Hadronic parity violation

M.W. Ahmed,[1,*] J.D. Bowman,[2,†] C. Crawford,[3,‡] N. Fomin,[4,§] H. Gao,[5,¶] M.T. Gericke,[6,**] V. Gudkov,[7,††] B.R. Holstein,[8,‡‡] C.R. Howell,[5,§§] P. Huffman,[9,¶¶] W. van Oers,[10,***] S. Penttilä,[2,†††] M.R. Schindler,[7,‡‡‡] W.M. Snow[§§§],[11,¶¶¶] and Y.K. Wu[5,]

[1] *NC-Central Univ., Durham, NC*
[2] *Oak Ridge National Laboratory, Oak Ridge, TN*
[3] *University of Kentucky, Lexington, KY*
[4] *University of Tennessee, Knoxville, TN*
[5] *Duke University, Durham, NC*
[6] *University of Manitoba, Winnipeg, Manitoba, Canada*
[7] *University of South Carolina, Columbia, SC*
[8] *University of Massachusetts, Amherst, MA*
[9] *NC-State University, Raleigh, NC*
[10] *TRIUMF, Vancouver, BC, Canada*
[11] *Indiana University/CEEM, Bloomington, IN*

Hadronic parity violation probes both the neutral-current nonleptonic weak interactions and nonperturbative strong dynamics. The current and projected availability of high-intensity neutron and photon sources and continuing developments in theoretical methods provide the opportunity to greatly expand our understanding of hadronic parity violation in few-nucleon systems. The current status of these efforts and future plans are discussed.

I. EXECUTIVE SUMMARY

Quark-quark weak interactions in the Standard Model induce parity-odd nucleon-nucleon interactions. Hadronic parity violation provides a unique probe of neutral-current nonleptonic weak interactions as well as of nonperturbative strong dynamics. Neutral-current interactions are suppressed in flavor-changing hadronic decays, making hadronic parity violation between nucleons the only accessible approach to study neutral-current effects. And because parity-violating NN interactions are the manifestation of the interplay of nonperturbative strong effects and the short-range weak interactions between quarks, they are sensitive to short-distance quark-quark correlations inside the nucleon. Weak NN amplitudes at low energy are suppressed by six to seven orders of magnitude compared to strong NN amplitudes and are therefore difficult to observe. The preliminary result from the NPDGamma experiment at ORNL, the first new sensitive experimental result in the NN system in many years, shows that at least one NN weak amplitude is smaller than expected on symmetry arguments alone. It strongly supports the longstanding suspicion from analysis of previous data that NN weak amplitudes are sensitive to poorly-understood aspects of nonperturbative QCD dynamics.

The availability of high-intensity sources of neutrons and photons such as the FnPB at the Spallation Neutron Source at ORNL, the new NG-C neutron beam at the NCNR at NIST, and an upgraded HIγS gamma facility at TUNL along with the controls for systematic uncertainties possible at these facilities provides new opportunities to greatly improve

§§§ Corresponding Author
*Electronic address: ahmed@tunl.duke.edu
†to be confirmed; Electronic address: bowmanjd@ornl.gov
‡Electronic address: crawford@pa.uky.edu
§Electronic address: nfomin@utk.edu
¶Electronic address: gao@phy.duke.edu
**to be confirmed; Electronic address: Michael.Gericke@umanitoba.ca
††Electronic address: gudkov@sc.edu
‡‡Electronic address: holstein@physics.umass.edu
§§Electronic address: howell@tunl.duke.edu
¶¶Electronic address: paul_huffman@ncsu.edu
***Electronic address: vanoers@triumf.ca
†††to be confirmed; Electronic address: penttilasi@ornl.gov
‡‡‡Electronic address: mschindl@mailbox.sc.edu
¶¶¶Electronic address: wsnow@indiana.edu
Electronic address: wu@fel.duke.edu

our experimental information on hadronic parity violation. Successful completion of the $\vec{n}+{}^3\text{He}\to{}^3\text{H}+p$ experiment now in progress at FnPB, the $\vec{n}+{}^4\text{He}$ spin rotation experiment in preparation for NIST, and a measurement of the parity-violating asymmetry in the photodisintegration of the deuteron near threshold at an upgraded HIγS facility can provide enough information to map out a major portion of the landscape of hadronic parity violation in few-nucleon systems in combination with the existing data from other probes. P-odd deuteron photodisintegration near threshold is the most interesting process to measure: besides $\vec{p}+p$ scattering it is the only foreseeable experiment which is sensitive to the elusive $\Delta I=2$ component of the NN weak interaction, it comes from one 4-quark operator above Λ_{QCD}, and it is the easiest target for a quantitative lattice calculation from the Standard Model, see the position paper on lattice QCD and hadronic parity violation.

Effective field theory methods are ideally suited to analyze and interpret the experimental results. They can treat parity-conserving and parity-violating interactions as well as external currents within a unified framework, provide estimates of theoretical errors, and are model independent; they establish a direct connection to the underlying Standard Model through the explicit incorporation of all known QCD symmetries. In order to avoid the complexities of nuclear structure, the main focus should be on *ab initio* calculations of parity-violating observables in systems from two to up to five nucleons. The recent progress in the application of effective field theories to few-nucleon systems should make it possible to determine PV observables in processes including $n+{}^4\text{He}$ and $p+{}^4\text{He}$ scattering. The weak amplitudes at the nucleon level should ultimately be connected to the parameters of the Standard Model. Ultimately, an understanding of the neutral-current weak interaction and its manifestation in hadronic parity violation from the Standard Model will require a coordinated effort between experiment, theory and computational physics. We endorse the position paper on lattice QCD and parity violation and the broader computational nuclear physics white paper [1].

II. INTRODUCTION

Hadronic parity violation offers a window into one of the least understood sectors of the Standard Model, the neutral-current nonleptonic weak interactions. Weak interactions are well-understood at the quark level, and neutral-current contributions are highly suppressed in flavor-changing hadronic decays. The only experimentally accessible approach is thus to study the parity-violating (PV) component of nucleon-nucleon (NN) interactions and its manifestation in nuclear systems.

Hadronic parity-violation is also a unique probe of nonperturbative dynamics of the strong interactions at low energies. With the weak interactions known at the quark level, their manifestation in PV NN interactions is the result of an interference with the nonperturbative strong effects that confine the quarks in the nucleons and lead to the residual strong NN interaction. The large mass of the weak gauge bosons implies that the range of the weak interactions (approximately 0.002 fm) is very small compared to the size of the nucleon (roughly 1 fm). The weak NN interactions are therefore sensitive to short-distance correlations between quarks inside the nucleon, and their manifestations at the hadronic level provide information about these correlations without the need of an external probe.

For low-energy nuclear reactions, hadronic parity violation can be described in terms of interactions between nucleons. The complex interplay between weak and nonperturbative strong physics is encoded in a small number of PV NN amplitudes. Experimental observables are linear combinations of the NN amplitudes, and the relative weightings of these NN amplitudes must be calculated to map out the PV landscape with an appropriate suite of measurements. This information should be derived from two- and few-nucleon systems to avoid the still-unknown complexities of nuclear structure.

Not enough experimental information from two- and few-nucleon systems is available yet to reliably determine all of the weak NN amplitudes. However, the existing and projected availability of high-intensity sources of neutrons and photons combined with ongoing technical improvements in the control of systematic uncertainties make new experiments possible. In parallel, the theoretical tools needed for a reliable and systematic analysis and interpretation of the experimental results continue to be developed. In particular, effective field theory (EFT) methods that are applicable to few-nucleon systems provide model-independent results which by construction obey the known symmetries of QCD along with theoretically justifiable error estimates.

Ultimately, the weak NN amplitudes have to be related to Standard Model parameters by calculations at the quark level. They provide a qualitatively distinct piece of low-energy data that any nonperturbative QCD calculation has to reproduce. The relative size of the various amplitudes can provide a hint at the underlying dynamics. The first lattice QCD calculation of a hadronic parity violation amplitude appeared recently [2]. The importance of lattice QCD calculations in determining PV nucleon interactions was also highlighted in the 2009 workshop "Forefront Questions in Nuclear Science and the Role of Computing at the Extreme Scale" [3]. Since little is known about the PV nucleon couplings, they provide an opportunity to utilize lattice QCD and EFT to make predictions in the nonperturbative regime, which in turn can be experimentally tested.

III. CURRENT EXPERIMENTAL STATUS

Here we summarize the experimental progress in the field of NN weak interactions since the last Long Range plan:

1. A 2011 NSAC review of the subfield of fundamental neutron physics identified NPDGamma as the highest priority experiment in NN weak interaction physics. NPDGamma was selected as the first experiment to run on the new FnPB facility for neutron physics at the Spallation Neutron Source at Oak Ridge National Lab. NPDGamma measures the parity-odd asymmetry of the 2.2 MeV photons from polarized slow neutron capture on protons and is sensitive to a S-P NN weak transition amplitude in the $\Delta I = 1$ channel corresponding to weak pion exchange. NPDGamma has finished taking data and data analysis is in progress. The preliminary result for the parity-violating asymmetry A_γ is that it is small with a statistical error of ~ 13 ppb and with negligible systematic error [4]. This result is consistent with both the longstanding result from experiments and theoretical analysis of parity violation in ^{18}F, which sees no evidence for a $\Delta I = 1$ NN weak amplitude from pion exchange, and with a recent pioneering lattice calculation [2].

   Here are some of the implications of this result:

   (a) The size of the S-P NN weak transition amplitude in the $\Delta I = 1$ channel corresponding to weak pion exchange is now tightly constrained for the first time with data from a two-nucleon system.

   (b) The size of this amplitude is small compared to the size of the $\Delta I = 0$ NN weak amplitudes which have been constrained by previous experimental observations of parity violation in proton scattering. The four-quark operators responsible for NN weak interactions in $\Delta I = 0$ and $\Delta I = 1$ channels have similar strength at the electroweak scale, and the perturbative QCD evolution of these operators from the electroweak scale down to Λ_{QCD} does not change this. We therefore suspect that this large difference is a sign of interesting nonperturbative QCD dynamics. We also expect that the $\Delta I = 1$ NN weak amplitudes are dominated by quark-quark neutral currents as the charged current contributions at the electroweak scale are suppressed by a factor of V_{us}^2. If so, the NPDGamma result implies that quark-quark neutral currents seem to be suppressed in NN weak transition amplitudes.

   (c) The long range of the $\Delta I = 1$ NN weak amplitude corresponding to weak pion exchange contributes to almost all parity-odd observables in two- and few-nucleon systems. The NPDGamma result that this amplitude is both small and tightly constrained makes it easier to extract new information on the other NN weak transition amplitudes from other experiments in two- and few-nucleon systems.

2. Important progress has been made on two other parity violation experiments in few-nucleon systems. An experiment to measure the proton asymmetry in polarized slow neutron capture on ^{3}He (the $\vec{s_n} \cdot \vec{k}_p$ correlation in $\vec{n} + {}^3\text{He} \rightarrow {}^3\text{H} + p$) is now installed on the FnPB at the SNS and will soon start to take data. A statistically-limited null result in polarized slow neutron spin rotation in n+^{4}He was measured on the NG-6 beamline at NIST [5], and a new spin rotation apparatus is under construction which is proposed to run on the new more intense NG-C beam at NIST. The projected precision of both of these experiments is enough to tightly constrain linear combinations of parity-odd transition amplitudes. Also, in both of these parity-odd observables the relative signs of the $\Delta I = 0$ and $\Delta I = 1$ transition amplitudes are different from the isospin-conjugate $p + {}^4$He system, where a nonzero parity-odd asymmetry was measured earlier at PSI.

IV. EXPERIMENTAL OPPORTUNITIES

We see two clear scientific opportunities for experimental progress in NN weak interaction physics using neutron and photon beams:

1. The experiments on n-^{3}He parity violation at SNS and on parity-odd neutron spin rotation in n+^{4}He at NIST should be completed with enough sensitivity to constrain NN weak amplitudes.

2. The highest scientific priority in experimental NN weak interaction physics is the measurement of the parity-odd helicity dependence of the photodisintegration of the deuteron near threshold $\vec{\gamma} + D \rightarrow n + p$. Together with the longitudinal asymmetry in $\vec{p} + p$ scattering this observable is sensitive to the experimentally elusive $\Delta I = 2$ NN weak amplitude. This amplitude is especially interesting from a theoretical point of view as it comes from one $\Delta I = 2$ effective 4-quark operator above Λ_{QCD} and it is the most accessible channel for a calculation from the Standard Model using lattice gauge theory. This experiment could be done in the future at the HIγS facility with upgrades to both the beam intensity and to the capability for rapid and controlled helicity flipping of the photon beam. Such an upgrade could also enable other parity violation experiments in few nucleon systems.

V. THEORETICAL STATUS

Traditionally PV NN interactions have been described in a meson-exchange picture in analogy to many parity-conserving (PC) NN models. Most widely used has been the DDH formulation given in Ref. [6], which also provides estimated ranges for the PV couplings appearing in the model. The available experimental results from two- to many-nucleon systems can be described in terms of four DDH parameters, provided a one-body PV potential is derived in the case of heavy nuclei [7]. In particular, only one $\Delta I = 1$ parameter is needed to describe the experimental data.

Over the last decades, EFTs have emerged as alternatives to phenomenological models of the NN interactions, both in the PC and PV sectors. EFTs are model independent, and provide systematic theoretical error estimates and a connection to QCD via symmetry principles. The use of EFTs to study hadronic parity violation goes back to the 90s [8], with a comprehensive analysis of PV Lagrangians given in Ref. [9]. EFTs have now been applied to PV observables in two-, three-, and four-nucleon systems (see Ref. [10] for a recent review), including the corresponding observables discussed in the previous sections. Such calculations play an important role in assessing whether measurements are feasible and, if so, in the planning and the subsequent analysis of the corresponding experiments. EFT methods continue to be developed, with a particular emphasis on the application to few-nucleon systems. For example, $p + {}^4$He scattering at low energy was recently calculated using chiral EFT potentials [11].

There has been tremendous progress in the development of lattice QCD as a reliable tool to compute basic properties of low-energy nuclear and hadronic physics. We are transitioning to an era in which lattice QCD is now being utilized to make theoretical predictions of important low-energy quantities which are either significantly challenging or currently not possible to measure experimentally. For example, the pioneering calculation of the PV pion-nucleon coupling in Ref. [2] showed that lattice QCD can have significant impact on our understanding of hadronic parity violation. In particular, it is possible to utilize lattice QCD to make predictions of the yet undetermined PV coupling constants appearing in the PV EFT, which in turn can be tested experimentally. If successful, this program could establish a quantitative connection through two nonperturbative strong interaction scales (Λ_{QCD} and the $\sim$ MeV scale of NN bound state dynamics) from quark-level interactions to observables in few-nucleon systems.

Recent theoretical progress includes the following achievements:

1. It was shown that, unlike in the PC sector, PV three-nucleon interactions are not enhanced at very low energy and do not contribute beyond about 10% effects [12]. This means that at very low energy the five PV low-energy constants (LECs) are sufficient to describe parity violation in few-nucleon systems.

2. The PV asymmetry in $\vec{n} + {}^3\text{He} \rightarrow {}^3\text{H} + p$ was calculated employing chiral EFT for both PC and PV interactions [13]. This calculation is essential for the interpretation of the upcoming measurement of this observable at the FnPB.

3. The PV pion-nucleon coupling h^1_π was calculated in lattice QCD in Ref. [2]. This was a pioneering calculation, and as such did not aim to control all systematics, but rather to demonstrate the feasibility of such calculations, and to place a rigorous estimate on the value of this important PV coupling. The resulting value of $h^{1,\text{con}}_\pi = (1.099 \pm 0.505^{+0.058}_{-0.064}) \times 10^{-7}$ is in agreement with experimental bounds.

4. The relationships and connections between two different descriptions of NN weak interactions, the model-dependent DDH approach and the various versions of EFT, have been clarified.

VI. THEORETICAL OPPORTUNITIES

There are a number of opportunities for theoretical progress in hadronic parity violation. These include:

1. The ongoing improvements in the application of EFT methods to few-nucleon systems put consistent calculations of the PV asymmetry in $\vec{p} + {}^4$He and the spin rotation angle in $\vec{n} + {}^4$He within reach. These calculations are challenging but are of high priority as experimental results for these observables either exist (for $\vec{p} + {}^4$He) or can be measured ($\vec{n} + {}^4$He).

2. The power counting analysis of EFTs is based on the assumption that the couplings are natural in size. Experimental results that reveal a pattern of values for the LECs different from O(1) are an indication of nontrivial QCD dynamics. An updated analysis of the EFT power counting will be required in that case.

3. Lattice QCD plays an equally important role in establishing the connection between the fundamental Standard Model parameters to weak NN amplitudes. The $\Delta I = 2$ amplitude presents an especially interesting target for investigation because it only receives contributions from connected quark diagrams (not the computationally demanding disconnected loop diagrams) and the isotensor nature of the operator prevents mixing under renormalization. First lattice QCD results from the CalLat Collaboration are anticipated in the near future, see eg. the position paper on lattice QCD and parity violation. The determination of this quantity from experiment is difficult and currently not well constrained. It further contributes significantly to the uncertainty in the determination of the $\Delta I = 0$ amplitude [14]. Therefore, this amplitude presents a very exciting opportunity to use lattice QCD and EFT to make a precise prediction of a NN weak amplitude directly from the Standard Model.

VII. HIγS2: THE COMPTON γ-RAY SOURCE

The measurement of the parity-violating asymmetry of photodisintegration of the deuteron to an accuracy of 10^{-8} requires a high intensity circularly polarized γ-ray beam with high polarization ($> 90\%$) and narrow beam energy spread (< 100 keV FWHM at about 2.4 MeV). The current facility best suited to deliver the γ-ray beam for this experiment is the High Intensity Gamma-ray Source (HIγS) at the Triangle Universities Nuclear Laboratory (TUNL). The γ-ray beam at HIγS is produced by Compton backscattering of the photons inside the optical cavity of a storage-ring based Free-Electron Laser from circulating electron bunches. The current capabilities of HIγS are: (1) delivery of γ-ray beams on target in the energy of 1 to 100 MeV with beam energy spread selected by collimation as low as about 1% FWHM, (2) a beam intensity on target with 5% energy spread as high as 10^9 gammas/s, (3) linear or circular beam polarization with magnitude of polarization greater than 95%. To carry out the proposed parity violation experiment will require an upgrade of HIγS to increase the beam intensity by about two orders of magnitude and to provide the capability of fast reversal of the beam helicity with precision control and diagnostics of the spatial and energy distributions of the beam. A two-stage upgrade of HIγS is envisaged. The first stage is an upgrade of the electron injector system to increase the average charge injection rate into the storage ring and to enhance the overall reliability of the accelerator drivers. This stage is motivated by the Compton-scattering research program at HIγS and is also needed for the parity-violation experiments. This part of the accelerator upgrade will start around 2018. The second stage in the upgrade is the installation of an optical cavity in the straight section of the storage ring that is driven by an external laser. The photons in the optical cavity will produce γ-rays by Compton scattering from the electron bunches circulating in the storage ring. The schedule for starting construction is around 2021.

A schematic diagram of HIγS2 is shown in Fig. 1. The HIγS2 γ-ray beam is produced by colliding a high-current electron beam with photons inside an optical cavity that is driven by a powerful external laser. The electron beam is provided by the storage ring which will be operated with 32 electron bunches with a total current up to about 500 mA. An average optical power of about 10 to 20 KW will be built up inside the high-finesse Fabry-Perot resonator. Compared with the FEL driven HIγS, a higher average intracavity laser power and significantly reduced beam sizes at the collision point make it possible for the HIγS2 to achieve a total gamma flux of 10^{11} to 10^{12} γ/s in the energy range of 2 to 12 MeV. In addition to the substantial intensity increase, the HIγS2 facility will produce γ-ray beams with a better monochromaticity and the ability to rapidly switch the γ-ray beam helicity at a rate of tens of Hz or higher. The fast helicity switch of the γ-ray beam will be realized by changing the polarization of the laser beam outside the Fabry-Perot resonator using polarizing optics such as Pockels cells and wave plates.

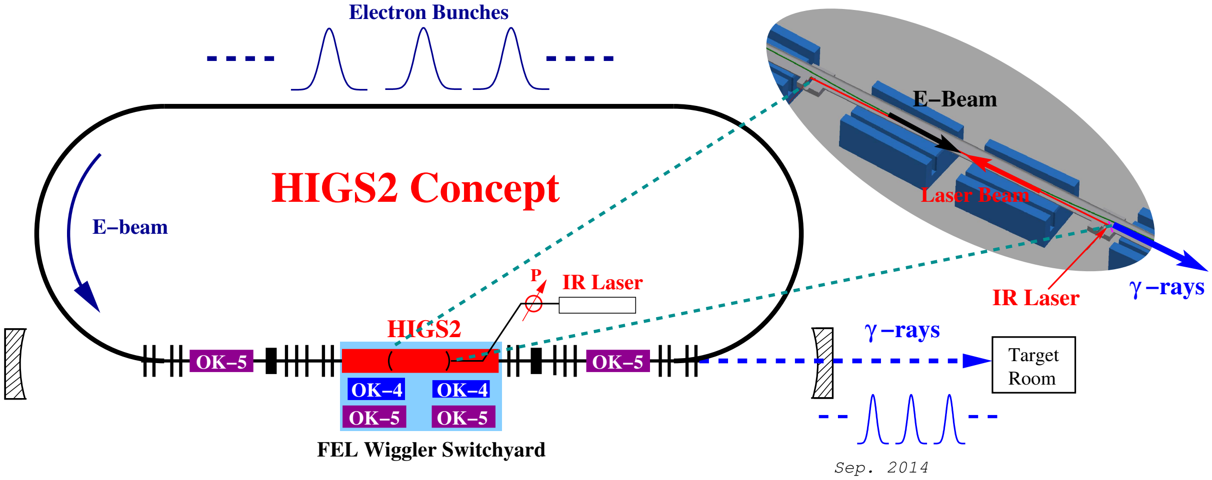

FIG. 1: The schematic layout of the HIγS2 Compton γ-ray source. The HIγS2 is located in one of the two long straight sections of the electron storage ring. Guided by a set of deflection magnets, the electron beam enters and exits the high-power Fabry-Perot resonator to collider with the photon pulse in the center of the resonator. The polarization of the γ-ray beam is rapidly switchable by changing the polarization of the laser beam from the external infrared drive laser using polarizing optics.

Acknowledgments

We thank W. Haxton and A. Walker-Loud for interesting discussions and comments on the manuscript.

[1] A. Burrows *et al.*, Computational nuclear physics meeting: Report, (2014).
[2] J. Wasem, Phys.Rev. **C85**, 022501 (2012), 1108.1151.
[3] *"Scientific Grand Challenges: Forefront Questions in Nuclear Science and the Role of Computing at the Extreme Scale," Workshop sponsored by the DOE Office of Nuclear Physics and the Office of Advanced Scientific Computing.*, (2009).
[4] J. Bowman, presentation at the Electron-Nucleus Scattering XIII conference, Elba, Italy (2014).
[5] W. Snow *et al.*, Phys.Rev. **C83**, 022501 (2011).
[6] B. Desplanques, J. F. Donoghue, and B. R. Holstein, Annals Phys. **124**, 449 (1980).
[7] J. Bowman, presentation at INT program on "Electric Dipole Moments and CP Violations" (2007).
[8] D. B. Kaplan and M. J. Savage, Nucl.Phys. **A556**, 653 (1993).
[9] S.-L. Zhu, C. Maekawa, B. Holstein, M. Ramsey-Musolf, and U. van Kolck, Nucl.Phys. **A748**, 435 (2005), nucl-th/0407087.
[10] M. Schindler and R. Springer, Prog.Part.Nucl.Phys. **72**, 1 (2013), 1305.4190.
[11] G. Hupin, S. Quaglioni, and P. Navrtil, (2014), 1409.0892.
[12] H. W. Griesshammer and M. R. Schindler, Eur.Phys.J. **A46**, 73 (2010), 1007.0734.
[13] M. Viviani *et al.*, (2014), 1403.2267.
[14] W. Haxton and B. Holstein, Prog.Part.Nucl.Phys. **71**, 185 (2013), 1303.4132.