Searching for Evidence of Time-Reversal Violation in Neutron-Nucleus Resonance Interactions

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The Standard Model of physics is the most complete, most robust, most well-tested theory in physics; it is our 'rulebook' which describes all of the known particles and their interactions. It is the culmination of the work of thousands of physicists over thousands of years and has been found to be an amazingly self-consistent theory. However, even with such an enthusiastic endorsement, we know that the Standard Model is not completely 'correct.' For one, it doesn't include the gravitational interaction, which the physics community as a whole is pretty sure is a real thing. It also cannot presently explain many outstanding problems in physics, one of which is the baryon asymmetry of the Universe, or to put more simply: where did all of the matter that constitutes the Universe come from? And where is the antimatter?

Nature adores symmetry. In the laboratory, for example, high-energy gamma rays can split into particle-antiparticle pairs in a process known as 'pair production.' But that's just the thing–these reactions ALWAYS occur in particle-antiparticle pairs, and we have not yet seen any experimental evidence to the contrary. Therefore, it would seem that during the Big Bang, matter and antimatter should have been produced in exactly equal amounts. These matter-antimatter particle pairs would then collide and annihilate into photons, leaving almost nothing but a Universe made of radiation. But this is not what we see–we see a Universe made of matter. How can this be?

In 1967, Andrei Sakharov proposed three conditions that, together, could explain the matter-antimatter asymmetry of the Universe: during these matter-antimatter generating reactions, charge conjugation symmetry (C) and time-reversal symmetry (T) must be violated, and the evolution of the Universe must take place outside of thermal equilibrium (so that such a matter imbalance would be 'frozen in') [1]. My Ph.D. research focuses on the second condition: the violation of time-reversal symmetry. While this sounds like the plot of a Dr. Who episode, time-reversal violation is a term given to physical processes which do not seem to play by the same 'rules' of physics if the dynamics of the system are reversed (like watching a movie backwards). In other words, if the dynamics of a physical system are thought of as moving forward in time from an initial state to a final state, time-reversal violation can be tested by reversing the final state's conditions and seeing if the system retraces its steps or not to its original state. In the present formulation of the Standard Model, time-reversal violation (T-violation) is known to exist; it has been measured in the decay of B and K mesons. However, T-violation is highly suppressed in the Standard Model, leaving it unable to explain the observed matter-antimatter imbalance. This means that even though we know it exists, we need to find new sources of T-violation in order to understand this matter excess, a problem known as baryogenesis.

The Neutron OPtics Time Reversal EXperiment (NOPTREX) collaboration seeks to find evidence of T-violation in a system that has not yet been probed: resonant neutron-nucleus interactions of heavy nuclei. Specifically, the NOPTREX collaboration's planned experiment will measure the transmission of polarized neutrons through a polarized nuclear target in hopes of identifying a parity- and time-reversal-violating signal. One of the reasons that this system is particularly attractive is because the complex, many-body structure of the nucleus provides a natural amplification mechanism that magnifies the potential time-reversal violating signal by many orders of magnitude ($\sim 10^6$).

It may seem tricky to investigate a physical phenomenon such as time-reversal violation that requires one to be able to push a magical 'rewind' button in the laboratory–however, as described earlier, time reversal is really reversing the *dynamics* of a system. By judiciously choosing experimental observables that 1) we know how they transform under time reversal, and 2) we can easily control in the laboratory, we can construct an experiment in which we can effectively mimic 'time reversal' by appropriately modifying all relevant observables (for example, reversing linear momenta and particle spins, or the direction of relevant $\vec{B}$ fields) and performing the experiment in a 'time-reversed' configuration to see if we measure the same result.

The NOPTREX theory proposes that, for polarized neutron transmission through a polarized nuclear target, a potentially time-violating nuclear cross-section, σ_{TP}, can be related to a parity-violating nuclear cross-section, σ_P in the following manner [2]:

$$\sigma_{TP} \propto \kappa(J)\sigma_P$$

where $\kappa(J)$ is a spin-weighted angular momentum proportionality term (of order ~ 1). Both $\kappa(J)$ and σ_P are specific to a given nuclear target material; in addition, because σ_{TP} is related to the product of $\kappa(J)$ and σ_P, it is of great importance that both quantities are known to a high degree of precision so that a precise determination of σ_{TP} can be made. As such, it is imperative that we choose an optimal target nucleus that has a large value of $\kappa(J)$, exhibits a large degree of parity violation (i.e. σ_P is large), and for which both quantities have been determined precisely. $\kappa(J)$ is being measured for various nuclei by collaborators at JPARC, and a precision measurement of σ_P (a $\sim 1\%$ uncertainty on a 10^{-4} signal, so ppm precision) is the work that I am doing at the Los Alamos Neutron Scattering CEnter (LANSCE).

Parity violation was the subject of the 1957 Nobel Prize in physics, and is the direct result of the weak interaction not treating right- and left-handed particles equitably. In our neutron scattering experiments, parity violation enters through neutron-nucleus resonance interactions, whereby—at certain quantum energies—an incident neutron can collide with a target nucleus and briefly bind to it, during which time it can interact weakly with the nucleus, where the amplitudes of these resonances can differ depending on the helicity (handedness) of the incident neutrons. By scattering neutrons of right- and left- handed helicities through our target materials and measuring the asymmetry in the respective resonance amplitudes, we can determine the degree to which a particular handedness is favored—this is parity violation.

The key to these measurements is that we need to do them *precisely.* Thus, great care has been taken in designing a cryogenic, low-noise, high-statistics experiment in order to reduce the statistical and systematic uncertainties of these measurements. I was the primary graduate student responsible for running this experiment, which is the most precise measurement of symmetry violation on a neutron-nucleus resonance ever performed. I wrote GEANT4 simulations to help determine optimal neutron detector geometries to inform decisions on their design and fabrication, tested prototypical detectors, helped to build and test the large (multi-ton) experimental apparatus (described in [3]), wrote the software that was used to run the data acquisition, was the principal student on shift for the majority of the data run which spanned from Nov. 2017 to Dec. 2019, and am now presently working on the analysis of this large dataset.

In the grander scheme, NOPTREX is not the only experiment looking for additional, Beyond the Standard Model (BSM) sources of T-violation. There are many other experimental pursuits, such as the electric dipole moment of the neutron, for which NOPTREX provides a complementary measurement due to probing different sectors of BSM physics. In this way, not only would a nonzero T-violation measurement be exciting, but because NOPTREX is designed to be a good 'null-test' measurement, even a zero measurement would be useful!

1. A. D. Sakharov, "Violation of CP invariance, C asymmetry, and baryon asymmetry of the universe." JETP, **5**, pp. 24-27, 1967.

2. D. Bowman and V. Gudkov, "On the Search for Time Reversal Invariance Violation in Neutron Transmission", Phys. Rev. C **90**, 065503 (2014).

3. D. C. Schaper et al., "A modular apparatus for use in high-precision measurements of parity violation in polarized eV neutron transmission." Nucl. Instrum. Methods Phys. Res. A **969**, 2020.