Neutrino and Nuclear Properties from Coherent Elastic Neutrino-Nucleus Scattering

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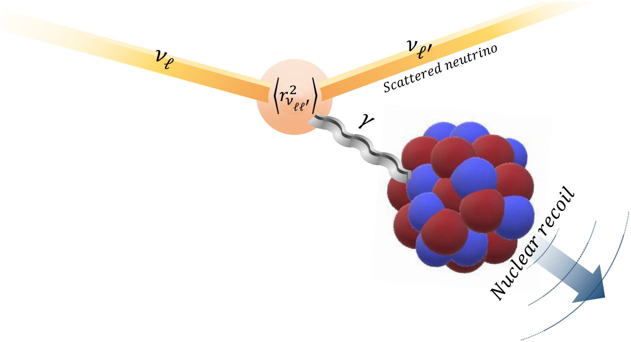
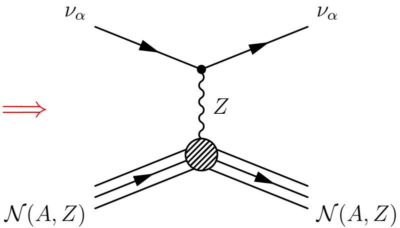


Coherent Elastic Neutrino-Nucleus Scattering

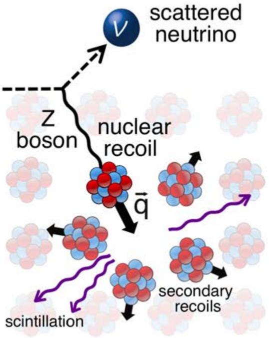
- CEνNS: pronounced "sevens"
- Neutral-Current (NC) interaction:

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

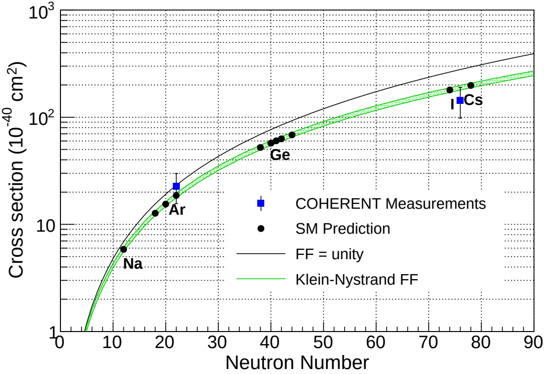
Standard Model $\Longrightarrow$



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



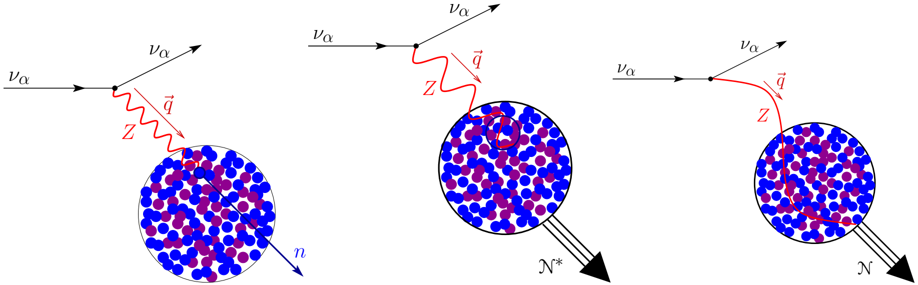
- Big cross section enhancement for heavy nuclei $\mathcal{N}(A, Z)$ with large neutron numbers $N = A - Z$:
  - Incoherent NC scattering: $\sigma_{\text{NC}}(\nu\mathcal{N}) \sim \sum_i |\mathcal{A}(\nu n_i)|^2 \propto N_{\mathcal{N}}$
  - Coherent NC scattering: $\sigma_{\text{NC}}(\nu\mathcal{N})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



[COHERENT, arXiv:2003.10630]

- $N_{^{40}\text{Ar}} = 22$
- $N_{^{133}\text{Cs}} = 78$
  $N_{^{127}\text{I}} = 74$
- $N_{\text{CsI}} / N_{^{40}\text{Ar}} \simeq 3.5$
- $N_{\text{CsI}}^2 / N_{^{40}\text{Ar}}^2 \simeq 11.9$

Neutrino-Nucleus Scattering



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

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

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

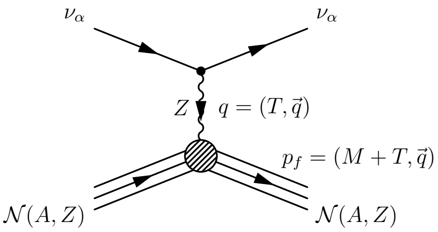
$$|\vec{q}|\,R \lesssim 1$$

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

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

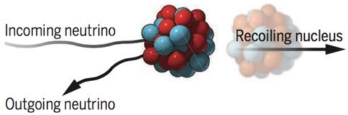
$$R \approx 1.2\,A^{1/3}\,\text{fm} \approx 5\,\text{fm}$$

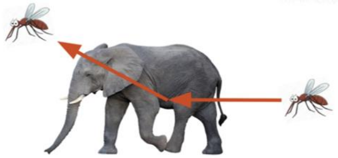
- CEνNS for $|\vec{q}| \lesssim 40\,\text{MeV}$



- Non-Relativistic nuclear recoil:

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





- Observable nuclear recoil kinetic energy:

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

- 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

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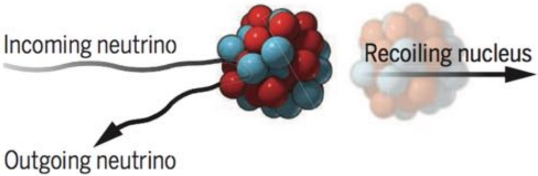
(Received 15 October 1973; revised manuscript received 19 November 1973)

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. Ideally the apparatus should

- 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 $\vec{p}_{\nu_f} = -\vec{p}_{\nu_i}$

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

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

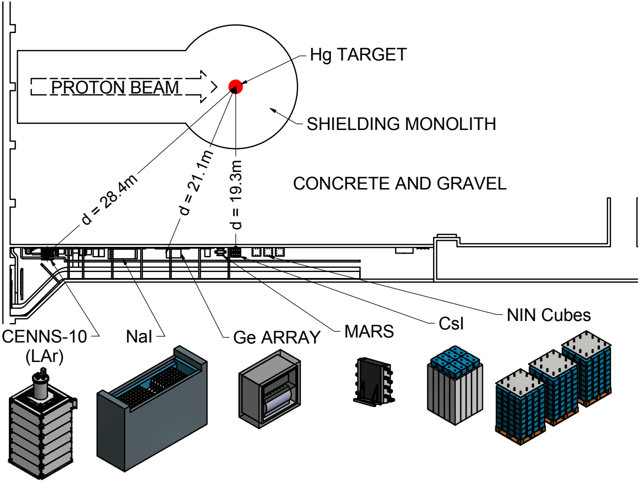
Low-energy neutrinos are needed!

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

- Main natural sources: Sun, Supernova, Geoneutrinos.
- Main artificial sources: Reactor, Stopped pions, Radioactive nuclei.

The COHERENT Experiment

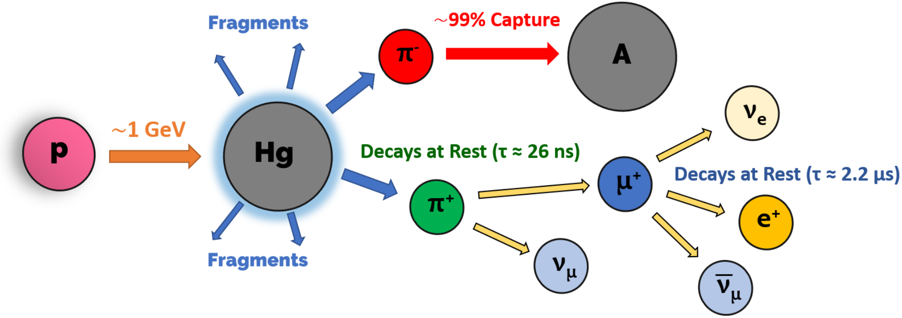
Oak Ridge Spallation Neutron Source



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:

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

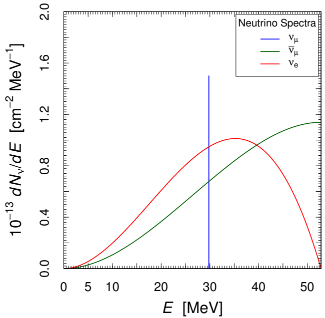
$$\frac{dN_{\nu_\mu}}{dE_\nu} = \eta\,\delta\left(E_\nu - \frac{m_\pi^2 - m_\mu^2}{2m_\pi}\right)$$

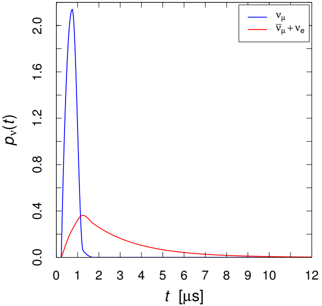
- Delayed $\bar{\nu}_\mu$ and ν_e from the subsequent muon decays:

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

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

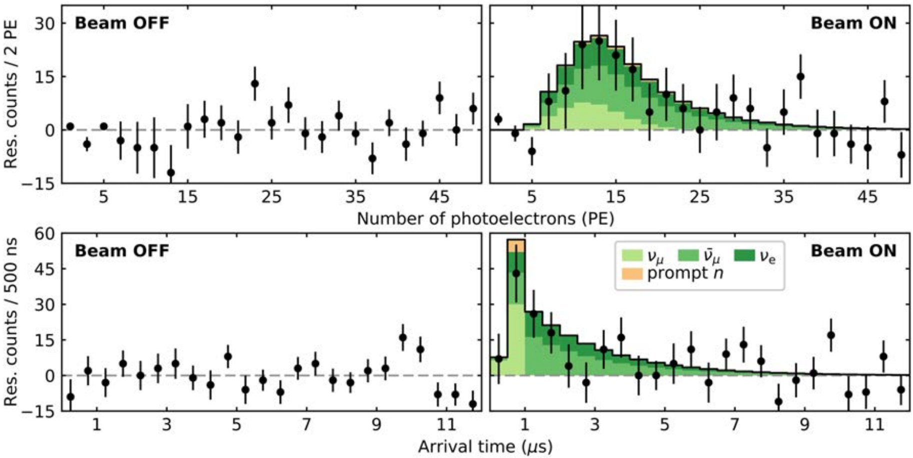
$$\frac{dN_{\nu_e}}{dE_\nu} = \eta\,\frac{192E_\nu^2}{m_\mu^3}\left(\frac{1}{2} - \frac{E_\nu}{m_\mu}\right)$$





COHERENT 2017: Cesium Iodide (CsI)

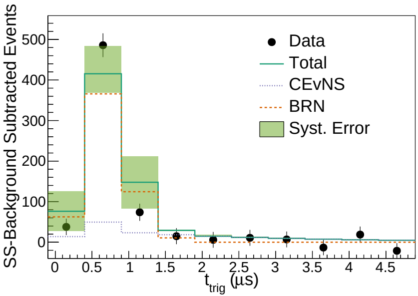
[arXiv:1708.01294]

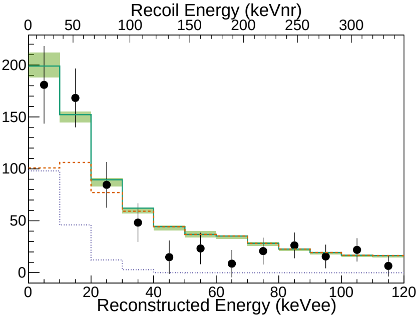


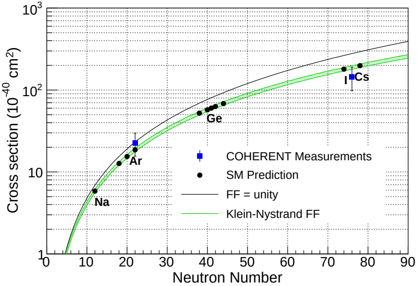
$^{133}_{55}\mathrm{Cs}_{78}$ and $^{127}_{53}\mathrm{I}_{74}$ $\leftarrow$ Heavy nuclei well suited for CEνNS

COHERENT 2020: Argon (Ar)

[arXiv:2003.10630]







${}^{40}_{18}\mathrm{Ar}_{22}$ not so heavy

Verified theoretical $\sigma \propto N^2$

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 $\mathcal{N}$:

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

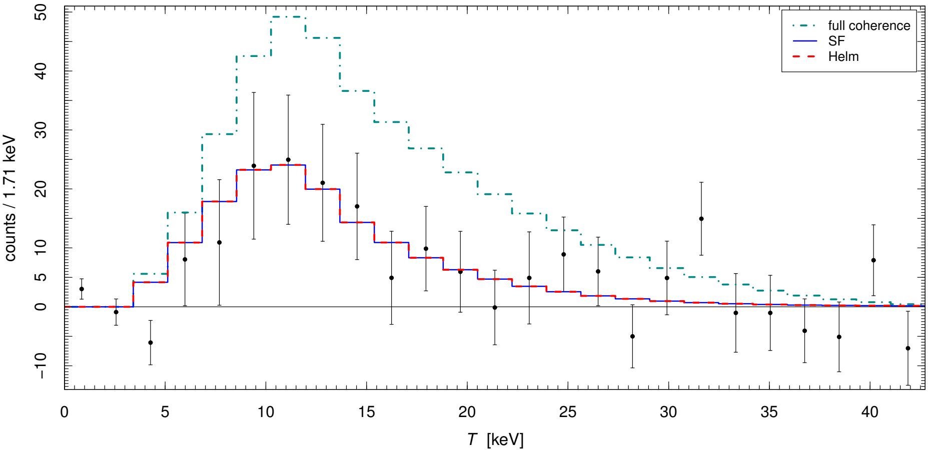
$$g_V^n = -\frac{1}{2} \qquad g_V^p = \frac{1}{2} - 2\sin^2\vartheta_W(Q^2 \simeq 0) = 0.0227 \pm 0.0002$$

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

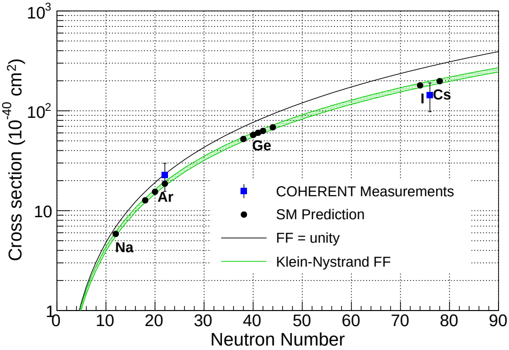
- The nuclear form factors $F_N(|\vec{q}|)$ and $F_Z(|\vec{q}|)$ describe the loss of coherence for $|\vec{q}|R \gtrsim 1$. [see: Bednyakov, Naumov, arXiv:1806.08768]

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

- For CsI:



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



[COHERENT, arXiv:2003.10630]

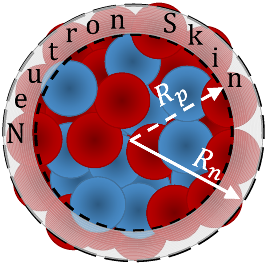
- Partial coherency is described by the nuclear neutron form factor
- $F_N(|\vec{q}|)$ is the Fourier transform of the neutron distribution in the nucleus $\rho_N(r)$:

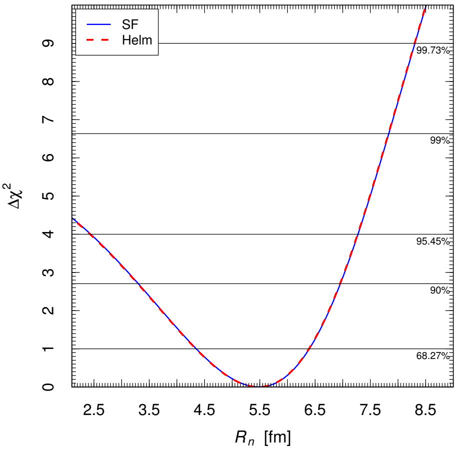
$$F_N(|\vec{q}|) = \int e^{-i\vec{q}\cdot\vec{r}}\, \rho_N(r)\, d^3r$$

- Measurable parameter: the radius R_n of the nuclear neutron distribution

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:

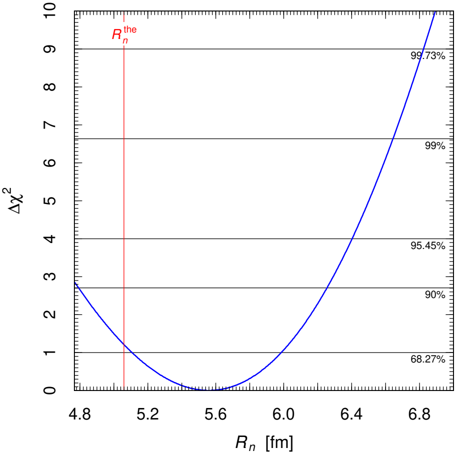
$$R_n(\mathrm{CsI}) = 5.5^{+0.9}_{-1.1}\,\mathrm{fm}$$

[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

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

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



- With new 2020 COHERENT CsI data: [Pershey @ Magnificent CEνNS 2020]

$$R_n(\mathrm{CsI}) = 5.55 \pm 0.44\,\mathrm{fm}$$

[Cadeddu et al, arXiv:2102.06153]

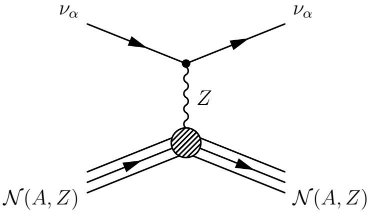
- The uncertainty is large, but it can be improved in future.
- Predictions of nuclear models:

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

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

BSM Neutrino Interactions in CEνNS

Standard Model NC



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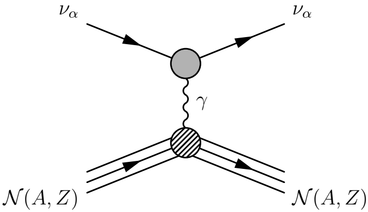
Electromagnetic Interactions



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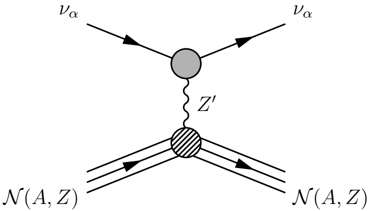
BSM Vector Mediator



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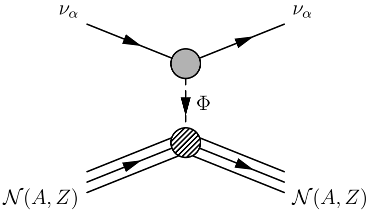
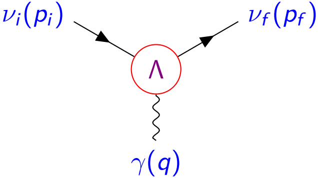
BSM Scalar Mediator



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:

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

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)

Electromagnetic Vertex Function

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

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

$q^2 = 0 \implies$ charge → q, anapole → a, magnetic → μ, electric → ε

- Hermitian form factors: $F_Q = F_Q^\dagger$, $F_A = F_A^\dagger$, $F_M = F_M^\dagger$, $F_E = F_E^\dagger$

- Majorana neutrinos: $F_Q = -F_Q^T$, $F_A = F_A^T$, $F_M = -F_M^T$, $F_E = -F_E^T$

  no diagonal charges and electric and magnetic moments in the mass basis

- For left-handed ultrarelativistic neutrinos $\gamma_5 \to -1 \Rightarrow$ The phenomenology of the charge and anapole are similar and the phenomenology of the magnetic and electric moments are similar.

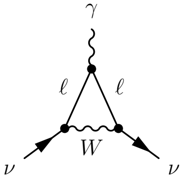
- For ultrarelativistic neutrinos the charge and anapole terms conserve helicity, whereas the magnetic and electric terms invert helicity.

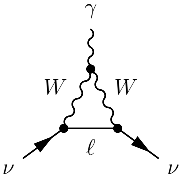
Neutrino Charge Radius

- 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

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





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

- In the Standard Model:

[Bernabeu et al, PRD 62 (2000) 113012, NPB 680 (2004) 450]

$$\langle r^2_{\nu_\ell} \rangle_{\text{SM}} = -\frac{G_{\text{F}}}{2\sqrt{2}\pi^2} \left[3 - 2 \log\left(\frac{m_\ell^2}{m_W^2} \right) \right]$$

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

Experimental Bounds

Method	Experiment	Limit [cm^2]	CL	Year
Reactor $\bar{\nu}_e\, e^-$	Krasnoyarsk	$\lvert\langle r^2_{\nu_e}\rangle\rvert < 7.3 \times 10^{-32}$	90%	1992
	TEXONO	$-4.2 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 6.6 \times 10^{-32}$	90%	2009
Accelerator $\nu_e\, e^-$	LAMPF	$-7.12 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 10.88 \times 10^{-32}$	90%	1992
	LSND	$-5.94 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 8.28 \times 10^{-32}$	90%	2001
Accelerator $\nu_\mu\, e^-$	BNL-E734	$-5.7 \times 10^{-32} < \langle r^2_{\nu_\mu}\rangle < 1.1 \times 10^{-32}$	90%	1990
	CHARM-II	$\lvert\langle r^2_{\nu_\mu}\rangle\rvert < 1.2 \times 10^{-32}$	90%	1994

[see the review CG, Studenikin, arXiv:1403.6344

and the update in Cadeddu, CG, Kouzakov, Y.F. Li, Studenikin, Y.Y. Zhang, arXiv:1810.05606]

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

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

- 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

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

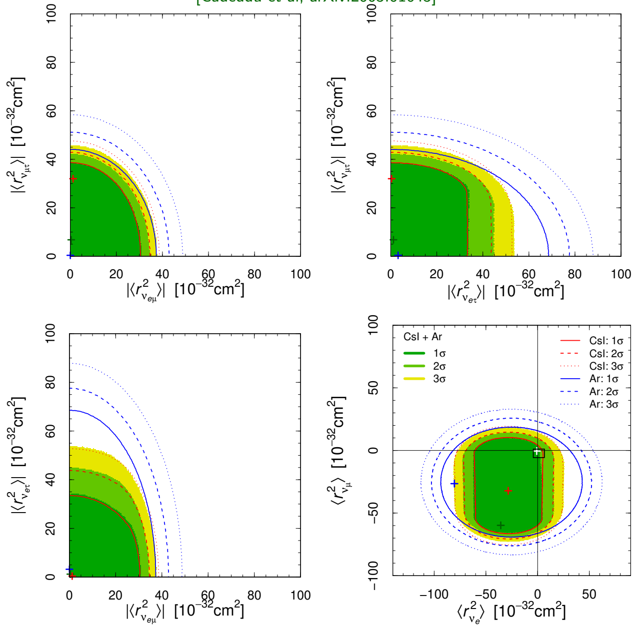
- Transition charge radii generate the incoherent contribution

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

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

COHERENT constraints on neutrino charge radii

[Cadeddu et al, arXiv:2005.01645]



Neutrino Electric Charges

- Neutrinos can be millicharged particles in theories beyond the Standard Model.
- Neutrino charge contributions to ν_ℓ–$\mathcal{N}$ CEνNS:

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

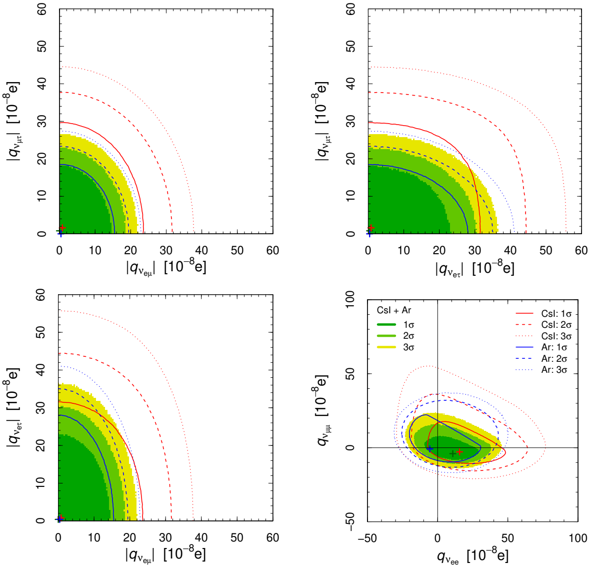
- $q_{\bar{\nu}_{\ell\ell'}} = -q_{\nu_{\ell\ell'}}$, but also $g_V^{p,n}(\bar{\nu}) = -g_V^{p,n}(\nu)$.

Approximate limits on neutrino millicharges

Limit	Method	Reference
$\lvert q_{\nu_e} \rvert \lesssim 3 \times 10^{-21}\, e$	Neutrality of matter	Raffelt (1999)
$\lvert q_{\nu_e} \rvert \lesssim 3.7 \times 10^{-12}\, e$	Nuclear reactor	Gninenko et al (2006)
$\lvert q_{\nu_e} \rvert \lesssim 1.5 \times 10^{-12}\, e$	Nuclear reactor	Studenikin (2013)
$\lvert q_{\nu_\mu} \rvert \lesssim 3 \times 10^{-8}\, e$	COHERENT CEνNS	Cadeddu et al (2020)
$\lvert q_{\nu_{\mu\tau}} \rvert \lesssim 2 \times 10^{-8}\, e$	COHERENT CEνNS	Cadeddu et al (2020)
$\lvert q_{\nu_\mu} \rvert \lesssim 3 \times 10^{-9}\, e$	LSND	Das et al (2020)
$\lvert q_{\nu_\tau} \rvert \lesssim 4 \times 10^{-6}\, e$	DONUT	Das et al (2020)
$\lvert q_{\nu_\tau} \rvert \lesssim 3 \times 10^{-4}\, e$	SLAC e^- beam dump	Davidson et al (1991)
$\lvert q_{\nu_\tau} \rvert \lesssim 4 \times 10^{-4}\, e$	BEBC beam dump	Babu et al (1993)
$\lvert q_{\nu} \rvert \lesssim 6 \times 10^{-14}\, e$	Solar cooling (plasmon decay)	Raffelt (1999)
$\lvert q_{\nu} \rvert \lesssim 2 \times 10^{-14}\, e$	Red giant cooling (plasmon decay)	Raffelt (1999)

COHERENT constraints on neutrino millicharges

[Cadeddu et al, arXiv:2005.01645]



- The bounds on the charges involving the electron neutrino flavor

  $q_{\nu_{ee}}$ $q_{\nu_{e\mu}}$ $q_{\nu_{e\tau}}$

  are not competitive with respect to those obtained in reactor neutrino experiments, that are at the level of $10^{-12}\,e$ in neutrino-electron elastic scattering experiments.

- The bounds on

  $q_{\nu_{\mu\mu}}$ $q_{\nu_{\mu\tau}}$

  are the first ones obtained from laboratory data.

Neutrino Magnetic and Electric Moments

- Extended Standard Model with Dirac massive neutrinos ($\Delta L = 0$):

$$\mu_{kk}^{\text{D}} \simeq 3.2 \times 10^{-19} \mu_{\text{B}} \left(\frac{m_k}{\text{eV}} \right) \qquad \varepsilon_{kk}^{\text{D}} = 0$$

$$\left.\begin{array}{c} \mu_{kj}^{\text{D}} \\ i\varepsilon_{kj}^{\text{D}} \end{array}\right\} \simeq -3.9 \times 10^{-23} \mu_{\text{B}} \left(\frac{m_k \pm m_j}{\text{eV}} \right) \sum_{\ell=e,\mu,\tau} U_{\ell k}^{*} U_{\ell j} \left(\frac{m_\ell}{m_\tau} \right)^2$$

off-diagonal moments are GIM-suppressed

[Fujikawa, Shrock, PRL 45 (1980) 963; Pal, Wolfenstein, PRD 25 (1982) 766; Shrock, NPB 206 (1982) 359; Dvornikov, Studenikin, PRD 69 (2004) 073001, JETP 99 (2004) 254]

- Extended Standard Model with Majorana massive neutrinos ($|\Delta L| = 2$):

$$\mu_{kj}^{\text{M}} \simeq -7.8 \times 10^{-23} \mu_{\text{B}}\, i \,(m_k + m_j) \sum_{\ell=e,\mu,\tau} \text{Im}\left[U_{\ell k}^{*} U_{\ell j} \right] \frac{m_\ell^2}{m_W^2}$$

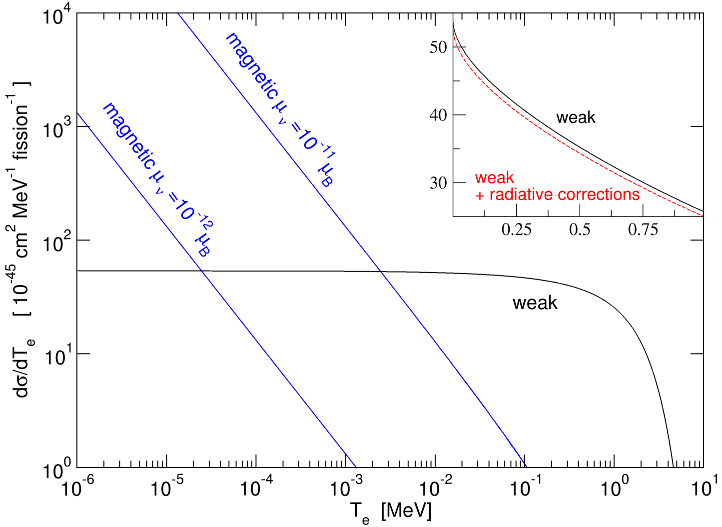
$$\varepsilon_{kj}^{\text{M}} \simeq 7.8 \times 10^{-23} \mu_{\text{B}}\, i \,(m_k - m_j) \sum_{\ell=e,\mu,\tau} \text{Re}\left[U_{\ell k}^{*} U_{\ell j} \right] \frac{m_\ell^2}{m_W^2}$$

[Shrock, NPB 206 (1982) 359]

GIM-suppressed, but additional model-dependent contributions of the scalar sector can enhance the Majorana transition dipole moments

[Pal, Wolfenstein, PRD 25 (1982) 766; Barr, Freire, Zee, PRL 65 (1990) 2626; Pal, PRD 44 (1991) 2261]

$$\left(\frac{d\sigma_{\nu e^-}}{dT_e}\right)_{\text{mag}} = \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_e} - \frac{1}{E_\nu}\right)\left(\frac{\mu_\nu}{\mu_B}\right)^2$$



Method	Experiment	Limit $[\mu_B]$	CL	Year
Reactor $\bar{\nu}_e\, e^-$	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
Accelerator $\nu_e\, e^-$	LAMPF	$\mu_{\nu_e} < 1.1 \times 10^{-9}$	90%	1992
Accelerator $(\nu_\mu, \bar{\nu}_\mu)\, e^-$	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 $(\nu_\tau, \bar{\nu}_\tau)\, e^-$	DONUT	$\mu_{\nu_\tau} < 3.9 \times 10^{-7}$	90%	2001
Solar $\nu_e\, e^-$	Super-Kamiokande	$\mu_S(E_\nu \gtrsim 5\,\text{MeV}) < 1.1 \times 10^{-10}$	90%	2004
	Borexino	$\mu_S(E_\nu \lesssim 1\,\text{MeV}) < 2.8 \times 10^{-11}$	90%	2017

[see the review CG, Studenikin, arXiv:1403.6344]

- Gap of about 8 orders of magnitude between the experimental limits and the $\lesssim 10^{-19}\,\mu_B$ prediction of the minimal Standard Model extensions.
- $\mu_\nu \gg 10^{-19}\,\mu_B$ discovery $\Rightarrow$ non-minimal new physics beyond the SM.
- Neutrino spin-flavor precession in a magnetic field

[Lim, Marciano, PRD 37 (1988) 1368; Akhmedov, PLB 213 (1988) 64]

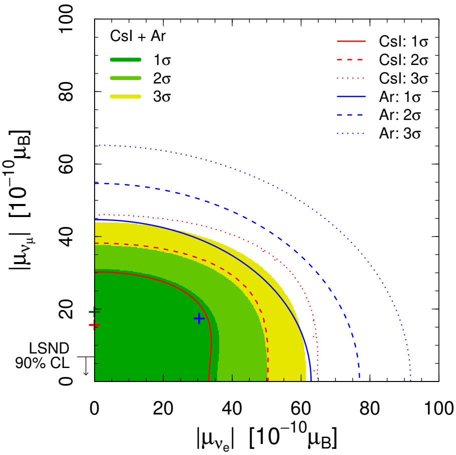
- Neutrino magnetic (and electric) moment contributions to CEνNS $\nu_\ell + \mathcal{N} \to \sum_{\ell'} \nu_{\ell'} + \mathcal{N}$:

$$\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\left[g_V^n N F_N(|\vec{q}|) + g_V^p Z F_Z(|\vec{q}|)\right]^2 + \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right) Z^2 F_Z^2(|\vec{q}|) \sum_{\ell' \neq \ell} \frac{|\mu_{\ell\ell'}|^2}{\mu_B^2}$$

- The magnetic moment interaction adds incoherently to the weak interaction because it flips helicity.
- The m_e is due to the definition of the Bohr magneton: $\mu_B = e/2m_e$.

COHERENT constraints on ν magnetic moments

[Cadeddu et al, arXiv:2005.01645]



- The sensitivity to $|\mu_{\nu_e}|$ is not competitive with that of reactor experiments:

$$|\mu_{\nu_e}| < 2.9 \times 10^{-11}\,\mu_B \quad (90\%\ \text{CL})$$

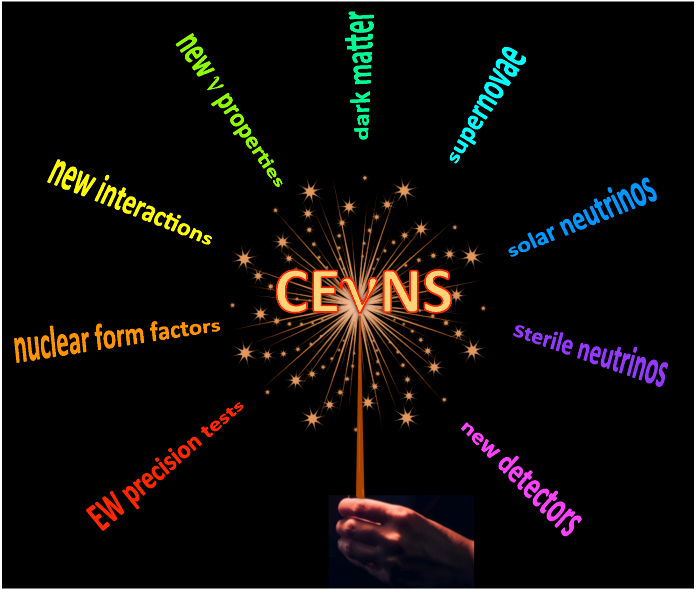
[GEMMA, AHEP 2012 (2012) 350150]

- The constraint on $|\mu_{\nu_\mu}|$ is not too far from the best current laboratory limit:

$$|\mu_{\nu_\mu}| < 6.8 \times 10^{-10}\,\mu_B \quad (90\%\ \text{CL})$$

[LSND, PRD 63 (2001) 112001]

Conclusions



[E. Lisi, Neutrino 2018]