

**Scientific Importance.** Understanding of the unknown nature of Dark Matter (DM) is an outstanding problem in the Cosmic Frontier of particle physics research [1]. The popular model of Supersymmetry was long thought to supply a compelling solution in its prediction of the lightest supersymmetric particle as a DM candidate, but the theory was not confirmed [2] at the Large Hadron Collider. Another viable DM candidate, the axion particle, has been sought for a few decades without success [2]. The HEP community has highlighted the importance of pursuing all possible avenues to search for DM candidates based on other unanswered questions in physics [1, 13].

Experiments with cold neutrons supply a unique opportunity to explore another viable and testable DM model, where DM consists of “Mirror Matter” (MM) particles [3]. This MM is an exact copy of Ordinary Matter (OM), with the same interactions and same particle content, but interacting with OM only via gravity. In this model the neutron ( $n$ ) as a neutral particle can be transformed [4] by oscillation to its twin in the mirror sector, the “mirror” neutron ( $n'$ ), which, being a dark matter particle, is not visible by OM detectors. The  $n \rightarrow n'$  oscillations have been proposed as an explanation [5] of the long-standing neutron lifetime anomaly [6], i.e., the discrepancy between two existing state-of-the-art methods of  $n$  lifetime measurements. The neutron lifetime is a critical input to understanding the non-unitarity in the quark-mixing matrix, one of the highest priorities identified by the Fundamental Symmetries, Neutrons, and Neutrinos community [11] for the decadal DOE NP’s Long Range Planning exercise.

We have demonstrated use of a novel technique, neutron regeneration, to search for the rare processes of  $n \rightarrow n'$  predicted by different versions of the MM model as described below. With the GP-SANS-based experiment proposed here, we will search for the neutron Transition Magnetic Moment ( $n$ TMM),  $\eta$ , an electromagnetic property of  $n \rightarrow n'$  transformations predicted in a particular extension of the MM model with degenerate masses [8]. The TMM is known to be a mechanism in specific transitions of neutral particles, such as in the processes  $\Sigma^0 \rightarrow \Lambda^0 + \gamma$  [9] and in the flavor oscillations of the neutrino [10]. This MM model of  $n$ TMM [8] also could provide an alternate explanation of the neutron lifetime anomaly.

The broader program of neutron oscillations was featured as a key Frontier sub-topic in the APS DPF Snowmass Community Planning Process [14]. Building on the success of the Fundamental Neutron Physics Beamline at SNS, and the COHERENT [15] and PROSPECT [16] experiments, ORNL Physics Division is pursuing this research area as a new initiative to expand the fundamental physics program at ORNL’s neutron facilities supported by DOE NP. The experiment proposed here is a part of UT/ORNL grant from DOE/NP DE-SC0023149 “Search for Hidden Sector Neutrons at the High Flux Isotope Reactor.” The SNS and HFIR can be applied to dark matter research and these benefits should be assessed, as recognized in the charge to the Basic Energy Science Advisory Committee in 2019 [17]. The exotic process probed by this experiment is of great interest in ruling out part of the parameter space for DM candidates as well as exotic explanations for the neutron lifetime anomaly.

**Preliminary Work.** We have completed data-taking for a series of experiments to explore one version of this MM model, mirror neutron  $n \rightarrow n'$  oscillation with non-degenerate masses  $\Delta m \neq 0$  of  $n$  and  $n'$  [5] at SNS and HFIR. This model proposed to explain the neutron lifetime anomaly [6] was explored and refuted in a first experiment at SNS MagRef beamline (IPTS-22937.1), published in Physical Review Letters [7]. A second SNS experiment (IPTS-22937.2) significantly improved the exclusion limits on the mixing angle parameter  $\theta_0$  of this model. The corresponding paper has been submitted to Physical Review D (PRD) [20]. An ultimate limit on this model will be set from the data collected in January 2024 at HFIR (IPTS-27957.2) thanks to a much higher neutron intensity in the GP-SANS beamline. This data is currently being analyzed to be prepared for a future publication in PRD. Studies of the GP-SANS beamline and detector relevant for this and other low-background rare phenomena searches, performed in IPTS-24916 and IPTS-27957.2, are being prepared for submission to Review of Scientific Instruments. These studies confirmed the low-background GP-SANS detector performance necessary for the currently proposed measurement of  $n$ TMM. The setup described in this proposal was developed in collaboration with the GP-SANS instrument scientist.

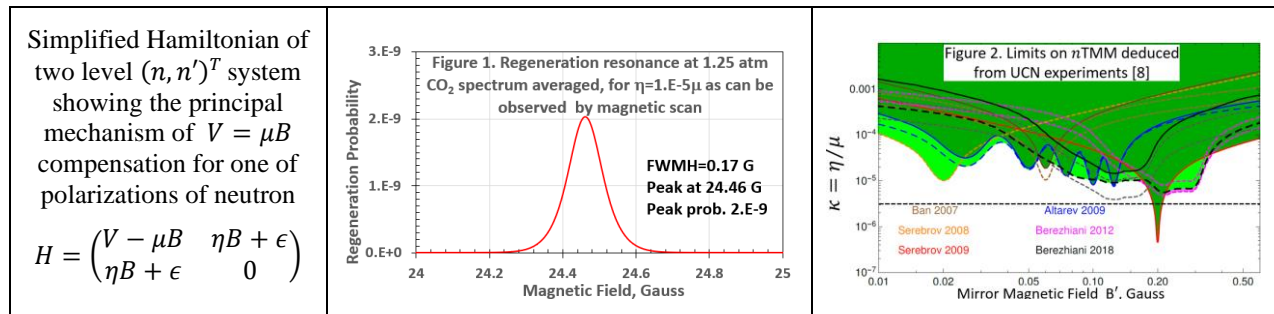
**Choice of Instrument.** According to our studies [18-19], the high time-averaged intensity, long beam guides, and large area detector with relatively low background provided by the GP-SANS instrument will enable sensitive searches for regeneration of mirror neutrons. In addition, our team has gained experience using GP-SANS and now has better understanding of its detector, as well as beam intensity, beam profile and divergence, which help support fundamental physics research at this instrument. Proposed measurement is the next step in a staged campaign at GP-SANS to quantify  $n \rightarrow n'$  oscillation limits.

**Experiment Plan.** The CG-2 beamline at HFIR upstream of the sample position consists of eight 2-m long evacuated sections. In the two downstream sections, the neutron guide will be replaced with two ~2-m long, 0.215 m diameter cylindrical vessels filled with 1.25 atm of CO<sub>2</sub> gas. Between the two cylinders, there will be a 3.5-mm plate of Cadmium which will fully absorb the cold neutron beam (in the absence of the rare phenomenon). Four layers of copper wire tightly wound on the aluminum body of the cylinders create a variable 20-30 G magnetic field inside. One of the

cylinders has been constructed and is being tested by the University of Tennessee and the University of Kentucky, with engineering support from ORNL to ensure compliance with instrument and safety requirements. The two magnets are expected to be commissioned by mid-summer 2024.

To measure the effect of  $n \rightarrow n'$  with a  $n$ TMM,  $\eta \ll \mu$ , the dipole neutron magnetic moment, we will use the neutron regeneration method. The presence of a  $n$ TMM increases the mixing strength of a possible  $n \rightarrow n'$  transformation proportional to the applied magnetic field  $B$ . On the other hand, a magnetic field  $B$ , acting only on  $n$  but not on  $n'$ , increases the energy level split between  $n$  and  $n'$  and thus suppresses the probability of  $n \rightarrow n'$  oscillations. The energy of neutrons in a magnetic field of  $B \approx 25$  Gauss will be compensated for one polarization of neutrons in the beam by the optical potential of  $\text{CO}_2$  gas,  $V \cong 0.15 \text{ neV}$ . When compensated, the transition probability of  $n \rightarrow n'$  will depend only on the enhanced oscillations arising from the presence of the  $n$ TMM and will quadratically increase with time. At the value of magnetic field corresponding to the compensation of the optical potential  $V$ , we expect to observe a resonance behavior under variation of the magnetic field  $B$  with the maximum determined by the magnitude of the  $n$ TMM. For this model [8] to explain the neutron lifetime discrepancy, the transformation  $n \rightarrow n'$  in the resonance would have to occur inside the first magnet with an estimated probability  $\approx 10^{-5}$ . Between the two magnets, the 3.5-mm Cd plate will fully absorb the incident neutron beam with a suppression factor of more than  $10^{20}$ , however, it will allow mirror neutrons (as DM particle) to pass through. In the second magnet, mirror neutrons will be regenerated back into ordinary neutrons with a similar transformation probability. These regenerated neutrons can be detected in the GP-SANS detector. Figure 1 shows the shape of the expected regenerated resonance peak in red. Switching off the magnetic field will remove this regeneration effect, providing a background measurement. The absence of a resonance above background level in the GP-SANS detector will allow to set a limit on the  $n$ TMM or provide a first direct measurement of this quantity in case of discovery.

Our earlier measurements in IPTS-24916 have determined a beam intensity of  $\sim 3.5 \times 10^9 \text{ s}^{-1}$  in the GP-SANS beam guide for the white spectrum with  $\lambda > 2\text{\AA}$ . Assuming a  $n$ TMM of  $\eta = 10^{-5}\mu$ , we expect a counting rate of  $\sim 3.5$  regenerated neutrons per second and a background rate of  $\sim 1$  count per second in the region of interest of the detector. In one hour of continuous beam time at the resonance condition we should be able to exclude the effect of  $n \rightarrow n'$  due to  $n$ TMM with  $>3\sigma$  significance down to the level of  $\kappa = \eta/\mu = 3 \cdot 10^{-6}$ . Due to finite accuracy in determination of both  $V$  and  $\mu B$ , as well as due to the possible presence of an unknown mirror magnetic field  $B'$ , we will need to scan the magnetic field in the range  $25 \pm 1 \text{ G}$  across with 20-25 field values. Each point will require two one-hour runs with magnets ON and OFF for background subtraction. The corresponding exclusion limit as shown in Figure 2 will exceed the earlier indirect estimates [8] of  $n$ TMM obtained from prior ultracold neutron experiments in the range  $B < 0.5$  Gauss. If the background rate will be higher than the optimistically expected 1 cps, the measurement time will need to be increased correspondingly. The magnetic field will be monitored during beam time by recording the calibrated current in the coils with accuracy better than 0.1%. In this proposal we request 72 hours of beam time for the measurements plus 24 hours for studying the experiment settings, including background minimization per ROI and intensity calibration using both gold foil activation and a low efficiency calibrated neutron monitor.



**Data Analysis and Scientific Outcome.** Standard analysis tools including Python and ROOT will be used and have already been developed for the NeXuS data format. Graduate and undergraduate students from the University of Tennessee, University of Kentucky, and collaborators from the Universities of Stockholm and European Spallation Source will take part in the data analysis. The impact of an observation of  $n \rightarrow n'$  transformation signal cannot be overstated: it would be the first clues on the particle nature of Dark Matter and would completely revolutionize our understanding of the Standard Model of Particle Physics. A positive result from this experiment might additionally lead to a solution to the neutron lifetime anomaly. A negative result will rule out the  $n$ TMM model as a possible explanation of this anomaly. This measurement will be the first dedicated experiment directly searching for a  $n$ TMM.

## Safety Considerations

This experiment will use a high neutron absorption Cd target which may result in radiation hazards. Instructions from radiological control technicians will be followed to implement proper safety controls. This experiment will use electrical equipment that may not be NRTL-listed. All non-listed electrical equipment will be inspected and approved by an ORNL Electrical Equipment Inspector before use. Two pressure vessels will be installed in place of the last two sections of the neutron guide. They will be designed and certified by professional engineering staff within the Physics Division and checked by ESQ&H safety staff matrixed to Neutron Sciences Directorate.

## References

1. Proceedings of the 2021 US Community Study of the Future of Particle Physics (Snowmass 2021), <https://www.slac.stanford.edu/econf/C210711/>.
2. The Review of Particle Physics, R.L. Workman *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022) and 2023 update. <https://pdg.lbl.gov/#home>.
3. A. Berezhiani, Through the Looking-Glass: Alice Adventures in Mirror World, in the book "From Fields to Strings: Circumnavigating Theoretical Physics: A Conference in Tribute to Ian Kogan", 2005, pp 2147-2195, [https://doi.org/10.1142/9789812775344\\_0055](https://doi.org/10.1142/9789812775344_0055).
4. Z. Berezhiani and L. Bento, "Neutron – Mirror Neutron Oscillation: How Fast Might It Be?" Phys. Rev. Lett. **96** 081801 (2006).
5. Z. Berezhiani, "Neutron Lifetime Puzzle and Neutron – Mirror Neutron Oscillation," Eur. Phys. J. C79 (2019) no.6, 484; arXiv:1807.07906 (2018).
6. F. E. Wietfeldt, "Measurements of the Neutron Lifetime," Atoms **6** 70 (2018).
7. L.J. Broussard (Oak Ridge), J.L. Barrow (Tennessee U.), L. DeBeer-Schmitt (Oak Ridge), T. Dennis (East Tennessee State U.), M. R. Fitzsimmons (Oak Ridge and Tennessee U.), M. J. Frost (Oak Ridge), et al., "Experimental Search for Neutron to Mirror Neutron Oscillations as an Explanation of the Neutron Lifetime Anomaly", Phys. Rev. Lett. 128 (2022) 21, 212503, [e-Print: 2111.05543 \[nucl-ex\]](https://arxiv.org/abs/2111.05543) (2021).
8. Z. Berezhiani, R. Biondi, Y. Kamyshev, L. Varriano, "On the Neutron Transition Magnetic Moment," MDPI Physics 1 (2019) no.2, 271-289, arXiv:1812.11141 (2018).
9. P. C. Petersen, and others, Measurement of the  $\Sigma^0 \rightarrow \Lambda$  Transition Magnetic Moment, (1986), Phys. Rev. Lett. 57, 949.
10. A. de Gouvía and S. Shalgar, Transition magnetic moments and collective neutrino oscillations: three-flavor effects and detectability, [Journal of Cosmology and Astroparticle Physics](https://arxiv.org/abs/1304.0341), Volume 2013, April 2013.
11. Acharya, B.; et al. "Fundamental Symmetries, Neutrons, and Neutrinos (FSNN): Whitepaper for the 2023 NSAC Long Range Plan." (2023). arXiv:2304.03451
13. M. Battaglieri et al., "US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report," arXiv:1707.04591 (2017).
14. J.L. Barrow (MIT), Leah Broussard (Oak Ridge), James M. Cline (McGill U.), et al., "Theories and Experiments for Testable Baryogenesis Mechanisms: A Snowmass White Paper", (Mar 14, 2022), Contribution to 2022 Snowmass Summer Study, e-Print: 2203.07059 [hep-ph].
15. D. Akimov et al., "Observation of coherent elastic neutrino-nucleus scattering," Science **357** 1123 – 1126 (2017), <https://arxiv.org/abs/1708.01294>.
16. J. Ashenfelter et al., "First search for short-baseline neutrino oscillations at HFIR with PROSPECT," Phys. Rev. Lett. 121 (2018) no.25, 251802, arXiv:1806.02784 (2018).
17. Basic Energy Science Update at BES Advisory Committee Meeting, March 7, 2019, slides 23-25 "New BESAC Charge from Dr. Binkley (Feb.5, 2019), [link](https://arxiv.org/abs/1902.08264).
18. L. J. Broussard, "New Search for Mirror Neutrons at HFIR," in Proceedings of the 2017 Meeting of the APS Division of Particles and Fields DPF 2017, e-Conf C17-07-31 (2017), <https://arxiv.org/abs/1710.00767>.
19. L. J. Broussard et al, "New Search for Mirror Neutron Regeneration," EPJ Web Conf. 219 (2019) 07002, <https://arxiv.org/abs/1912.08264>.
20. F. M. Gonzalez et al., "Improved Limits on  $n \rightarrow n'$  Transformation from the Spallation Neutron Source", Submitted to PRD, arXiv:2402.15981.