Probes of Heavy Sterile Neutrinos

Patrick D. Bolton\textsuperscript{1}, Frank F. Deppisch\textsuperscript{2}, P. S. Bhupal Dev\textsuperscript{3}

\textsuperscript{1)SISSA, International School for Advanced Studies and INFN, Sezione di Trieste, Via Bonomea 265, I-34136 Trieste, Italy}
\textsuperscript{2)Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, U.K.}
\textsuperscript{3)Department of Physics and McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130, U.S.A.}

Abstract

We review probes of heavy sterile neutrinos, focusing on direct experimental searches and neutrinoless double beta decay. Working in a phenomenological parametrization, we emphasize the importance of the nature of sterile neutrinos in interpreting neutrinoless double beta decay searches. While current constraints on the active-sterile neutrino mixing are already stringent, we highlight planned future efforts that will probe regimes motivated by the lightness of active neutrinos.

1 Introduction

The lack of right-handed neutrino states \( N_j \) is an intriguing feature of the Standard Model (SM). Their presence is not strictly required, unlike for the other SM fermions, as we only observe neutrinos through their left-handed SM interactions, and the small but finite masses could be understood with the active left-handed states \( \nu_l \) only, assuming their Majorana nature. This does not mean that right-handed neutrinos do not exist, though: Because they would be sterile, i.e., uncharged under the SM gauge interactions, they participate only in the Yukawa interaction \(-y_\nu \bar{L}_\ell \cdot H N_j\) with a left-handed lepton doublet and the Higgs doublet. If small, \( y_\nu \sim m_\nu/v \lesssim 10^{-12} \) (\( v = 174 \text{ GeV} \)), this would generate light Dirac neutrino masses \( m_\nu \lesssim 0.1 \text{ eV} \) seen in oscillations and constrained by absolute mass searches such as tritium decay and cosmological observations.

The introduction of sterile, right-handed neutrino states opens up the possibility of lepton number violation. Whereas total lepton number is an accidental symmetry in the SM, sterile neutrinos can have a Majorana mass term, \(-\frac{1}{2} M^{ij} \bar{N}_i N_j\), violating lepton number by two units, unless it is explicitly forbidden by an additional symmetry beyond the SM gauge ones. Such a Majorana mass term is fairly unconstrained from a theoretical point of view, as it is not connected to the SM electroweak symmetry breaking. It can in principle have any scale from eV and below to scales far above the SM.

With both the Yukawa and a heavy sterile Majorana mass term present, the neutrino spectrum consists of three (mostly) active light neutrinos and two or more (mostly) sterile neutrinos, all having Majorana character. This is the celebrated seesaw mechanism (of type 1), connecting the light neutrino masses to the heavy Majorana mass scale \( m_N \) as \( |m_\nu| \sim (y_\nu v)^2/m_N = |V_{\nu N}|^2 m_N \), applicable if \( y_\nu v \ll m_N \). Here, \( |V_{\nu N}| \approx y_\nu v/m_N \) is the active-sterile mixing strength. Its main phenomenological consequence is that it generates suppressed charged and neutral current interactions between the sterile state \( N \) and a SM charged lepton or neutrino of flavour \( \ell = e, \mu, \tau \). The lightness of active neutrinos can thus

\textsuperscript{a}Corresponding Author: f.deppisch@ucl.ac.uk
be explained by either making the sterile neutrinos heavy or the Yukawa coupling weak. The admixture of a sterile neutrino with an active one, $N^\text{mass} \sim N - V_{eN} \nu$, is in either case small, 
\[
|V_{eN}| = \sqrt{m_\nu / m_N} \lesssim 10^{-6} \sqrt{100 \text{ GeV} / m_N}.
\]

There is a third way of keeping the active neutrinos light: If lepton number were to be conserved in the sterile neutrino sector, no light masses are generated. This is not only achieved in the limits $m_N \to 0$ and $m_N \to \infty$ but also if pairs of sterile states form Dirac particles themselves. By violating lepton number symmetry slightly, e.g., through a Majorana mass $\mu \ll m_N$, light neutrino masses are generated, $|m_\nu| \sim (y_\nu v / m_N)^2 \mu = |V_{eN}|^2 \mu$, while the heavy sterile neutrinos form quasi-Dirac pairs with a small mass splitting $\Delta m_N \sim \mu$. This concept applies to extended scenarios such as the inverse seesaw mechanism where the scale of lepton number breaking $\mu$ is decoupled from the heavy neutrino mass $m_N$.

This proceedings report is based on our paper comparing the sensitivity of direct searches with that of neutrinoless double beta ($0\nu\beta\beta$) decay$^1$. It utilizes a phenomenological parametrization describing the general mixing of two heavy sterile neutrino states with one generation of active neutrino where the purely Majorana and Dirac scenarios can be understood as limiting cases.

2 Current Constraints and Future Sensitivities

We briefly describe the different classes of probes. For details we refer the reader to our paper$^1$, its accompanying website www.sterile-neutrino.org and other recent literature$^2$. We concentrate on the mixing strength $|V_{eN}|$ of a heavy sterile neutrino with electron flavour as this is the one relevant for $0\nu\beta\beta$ decay. Current constraints on $|V_{eN}|$ as a function of the heavy sterile neutrino mass $m_N$ are shown in Fig. 1, over the broad mass range $0.1 \text{ eV} < m_N < 10 \text{ TeV}$. The diagonal line labelled Seesaw indicates the mixing strength expected in canonical seesaw, $m_\nu = |V_{eN}|^2 m_N$, generating a light neutrino mass $m_\nu = 0.05 \text{ eV}$. Reaching it may be considered the ultimate goal for sterile neutrino searches, though, both larger (e.g., in inverse seesaw models) and smaller (where other contributions dominate the generation of light masses) mixing strengths are possible.

It may be surprising that sterile neutrinos, having no inherent gauge charges, are constrained from so many directions, but the active-sterile mixing causes the sterile neutrino...
Figure 2 – As Fig. 1, but showing the projected sensitivities of future searches (open curves), including $0\nu\beta\beta$ decay, over the existing constraints (shaded regions). The region in light blue is disallowed for both Dirac and Majorana sterile neutrinos whereas the region in light red applies only for Majorana neutrinos. The $0\nu\beta\beta$ decay sensitivities are for a heavy sterile Majorana (red) and quasi-Dirac neutrino (teal) for the half-life $T^{0\nu}_{1/2} = 10^{28}$ yr in $^{76}$Ge. Adapted from the companion paper, with detailed descriptions of the various probes therein and in the accompanying website www.sterile-neutrino.org.

Heavy sterile neutrinos can decay, either promptly or with a macroscopic proper decay length,

$$L_N \approx 25 \text{ mm} \cdot \frac{10^{-10}}{|V_{eN}|^2} \cdot \left( \frac{10 \text{ GeV}}{m_N} \right)^2,$$

where this approximation is roughly valid for $1 \text{ GeV} \lesssim m_N \lesssim m_W$. This improves detectability and especially the long-lived particle (LLP) signature, in combination with high intensity production mechanisms, allows probing sterile neutrinos with very small mixing strengths, close to the canonical seesaw floor. If a heavy sterile neutrino were to be discovered near this line, it would most likely be of Majorana nature. Most probes, such as direct searches, where sterile neutrinos are produced on-shell, are sensitive to both Majorana and Dirac neutrinos. Only those probes relying on a total lepton number violating signal require a Majorana sterile neutrino, c.f. Fig. 2, where corresponding limits are highlighted in red.

The strong reach of high-luminosity, displaced-vertex searches is especially apparent in Fig. 2, which shows sensitivities of proposed experiments (open curves) in comparison with current constraints (shaded regions).

### 2.1 High-energy Colliders

Sterile neutrinos are produced in high-energy collisions through charged and neutral currents such as $pp \rightarrow W^+ \rightarrow e^+ N$ and $pp \rightarrow Z \rightarrow \nu N$. For example, the proposed FCC-ee will be a powerful $Z$ factory with low background for displaced vertices in a large detector volume.

### 2.2 Meson Decays and Beam-Dump Experiments

Likewise, beam-dump experiments and meson factories produce a large number of mesons that subsequently decay to heavy sterile neutrinos, e.g., $K^+ \rightarrow e^+ N$. The most sensitive direct limits are currently from NA62 and the long baseline neutrino oscillation experiment T2K, exploiting this route in existing facilities. Future searches such as SHiP can be purpose-built with optimized LLP detectors.
2.3 Beta Decays and Nuclear Processes

Sterile neutrinos mixing with electron-flavour and masses $m_N \lesssim 1$ MeV can be produced in nuclear beta decays and other weak nuclear processes. They will suppress the rate and can produce a detectable kink in the decay spectrum. Strong advancements in such searches are expected, with the recent BeEST experiment\(^3\) improving previous limits by almost two orders of magnitude ($^{7}$Be). Future searches by the same collaboration and, e.g., the HUNTER proposal\(^4\) aim to go below the region disfavoured by cosmological considerations, probing a parameter space where the sterile neutrino can be a viable Dark Matter candidate.

2.4 Active-Sterile Neutrino Oscillations

Sterile neutrinos can be produced through oscillations with the active states. Persistent anomalies around the squared mass difference $\Delta m^2_{14} = m^2_N - m^2_\nu \approx 1$ eV$^2$ hint at the presence of a sterile neutrino around this scale. Interpreted conservatively, oscillation experiments provide constraints on light eV-scale sterile neutrinos. Heavier sterile neutrinos can also be probed through the resulting deficit of active neutrinos detected, though this requires a very good understanding of the absolute neutrino flux. For DUNE, this is indicated by the contour labelled DUNE Indirect\(^5\).

2.5 Electroweak Precision Data and Indirect Laboratory Constraints

Likewise, any mixing with sterile neutrinos means that the active neutrino mixing matrix itself is non-unitary. This is visible in charged current and neutral current processes, altering electroweak precision data (EWPD) observables.

2.6 Cosmological and Astrophysical Constraints

Sterile neutrinos are produced in the early universe through scattering or oscillation. If decaying at times later than $\sim 1$ s, they affect the abundance of primordial elements in big bang nucleosynthesis (BBN). Decays of longer-lived sterile neutrinos will inject radiation degrees of freedom, i.e., light active neutrinos, which are strongly constrained. Furthermore, the loop-induced decay $N \to \nu \gamma$ is detectable in astrophysical X-ray observations. Quasi-stable sterile neutrinos will act as Dark Matter and must not overclose the universe ($\text{CMB}+\text{BAO}+H_0$). Taken at face value, such considerations disfavour much of the parameter space $m_N \lesssim 1$ GeV accessible in laboratory experiments. They can be relaxed in extended scenarios, e.g., where sterile neutrinos decay to a dark sector modifying their lifetime.

2.7 Neutrinoless Double Beta Decay

The most sensitive probe of the Majorana nature of light active neutrinos is $0\nu\beta\beta$ decay\(^6\). Observing this rare nuclear process in select isotopes such as $^{76}$Ge $\to^{76}$Se $+ e^- e^-$, is only possible if total lepton number is violated. It would prove that the light active neutrinos are Majorana fermions. In addition, $0\nu\beta\beta$ decay is sensitive to other exotic sources of lepton number violation, typically at or below the $\mathcal{O}(10)$ TeV scale\(^7,8,9,10\).

This includes the exchange of sterile neutrinos. In particular, $0\nu\beta\beta$ decay is highly sensitive to heavy Majorana neutrinos. In this case, the decay half-life $T_{1/2}^{0\nu}$ for $m_N \gtrsim 100$ MeV is approximately given by

$$10^{28} \text{ yr} \approx \left( \frac{|V_{eN}|^2}{10^{-9}}, \frac{1 \text{ GeV}}{m_N} \right)^2, \tag{3}$$

For lighter sterile neutrinos, $m_N \lesssim 100$ MeV, the rate is proportional to $m^2_N$,

$$10^{28} \text{ yr} \approx \left( \frac{|V_{eN}|^2}{10^{-9}}, \frac{m_N}{15 \text{ MeV}} \right)^2, \tag{4}$$

The above approximations use nuclear matrix elements for the isotope $^{76}$Ge\(^10\). The behaviour changes around the nuclear momentum scale $\approx 100$ MeV of $0\nu\beta\beta$ decay, and at the crossover the momentum dependence should be accounted for more carefully\(^11,12\).
The above sensitivities are normalized with respect to the half-life $T_{1/2}^{0\nu}(^{76}\text{Ge}) = 10^{28}\text{ yr}$. This is the projected sensitivity of LEGEND-1000, one among a range of proposed experiments mainly aiming to probe the light active Majorana neutrino parameter space for an inverted mass ordering. Current experimental limits are of the order $T_{1/2}^{0\nu} \gtrsim 10^{20}\text{ yr}$.\textsuperscript{14,15}

In Fig. 2, the future sensitivity to Majorana sterile neutrinos is given by the red band labelled $0\nu\beta\beta (N)$, where the width indicates the theoretical uncertainty from nuclear matrix elements. This includes the potential quenching of the axial nuclear coupling strength.\textsuperscript{16}

Future $0\nu\beta\beta$ decay experiments can reach sensitivities $|V_{eN}|^2 \approx 2 \times 10^{-10}$ to $10^{-9}$, in the regime $10\text{ MeV} \lesssim m_N \lesssim 1\text{ GeV}$. This is in the range expected for the canonical seesaw with $m_N \approx 1\text{ MeV}$, and also comparable to future direct searches in this mass window such as PIONEER and DUNE.

For masses and mixing outside this range, the nominal sensitivity to heavy sterile Majorana neutrinos is still strong, but as mentioned above, the light masses naturally require that sterile neutrinos are quasi-Dirac states with an associated small mass splitting that suppresses $0\nu\beta\beta$ decay. For example, with a pair of quasi-Dirac sterile neutrino states of average mass $m_N$ and relative mass splitting $\delta_N = \Delta m_N/m_N$, Eq. (3) is modified to

$$\frac{10^{28}\text{ yr}}{T_{1/2}^{0\nu}} \approx \left( \frac{\delta_N}{10^{-2}} \cdot \frac{|V_{eN}|^2}{10^{-10}} \cdot \frac{1\text{ GeV}}{m_N} \right)^2.$$

Larger masses $m_N \gtrsim 10\text{ GeV}$ and splittings are in principle possible but they require a fine-tuned cancellation of the induced loop contribution to the light neutrino masses.\textsuperscript{18,19,1} Direct searches looking for lepton number conserving signals do not have such a suppression and they can probe purely Dirac-type sterile neutrinos.

The above discussion assumes that the sterile neutrino contribution saturates the $0\nu\beta\beta$ decay sensitivity, but other mechanisms may be present. Most directly, the light active neutrinos (if Majorana) will induce the effective $0\nu\beta\beta$ mass $m_{\beta\beta}$ that destructively interferes with sterile neutrinos for $m_N \lesssim 100\text{ MeV}$ if these participate in the seesaw mechanism. For $m_N \ll 100\text{ MeV}$, light and heavy neutrino contributions will cancel to zero in this case.

The effect of all three types of suppression is indicated in Fig. 2 by the teal band labelled $0\nu\beta\beta (N_1, N_2)$. A quasi-Dirac sterile neutrino nature with $\delta = 10^{-2}$ leads to an overall reduction of sensitivity with respect to the red Majorana band, the interference with the light active neutrino contribution (with $m_\nu = m_{\beta\beta} = 10^{-3}\text{ eV}$, also indicated by the lower diagonal Seesaw line) induces a steeper slope for $m_N < 100\text{ MeV}$, and strong loop corrections to the light neutrino masses of 10% or more are present to the top and right of the line labelled Loop.

\section{Discussion}

Given their curious absence from the SM and their importance as the potential origin of the light neutrino masses, it is only right that sterile neutrinos are being probed in a large number of experiments and observations. We have briefly highlighted the main approaches to search for sterile neutrinos in the experimentally accessible range $1\text{ eV} \lesssim m_N \lesssim 10\text{ TeV}$. Beyond this regime, we must primarily resort to theoretical considerations, e.g., the stability of the Higgs potential modified by the Yukawa couplings of the sterile neutrinos.

Apart from their connection to neutrino masses, sterile neutrinos may play a crucial role in explaining the matter-antimatter asymmetry of the universe through their participation in various leptogenesis scenarios. This provides a major, additional motivation to search for sterile neutrinos, especially in the range $1\text{ GeV} \lesssim m_N \lesssim 100\text{ GeV}$.

Lastly, sterile neutrinos may have additional interactions beyond the ones induced by the active-sterile mixing, leading to other portals such as transition magnetic moments or exotic gauge interactions.

\section*{Acknowledgments}

F.F.D. acknowledges support from the UK Science and Technology Facilities Council (STFC) via the Consolidated Grants ST/P00072X/1 and ST/T000880/1. P.D.B. has received support from the European Union’s Horizon 2020 research and innovation programme under
the Marie Skłodowska-Curie grant agreement No. 860881-HIDDeN. The work of B.D. is supported in part by the US Department of Energy under Grant No. DE-SC0017987.

References

1. Patrick D. Bolton, Frank F. Deppisch, and P. S. Bhupal Dev. Neutrinoless double beta decay versus other probes of heavy sterile neutrinos. *JHEP*, 03:170, 2020.
2. Asli M. Abdullahi et al. The Present and Future Status of Heavy Neutral Leptons. In *2022 Snowmass Summer Study*, 3 2022.
3. S. Friedrich et al. Limits on the Existence of sub-MeV Sterile Neutrinos from the Decay of $^7$Be in Superconducting Quantum Sensors. *Phys. Rev. Lett.*, 126(2):021803, 2021.
4. C. J. Martoff et al. HUNTER: precision massive-neutrino search based on a laser cooled atomic source. *Quantum Sci. Technol.*, 6(2):024008, 2021.
5. S. Carbaş and A. M. Gago. Indirect search of Heavy Neutral Leptons using the DUNE Near Detector. *arXiv*, 2202.09217, 2 2022.
6. Matteo Agostini, Giovanni Benato, Jason A. Detwiler, Javier Menéndez, and Francesc Vissani. Toward the discovery of matter creation with neutrinoless double-beta decay. *arXiv*, 2202.01787, 2 2022.
7. M. Doi et al. Neutrino mass, the right-handed interaction and the double beta decay. i: Formalism. *Phys. Theor. Phys.*, 66:1739, 1983.
8. V. Cirigliano, W. Dekens, J. de Vries, M.L. Graesser, and E. Mereghetti. Neutrinoless double beta decay in chiral effective field theory: lepton number violation at dimension seven. *JHEP*, 12:082, 2017.
9. Lukas Graf, Frank F. Deppisch, Francesco Iachello, and Jenni Kotila. Short-range neutrinoless double beta decay mechanisms. *Phys. Rev. D*, 98:095023, Nov 2018.
10. Frank F. Deppisch, Lukas Graf, Francesco Iachello, and Jenni Kotila. Analysis of light neutrino exchange and short-range mechanisms in $0\nu\beta\beta$ decay. *Phys. Rev. D*, 102(9):095016, 2020.
11. A. Babič, S. Kovalenko, M. I. Krivoruchenko, and F. Šinkovic. Interpolating formula for the $0\nu\beta\beta$-decay half-life in the case of light and heavy neutrino mass mechanisms. *Phys. Rev. D*, 98(1):015003, 2018.
12. Wouter Dekens, Jordy de Vries, Kaori Fuyuto, Emanuele Mereghetti, and Guanghui Zhou. Sterile neutrinos and neutrinoless double beta decay in effective field theory. *JHEP*, 06:097, 2020.
13. Anna Julia Zsigmond. LEGEND: The future of neutrinoless double-beta decay search with germanium detectors. *J. Phys. Conf. Ser.*, 1468(1):012111, 2020.
14. A. Gando et al. Search for Majorana Neutrinos Near the Inverted Mass Hierarchy Region with KamLAND-Zen. *Phys. Rev. Lett.*, 117:082503, Aug 2016.
15. M. Agostini et al. Final Results of GERDA on the Search for Neutrinoless Double-$\beta$ Decay. *Phys. Rev. Lett.*, 125(25):252502, 2020.
16. Frank F. Deppisch and Jonni Suhtonen. Statistical analysis of $\beta$ decays and the effective value of $g_A$ in the proton-neutron quasiparticle random-phase approximation framework. *Phys. Rev. C*, 94(5):055501, 2016.
17. W. Altmanshofer et al. PIONEER: Studies of Rare Pion Decays. *arXiv*, 2203.01981, 3 2022.
18. Manimala Mitra, Goran Senjanovic, and Francesco Vissani. Neutrinoless Double Beta Decay and Heavy Sterile Neutrinos. *Nucl. Phys. B*, 856:26–73, 2012.
19. J. Lopez-Pavon, S. Pascoli, and Chan-fai Wong. Can heavy neutrinos dominate neutrinoless double beta decay? *Phys. Rev. D*, 87(9):093007, 2013.
20. Patrick D. Bolton, Frank F. Deppisch, Kåre Fridell, Julia Harz, Chandan Hati, and Suchita Kulkarni. Probing Active-Sterile Neutrino Transition Magnetic Moments with Photon Emission from CeNS. *arXiv*, 2110.02233, 10 2021.
21. Wei Liu, Suchita Kulkarni, and Frank F. Deppisch. Heavy Neutrinos at the FCC-hh in the $U(1)_{B−L}$ Model. *arXiv*, 2202.07310, 2 2022.
22. Rojalin Padhan, Manimala Mitra, Suchita Kulkarni, and Frank F. Deppisch. Displaced fat-jets and tracks to probe boosted right-handed neutrinos in the $U(1)_{B−L}$ model. In *2022 Snowmass Summer Study*, 3 2022.