TREX: search for Time Reversal invariance violation in neutron nucleus EXperiment

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We propose experiment to search for Time Reversal Invariant Violating (TRIV) effects in neutron transmission through polarized nuclei at the Spallation Neutron Source at Oak Ridge National Laboratory. This forward transmission experiment is a null test for time reversal invariance violation and can have a discovery potential of up to 10^2-10^4 compared to current limits on TRIV interactions of nucleons.

I. EXECUTIVE SUMMARY

The search for new sources of time reversal invariance violation (TRIV) is one of the highest intellectual priorities in nuclear/particle/astrophysics as new sources of CP-violation, beyond the Standard Model, are necessary to explain the observed matter-antimatter asymmetry of the universe. Theoretical progress to identify the large number of possible sources for TRIV has made it very clear that any single type of TRIV search cannot be equally sensitive to all possible mechanisms. It is therefore essential to pursue any experiments in different systems which can be realized with sufficient sensitivity to discover something new. Since TRIV in the nucleon sector has not yet been observed a nonzero observation in any nuclear system, no matter how complicated, is of fundamental importance. The basic idea of this experiment is to investigate TRIV in neutron interactions in a highly excited nucleus by searching for a term in the neutron forward scattering amplitude of the form $\vec{\sigma}_n \cdot (\vec{k}_n \times \vec{I})$, where $\vec{\sigma}_n$ is the spin of the neutron, $\vec{k}_n$ is the neutron momentum, and $\vec{I}$ is the spin of the nucleus. This observable is both parity (P) odd and time reversal (T) odd. It is also a null test for TRIV which is in principle free from the effects of final state interactions.

We argue that the time is now ripe to pursue this experiment because of three key developments:

(1) New technology makes a very sensitive experiment possible. Intense sources of pulsed epithermal neutrons are now available. In addition to the high CW intensity of neutrons at the relevant resonance energies available from the 2000K graphite hot sources at the ILL and FRM-II, we now also have available bright pulsed sources of epithermal neutrons at MW-class neutron facilities like SNS and JSNS. The separation of neutron energies by time-of-flight from these pulsed sources allows a powerful search for systematic errors in these experiments by looking on and off the neutron resonance energy at both the transmitted and scattered neutrons. Furthermore, the technologies for both the production of epithermal polarized neutrons using polarized ^{3}He neutron spin filters developed for neutron scattering applications and for the production and control of polarized nuclei of the relevant species have both greatly improved. The neutron scattering instruments at the ILL and FRM which use eV neutrons are available for target scattering characterization studies.

(2) New theoretical work has sharpened our understanding of the potential reach of an experiment of this sort and clarified the range of possible sources of T violation possible in the nucleon sector. Recent effective theory analyses have identified a variety of possible P-odd T-odd operators which can operate in and between nucleons. The isospin dependence of the NN weak interaction may be very strong based on analysis of existing data coupled with the preliminary results of NPDGamma. The interference of different spin channels available to a T-odd and P-odd amplitude on a p-wave resonance could further amplify the amplitude beyond present theoretical estimates. Theoretical calculations have also shown that both the P-odd and T-odd P-odd amplitudes can be rather sensitive to the short-range component of NN interactions. Taken together, these results mean that the potential exists for additional amplifications of the ratio λ_{PT} beyond those already identified in previous work.

(3) A new approach to the measurement technique has recently been proposed. Although the idea for an experiment of this type is far from new, the great majority of proposed methods have exhibited, upon further analysis, excessive

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sensitivity to the relative alignment of the neutron and target polarizations in polarization analysis. The two key aspects of the new proposal which differ from the great majority of previous approaches are (a) to involve only one neutron beam polarizer and a polarized target and forego any downstream analysis of the polarization, and (b) to explicitly realize the motion-reversed condition corresponding to the time reversal transformation through the mechanical rotation of the apparatus and the reversal of all spin-dependent external and internal neutron optical fields (a similar operation was realized in the past in slow neutron beam searches for the neutron EDM).

Our proposed experiment has several advantages over the previous proposals for T-violating transmission experiments which have been limited by the understanding of systematic errors. The estimate of the statistical uncertainty that could be achieved in 10^7 seconds of data collection on the water moderator of Flight Path 16A at the Spallation Neutron Source at Oak Ridge National Laboratory leads the possibility to measure the ratio of the TRIV to PV asymmetries of $6.0 \cdot 10^{-6}$. This can result in 2-4 orders of magnitude improvement on the current limit on TRIV interactions.

II. TREX: MOTIVATION AND EXPERIMENTAL PROPOSAL

T-violation experiments involving nuclear resonances of complex nuclei are a sensitive system for such a search. The international proto-collaboration TREX is analyzing the scientific reach which is now possible in a TRIV search through an asymmetry in polarized neutron transmission on epithermal p-wave resonances of polarized nuclei. Multiple papers [1–5] have suggested that T-violation in complex nuclei has the potential to be about 2-4 orders of magnitude more sensitive than the current limit from neutron Electric Dipole Moment(EDM) experiments. A sensitive search for TRIV in this process expands the variety of nuclear systems available to search for T-violating parameters in various theories. This helps provide assurance that possible "accidental" cancellation of T-violating effects due to unknown structural factors related to the strong interactions in particular systems can be avoided. It should also possess different sensitivity to the many possible kinds of new sources of T violation in the NN system [6–9].

The basic idea of this experiment is to investigate TRIV in neutron interactions in a highly excited nucleus by searching for a term in the neutron forward scattering amplitude of the form $\vec{\sigma}_n \cdot (\vec{k}_n \times \vec{I})$, where $\vec{\sigma}_n$ is the spin of the neutron, $\vec{k}_n$ is the neutron momentum, and $\vec{I}$ is the spin of the nucleus. This observable is both parity (P) odd and time reversal (T) odd. The highly excited states in heavy nuclei involved in this type of search offer a qualitatively different environment from the nuclear ground states probed by electric dipole moment experiments. Just like nucleon EDMs, moreover, a search for T violation in a forward scattering amplitude is a null test for time reversal invariance and is in principle insensitive to so-called final state effects [4, 5, 10]. In particular, it is completely different from the classical textbook comparisons of nuclear reaction cross sections for forward and reversed processes, which measure cross section differences, since by the optical theorem cross section differences in the forward direction are proportional to forward scattering amplitude differences and therefore can be much more sensitive.

Furthermore, systems which would amplify the size of TRIV interactions have already been identified by experiment. Amplifications of P-odd neutron amplitudes by factors of $10^5 - 10^6$ above the 10^{-7} effects expected for weak nuclear interactions have already been observed [11] in certain heavy nuclei such as ^{139}La, ^{131}Xe, and ^{81}Br on p-wave resonances in the eV energy range. The mechanism for this amplification has been understood theoretically for decades and is well enough understood to know that, up to possible spin-dependent factors, the same amplification factor will apply on resonance to a P-odd and T-odd amplitude. Although the nuclear states involved are extremely complicated at the level of the many-body nuclear wave functions, one can relate the forward scattering amplitude with reasonable accuracy to the interference between s-wave and p-wave resonances. One can also form a dimensionless ratio $\lambda_{PT} = \frac{A_{PT}}{A_P}$ of the T-odd, P-odd asymmetry A_{PT} of interest to the measured P-odd asymmetry A_P at the position of the enhanced p-wave resonance energy. Since this ratio involves expectation values in the same compound nuclear wave functions it possesses a relatively clean theoretical interpretation. Many theoretical calculations of λ_{PT} in various models for T violation have been performed. The table I shows some theoretical estimates of λ_{PT} in various theories whose accuracy is estimated to be at the order-of-magnitude level. A measurement of λ_{PT} at the level of 10^{-5} is expected to possess a sensitivity to T violation which is very interesting scientifically.

The idea to use polarized neutron transmission on epithermal resonances to search for time reversal violation has been known for a long time, so what is new? We argue that the time is now ripe to pursue this experiment because of three key developments:

(1) New technology makes a very sensitive experiment possible. Intense sources of pulsed epithermal neutrons are available. In addition to the high CW intensity of neutrons at the relevant resonance energies available from the 2000K graphite hot sources at the ILL ad FRM-II, we now have available bright pulsed sources of epithermal neutrons at MW-class neutron facilities like SNS and JSNS. The separation of neutron energies by time-of-flight from these pulsed sources allows a powerful search for systematic errors in these experiments by looking on and off the neutron resonance energy at both the transmitted and scattered neutrons. Furthermore, the technologies for both the

production of epithermal polarized neutrons using polarized ^{3}He neutron spin filters developed for neutron scattering applications and for the production and control of polarized nuclei of the relevant species have both greatly improved.

(2) New theoretical work has sharpened our understanding of the potential reach of an experiment of this sort and clarified the range of possible sources of T violation possible in the nucleon sector. The isospin dependence of the NN weak interaction may be very strong based on analysis of existing data coupled with the preliminary results of NPDGamma. The interference of different spin channels available to a T-odd and P-odd amplitude on a p-wave resonance could further amplify the amplitude beyond present theoretical estimates. Theoretical calculations have also shown that both the P-odd and T-odd P-odd amplitudes can be rather sensitive to the short-range NN interactions. Taken together, these results mean that the potential exists for additional amplifications of the ratio λ_{PT} beyond those already identified.

(3) A new approach to the measurement technique has recently been proposed. Although the idea for an experiment of this type is far from new, the great majority of proposed methods have exhibited, upon further analysis, excessive sensitivity to the relative alignment of the neutron and target polarizations. The two key aspects of the new proposal which differ from the great majority of previous approaches are (a) to involve only two polarizers/analyzers and forego any additional analysis of the polarization, and (b) to explicitly realize the motion-reversed condition corresponding to the time reversal transformation through the mechanical rotation of the apparatus (a similar operation was realized in the past in slow neutron beam searches for the neutron EDM).

From optical theorem, we know that

$$\sigma_{tot} = \frac{4\pi}{k} Im(f) \tag{1}$$

where f is the amplitude of zero-angle elastic scattering. By measuring the transmission difference at zero angle for elastic scattering, where $\mathbf{k_i} = \mathbf{k_f}$, we can directly relate the attenuation of the neutron beam to the total cross section and thus avoid any FSI effects. The transmission difference that we measure can be given as

$$\Delta\sigma_{TP} = \frac{4\pi}{k} Im(f_+ - f_-) \tag{2}$$

where $f_\pm$ are the scattering amplitudes for the "$\pm$" configurations. The "+" state denotes $\vec{\sigma}_n \cdot (\vec{k}_n \times \vec{I})$, and the "$-$" state denotes $-\vec{\sigma}_n \cdot (-\vec{k}_n \times -\vec{I})$.

The experiment will require a large flux of eV polarized neutrons, a polarized nuclear target, and a high count rate time of flight neutron detector for detection of zero angle elastically scattered neutrons with sharp neutron energy resolution. The experiment will also require the ability to flip neutron polarization, nuclear target polarization, and neutron momentum direction simultaneously, as shown on Fig.(1).

Considerable progress has been made on the first problem. Groups at KEK [12, 13], Kyoto University [14], and PSI [15] achieved substantial (50%) polarizations of ^{139}La nuclei in lanthanum aluminate crystals in volumes as large as 10 cc. The 0.734 eV resonance in ^{139}La has a P-odd longitudinal asymmetry of 9.5% [16] and is therefore a good candidate for TRIV studies.

For practical implementation of the proposed experiment based on the TRIV transmission theorem, we propose to use cells of polarized ^3He as a neutron spin filter. The direction of the polarization of the ^3He is always parallel to the magnetic field and reverses when the field direction is reversed adiabatically (ferromagnetic polarizers and analyzers can be difficult to use in this experiment because hysteresis effects prevent their precise reversal). It is essential that the values of the classical fields be stable in time and reversible. The magnetic field strengths and the polarizations of ^3He and the target medium can be accurately monitored using nuclear-magnetic-resonance techniques. Since the earth's magnetic field cannot be reversed, it must be compensated or shielded.

Model	λ_{PT}
CKM δ phase	$\leq 10^{-10}$
Left-right symmetry	$\leq 4 \times 10^{-3}$
Horizontal symmetry	$\leq 10^{-5}$
Charged Higgs bosons	$\leq 2 \times 10^{-6}$
Neutral Higgs bosons	$\leq 3 \times 10^{-4}$
θ QCD	$\leq 5 \times 10^{-5}$
nEDM (single-loop)	$\leq 4 \times 10^{-3}$
Atomic EDM (^{199}Hg)	$\leq 2 \times 10^{-3}$

TABLE I: Theoretical estimates of λ_{PT} [2]

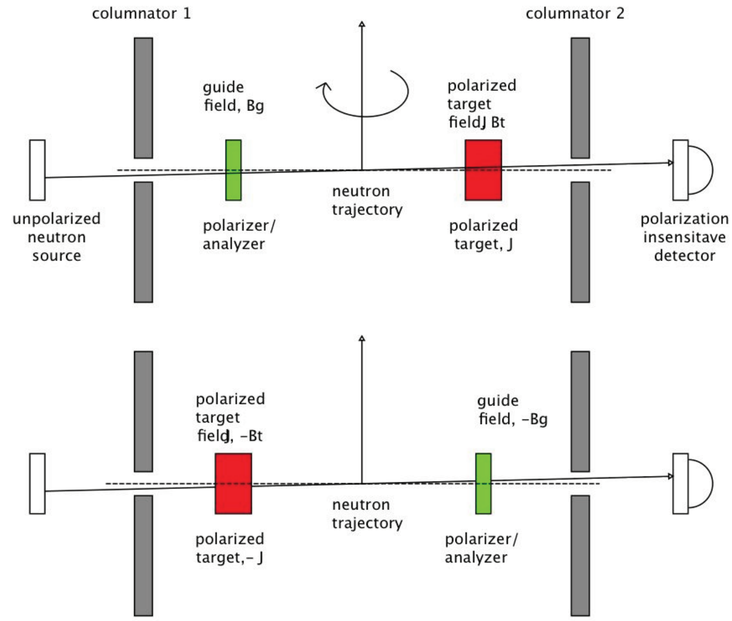

FIG. 1: Schematic representation of an apparatus to measure TRIV in neutron optics.

Consider ^{139}La nuclei in lanthanum aluminate crystals which have amplified parity violation at the 0.734 eV resonance. Using the experimentally achieved value of ^{139}La polarization of 47.5%, we can estimate [17, 18] the nuclear pseudomagnetic field inside the crystal as a function of neutron energy (see Fig. 2), which shows the pseudomagnetic field is opposite the applied field.) This gives an advantage for using lanthanum aluminate crystals, since values of TRIV effects in neutron optics, in general, are inversely proportional to the sum of magnetic and pseudo magnetic fields [18, 19].

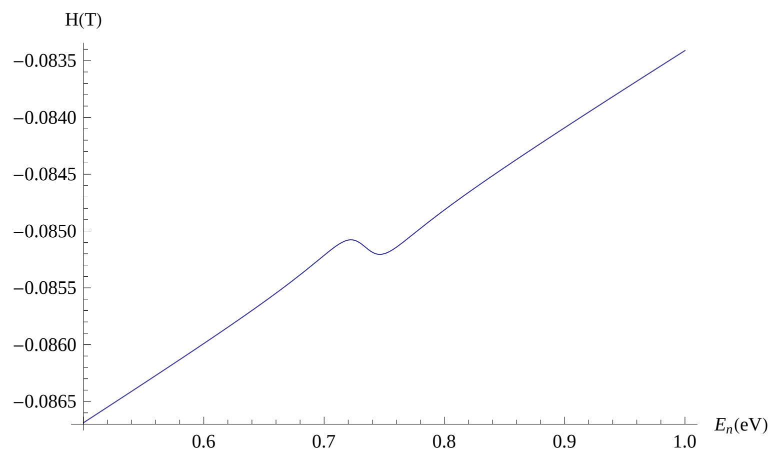

FIG. 2: Pseudo-magnetic field in Lanthanum Aluminate crystals.

We make a rough estimate of the statistical uncertainty in the T-odd cross section that could be achieved in 10^7 seconds of data collection on the water moderator of Flight Path 16A at the Spallation Neutron Source at Oak Ridge National Laboratory. At the present time the Flight Path has not been instrumented. We assume a neutron production current of 1.4 mA at 1 GeV proton energy. We carry out the estimate for the 0.734 eV resonance in ^{139}La. We assume that the target is one-interaction-length of dynamically polarized lanthanum aluminate and that the neutron beam is polarized by a one-interaction-length 70% polarized ^3He spin filter. We estimated the neutron flux expected on FP16A using the measurement of the flux from the water moderator of Flight Path 2 at the Los Alamos Neutron Scattering Center at the Los Alamos National Laboratory. Roberson et al. [20] found that the moderator brightness was well described by the expression

$$\frac{d^3N}{dAdtd\Omega} = k\frac{\Delta E}{E}\left(\frac{E}{1eV}\right)^{\gamma}\left(\frac{i}{e}\right)(neutrons\ cm^{-2}sec^{-1}sr^{-1}), \tag{3}$$

with $k = 5.8 \cdot 10^{-3}$ and $\gamma = 0.1$. E is the neutron energy, i is the proton current, e is the charge quantum, A is the area of the moderator that is viewed, ΔE is the range of neutron energies accepted, and Ω is the solid angle acceptance of the apparatus. We assume that the neutron production rate is proportional to the proton energy and increase k by 1000/800, the ratio of proton energies. We assume that SNS will operate at 1.4 MW and $i = 1.4\ mW$. We assume that $A = 100cm^2$ and that the acceptance of the apparatus is defined by a 10 cm diameter polarized target located 15 meters from the moderator: $\Omega = 3.5 \cdot 10^{-5}\ sr$. We set $\Delta E = .045$ the total width of the resonance. The neutron flux in this case is $dN/dt = 7.8 \cdot 10^7\ neutrons/sec$.

In order to determine the uncertainty in the TRIV asymmetry we must make some assumptions concerning running time, source, polarizer, polarized target, detector, and cross sections. We assume a running time of $10^7\ sec$. We use previous measurements of the peak value of the resonance cross section (2.9 barns), the potential scattering cross section (3.1 barns), and the capture cross section at the resonance energy (1.6 barns). The cross sections of aluminum and oxygen are 3.8 barns and 1.4 barns [21]. We calculate that the neutron polarization is 46% and the transmission of the polarizer is 46% for the ^{3}He polarization of 70%. We assume a one-interaction-length $LaAlO_3$ target. We reduce the transmission by a factor of 2 to account for various windows. The transmission of the apparatus is then estimated to be 11%. The transmitted beam intensity in ΔE is $Flux = .86 \cdot 10^7\ neutrons/sec$. The fractional uncertainty in TRIV cross section is given by

$$\frac{\delta\sigma}{\sigma} = \frac{1}{\sqrt{Flux \cdot Time}}\frac{\sum \sigma_k}{\sigma_p}. \tag{4}$$

(The sum runs over all the cross sections given above.) If we adopt the fractional parity-violating asymmetry for the resonance to be 9.5% [16], we obtain an uncertainty in λ , the ratio of the TRIV to PV asymmetries of $6.0 \cdot 10^{-6}$.

Room for more theoretical work to better estimate the sensitivity of such a measurement exists. The theory for the amplification of discrete symmetry violation in heavy nuclei is well-developed and tested experimentally both for isospin violation and for parity violation, the latter largely through the work of the TRIPLE collaboration. Discussions of theoretical issues related to this experiment are planned at the workshop “Time-reversal Tests in Nuclear and Hadronic Processes” at the Amherst Center for Fundamental Interactions at the University of Massachusetts, Amherst in November 2014. The estimated sensitivity of TREX is comparable to other sensitive searches for T violation including electric dipole moments. TREX can be a factor of $10^2 - 10^4$ times [4] more sensitive than the existing limit on the neutron EDM (3×10^{-26} e·cm): up to 2 orders of magnitude from the resonant enhancement, up to 1 order of magnitude if the relevant NN weak amplitude contributing to the parity violation is from pion exchange which as we now know from the preliminary $np \to d\gamma$ result is suppressed, and up to 1 order of magnitude from the (unmeasured) spin factor. Therefore, TREX can probe new possible physical mechanisms which can give rise to TRI violation.

There is also relevant experimental work in progress. At J-PARC there is an ongoing program to measure the gamma angular distributions on the 0.7 eV p-wave resonance in ^{139}La in order to determine some spectroscopic information needed to help quantify the relative size of the T-odd and P-odd amplitude compared to the P-odd amplitude in this system. At NIST and SNS there are experiments to help determine the weak NN interaction in the $\Delta I = 0$ and $\Delta I = 1$ channels: NPDGamma (whose preliminary result shows that the $\Delta I = 1$ weak pion coupling is small), n-^{3}He parity violation is in progress at SNS, and n-^{4}He spin rotation is proposed for NIST. The combination of these results with existing data should greatly improve our knowledge of the weak NN interaction. New results expected from atomic physics measurements of nuclear anapole moments can provide more information to test the ability of nuclear theory to explain the relationship between free NN parity violation and NN parity violation in the ground state of a heavy nucleus.

The preparation of such an experiment would require some intermediate experimental steps, some of which we indicate here. It would be useful to measure both parity violation in transmission and parity-conserving gamma correlations on the p-wave resonances in ^{131}Xe and ^{81}Br as the resonance properties of these p-wave nuclei are not nearly as well studies as the ^{139}La resonance. Some research and development for both the ^{3}He polarizer and the ^{3}He neutron drift detector is needed. The experiment requires a current-mode epithermal neutron detector with 2 μs timing resolution to be able to resolve neuron energies as high as a few-eV p-wave resonances to help reject systematic effects.

Our proposed experiment has several advantages over the previous generation of proposals for P-odd T-odd transmission experiments which have been limited by the understanding of systematic errors. TREX proposes a rotating apparatus to flip the neutron momentum direction. To flip the neutron polarization, we will perform a spin flip of the

^{3}He polarization. The ^{3}He and nuclear target polarization can be flipped by applying a small resonant radiofrequency transverse field, and simultaneously flip of the B field adiabatically. A schematic of our experimental is given in figure 1.

Understanding the origin of the baryon asymmetry off the universe is one of the highest intellectual priorities in nuclear/particle/astrophysics. A. Sakharov [22] suggested that time-reversal-invariance violation is an essential requirement to produce a matter-antimatter asymmetry. To date TRI violation has only been observed in K and B meson systems. However the strength of TRI violation in this system is several orders of magnitude too small to explain the cosmological data. Many physicists have postulated theories to produce larger TRI violation through Beyond Standard Model particles, and the search for new sources of TRI violation can provide important insight into this field. The TREX collaboration plans to search for TRI violation through the measurement of a triple correlation $\vec{\sigma} \cdot (\vec{k}_n \times \vec{I})$ in a p-wave nuclear resonance of ^{139}La. The experiment requires an intense polarized epithermal neutron beam, a polarized nuclear target, and a fast timing resolution current-mode neutron detector.

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