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Distinguishing Dirac vs Majorana Neutrinos at CEνNS experiments

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A transition magnetic moment between active and sterile neutrinos can induce the Primakoff upscattering process at the coherent elastic neutrino nucleus scattering experiments, leading to very stringent limits on the transition dipole coupling as a function of the sterile neutrino mass. Here we discuss how a novel radiative upscattering mode with an additional photon emitted in the final state can lead to exploration of new parameter space in the transition dipole coupling vs. sterile neutrino mass plane and provide distinguishable differential distributions for a Dirac vs Majorana sterile state mediating such a mode.

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1. Introduction

Coherent Elastic Neutrino-Nucleus Scattering (CEνNS) via the Standard Model (SM) weak neutral current was originally proposed in [1]. Very recently, the COHERENT collaboration have reported the first observation of CEνNS process with a 6.7σ confidence level [2]. Since the first observation of the CEνNS process by COHERENT collaboration using a detector sensitive to nuclear recoil energy as low as few KeV, several new experiments have been proposed with upgraded detector technologies. These future genration experiments can probe nuclear recoil energy as small as eV with only gram scale detectors [3, 4]. Therefore, in near future, the CEνNS experiments will not only verify the SM predictions with high precision, but also will be sensitive to effects of new physics (NP) beyond the SM mediating new interactions between neutrino and nucleus. One such new physics observable explored extensively in the literature is the Primakoff upscattering, where an active neutrinos scatters off a nucleus to a heavy sterile state via a active to sterile transition magnetic dipole moment. Such a dipole portal has been extensively studied in the literature to constrain the parameter space of transition dipole moment vs sterile neutrino mass for the different active neutrino flavours using a variety of low-scale and astrophysical observables across a large range of relatively light sterile neutrino mass [5]. Here we will discuss how a radiative mode of the upscattering with emission of an additional photon and neutrino in the final state can probe new ranges of parameter space beyond the currently constrained part of the parameter space and can potentially provide distinguishable distributions for Dirac vs Majorana sterile states mediating such a mode.

2. Neutrino Transition Magnetic Dipole Moment and Radiative Upscattering

A transition magnetic dipole moment between an active and a sterile neutrino can be expressed in the effective form

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

where $\mu^{\alpha}_{\nu N}$ corresponds to the the transition dipole moment, $F^{\mu\nu} = \partial^{\mu} A^{\nu} - \partial^{\nu} A^{\mu}$ is the usual electromagnetic field strength, $\nu_{\alpha L}$ corresponds to an active light neutrino field of flavour α and N is a gauge-singlet sterile state. Above the EW scale the effective operator given in Eq. (1) can be matched to SM gauge group invariant dimension-six effective operators containing the $\mathrm{SU}(2)_L$ and $\mathrm{U}(1)_Y$ gauge fields W^a_μ and B_μ and the SM Higgs doublet H.

The transition dipole portal as given in Eq. (1) can induce the Primakoff upscattering process $\nu_\alpha A \to N A$ [5, 6], where an incoming active neutrino ν_α scatters off a target nucleus A through photon exchange to an outgoing sterile neutrino N. The computation of differential cross section for such a process w.r.t. the nuclear recoil is straightforward and provides an identical result for an outgoing Dirac vs Majorana neutrino. Therefore, such a mode can be used to derive constraints on the the dipole coupling $\mu^{\alpha}_{\nu N}$ as a function of the sterile neutrino mass m_N, however no information about the nature of the outgoing sterile state can be obtained.

Interestingly, if the outgoing sterile state in the upscattering process decays to an active neutrino or another sterile neutrino through again a dipole portal interaction emitting an outgoing photon of the final state, then the outgoing photon can be used to learn the nature of the decaying sterile

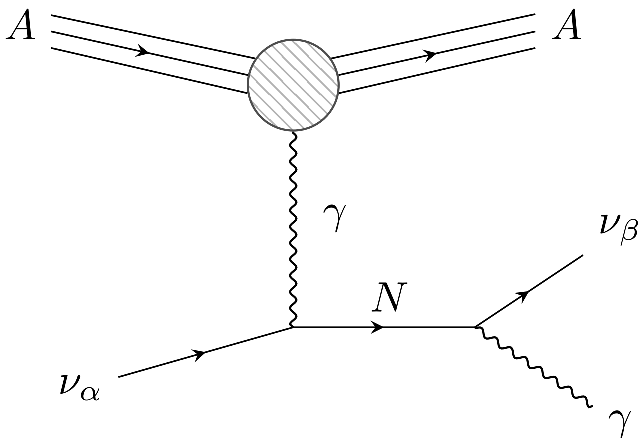

Figure 1: The radiative upscattering process $\nu_\alpha A \to \nu_\beta A\gamma$ mediated by transition magnetic moments between active and sterile neutrinos.

neutrino, as pointed out in [7]. We refer to this mode as radiative upscattering. If the sterile state mediating this radiative upscattering mode can be produced on shell then the rate of this process can get resonantly enhanced. The rate of this process is surpassed w.r.t the standard Primakoff upscattering by an additional power of $\mu^\alpha_{\nu N}$; however, if the outgoing photon can be detected at the CEνNS experiments then a coincidence of the nuclear recoil with this additional signal can be used to avoid the standard backgrounds present for the Primakoff upscattering. Fig. 1 shows a Feynman diagram for the relevant radiative upscattering mode.

Depending on the whether the sterile state mediating the radiative upscattering process decays into an active light neutrino or another light sterile state, the radiative mode can potentially explore new parts of the parameter space on the dipole coupling $\mu^\alpha_{\nu N}$ vs. the sterile neutrino mass m_N plane, beyond the reach of standard Primakoff upscattering. Furthermore, the differential distributions of the outgoing photon for this mode gives distinguishable profiles depending on whether the sterile state mediating sucha mode is Dirac or Majorana. Therefore a study of the differential distributions for this mode can potentially provide valuable hints towards the the nature and mass generation mechanism of active neutrinos.

As a case study, the NUCLEUS experiment [3, 4] located at the CHOOZ reactor facility was explored in [7]. The NUCLEUS experiment with its currently planned experimental set up and future upgrade provides a realistic possibility of detecting the outgoing photon and to study the energy and angle distributions of this outgoing photon.

3. Summary of Current Constraints and Prospects of the Radiative Upscattering mode

The transition dipole coupling $\mu^\alpha_{\nu N}$ have been constrained in the literature from from a variety of low-energy experiments as well as astrophysical probes. These constraints are generally dependent on the flavour of the light neutrino involved.

In nuclear reactor neutrino source based experiments the beta decay of fission products produces a flux of electron antineutrinos $\bar{\nu}_e$, therefore they can mainly probe $\mu^e_{\nu N}$. The $\mu^e_{\nu N}$ dipole coupling has been constrained using LEP and LSND experiments in [5], XENON1T experiment in [8] and Borexino experiment in [8, 9]. The future possible constraints are explored for SBND, MicroBooNE and SHiP experiments in [5], for the DUNE near detector in [10] and for SuperCDMS experiment in [11]. The $\mu^\mu_{\nu N}$ coupling has been constrained using COHERENT experiment in [12], CHARM-II in [13], NOMAD in [14] and MiniBooNE in [5]. The future potential constraints on $\mu^\mu_{\nu N}$ has been explored for the DUNE near detector in [10] and for MicroBooNE in [5]. The $\mu^\tau_{\nu N}$ coupling has been constrained using DONUT experiment in [13]. Astrophysical constraints applicable on the dipole portal coupling of all flavour come from SN1987A [5], the CMB, stellar cooling, and the abundance of ^{4}He from BBN [8], as well as neutrino-photon decoupling around the time of BBN [13].

While the incoming neutrino in an experiment like NUCLEUS, employing CHOOZ reactor facility as its neutrino source, will predominantly be of electron flavour, for the radiative upscattering process the outgoing light neutrino can also be of the muon- and tau-flavour. Therefore, the radiative upscattering process can probe the product of different flavour dipole portal couplings $\mu^e_{\nu N}\, \mu^\mu_{\nu N}$ and $\mu^e_{\nu N}\, \mu^\tau_{\nu N}$. In addition, the sterile state mediating the radiative upscattering process can decay into another light sterile state through a sterile to sterile transition dipole moment, which is much less severely constrained by terrestrial experiments. Therefore, for a outgoing light sterile neutrino the radiative upscattering process can probe a much more larger parameter space of the active to sterile transition dipole moment $\mu^e_{\nu N}$ reaching currently unexplored parameterspace by the other experiments [7],.

4. Differential Distributions and Distinction Between Dirac vs. Majorana Sterile States

A detailed derivation and technical details of the full calculation of the differential cross section for the three body final state radiative upscattering process $\nu_\alpha A \to \nu_\beta A \gamma$ can be found in [7]. It is possible to integrate over some of the averaged out variables to derive double differential cross sections for the radiative upscattering process in outgoing photon energy and outgoing photon angle (w.r.t the direction of the incoming neutrino beam). Studying such double differential distributions it was found in [7] that the distributions look significantly different when the intermediate sterile state is Dirac vs. Majorana. Such double differential cross section presents significantly more events for higher outgoing photon energy in Majorana case as compared to the Dirac case for small outgoing photon angles. These double differential dtstributions can further be integrated over one of the variables using the incoming reactor neutrino energy distribution to construct single distributions of the event rate for the radiative upscattering w.r.t. the outgoing photon energy and angle. The single distribution of the radiative upscattering event rate w.r.t. the outgoing photon energy shows very distinct behaviours for Dirac vs. Majorana intermediate sterile state. The Mojorana sterile state case presents a symmetric distribution in the outgoing photon energy with almost equal events over and below a central energy of outgoing photon. On the other hand, the Dirac case presents an asymmetric distribution in outgoing photon energy with a clear preference towards low outgoing photon energy and less event rate for higher outgoing photon energy.

5. Conclusions

We have discuss a novel radiative mode of the upscattering with emission of an additional photon and neutrino in the final state proposed in [7]. Depending on the decay mode of the intermediate sterile state mediating such a radiative mode new parameter space of dipole portal coupling for neutrinos can be accessible at the CEνNS experiments. Given the purely neutrino or antineutrino beam accessible from reactors at the CEνNS experiments, in contrast to astrophysical or collider probes, it is possible to distinguish the Dirac vs. Majorana nature of the sterile neutrino mediating the radiative upscattering mode by detecting the outgoing photon and studying the energy and angular distribution of the radiative scattering rate. This can provide valuable hints towards the nature and mass generation mechanism of active neutrinos.

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