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Heavy Neutral Leptons via Mixing and Transition Dipole Moments

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A well-motivated extension to the Standard Model (SM) that can generate the observed light neutrino masses is the SM gauge-singlet fermion; the minimum number of singlet fermions required to produce the observed neutrino oscillation data is two. Unless explicitly forbidden by an additional symmetry beyond the SM, it is possible to write a Majorana mass term for these singlet states that violates lepton number by two units. The scale associated with such a term is unrelated to the electroweak symmetry breaking of the SM and can in principle lie anywhere from an eV to the Planck scale. This opens up a rich phenomenology that crucially depends on how the singlet states are coupled to the SM; two possibilities are the *mass-mixing* and *dipole* portals. Here, we briefly review the theory, phenomenology, and corresponding constraints on the two portals.

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1. Introduction

An immediate extension to the SM to accommodate the observed light neutrino masses is the SM gauge-singlet field N_R. At $d = 5$ and below, the following operators preserving the SM gauge symmetry can be written

$$\mathcal{L}_m = -\frac{1}{2} M_R \bar{N}_R^c N_R - Y_\nu \bar{L} N_R \tilde{H} + \frac{C_{NH}}{\Lambda} (\bar{N}_R^c N_R) H^\dagger H + \frac{C_{LH}}{\Lambda} (\bar{L}\tilde{H})(\tilde{H}^T L^c) + \text{h.c.}\,, \tag{1}$$

where $\tilde{H} = i\sigma_2 H^*$ and $N_R^c = C\bar{N}_R^T$ (with σ_2 and C being the second Pauli matrix and charge conjugation matrix, respectively), Y_ν is the neutrino Yukawa coupling, and M_R is a Majorana mass for the sterile states [1–4]. *A priori*, the scale M_R is unrelated to the electroweak symmetry breaking (EWSB) scale $v = \langle H^0 \rangle = 174$ GeV and can take any value from below an eV to the Planck scale.

If the Majorana mass M_R is very large, integrating out the singlet states N_R produces the Weinberg operator and Majorana masses for the light neutrinos; this is nothing other than the type-I seesaw [5]. The neutrino masses are given by $m_\nu \sim (vY_\nu)^2/m_N = |U_{\ell N}|^2 m_N$, where m_N is the singlet mass and $|U_{\ell N}| = vY_\nu/m_N$ is the active-sterile mixing strength (for the flavour $\ell = e, \mu, \tau$). If more than one singlet fermion is introduced, the small neutrino masses may instead be the result of cancellations between the singlet fermion contributions, e.g., the *inverse seesaw* mechanism [6]. This scenario relies on lepton number being an approximate symmetry, broken by small Majorana masses of the singlet fermions. Pairs of singlet fermions form *quasi-Dirac* neutrinos, with small mass splittings, opposite CP phases, and in principle large active-sterile mixing.

2. Mass-Mixing Portal

If singlet fermions below the TeV scale are indeed present, the *mass-mixing portal* has direct and indirect consequences in laboratory experiments, astrophysics, and cosmology; for an overview see Refs. [7, 8]. Singlet fermions participate in the charged-current and neutral-current SM interactions, albeit suppressed by the active-sterile mixing $|U_{\ell N}|$. Singlet fermions can therefore be produced on-shell and subsequently decay promptly or over macroscopic distances, the latter providing the clean signature of a *long-lived particle* (LLP). Alternatively, they can contribute virtually to neutrinoless double beta ($0\nu\beta\beta$) decay [7, 9, 10] and the charged lepton flavour violating (cLFV) processes $\mu \to e\gamma$, $\mu \to 3e$ and $\mu - e$ conversion in nuclei [11–13], or introduce non-unitarity effects in SM processes involving the light neutrinos [14–16]. For singlet masses from the eV to TeV scale, upper limits on $|U_{\ell N}|^2$ have been placed by neutrino oscillations, beta decays, meson decays, beam dump experiments, colliders, EW precision data, cosmic microwave background (CMB) measurements, supernovae dynamics, and X-ray telescopes, shown in Fig. 1 [7]. In the future, bounds on $|U_{\ell N}|^2$ above 100 MeV could be pushed down to the seesaw line, $|U_{\ell N}|^2 = m_\nu/m_N$, via displaced-vertex searches at beam dump experiments and colliders.

3. Dipole Portal

It is also possible for singlet fermions N_R to couple to the SM via the so-called *dipole portal*. In the SM extended to include a singlet fermion N_R, it is possible to write the following operators

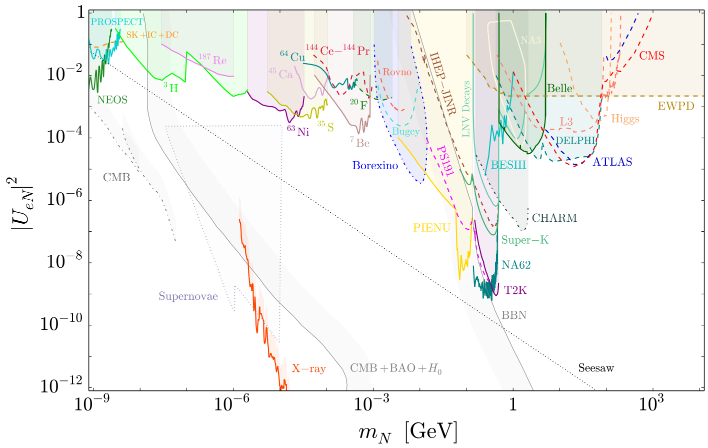

Figure 1: Existing constraints on the electron-flavour active-sterile mixing strength $|U_{eN}|^2$ as a function of the sterile neutrino mass m_N [7].

at $d = 7$ and below,

$$\mathcal{L}_d \supset \frac{C_{NNB}}{\Lambda} g' (\bar{N}_R^c \sigma_{\mu\nu} N_R) B^{\mu\nu} + \frac{C_{NB}}{\Lambda^2} g' (\bar{L} \sigma_{\mu\nu} N_R) \tilde{H} B^{\mu\nu}$$
$$+ \frac{C_{NHB}}{\Lambda^3} g' (\bar{N}_R^c \sigma_{\mu\nu} N_R)(H^\dagger H) B^{\mu\nu} + \frac{C_{LHB}}{\Lambda^3} g' (\bar{L}\tilde{H}) \sigma_{\mu\nu} (\tilde{H}^T L^c) B^{\mu\nu} + \text{h.c.}\,, \tag{2}$$

where g' and $B^{\mu\nu}$ are the $\mathrm{U}(1)_Y$ gauge coupling and field strength tensor, respectively [17–19]. There are also operators with coefficients C_{NW}, C_{NHW} and C_{LHW} which have $g' \to g$, $B^{\mu\nu} \to W^{I\mu\nu}$ and appropriate insertions of the $\mathrm{SU}(2)_L$ generator τ^I.

If the singlet fermions are much heavier than the EW scale, they must be integrated out, generating the operators above with coefficients C_{LHB} and C_{LHW}. After EWSB, these operators induce (transition) magnetic moments for light Majorana neutrinos. A technical issue for large magnetic moments among the light neutrinos is that they generally imply large neutrino masses, implying some degree of fine-tuning [20, 21]. However, it has been shown that these strict bounds can be evaded in the Majorana case if there are symmetries that suppress the neutrino mass, but not the magnetic moment [22–25]. If the singlet fermions N_R are instead below the EW scale, they must be kept in the effective theory at low energies. Generically, a transition magnetic moment between a light neutrino and a heavy singlet state is described by

$$\mathcal{L}_d \supset \frac{1}{2} \mu_{\nu N} (\bar{\nu}_L \sigma_{\mu\nu} N_R) F^{\mu\nu} + \text{h.c.}\,, \tag{3}$$

where $F^{\mu\nu}$ is the electromagnetic field strength tensor. The transition magnetic moment in Eq. (3) also radiatively generates neutrino masses; however, large $\mu_{\nu N}$ can be made compatible with small m_ν if the singlet states combine to form quasi-Dirac neutrinos.

Like the active-sterile mixing, transition magnetic moments between active neutrinos and singlet states can also be probed in laboratory experiments, astrophysics, and cosmology. For example, singlet states can be produced on-shell through Primakoff-type upscattering, i.e., via the exchange of a photon with a nucleus A. This process can be probed by a variety of experiments for singlet fermion masses below 100 MeV; for example, those searching for the coherent elastic

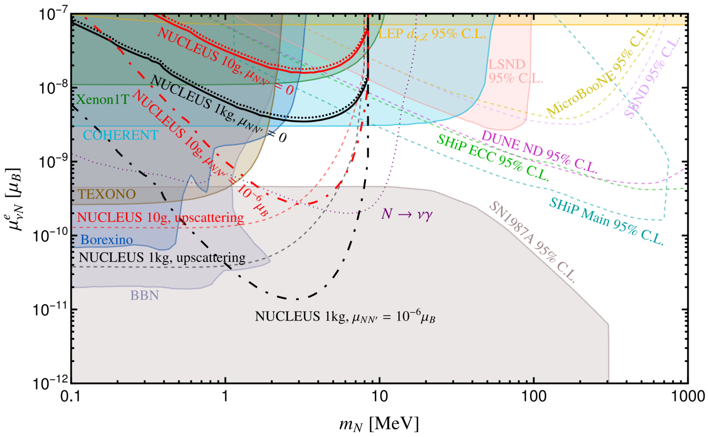

Figure 2: Existing constraints (shaded regions) and future sensitivities (dashed lines) for the effective electron-flavour transition magnetic dipole moment $\mu^e_{\nu N}$ as a function of the sterile neutrino mass m_N [26].

neutrino-nucleus scattering (CEνNS) process [27] such as COHERENT [28] and NUCLEUS [29]. If these are capable of observing outgoing photons with energies $E_\gamma \sim$ MeV, they may also be able to search for the upscattering $\nu A \to NA$ followed by the radiative decay $N \to \nu\gamma$, which benefits from a lower background [26]. This signal could be further enhanced if a transition magnetic moment exists between N and another lighter state N'; the decay $N \to N'\gamma$ may then proceed via the less constrained transition magnetic moment $\mu_{N'N}$. The bounds from CEνNS [30, 31], along with those from beam dump experiments [32, 33], colliders [34, 35], neutrino observatories [36, 37], dark matter experiments [38–40], supernovae [38] and Big Bang Nucleosynthesis (BBN) [41, 42], are shown in Fig. 2; for reviews of these constraints, see Refs. [38, 43].

If the production and subsequent decay of a heavy singlet fermion are observed (for example, the upscattering $\nu A \to NA$ followed by the decay $N \to \nu\gamma$) it has been noted in the literature that the kinematics of the decay depends on the (quasi)-Dirac or Majorana nature of the singlet fermion [44–46]. Simply from the conservation of angular momentum and CPT invariance, it can be shown that the angular distribution in the rest frame of the $N \to \nu\gamma$ decay is isotropic for Majorana N and proportional to $(1 + \cos\theta_\gamma)$ for Dirac N. This results in different angular distributions after boosting to the lab frame; furthermore, in the lab frame, the distribution in the photon energy E_γ is flat in the Majorana case and decreases linearly in the Dirac case.

To conclude, singlet fermions are a well-motivated extension of the SM to explain the light neutrino masses. Additionally, they can be directly produced and indirectly impact low-energy observables via the *mass-mixing* or *dipole* portals. As such, bounds can be placed on the active-sterile mixing $|U_{\ell N}|^2$ and transition magnetic moment $\mu^\ell_{\nu N}$ (for the flavour $\ell = e, \mu, \tau$) as a function of m_N. If a singlet fermion is observed, it may be possible to identify whether it is a (quasi)-Dirac or Majorana fermion through careful measurements of final-state kinematics or the detection of lepton number violating processes such as $0\nu\beta\beta$ decay and same-sign collider signatures.

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