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Transition neutrino magnetic moments in CEνNS

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Abstract. Coherent Elastic Neutrino Nucleus Scattering (CEνNS) is a novel technique to look for new physics beyond the Standard Model. We study the prospects of probing a transition magnetic moment in CEνNS experiments. Showing the NUCLEUS experiment as an example, we demonstrate that properties of a potential sterile neutrino can be deduced.

1. Introduction

Coherent neutrino nucleus scattering (CEνNS) was observed for the first time at the COHERENT experiment in 2017 [1]. One of the major difficulties in observing such scatterings is the smallness of the nuclear recoil that is induced, with recoil energies being in the keV range. The near-future a experiment NUCLEUS [2, 3], located at the CHOOZ nuclear site in France, aims to reach a sensitivity to nuclear recoils in the $\mathcal{O}(10)$ eV range.

After the first observation of CEνNS, the novelty in CEνNS experiments has shifted from confirming the existence of this process, which is predicted by the Standard Model (SM), to using it as an observable to constrain neutrino oscillation parameters [4, 5] or search for New Physics (NP) beyond the SM (BSM) [6–11]. A possible BSM scenario that could induce a signal in CEνNS experiments is the existence of an enhanced neutrino magnetic moment. This magnetic moment, connecting neutrinos with photons, can provide an additional interaction channel between neutrinos and nuclei, thereby enhancing the CEνNS signal.

One further possibility is that one of the fermions participating in the magnetic moment vertex is sterile neutrino N, which can be of either Dirac or Majorana nature, rather than an active SM neutrino $\nu_{\alpha L}$. Such a vertex can be realized by the Lagrangian

$$\mathcal{L} \supset \mu^{\alpha}_{\nu N} \bar{\nu}_{\alpha L} \sigma_{\mu\nu} P_R N F^{\mu\nu} + \text{h.c.}\,, \tag{1}$$

where $F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$ is the field strength tensor corresponding to the electromagnetic field A^μ. The terms in Eq. (1) correspond to dimension 5 effective field theory (EFT) operators, that can be UV-completed in for example renormalisable inverse see-saw models, for both Dirac and Majorana active neutrinos [12, 13].

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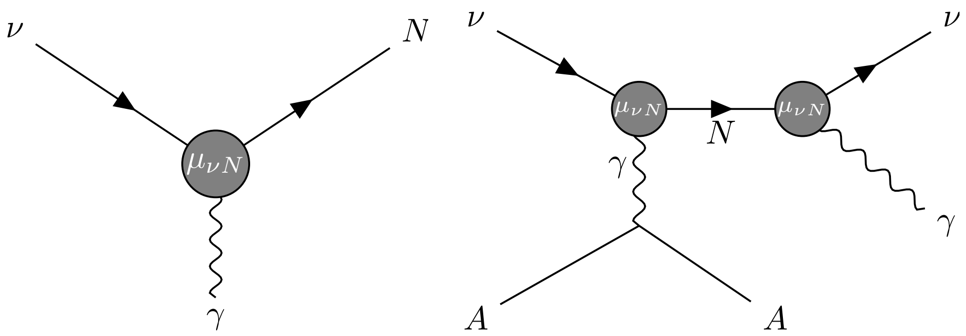

Figure 1. Left: Neutrino transition magnetic moment vertex. **Right:** Primakoff upscattering of a neutrino ν to a sterile neutrino N via a nucleus A, with subsequent decay of the sterile neutrino to an active neutrino and a photon.

The evidence for non-zero neutrino masses, coming from neutrino oscillation experiments [14], motivates the search for sterile neutrinos that could take part in the active neutrino mass generation mechanism. In case the sterile neutrino is a Majorana particle, the transition magnetic moment vertex will also contribute to a radiative neutrino Majorana mass term [6], possibly explaining the origin of active neutrino masses.

2. Radiative CEνNS

The transition neutrino magnetic moment, shown in Fig. 1 (left), can lead to Primakoff upscattering in CEνNS events, where an incoming active neutrino transitions into a sterile neutrino in its interaction with the nucleus. Assuming that the sterile neutrino is heavy, it can decay back into an active neutrino and an additional photon via the same vertex that produced the initial upscattering, as depicted in Fig. 1 (right).

In Ref. [6], we proposed a new type of experimental search, where the possibility to detect a final state photon is present in CEνNS experiments. This could allow for efficient background rejection, while simultaneously a providing new way to search for sterile neutrinos. In such a set-up, a photon detector is placed a distance l_0 downstream of a CEνNS target. The sterile neutrinos that decay via the transition magnetic moment before reaching the photon detector will emit a photon that can be detected. This requirement of decaying within the experimental set-up can be accounted for in the effective width of the sterile neutrino $\Gamma_N \propto 1/l_0$, such that longer distances l_0 generally lead to a larger proportion of N being able to provide a signal [6]. If the nuclear recoil in the upscattering is also recorded, the photon- and nuclear recoil signals are coincident and can provide a clear signature for these types of radiative CEνNS events.

3. Constraints

There are numerous constraints on the neutrino transition magnetic moment coupling. This coupling is flavour dependent, and therefore different experiments probe different flavour couplings (depending on the source of neutrinos in terms of their flavour). For experiments that use neutrinos from pion decays, the most stringent constraints are provided for the μ-flavour coupling. Astrophysical observations generally constrain flavour-universally, and most stringently so in the low-m_N part of the parameter space.

The NUCLEUS experiment uses a nuclear reactor as the source of neutrinos, where electron-flavour antineutrinos are emitted in the β-decays of fission products. Therefore, the relevant constraints to consider for NUCLEUS are those on the electron-flavour neutrino transition magnetic moment coupling $\mu^e_{\nu N}$. As shown in Fig. 2, the parameter space of this coupling is constrained by both astrophysical observations and laboratory experiments.

The reach of of the near-future NUCLEUS experiment for the radiative CEνNS mode with an active neutrino final state, in the case where final state photon detection is possible and 10g

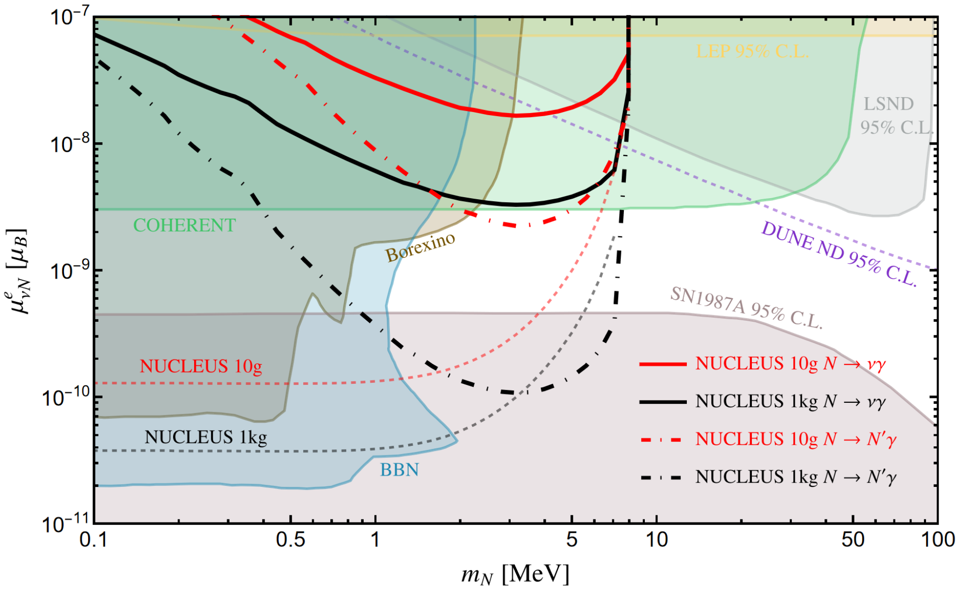

Figure 2. Parameter space of the electron flavour neutrino transition magnetic dipole moment $\mu^e_{\nu N}$ as a function of the sterile neutrino mass m_N. The reach of the NUCLEUS experiment for the radiative CEνNS mode is shown in red solid and dot-dashed lines for the near-future 10g detector and black solid and dot-dashed lines for the far-future 10 kg upgrade, where solid lines refer to an active neutrino final state and dot-dashed lines correspond to another sterile fermion N' in the final state, assuming a 3 year run time [6]. Existing constraints are shown in coloured areas. Astrophysical constraints come from Borexino, SN1987A, and BBN [15], while laboratory constraints come from LSND, LEP [16], and COHERENT [6]. Future projections are shown in dashed lines for DUNE near detector [17] and NUCLEUS for Primakoff upscattering [6]. All constraints are given at 90% C.L. unless otherwise stated.

of target material is used, is within the region excluded by the COHERENT experiment in the parameter space of $\mu^e_{\nu N}$ and m_N, assuming a 3 year run time for NUCLEUS [6]. A possible far-future upgrade of NUCLEUS, consisting of 1kg of target material, would have a much greater reach in the parameter space than the near-future 10g experiment. However, also the region that would be explored by the upgrade is excluded by the COHERENT experiment.

The exclusion line in Fig. 2 corresponding to the COHERENT experiment assumes that Primakoff upscattering via a neutrino transition magnetic moment would cause a deviation from the standard CEνNS signal, and since such a deviation is not seen, a part of the relevant parameter space is excluded [6]. Therefore, the process that corresponds to the exclusion line from COHERENT includes one instance of the neutrino transition magnetic moment, while the exclusion line from NUCLEUS, corresponding to the radiative CEνNS mode, includes two instances. Therefore, prime objective in the search for a radiative CEνNS mode is not to constrain new regions of parameter space, but rather to find the details of a possible signal coming from Primakoff upscattering. As seen in Ref. [6], the potential Primakoff upscattering exclusion limit from the near- and far-future NUCLEUS is well within new regions of parameter space. Furthermore, in the radiative mode, it is possible that the decay of N contains final state fermions N' other than the active electron-flavour neutrino, possibly enhancing the experimental reach of the radiative mode further.

4. Conclusion

One possible method to search for NP in the neutrino sector is via CEνNS experiments, where the sterile neutrino could be produced in Primakoff upscattering events. The improved sensitivity in the near-future CEνNS experiment NUCLEUS will allow sterile neutrnios with MeV-scale masses to be probed in regions of parameter spacethat are so far unconstrained [6].

The final state photon in radiative CEνNS events could in principle be detected if a photon detector is placed downstream of the CEνNS target [6]. A coincident signal of a final state photon and a nuclear recoil in the CEνNS target could reduce the background, and help to identify the process producing the signals.

The potential that CEνNS experiments have in providing more details about the properties of neutrinos is largely still untapped, due mainly to the novelty of such experiments. Therefore, the future of CEνNS is very exciting, and the next generation of experiments will be crucial in the development of this relatively new search mode.

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