Searches for Transformations of Neutrons to Sterile Neutrons and Antineutrons at ORNL and ESS

A Short Overview of Opportunities for Exploratory, Coincident, Small Scale Dark Sector & Baryon Number Violation Experiments

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Suggested Snowmass Topical Groups:

- (RF3) Rare Processes and Precision Frontier: Small Experiments
- (RF4) Rare Processes and Precision Frontier: Baryon and Lepton Number Violating Processes
- (RF6) Rare Processes and Precision Frontier: Dark Sectors

Abstract

Neutron transformations into sterile neutrons provide a unique and comparatively unexplored portal onto a dark sector, an apparent necessity to explain astronomical observations. Sterile neutron transformations have been proposed as an experimental signature for a rich dark sector candidate, mirror matter. Dark sectors also offer a compelling explanation of many anomalies across fundamental physics, such as the neutron lifetime anomaly. An experimental program to search for these transformations is underway using Basic Energy Science neutron scattering facilities at Oak Ridge National Laboratory (ORNL): the High Flux Isotope Reactor and Spallation Neutron Source. A decadal program of searches has also been proposed at the European Spallation Source (ESS) using a dedicated instrument on the ANNI/HIBEAM beamline. The high fluxes of neutrons available at these facilities will enable a suite of searches for these feeble interactions, targeting prior reported anomalous results as well as some previously unexplored processes. In addition to making world leading measurements of exciting beyond Standard Model phenomena, this program will also achieve research and design development goals moving toward a high sensitivity neutron-antineutron transformation experiment, NNBAR, to take place at the ESS Large Beamport in ~ 2030.

Despite decades of searches, the particle nature of dark matter (DM) remains unknown. A growing priority for the particle physics community is to pursue new methodologies to discover potential dark sectors. The importance of pursuing all feasible avenues in searches for DM candidates, usually based on observed anomalies or other unanswered questions in physics, has recently been highlighted[1]. One rich theoretical model conceives the existence of a parallel sterile or *mirror* sector comprising all or part of the dark sector (see reviews[2–4]). This mirror sector could be imbued with identical gauge symmetries to those of the ordinary Standard Model (SM) related by a Z_2 symmetry, denoted SM′. If one ignores the trivial noninteracting hypothesis and instead assumes the existence of interactions and mixing between the SM and SM' such that $\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{SM'} + \mathcal{L}_{\mathbf{mix}}$, neutral particle oscillations could spontaneously occur in vacuum. Thus, neutrinos, photons, and neutrons (n) could transition into sterile, "mirror" twin states[5]. A mirror neutron (n') would be just such a sterile twin belonging to the SM′ gauge group, and would therefore be invisible to ordinary matter detectors. Some versions of this model provide explanations for the long-standing n β-decay lifetime (τ_n) anomaly, the 4.1σ discrepancy[6] between τ_n as measured in a "bottle" using ultracold neutrons (UCNs) (rate of disappearance of n) and τ_n as measured in a cold n "beam" (rate of appearance of protons vs. n flux). Further, some disagreement is apparent in n magnetic versus material bottle experiments[7] (Fig. 1). Material traps may have some poorly understood contributions from sources of UCN loss[8] which could be consistent with BSM physics. Sterile n' transformations have been proposed as a possible effect impacting either UCN bottle[9] or cold n beam[7] experiments. The possibility of n dark decay has also been proposed[10], sparking several experimental searches that strongly constrained that prospect[11–13].

An attractive feature of this class of models is that the associated experimental tests utilize an underemployed tool among DM searches–the n. Thermal and cold n sources are used by a wide range of scientific disciplines to provide insight into phenomena generally unreachable by other means, such as photons or charged particles. These unique benefits are reflected in the significant investments made in accelerator based n sources since the beginning of this century, of which the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL) and the European Spallation Source (ESS), now under construction, are exquisite examples. This is also seen in the operating lifetimes of reactor-based n sources, most of which were built last century yet successfully continue their missions to this day, such as ORNL's High Flux Isotope Reactor (HFIR). The importance of a HFIR upgrade to 100 MW and a SNS Second Target Station have been recognized for their fundamental physics capabilities[14;15]. As primarily Basic Energy Science facilities, their scientific focus has been mainly on material sciences, though a dedicated beamline for fundamental nuclear physics at the SNS[16] has produced a vibrant program of studies of hadronic parity violation[17], precision β-decay[18], and a search for the n electric dipole moment (nEDM)[19]. While thus far these facilities' contributions to particle physics have been limited to only a handful of experimental endeavors, significant impacts have already been made through the discovery of coherent elastic neutrino nucleus scattering at the SNS by COHERENT[20] and the first measurement of the neutrino flux and energy spectrum from a highly-enriched uranium nuclear reactor core by PROSPECT[21;22]. These experiments have demonstrated the tremendous strength and potential that n facilities have for particle physics. ORNL's Physics Division is more broadly pursuing particle physics applications of ns in parallel to their active neutrino physics program, as a new initiative to expand their fundamental science program. ORNL's n facilities can be applied to DM research, and these benefits should be comprehensively assessed as recognized in the recent charge to the Basic Energy Science Advisory Committee[23]. A symbiotic set of experiments[24] is underway which could add still more potential to ORNL's growing fundamental physics capacity, including research and development for future experiments at the ESS[25].

The oscillation or transformation probability of the $n \to n'$ process is sensitive to an energy splitting between the n and n' state, such that the process is not noticeable in the typical environments of the n in nuclei, neutron stars, or even in terrestrial experiments; due to the earth's ambient magnetic field, one should expect suppression of any potentially fast neutral particle oscillation. Further, the potential existence of mirror magnetic fields in the dark sector (generated by e.g. gas ionization[26–28]) would lead to similar suppression. Thus, by utilizing experimental volumes instrumented with precise magnetic field control, one could either enhance (or suppress) such oscillations by effective vectorial alignment and cancellation. Such effects could include first or second order (or higher) transitions, i.e. *disappearance* via $n \to n'$ and subsequent *regeneration* via $n \to n' \to n$.

The possibility of n transformations into a dark sector has prompted several UCN-based disappearance-style $n \to n'$ searches, with a deviation from the null result being reported in the combined data set[28;29]. A sensitive approach using UCN has been proposed and tested by the Paul Scherrer Institute nEDM collaboration[30]. A positive signal in a UCN-based search can be difficult to interpret due to the sometimes poorly understood sources of UCN losses. Cold n beams enable an alternative

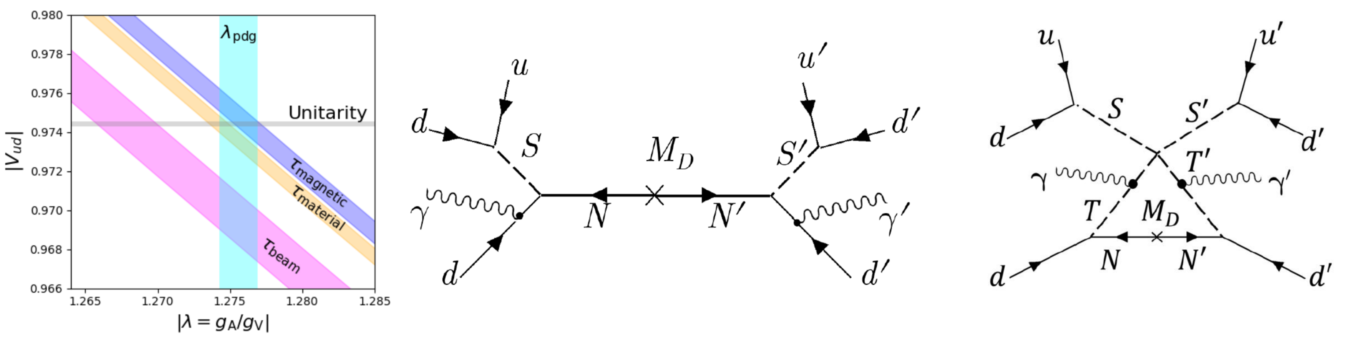

Figure 1: Left: SM quark mixing matrix parameter V_{ud} vs. λ, an observable in neutron β-decay. Within the SM, the unitarity condition holds. Disagreement is observed between beam, material bottle, and magnetic bottle τ_n results. Right: Possible $n \to n'$ transition diagrams[9] dressed with photons, compensating for potential field suppression. Such interactions could explain the τ_n anomaly.

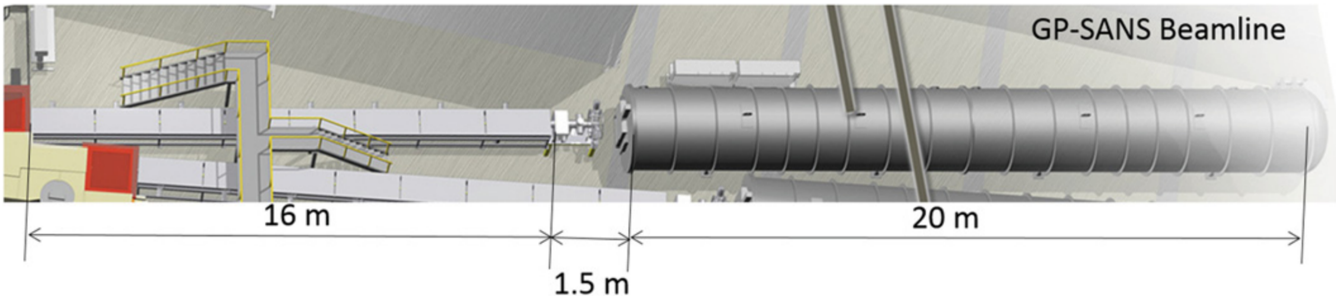

Figure 2: Top view of the HFIR GP-SANS beamline at HFIR used for $n \to n' \to \{n, \bar{n}\}$ searches, described in the text.

and unambiguous $n \to n' \to n$ search potential to refute or confirm the possibility of this BSM process. The basic concept of a cold n search for sterile n' partners is akin to experimental tests for "light shining through walls"[31]. Fig. 2 depicts the General Purpose: Small Angle Neutron Scattering (GP-SANS) instrument at HFIR used for these sterile n searches. The 16 m upstream section is implemented for $n \to n'$, followed by a 1.5 m section for a beam trap (the "wall"), n monitors, and/or other magnetic control elements, and finally the 20 m long vacuum tank used for $n' \to n$ regeneration, which houses the downstream, low background n detector. As seen in Figs. 3, with magnetic field control and directional field strength scanning, a disappearance signal would manifest as a flux deficit, while a regeneration signal appears as an anomalous signal above background. In the latter approach, a beam trap is implemented to absorb all SM ns while sterile n's pass through unencumbered, to be regenerated and later observed in the detector downstream. Each of these approaches have the required sensitivity to unambiguously confirm or refute previously reported anomalous results even within the short beamtimes typically allotted at HFIR.

A more recent variant of the mirror sector theory[7] hypothesizes that the masses of the n and n' are slightly nondegenerate due to a spontaneous symmetry breaking mechanism. The magnetic field in the NIST Beam Lifetime experiment[32] can compensate for such a small mass difference, Δm, resulting in uncounted mirror protons (p'), thus offering a potential explanation of the τ_n anomaly. An expanded version of the theory[9] with degenerate n and n' masses is based on the concept of a n transition magnetic moment (nTMM) induced by a $n \to n'$ transition. Following this[9], one finds that the gradients of magnetic field potential (equivalent to a classical force) will allow for separation between mixing components of the two-level $\{n, n'\}$ wave function since a force is exerted only on the SM n, hypothetically enhancing the rate of $n \to n'$ production. The reported $\sim 5\sigma$ anomalous result remains consistent with such a process[28;29]. Still more, a compelling set of arguments[33;34] have been put forward on how such a mirror sector could act as a transitional shortcut for the direct observation of *inducible* baryon number violating modes such as neutron-antineutron transformations ($n \to \bar{n}$) via $n \to n' \to \bar{n}$ with direct consequences for cobaryogenesis mechanisms[33] in conjunction with the dark sector. There could also exist commensurate signals in n spin precession, accessible via n spin-echo apparatuses[35]. With the current capabilities of HFIR, these small scale experiments can produce world-leading sensitivities to DM searches via $n \to n'$ transitions.

The experiments performed at the HFIR can also be utilized for R&D as a means of preparation for future searches at the ESS ANNI[36]/ HIBEAM[25] fundamental physics beamline. The ORNL program will continue up to the middle of the decade, until the long shutdown of HFIR for a planned beryllium changeout. At this point, the HIBEAM program can commence during the early period of ESS operation before full the beam power of 5 MW is available ~ 2030. The ANNI beamline has 50 m of space available for flexibility in implementation of these experimental searches where a dedicated instrument can be optimized, e.g., a 50 m $n \to n'$ search, or a 25 m + 25 m $n \to n' \to n/\bar{n}$ search. Fig. 3 depicts the sensitivity of the HIBEAM program to $n \to n'$ oscillation times for various experiment durations and potential detector radii. These sensitivities are produced using a full source and outgoing cold n beam simulation, resulting in $\sim 10^{10-11}$ n/s on the n detector.

In conclusion, by leveraging existing Basic Energy Science facilities against modest investment, exciting new directions for searches of feeble interactions with dark sectors can be accessed at ORNL. The HIBEAM program at the ESS provides an opportunity for enhanced sensitivity using an optimal setup to search for $n \to n'$ oscillation times approaching τ_n. This work will also inform the NNBAR[25;37] Collaboration on backgrounds, beam dynamics, magnetic field controls, and detector design, empowering the future full free $n \to \bar{n}$ experiment[25;37–41] at the ESS's Large Beamport.

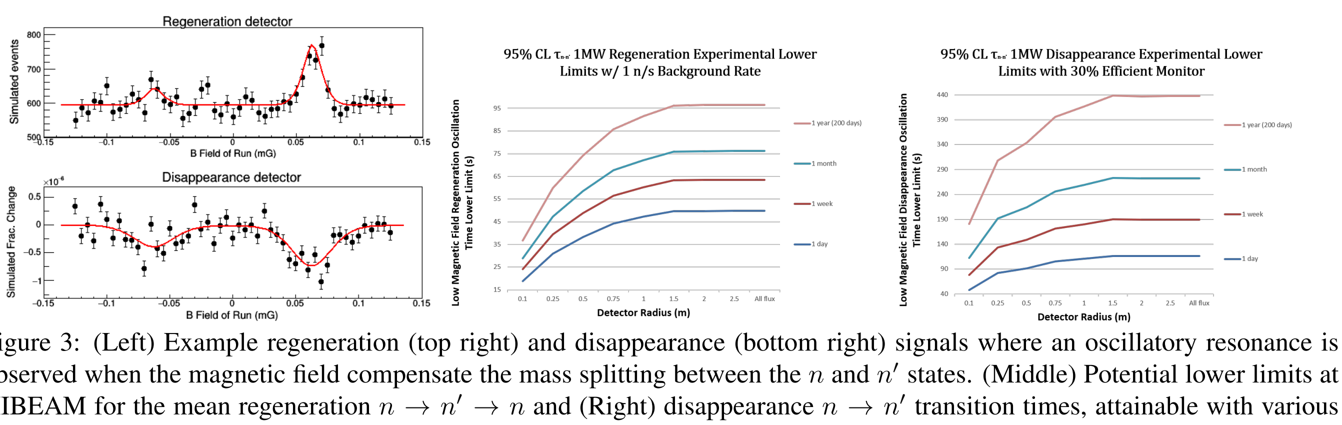

Figure 3: (Left) Example regeneration (top right) and disappearance (bottom right) signals where an oscillatory resonance is observed when the magnetic field compensate the mass splitting between the n and n' states. (Middle) Potential lower limits at HIBEAM for the mean regeneration $n \to n' \to n$ and (Right) disappearance $n \to n'$ transition times, attainable with various run times and detector sizes with the expected background rate.

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