Parity-odd Gamma-ray Asymmetry in Polarized Neutron Capture on Hydrogen: The NPDGamma Experiment

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* for the NPDGamma collaboration
Traditional Theoretical Description

Meson-exchange Model

- One-meson-exchange potential
- Model dependent

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<th>Coupling</th>
<th>DDH reasonable range</th>
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<td>+4.6</td>
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<td>$h_\rho^0$</td>
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<td>$h_\omega^0$</td>
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<td>$h_\omega^1$</td>
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in units of $\times 10^{-7}$

$h_\rho^I$ is set to zero

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$\rho$ is set to zero

Motivation for NPDGamma and other few-nucleon experiments using neutrons

NPDGamma

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

- Dominated by a \( \Delta I=1 \) \( ^3S_1-^3P_1 \) parity-odd transition in the \( n-p \) system (\( \pi \)-exchange)
- \( h_{\pi}^I \) coupling can be isolated (heavy meson contributions very small)
- \( A_\gamma \approx -0.11 \ h_{\pi}^I \) (\( A_\gamma \approx -5 \times 10^{-8} \) using DDH “best value”)
- Also charged currents are suppressed for \( \Delta I=1 \), so potential to study neutral currents (not present in strangeness-changing HWI)
More Recent Theoretical Developments

Effective Field Theory (EFT)

\[ \Lambda_0^{1S_0-3P_0} = -g_\rho (2 + \chi_\rho) b_\rho^0 - g_\omega (2 + \chi_\omega) b_\omega^0 \]
\[ \Lambda_0^{3S_1-1P_1} = -3 g_\rho \chi_\rho b_\rho^0 + g_\omega \chi_\omega b_\omega^0 \]
\[ \Lambda_1^{1S_0-3P_0} = -g_\rho (2 + \chi_\rho) b_\rho^1 - g_\omega (2 + \chi_\omega) b_\omega^1 \]
\[ \Lambda_1^{3S_1-3P_1} = \sqrt{\frac{1}{2}} g_{\pi NN} \left( \frac{m_\rho}{m_\pi} \right)^2 b_\pi^1 + g_\rho (b_\rho^1 - b_\rho^{1'}) - g_\omega b_\omega^1 \]
\[ \Lambda_2^{1S_0-3P_0} = -g_\rho (2 + \chi_\rho) b_\rho^2 \]

Not dependent on a model
Consistent with the symmetries and degrees of freedom of QCD

Hierarchy of Parameters in Large-\(N_c\) Expansion

Two leading order (LO)

\[ \Lambda_0^+ \equiv \frac{3}{4} \Lambda_0^{3S_1-1P_1} + \frac{1}{4} \Lambda_0^{1S_0-3P_0} \sim N_c \]
\[ \Lambda_2^{1S_0-3P_0} \sim N_c \]

Three next-to-next-to leading order (\(N^2\text{LO}\))

\[ \Lambda_0^- \equiv \frac{1}{4} \Lambda_0^{3S_1-1P_1} - \frac{3}{4} \Lambda_0^{1S_0-3P_0} \sim 1/N_c \]
\[ \Lambda_1^{1S_0-3P_0} \sim \sin^2 \theta_w \]
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Isolated in \( \gamma \) polarization in \(^{18}\text{F} \) decay and NPDGamma
A Long Way Coming

First Stage at the Los Alamos Neutron Science Center (LANL)

- Letter of intent in 1998
- Construction of FP12
- Data taking at Los Alamos in 2006-2007
- Statistically limited result: $A_\gamma = [-1.2 \pm 2.1{\text{(stat.)}} \pm 0.2{\text{(syst.)}}] \times 10^{-7}$

Second Stage at the Spallation Neutron Source (ORNL)

- More intense neutron flux available
- Modifications to some components, installation and commissioning (2008-2012)
- $H_2$ data taking at the SNS (November 2012 - March 2014)
- Apparatus decommissioned in the Summer of 2014 and partially reinstalled again in 2016 for background asymmetry measurement (Aluminium inconsistencies)
- Final result to be announced at the CIPANP 2018 meeting
- Preliminary result: $A_\gamma = [-3.1 \pm 1.5{\text{(stat.)}} \pm 0.3{\text{(syst.)}}] \times 10^{-8}$
  [David Blyth, PhD thesis, Arizona State University (2017)]
The Experiment

@ FnPB
The Experiment

Neutron Flux

60 pulses per second
The Experiment

Neutron Flux

60 pulses per second
The Experiment

Neutron Flux

60 pulses per second
The Experiment

Neutron Flux

60 pulses per second

\[ 5.4 \times 10^8 \text{ n/cm}^2/s/MW \]
The Experiment

Neutron Flux

60 pulses per second

$5.4 \times 10^8 \text{ n/cm}^2\text{s/MW}$
The Experiment

Beam Monitors

- Ionization chamber with N$_2$ and some $^3$He (1-2%)
- About 1% of the neutrons are absorbed
- Number of neutron per pulse determined to a precision of 10$^{-4}$
The Experiment

Super Mirror (SM) Polarizer

- Magnetized Fe/Si SM
- Scattering length $b \pm p$, with $p$ the magnetic component

Fe/Si on boron float glass, no Gd

$m=3.0$ = critical angle
$n=45$ = channels
$R=9.6 \text{ m}$ = radius of curvature
$L=40 \text{ cm}$ = length
$d=0.3\text{ mm}$ = vane thickness

$T=25.8\%$ = transmission
$P=95.3\%$ = polarization
$N=2.2 \times 10^{10} \text{ n/s}$ = output flux (chopped)
The Experiment

Holding Magnetic Field and RF Spin Rotator

\[ B_0 = B_0 \hat{x} \]

\[ B_{RF} = B_1 \hat{z} \cos(\omega_L t) = B^+_{RF} + B^-_{RF} \]

\[ B^\pm_{RF} = \frac{B_1}{2} \left[ \hat{z} \cos(\pm \omega_L t) - \hat{y} \sin(\pm \omega_L t) \right] \]

\[ B_1 = \frac{n \pi \hbar}{\mu_n L t_{lof}} \]

The Experiment

LH$_2$ Target


$\phi_{\text{ortho-H}_2} < 0.0015$
The Experiment

LH$_2$ Target

Scattering cross section of neutrons on para-H$_2$

The Experiment

Gamma-ray Detector

- 48 CsI detectors
- 3π acceptance
- Current mode operation (5x10^7 gammas/pulse)
Extraction of $A_\gamma$

Corrections

- Neutron polarization ($P_n$)
- Spin Flipper efficiency ($\epsilon_{SR}$)
- Neutron depolarization ($C_d$)
- Background prompt gammas from materials other than hydrogen, which contribute in different fractions ($F_{BG}$). The main background contribution comes from Aluminum ($\sim 20\%$)
- Geometrical factors ($G_{UD}$ and $G_{LR}$), which include the finite structure of the beam, the effective solid angle of the detector, the spatial distribution of the material in question and other effects
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\[
A_{\gamma,\text{raw}} = \frac{1}{2} \left( \frac{Y_\theta^\uparrow - Y_{\theta+\pi}^\uparrow}{Y_\theta^\uparrow + Y_{\theta+\pi}^\uparrow} - \frac{Y_\theta^\downarrow - Y_{\theta+\pi}^\downarrow}{Y_\theta^\downarrow + Y_{\theta+\pi}^\downarrow} \right)
\]

\[
A_{\gamma} = P_n \epsilon_{SR} C_d \left( A_{\gamma,\text{raw}} - \sum_i \frac{A_{\gamma,i}}{P_{n,i} \epsilon_{SR,i} C_{d,i}} \right)
\]

\[
A_{\gamma,i} = A_{\gamma,i}^{PV} G_{UD,i} + A_{\gamma,i}^{PC} G_{LR,i}
\]

Monte Carlo
The Aluminium Background

- Capture of neutrons on $^{27}$Al produces $^{28}$Al$^*$
- Several (3-4) prompt gammas are emitted in the transition to $^{28}$Al g.s. (total energy of 7.8 MeV)
- Asymmetries (PV and PC) correlated to the neutron spin are expected in the emission of prompt gammas

- After the experiment was decommissioned and analysis was nearing completion, inconsistencies revealed the dedicated Aluminium target was not 6061 alloy
- The uncertainty goal of the experiment was not achievable without a new background subtraction strategy
- The experiment was partially mounted again in 2016 to perform measurements with background targets made out of the actual windows of the LH$_2$ target cryostat and other components
# Systematic Uncertainties (preliminary)

<table>
<thead>
<tr>
<th>False Asymmetries</th>
<th>Process</th>
<th>$A_\gamma$, PV unc.</th>
<th>$A_\gamma$, PC unc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stern-Gerlach</td>
<td>$\vec{\mu} \cdot \nabla B$</td>
<td>$8 \times 10^{-11}$</td>
<td>$9 \times 10^{-9}$</td>
</tr>
<tr>
<td>Mott-Schwinger</td>
<td>$\vec{n} + p \rightarrow \vec{n} + p$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\gamma$-ray circular polarization</td>
<td>$\vec{n} + p \rightarrow d + \gamma$</td>
<td>$7 \times 10^{-13}$</td>
<td></td>
</tr>
<tr>
<td>$\beta$ decay in flight</td>
<td>$\vec{n} \rightarrow e^- + p + \bar{\nu}$</td>
<td>$3 \times 10^{-11}$</td>
<td></td>
</tr>
<tr>
<td>Radiative $\beta$ decay</td>
<td>$\vec{n} \rightarrow e^- + p + \bar{\nu} + \gamma$</td>
<td>$2 \times 10^{-11}$</td>
<td></td>
</tr>
<tr>
<td>Capture on $^6$Li</td>
<td>$\vec{n} + ^6$ Li $\rightarrow ^7$ Li$^*$ $\rightarrow \alpha + t$</td>
<td>$2 \times 10^{-12}$</td>
<td>$&lt; 1 \times 10^{-9}$</td>
</tr>
<tr>
<td>$^{28}$Al $\beta$ decay</td>
<td>$\vec{n} + ^{27}$ Al $\rightarrow ^{28}$ Al $\rightarrow ^{28}$ Si $+ e^-$ alloy($\vec{n}, \gamma s$)</td>
<td>$&lt; 1 \times 10^{-9}$</td>
<td>$6 \times 10^{-9}$</td>
</tr>
<tr>
<td>Capture on Al alloy</td>
<td></td>
<td>$2 \times 10^{-9}$</td>
<td>$6 \times 10^{-10}$</td>
</tr>
<tr>
<td>Beam power modulation</td>
<td></td>
<td>$6 \times 10^{-10}$</td>
<td>$8 \times 10^{-10}$</td>
</tr>
<tr>
<td>Instrumental</td>
<td></td>
<td>$&lt; 1 \times 10^{-9}$</td>
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<th>Multiplicative Factors</th>
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<td>Geometric factors</td>
<td>Detector-dependent</td>
<td>3%</td>
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<td>Beam polarization</td>
<td>0.936(5)</td>
<td>0.5%</td>
</tr>
<tr>
<td>LH$_2$ SF efficiency</td>
<td>0.969(9)</td>
<td>0.9%</td>
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<tr>
<td>2016 SF efficiency</td>
<td>0.997(3)</td>
<td>0.3%</td>
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<tr>
<td>Beam depolarization</td>
<td>0.946 (avg. for LH$_2$)</td>
<td>1.4%</td>
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The New Landscape for NPDGamma

In the context of new theoretical descriptions and the hierarchization of parameters in large-$N_c$ expansion, NPDGamma, as well as gamma polarization from $^{18}$F, can provide a tests for this theory, measuring the two N$^2$LO parameters.

NPDGamma preliminary result is

$$A_\gamma = [-3.1 \pm 1.5\text{(stat.)} \pm 0.3\text{ (syst.)}] \times 10^{-8}$$


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Assuming $A_\gamma$ centered in zero and statistical uncertainty of $1.3 \times 10^{-8}$

Improvement Possibilities

• One either has to do this measurement on a pulsed neutron beam or at least pulse the beam in some way so that one can analyze the transient signals in the gamma detectors.

• We were not limited by systematics. In this experiment they were \( \sim 3 \times 10^{-9} \). This could be decreased to about \( 1 \times 10^{-9} \).

• It would be nice to try to find something better than Aluminum. A different Al alloy or one could try Titanium for the target vessel.

• Put the Lithium plastic inside the hydrogen target vessel?

• 4300 hours life time with average beam power about 1 MW at SNS for the LH\(_2\) running gave a statistical error of \( \sim 1.5 \times 10^{-8} \). Other potential beams/sources?
Summary

• The NPDGamma is about to conclude a long-time effort to measure the gamma asymmetry in the capture of polarized neutrons on Hydrogen, with in unprecedented precision ($\sim 1.5 \times 10^{-8}$ stat.)

• The process is dominated by a $\Delta I=1$ $^3S_1-^3P_1$ parity-odd transition ($\pi$-exchange) and therefore this experiment is appropriate to constrain the $h_\pi$ weak coupling (longest range interaction in meson-exchange models).

• The value observed by the NPDGamma collaboration is smaller than the value predicted in the DDH model by about a factor of 0.6.

• More recent theoretical approaches (EFT + large-$N_c$ expansion) have produced a hierarchization of LEC in LO (2) and $N^2$LO (3). The LEC related to the observable measured in NPDGamma, $A_{^3S_1-^3P_1}$, is a $N^2$LO.
The NPDGamma Collaboration
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