The NPDGamma Experiment

First Observation of the Parity-Violating Asymmetry in Polarized Cold Neutron Capture on Hydrogen

Michael Gericke

University of Manitoba, Canada

For the NPDGamma Collaboration

XIII Quark Confinement and the Hadron Spectrum

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Observable:

NPDGamma measured the radiative neutron capture cross-section as a function of neutron spin:

The observable is the parity-vilating up-down asymmetry in the angular distribution of gamma rays with respect to the neutron spin direction

\[ A_{meas} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} = C (A_{\gamma PV} \cos(\theta_\gamma) + A_{\gamma PC} \sin(\theta_\gamma)) \]

\[ \vec{n} + p \rightarrow d + \gamma \]

\[ \sigma \propto \left| \langle \psi_f | E1 | \psi_i \rangle \right|^2 \]

We get parity-odd \textbf{E1} transitions between parity admixed initial and final states:

\[ |\psi_{i,f}\rangle = |\psi_0\rangle + \frac{\langle \psi_1 | V_{PNC} | \psi_0 \rangle}{\Delta E} |\psi_1\rangle \]

\[ H = H_S + V_{PNC} \]

The form of \( V_{PNC} \) is model dependent (see later …)
Observable:

To lowest order in $L$ and $V_{PNC}$, the surviving transitions are:

**Parity even**  \[
\langle I = 0, {}^3S_1 | M1 | I = 1, {}^1S_0 \rangle
\]

**Parity odd**  \[
a_1 \langle I = 0, {}^3S_1 | E1 | I = 1, {}^3P_1 \rangle
\]

**Parity odd**  \[
a_1 \langle I = 1, {}^3P_1 | E1 | I = 0, {}^3S_1 \rangle
\]

The corresponding asymmetry is:

\[
A_{\gamma PV} = -2\sqrt{2} \frac{\langle E1 \rangle}{\langle M1 \rangle}
\]

This asymmetry has not been seen in this simple system, but there is no reason why it shouldn’t be there.

So how big is it?

Various models (meson exchange, $EFT(\pi)$, $\chi PT$, Large $N_C$, LQCD (?) ) predict the size to be

\[
A_{\gamma PV} \sim -50 \text{ ppb}
\]

But which model does a reasonable job at explaining why it is so small?

NPDGamma goal was a 10% measurement

Very challenging …
Experiment History:

NPDGamma has a long history:

- First hardware development started in the late 1990s
- First phase measurement at LANL in 2006
  - Too little statistics (low beam power)
  - Beam pulse frequency not ideal $\Rightarrow$ systematic effects
- Move to ORNL and reconstruct 2009 – 2011
- Run between 2011-2013 and 2016
- Final analysis completed
- In publication mode (arXiv:\textbf{1807.10192})
Experiment Layout:

- ORNL Spallation Neutron Source (SNS)
- Fundamental neutron physics beam (FnPB) line
- LH2 moderator
- 17 m long guide ~ 20 m to experiment
- One polyenergetic cold beam line
- One monoenergetic (0.89 nm) beam line
- ~ 40 m to nEDM UCN source
- 4 frame overlap choppers
- 60 Hz pulse repetition
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Experiment Layout:

NPDGamma Setup:
Experiment Layout:

Beam spectrum and chopped pulses

- Beam monitor signal
- Missing Wrap around
- Dropped Pulse
- Wrap around

Measured neutron beam spectrum

- Main chopped spectrum ~3-6 Å
- Wraparound neutrons on order $10^{-2}$
Experiment Layout:

Beam polarization (NIM, A 895 (2018) 19–28)

[Diagram of beam polarization setup]

- Chopper1
- Chopper2
- Shutter
- Guide
- Polarizer
- Spin rotator
- Lead shielding
- "Racetrack" holding field coils

[Graphs showing polarization vs. wavelength]

- Center, Beam-Left
- Center
- Center, Beam-Right

Wavelength (Å):
- 3.8 to 5.8

Polarization:
- 0.9 to 0.98

McStas Model Polarization
- Beam-Average Polarization

Wavelength (Å):
- 3.5 to 7
Experiment Layout:

Spin rotator
Experiment Layout:

NPDGamma Target (PhysRev B 91, 180301(R) (2015)
Experimental Layout:

NPDGamma Detector (NIM A 540, 328 (2005))

- Consists of 4 rings with 12 detectors each

- CsI(Tl) scintillator crystals coupled to 3 inch vacuum photodiodes

- Covers a solid angle of $\sim 3\pi$

- Rate per detector $\sim 100$ MHz

- Operated in current mode

- Gain provided by low noise solid state preamplifiers.
Detector Signal and Background:

- **Total Signal**
  - Prompt Hydrogen
  - Prompt Aluminum
  - β Delayed Aluminum
  - Electronic Pedestal

- **Hydrogen signal**
- **β-delayed aluminum signal**
- **Electronic pedestal**

**H:** 80%
**Al:** 20%
**β -delayed:** 5%
Analysis Procedure:

Raw asymmetries are measured simultaneously for each detector pair to filter pulse to pulse intensity fluctuations and for a valid spin sequence of eight pulses

\[
\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\downarrow\downarrow
\]

to suppress detector gain drifts up to second order.

Point target and detector:

\[
\frac{d\sigma}{d\Omega} \propto \frac{1}{4\pi} \left(1 + A_{\gamma PV} \cos(\theta_{\gamma})\right)
\]

Acceptance corrected:

\[
\cos(\theta_{\gamma}) \rightarrow G_d(\langle z, \theta, \phi \rangle)
\]

Detector yield:

\[
Y_d = \frac{V_d}{4\pi} \left(1 + A_{\gamma PV} \ G_d \ P_n \ R_n \ S_n\right)
\]

Detector pair asymmetry:

\[
A_{meas} = \frac{\sqrt{\alpha} - 1}{\sqrt{\alpha} + 1} \quad \alpha \equiv \frac{Y_d^{\uparrow} \ Y_d^{\uparrow+6}}{Y_d^{\downarrow} \ Y_d^{\downarrow+6}}
\]

Geometric mean detector pair asymmetry removes beam and pedestal variations.
Analysis Procedure:

Beam monitor data and dropped pulse cuts:

About 15% of data is removed by cuts

Varying cuts does not affect the asymmetry

Cuts are independent of polarization
Extraction of Physics Asymmetry:

Take into account aluminum background fraction and independently measured aluminum asymmetry for each detector pair.

Also take into account the parity-conserving left-right asymmetry.

\[
A_{\text{meas}}^p = f_H P_{\text{tot}}^H \left( G_{UD,p}^H A_{\gamma PV}^H + G_{LR,p}^H A_{\gamma PC}^H \right) + f_{Al} P_{\text{tot}}^{Al} \left( G_{UD,p}^{Al} A_{\gamma PV}^{Al} + G_{LR,p}^{Al} A_{\gamma PC}^{Al} \right)
\]

Combine the beam polarization, spin rotation efficiency, and depolarization into one \( P_{\text{tot}} \)

Subtract the measured Aluminum PV and PC asymmetries

Plot the pair asymmetries and extract the PV and PC asymmetries from a fit to the data.

\[
A_{PV}^{Al} = (-12 \pm 3) \times 10^{-8}
\]
Final Result for the Hydrogen Asymmetry:

Three independent analysis approaches were pursued, with independent cut methodologies.

\[ A_{PV}^H = \left( -3.0 \pm 1.4 \text{ (stat)} \pm 0.2 \text{ (sys)} \right) \times 10^{-8} \]
Theory and Implications:

Goals of $\Delta S = 0$ HWI studies:

1. Answer how the symmetries of QCD characterize the HWI in strongly interacting systems

   The HWI is just a residual effect of the q-q weak interaction for which the range is set by the mass of the Z,W bosons which is much smaller than the size of nucleons, as determined by QCD dynamics.

   HWI probes short range qq correlations at low energy

   Best hope for the future are possible calculations in LQCD

2. Try to shed some light on the puzzles in the $\Delta S = 1$ sector of the HWI
Overview:

- **Meson exchange model: PV potential** \( \pi, \rho, \text{ and } \omega \) with strong and weak vertex. Leads to 7 Weak couplings
  - W. C. Haxton and B. R. Holstein, Progress in Particle and Nuclear Physics, 2013

- **\( EFT(\pi), \chi EFT \):** 5 LEC constants, model independent

- **\( 1/N_C \) expansions:** \( N_C \rightarrow \) large gives hierarchy of couplings

- **LQCD calculations of HWI couplings**
  - A. Walker-Loud – expensive, but forthcoming re-calculation of pion coupling in NN

- Low energy NN interaction in terms of the lowest energy mesons in which the pseudoscalar $\pi$ meson and $\rho$ and $\omega$ vector mesons couple a weak vertex to a strong vertex.

- To relate to observables, need to calculate matrix elements. DDH used quark model, SU(6) symmetry, and non-leptonic hyperon decays to make estimates of the couplings.

e.g. pion coupling:

$$H_{PC} = ig_{\pi NN} \int dx \bar{\psi} \gamma_5 \psi \cdot \phi$$

$$H_{PNC} = \frac{h_\pi}{\sqrt{2}} \int dx \bar{\psi} \psi \tau \times \phi$$

$$\langle f | V_{PNC} | i \rangle = \left( N_{f1} N_{f2} \right) \left| H_{PC} \frac{1}{E_0 - H_0 + i\varepsilon} H_{PNC} \right| N_{i1} N_{i2} \rangle + \text{h.c.}$$

$$\frac{i h_\pi^1 g_{\pi NN}}{m_N \sqrt{36}} (\tau_1 \times \tau_2)_z (\sigma_1 + \sigma_2) \left[ p_1 - p_2, \frac{e^{-m_n r}}{4\pi r} \right]$$

Weak pion-nucleon coupling.

\[
V_{DDH}^{PV}(r) = \frac{i}{\sqrt{2}} \frac{h_{\pi}^{1}g_{\pi NN}}{} \left( \frac{(\tau_1 \times \tau_2)}{2} \right)_z (\sigma_1 + \sigma_2) \cdot \left[ \frac{p_1 - p_2}{2m_N}, w_\pi(r) \right]
\]

\[
- g_{\rho} \left( h_{\rho}^{0} \tau_1 \cdot \tau_2 + h_{\rho}^{1} \left( \frac{(\tau_1 \times \tau_2)}{2} \right)_z + \frac{h_{\rho}^{2}}{2\sqrt{6}} \left((3\tau_1 \cdot \tau_2)_z - \tau_1 \cdot \tau_2\right) \right)
\]

\[
\times \left( (\sigma_1 - \sigma_2) \cdot \left\{ \frac{p_1 - p_2}{2m_N}, w_\rho(r) \right\} + i(1 + \chi_V)\sigma_1 \times \sigma_2 \cdot \left[ \frac{p_1 - p_2}{2m_N}, w_\rho(r) \right] \right)
\]

\[
- g_{\omega} \left( h_{\omega}^{0} + h_{\omega}^{1} \left( \frac{(\tau_1 \times \tau_2)}{2} \right)_z \right)
\]

\[
\times \left( (\sigma_1 - \sigma_2) \cdot \left\{ \frac{p_1 - p_2}{2m_N}, w_\omega(r) \right\} + i(1 + \chi_S)\sigma_1 \times \sigma_2 \cdot \left[ \frac{p_1 - p_2}{2m_N}, w_\omega(r) \right] \right)
\]

\[
+ \left( \frac{(\tau_1 \times \tau_2)}{2} \right)_z (\sigma_1 + \sigma_2) \cdot g_{\rho}h_{\rho}^{1} \left\{ \frac{p_1 - p_2}{2m_N}, w_\rho(r) \right\} - g_{\omega}h_{\omega}^{1} \left\{ \frac{p_1 - p_2}{2m_N}, w_\omega(r) \right\}
\]

\[
- ig_{\rho}h_{\rho}^{1'} \left( \frac{(\tau_1 \times \tau_2)}{2} \right)_z (\sigma_1 + \sigma_2) \cdot \left[ \frac{p_1 - p_2}{2m_N}, w_\rho(r) \right]
\]

\[
O_{PV} = a_{\pi}^{1} h_{\pi}^{1} + a_{\rho}^{0} h_{\rho}^{0} + a_{\rho}^{1} h_{\rho}^{1} + a_{\rho}^{2} h_{\rho}^{2} + a_{\omega}^{0} h_{\omega}^{0} + a_{\omega}^{1} h_{\omega}^{1}
\]
Theory and Implications:


\[
O_{PV} = a_{\pi}^1 h_{\pi}^1 + a_{\rho}^0 h_{\rho}^0 + a_{\rho}^1 h_{\rho}^1 + a_{\rho}^2 h_{\rho}^2 + a_{\omega}^0 h_{\omega}^0 + a_{\omega}^1 h_{\omega}^1
\]


<table>
<thead>
<tr>
<th>DDH Weak Coupling</th>
<th>((A_\gamma)) np (\rightarrow) d(\gamma)</th>
<th>((A_\gamma)) nd (\rightarrow) t(\gamma)</th>
<th>((\phi_{PV})) n-p ((\mu)rad/m)</th>
<th>((\phi_{PV})) n-(\alpha) ((\mu)rad/m)</th>
<th>p-p</th>
<th>p-(\alpha)</th>
<th>((A_{pZ}^3)) n(^3)He (\rightarrow) tp</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a_{\pi}^1)</td>
<td>-0.107</td>
<td>-0.92</td>
<td>-3.12</td>
<td>-0.97</td>
<td>0</td>
<td>-0.340</td>
<td>-0.189</td>
</tr>
<tr>
<td>(a_{\rho}^0)</td>
<td>0</td>
<td>-0.50</td>
<td>-0.23</td>
<td>-0.32</td>
<td>0.079</td>
<td>0.140</td>
<td>-0.036</td>
</tr>
<tr>
<td>(a_{\rho}^1)</td>
<td>-0.001</td>
<td>0.103</td>
<td>0</td>
<td>0.11</td>
<td>0.079</td>
<td>0.047</td>
<td>0.019</td>
</tr>
<tr>
<td>(a_{\rho}^2)</td>
<td>0</td>
<td>0.053</td>
<td>-0.25</td>
<td>0</td>
<td>0.032</td>
<td>0</td>
<td>0.0006</td>
</tr>
<tr>
<td>(a_{\omega}^0)</td>
<td>0</td>
<td>-0.160</td>
<td>-0.23</td>
<td>-0.22</td>
<td>-0.073</td>
<td>0.059</td>
<td>-0.033</td>
</tr>
<tr>
<td>(a_{\omega}^1)</td>
<td>0.003</td>
<td>0.002</td>
<td>0</td>
<td>0.22</td>
<td>0.073</td>
<td>0.059</td>
<td>0.041</td>
</tr>
</tbody>
</table>
Theory and Implications:

Meson exchange picture (DDH - B. Desplanques, J. F. Donoghue, and B. R. Holstein)

For NPDGamma

Prediction:

\[ A_{PV}^H \approx -0.107 h_\pi^{\Delta I=1} \approx -5 \times 10^{-8} \]

Asymmetry result:

\[ A_{PV}^H = (-3.0 \pm 1.4 \pm 0.2) \times 10^{-8} \]

Leads to a determination of the coupling

\[ h_\pi^1 = (0.26 \pm 0.12 \pm 0.02) \times 10^{-6} \]

Note: LQCD

J. Wasem PRC C 85 (2012)
Result is being recalculated
Theory and Implications:


- Choose the lowest mass hadrons possible: pions
- Below pion production, can choose photons and nucleons (instead of gluons, which are in bound states) as the only dynamical degrees of freedom, non-relativistic

\[
\mathcal{L}_{PV} = - \left[ C^{(3S_1-1P_1)} (N^T \sigma^2 \bar{\tau}^2 N)^\dagger \cdot (N^T \sigma^2 \tau^2 \bar{D} N) \right.
+ C^{(1S_0-3P_0)}_{(\Delta I=0)} (N^T \sigma^2 \tau^2 \bar{\tau} N)^\dagger \left( N^T \sigma^2 \bar{\sigma} \cdot \tau^2 \bar{\tau}^\dagger \bar{D} N \right) \\
+ C^{(1S_0-3P_0)}_{(\Delta I=1)} \epsilon_{3ab} (N^T \sigma^2 \tau^2 \tau^a N)^\dagger \left( N^T \sigma^2 \bar{\sigma} \cdot \tau^2 \tau^b \bar{D} N \right) \\
+ C^{(1S_0-3P_0)}_{(\Delta I=2)} I_{ab} (N^T \sigma^2 \tau^2 \tau^a N)^\dagger \left( N^T \sigma^2 \bar{\sigma} \cdot \tau^2 \tau^b \bar{D} N \right) \\
+ C^{(3S_1-3P_1)} \epsilon_{ijk} (N^T \sigma^2 \sigma^i \tau^2 N)^\dagger \left( N^T \sigma^2 \sigma^k \tau^2 \tau^3 \bar{D}^i N \right) + \text{H.c.},
\]

- 5 LECs. Currently can only do calculations in few-body systems
Theory and Implications:


- Schindler et al. showed that the two terms are related to one another by a factor of 3 up to $\mathcal{O}(1/N_C^2)$ corrections. So we go from 5 to 4 LECs

$$C^{(3S_1-1P_1)} = 3 C^{(1S_0-3P_0)}_{\Delta I=0}$$

- In the large $N_C$ formalism (M. R. Schindler, R. P. Springer, and J. Vanasse, PRC 93 (2016) 025502)

\[
C^{(3S_1-1P_1)} \sim N_c, \\
C^{(1S_0-3P_0)}_{\Delta I=0} \sim N_c, \\
C^{(1S_0-3P_0)}_{\Delta I=1} \sim N_c^0 \sin^2 \theta_W, \\
C^{(1S_0-3P_0)}_{\Delta I=2} \sim N_c, \\
C^{(3S_1-3P_1)} \sim N_c^0 \sin^2 \theta_W.
\]

From NPDGamma

$$\frac{C^{3S_1-3P_1}}{C_0} = (-7.4 \pm 3.5 \pm 0.5) \times 10^{-11} \text{ MeV}^{-1}$$
Theory and Implications:

In the large $N_C$ formalism Gardner, Haxton, Holstein, ARNPS 67, 69 (2017)

$$V_{LO}^{PNC} (r) = \Lambda_0^{1S_0-3P_0} \left( \frac{1}{i} \frac{\nabla_A \delta^3(r)}{2m_N} \cdot (\sigma_1 - \sigma_2) - \frac{1}{i} \frac{\nabla_S \delta^3(r)}{2m_N} \cdot i(\sigma_1 \times \sigma_2) \right)$$

$$+ \Lambda_0^{3S_1-1P_1} \left( \frac{1}{i} \frac{\nabla_A \delta^3(r)}{2m_N} \cdot (\sigma_1 - \sigma_2) + \frac{1}{i} \frac{\nabla_S \delta^3(r)}{2m_N} \cdot i(\sigma_1 \times \sigma_2) \right)$$

$$+ \Lambda_1^{1S_0-3P_0} \left( \frac{1}{i} \frac{\nabla_A \delta^3(r)}{2m_N} \cdot (\sigma_1 - \sigma_2)(\tau_{1z} + \tau_{2z}) \right)$$

$$+ \Lambda_1^{3S_1-3P_1} \left( \frac{1}{i} \frac{\nabla_A \delta^3(r)}{2m_N} \cdot (\sigma_1 + \sigma_2)(\tau_{1z} - \tau_{2z}) \right)$$

$$+ \Lambda_2^{1S_0-3P_0} \left( \frac{1}{i} \frac{\nabla_A \delta^3(r)}{2m_N} \cdot (\sigma_1 - \sigma_2)(\tau_1 \otimes \tau_2)_{20} \right),$$

$$\Lambda_1^{3S_1-3P_1} \frac{1}{\sqrt{2}} g_{\pi NN} h_\pi^1 \left( \frac{m_\rho}{m_\pi} \right)^2 + g_\rho (h_\rho^1 - h_\rho^{1'}) - g_\omega h_\omega^1 + 2 G_6 \sim \sin^2 \theta_w$$

From NPDGamma

$$\Lambda_1^{3S_1-3P_1} = 810 \pm 380 \times 10^{-7}$$

$$h_\rho^0 \sim \sqrt{N_c}, \quad h_\rho^2 \sim \sqrt{N_c}$$

$$\frac{h_\rho^{1'}}{\sin^2 \theta_W} \lesssim \sqrt{N_c}, \quad \frac{h_\omega^1}{\sin^2 \theta_W} \sim \sqrt{N_c}$$

$$\frac{h_\rho^1}{\sin^2 \theta_W} \lesssim \frac{1}{\sqrt{N_c}}, \quad \frac{h_\pi^1}{\sin^2 \theta_W} \lesssim \frac{1}{\sqrt{N_c}}, \quad h_\omega^0 \sim \frac{1}{\sqrt{N_c}}$$
Summary:

- NPDGamma performed a high statistics measurement of the parity-violating gamma asymmetry in neutron proton capture.
- First time observed a non-zero value for the effect.
- Together with other few-body HWI measurements (p-p, p-\(\alpha\), n\(^3\)He, etc.) can constrain couplings in various theories that attempt to explain the lower energy hadronic weak interaction, in the strong-coupling regime.
- PRL with results will come out soon.

Thank you!