Low-energy probes of sterile neutrino transition magnetic moments

Dimitrios K. Papoulias

University of Ioannina, Greece
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in collab. with O. Miranda, O. Sanders, M. Tórtola and J. Valle

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Outline

1. CEvNS and $\nu - e^-$ scattering within the sterile dipole portal
    - electromagnetic cross sections
    - formalism of transition magnetic moments (TMMs)
2. Results
    - expected signal in CEvNS and $\nu - e^-$ scattering experiments
    - extraction of constraints and projected sensitivities
    - comparison with other experiments
3. Summary

Electromagnetic contribution to CEνNS cross section

The Electromagnetic CEνNS cross section reads [Vogel, Engel.: PRD 39 [1989] 3378

$$\frac{\mathrm{d}\sigma_{\nu\mathcal{N}\to\nu\mathcal{N}}}{\mathrm{d}E_r} = \frac{\pi a_{\mathrm{EM}}^2 \mu_\nu^2 Z^2}{m_e^2}\left[\frac{1}{E_r} - \frac{1}{E_\nu}\right] F_p^2(Q^2)$$

Massive sterile neutrino in the final state?

[McKeen, Pospelov: PRD82 (2010)]

$$\frac{\mathrm{d}\sigma_{\nu\mathcal{N}\to\nu_s\mathcal{N}}}{\mathrm{d}E_r} = \frac{\pi a_{\mathrm{EM}}^2 \mu_\nu^2 Z^2}{m_e^2}\left[\frac{1}{E_r} - \frac{1}{E_\nu} - \frac{m_4^2}{2E_\nu E_r M}\left(1 - \frac{E_r}{2E_\nu} + \frac{M}{2E_\nu}\right) + \frac{m_4^4(E_r - M)}{8E_\nu^2 E_r^2 M^2}\right] F_p^2(Q^2)$$

The helicity preserving SM cross section adds incoherently with the helicity-violating EM cross section

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}E_r}\right)_{\mathrm{tot}} = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}E_r}\right)_{\mathrm{SM}} + \left(\frac{\mathrm{d}\sigma}{\mathrm{d}E_r}\right)_{\mathrm{EM}}$$

$\boldsymbol{\mu_\nu^2}$ is the effective neutrino magnetic moment in the mass basis relevant to a given neutrino beam (reactor, πDAR, solar etc.)

Electromagnetic neutrino vertex

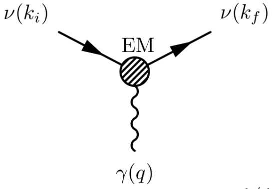
Dirac neutrinos: $H_{\mathsf{EM}}^{\mathrm{D}} = \frac{1}{2}\bar{\nu}_R \lambda \sigma^{\alpha\beta} \nu_L F_{\alpha\beta} + \mathrm{h.c.}$

- $\lambda = \mu - i\epsilon$ is an arbitrary complex matrix
- $\mu = \mu^\dagger$ and $\epsilon = \epsilon^\dagger$.

Majorana neutrinos: $H_{\mathsf{EM}}^{\mathrm{M}} = -\frac{1}{4}\nu_L^{\mathsf{T}} C^{-1} \lambda \sigma^{\alpha\beta} \nu_L F_{\alpha\beta} + \mathrm{h.c.}$

- $\lambda = \mu - i\epsilon$: antisymmetric complex matrix ($\lambda_{\alpha\beta} = -\lambda_{\beta\alpha}$)
- $\mu^{\mathsf{T}} = -\mu$ and $\epsilon^{\mathsf{T}} = -\epsilon$ are two imaginary matrices.
- three complex or six real parameters are required

In contrast to the Dirac case, vanishing diagonal moments are implied for Majorana neutrinos, $\mu_{ii}^{\mathrm{M}} = \epsilon_{ii}^{\mathrm{M}} = 0$.



[Schechter, Valle: PRD 24 (1981), PRD 25 (1982)]

Effective neutrino magnetic moment in terms of TMMs

Is expressed in terms of the neutrino magnetic moment matrix and the amplitudes of positive and negative helicity states $\mathfrak{a}_+$ and $\mathfrak{a}_-$,

- flavor basis [Grimus, Schwetz: Nucl. Phys. B587 (2000)]

$$\left(\mu_\nu^F\right)^2 = \mathfrak{a}_-^\dagger \lambda^\dagger \lambda \mathfrak{a}_- + \mathfrak{a}_+^\dagger \lambda \lambda^\dagger \mathfrak{a}_+ \,,$$

Introducing the transformations ($U_{4\times4}$ lepton mixing matrix)

$$\tilde{\mathfrak{a}}_- = U^\dagger \mathfrak{a}_-, \qquad \tilde{\mathfrak{a}}_+ = U^\mathsf{T} \mathfrak{a}_+, \qquad \tilde{\lambda} = U^\mathsf{T} \lambda U \,,$$

- mass basis

$$\left(\mu_\nu^M\right)^2 = \tilde{\mathfrak{a}}_-^\dagger \tilde{\lambda}^\dagger \tilde{\lambda} \tilde{\mathfrak{a}}_- + \tilde{\mathfrak{a}}_+^\dagger \tilde{\lambda} \tilde{\lambda}^\dagger \tilde{\mathfrak{a}}_+$$

- λ ($\tilde{\lambda}$): 4×4 antisymmetric transition magnetic moment (TMM) matrix flavor (mass) basis

TMMs in mass basis: reactor and π-DAR neutrinos

electron (anti)neutrinos: ν_e or $\bar{\nu}_e$

$$\left(\mu^M_{\nu_e \to \nu_s}\right)^2 \approx |\tilde{\lambda}_{14}|^2 \, c_{13}^2 c_{12}^2 + |\tilde{\lambda}_{24}|^2 \, c_{13}^2 s_{12}^2 + |\tilde{\lambda}_{34}|^2 \, s_{13}^2 \,,$$

muon (anti)neutrinos: ν_μ or $\bar{\nu}_\mu$

$$\begin{aligned}\left(\mu^M_{\nu_\mu \to \nu_s}\right)^2 \approx\ & |\tilde{\lambda}_{14}|^2 \left(c_{23} s_{13} s_{23} \sin 2\theta_{12} \cos\delta + c_{23}^2 s_{12}^2 + c_{12}^2 s_{13}^2 s_{23}^2\right) \\ & + |\tilde{\lambda}_{24}|^2 \left(-c_{23} s_{13} s_{23} \sin 2\theta_{12} \cos\delta + c_{23}^2 c_{12}^2 + s_{12}^2 s_{13}^2 s_{23}^2\right) \\ & + |\tilde{\lambda}_{34}|^2 c_{13}^2 s_{23}^2 \,.\end{aligned}$$

we are interested in TMMs from active to sterile states

- active-active terms with $\tilde{\lambda}_{12}$, $\tilde{\lambda}_{13}$ and $\tilde{\lambda}_{23}$ ignored
- cross terms $\tilde{\lambda}_{i4}\tilde{\lambda}_{j4}$ ignored
- assumed $\sin^2\theta_{i4} \leq 0.01$ (OK for keV sterile neutrinos)

[Miranda, DKP, Sanders, Tórtola, Valle: arXiv: 2109.09545 [hep-ph]]

TMMs in mass basis: solar neutrinos

general expression including oscillation effects

$$\left(\mu^{M}_{\nu,\text{eff}}\right)^2 (L, E_\nu) = \sum_j \left| \sum_i K^*_{\alpha i} e^{-i\,\Delta m^2_{ij} L/2E_\nu}\, \tilde{\lambda}_{ij} \right|^2$$

- 3×(3+m) rectangular matrix K is the upper truncation of the (3+m)×(3+m) unitary matrix diagonalizing the neutrinos
- m is the number of sterile neutrinos
- charged leptons are in their mass-diagonal basis
- i and j run over the total number of neutrino mass eigenstates.

for one sterile neutrino (m=1)

$$\begin{aligned}(\mu^{M}_{\nu,\,\text{sol}})^2 \quad &= \quad P_{e1}(|\tilde{\lambda}_{12}|^2 + |\tilde{\lambda}_{13}|^2 + |\tilde{\lambda}_{14}|^2) + P_{e2}(|\tilde{\lambda}_{12}|^2 + |\tilde{\lambda}_{23}|^2 + |\tilde{\lambda}_{24}|^2) \\ &+ \quad P_{e3}(|\tilde{\lambda}_{13}|^2 + |\tilde{\lambda}_{23}|^2 + |\tilde{\lambda}_{34}|^2) + P_{e4}(|\tilde{\lambda}_{14}|^2 + |\tilde{\lambda}_{24}|^2 + |\tilde{\lambda}_{34}|^2)\,,\end{aligned}$$

- P_{ei}: solar neutrino transition probability from the originally created ν_e state to the mass eigenstate ν_i

[Miranda, DKP, Sanders, Tórtola, Valle: arXiv: 2109.09545 [hep-ph]]

Interference between magnetic and weak interactions

Non-zero contribution for massive final state neutrinos

[Grimus, Stockinger: PRD 57 [1998]]

$$\left(\frac{\mathrm{d}\sigma_{\bar{\nu}_e e^- \to \nu_s e^-}}{\mathrm{d}E_r}\right)^{\text{interf}} = \frac{\alpha_{\text{em}} G_F\, m_4}{\sqrt{2}E_\nu\, m_e} \mathrm{Re}\left[\sum_{j,n} e^{-i\frac{\Delta m^2_{jn} L}{2E_\nu}} U_{ej} U^*_{en}\, \tilde{\lambda}_{j4} \left(\frac{m_e}{E_\nu} - \frac{E_r}{E_\nu}\right) Z^{V*}_{n4} + \left(2 - \frac{E_r}{E_\nu}\right) Z^{A*}_{n4}\right]$$

- $Z^{V,A}_{jk} = U_{ej} U^*_{ek} + \delta_{jk} \tilde{g}_{V,A}$ with $\tilde{g}_V = -1/2 + 2\sin^2\theta_W$ and $\tilde{g}_A = -1/2$
- For $\nu_e - e^-$ scattering: $\tilde{g}_A \to -\tilde{g}_A$ and $Z^{V,A}_{jk} \to (Z^{V,A}_{jk})^*$

- incident ν_e or $\bar{\nu}_e$: $\frac{\mathrm{d}\sigma}{\mathrm{d}E_r} \propto \frac{m_4}{m_e} \sin 2\theta_{14}$
- incident ν_μ or $\bar{\nu}_\mu$, $\frac{\mathrm{d}\sigma}{\mathrm{d}E_r} \propto \frac{m_4}{m_e} c_{14} s^2_{24}$
- interference is vanishing for the case of solar neutrinos

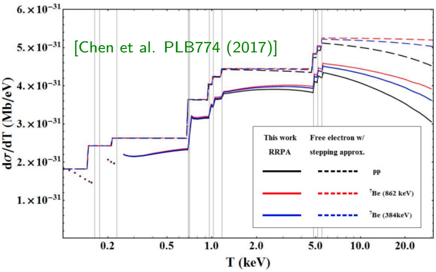
For CEνNS one needs the replacements

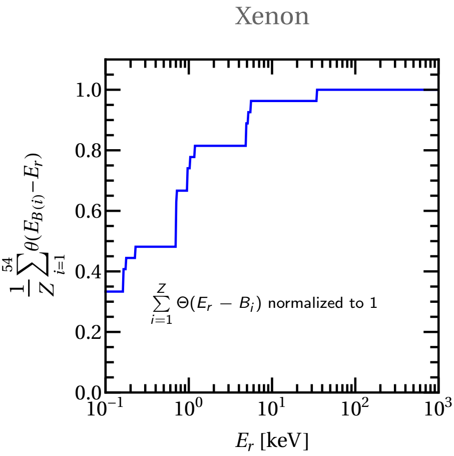
- $\tilde{\lambda}_{ij} \to \tilde{\lambda}_{ij} Z F_p(q^2)$
- $\tilde{g}_V \to \mathcal{Q}_V$ and $\tilde{g}_A \to \mathcal{Q}_A$
- $m_e \to M$

Binding effects in neutrino electron scattering

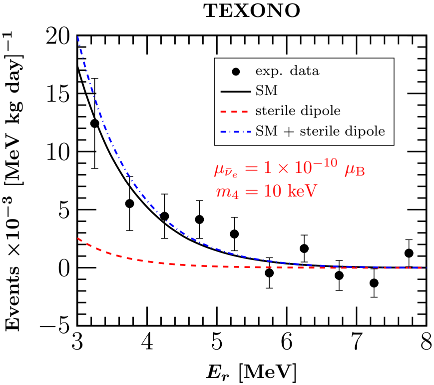
$$\left(\frac{\mathrm{d}\sigma_{\nu_\alpha - e^-}}{\mathrm{d}E_r}\right)_{\text{SM}} = \frac{1}{Z}\sum_{i=1}^{Z}\Theta(E_r - B_i)\left(\frac{\mathrm{d}\sigma_{\nu_\alpha - e^-}}{\mathrm{d}E_r}\right)_{\text{SM}}^{\text{free}}$$

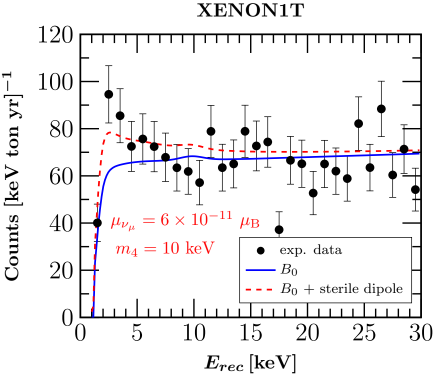
- B_i: binding energy of ith atomic (sub)shell.
- takes into account only those electrons that can be ionized by an energy deposition E_r
- effect important below a few keV recoil energies





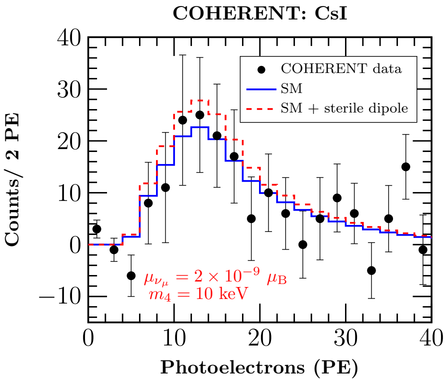
Neutrino electron scattering: TEXONO & XENON1T

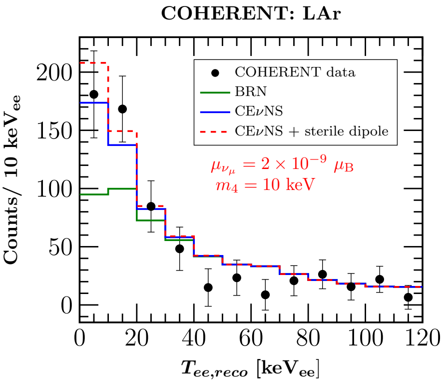




[Miranda, DKP, Sanders, Tórtola, Valle: arXiv: 2109.09545 [hep-ph]]

CEvNS: COHERENT

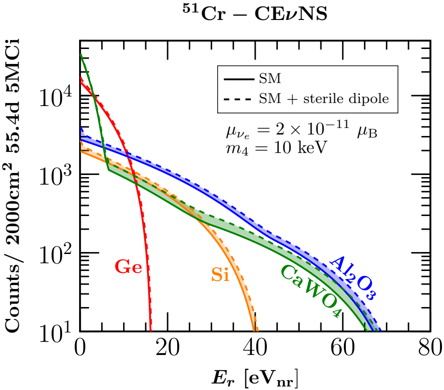


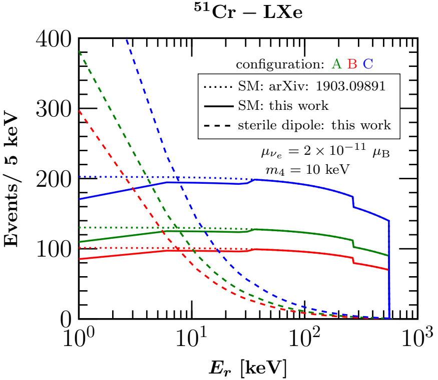


[Miranda, DKP, Sanders, Tórtola, Valle: arXiv: 2109.09545 [hep-ph]]

CEvNS and $\nu - e^-$ scattering: ^{51}Cr source

[Miranda, DKP, Sanders, Tórtola, Valle: arXiv: 2109.09545 [hep-ph]]





configurations from

[Bellenghi et al. Eur.Phys.J.C 79 (2019)]

- cylindrical $2000\ \mathrm{cm}^3$ detector 25 cm from a 5 MCi ^{51}Cr source
- flux: $1.1 \times 10^{13}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- threshold: $E_r^{\text{thres}} = 8\ \mathrm{eV_{nr}}$
- exposure time: 2 half-lives i.e. 55.4 days

configurations from

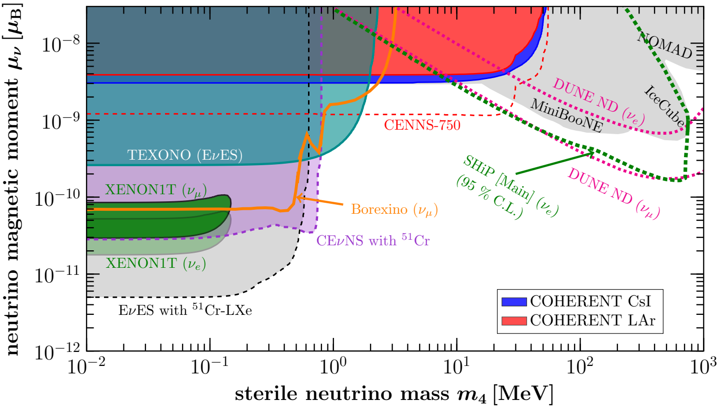
[Link and Xu JHEP 08 (2019)]

	R^0_{Cr51}	Δt
Configuration A	5 MCi ^{51}Cr	100 days
Configuration B	5 MCi ^{51}Cr	50 days
Configuration C	10 MCi ^{51}Cr	50 days

Sensitivity: effective case

[Miranda, DKP, Sanders, Tórtola, Valle: arXiv: 2109.09545 [hep-ph]]

The global picture of the sterile dipole portal



Complementary constraints to large-scale experiments

- COHERENT covers a wide region in sterile neutrinos mass space
- ^{51}Cr-based CEvNS and EvES experiments can probe the XENON1T excess

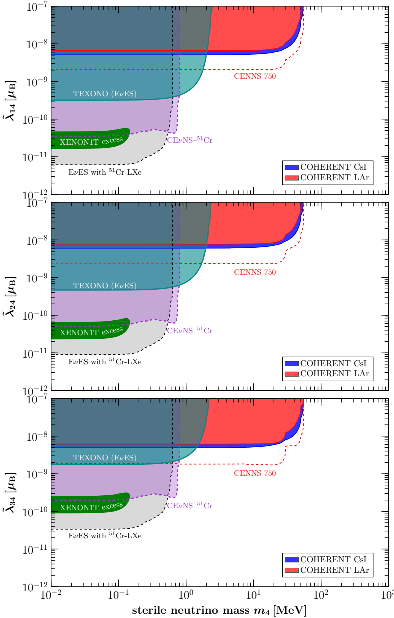
- **other bounds from:** DUNE (2105.09699 & 2105.09357), SHiP/NOMAD (1803.03262), Borexino (2007.15563), IceCube (1707.08573)

Sensitivity: TMMs

Advantages of TMM formalism

- is a complete formalism based on fundamental parameters
- allows direct comparisons when using different neutrino source

[Miranda, DKP, Sanders, Tórtola, Valle: arXiv: 2109.09545 [hep-ph]]



Summary

Analysis

- presented the effective μ_ν formalism in terms of fundamental parameters relevant to reactor, π-DAR and solar neutrinos
- considered CEvNS and EvES with a massive sterile neutrino final state

Results

- COHERENT can cover a large space in sterile mass, previously unexplored
- Reactor experiments are more sensitive to the magnetic moment
- ^{51}Cr-based neutrino experiments can probe XENON1T
- complementarity with large-scale experiments (DUNE, IceCube, NOMAD, SHiP)

Thank you for your attention !

Extras