Measurement of the neutrino magnetic moment at the NOvA experiment

Technical note

Robert Kralik[1]

[1]University of Sussex, Brighton, UK

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Abstract

This is the abstract

Contents

1 Introduction

Main motivations for the analysis. Briefly mention that there was a previous study by Biao, what were the results there and what limitations (or maybe talk about this in the Experimental overview?).

Maybe briefly mention the overview of the theory and experimental overview.

2 Literature review

2.1 Theoretical overview

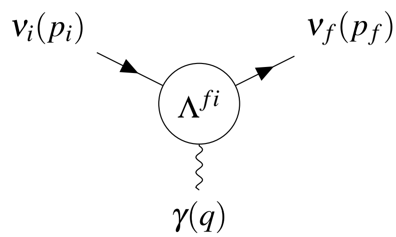

Figure 1: Effective coupling of neutrinos with one photon electromagnetic field.

2.2 Electromagnetic properties of the neutrino

In the standard model, neutrino can have electromagnetic interaction only at a higher order of the perturbative expansion of the interaction - from loop diagrams.

In the one photon approximation, the electromagnetic interactions of a neutrino field $(\nu_k(x), k \in \{1,...,N\})$, for N neutrino mass states, can be described by the effective interaction Hamiltonian [1]

$$\mathscr{H}_{em}^{(\nu)}(x) = \sum_{k,j=1}^{N} \overline{\nu}_k(x)\Lambda_\mu^{kj}\nu_j(x)A^\mu(x) \tag{1}$$

and the amplitude of neutrino-to-neutrino interaction for **Dirac** neutrinos shown on fig.1 is

$$\langle \nu_f(p_f)|j_\mu^{(\nu)}(x)|\nu_i(p_i)\rangle = e^{i(p_f-p_i)x}\overline{u}_f(p_f)\Lambda_\mu^{fi}(p_f,p_i)u_i(p_i), \tag{2}$$

where p_f and p_i are the final and initial four momentums respectively and $u/\overline{u}$ are the solutions to the Dirac equation for a free particle. We take into account possible transitions between different mass states ν_i and ν_f [1].

The vertex function $\Lambda_\mu^{fi}(p_f,p_i)$ is a matrix and in the most general case it can be written in terms of linearly independent products of Dirac matrices (γ) and four momentum of the photon $(q = p_f - p_i)$:

$$\begin{aligned}\Lambda_\mu^{fi}(p_f,p_i) =& \mathbb{F}_1^{fi}(q^2)q_\mu + \mathbb{F}_2^{fi}(q^2)q_\mu\gamma_5 + \mathbb{F}_3^{fi}(q^2)\gamma_\mu + \mathbb{F}_4^{fi}(q^2)\gamma_\mu\gamma_5 + \\ & \mathbb{F}_5^{fi}(q^2)\sigma_{\mu\nu}q^\nu + \mathbb{F}_6^{fi}(q^2)\varepsilon_{\mu\nu\rho\gamma}q^\nu\sigma^{\rho\gamma},\end{aligned} \tag{3}$$

where $\mathbb{F}_i^{fi}(q^2)$ are six Lorentz invariant form factors. For $f = i$ they are called "diagonal" and for $f \neq i$ "transition form factors" [1].

Applying conditions of hermiticity $\left(\mathscr{H}_{em}^{(\nu)\dagger} = \mathscr{H}_{em}^{(\nu)}\right)$ and of conservation of the current (continuity equation: $\partial^\mu j_\mu^{(\nu)}(x) = 0$), we can rewrite the vertex function as

$$\Lambda_\mu^{fi}(q) = \left(\gamma_\mu - q_\mu \not{q}/q^2\right)\left[\mathbb{F}_Q^{fi}(q^2) + \mathbb{F}_A^{fi}(q^2)q^2\gamma_5\right] - i\sigma_{\mu\nu}q^\nu\left[\mathbb{F}_M^{fi}(q^2) + i\mathbb{F}_E^{fi}(q^2)\gamma_5\right], \tag{4}$$

where $\mathbb{F}_Q^{fi}, \mathbb{F}_M^{fi}, \mathbb{F}_E^{fi}$ and $\mathbb{F}_A^{fi}$ are hermitian matrices representing the real charge, dipole magnetic, dipole electric and anapole neutrino form factors. In coupling with a real photon $(q^2 = 0)$ these become the neutrino charge, magnetic, electric and anapole moment [1].

For antineutrinos the form factors are transformed as:

$$\overline{\mathbb{F}}_{\Omega}^{fi} = -\mathbb{F}_{\Omega}^{if} = -\left(\mathbb{F}_{\Omega}^{fi}\right)^{\star} \quad \Omega = Q, M, E, \tag{5}$$

$$\overline{\mathbb{F}}_{A}^{fi} = \mathbb{F}_{A}^{if} = \left(\mathbb{F}_{A}^{fi}\right)^{\star}. \tag{6}$$

In case of **Majorana neutrinos**, the general expression for the vertex function in terms of charge, magnetic, electric and anapole form factors looks the same as for Dirac neutrinos. However, since Majorana antineutrinos are the same particle as Majorana neutrinos, from eq.5,6 we can see that:

$$\mathbb{F}_{\Omega}^{M} = -\left(\mathbb{F}_{\Omega}^{M}\right)^{T} \quad \Omega = Q, M, E, \tag{7}$$

$$\mathbb{F}_{A}^{M} = \left(\mathbb{F}_{A}^{M}\right)^{T}. \tag{8}$$

Therefore the Majorana charge, magnetic and electric form factor matrices are antisymmetric and the anapole form factor matrix is symmetric. This means that Majorana neutrino doesn't have any diagonal charge and dipole magnetic and electric moments, but it can have transition charge and magnetic and electric moment [1].

[NuMMBasicsAndAstro_2022.pdf] One of the most important for astrophysics consequences of neutrino nonzero effective magnetic moments is the neutrino helicity change $\nu_l \to \nu_R$ with the appearance of nearly sterile right-handed neutrinos ν_R. In general, this phenomena can proceed in three different mechanisms:

1. the helicity change in the neutrino magnetic moment scattering on electrons (or protons and neutrons),
2. the neutrino spin and spin-flavour precession in an external magnetic field, and
3. the neutrino spin and spin-flavour precession in the transversally moving matter currents or in the transversally polarized matter at rest

For completeness note that the important astrophysical consequence of nonzero neutrino millicharges is the neutrino deviation from the rectilinear trajectory.

2.2.1 Neutrino electric and magnetic dipole moments

Evaluating the one loop diagrams in the minimal extension of the standard model with right handed (Dirac) neutrinos gives us the first approximation of the electric and magnetic moments $\left(q^2 = 0\right)$:

$$\left.\begin{matrix} \mu_{kj}^{D} \\ i\varepsilon_{kj}^{D} \end{matrix}\right\} \simeq \frac{3eG_F}{16\sqrt{2}\pi^2}\left(m_k \pm m_j\right)\left(\delta_{kj} - \frac{1}{2}\sum_{l=e,\mu,\tau} U_{lk}^{\star} U_{lj} \frac{m_l^2}{m_W^2}\right), \tag{9}$$

where m_k, m_j are the neutrino masses, but m_l are the masses of charged leptons which appear in the loop diagrams. Higher order electromagnetic corrections were neglected, but those can also have a significant contribution [1].

There are no diagonal electric moments $\left(\varepsilon_{kk}^{D}=0\right)$ and the diagonal magnetic moments are approximately

$$\mu_{kk}^{D}\simeq\frac{3eG_{F}m_{k}}{8\sqrt{2}\pi^{2}}\simeq3.2\times10^{-19}\left(\frac{m_{k}}{\mathrm{eV}}\right)\mu_{B},\tag{10}$$

where μ_B is the Bohr magneton [1].

The transition magnetic moments are suppressed with respect to the largest of the diagonal magnetic moments by at least a factor of 10^{-4} due to the m_W^2 in denominator and the transition electric moments are even smaller than that due to the mass difference [1]. Therefore an experimental observation of a magnetic moment larger than in eq.10 would indicate physics beyond the minimally extended standard model [2].

Majorana neutrinos can be obtained by either adding a $\mathrm{SU}(2)_L$ Higgs triplet, or right handed neutrinos together with a $\mathrm{SU}(2)_L$ Higgs singlet. If we neglect the Feynman diagrams which depend on the model of the scalar sector, the magnetic and electric dipole moments are

$$\mu_{kj}^{M}\simeq-\frac{3ieG_{F}}{16\sqrt{2}\pi^{2}}\left(m_{k}+m_{j}\right)\sum_{l=e,\mu,\tau}\mathrm{Im}\left[U_{lk}^{\star}U_{lj}\right]\frac{m_{l}^{2}}{m_{W}^{2}},\tag{11}$$

$$\varepsilon_{kj}^{M}\simeq\frac{3ieG_{F}}{16\sqrt{2}\pi^{2}}\left(m_{k}-m_{j}\right)\sum_{l=e,\mu,\tau}\mathrm{Re}\left[U_{lk}^{\star}U_{lj}\right]\frac{m_{l}^{2}}{m_{W}^{2}}.\tag{12}$$

These are difficult to compare to the Dirac case, due to possible presence of Majorana phases in the PMNS matrices, but it is clear that they have the same order of magnitude as Dirac transition dipole moments. However, the neglected model dependent contributions can enhance the transition dipole moments [1].

It is possible [2] to obtain "natural" upper limits on the size of neutrino magnetic moment by calculating its contribution to the neutrino mass by standard model radiative corrections. For Dirac neutrinos the radiative correction induced by neutrino magnetic moment, generated at an energy scale Λ, to the neutrino mass is generically

$$m_{\nu}^{D}\sim\frac{\mu_{\nu}^{D}}{3\times10^{-15}\mu_{B}}\left[\Lambda\left(\mathrm{TeV}\right)\right]^{2}\mathrm{eV}.\tag{13}$$

So for $\Lambda\simeq1\mathrm{TeV}$ and $m_\nu\lesssim0.3\mathrm{eV}$ the limit becomes $\mu_\nu^D\lesssim10^{-15}\mu_B$. This applies only if the new physics is well above the electroweak scale ($\Lambda_{EW}\sim100\mathrm{GeV}$). It is possible to get Dirac neutrino magnetic moment higher than this limit, for example in frameworks of minimal super-symmetric standard model, by adding more Higgs doublets, or by considering large extra dimensions [1].

The limit for Majorana neutrino magnetic moment is less stringent, due to the antisymmetry condition from eq.7 and considering $m_\nu\lesssim0.3\mathrm{eV}$ can be expressed as

$$\mu_{\tau\mu},\mu_{\tau e}\lesssim10^{-9}\left[\Lambda\left(\mathrm{TeV}\right)\right]^{-2}\tag{14}$$

$$\mu_{\mu e}\lesssim3\times10^{-7}\left[\Lambda\left(\mathrm{TeV}\right)\right]^{-2}\tag{15}$$

which is shown in the flavour basis , which relates to the framework used previously as

$$\mu_{ij}=\sum_{\alpha\beta}\mu_{\alpha\beta}U_{\alpha i}^{\star}U_{\beta j},\quad\alpha,\beta\in\left\{e,\mu,\tau\right\}.\tag{16}$$

This limits imply, that if a magnetic moment $\mu \gtrsim 10^{-15}\mu_B$ would be measured, it is plausible neutrinos are Majorana fermions and the scale of lepton violation would be well below the conventional see-saw scale [2].

2.3 Measuring neutrino magnetic moment

2.3.1 Effective neutrino magnetic moment

What we measure in experiments is an effective "flavour" magnetic moment, which is influenced by mixing of "mass" magnetic moments (and electric moments) and oscillations. In the ultrarelativistic limit this is

$$\mu^2_{\nu_l}(L, E_\nu) = \sum_j \left| \sum_k U^\star_{lk} e^{-i\Delta m^2_{kj} L/2E_\nu} \left(\mu_{jk} - i\varepsilon_{jk}\right) \right|^2 . \tag{17}$$

What is called the effective magnetic moment (often just magnetic moment) therefore contains contributions from both the neutrino magnetic and electric moment [1].

For antineutrinos, the effective magnetic moment is

$$\mu^2_{\bar{\nu}_l}(L, E_\nu) = \sum_j \left| \sum_k U^\star_{lk} e^{+i\Delta m^2_{kj} L/2E_\nu} \left(\mu_{jk} - i\varepsilon_{jk}\right) \right|^2 . \tag{18}$$

So the only difference is in the phase induced by neutrino oscillations.

For experiments with baselines short enough for neutrino oscillations to not develop ($\frac{\Delta m^2 L}{2E_\nu} \ll 1$), such as the NOvA ND, the effective magnetic moment can be expressed as

$$\mu^2_{\nu_l} \simeq \mu^2_{\bar{\nu}_l} \simeq \sum_j \left| \sum_k U^\star_{lk} \left(\mu_{jk} - i\varepsilon_{jk}\right) \right|^2 = \left[U\left(\mu^2 + \varepsilon^2\right)U^\dagger + 2\,\mathrm{Im}\left(U\mu\varepsilon U^\dagger\right)\right]_{ll'}, \tag{19}$$

which is independent of the neutrino energy and of the source to detector distance.

It is important to mention, that since the effective magnetic moment depends on the flavour of the studied neutrino, it is different for different types of neutrino experiment. Also the solar neutrino experiments need to include the effect of the solar matter on the neutrino oscillations. Therefore the reports on the value (or upper limit) of the effective neutrino magnetic moment are not directly comparable between different types of neutrino experiments.

2.3.2 Neutrino-on-electron elastic scattering

The most sensitive method to measure neutrino magnetic moment is the low energy elastic scattering of (anti)neutrinos on electrons [1]. This interaction has two observables, the recoil electron's kinetic energy (T_e) and the recoil angle with respect to the incoming neutrino beam (θ). From simple $2 \to 2$ kinematics we can get

$$\left(P_\nu - P_{e'}\right)^2 = \left(P_{\nu'} - P_e\right)^2 , \tag{20}$$

$$m_\nu^2 + m_e^2 - 2E_\nu E_{e'} + 2E_\nu p_{e'} \cos\theta = m_\nu^2 + m_e^2 - 2E_{\nu'} m_e. \tag{21}$$

Using the energy conservation

$$E_\nu + m_e = E_{\nu'} + E_{e'} = E_{\nu'} + T_e + m_e \Rightarrow E_{\nu'} = E_\nu - T_e \tag{22}$$

we get

$$E_\nu p_{e'} \cos\theta = E_\nu E_{e'} - E_{\nu'} m_e = E_\nu (T_e + m_e) - (E_\nu - T_e) m_e = T_e (E_\nu + m_e), \tag{23}$$

$$\cos\theta = \frac{E_\nu + m_e}{E_\nu} \sqrt{\frac{T_e^2}{E_{e'}^2 - m_e^2}} = \frac{E_\nu + m_e}{E_\nu} \sqrt{\frac{T_e^2}{T_e^2 + 2T_e m_e}}. \tag{24}$$

And finally we get

$$\cos\theta = \frac{E_\nu + m_e}{E_\nu} \sqrt{\frac{T_e}{T_e + 2m_e}}. \tag{25}$$

Electron's kinetic energy is kinematically constrained by

$$T_e \leq \frac{2E_\nu^2}{2E_\nu + m_e}. \tag{26}$$

Considering $E_\nu \sim \mathsf{GeV}$, we can approximate $\frac{m_e^2}{E_\nu^2} \to 0$ and in the small angle approximation we get from eq.25

$$T\theta^2 \cong 2m_e \left(1 - \frac{T_e}{E_\nu}\right) < 2m_e. \tag{27}$$

In the ultrarelativistic limit, the neutrino magnetic moment changes the neutrino helicity, turning active neutrinos into sterile. Since the SM weak interaction conserves helicity we can add the two contribution to the neutrino on electron cross section incoherently [1]:

$$\frac{d\sigma_{\nu_l e^-}}{dT_e} = \left(\frac{d\sigma_{\nu_l e^-}}{dT_e}\right)_{\mathsf{SM}} + \left(\frac{d\sigma_{\nu_l e^-}}{dT_e}\right)_{\mathsf{MAG}}. \tag{28}$$

The standard model contribution can be expressed as [1]:

$$\left(\frac{d\sigma_{\nu_l e^-}}{dT_e}\right)_{\mathsf{SM}} = \frac{G_F^2 m_e}{2\pi} \left\{ \left(g_V^{\nu_l} + g_A^{\nu_l}\right)^2 + \left(g_V^{\nu_l} - g_A^{\nu_l}\right)^2 \left(1 - \frac{T_e}{E_\nu}\right)^2 + \left(\left(g_A^{\nu_l}\right)^2 - \left(g_V^{\nu_l}\right)^2\right) \frac{m_e T_e}{E_\nu^2} \right\}, \tag{29}$$

where the coupling constants g_V and g_A are different for different neutrino flavours and for antineutrinos. Their values are:

$$g_V^{\nu_e} = 2\sin^2\theta_W + 1/2, \qquad g_A^{\nu_e} = 1/2, \tag{30}$$

$$g_V^{\nu_{\mu,\tau}} = 2\sin^2\theta_W - 1/2, \qquad g_A^{\nu_{\mu,\tau}} = -1/2. \tag{31}$$

For antineutrinos $g_A \to -g_A$.

Using expressions 25 and 27 we can also derive [3] cross sections with respect to $\cos\theta$, θ^2 and $T\theta^2$:

$$\left(\frac{d\sigma_{\nu_l e^-}}{d\cos\theta}\right)_{\mathsf{SM}} = \frac{2G_F^2 E_\nu^2 m_e^2 \cos\theta\,(E_\nu + m_e)^2}{\pi\left((E_\nu+m_e)^2 - E_\nu^2\cos^2\theta\right)^2} \left\{ \left(g_V^{\nu_l} + g_A^{\nu_l}\right)^2 + \left(g_V^{\nu_l} - g_A^{\nu_l}\right)^2 \left(1 - \frac{2m_e E_\nu \cos^2\theta}{(E_\nu+m_e)^2 - E_\nu^2\cos^2\theta}\right)^2 + \left(\left(g_A^{\nu_l}\right)^2 - \left(g_V^{\nu_l}\right)^2\right) \frac{2m_e^2\cos^2\theta}{\left((E_\nu+m_e)^2 - E_\nu^2\cos^2\theta\right)} \right\}, \quad (32)$$

$$\left(\frac{d\sigma_{\nu_l e^-}}{d\theta^2}\right)_{\mathsf{SM}} = \frac{G_F^2 m_e^2}{\pi\left(\theta^2 + \frac{2m_e}{E_\nu}\right)^2} \left\{ \left(g_V^{\nu_l} + g_A^{\nu_l}\right)^2 + \left(g_V^{\nu_l} - g_A^{\nu_l}\right)^2 \left(\frac{\theta^2}{\theta^2 + \frac{2m_e}{e_\nu}}\right)^2 + \left(\left(g_A^{\nu_l}\right)^2 - \left(g_V^{\nu_l}\right)^2\right) \frac{2m_e^2}{E_\nu^2\left(\theta^2 + \frac{2m_e}{E_\nu}\right)} \right\}, \quad (33)$$

$$\left(\frac{d\sigma_{\nu_l e^-}}{dT\theta^2}\right)_{\mathsf{SM}} = \frac{G_F^2 E_\nu}{4\pi} \left\{ \left(g_V^{\nu_l} + g_A^{\nu_l}\right)^2 + \left(g_V^{\nu_l} - g_A^{\nu_l}\right)^2 \left(\frac{T\theta^2}{2m_e}\right)^2 + \left(\left(g_A^{\nu_l}\right)^2 - \left(g_V^{\nu_l}\right)^2\right) \frac{m_e}{E_\nu}\left(1 - \frac{T\theta^2}{2m_e}\right) \right\}. \quad (34)$$

The neutrino magnetic moment contribution is (include derivation from [4]) [1]:

$$\left(\frac{d\sigma_{\nu_l e^-}}{dT_e}\right)_{\mathsf{MAG}} = \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_e} - \frac{1}{E_\nu}\right)\left(\frac{\mu_{\nu_l}}{\mu_B}\right)^2, \quad (35)$$

where α is the fine structure constant.

Analogically to previous, we can also express this cross section in $\cos\theta$, θ^2 and $T\theta^2$:

$$\left(\frac{d\sigma_{\nu_l e^-}}{d\cos\theta}\right)_{\mathsf{MAG}} = \frac{2\pi\alpha^2(E_\nu+m_e)^2}{m_e^2\cos\theta} \frac{(E_\nu+m_e)^2 - E_\nu^2\cos^2\theta - 2m_e E_\nu\cos^2\theta}{\left((E_\nu+m_e)^2 - E_\nu^2\cos^2\theta\right)^2}\left(\frac{\mu_{\nu_l}}{\mu_B}\right)^2, \quad (36)$$

$$\left(\frac{d\sigma_{\nu_l e^-}}{d\theta^2}\right)_{\mathsf{MAG}} = \frac{\pi\alpha^2}{m_e^2}\frac{\theta^2}{\left(\theta^2 + \frac{2m_e}{E_\nu}\right)}\left(\frac{\mu_{\nu_l}}{\mu_B}\right)^2, \quad (37)$$

$$\left(\frac{d\sigma_{\nu_l e^-}}{dT\theta^2}\right)_{\mathsf{MAG}} = \frac{\pi\alpha^2}{4m_e^4}\frac{T\theta^2}{\left(1-\frac{T\theta^2}{2m_e}\right)}\left(\frac{\mu_{\nu_l}}{\mu_B}\right)^2. \tag{38}$$

The magnetic moment contribution exceeds the standard model contribution for low enough T_e [1]:

$$T_e \lesssim \frac{\pi^2\alpha^2}{G_F^2 m_e^3}\left(\frac{\mu_\nu}{\mu_B}\right)^2 \simeq 2.9\times 10^{19}\left(\frac{\mu_\nu}{\mu_B}\right)^2 [\mathsf{MeV}], \tag{39}$$

which does not depend on the neutrino energy and makes neutrino experiment sensitive to lower energetic neutrinos more sensitive to the neutrino magnetic moment.

2.4 Experimental overview

2.5 Direct muon (anti)neutrino magnetic moment measurements

2.5.1 NOvA (Biao's thesis)

- ν_μ only
- Only comparing total event counts - 25 events observed and 23.78 expected
- Put an upper limit (90% C.L.) of $\mu_{\nu_\mu} < 1.58 \times 10^{-9} \mu_B$ with 10.9% systematic uncertainty on the standard model background
- Used 3.62×10^{20} POT of data (6.74×10^{23} POT for MC) with $T\theta^2 < 0.003\mathrm{GeV} \times \mathrm{Rad}^2$, $0.3 < T < 0.9\mathrm{GeV}$

2.5.2 MiniBooNE

- ν_μ only
- Observed excess of events (seems a bit too high)

2.5.3 E734 at the Alternating Gradient Synchrotron (AGS) of the Brookhaven National Laboratory

- **Both ν_μ and $\overline{\nu}_\mu$**
- $\mu_{\nu_\mu} < 8.5 \times 10^{-10} \mu_B$

2.5.4 LSND

2.6 Direct electron (anti)neutrino magnetic moment measurements

2.7 Solar neutrino magnetic moment measurements

2.7.1 XENONnT

First results published in arXiv:2207.11330[5] on 22 July 2022.

- 5.9 tonne dual-phase liquid xenon TPC dark matter detector
- Region Of Interest is (1,140) keV
- Very low background (5 times lower than XENON1T)
- Tritium excluded as the potential background (also in XENON1T)
- No excess found - XENON1T excess excluded with 4σ
- The 90% C.L. upper limit on solar neutrinos with an "enhanced" magnetic moment is $\mu_{\nu_{sol}} < 6.3 \times 10^{-12} \mu_B$, the strongest non-astronomical limit so far (see fig.2)

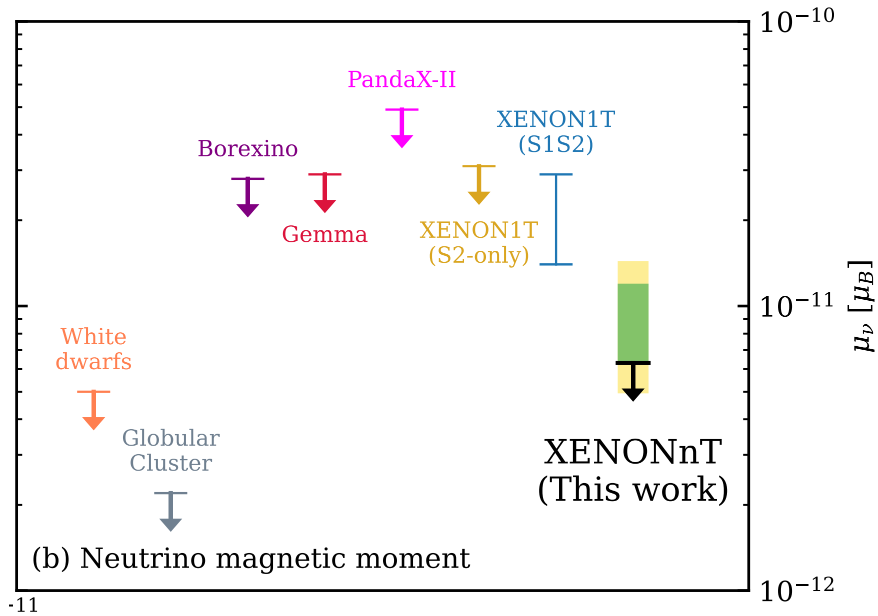

Figure 2: 90% C.L. upper limit on solar neutrinos with an enhanced magnetic moment.

Amir Khan used[6] XENONnT's results and derived limits on electromagnetic properties for the three SM neutrino flavours (see fig.3). For ν_μ they

2.7.2 XENON1T

2.7.3 BOREXINO

Should be $\mu_{\nu_e} < 2.8 \times 10^{-11} \mu_B$ [BorexinoLimit2017.pdf]

2.7.4 GEMMA

Should be $\mu_{\nu\ Eff} < 2.9 \times 10^{-11} \mu_B$. [GemmaLimits2013.pdf]

2.8 Other

2.8.1 LHC Forward Physics Facilities

Preliminary sensitivity studies for future experiments (namely for FLArE and FASERν2)

- LHC's Forward Physics Facilities study high energy (TeV) neutrinos of all flavours from the ATLAS interaction point.
- Large opportunity to study tau neutrinos in more detail

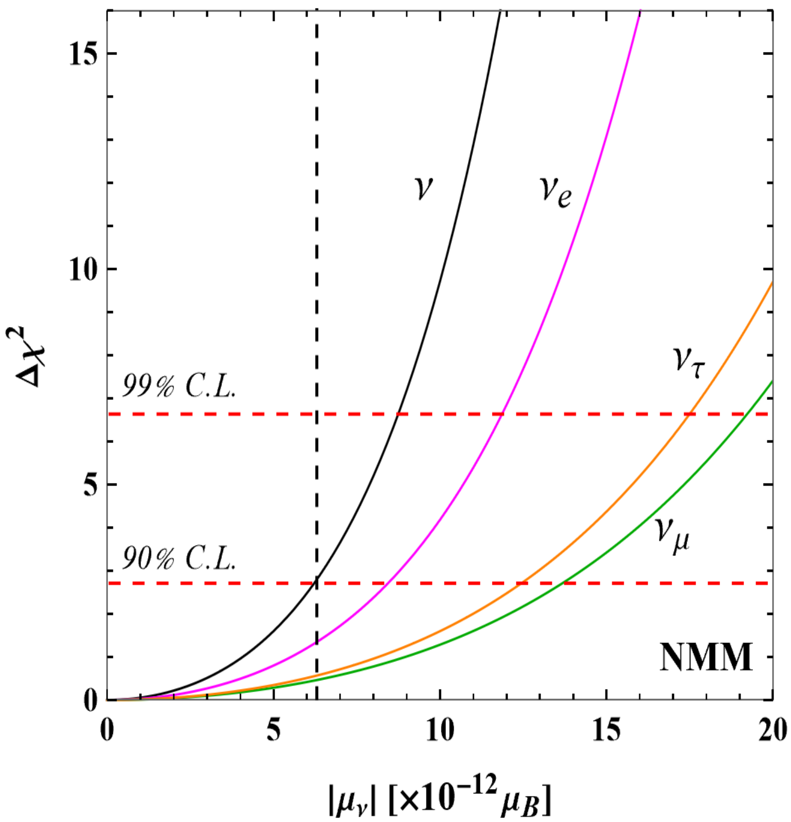

Figure 3: One-dimensional $\Delta\chi^2$ distribution with 90% and 99% C.L. boundaries of neutrino magnetic moments. The distribution in black corresponds to the effective flavor independent magnetic moment

2.9 Astrophysics

[NuMMBasicsAndAstro_2022.pdf] Neutrino electromagnetic processes that could be studied/observed in astrophysics

- Neutrino radiative decay
  - Decay of heavier neutrino flavour into a lighter neutrino and a photon
  - "The neutrino radiative decay has been constrained from the absence of decay photons in studies of the solar, supernova and reactor (anti)neutrino fluxes, as well as of the spectral distortions of the cosmic microwave background radiation."
  - Less stringent than the plasmon decay into a nu-antinu pairs
- Plasmon decay to neutrino-antineutrino pair
  - "For constraining neutrino electromagnetic properties, and obtaining upper bounds on neutrino magnetic moments in particular, the most interesting process is the plasmon decay into a neutrino-antineutrino pair [11]"
  - Plasmon decay frees the energy from the stars plasma in form of neutrinos that escape and therefore speeds up the star cooling
  - "observed properties of globular cluster stars provides new upper bounds on the effective neutrino magnetic moment $\mu_{ef} \leq (1.2 - 2.6) \times 10^{-12} \mu_B$ that is valid for both cases of Dirac and Majorana neutrinos."
- Transition of neutrino helicities $\nu_L \rightarrow \nu_R$ from active to sterile neutrinos
  - Supernovas would cool much faster - not observed for 1987A by Kamioka II and IMB, constraining Dirac neutrino mag. moment

3 Analysis overview

What are we trying to achieve? Are we aiming for purity or efficiency?

Trying to select nu-on-e events with low electron recoil energies.

What are we going to do with these events afterwards?

Are we just going to compare the event counts of signal and background (and possibly correct the background based on some other "sideband" selection?), or are we doing a fit to some spectra - either electron energy, angle or ETh2.

Describe what I'm talking about in this section (datasets, weights, selection, resolution, fitting framework).

3.1 Datasets and Event Reconstruction details

For this analysis we are using the near detector samples with a standard Production 5.1 reconstruction. To tackle low number of ν-on-e and ν_eCC MEC events (after full selection) in the nominal simulation sample, and to increase speed and lower the computation costs of each study, we are using the following samples for the signal and background components, for the nominal prediction as well as systematically shifted.

For data we are only planning to unveil them after fully approved by the collaboration and we will be using the following data sample...

Yiwen has already looked at data for the following samples and the results are here...

Should I mention the POT counting here or somewhere else?

The use of the samples can be briefly summarised as follows:

Signal	Enhanced ν-on-e sample
ν-on-e background	Enhanced ν-on-e sample
ν_eCC MEC background	Enhanced ν_eCC MEC sample
Other background	Flat sumdecaf

Table 1: Overview of simulation samples used.

Enhanced ν-on-e sample

Created by Wenjie Wu (was it just him or also Yiwen?) to do ... and fully described in the technote [7]. Using the overlayed and filematched samples for consistency.

We only have the selected few systematics definitions because ...

Describe the differences

- Missing cross section parameters - unable to use cross section weights or so
- Special mode for nu-on-e elastic scattering 10005

List all the nu-on-e sample definitions used is on table 2.

Nominal:

`prod_caf_R20-11-25-prod5.1reco.g_nd_genie_N1810j0211a_nonswap_fhc_nova_v08_full_v1_nuone_overlay`

Systematically shifted samples:

`prod_caf_R20-11-25-prod5.1reco.g_nd_genie_N1810j0211a_nonswap_fhc_nova_v08_full_calibup_v1_nuone_overlay`

`prod_caf_R20-11-25-prod5.1reco.g_nd_genie_N1810j0211a_nonswap_fhc_nova_v08_full_calibdown_v1_nuone_overlay`

`prod_caf_R20-11-25-prod5.1reco.g_nd_genie_N1810j0211a_nonswap_fhc_nova_v08_full_ckvup_v1_nuone_overlay`

`prod_caf_R20-11-25-prod5.1reco.g_nd_genie_N1810j0211a_nonswap_fhc_nova_v08_full_ckvdown_v1_nuone_overlay`

`prod_caf_R20-11-25-prod5.1reco.g_nd_genie_N1810j0211a_nonswap_fhc_nova_v08_full_lightlevelup_v1_nuone_overlay`

`prod_caf_R20-11-25-prod5.1reco.g_nd_genie_N1810j0211a_nonswap_fhc_nova_v08_full_lightleveldown_v1_nuone_overlay`

Table 2: SAMWEB definitions for the ν-on-e samples.

Enhance ν_eCC MEC sample

Created by Yiwen Xiao [7] to tackle the low statistics of the ν_ECC MEC background events and subsequently large and unphysical cross section weights.

List all the nueCC MEC sample definitions used. Do this after creating the filematched definitions maybe?

Nominal:

`prod_flatsumdecaf_R20-11-25-prod5.1reco.g_nd_genie_N1810j0211a_nonswap_fhc_nova_v08_full_v1_g4rwgt_respin_batch2_filematchedSystematics`

Systematically shifted samples:

`prod_flatsumdecaf_R20-11-25-prod5.1reco.e_nd_genie_N1810j0211a_nonswap_fhc_nova_v08_full_calibdown_v1_batch2_filematchedSystematics_calibdown_v1`

Table 3: SAMWEB definitions of the other background samples. THIS IS JUST A PLACEHOLDER!

Near detector flat summed decaf sample

What are the cuts used for the DeCAF sample? Why was it created? What is the effect of these cuts?

What is the "Nominal g4rwgt respin flatcaf" and should I be using that instead of the nominal flatcaf?

There's also 3 flavour concats - what are those? there are both numu and nue and they're for the ND... What are the cuts used to create these?

There's Genie Skew Fix and then there's Genie reweight - what is the reweight and why? What should be used in the end? Are the systematic samples compatible with any of those? Or are they the most up-to-date (i.e. with Genie Skew Fix and with the reweight?)

Should I include here also why did I choose to use the decafs instead of cafs? Maybe just point to my talks where I show the plot how much faster it is and that it doesn't matter much for the result. Maybe discuss how different the result would be if I used cafs instead of decafs...

List all the flat sumdecaf definitions used.

Nominal: `prod_flatsumdecaf_R20-11-25-prod5.1reco.g_nd_genie_N1810j0211a_nonswap_fhc _nova_v08_full_v1_g4rwgt_respin_batch2_filematchedSystematics`
Systematically shifted samples: `prod_flatsumdecaf_R20-11-25-prod5.1reco.e_nd_genie_N1810j0211a_nonswap_fhc _nova_v08_full_calibdown_v1_batch2_filematchedSystematics_calibdown_v1`

Table 4: SAMWEB definitions of the other background samples. First figure out what definitions should I use

3.2 Analysis weights

What are the weights we are using and why?

List of weights for each sample, maybe table again?

Signal	PPFX and Neutrino magnetic moment weight
ν-on-e background	PPFX and Radiative correction weights
ν_eCC MEC background	PPFX and prod5.1 GSF XSec weights
Other background	PPFX and prod5.1 GSF XSec weights

Table 5: Overview of simulation samples used.

PPFX weight

What does this do (one sentence).

Neutrino magnetic moment as a weight

What does this do and why does it work? Reference the theory part as to why is the magnetic moment signal simply a rescaling of the GENIE cross section.

Mention here where did I get the original GENIE cross section from (reference Yiwen's talk or technote, plus the original paper that was used).

Maybe event write out the actual expressions here. Or at least the standard model constants.

Name of the weight in CAFAna/nuone namespace

Radiative correction weight

Why are we doing this? (reference Yiwen's talk/technote). Using the same tree-level cross section from GENIE as in the neutrino magnetic moment weight.

Write out the actual version of the weight.

Say that we are not using the third part of the correction because it is tiny and it makes no difference. (tried and tested)

Prod5.1 GSF XSec weight

Briefly describe what does this do. Also mention Yiwen's talk/technote about the large XSec weights that made her create an enhanced nueCC MEC sample.

We are only using the for the background since we assume that the cross section for the signal is perfect. Also there are not weights for this kind of interaction.

3.3 Event selection

Should this be a separate section or is it all right to keep it here? It will have a lot of plots...

What is the signal and all the background samples definition? Difference between using kIsVtxCont and the fiducial volume. Is there a fundamental difference or preference? Or does it just depend on me? The results/counts are quite different...

Currently we are using the exact same selection as is used by the ND group [7] and very similar to the Light Dark Matter analysis (cite their technote).

Brief overview of the cuts that are being used in text.

Pre-selection consists of... basic quality cuts including the cuts from the ND DeCAF selection.

Containment and fiducial cuts.

Single shower/particle cuts.

Energy cut - should this be removed? What is the effect on the event count? Why was this included in the first place (the identifiers are not as strong for lowere energies - is this true though? - also there are further unexplored backgrounds that would need to be further studied and explore. Maybe depends on where would we move the cut...)

Convolution neural networks.

ETh2 cut.

Using the many plots below that show the effect of each of the cuts on the signal and all background events. (For signal we are showing NuMM=...)

The final event count and efficiency of each of the cuts is shown on the table ... Table ... shows the dissemination of background into the individual components.

From here we can see that ... Maybe what can be improved is...

1. Very brief description of common-sense preselection cuts in decafs - this might already be described when introducing the definitions...

2. Description of all variables used for selection in this analysis

3. Plots of all variables used for selection in this analysis, showing the distribution with L: no cuts and R: cumulative cuts up to this point.

4. Test explaining the motivation for each selection cut.

Describe/point to the ND group's event selection Plots of event selection variables distribution with two columns. Left distribution with no cuts applied and right with all previous cuts applied.

3.4 Resolution and binning

The electron energy and angle distributions and resolutions. Are we going to fit in E, Th, or ETh2? Is there something else?

Show plots of Reco V True for both energy and angle. (Should I show it with or without the energy cut?). Also show the resolution plots.

3.5 Systematic uncertainties

Plots showing combined uncertainties for signal and backgrounds

Normalization systematics

Should we include normalization systematics?

Neutrino flux systematics

Using the PCA vs using the PPFX universes+beam transport separately. Plots of energy showing shifts for signal and backgrounds separately

[to do]: understand differences with ND and 3F methods

Detector systematics

Plots of energy showing shifts for signal and backgrounds separately

Cross section systematics

Only for the non nu-on-e background. Assuming the nu-on-e events (including the signal events) are precisely known.

Plots of energy showing shifts for signal and backgrounds separately

3.6 Fitting framework

How does the fitting framework work? It's based on the framework developed by Mu Wei for the Light Dark Matter analysis (ref.) which was developed together (is this fair?). Basic description of the framework.

Also this framework is used for both LDM and NuMM together. It is trivial to simply switch between including the NuMM or LDM in it. This was done to save space in creating predictions since our backgrounds are exactly the same (or at least they should be...). Theoretically this could be separated into two difference frameworks.

- <NDPredictionSingleElectron> Prediction class which holds the LDM as a special 2-D spectrum (not used for NuMM), and NuMM, ν-on-e background, ν_eCC MEC background and other background as simple 1-D spectra. Also scaling each spectra by...
- <NDPredictionSystSingleElectron> class derived from PredictionInterp that takes in the NDPredictionSingleElectron and applies systematic shifts to it. Includes the interpolation/extrapolation between the systematic shifts.
- FitVariables and what do they do
- Fitter which does exactly what... What are the parameters of the fit? What are the results/outputs?

4 Results / Fake data studies

[to do]: talk about the shape-only versus normalisation-only strategies for the differential versus single-bin analyses.

I think it might be a good idea to talk about this already in the analysis overview section.

I need to also discuss fake data studies. Should I talk about this now? Probably

4.1 Counting experiment

Single bin analysis - total numbers of signal and backgrounds predicted. Possible background corrections and its effect on the background uncertainties.

4.2 Binned experiment

Plots showing delta chi2 for stats and systs separately. Plot showing the chi2 with limits. Maybe talk about using different binning and variables and the effect.

Also need to somehow quantify the various fitter settings, like different seeding values, different range of profiling. Should I talk about Feldman-Cousins?

4.2.1 Sensitivities and limits

5 Conclusion

Report the limit with its uncertainty.

Very briefly discuss differences with current world limit and how the techniques differ.

Very briefly summarise expectations for future measurements.

References

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[3] A. O. Barut and Z. Z. Aydin. Angular distribution in electron-neutrino scattering and the anomalous magnetic moment of the neutrino. *Nuovo Cim. A*, 101:677–682, 1989. `doi:10.1007/BF02848090`.

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[5] E. Aprile et al. Search for New Physics in Electronic Recoil Data from XENONnT. *Phys. Rev. Lett.*, 129:161805, Oct 2022. URL: `https://link.aps.org/doi/10.1103/PhysRevLett.129.161805`, `arXiv:2207.11330`, `doi:10.1103/PhysRevLett.129.161805`.

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[7] Wenjie Wu and Yiwen Xiao. Neutrino-Electron Elastic Scattering in the NOvA Near Detector - Technote. NOVA Document 56383, October 2023. NOvA technical note. URL: `https://nova-docdb.fnal.gov/cgi-bin/sso/ShowDocument?docid=56383`.