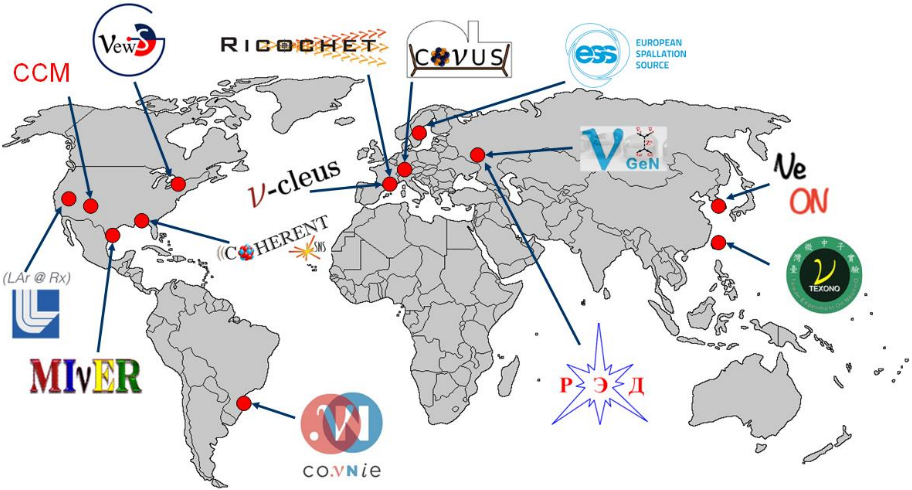


γ=10 boosted ^{18}Ne ν_e

Tunable energy, but not pulsed

Does not exist yet

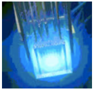
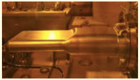
[Scholberg @ CNNP2017]



CEvNS search and study experiments around the world

[Konovalov @ Magnificent CEνNS 2020]

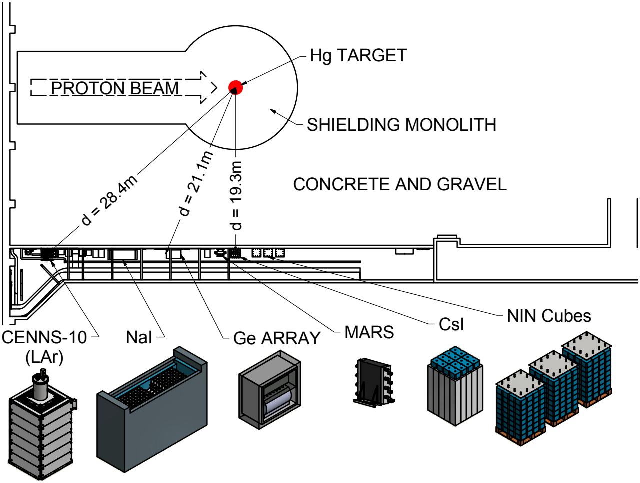
Reactor vs stopped-pion for CEvNS

Source	Flux/ ν's per s	Flavor	Energy	Pros	Cons
Reactor 	2e20 per GW	nuebar	few MeV	• huge flux	• lower xscn • require very low threshold • CW
Stopped pion 	1e15	numu/ nue/ nuebar	0-50 MeV	• higher xscn • higher energy recoils • pulsed beam for bg rejection • multiple flavors	• lower flux • potential fast neutron in-time bg

[Scholberg @ CNNP2017]

The COHERENT Experiment

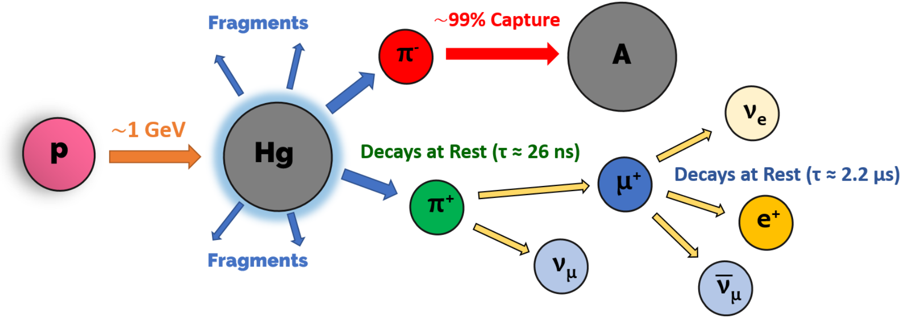
Oak Ridge Spallation Neutron Source



14.6 kg CsI
scintillating crystal

[COHERENT, arXiv:1803.09183]

Stopped-Pion (πDAR) Neutrinos



[M. Green @ Magnificent CEvNS 2019]

Stopped-Pion Neutrino Spectrum

- Prompt monochromatic ν_μ from stopped pion decays:

$$\pi^+ \to \mu^+ + \nu_\mu$$

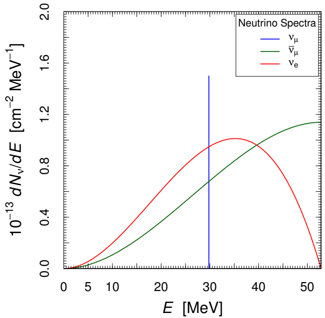
$$\frac{dN_{\nu_\mu}}{dE_\nu} = \eta\,\delta\left(E_\nu - \frac{m_\pi^2 - m_\mu^2}{2m_\pi}\right)$$

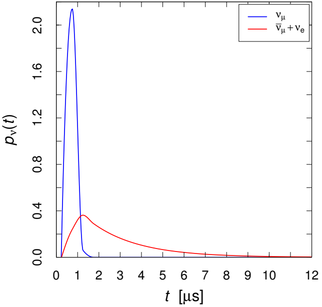
- Delayed $\bar{\nu}_\mu$ and ν_e from the subsequent muon decays:

$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

$$\frac{dN_{\nu_{\bar{\mu}}}}{dE_\nu} = \eta\,\frac{64E_\nu^2}{m_\mu^3}\left(\frac{3}{4} - \frac{E_\nu}{m_\mu}\right)$$

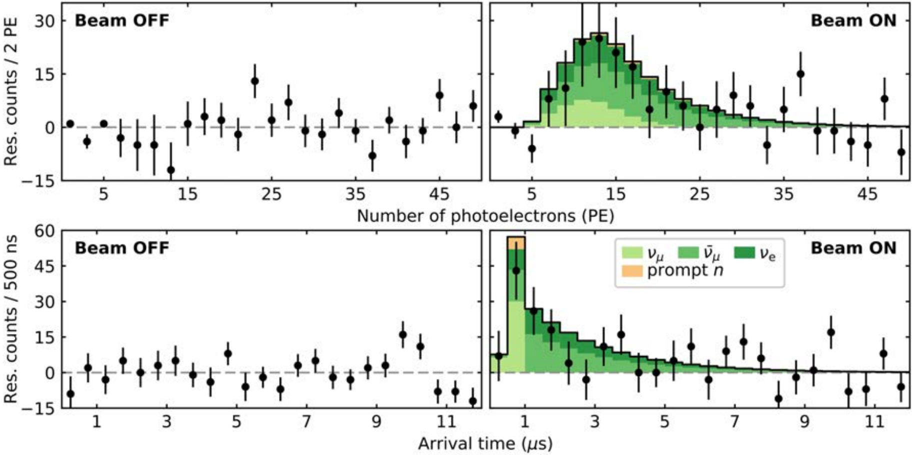
$$\frac{dN_{\nu_e}}{dE_\nu} = \eta\,\frac{192E_\nu^2}{m_\mu^3}\left(\frac{1}{2} - \frac{E_\nu}{m_\mu}\right)$$





COHERENT 2017: Cesium Iodide (CsI)

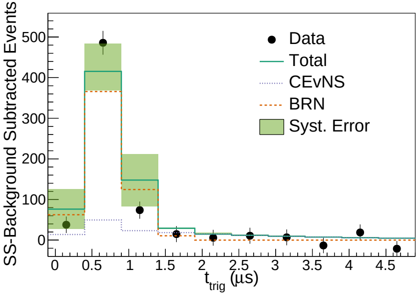
[arXiv:1708.01294]

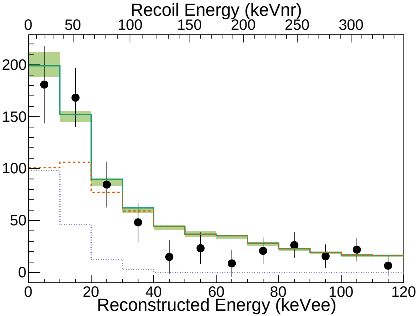


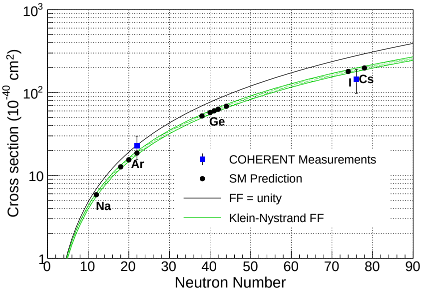
$^{133}_{55}\mathrm{Cs}_{78}$ and $^{127}_{53}\mathrm{I}_{74}$ $\leftarrow$ Heavy nuclei well suited for CEνNS

COHERENT 2020: Argon (Ar)

[arXiv:2003.10630]







- ${}^{40}_{18}\mathrm{Ar}_{22}$ not so heavy
- Verified theoretical $\sigma \underset{\sim}{\propto} N^2$
- $N_{^{40}\mathrm{Ar}} = 22$
- $N_{^{133}\mathrm{Cs}} = 78$, $N_{^{127}\mathrm{I}} = 74$
- $N_{\mathrm{CsI}} / N_{^{40}\mathrm{Ar}} \simeq 3.5$
- $N^2_{\mathrm{CsI}} / N^2_{^{40}\mathrm{Ar}} \simeq 11.9$

CEνNS Cross Section

Standard Model: $$\frac{d\sigma_{\nu\mathcal{N}}}{dT}(E_\nu, T) = \frac{G_F^2 M}{4\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\left[Q_W^{\mathcal{N}}(Q^2)\right]^2$$

- Weak charge of the nucleus $\mathcal{N}$:

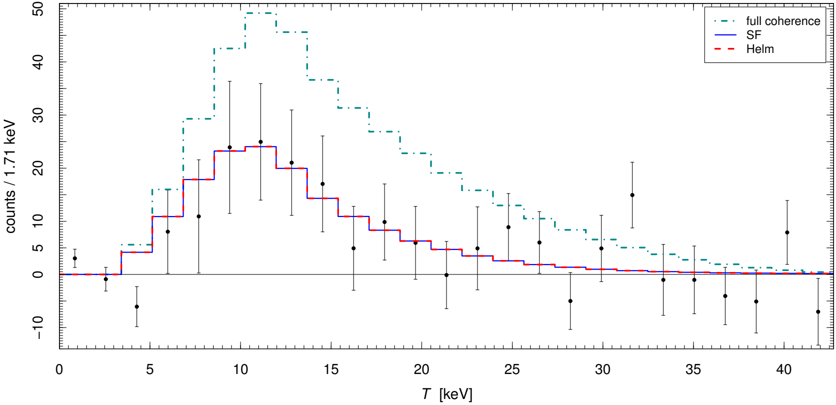
$$Q_W^{\mathcal{N}}(Q^2) = g_V^n \, N_{\mathcal{N}} \, F_N^{\mathcal{N}}(|\vec{q}|) + g_V^p \, Z_{\mathcal{N}} \, F_Z^{\mathcal{N}}(|\vec{q}|)$$

$$g_V^n = -\frac{1}{2} \qquad g_V^p = \frac{1}{2} - 2\sin^2\vartheta_W(Q^2 \simeq 0) = 0.0227 \pm 0.0002$$

The neutron contribution is dominant! $\Longrightarrow$ $\frac{d\sigma_{\nu\mathcal{N}}}{dT} \underset{\sim}{\propto} N_{\mathcal{N}}^2$

- The nuclear form factors $F_N(|\vec{q}|)$ and $F_Z(|\vec{q}|)$ describe the loss of coherence for $|\vec{q}|R \gtrsim 1$. [Patton et al, arXiv:1207.0693; Bednyakov, Naumov, arXiv:1806.08768; Papoulias et al, arXiv:1903.03722; Ciuffoli et al, arXiv:1801.02166; Canas et al, arXiv:1911.09831; Van Dessel et al, arXiv:2007.03658]

- In the COHERENT experiment neutrino-nucleus scattering is not completely coherent. For CsI:



[Cadeddu, CG, Y.F. Li, Y.Y. Zhang, PRL 120 (2018) 072501, arXiv:1710.02730]

- Partial coherency gives information on the nuclear neutron form factor $F_N(|\vec{q}|^2)$, which is the Fourier transform of the neutron distribution in the nucleus.
- Measurable parameter: the radius R_n of the nuclear neutron distribution.

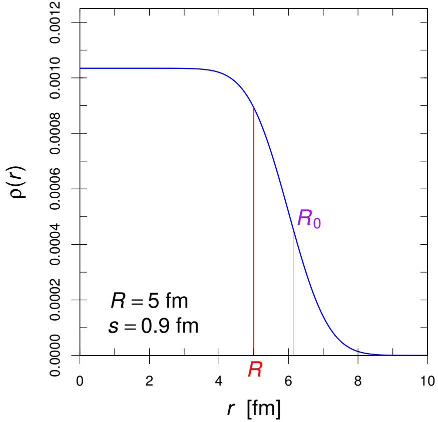
Helm form factor: $F_N^{\text{Helm}}(|\vec{q}|^2) = 3\,\frac{j_1(|\vec{q}|R_0)}{|\vec{q}|R_0}\,e^{-|\vec{q}|^2 s^2/2}$

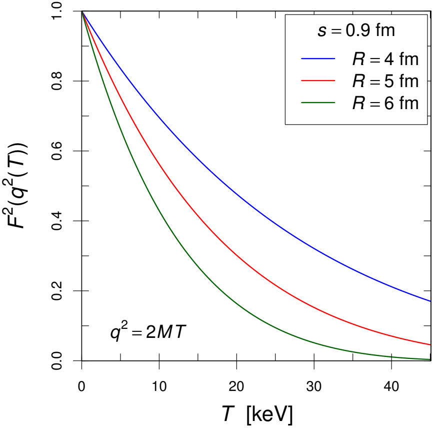
Spherical Bessel function of order one: $j_1(x) = \sin(x)/x^2 - \cos(x)/x$

Obtained from the convolution of a sphere with constant density with radius R_0 and a gaussian density with standard deviation s

Rms radius: $R^2 = \langle r^2 \rangle = \frac{3}{5}\,R_0^2 + 3s^2$

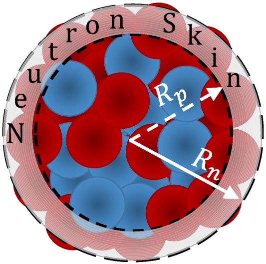
Surface thickness: $s \simeq 0.9\,\text{fm}$

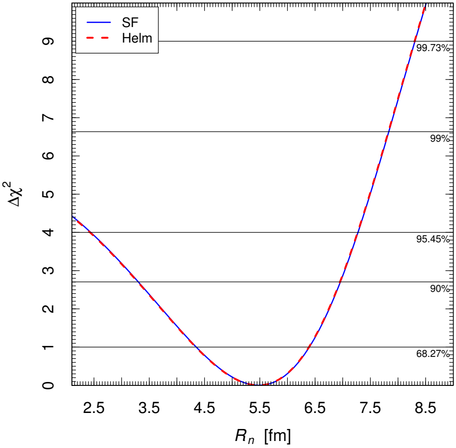




The Nuclear Proton and Neutron Distributions

- The nuclear proton distribution (charge density) is probed with electromagnetic interactions.
- Most sensitive are electron-nucleus elastic scattering and muonic atom spectroscopy.
- Hadron scattering experiments give information on the nuclear neutron distribution, but their interpretation depends on the model used to describe non-perturbative strong interactions.
- More reliable are neutral current weak interaction measurements.
  But they are more difficult.
- Before 2017 there was only one measurement of R_n with neutral-current weak interactions through parity-violating electron scattering:
  $R_n(^{208}\text{Pb}) = 5.78^{+0.16}_{-0.18}\,\text{fm}$ [PREX, PRL 108 (2012) 112502]
  Larger than $R_p(^{208}\text{Pb}) = 5.5028 \pm 0.0013\,\text{fm} \Longrightarrow$ Neutron Skin





- Fit of the 2017 COHERENT CsI data:

$$R_n(\mathrm{CsI}) = 5.5^{+0.9}_{-1.1}\,\mathrm{fm}$$

[Cadeddu, CG, Li, Zhang, arXiv:1710.02730]

- $R_n(\mathrm{CsI}) \simeq R_n(^{133}\mathrm{Cs}) \simeq R_n(^{127}\mathrm{I})$
- First determination of R_n with neutrino-nucleus scattering.
- Best fit larger than

$$R_p(^{133}\mathrm{Cs}) = 4.821 \pm 0.005\,\mathrm{fm}$$

$$R_p(^{127}\mathrm{I}) = 4.766 \pm 0.008\,\mathrm{fm}$$

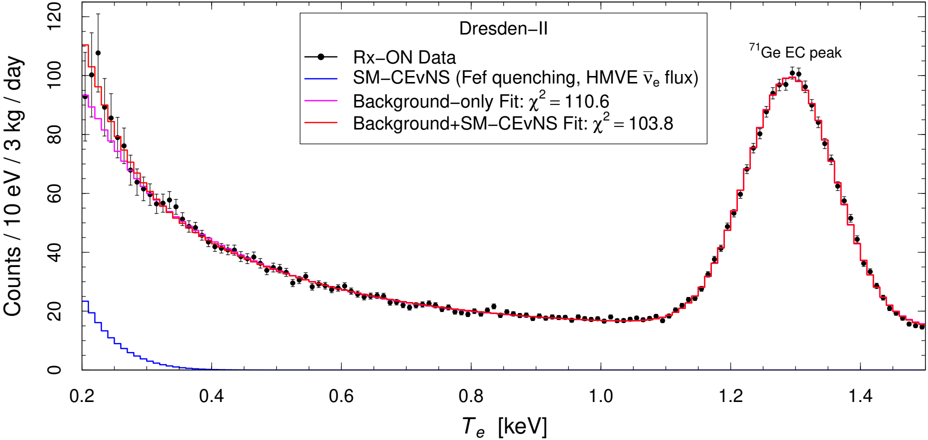
- Predictions of nuclear models:

$$R_n(\mathrm{CsI}) \approx 4.9 - 5.1\,\mathrm{fm}$$

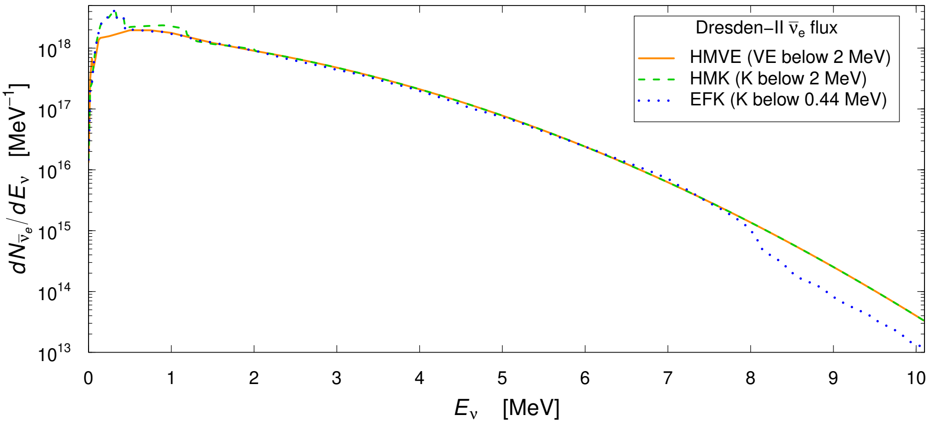
- A large R_n has important implications for:
  - Nuclear physics: a larger pressure of neutrons
  - Astrophysics: a larger size of neutron stars

Recent First Observation of Reactor $\bar{\nu}_e$ CEvNS

[Colaresi, Collar, Hossbach, Lewis, Yocum, arXiv:2202.09672]



- For a proper analysis the background must be fitted with signal using the information in the data release in the arXiv ancillary files. Thanks!
- BSM analyses that use the residuals obtained from the official SM fit are not correct and may obtain misleading results.
- Special thanks to the COHERENT Collaboration for the excellent data releases and the availability to help!

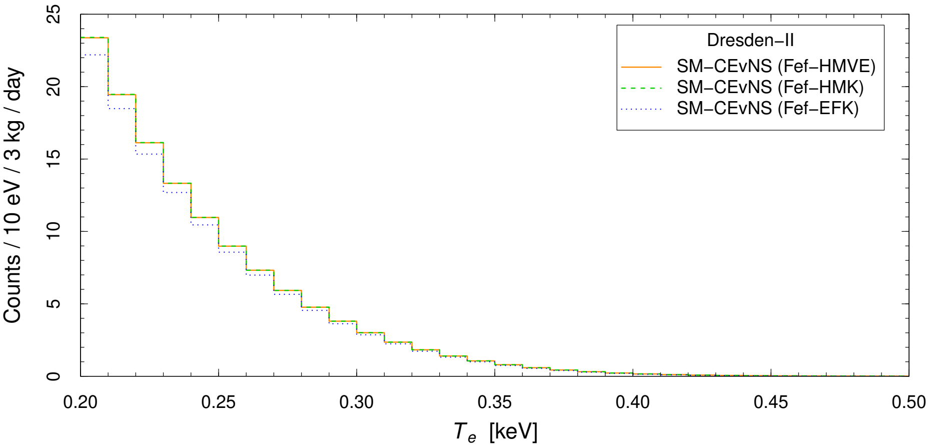


Kopeikin (2012): Usual $\bar{\nu}_e$ fluxes from ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu fission daughter nuclei plus low energy $\bar{\nu}_e$'s from

$$n + {}^{238}\text{U} \to {}^{239}\text{U} + \gamma$$

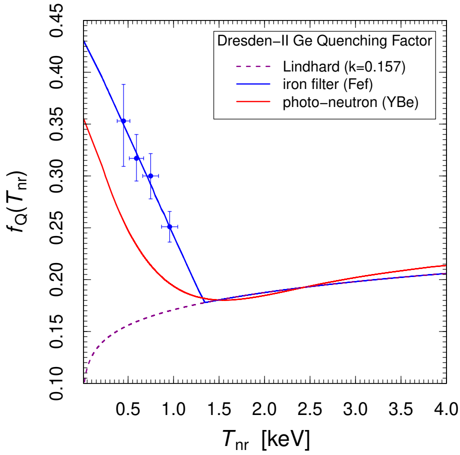
$$ {}^{239}\text{U} \to {}^{239}\text{Np} + e^- + \bar{\nu}_e$$

$$ {}^{239}\text{Np} \to {}^{239}\text{Pu} + e^- + \bar{\nu}_e$$



- Small dependence of the predicted SM CEvNS signal on the difference between the HM and EF fluxes at high energy.

$$E_\nu^{\text{min}}(\text{CEvNS}) \simeq \sqrt{\frac{MT_{\text{nr}}}{2}}: \text{ e.g., } T_{\text{nr}} \simeq 0.2 \text{ keV} \quad \Longrightarrow \quad E_\nu^{\text{min}}(\text{CEvNS}) \simeq 2.5 \text{ MeV}$$



- The Quenching Factor describes the suppression of the ionization yield produced by a nuclear recoil compared to an electron recoil.

- Electron-equivalent energy:

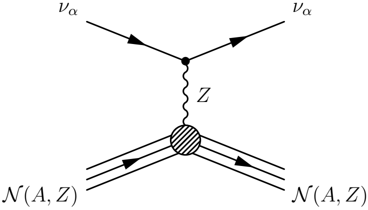
$$T_e = f_Q(T_{nr})\, T_{nr}$$

- Dresden-II Ge Quenching Factor models:
  - Fef: iron filtered neutron beam
  - YBe: photo-neutron $^{88}Y/Be$ source [Colaresi et al, arXiv:2202.09672]

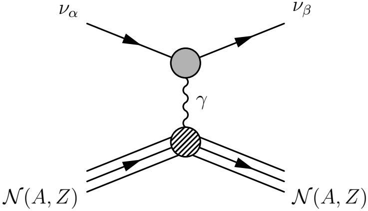
- The difference between Fef and YBe is considered as the Quenching Factor systematic uncertainty [Coloma et al, arXiv:2202.10829]

SM and BSM CEνNS Neutrino Interactions

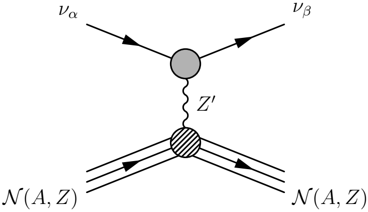
Standard Model NC



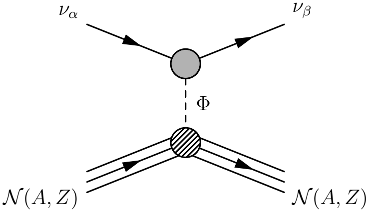
Electromagnetic Interactions



BSM Vector Mediator



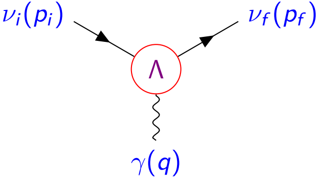
BSM Scalar Mediator



Neutrino Electromagnetic Interactions

- Effective Hamiltonian: $\mathcal{H}_{\text{em}}^{(\nu)}(x) = j_{\mu}^{(\nu)}(x) A^{\mu}(x) = \sum_{k,j=1} \overline{\nu_k}(x) \Lambda_{\mu}^{kj} \nu_j(x) A^{\mu}(x)$

- Effective electromagnetic vertex:



$$\langle \nu_f(p_f) | j_{\mu}^{(\nu)}(0) | \nu_i(p_i) \rangle = \overline{u_f}(p_f) \Lambda_{\mu}^{fi}(q) u_i(p_i)$$

$$q = p_i - p_f$$

- Vertex function (mass basis):

$$\Lambda_{\mu}(q) = \left(\gamma_{\mu} - q_{\mu} \not{q}/q^2\right) \left[F_Q(q^2) + F_A(q^2) q^2 \gamma_5\right] - i \sigma_{\mu\nu} q^{\nu} \left[F_M(q^2) + i F_E(q^2) \gamma_5\right]$$

Lorentz-invariant form factors: charge (F_Q), anapole (F_A), magnetic (F_M), electric (F_E)

$q^2 = 0 \implies$ Q, A (helicity-conserving); μ, ε (helicity-flipping)

- Effective vertex function for ultrarelativistic neutrinos at low q^2:

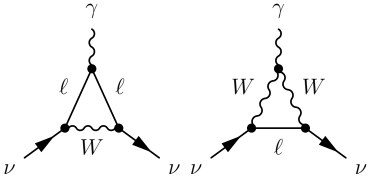
$$\Lambda_{\mu}(q) \simeq \left(\gamma_{\mu} - q_{\mu} \not{q}/q^2\right) \left[F_Q(q^2) - A q^2\right] - i \sigma_{\mu\nu} q^{\nu} \left[\mu - i\varepsilon\right]$$

Neutrino Charge Radius

- In the Standard Model neutrinos are neutral and there are no electromagnetic interactions at the tree-level.

- Radiative corrections generate an effective electromagnetic interaction vertex

$$\Lambda_\mu(q) = \left(\gamma_\mu - q_\mu \not{q}/q^2\right) F(q^2)$$



- $F(q^2) = \cancel{F(0)} + q^2 \left.\frac{dF(q^2)}{dq^2}\right|_{q^2=0} + \ldots = q^2 \frac{\langle r^2 \rangle}{6} + \ldots$

- In the Standard Model: [Bernabeu et al, PRD 62 (2000) 113012, NPB 680 (2004) 450]

$$\langle r^2_{\nu_\ell} \rangle_{\text{SM}} = -\frac{G_F}{2\sqrt{2}\pi^2}\left[3 - 2\log\left(\frac{m^2_\ell}{m^2_W}\right)\right]$$

$$\langle r^2_{\nu_e} \rangle_{\text{SM}} = -8.2 \times 10^{-33}\,\text{cm}^2$$
$$\langle r^2_{\nu_\mu} \rangle_{\text{SM}} = -4.8 \times 10^{-33}\,\text{cm}^2$$
$$\langle r^2_{\nu_\tau} \rangle_{\text{SM}} = -3.0 \times 10^{-33}\,\text{cm}^2$$

- Neutrino charge radii contributions to ν_ℓ–$\mathcal{N}$ CEνNS:

$$\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\Bigg\{\Bigg[\underbrace{-\frac{1}{2}}_{g_V^n} N F_N(|\vec{q}|) + \Bigg(\underbrace{\frac{1}{2} - 2\sin^2\vartheta_W}_{g_V^p \simeq 0.023} - \frac{2}{3} m_W^2 \sin^2\vartheta_W \langle r_{\nu_{\ell\ell}}^2\rangle\Bigg) Z F_Z(|\vec{q}|)\Bigg]^2 + \frac{4}{9} m_W^4 \sin^4\vartheta_W Z^2 F_Z^2(|\vec{q}|) \sum_{\ell' \neq \ell} |\langle r_{\nu_{\ell'\ell}}^2\rangle|^2 \Bigg\}$$

- In the Standard Model there are only diagonal charge radii $\langle r_{\nu_\ell}^2\rangle \equiv \langle r_{\nu_{\ell\ell}}^2\rangle$ because lepton numbers are conserved.

- Diagonal charge radii generate the coherent shifts

$$\sin^2\vartheta_W \to \sin^2\vartheta_W\left(1 + \frac{1}{3} m_W^2 \langle r_{\nu_\ell}^2\rangle\right) \quad \Longleftrightarrow \quad \nu_\ell + \mathcal{N} \to \nu_\ell + \mathcal{N}$$

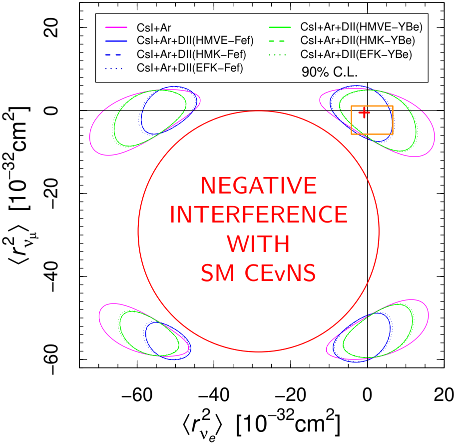
- Transition charge radii generate the incoherent contribution

$$\frac{4}{9} m_W^4 \sin^4\vartheta_W Z^2 F_Z^2(|\vec{q}|) \sum_{\ell' \neq \ell} |\langle r_{\nu_{\ell'\ell}}^2\rangle|^2 \quad \Longleftrightarrow \quad \nu_\ell + \mathcal{N} \to \sum_{\ell' \neq \ell} \nu_{\ell' \neq \ell} + \mathcal{N}$$

[Kouzakov, Studenikin, PRD 95 (2017) 055013, arXiv:1703.00401]

Bounds on Diagonal Neutrino Charge Radii

- The transition charge radii are assumed to be zero or negligible.
- Test of SM prediction and search for lepton flavor conserving BSM physics.



[Atzori Corona et al, arXiv:2205.09484]

Dresden-II data analysis options:

- Reactor $\bar{\nu}_e$ flux:
  - **HMVE**: Huber-Mueller (2011) + Vogel-Engel (1989) ($E_\nu < 2$ MeV)
  - **HMK**: Huber-Mueller + Kopeikin (2012) ($E_\nu < 2$ MeV)
  - **EFK**: Estienne-Fallot (2019) + Kopeikin (2012) ($E_\nu < 0.44$ MeV)
- Quenching factor:
  - **Fef**: iron filter
  - **YBe**: photo-neutron
- Previous bounds (orange):
  - Reactor $\bar{\nu}_e \, e^-$: TEXONO
  - Accelerator $\nu_\mu \, e^-$: BNL-E734

Bounds on Diagonal Neutrino Charge Radii

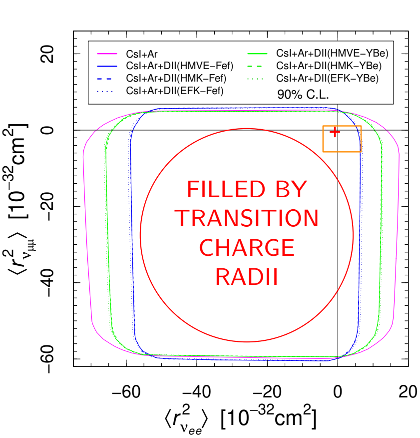
Method	Experiment	Limit $[10^{-32}\ \text{cm}^2]$	C.L.	Year
Reactor $\bar{\nu}_e\, e^-$	Krasnoyarsk	$\lvert\langle r^2_{\nu_e}\rangle\rvert < 7.3$	90%	1992
	TEXONO	$-4.2 < \langle r^2_{\nu_e}\rangle < 6.6^{a}$	90%	2009
Accelerator $\nu_e\, e^-$	LAMPF	$-7.12 < \langle r^2_{\nu_e}\rangle < 10.88^{a}$	90%	1992
	LSND	$-5.94 < \langle r^2_{\nu_e}\rangle < 8.28^{a}$	90%	2001
Accelerator $\nu_\mu\, e^-$	BNL-E734	$-5.7 < \langle r^2_{\nu_\mu}\rangle < 1.1^{a,b}$	90%	1990
	CHARM-II	$\lvert\langle r^2_{\nu_\mu}\rangle\rvert < 1.2^{a}$	90%	1994
CEvNS [arXiv:2205.09484]	COHERENT + Dresden-II	$-7.1 < \langle r^2_{\nu_e}\rangle < 11.2$ $-8.1 < \langle r^2_{\nu_\mu}\rangle < 4.3$	90%	2022

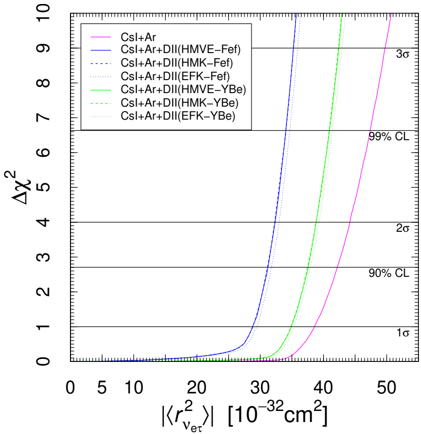
a Corrected by a factor of two due to a different convention.

b Corrected in Hirsch, Nardi, Restrepo, hep-ph/0210137.

[Previous CEvNS results: Papoulias et al, arXiv:1711.09773, arXiv:1907.11644, arXiv:2003.12050; Khan and Rodejohann, arXiv:1907.12444; Cadeddu et al, arXiv:1810.05606, arXiv:1908.06045, arXiv:2005.01645]

General CEvNS Constraints on Neutrino Charge Radii





$$|\langle r^2_{\nu_{e\mu}} \rangle| < 33 \times 10^{-32}\,\text{cm}^2$$
$$|\langle r^2_{\nu_{e\tau}} \rangle| < 43 \times 10^{-32}\,\text{cm}^2 \qquad (3\sigma)$$
$$|\langle r^2_{\nu_{\mu\tau}} \rangle| < 36 \times 10^{-32}\,\text{cm}^2$$

[Atzori Corona et al, arXiv:2205.09484]

Effective charge radii in the flavor basis:

$$\langle r^2_{\nu_{\alpha\beta}} \rangle = \sum_{j,k} U^*_{\alpha j} U_{\beta k} \langle r^2_{\nu_{jk}} \rangle$$

Neutrino Magnetic and Electric Moments

- Effective dimension-5 Lagrangian:

$$\mathcal{L}_{\text{mag}} = \frac{1}{2} \sum_{k,j=1}^{\mathcal{N}} \overline{\nu_{Lk}}\, \sigma^{\alpha\beta} \left(\mu_{kj} + \varepsilon_{kj}\, \gamma_5 \right) N_{Rj}\, F_{\alpha\beta} + \text{H.c.}$$

- $\mathcal{N} = 3$, $N_{Rj} = \nu_{Rj}$, and $\Delta L = 0$ $\implies$ Dirac neutrinos with diagonal and off-diagonal (transition) magnetic and electric moments.
  Simplest SM extension:

  $$\mu_{kk}^{\text{D}} \simeq 3.2 \times 10^{-19} \mu_{\text{B}} \left(\frac{m_k}{\text{eV}} \right)$$ Strongly suppressed by small m_k!

- $\mathcal{N} = 3$ and $N_{Rj} = \nu_{Lj}^{c}$ $\implies$ Majorana neutrinos with transition magnetic and electric moments only

- $\mathcal{N} > 3$ $\implies$ active + sterile Dirac ($\Delta L = 0$) or Majorana neutrinos

  "neutrino dipole portal" or "neutrino magnetic moment portal"

- Neutrino magnetic (and electric) moment contributions to CEνNS:

$$\frac{d\sigma_{\nu_\alpha\text{-}\mathcal{N}}}{dT}(E_\nu, T) = \frac{G_{\text{F}}^2 M}{\pi} \left(1 - \frac{MT}{2E_\nu^2}\right) \left[g_V^n N F_N(|\vec{q}|) + g_V^p Z F_Z(|\vec{q}|)\right]^2 + \frac{\pi\alpha^2}{m_e^2} \left(\frac{1}{T} - \frac{1}{E_\nu}\right) Z^2 F_Z^2(|\vec{q}|) \frac{\mu_{\nu_\alpha}^2}{\mu_{\text{B}}^2}$$

- The magnetic moment interaction adds incoherently to the weak interaction because it flips helicity.

- Effective magnetic moment of flavor neutrinos:

$$\mu_{\nu_\alpha}^2 = \sum_j \left| \sum_k U_{\alpha k}^* \left(\mu_{jk} - i\varepsilon_{jk}\right) \right|^2$$

[Grimus, Stockinger, hep-ph/9708279; Beacom, Vogel, hep-ph/9907383; CG, Studenikin, arXiv:1403.6344]

- Neglecting the electric moments:

$$\mu_{\nu_\alpha}^2 = \sum_{i,j} U_{\alpha i} \, (\mu^2)_{ij} \, U_{\alpha j}^* \quad \text{with} \quad (\mu^2)_{ij} = \sum_k \mu_{ik}\mu_{kj}$$

- Neutrino-electron elastic scattering (ES) contribution in the COHERENT CsI and Dresden-II Ge detectors. [Coloma et al, arXiv:2202.10829]

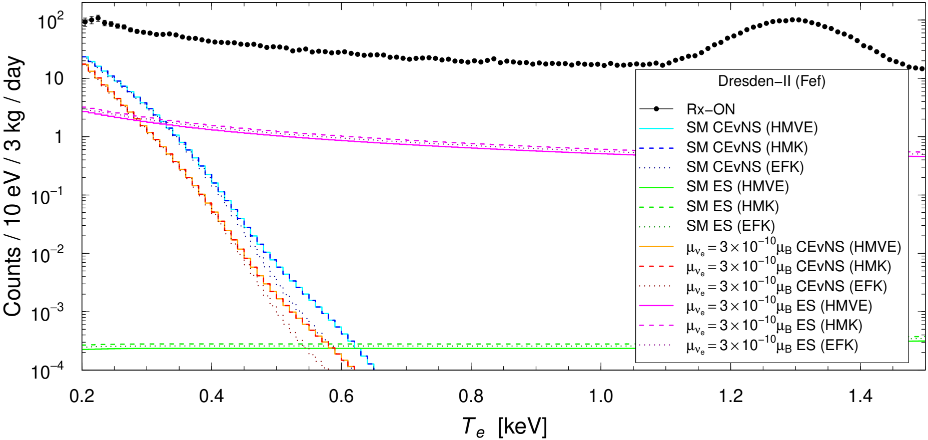
- Negligible SM contribution:

$$\frac{d\sigma^{\text{ES}}_{\nu_\alpha-\mathcal{A}}}{dT_\text{e}}(E, T_\text{e}) = Z^{\mathcal{A}}_{\text{eff}}(T_e)\,\frac{G_\text{F}^2 m_e}{2\pi}\left[\left(g_V^{\nu_\alpha}+g_A^{\nu_\alpha}\right)^2+\left(g_V^{\nu_\alpha}-g_A^{\nu_\alpha}\right)^2\left(1-\frac{T_e}{E}\right)^2 - \left(\left(g_V^{\nu_\alpha}\right)^2-\left(g_A^{\nu_\alpha}\right)^2\right)\frac{m_e T_e}{E^2}\right]$$

$$g_V^{\nu_e} = 2\sin^2\theta_W + \frac{1}{2}, \quad g_A^{\nu_e} = \frac{1}{2}, \quad g_V^{\nu_\mu} = 2\sin^2\theta_W - \frac{1}{2}, \quad g_A^{\nu_\mu} = -\frac{1}{2}$$

- Significant neutrino magnetic moment contribution for small T_e:

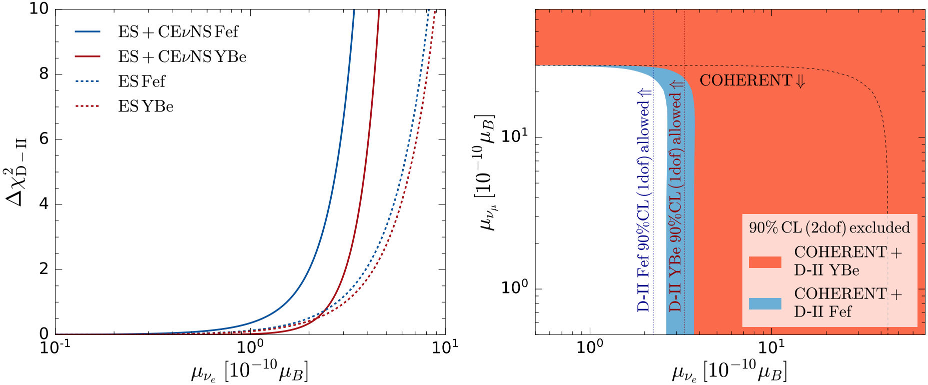
$$\frac{d\sigma^{\text{ES, MM}}_{\nu_\alpha\text{-}\mathcal{A}}}{dT_\text{e}}(E, T_\text{e}) = Z^{\mathcal{A}}_{\text{eff}}(T_\text{e})\frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_e}-\frac{1}{E}\right)\left|\frac{\mu_{\nu_\alpha}}{\mu_\text{B}}\right|^2$$



- SM ES are practically negligible, whereas magnetic moment ES are not negligible.
- ES predictions are flatter than CEvNS and depend more on the reactor flux model because

$$E_\nu^{\min}(\text{ES}) \simeq \sqrt{m_e T_e/2}: \text{ e.g., } T_e \simeq 0.5 \text{ keV} \implies E_\nu^{\min}(\text{ES}) \simeq 10 \text{ keV}$$

$$E_\nu^{\min}(\text{CEvNS}) \simeq \sqrt{M T_{\text{nr}}/2}: \text{ e.g., } T_{\text{nr}} \simeq 0.5 \text{ keV} \implies E_\nu^{\min}(\text{CEvNS}) \simeq 4 \text{ MeV}$$

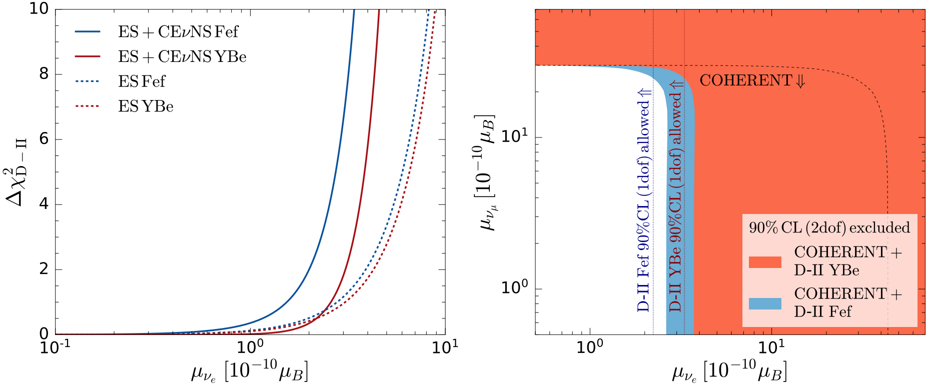


[Coloma, Esteban, Gonzalez-Garcia, Larizgoitia, Monrabal, Palomares-Ruiz, arXiv:2202.10829]

$|\mu_{\nu_e}| < 2.2 \times 10^{-10}\,\mu_B$ HMVE CEvNS+ES Fef 90% C.L.

$$\frac{|\mu_{\nu_e}|}{10^{-10}\,\mu_B} < \left\{ \begin{array}{l} \left.\begin{array}{l} 2.3\,(\text{HMVE or HMK}) \\ 2.5\,(\text{EFK}) \end{array}\right\} \text{CEvNS} \\ \left.\begin{array}{l} 2.1\,(\text{HMVE or HMK}) \\ 2.2\,(\text{EFK}) \end{array}\right\} \text{CEvNS+ES} \end{array} \right\} \quad \text{Fef} \quad 90\%\ \text{C.L.}$$

[Atzori Corona et al, arXiv:2205.09484]



[Coloma, Esteban, Gonzalez-Garcia, Larizgoitia, Monrabal, Palomares-Ruiz, arXiv:2202.10829]

$|\mu_{\nu_e}| < 3.3 \times 10^{-10}\,\mu_B$ HMVE CEvNS+ES YBe 90% C.L.

$$\frac{|\mu_{\nu_e}|}{10^{-10}\,\mu_B} < \left\{ \begin{array}{l} \left.\begin{array}{l} 3.7\,(\text{HMVE or HMK}) \\ 3.8\,(\text{EFK}) \end{array}\right\} \text{CEvNS} \\ \left.\begin{array}{l} 3.2\,(\text{HMVE or HMK}) \\ 3.3\,(\text{EFK}) \end{array}\right\} \text{CEvNS+ES} \end{array} \right\}$$

YBe 90% C.L.

[Atzori Corona et al, arXiv:2205.09484]

Bounds on $|\mu_{\nu_e}|$ and $|\mu_{\nu_\mu}|$

Method	Experiment	Limit $[\mu_B]$	CL	Year
Reactor ES $(\bar{\nu}_e\, e^-)$	Krasnoyarsk	$|\mu_{\nu_e}| < 2.4 \times 10^{-10}$	90%	1992
	Rovno	$|\mu_{\nu_e}| < 1.9 \times 10^{-10}$	95%	1993
	MUNU	$|\mu_{\nu_e}| < 9 \times 10^{-11}$	90%	2005
	TEXONO	$|\mu_{\nu_e}| < 7.4 \times 10^{-11}$	90%	2006
	GEMMA	$|\mu_{\nu_e}| < 2.9 \times 10^{-11}$	90%	2012
Reactor CEvNS+ES	Dresden-II [Coloma et al, arXiv:2202.10829] [Atzori Corona et al, arXiv:2205.09484]	$|\mu_{\nu_e}| < 3.3 \times 10^{-10}$	90%	2022
Accelerator ES $(\nu_\mu\, e^-)$	BNL-E734	$|\mu_{\nu_\mu}| < 8.5 \times 10^{-10}$	90%	1990
	LAMPF	$|\mu_{\nu_\mu}| < 7.4 \times 10^{-10}$	90%	1992
	LSND	$|\mu_{\nu_\mu}| < 6.8 \times 10^{-10}$	90%	2001
Accelerator CEvNS+ES	COHERENT [Coloma et al, arXiv:2202.10829] [Atzori Corona et al, arXiv:2205.09484]	$|\mu_{\nu_\mu}| < 2 \times 10^{-9}$	90%	2022

[See also: Liao et al, arXiv:2202.10622; Aristizabal Sierra et al, arXiv:2203.02414; Khan, arXiv:2203.08892]

[Previous CEvNS results: Papoulias et al, arXiv:1711.09773, arXiv:1905.03750, arXiv:1907.11644, arXiv:2003.12050; Khan and Rodejohann, arXiv:1907.12444; Cadeddu et al, arXiv:1908.06045, arXiv:2005.01645; CONUS, arXiv:2201.12257]

[Future prospects: Miranda et al, arXiv:1905.03750]

Vector-Mediated Non-Standard Interactions

- General CEvNS cross section:

$$\frac{d\sigma_{\nu_\alpha\text{-}\mathcal{N}}}{dT}(E,T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E^2}\right) Q_{W,\alpha}^2$$

- Very heavy vector mediator: Effective neutral-current NSI Hamiltonian:

$$\mathcal{H}_{\text{NSI}}^{\text{CE}\nu\text{NS}} = 2\sqrt{2} G_F \sum_{\alpha,\beta=e,\mu,\tau} \left(\overline{\nu_{\alpha L}} \gamma^\rho \nu_{\beta L}\right) \sum_{f=u,d} \varepsilon_{\alpha\beta}^{fV} \left(\overline{f} \gamma_\rho f\right)$$

$$Q_{W,\alpha}^2 = \left[\left(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}\right) Z F_Z(|\vec{q}|^2) + \left(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV}\right) N F_N(|\vec{q}|^2)\right]^2 + \sum_{\beta\neq\alpha} \left|\left(2\varepsilon_{\alpha\beta}^{uV} + \varepsilon_{\alpha\beta}^{dV}\right) Z F_Z(|\vec{q}|^2) + \left(\varepsilon_{\alpha\beta}^{uV} + 2\varepsilon_{\alpha\beta}^{dV}\right) N F_N(|\vec{q}|^2)\right|^2$$

- Many parameters with possible cancellation effects.

- Several phenomenological analyses: general or simplified by assumptions on the parameters.

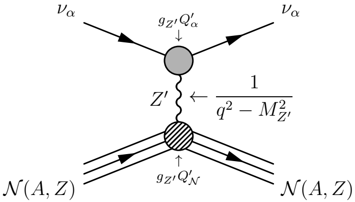
[COHERENT, arXiv:1708.01294, arXiv:2003.10630, arXiv:2110.07730; Coloma et al, arXiv:1708.02899, arXiv:1911.09109, arXiv:2202.10829; Liao et al, arXiv:1708.04255, arXiv:1711.03521, arXiv:2002.03066; Papoulias et al, arXiv:1711.09773, arXiv:1907.11644, arXiv:2003.12050; Khan and Rodejohann, arXiv:1907.12444; CG, arXiv:1909.00466; Canas et al, arXiv:1911.09831; Denton and Gehrlein, arXiv:2008.06062; CONUS, arXiv:2110.02174; Chaves and Schwetz, arXiv:2102.11981]

Light Vector Mediator Models

- Non-standard interactions mediated by a vector boson Z' with mass $M_{Z'} \lesssim 100$ GeV, associated with a new $U(1)'$ gauge symmetry.
- Generic lepton flavor conserving Lagrangian:

$$\mathcal{L}_{Z'}^{V} = -g_{Z'} \, Z'_{\mu} \left[\sum_{\alpha=e,\mu,\tau} Q'_{\alpha} \, \overline{\nu_{\alpha L}} \gamma^{\mu} \nu_{\alpha L} + \sum_{q=u,d} Q'_{q} \, \overline{q} \gamma^{\mu} q \right]$$

- CEvNS:



- Many models, that can be divided in
  - Anomaly-free models generated by appropriate combinations of

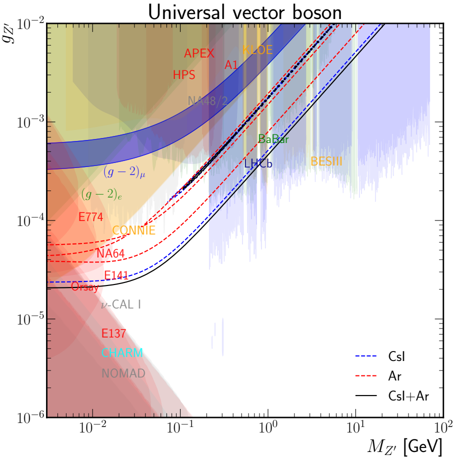
$$B, \; L_e, \; L_\mu, \; L_\tau$$

  - Anomalous models, assuming that the anomalies are canceled by the contributions of non-standard fermions an extended theory.

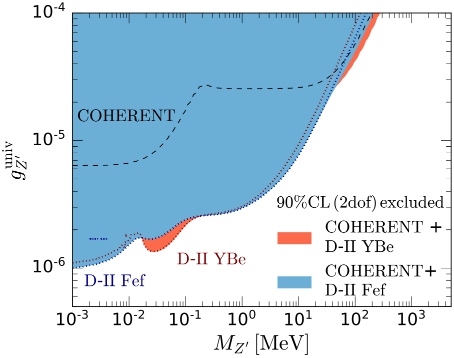
Light Vector Mediator: Universal Z'

- Cross section: $$\frac{d\sigma_{\nu\text{-}\mathcal{N}}}{dT}(E_\nu, T) = \frac{G_\mathrm{F}^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right) Q_\mathrm{W}^2$$
- Weak charge: $$Q_\mathrm{W} = Q_\mathrm{W}^\mathrm{SM} + \frac{3g_{Z'}^2}{\sqrt{2}G_F}\left(\frac{ZF_Z(|\vec{q}|) + NF_N(|\vec{q}|)}{|\vec{q}|^2 + M_{Z'}^2}\right)$$
- Since $Q_\mathrm{W}^\mathrm{SM} \simeq -N/2$, for $M_{Z'} \gg |\vec{q}| \approx 30MeV$ there is a cancellation for $$Q_\mathrm{W} \approx -\frac{N}{2} + \frac{3g_{Z'}^2}{\sqrt{2}G_F}\left(\frac{Z+N}{M_{Z'}^2}\right) = 0 \quad \Leftrightarrow \quad g_{Z'} \approx 1.4 \times 10^{-6}\,\frac{M_{Z'}}{\mathrm{MeV}}$$
- There is a degeneracy with the SM contribution for $$Q_\mathrm{W} \approx -\frac{N}{2} + \frac{3g_{Z'}^2}{\sqrt{2}G_F}\left(\frac{Z+N}{M_{Z'}^2}\right) = \frac{N}{2} \quad \Leftrightarrow \quad g_{Z'} \approx 2 \times 10^{-6}\,\frac{M_{Z'}}{\mathrm{MeV}}$$

Light Vector Mediator: Universal Z'



2σ [Atzori Corona et al, arXiv:2202.11002]



[Coloma et al, arXiv:2202.10829]

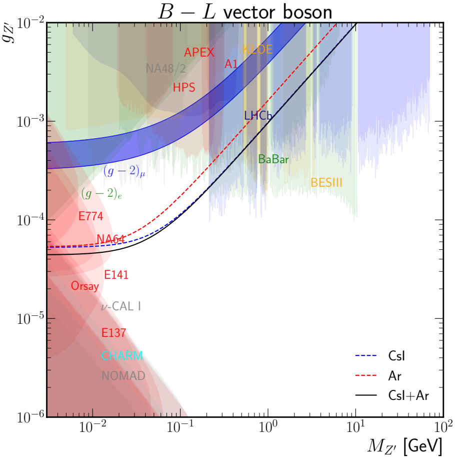
CEvNS: $|\vec{q}|^2 \simeq 2MT_{\rm nr}$

ES: $|\vec{q}|^2 \simeq 2m_e T_e$

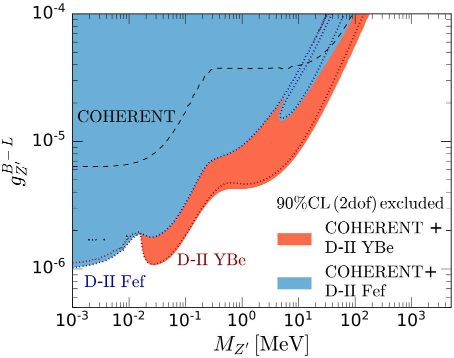
[Previous CEvNS results: Liao and Marfatia, arXiv:1708.04255; Papoulias et al, arXiv:1711.09773, arXiv:1907.11644; Khan and Rodejohann, arXiv:1907.12444; CONNIE, arXiv:1910.04951; Cadeddu et al, arXiv:2008.05022; CONUS, arXiv:2110.02174]

Light Vector Mediator: Z'_{B-L}

Weak charge: $$Q_W = Q_W^{SM} - \frac{g_{Z'}^2}{\sqrt{2}G_F}\left(\frac{ZF_Z(|\vec{q}|) + NF_N(|\vec{q}|)}{|\vec{q}|^2 + M_{Z'}^2}\right)$$



Anomaly Free!



2σ [Atzori Corona et al, arXiv:2202.11002]

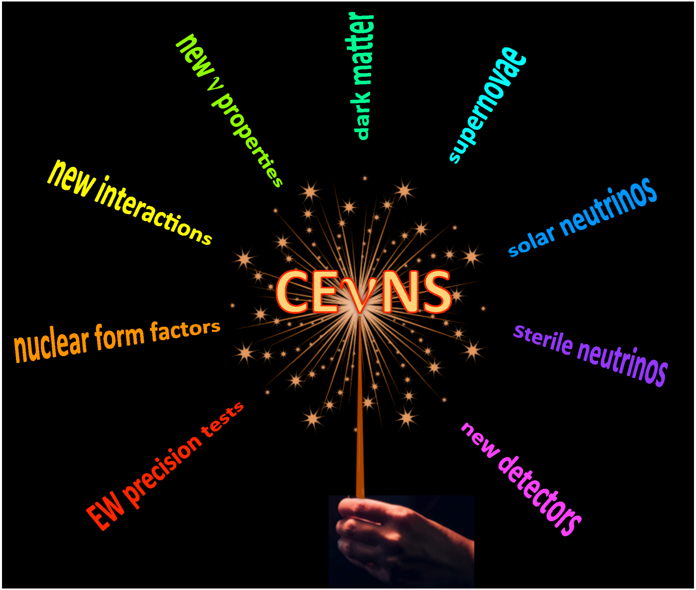
[Coloma et al, arXiv:2202.10829]

[Previous CEvNS results: Miranda et al, arXiv:2003.12050; Cadeddu et al, arXiv:2008.05022]

Remarks

- The ES effects in Dresden and Coherent CsI lead to dramatic improvements of the bounds on the electric charges of ν_e and ν_μ.
  [Atzori Corona et al, arXiv:2205.09484]
- CEvNS can probe neutrino interactions with BSM scalars.
  [Cerdeno et al, arXiv:1604.01025; Farzan et al, arXiv:1802.05171; Aristizabal Sierra et al, arXiv:1806.07424; Khan and Rodejohann, arXiv:1907.12444; Aristizabal Sierra et al, arXiv:1910.12437; Miranda et al, arXiv:2003.12050; Suliga and Tamborra, arXiv:2010.14545; CONUS, arXiv:2110.02174; Li and Xia, arXiv:2201.05015; Atzori Corona et al, arXiv:2202.11002; Liao et al, arXiv:2202.10622; Coloma et al, arXiv:2202.10829]
- CEvNS can probe general BSM neutrino interactions.
  [Lindner et al, arXiv:1612.04150; Aristizabal Sierra et al, arXiv:1806.07424; Brdar and Rodejohann, arXiv:1810.03626; Chang and Liao, arXiv:2002.10275; Li et al, arXiv:2005.01543; CONUS, arXiv:2110.02174]
- CEvNS can determine the neutron distribution in the nucleus.
  [Cadeddu et al, arXiv:1710.02730, arXiv:2005.01645, arXiv:1908.06045; Aristizabal Sierra et al, arXiv:1902.07398; Huang and Chen, arXiv:1902.07625; Papoulias et al, arXiv:1903.03722, arXiv:1907.11644; Miranda et al, arXiv:2003.12050]
- CEvNS can determine the value of the electroweak mixing angle.
  [Papoulias et al, arXiv:1711.09773, arXiv:1907.11644; Cadeddu et al, arXiv:1808.10202, arXiv:2005.01645, arXiv:1908.06045, arXiv:2205.09484; Huang and Chen, arXiv:1902.07625; Miranda et al, arXiv:1902.09036, arXiv:2003.12050; Khan and Rodejohann, arXiv:1907.12444; COHERENT, arXiv:2110.07730]
- CEvNS can probe active neutrino disappearance into sterile states.
  [Papoulias and Kosmas, arXiv:1711.09773; Blanco et al, arXiv:1901.08094; Miranda et al, arXiv:1902.09036]
- In the future it may be possible to observe Coherent Elastic Neutrino-Atom Scattering (CEvAS) with a very low energy threshold of a few meV. [Sehgal and Wanninger, PLB 171 (1986) 107; Cadeddu et al, arXiv:1907.03302]

CEvNS magic, to be continued ...



[E. Lisi, Neutrino 2018]

Conclusions

- In 2017, the observation of CEνNS in the COHERENT experiment opened the way for new powerful measurements of weak interactions, nuclear structure, non-standard neutrino properties.
- In 2022 CEνNS induced by reactor $\bar{\nu}_e$'s have been observed for the first time in the Dresden-II experiment.
- Other CEνNS experiments with reactor $\bar{\nu}_e$'s: CONUS, CONNIE, NU-CLEUS, MINER, Ricochet, TEXONO, νGEN, ...
- It is important to continue and improve CEνNS observation not only with $\bar{\nu}_e$ from reactors, but also with ν_μ beams (as in COHERENT) in order to explore the properties of ν_μ, that are typically less constrained than the properties of ν_e.
- Future: new COHERENT CEνNS measurements with 1 ton LAr detector, a large array of NaI detectors, and an array of Germanium detectors.
- Powerful project at the European Spallation Source (ESS) in Lund, Sweden, with an order of magnitude increase in neutrino flux with respect to the Oak Ridge SNS.