NOPTREX: A Neutron OPtics Time Reversal EXperiment to search for Time Reversal Violation in Neutron-Nucleus Resonance Interactions

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We propose to use p-wave neutron-nucleus resonances in heavy nuclei, which are known from experiment to amplify parity-odd amplitudes by 10^6, to search for parity-odd and time reversal-odd interactions. Forward transmission of polarized neutrons ($\vec{s}_n$) of momentum $\vec{k}_n$ through polarized nuclear targets ($\vec{I}$) sensitive to the P-odd/T-odd forward amplitude term $\vec{s_n}\cdot(\vec{k_n}\times\vec{I})$, can be realized as a null test for time reversal violation in the neutron optical limit. Recent neutron spectroscopy experiments have shown that the 0.7 eV p-wave resonance in ^{139}La can also amplify P-odd/T-odd neutron-nucleus interactions by 10^6. The statistical sensitivity to the P-odd/T-odd forward scattering amplitude achievable at present MW-class short pulsed spallation neutron sources in polarized neutron transmission through polarized ^{139}La at the 0.7 eV p-wave resonance is comparable to near-term neutron electric dipole moment searches but with different sensitivities to possible BSM P-odd/T-odd amplitudes. Neutron optical components used in a recent demonstration of negligible decoherence of slow neutron beams entangled in spin, position, and energy degrees of freedom passing through macroscopic amounts of matter can enable the apparatus to be configured as an interferometer for systematic error suppression.

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New sources of time reversal violation are needed to explain the baryon asymmetry of the universe in Big Bang cosmology according to the Sakhaorv argument [1]. Neutron interactions with heavy nuclei at certain compound nuclear p-wave resonances can be used to search for P-odd/T-odd interactions through a term in the neutron forward scattering amplitude of the form $\vec{s}_n\cdot(\vec{k}_n\times\vec{I})$, where $\vec{s}_n$ is the spin of the neutron, $\vec{k}_n$ is the neutron momentum, and $\vec{I}$ is the spin of the nucleus. The highly excited states in heavy nuclei involved in this type of search offer a qualitatively different environment from the ground states probed by electric dipole moment experiments of nucleons and nuclei. The ratio of the P-odd and T-odd amplitude to the P-odd amplitude on the same p-wave resonance is quite insensitive to unknown properties of the compound resonant states involved. In the case of the forward elastic neutron scattering amplitude, since the state of the polarized target does not change and since the optical theorem relates the imaginary part of the forward scattering amplitude to the cross section, the cross section differences for the forward and time reversed processes are proportional to amplitude differences and therefore can realize a sensitive null test for T invariance which is in principle free from the effects of final state interactions [2–4].

Amplifications of P-odd neutron amplitudes in compound nuclear resonances by factors of 10^6 above the 10^{-7} effects expected for weak NN amplitudes compared to strong NN amplitudes have already been observed [5] in measurements of $\Delta\sigma_P$ several heavy nuclei, including some at p-wave resonances in the few eV energy range such as ^{139}La [6], ^{131}Xe [7, 8], and ^{81}Br [9–11]. This amplification from mixing of nearby s and p-wave resonances was predicted theoretically before it was measured, and the same resonance amplification factor applies to a P-odd and T-odd amplitude up to factors of order unity. Although the nuclear states involved are extremely complicated at the level of the many-body nuclear wave functions, one can form a dimensionless ratio $\lambda_{PT}=\frac{\Delta\sigma_{TP}}{\Delta\sigma_P}=\kappa(J)\frac{<\phi_p|V_{PT}|\phi_s>}{<\phi_p|V_P|\phi_s>}$ of the T-odd, P-odd asymmetry $\Delta\sigma_{TP}$ of interest to the measured P-odd asymmetry $\Delta\sigma_P$ at the position of the enhanced p-wave resonance energy, the ratio $\frac{<\phi_p|V_{PT}|\phi_s>}{<\phi_p|V_P|\phi_s>}$ of the matrix elements of the P-odd and T-odd interaction to the P-odd interaction between the same pair of s and p wave resonance states $|\phi_s>$ and $|\phi_p>$, and a spin-weighted sum of resonance partial widths $\kappa(J)$ which can be determined experimentally using (n, γ) spectroscopy. Since this ratio involves expectation values in the same compound nuclear wave functions it can possess a clean theoretical interpretation.

The statistical uncertainty that could be achieved in such an experiment after 10^7 seconds of data in ^{139}La at a MW-class short pulse neutron spallation source implies that one can measure the ratio λ_{PT} to $1\times10^{-4}-1\times10^{-5}$ sensitivity, which translates into an improved sensitivity to P-odd and T-odd neutron-nucleus interactions of about an order of magnitude [3, 4, 12–14]. The 0.7 eV resonance in ^{139}La has a P-odd longitudinal asymmetry of 9.5% [6] and is therefore a good candidate for this search. κ has been constrained recently in ^{139}La [15] to be at least of order 1, and ongoing experiments at JPARC will soon measure κ in other NOPTREX candidate nu-

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clei. Groups at KEK [16], Kyoto University [17], and PSI [18] achieved substantial (up to 50%) polarization of ^{139}La nuclei in lanthanum aluminate crystals in volumes as large as 10 *cc*, enough for the experiment, and R&D to polarize ^{81}Br [19] and ^{131}Xe [20] is in progress. Ongoing R&D on high phase space acceptance supermirror neutron optics has the potential to improve the statistical sensitivity in the future by another order of magnitude.

This estimated sensitivity accessible today is comparable to that being proposed for the next-stage neutron EDM searches. However as the neutron-nucleus system possesses interactions not present in the single neutron system involved in nEDM searches, it is quite possible that P and T violation might be seen in one of these observables but not the other [21–24]. In particular, the NOPTREX observable is sensitive to axion-like particles with masses in the eV-MeV range [25, 26]. It is therefore very important to pursue such a search if one can suppress the potential sources of systematic error. As no such polarized neutron optics search for P-odd and T-odd interactions has ever been conducted, the first real experiment will represent a pioneering effort.

The bright pulsed sources of epithermal neutrons at MW-class spallation neutron facilities like SNS and JSNS have enough intensity at eV energies to reach the statistical accuracy required for a sensitive search. The separation of neutron energies by time-of-flight from these pulsed sources also allows a powerful search for systematic errors by looking above and below the neutron resonance energy at both the transmitted and scattered neutrons. Existing technology for eV neutron polarization using polarized ^{3}He neutron spin filters suffice for the measurement.

Birefringent neutron optical devices recently developed for neutron spectroscopy can convert the NOPTREX experimental apparatus into a spin-path interferometer, similar to the Ramsey separated oscillatory field configuration used in electric dipole moment searches but operating with paths separated in space rather than in time. These devices were recently used to entangle the neutron spin and position or the neutron spin, position, and energy variables into Bell and GHZ states, whose degree of quantum entanglement was quantified by measuring the appropriate Bell and GHZ entanglement witnesses [27, 28]. The correlation observables in this experiment took the largest possible value allowed by quantum mechanics despite the passage of the polarized neutrons through macroscopic amounts of matter. The small decoherence of the transmitted neutron state confirmed by this work implies that neutron interferometric methods based on this technology can be applied to NOPTREX to help isolate the P-odd/T-odd signal of interest from many possible sources of systematic error and help ensure that the neutron optical T-odd null test condition is satisfied.

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[1] A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. **5**, 32 (1967).
[2] V. P. Gudkov, Phys. Lett. **B243**, 319 (1990).
[3] V. P. Gudkov and Y-H. Song, Hyperfine Interact.**214**, 105 (2013).
[4] J. D. Bowman and V. P. Gudkov, Phys. Rev. **C90**, 065503 (2014).
[5] G. E. Mitchell, J. D. Bowman, and H. A. Weidenmuller, Rev. Mod. Phys. **71**, 445 (1999).
[6] V. W. Yuan *et al.*, Phys.Rev. C**44**, 2187 (1991).
[7] J.J. Szymanski, W. M. Snow *et al.*, Phys. Rev. C **53**, R2576 (1996).
[8] V. R. Skoy *et al.*, Phys. Rev. C **53**, R2573 (1996).
[9] V.P. Alfimenkov, S.B. Borzakov, Vo Van Thuan, Yu.D. Mareev, L.B. Pikelner, A.S. Khrykin, and E.I. Sharapov, Nucl. Phys. A **398**, 93 (1983).
[10] C.M. Frankle *et al.*, Phys. Rev. C **46**, 1542 (1992).
[11] H.M. Shimizu, T. Adachi, L. Ishimoto, A. Masaike, Y. Masuda, and K. Morimoto, Nucl. Phys. A **552**, 293 (1993).
[12] V. E. Bunakov and V. P. Gudkov, Nucl. Phys. **A401**, 93 (1983).
[13] V. P. Gudkov, Phys. Rept. **212**, 77 (1992).
[14] A. G. Beda and V. R. Skoy, Physics of Particles and Nuclei **38**, 1063 (2007).
[15] T. Okudaira, S. Takada, K. Hirota, A. Kimura, M. Kitaguchi, J. Koga, K. Nagamoto, T. Nakao, A. Okada, K. Sakai, H. M. Shimizu, T. Yamamoto, and T. Yoshioka, Phys. Rev. C **97**, 034622 (2018).
[16] Y. Masuda, *International Workshop on Polarized Ion Sources and Polarized Gas Jets*, National Laboratory of High Energy Physics, Ibaraki-ken, Japan (1990).
[17] Y. Takahashi, T. Yabuzaki, and H. M. Shimizu, Nucl. Instrum. Meth. **A336**, 583 (1993).
[18] P. Hautle and M. Iinuma, Nucl. Instrum. Meth. **A440**, 638 (2000).
[19] C. D. Keith, private communication (2019).
[20] B. Goodson, private communication (2019).
[21] M. Pospelov, Phys. Lett. **B530**, 123 (2002).
[22] M. Pospelov and A. Ritz, Ann. Phys. **318**, 119 (2005).
[23] Y. H. Song, R. Lazauskas, and V. P. Gudkov, Phys. Rev. **C84**, 025501 (2011).
[24] Y. H. Song, R. Lazauskas, and V. P. Gudkov, Phys. Rev. **C87**, 015501 (2013).
[25] S. Mantry, M. Pitschmann, and M. J. Ramsey-Musolf, Phys. Rev. D **90**, 054016 (2014).
[26] P. Fadeev and V. V. Flambaum, Phys. Rev. C **100**, 015504 (2019).
[27] S. Lu, A. A. Md. Irfan, J. Shen, S. J. Kuhn, W. M. Snow, D. V. Baxter, R. Pynn, and G. Ortiz, Phys. Rev. A **101**, 042318 (2020).
[28] J. Shen, S. Kuhn, D. Baxter, R. Dalgleish, F. Li, S. Lu, G. Ortiz, J. Plomp, S. Parnell, R. Pynn, W. M. Snow, and A. Washington, Nature Comm. **11**, 930 (2020).