Searches for Mirror Neutrons as a Path to NNBAR: A Fundamental Symmetries Townhall Topical White Paper

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Neutrons oscillating into dark sector counterparts have been proposed as a mechanism to explain such varied questions as Baryon Number violation, the nature of dark matter, and anomalies in precision fundamental neutron experiments. Several experimental efforts both in the United States and Europe have recently been developed to probe the possibility of these rare processes. In this white paper, we describe the experimental program at Oak Ridge National Laboratory of small-scale searches for neutrons oscillating into mirror neutrons using the novel technique of cold neutron regeneration. The techniques used in these experiments can ultimately be used as a proving ground for a future high sensitivity search for neutrons oscillating into antineutrons.

The Standard Model (SM), although featuring unprecedented predictive power, lacks an explanation for the observed matter/antimatter asymmetry in the universe and fails to explain the nature of dark matter or dark energy. Searching for valid mechanisms to explain this asymmetry was identified as one of the main priorities for nuclear physics in the most recent Long Range Plan (LRP) for Nuclear Science [1]. Free neutrons (n), traditionally used to study materials, can be a powerful probe into these fundamental symmetries through potential exotic interactions with Beyond the Standard Model (BSM) physics. Addressing the question of baryogenesis and the possible role of neutron oscillations has strong backing from the theoretical community crossing the boundaries of nuclear and particle physics [2, 3]. Here, a recently initiated program of small-scale experimental efforts to search for BSM interactions of the neutron which violate Baryon Number ($\mathcal{B}$) at Oak Ridge National Laboratory (ORNL) is described. These studies will inform future high sensitivity searches for Baryon Number violation (BNV) at the European Spallation Source (ESS). This program was spearheaded by ORNL and University of Tennessee, Knoxville, and the collaboration has expanded to include University of Kentucky, Indiana University, University of Stockholm, and the ESS. Support in the upcoming LRP for the investment in the proposed small-scale program at ORNL would ensure that US institutions develop the expertise and are well situated to take a leading role in the ESS searches as part of the HIBEAM program later this decade and the high sensitivity, large-scale NNBAR experiment beyond this LRP period [4].

The most compelling motivation for these searches is the observed abundance of matter over antimatter in the universe, which implies a mechanism for violation of either Baryon Number ($\mathcal{B}$) or Lepton Number ($\mathcal{L}$). In the SM, the combination $\mathcal{B}-\mathcal{L}$ is an exact symmetry, but the individual numbers $\mathcal{B}$ and $\mathcal{L}$ are only accidental symmetries. This has led to large-scale experimental efforts searching for proton decays, a $\Delta\mathcal{B} = 1$, $\Delta\mathcal{L} = 1$ process, and neutrinoless double-β decays, a $\Delta\mathcal{L} = 2$ process [5]. As the neutron lacks a net charge, oscillations between neutron (n) and antineutrons ($\bar{n}$) have been proposed as a testable mechanism for a $\Delta\mathcal{B} = 2$ process that is presently underexplored [6]. Additionally, the neutron could uniquely couple to dark sectors leading to a $\Delta\mathcal{B} = 1, \Delta\mathcal{L} = 0$ interaction.

Although many mechanisms for the particle nature of dark matter have been proposed, to date none of these have been discovered in the laboratory. The high-energy particle physics community and the astrophysics communities have highlighted the importance of parallel searches for various mechanisms for dark matter [7]. One specific dark sector model proposes the existence of a parallel sterile or *mirror* sector with the same particles and gauge interactions as the

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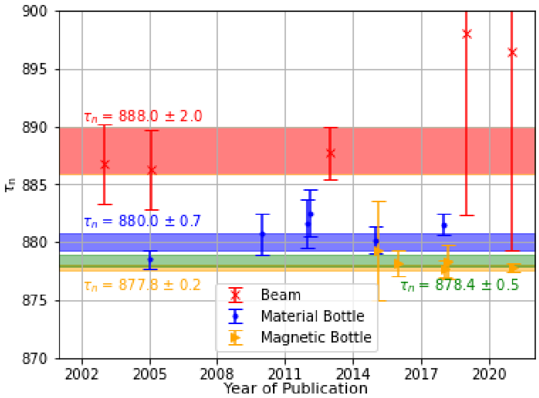

FIG. 1: Measurements of the neutron lifetime utilizing bottles and beams.

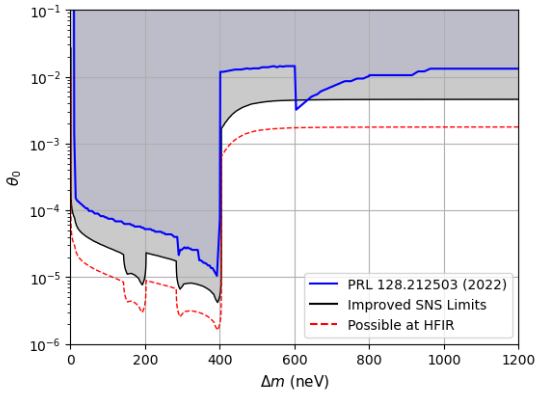

FIG. 2: Anticipated improvement in oscillation probability limit as compared to work performed at SNS in 2019 [24].

ordinary Standard Model (SM) [8–10]. This Mirror Model (SM') could be related to the SM via a Z_2 symmetry, and interactions between the SM and SM' could be described through the introduction of a $\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm SM'} + \mathcal{L}_{\rm mix}$. Neutral particles, such as neutrinos, photons, and even n, have recently become a tantalizing possibility for this mixing [11]. A mirror neutron (n') would be a sterile twin to the ordinary neutron (n), which could undergo the transition $n \to n'$. The broader topic of neutron oscillations has been an active area of research, becoming a Frontier sub-topic for the American Physical Society Division of Particles and Fields Snowmass Community Planning Process [12, 13].

Anomalies in precision measurements can provide clues to the origin of these important questions about the nature of matter in the universe. Experiments to measure the lifetime of the free neutron τ_n have a $> 4\sigma$ discrepancy between measurements either counting decay products produced by a "beam" of cold neutrons or through disappearances of ultracold neutrons (UCN) trapped in a material or magnetic "bottle," which can be seen in figure 1 [14–17]. The "beam" method specifically measures the decay rate for the process $n \to p^+ e^- \bar{\nu_e}$ while the "bottle" method would be susceptible to $n \to \chi$, where χ can be anything, including BSM physics. The resolution of the neutron lifetime discrepancy was one of the highest scientific priorities recommended by the NSAC Subcommittee to Fundamental Nuclear Physics with Neutrons prior to the last Long Range Plan [18]. The oscillation between the SM and SM' states $n \to n'$ has been proposed as an explanation for this discrepancy, with diverse mechanisms of the transition between the two states parameterized to be able to describe the measured 1% branching ratio [19–21]. Searches measuring the loss rate in UCN traps have seen anomalous results as a function of magnetic field, potentially a signal for $n \to n'$ [22, 23].

These important physics problems can be addressed using novel approaches at US neutron facilities. ORNL is one of the USA's leading institutions for n research, as it is home to two high intensity neutron sources: the Spallation Neutron Source (SNS) and the High Flux Isotope Reactor (HFIR). These two facilities have predominately fallen under the scope of Basic Energy Science, where their scientific focus has been mainly using neutrons as a probe of material properties. The ORNL Physics Division has succeeded at pursuing fundamental physics research at these facilities, including work on the Fundamental Neutron Physics Beamline, COHERENT at the SNS, and PROSPECT at HFIR [25–28]. As recognized by the Basic Energy Science Advisory Committee in 2019, the SNS and HFIR can be beneficial facilities for researching BNV and dark matter [29].

A staged program of small-scale studies to search for $n \to n'$, using neutron scattering instruments at ORNL, has been developed in collaboration with the instrument scientists. The searches at ORNL are planned for the early part of the decade, and will be used to develop improved searches as part of HIBEAM at the ESS using a dedicated instrument toward the end of the decade [4]. The ORNL program has been launched with first searches for $n \to n'$ with non-degenerate masses requiring minimal resources or impact on the scattering instruments. Measurement schemes are being designed to subsequently search for a possible Transition Magnetic Moment of the n,n' system (nTMM). With modest investment, the program will culminate with a search for n,n' oscillations at low magnetic field, including a search for general mixing of n,n',$\bar{n}'$ and $\bar{n}$. The conclusion of the $n \to n'/\bar{n}' \to n/\bar{n}$ program gives opportunity for R&D for the high sensitivity NNBAR experiment, which will improve the limits on a search for free $n \to \bar{n}$ by three orders of magnitude. This program provides an economical opportunity to address important science questions of dark matter, BNV and baryogenesis, and anomalies observed in precision neutron physics experiments such as the neutron lifetime anomaly and unexplained disappearance of neutrons in ultracold neutron-based mirror neutron searches.

The first stage of this program addresses one particular Mirror Matter model with a non-degeneracy between the mass of the n and n', Δm which predicts a $n \to n'$ oscillation frequency that could explain the neutron lifetime discrepancy [19]. A first search was performed using an SNS scattering instrument, which rejected this mechanism as an explanation for the neutron lifetime discrepancy using the neutron regeneration technique $n \to n' \to n$ [24]. Further searches for this particular model as a form of BNV and dark matter have been performed at SNS, and beamtime has been awarded at a much higher intensity beamline at HFIR in 2023. As part of these rare searches, detailed characterizations of the instrument beamlines and detectors were conducted including efforts to reduce the backgrounds of both the HFIR and SNS instruments, resulting in an overall benefit for these instruments' primary program. Improved sensitivity at lower or higher mass splittings, respectively, are available from searches at the Institut Laue Langevin (ILL) using beams of UCN [30], and from a search for "hidden neutrons" using fast neutrons using the STEREO detector [31].

Building off of this success, other variants of the mirror model theory can be probed at ORNL. One modification invokes a nTMM between the neutron and mirror neutron states to potentially explain the difference in measured lifetimes between material and magnetic bottles [20]. This nTMM effect can be searched for parasitically using the same experimental apparatus as in the Δm search, or with transmission through a long time of flight in low fields, in the middle of this decade. In addition, the traditional way to search for $n \to n'$ assumes small energy splittings and implements $\mathcal{O}(10-100)$ mG laboratory magnetic fields, where in UCN experiments, some anomalous disappearance signals have been reported [22, 23]. The apparatus used for the n Electric Dipole Moment search at the Paul Scherrer Institute has been repurposed to attempt to address these anomalies in a UCN disappearance search [32, 33]. The cold neutron regeneration $n \to n' \to n$ technique presents a robust alternative, and feasibility studies have been performed for a search at HFIR and the NIST Center for Neutron Research [34], which could be performed in the middle to latter part of the decade. Significant increase in sensitivity will be available from the HIBEAM program at the ESS, late in the decade [4].

A recently proposed model links the dark sector as an intermediary between neutron and antineutron, predicting a shortcut via $n \to n' \to \bar{n}$ [35]. Present limits on $n \to n'$ are significantly lower ($\mathcal{O}(10^2)$ s) than limits directly on $n \to \bar{n}$ ($\mathcal{O}(10^7)$ s), allowing for the potential to eliminate large regions of parameter space with relatively inexpensive experiments, or to search for $n \to \bar{n}$ with couplings to magnetic fields. Such a search requires only the addition of an antineutron detector as an iteration over the previously described cold neutron regeneration search at low energy splitting, and would allow for preliminary commissioning of detectors and technologies for the future $n \to \bar{n}$ search at the ESS, NNBAR [36].

The NNBAR experiment represents a tremendous opportunity to make significant advancements in experimental sensitivity of a search for $n \to \bar{n}$. Design and optimization of the NNBAR experiment has previously and will continue to require scientific leadership from the US neutron physics community. Investment in the small-scale program of studies at ORNL described here, as a staged program leading into NNBAR, will provides a compelling opportunity for strong US leadership in this future high sensitivity neutron oscillation search. This program will also provide new, complementary opportunities for scientific and technical progress which can inform one of the most important science questions of our time, that of the origin and evolution of matter in our universe.

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