Probing Neutrino Magnetic Moments with Coherent Elastic Neutrino-Nucleus Scattering

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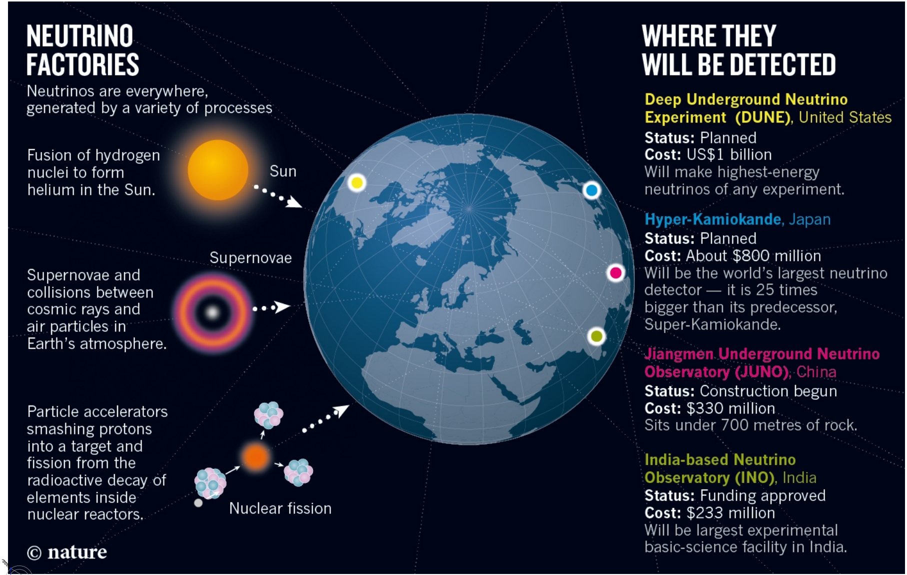
Outline

1. Coherent Elastic Neutrino Nucleus Scattering
2. Neutrino Magnetic Moments
3. Differential Rate
4. Numerical Results
5. Summary

Coherent Elastic Neutrino Nucleus Scattering (CEνNS)

Neutrino Sources



NEUTRINO FACTORIES

Neutrinos are everywhere, generated by a variety of processes

Fusion of hydrogen nuclei to form helium in the Sun.

Supernovae and collisions between cosmic rays and air particles in Earth's atmosphere.

Particle accelerators smashing protons into a target and fission from the radioactive decay of elements inside nuclear reactors.

WHERE THEY WILL BE DETECTED

Deep Underground Neutrino Experiment (DUNE), United States
Status: Planned
Cost: US$1 billion
Will make highest-energy neutrinos of any experiment.

Hyper-Kamiokande, Japan
Status: Planned
Cost: About $800 million
Will be the world's largest neutrino detector — it is 25 times bigger than its predecessor, Super-Kamiokande.

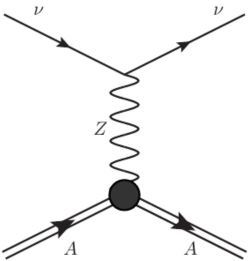
Jiangmen Underground Neutrino Observatory (JUNO), China
Status: Construction begun
Cost: $330 million
Sits under 700 metres of rock.

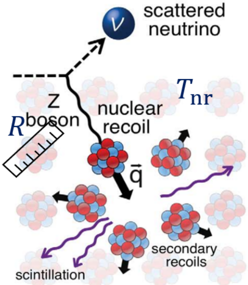
India-based Neutrino Observatory (INO), India
Status: Funding approved
Cost: $233 million
Will be largest experimental basic-science facility in India.

© nature

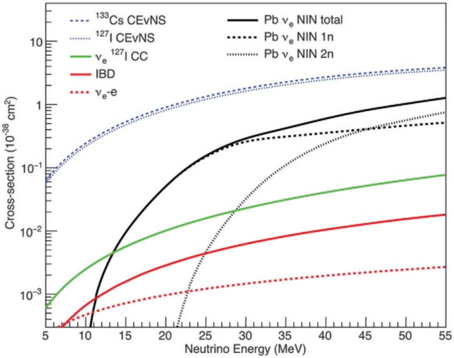
CEνNS Process

- Theoretically proposed in 1974 in the Standard Model (SM) framework. (Freedman, Phys.Rev.D 9 (1974))
- In the process, neutrinos collide with nucleus via Z boson followed by recoil nucleus.
- Incoming neutrinos interact with nucleus as a whole without changing its internal state.
- It can occur at low enough Q^2 where the de Broglie wavelength is large compared to nuclear radius.





- It provides relatively large σ among other neutrino interaction processes.
- Hard to detect; the nuclear recoil energy, T_{nr}, is around a few keV.
- Successfully detected by COHERENT Collaboration in 2017. (D. Akimov *et al.*, Science 357 (2017)).

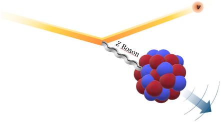


- The heavier the target, the greater the boost in the cross-section but the smaller the recoils.
- The CEνNS process is well predicted in the SM. Therefore, a measured deviation from it can provide a test of beyond SM (BSM) physics.

CEνNS Cross-Section

- CEνNS is a pure weak neutral current process mediated by a Z boson.
- The SM CEνNS differential cross section is given by

$$\left[\frac{d\sigma_{\nu\mathcal{N}}}{dT_{nr}}\right]_{SM} = \frac{G_F^2 m_N}{\pi}\left(Q_V^{SM}\right)^2 F^2(|\vec{q}|^2)\left(1-\frac{m_N T_{nr}}{2E_\nu^2}\right) \tag{1}$$



Weak charge of the nucleus

$$Q_V^{SM} = g_V^p Z + g_V^n N \tag{2}$$

with the proton and neutron couplings

$$g_V^p = 1/2(1-4sin^2\theta_W), g_V^n = -1/2 \tag{3}$$

Form Factor

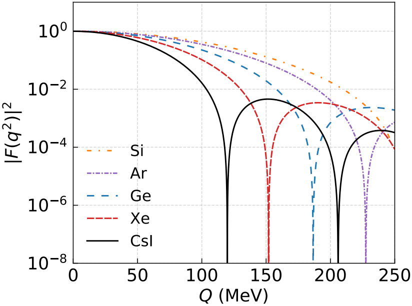
- The $F(|\vec{q}|^2)$ describes the structure of the nucleus.
- We use the Helm parameterization (Helm, 1956)

$$F(|\vec{q}|^2) = 3\frac{j_1(|\vec{q}|R)}{|\vec{q}|R} e^{-\frac{1}{2}|\vec{q}|^2 s^2}, \tag{4}$$

where j_1 is the first order Spherical Bessel function, and the momentum transfer is

$$Q^2 \equiv -q^2 = 2m_N T_{nr}. \tag{5}$$

- The CEνNS process is focused in the region $Q \lesssim 50$ MeV. For this scale, it can be taken to be $F^2(|\vec{q}|^2) \approx 1$.



N^2 Dependence

- A deviation from $\propto N^2$ prediction can be a signature of beyond-the-SM physics (Scholberg, 2021).
- $Q_V^2 = \Big(N - (1 - 4\sin^2\theta_W)Z\Big)^2$, $\sin^2\theta_W = 0,23857$

$$Q_V \propto N, \sigma \propto Q_V^2 \rightarrow \sigma \propto N^2 \tag{6}$$

- Verify the expected neutron-number dependence of cross-section:

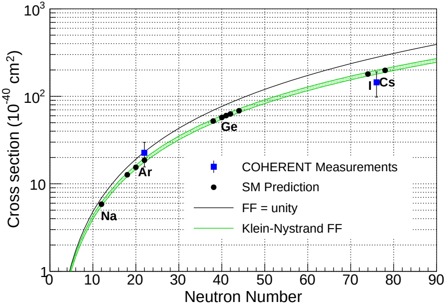
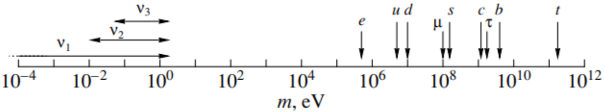


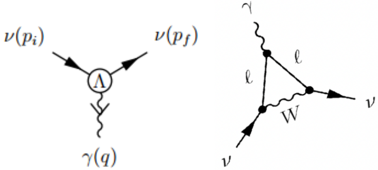
Figure from COHERENT, PRL 126, 012002 (2021).

Neutrino Magnetic Moments

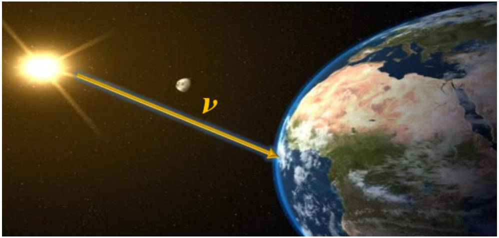
EM Properties of Neutrino

- Non vanishing mass of neutrinos are indicated by neutrino oscillation process (Pontecorvo, 1957; Maki *et. al.* 1962).
- This fact leads to the requirement of SM extension, since neutrinos are massless in the SM.
- Electromagnetic properties (magnetic moment, charge radius, milicharge) are one of the possibilities (Giunti & Studenikin, 2015).





- For neutrinos the electric charge is zero and there are no electromagnetic interactions at tree-level.
- Such interactions comes from quantum loops effects that allow neutrinos direct interaction with photon and charged particles.
- Important consequences can be observed in astrophysical environments, in which neutrinos propagate over long distances in vacuum and in matter (Jana, 2022).



Review of Sterile Neutrino

- It is possible that there are additional massive neutrinos, such as those at the eV scale suggested by anomalies found in short-baseline oscillation experiments (Aguilar, et. al., 2001; Abdurashitov, et. al., 2006).
- In the flavor basis the additional neutrinos are sterile. Measurement of the invisible width of the Z-boson that the number of light active neutrinos is three (Schael, et. al., 2006) and the existence of a heavy fourth generation of active fermions with an active neutrino heavier than $m_Z/2$ is disfavored by the experimental data (Lenz, 2013).
- From the theoretical point of view, it is likely that if there are sterile neutrinos, all neutrinos are Majorana particles, but the Dirac case is not excluded (Giunti and Studenikin, 2015).

Neutrino Magnetic Moment

- In mininal SM extensions in which neutrinos acquires Dirac masses through right-handed neutrinos the MM is given by (Rev.Mod.Phys. 87 (2015) 531)

$$\mu_\nu = \frac{3eG_F}{8\sqrt{2}\pi^2} m_\nu \cong 3.2 \times 10^{-19} (\frac{m_\nu}{eV}) \mu_B. \tag{7}$$

- The Lagrangian for the neutrino magnetic moment ($\sigma^{\alpha\beta} = i[\gamma^\alpha, \gamma^\beta]/2$) (Harnik *et. al.*, 2011):

$$\mathcal{L} \supset \mu_\nu \bar{\nu} \sigma^{\alpha\beta} \partial_\beta A_\alpha \nu, \tag{8}$$

  The photon A_α mediates the new interaction.
- The effective magnetic moment μ_ν is given in unit of Bohr magneton $\mu_B = \sqrt{4\pi\alpha_{\rm EM}}/(2m_e)$.
- For magnetic moment from the sterile neutrino (Phy. Rev. D 106,095022 (2022)):

$$\mathcal{L} \supset d \bar{\nu}_l \sigma^{\mu\nu} \nu_4 F_{\mu\nu}, \quad d^2 = \frac{\pi \alpha_{\mathsf{EM}}}{m_e^2} \left| \frac{\mu_{\nu l_4}}{\mu_B} \right|^2 . \tag{9}$$

The Cross-section

Many BSM theories predict a MM larger than the value in Eq(9). It adds incoherently to the cross-section:

- Contribution of the active neutrino magnetic moment is calculated by

$$\left[\frac{d\sigma}{dT_{nr}}\right]^{\nu_{\mathrm{a}}\mathrm{MM}} = \frac{\pi\alpha_{\mathrm{EM}}^2}{m_e^2}\left|\frac{\mu_{\nu_\ell}}{\mu_B}\right|^2 Z^2|F(|\vec{q}|^2)|^2\left(\frac{1}{T_{nr}}-\frac{1}{E_\nu}\right). \qquad (10)$$

  This may lead to detectable distortions of the recoil spectrum. μ_ν^2 is an effective neutrino magnetic moment relevant to a given neutrino beam.

- Regarding the case of sterile neutrino, with state ν_4 and mass m_4, the cross-section is obtained as

$$\begin{aligned}\left[\frac{d\sigma}{dT_{nr}}\right]^{\nu_{\mathrm{s}}\mathrm{MM}} &= \frac{\pi\alpha_{\mathrm{EM}}^2}{m_e^2}\left|\frac{\mu_\nu}{\mu_B}\right|^2 Z^2|F(|\vec{q}|^2)|^2\left(\frac{1}{T_{nr}}-\frac{1}{E_\nu}\right.\\ &\left.-\frac{m_4^2}{2E_\nu m_N T_{nr}}\left(1-\frac{m_N-T_{nr}}{2E_\nu}\right)-\frac{m_4^4(m_N-T_{nr})}{8E_\nu^2 m_N^2 T_{nr}^2}\right). \qquad (11)\end{aligned}$$

- Kinematic constraint of the sterile case is

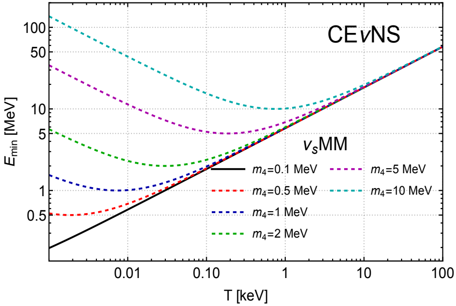
$$m_4^2 \lesssim 2m_N T_{nr} \left(\sqrt{\frac{2}{m_N T_{nr}}} E_\nu - 1 \right) , \tag{12}$$

- The minimum neutrino energy induced by ν_4 is

$$E_\nu^{min} = \frac{m_4^2 + 2m_N T_{nr}}{2(\sqrt{T_{nr}(T_{nr} + 2m_N)} - T_{nr})} , \tag{13}$$

which is higher than the active neutrino case.

- The E_ν^{min} continuously decreases as the increase of the recoil energy, until E_ν^{min} reaches the extreme value $E_\nu^{min} = m_4 + m_4^2/2m_N$.



Differential Rate

Differential Rate

- The differential rate of the CEνNS in general can be written as

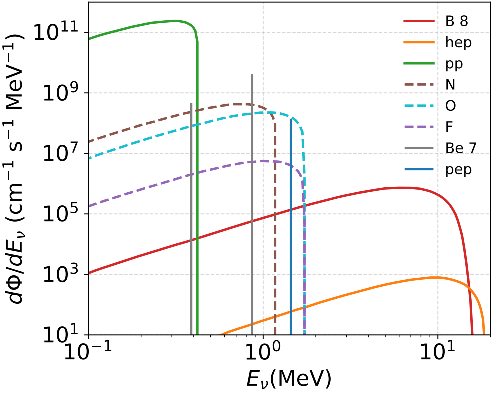
$$\frac{dR}{dT_{nr}} = \frac{\epsilon}{m_T} \int_{E_\nu^{min}}^{E_\nu^{max}} dE_\nu \frac{d\Phi(E_\nu)}{dE_\nu} \frac{d\sigma(E_\nu, T_{nr})}{dT_{nr}}, \tag{14}$$

  where $d\Phi(E_\nu)/dE_\nu$ represents solar neutrino flux. Here we consider BS05(OP) solar neutrino (Bahcall & Serenelli, 2005).
- In this equation, the ϵ is the exposure of the experiment, and m_T is the target nuclei.
- The nuclear recoil energy is converted from electron equivalent one with quenching factor.

Solar Neutrino Flux

Solar neutrinos: huge flux of neutrinos coming from the Sun spanning on a wide range of energies up to 20 MeV.

- Solar neutrino flux from BS05(OP) standard solar model.
- On the Earth, neutrino flux from ^{8}B and hep are the most observable.

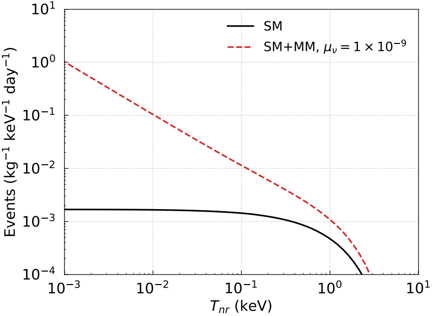


Numerical Results

Event Rate

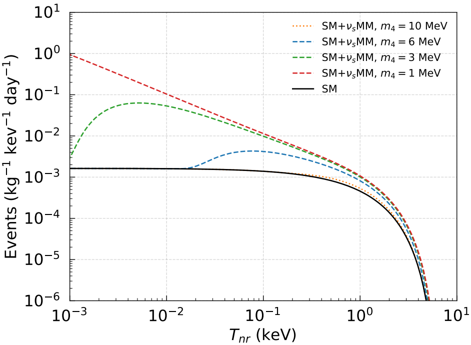
Predicted event rate of the ν_aMM as a function of the nuclear recoil energy for $\mu_\nu = 10^{-9}\mu_B$ (with μ_B is the Bohr magneton).

- The contribution of active neutrino magnetic moment (ν_aMM) is suppressed by the recoil energy T_{nr}.
- The effect of ν_aMM would become significant at low recoil energy.
- One needs the low threshold experiments for improved exploration.



Predicted event rate of the ν_sMM as a function of the nuclear recoil energy for $\mu_\nu = 10^{-9}\mu_B$ and several sterile neutrino masses.

- The ν_sMM contribution decreases with the increment of sterile neutrino masses.
- The contribution of the ν_sMM is similar to that of the ν_aMM case.
- However, the effect of the ν_sMM is suppressed at low recoil energies due to the presence of the sterile neutrino mass in the E_ν^{min} relation (13).



Statistical Analysis

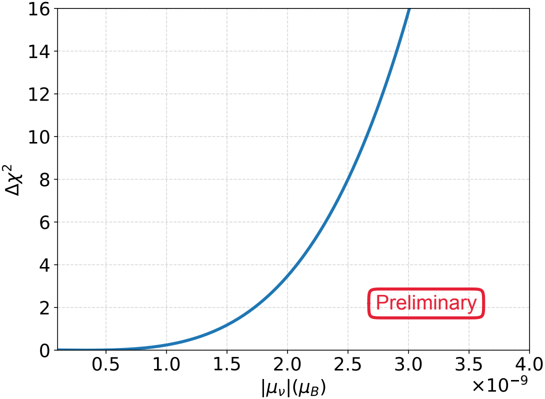
- We adopt the pull approach of the χ^2 function

$$\chi^2 = \min_{(\xi_j)} \sum_{i=1}^{20} \left(\frac{R^i_{obs} - R^i_{exp} - B - \sum_j \xi_j c^i_j}{\Delta^i} \right)^2 + \sum_j \xi_j \qquad (15)$$

.

- R^i_{obs} and R^i_{exp} are the observed and expected event rates, respectively.
- We use 20 data points from CDEX-10 experiment (Geng *et.al.*, 2023) for R^i_{obs} .
- Δ^i denotes the experimental uncertainty.
- The solar neutrino flux uncertainty is represented by c^i_j.

- The constraint on active neutrino magnetic moment

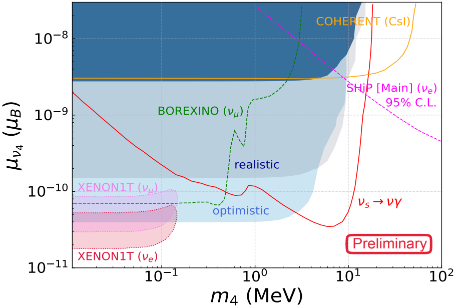


- The upper limit is obtained as $|\mu_\nu|(\mu_B) \lesssim 1.874 \times 10^{-9}$ at 90% CL.

Best limits @time of the paper: $|\mu_{\nu_e}| < 0.29 \times 10^{-10} \mu_B$ **GEMMA** @ 90% CL (reactor $\bar{\nu}$-e scattering) - also TEXONO and CONUS (CEvNS)

$|\mu_{\nu_\mu}| < 6.8 \times 10^{-10} \mu_B$ **LSND** @ 90% CL (accelerator ν_e-e scattering).

- We derive the new bound on sterile neutrino case from the recent CDEX10 data.
- We superimpose our projected sensitivities from realistic (%10) and optimistic (%1) scenarios.
- The upper-limit for the 90% C.L. with 2 d.o.f is found to be $\mu_{\nu_4} \lesssim 2.79 \times 10^{-9}$.



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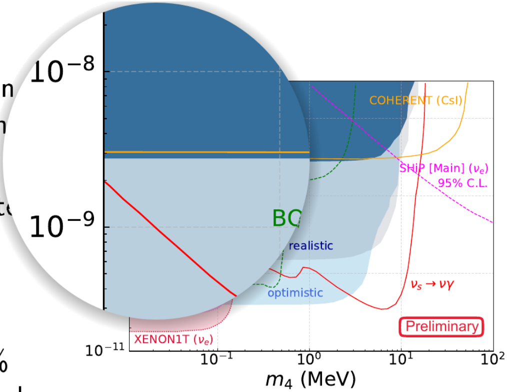

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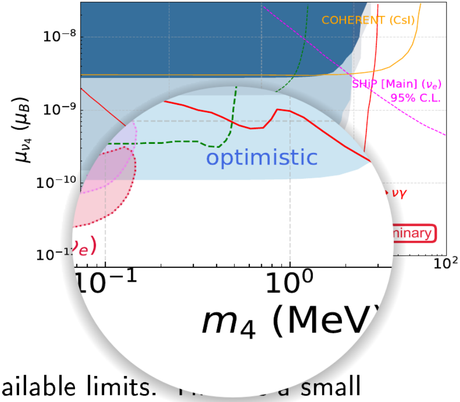

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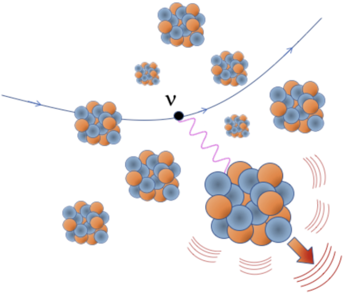
- For optimistic scenario, there is an improvement to the considered existing limits in the mass range of 0.2 -3 MeV.

Summary

Summary

- We have studied the magnetic moments for active and sterile neutrinos in the framework of CEνNS.
- Their effects to CEνNS are studied using solar-neutrino flux with CDEX10 data.
- Behavior of these properties are shown in the event-rate spectrum.
- We derive new constraints on magnetic moments of the active and sterile neutrinos.
- Although some of the limits obtained are not competitive with available results yet, they provide complementary and relevant information.
- The CEνNS process proves to be once again an important tool for testing sectors beyond SM with highly competitive precision.

Thank you for your attention!



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