Hadronic Parity Violation: Experiment

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Fundamental Symmetries, Neutrinos, Neutrons and related Nuclear Astrophysics Long-Range Plan Town Meeting

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Summary

Completed or Ready to run:

- $\vec{n} + p \rightarrow d + \gamma$ *(final analysis)*
- $\vec{n} + ^3\text{He} \rightarrow ^3\text{H} + p$ *(ready to commission)*
- Neutron Spin Rotation III *(upgrade in progress)*
- Francium anapole *(ongoing)*

Next step in HWI studies: PV Deuteron photo-disintegration

Probing Time Reversal Invariance via Hadronic PV:
feasibility studies, determination of systematic effects

Hadronic Weak Interaction

- Natural scale $\sim 10^{-7}$, set by relative size of meson vs boson exchange amplitudes
- Weak interaction at low momentum transfer between nucleons is accessible through measurements of small parity-odd amplitudes

Theoretical Frameworks

- DDH
- EFT
- Lattice QCD
Hadronic Weak Interaction – Theory

1. **DDH model** – uses valence quarks to calculate effective PV meson-nucleon coupling directly from SM via weak meson coupling constants

\[ h_\pi^1, h_\rho^0, h_\rho^1, h_\rho^1, h_\rho^2, h_\omega^0, h_\omega^1 \]

- Observables can be written as their combinations

\[ A = a_\pi^1 h_\pi^1 + a_\rho^0 h_\rho^0 + a_\rho^1 h_\rho^1 + a_\rho^2 h_\rho^2 + a_\omega^0 h_\omega^0 + a_\omega^1 h_\omega^1 \]

2. **Effective Field Theory**

- comprehensive formulation by Holstein, Ramsey-Musolf, van Kolck, Zhu and Maekawa
- model-independent, consistent treatment of PC and PV interactions, theoretical error estimates
- NN potentials are expressed in terms of several parameters whose linear combinations give us 5/6 (pionless/chiral) low energy coupling constants

3. **Lattice QCD**
Example: \( n+p \rightarrow d + \gamma \) (isolates \( \Delta I=1 \))

1. **DDH model**

\[
A = -0.11h^1_\pi + 0.001h^1_\rho + 0.004h^1_\omega
\]

Reasonable range: \(-11 < h^1_\pi < 0 \times 10^{-7}\) \(\Rightarrow h^1_\pi \approx 4.5 \times 10^{-7}\)

2. **Effective Field Theory**

\[
A_\gamma = \frac{4}{3\sqrt{\pi}} \frac{M^{\frac{3}{2}}}{\kappa_1 (1 - \gamma a^{(1S_0)})} g^{(3S_1 - 3P_1)}
\]

3. **Lattice QCD**

\[
h^1_{\pi NN} = 1.099 \pm 0.505^{+0.058}_{-0.064} \times 10^{-7}
\]

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-- J. Wasem, PRC C85 (2012)
Experimental Reach

Weak NN iso-scalar, iso-vector DDH coupling subspace

- $h^0_{\rho} + 0.7 h^0_{\omega}$

- $f_x - 0.12 h^1_{\rho} - 0.18 h^1_{\omega}$

- $pp$ 13.6 & 45 MeV
- $p - \alpha$
- $F, \gamma$
- $np \rightarrow dy$ proposed $\pm 1 \times 10^{-3}$
- NSR proposed $\pm 1 \times 10^{-7}$
- $n - ^3He$ proposed $\pm 2 \times 10^{-7}$
- LQCD
During the next decade, a program of few-body, hadronic PV experiments using polarized neutrons at the FNPB and elsewhere will provide data that can be interpreted with ab initio, few-body calculations and effective field theory methods to yield the lowest-order “primordial” PV nuclear interaction.

Among the scientific priorities:

III. Completion of the NPDGamma experiment to obtain a precision measurement of the weak isovector nucleon – nucleon pion coupling constant.
NPDGamma data taking completed in June 2014
The NPDGamma collaboration – 15+ years

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\textbf{DOE and NSF (USA)}
\textbf{NSERC (CANADA)}
\textbf{CONACYT (MEXICO)}
\textbf{BARC (INDIA)}
The NPDGamma collaboration – 15+ years

8 PhDs at LANL

4 PhDs at SNS

4 PhDs in progress
Final results coming very soon

Two independent analyses

\[ \vec{s}_n \cdot \vec{k}_\gamma \]

- Two independent analyses

\[ \frac{d\sigma}{d\Omega} \propto \frac{1}{4\pi} (1 + A_\gamma \cos \theta) \]

\[ dA \leq 1.3 \times 10^{-8} \]
$$n + ^3He \rightarrow ^3H+p$$

$$A_p \approx \langle \vec{\sigma}_n \cdot \vec{k}_p \rangle$$

$$\frac{d\sigma}{d\Omega} \approx \frac{\sigma_0}{4\pi} (1 + A_p \cos\theta)$$

Currently commissioning on the FnPB at the SNS

**GOAL:** $dA \sim 1.6 \times 10^{-8}$
**DDH:**

\[ A = -0.185h_\pi^1 - 0.038h_\rho^0 + 0.023h_\rho^1 - 0.001h_\rho^2 - 0.050h_\omega^0 - 0.023h_\omega^1 \]

**EFT:**

\[ A \sim a g_{(\Delta I=1)}^{(1S_0^3P_0)} + a' g_{(\Delta I=3)}^{(3S_1^3P_1)} + b g_{(\Delta I=0)}^{(1S_0^3P_0)} + b' g_{(\Delta I=1)}^{(3S_1^3P_1)} + c g_{(\Delta I=2)}^{(1S_0^3P_0)} \]

\[(a \approx a') > (b \approx b') > c\]
Cold neutrons are polarized in the y direction traveling in the z direction. They interact with the $^4$He over a length, $l$. The neutron spin gains $\phi_{PC} + \phi_{PV}$ and passes through the supermirror analyzer where the neutrons are detected. Accumulated phase differences between opposite helicity states cause transversely-polarized neutrons to corkscrew as they propagate through target.
PV Spin Rotation in $^4$He

**DDH:**
\[ \phi_{PV} = -0.97h_\pi^1 - 0.32h_\rho^0 + 0.11h_\rho^1 - 0.22h_\omega^0 + 0.22h_\omega^1 \]

**EFT:**
5-body calculation!

**NSR II**
\[ \frac{d\phi_{PV}}{dz} = [1.7 \pm 9.1 \,(stat) \pm 1.4 \,(sys)] \times 10^{-7} \, \text{rad/m} \]

**NSR III - projected**
\[ \frac{d\phi_{PV}}{dz} \leq 1.0 \times 10^{-7} \]
Hadronic parity violation

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Hadronic parity violation probes both the neutral-current nonleptonic weak interactions and non-perturbative 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.
Asymmetry $A^L_\gamma$ in $\gamma d \rightarrow np$ at leading order

- Leading-order asymmetry at threshold

\[
A^L_\gamma = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = -2 \sqrt{\frac{2}{\pi}} \frac{M^2_\gamma}{\kappa_1} \left( 1 - \gamma a^{1S_0} \right) \left[ \left( 1 - \frac{2}{3} \gamma a^{1S_0} \right) g^{(3S_1-1P_1)} + \frac{\gamma a^{1S_0}}{3} \left( g^{(1S_0-3P_0)}(\Delta I=0) - 2g^{(1S_0-3P_0)}(\Delta I=2) \right) \right],
\]

- Helicity-dependent asymmetry
  Detect either the n or p (neutron is easier)

- Information independent of and complementary to
  $\bar{n}p \rightarrow d\gamma$

J. Vanasse and M.R. Schindler, nucl-th/ 1404.0658

Schindler, Springer (2009); Vanasse, Schindler (2014)
Where to measure?

- $A_L^\gamma$ max at threshold $\Rightarrow$ low count rate
- Simplified figure of merit $(A_L^\gamma)^2 \times \sigma(\gamma d \rightarrow np)$

- $E_{\gamma} = 2.30$ MeV
- $\sigma = 600$ $\mu$b
- $A \sim 4 \times 10^{-7}$ (DDH adjusted)

Maximized for $\omega \approx [2.259, 2.264]$ MeV

Vanasse, Schindler (2014)
Need to observe $\sim 10^{16}$ γs to be sensitive to a $10^{-8}$ asymmetry

- The target will be liquid deuterium with thickness of about 67% attenuation of the γ-ray beam
- The neutron can be moderated in the liquid deuterium target, escape with low energy (~10 meV), and be detected efficiently in current mode in a $^3\text{He}/^4\text{He}$ ion chamber
- The transmitted and scattered γs can be measured using current-mode γ detectors located behind the $^3\text{He}/^4\text{He}$ ion chamber
- Cylindrical symmetry of detector array to help suppress possible systematic errors
**Features of HIgS2** (optimized for parity-violation measurements of g-ray induced reactions)

- g-ray beam produced by Compton-back scattering of electron bunches circulating in a storage ring from photons in a Fabry-Pérot optical cavity pumped with a high-powered external laser;
- Total g-ray beam flux = $10^{11}$ to $10^{12}$ g/s (~x1000 larger than HIgS) in energy range of 2 to 12 MeV;
- Circular beam polarization with magnitude > 95% and fast reversal of polarization direction using well established methods;
- Precision control and diagnostics of beam phase space; and
- Beam energy resolution selected by collimation.
Hadronic Parity Violation in Many Body Systems
FrPNC collaboration:
TRIUMF - Maryland - Manitoba
San Luis Potosi - William & Mary
Shanxi - Stony Brook - New South Wales

Goal: Weak interaction physics studies through parity non-conservation measurements in Fr:
- Nuclear spin dependent → anapole moment; hadronic influence.
- Nuclear spin independent → Standard model tests.

Sep 2012: Commissioning run (1)
- Fr laser trapping demonstrated
- Isotopes 209, 207*, 221

Nov 2012: Commissioning run (2),
- Hyperfine anomalies and isotope shifts in isotopes 209, 207, 213*, 206* in preparation for FrPNC.
  * not previously trapped

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A Search of Time Reversal Violation
TREX Experiment

Observable is a triple correlation

\[ \vec{\sigma}_n \cdot (\vec{k}_n \times \vec{I}) \]

At SNS

\[ \Delta A_{PT} = 6 \times 10^{-6} \]
A Search of Time Reversal Violation in Neutron Scattering - TREX Experiment

- Search of TR violation in compound nuclear resonances by transmitting polarized neutrons through a polarized target \(^2,^3\)
- Observable is the \(P\)-odd \(T\)-odd triple correlation \(\vec{\sigma}_n \cdot (\vec{k}_n \times \vec{I})\)
- Expected \(10^6\) enhancements in \(\mathcal{F}\) observables by complex nuclear structure\(^3\)
- \(10^2\)-\(10^4\) discovery potential for improvement of the current limits on TRIV interaction obtained from the EDM experiments\(^4\).
- Sensitivity of the TRex is given by \(\lambda\) parameter

\[
\lambda_{PT} = \frac{\delta \sigma_{PT}}{\delta \sigma_P}
\]

<table>
<thead>
<tr>
<th>Model</th>
<th>(\lambda_{PT})</th>
</tr>
</thead>
<tbody>
<tr>
<td>CKM (\delta) phase</td>
<td>(\leq 10^{-10})</td>
</tr>
<tr>
<td>Left-right symmetry</td>
<td>(\leq 4 \times 10^{-3})</td>
</tr>
<tr>
<td>Horizontal symmetry</td>
<td>(\leq 10^{-5})</td>
</tr>
<tr>
<td>Charged Higgs bosons</td>
<td>(\leq 2 \times 10^{-6})</td>
</tr>
<tr>
<td>Neutral Higgs bosons</td>
<td>(\leq 3 \times 10^{-4})</td>
</tr>
<tr>
<td>(\theta) QCD</td>
<td>(\leq 5 \times 10^{-5})</td>
</tr>
<tr>
<td>nEDM (single-loop)</td>
<td>(\leq 4 \times 10^{-3})</td>
</tr>
<tr>
<td>Atomic EDM ((^{199}\text{Hg}))</td>
<td>(\leq 2 \times 10^{-3})</td>
</tr>
</tbody>
</table>

Time-reversal Tests in Nuclear and Hadronic Processes
Thursday, November 6, 2014 - 8:45am to Saturday, November 8, 2014 - 5:00pm
Lederle Graduate Research Tower (LGRT) 419B, UMass Amherst

The workshop will address opportunities for tests of time-reversal invariance in neutron-nucleus interactions and weak decays as well as the related tests of C-invariance in rare eta decays. The program will focus on the relationship with tests of time-reversal invariance with electric dipole moment searches, methods for computing the hadronic and nuclear matrix elements, and experimental opportunities.

Co-organizers:
Liping Gan (U. North Carolina Wilmington)
Vladimir Gudkov (U. South Carolina)
Sean Tulin (York U.)
Completed or Ready to run:

- $\vec{n} + p \rightarrow d + \gamma$ (final analysis)
- $\vec{n} + ^3\text{He} \rightarrow ^3\text{H} + p$ (ready to commission)
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Strong community support

Probing Time Reversal Invariance via Hadronic PV:

feasibility studies, determination of systematic effects