Parity Violation in Photonuclear Reactions at HIGS
Submission to Fundamental Symmetries and Neutrino Physics Working Group

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We discuss the scientific motivation, possible experiments, and beam requirements for measurements of parity violation in photonuclear reactions at an upgraded HIGS facility, HIGS2. For a more detailed treatment, see the "white paper" in progress at http://www.tunl.duke.edu/higs2.php

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I. INTRODUCTION

This two page submission discusses the possibility of performing photonuclear reactions at an upgraded HIGS facility (HIGS2) that can observe parity violation (PV) induced from the weak interaction between nucleons. The physics considered here addresses Performance Measure F18, "Perform independent measurements of parity violation in few-body systems to constrain the nonleptonic weak interaction" from the 2007 NSAC Performance Measures document.

At the present time, it is unclear whether currently available measurements involving low energy nucleons are consistent with the Standard Model, or indeed with each other. The reason for this is that most such measurements involve heavy nuclei whose strong interactions, binding mechanism, etc., are not understood in terms of QCD. While it is likely that the PV observables in heavy nuclei are the result of weak interactions among only two or three constituent nucleons, that physics is not presently extractable from the complicated strong interaction physics involved.

To unambiguously extract the weak interactions among nucleons requires PV measurements in very light nuclei: the deuteron, tritium, He-3, and now perhaps even up to four nucleons, because the strong interactions in these very light systems are understood in terms of effective field theories (EFTs) that systematically incorporate the symmetries of QCD in a consistent fashion. At leading order, and at very low energies (e.g., photon energies below 10 MeV), there are five low energy PV constants (LECs) that parameterize the physics [1–3]. Before we know whether the Standard Model as encoded in the relevant EFT, EFT($\not\pi$), is correct, all five will have to be determined. These LECs are the PV version of the parity conserving LECs (which include scattering lengths, effective ranges, etc.) in that they must be fixed by experiment in the absence of a lattice, for example, determination. A complementary point of view is that utilizing weak interactions in few nucleon systems provides a unique probe of QCD in these systems, as the observables in question come from interference between weak and strong effects.

One constraint on the PV LECs is available from the low energy (13.6 MeV) PV longitudinal asymmetry from polarized protons scattering off unpolarized protons [4, 5], $A_L = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$ where $\sigma_\pm$ indicates the cross section from protons polarized along/against the incoming proton's direction of motion. A second independent measurement is underway at the Oak Ridge SNS, NPDGamma [6], an experiment that will measure the angular distribution of the exiting photon after polarized neutron capture on a proton, $\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = 1 + A_\gamma \cos\theta$, where A_γ is the PV-dependent quantity and θ is the angle between the direction of polarization of the neutron and the photon momentum.

We discuss in this paper the possibility of a third independent measurement: $\vec{\gamma} d \to np$. Note that this is *not* the same as an NPDGamma back reaction. Instead it is related to the time reversal of $np \to d\vec{\gamma}$ and constitutes a completely orthogonal observable to A_γ. Limits from previous attempts exist from Chalk River[7], and the reverse reaction [8, 9]. Experiments to measure this observable have been proposed at JLAB [10, 11], SPRING-8, and the Shanghai Synchroton.

What we propose here is an upgrade of the High Intensity Gamma Source (HIGS) at the Triangle Universities Nuclear Laboratory (TUNL) and Duke's Free Electron Laser Laboratory (DFELL). HIGS2 would provide unprecedented photon luminosity, polarization control, and energy resolution. The expected capabilities of the HIGS2 are: E_γ = 2 - 12 MeV; rapid switch linear and circular polarization at 90-99%; $10^{11} - 10^{12}$ photons per second in total flux; minimum energy resolution of less than 0.5% (with a tight collimation and a reduced gamma-ray beam intensity on target).

II. PV IN CIRCULARLY POLARIZED PHOTON BREAKUP OF THE DEUTERON

Naive dimensional analysis suggests that the PV asymmetry involved in $\vec{\gamma}d \to np$ is on the order of 10^{-7}. The relation between this asymmetry and weak couplings has been calculated by several authors, both as a function of gamma energy in hybrid calculations [12–18] and at threshold, where it is related by time reversal symmetry to the circular polarization of the photon in unpolarized neutron-proton capture [19, 20].

The desired statistical uncertainty of the measurement is 10^{-8}, which means about 10^{16} detected neutrons. About 4×10^{18} gammas are needed on target to achieve this statistical accuracy assuming a cross section of 1.0 mbarn at $E_\gamma = 2.5$ MeV and a liquid deuterium target of thickness 5×10^{24} deuterons/cm^2 and a product of solid angle and detection efficiency for the neutron counter of 0.5. Even with a flux of 10^{11} γs per second, about 450 days of running are required just to achieve the statistical accuracy.

While all the laser and accelerator components involved in the creation of HIGS2 are known technology, putting them together to create such a high performance machine has not yet been attempted. The technical requirements for an upgraded HIGS facility to be able to perform this measurement are quite stringent. They include the following: (1) The flux of 2.5 MeV circularly polarized photons should provide at least 10^{16} total photodisintegration reactions in the liquid deuterium (or perhaps D2O) target for the experiment in a calendar year of operation; (2) The helicity of the photons must be reversible at high frequencies ($1 - 100$ Hz) in a controllable pattern to be able to make the asymmetry measurement insensitive to slow drifts in detector efficiencies. A capability to insert unpolarized bursts of photons into the sequence may also be very important as a null test for certain false asymmetries; (3) Since this measurement almost certainly must be performed in current mode, the beam intensity noise within the frequency bandwidth of the helicity flip must be negligible compared to the noise from gamma counting statistics; (4) The variation of circular polarization and contamination with linear polarization components under changing gamma-ray beam conditions such as intensity, beam divergence, beam direction, mean energy, energy distribution, etc. must be measured and minimized. Laser technology developed for polarized electron production in the very successful parity violation measurements in electron scattering at Jefferson Lab may already be capable of satisfying conditions (2), (3), (4). Analysis of how these phase space properties get modified through laser backscattering is needed, and for a real experiment one must prove that these conditions are met.

We plan to detect both the neutrons (which can escape the target and be moderated in the deuterium target to slow neutron energies where they are easy to detect), the gammas transmitted through the target, and the gammas scattered into 4π. The liquid deuterium target can be surrounded by a graphite moderator to slow down the neutrons to thermal energies if needed, by a slow neutron ion chamber, and by a current mode gamma detector array. The current-mode gamma detectors could be very similar to those presently being used in the NPDGamma experiment, which are known to be free of systematic errors at the 1 ppb level [21, 22]. One can construct a current-mode ion chamber for the neutron detection which is quite insensitive to the intense gamma field around the target by using a chamber with a ^{4}He gas layer in front of a ^{3}He gas layer since the gamma interactions are almost identical whereas the neutrons absorb strongly in ^{3}He [23]. The signal could be formed as the helicity dependence of the ratio of the neutron to gamma signal. A transmission detector for the gammas through the target can be used to monitor some of the gamma beam properties.

There are several potential sources of systematic error that must be considered. For example, possible systematic effects which can come from the laser beam include, but are not limited to: degree of polarization in the beam; stability of photon flux upon helicity flip; and effect on polarization due to laser optics. We have identified the scalar invariants that can be present in photon reactions in the deuteron target that could pollute the desired signal. Many of these quantities have been measured in deuteron photodisintegration, and the system is simple enough that theoretical calculations can be conducted if necessary. HIGS2 may need to possess apparatus to measure or constrain such asymmetries in subsidiary measurements.

III. CONCLUSIONS AND OUTLOOK

We are not aware of any other facility in the world that has the potential to reach the desired photon luminosity and energy resolution as described here for HIGS2. All of the elements of the machine described above utilize proven technology. Even if additional experiments with slow neutrons are conducted after the NPDGamma experiment, the full complement of leading order low energy PV LECs cannot be obtained without measurements involving photons. In order to resolve the question of whether we understand PV in nuclei depends upon our understanding of PV in few nucleon systems, which requires the measurements of $\vec{\gamma}d \to np$.

If the PV asymmetry in $\vec{\gamma}d \to np$ is successfully measured at HIGS2 it will provide, along with the results from NPDGamma and the earlier proton asymmetry, three of the necessary five measurements needed to resolve the question of low energy PV in nuclei. At that point there is no barrier to obtaining other PV photo-induced asymmetries by using triton or He-3 targets at HIGS2. These may provide further independent measurements of the low energy PV LECs.

Further energy upgrades to HIGS2 may allow access to He-4, for example, but in that case the experiment will need to be analyzed using a pionful EFT. Heavier nuclei, where PV asymmetry enhancements may exist, are also possible targets.

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