The NPDGamnna Experiment

\[ A_{\gamma} \approx \hat{s}_n \cdot \hat{k}_{\gamma} \]

- hadronic PV formalism
- experimental setup
- LANSCE \( ) \) SNS
Simple Level Diagram of \( n-p \) System; \( \bar{n} + p \rightarrow d + \gamma \) is primarily sensitive to the \( \Delta I = 1 \) component of the weak interaction

- Weak interaction mixes in \( P \) waves to the singlet and triplet \( S \)-waves in initial and final states.
- Parity conserving transition is \( M1 \).
- Parity violation arises from mixing in \( P \) states and interference of the \( E1 \) transitions.
- \( A_\gamma \) is coming from \( ^3S_1 \rightarrow ^3P_1 \) mixing and interference of \( E1-M1 \) transitions - \( \Delta I = 1 \) channel.
Meson exchange model

- DDH formalism:
  - 6+1 meson-nucleon coupling constants
  - pion channel dominated by neutral current ($Z^0$)
  - PV effects: interference between strong and weak vertex

\[ \frac{e^2}{M_W^2} \frac{g^2}{m_\pi^2} \approx 10^{-7} \]

EFT approach

\[ V_{\text{EFT}}^{\text{PV}}(r) = V_{-1,LR}^{\text{PV}}(r) + V_{1,MR}^{\text{PV}}(r) + V_{1,SR}^{\text{PV}}(r) \]

\[ V_{-1,LR}^{\text{PV}}(r) = \frac{2}{\Lambda_3^3} \tilde{C}_6 \tau_\times \sigma_+ \cdot y_{\pi^-}(r) \sim h_\pi^1 \]

\[ V_{1,MR}^{\text{PV}}(r) = \frac{2}{\Lambda_3^3} \left\{ \tilde{C}_2^{2\pi} \tau_+ \sigma_+ \cdot y_{2\pi}^L(r) + \tilde{C}_6^{2\pi} \tau_\times \sigma_+ \cdot \left[ (1 - 1/(3g_A^2)) y_{2\pi}^L(r) - 1/3 y_{2\pi}^H(r) \right] \right\} \sim h_\pi^1 \]

\[ V_{\#}^{\text{PV}}(r) = V_{1,SR}^{\text{PV}}(r) = \frac{2}{\Lambda_3^3} \left\{ \left[ C_1 + (C_2 + C_4) \tau_+^z + C_3 \tau_+ + C_5 \tau_{zz} \right] \sigma_- \cdot y_{m+}(r) \right\} \sim h_\omega^0 h_\omega^1 h_\rho^1 h_\rho^0 h_\rho^2 \]

\[ + \left[ \tilde{C}_1 + (\tilde{C}_2 + \tilde{C}_4) \tau_+^z + \tilde{C}_3 \tau_+ + \tilde{C}_5 \tau_{zz} \right] \sigma_\times \cdot y_{m-}(r) \]

\[ + (C_2 - C_4) \tau_-^z \sigma_+ \cdot y_{m+}(r) + \tilde{C}_6 \tau_\times \sigma_+ \cdot y_{m-}(r) \right\} \sim h_{\rho}^{1'} \sim h_\pi^1 \]


Liu, nucl-th/0609078
Danilov Parameters

PV NN-interaction

\[ \Delta L = 1 \quad \Delta J = 0 \quad \Delta (S + I) = 1 \]

Zero range limit:

\[
\begin{align*}
\lambda_t & \propto (C_1 - 3C_3) - (\tilde{C}_1 - 3\tilde{C}_3) \\
\lambda_s^0 & \propto (C_1 + C_3) + (\tilde{C}_1 + \tilde{C}_3) \\
\lambda_s^1 & \propto (C_2 + C_4) + (\tilde{C}_2 + \tilde{C}_4) \\
\lambda_s^2 & \propto -\sqrt{8/3}(C_5 + \tilde{C}_5) \\
\rho_t & \propto \frac{1}{2}(C_2 - C_4) + C_6 .
\end{align*}
\]

\[
\begin{align*}
^3S_1 & \rightarrow ^1P_1, \quad I = 0 \\
^1S_0 & \rightarrow ^3P_0, \quad I = 1 \\
^3S_1 & \rightarrow ^3P_1, \quad I = 1 \rightarrow 0
\end{align*}
\]

Why study hadronic PV?

- probe of atomic, nuclear, and hadronic systems
  - map out coupling constants
  - resolve $^{18}$F, $^{133}$Cs discrepancy
  - probe nuclear structure effects
  - anapole and qq contributions to PV electron scattering

- probe of QCD in low energy non-perturbative regime
  - confinement, many-body problem
  - sensitive to qq correlations
  - measure QCD modification of qqZ coupling

\[
\begin{array}{|c|c|c|c|c|c|}
\hline
& np A_\gamma & nD A_\gamma & np \phi & n\alpha \phi & pp A_z & p\alpha A_z \\
\hline
f_\pi & -0.11 & 0.92 & -3.12 & -0.97 & & -0.34 \\
\hline
h_\rho^0 & -0.50 & -0.23 & -0.32 & & 0.08 & 0.14 \\
\hline
h_\rho^1 & -0.001 & 0.10 & 0.11 & & 0.08 & 0.05 \\
\hline
h_\omega^0 & 0.05 & -0.25 & & & 0.03 \\
\hline
h_\omega^1 & -0.16 & -0.23 & -0.22 & & 0.07 & 0.06 \\
\hline
\hline
\end{array}
\]

n-capture \hspace{1cm} spin rotation \hspace{1cm} elastic scattering

\[ n + p \rightarrow d + \gamma \]

\[ A_\gamma = -0.11 f_\pi + -0.001 h_\rho^1 + -0.003 h_\omega^1 \]

Bowman
Why study hadronic PV?

<table>
<thead>
<tr>
<th>Observable</th>
<th>$m_N \rho_t$</th>
<th>$m_N \lambda_t$</th>
<th>$m_N \lambda_s^0$</th>
<th>$m_N \lambda_s^1$</th>
<th>$m_N \lambda_s^2/\sqrt{6}$</th>
<th>Expt. ($10^{-7}$)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A^{pp}_{zz}(k)$</td>
<td>0</td>
<td>0</td>
<td>$4k/m_N$</td>
<td>$4k/m_N$</td>
<td>$4k/m_N$</td>
<td>$-0.93 \pm 0.21$</td>
<td>(52)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$-1.50 \pm 0.22$</td>
<td>(53)</td>
</tr>
<tr>
<td>$A^{pp}_{z\alpha}$</td>
<td>-1.07</td>
<td>-0.54</td>
<td>-0.72</td>
<td>-0.48</td>
<td>0</td>
<td>$-3.3 \pm 0.9$</td>
<td>(96)</td>
</tr>
<tr>
<td>$P_\gamma$</td>
<td>0</td>
<td>0.63</td>
<td>-0.16</td>
<td>0</td>
<td>0.32</td>
<td>$1.8 \pm 1.8$</td>
<td>(63)</td>
</tr>
<tr>
<td>$A^d_\gamma$</td>
<td>-0.107</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$0.6 \pm 2.1$</td>
<td>(65)</td>
</tr>
<tr>
<td>$d\phi^{n\alpha}/dz$</td>
<td>-2.68</td>
<td>1.34</td>
<td>1.8</td>
<td>-1.2</td>
<td>0</td>
<td>$8 \pm 14$</td>
<td>(76)</td>
</tr>
<tr>
<td>$A^t_\gamma$</td>
<td>-3.56</td>
<td>-1.39</td>
<td>-0.95</td>
<td>-0.24</td>
<td>1.18</td>
<td>$42 \pm 38$</td>
<td>(97)</td>
</tr>
</tbody>
</table>


$A^{pp}_L(13.6 \text{ MeV}) \approx -0.45 m_N \lambda_s^{pp}$,

$A^{pp}_L(45 \text{ MeV}) \approx -0.78 m_N \lambda_s^{pp}$,

$\frac{d}{dz} \phi^{np}_{n}(\text{th.})|_{\text{rad/m}} \approx 0.30 \tilde{C}_6^\pi + 2.50 m_N \lambda_s^{np} - 0.57 m_N \lambda_t + 1.41 m_N \rho_t$,

$P^{np}_{\gamma}(\text{th.}) \approx -0.16 m_N \lambda_s^{np} + 0.67 m_N \lambda_t \approx A^{d}_{L}(1.32 \text{ keV}+)$,

$A^{np}_{\gamma}(\text{th.}) \approx -0.27 \tilde{C}_6^\pi - 0.093 m_N \rho_t$.

Liu, nucl-th/0609078
**Existing measurements**

- Light nuclei gamma transitions (circular polarized gammas)
- Nuclear anapole moment (from laser spectroscopy)
- Polarized proton scattering asymmetries

\[ \bar{a} = - \int d^3r \ r^2 \vec{j}(r) \]
Existing measurements

Neutron spin rotation

Medium with circular birefringence
Linear polarization circular components
Spin rotation

Graph showing
- \((h_p^0 + 0.6h_{\omega 0})\)
- \((h_{p}^0 + 0.1h_{\omega 0})\)
- \((h_{p}^0 + 0.6h_{\omega 0})\)

DDH "reasonable range"
- \(^{18}\text{F}\)
- \(^{19}\text{F}\)
- \(^{133}\text{Cs}\)
- \(^{205}\text{Tl}\)

p-p and nuclei

Graphs showing:
- Spin rotation
- Neutron spin rotation
- Circular components
Measurement of the Parity - Violating Gamma Asymmetry $A_\gamma$ in the Capture of Polarized Cold Neutrons by Para-Hydrogen

NPDGamma Collaboration

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Bhabha Atomic Research Center

P.N. Seo
North Carolina State University

E. Sharapov
Joint Institute of Nuclear Research
Overview of NPDG experiment

\[ A_\gamma = -0.11 \ f_\pi \ \frac{1}{4} \ 5 \ \times 10^{-8} \]

\[ \frac{d\sigma}{1 + P_n A_\gamma \cos \theta + P_n A_{PC} \sin \theta} \]

\[ \delta A = 1 \ \times 10^{-8} \quad \text{for} \quad N \ \frac{1}{4} \ 3 \ \times 10^{16} \ \text{events} \]
Overview of NPDG experiment
Pulsed neutron beam

\[ \sim 6 \times 10^8 \text{ cold neutrons per 20 Hz pulse at the end of the 20 m supermirror guide (largest pulsed neutron flux)} \]
Time-of-flight beam profile

Neutron current at the end of a 24.3 m long guide with 150 μA proton current
Time-of-flight beam profile

Beam Monitor Signal

beam monitor preamplifier output (volts) vs. time (ms)
Beam stability
$^3$He neutron polarizer

- $n + ^3$He $\rightarrow ^3$H + p cross section is highly spin-dependent
  \[ \sigma_{J=0} = 5333 \text{ b } \lambda/\lambda_0 \]
  \[ \sigma_{J=1} \frac{1}{4} 0 \]

- 10 G holding field determines the polarization angle
  \[ rG < 1 \text{ mG/cm} \text{ to avoid Stern-Gerlach steering} \]

Steps to polarize neutrons:

1. Optically pump Rb vapor with circular polarized laser
2. Polarize $^3$He atoms via spin-exchange collisions
3. Polarize $^3$He nuclei via the hyperfine interaction
4. Polarize neutrons by spin-dependent transmission

$P_3 = 57\%$
Neutron Beam Monitors

- $^3$He ion chambers
- measure transmission through $^3$He polarizer

\[ T_{\pm} = e^{-nl\sigma(1 \mp P_3)} \quad T_0 = e^{-nl\sigma} \]

\[ T \equiv \frac{1}{2}(T_+ + T_-) = T_0 \cosh(nl\sigma P_3) \]

\[ P \equiv \frac{(T_+ - T_-)}{(T_+ + T_-)} = \tanh(nl\sigma P_3) \]

\[ = \sqrt{1 - T_0^2/T^2} \]

beam monitor measurement
fit to $\tanh(n_3 dl P_3)$

neutron polarization (%)

neutron time of flight at 21 meters (ms)

$n_3 l \sim 4.9$ bar-cm
$P_3 \sim 45\%$
Beam Polarization

For the time window: 10ms to 30ms

Average neutron polarization for the Dec.06 run cycle with Dino
RF Spin Rotator

- **essential to reduce instrumental systematics**
  - spin sequence: $\uparrow \downarrow \uparrow \downarrow \uparrow \downarrow$ cancels drift to 2\textsuperscript{nd} order
  - danger: must isolate fields from detector
  - false asymmetries: additive & multiplicative
- **works by the same principle as NMR**
  - RF field resonant with Larmor frequency rotates spin
  - time dependent amplitude tuned to all energies
  - compact, no static field gradients
16L liquid para-hydrogen target

- 30 cm long → 1 interaction length
- 99.97% para → 1% depolarization
- pressurized to reduce bubbles
- SAFETY !!

\[ \Delta E = 15 \text{ meV} \]
Ortho-Para Conversion Cycle
CsI(Tl) Detector Array

- 4 rings of 12 detectors each
  - 15 x 15 x 15 cm³ each
- VPD’s insensitive to B field
- detection efficiency: 95%
- current-mode operation
  - 5 x 10⁷ gammas/pulse
  - counting statistics limited
  - optimized for asymmetry
Asymmetry Analysis

\[
A_{\text{raw,p}}(t_i) = \frac{\mathcal{Y}_{A_p,\uparrow}(t_i) - \mathcal{Y}_{B_p,\uparrow}(t_i)}{\mathcal{Y}_{A_p,\uparrow}(t_i) + \mathcal{Y}_{B_p,\uparrow}(t_i)}
\]

\[
= \frac{\left(A_{UD}^{j,p}(t_i) + \beta A_{UD,b}^{j,p}(t_i)\right) \langle G_{UD}(t_i) \rangle + \left(A_{LR}^{j,p}(t_i) + \beta A_{LR,b}^{j,p}(t_i)\right) \langle G_{LR}(t_i) \rangle}{\langle A_{\text{raw}}^{j,p} - A_{g}^{p}A_{f}(t_i) - A_{\text{noise}}^{p} \rangle}
\]

\[
= \frac{1}{E(t_i)P_n(t_i)S(t_i)}
\]

\[
\langle G_{UD} \rangle = \langle \cos \theta \rangle
\]
Systematic Uncertainties

- activation of materials, e.g. cryostat windows
- Stern-Gerlach steering in magnetic field gradients
- L-R asymmetries leaking into U-D angular distribution (np elastic, Mott-Schwinger...)
- scattering of circularly polarized gammas from magnetized iron (cave walls, floor...)

→ estimated and expected to be negligible (expt. design)

Statistical and Systematic Errors

- $A_Y$
- stat. err. (proposal)

Systematics, e.g:

- statistical and systematic errors
- expected gamma asymmetry
- integrated statistical error
- Mott-Schweiger scattering
- parity allowed NPDGamma
- NDT Gamma
- neutron beta decay

Time in ms

slide courtesy Mike Snow
Left-Right Asymmetries

- Parity conserving: \( s_n \cdot k_n \times k_\gamma \)
- Three processes lead to LR-asymmetry
  - P.C. \( n+p \rightarrow d+\gamma \) asymmetry \( 0.23 \times 10^{-8} \)
    - Csoto, Gibson, and Payne, PRC 56, 631 (1997)
  - elastic \( n+p \rightarrow n+p \) scattering \( 2 \times 10^{-8} \)
    - beam steered by analyzing power of LH\(_2\)
    - eg. \(^{12}\)C used in p,n polarimetry at higher energies
    - P-wave contribution vanishes as \( k^3 \) at low energy
  - Mott-Schwinger scattering \( \sim 10^{-8} \) at 2 MeV
    - interaction of neutron spin with Coulomb field of nucleus
    - electromagnetic \( \square \) spin-orbit interaction
    - analyzing power: \( 10^{-7} \) at 45 deg

\[
H^\prime_{ern} = \mu \cdot \vec{B} = g\tilde{s}_n \cdot (\vec{E} \times \vec{v}_n)
= -\frac{1}{m} V(r) \vec{L} \cdot \tilde{s}_n
\]
Detector position scans

\[ Y \propto 1 + A^{PV}_\gamma \cos \theta + A^{PC}_\gamma \sin \theta \]

UP-DOWN

\[ s_n \cdot k_\gamma \]

LEFT-RIGHT

\[ s_n \cdot k_n \times k_\gamma \]

\[ Y \propto \frac{1}{r^2} \]

\[ Y_{,x} = 0 \]

\[ \delta r \]

detector

\[ Y_{,y} = 0 \]

target

5 mm resolution \sim 1 \text{ deg}
Engineering Runs

![Graph showing A_0 sin(θ) cos(θ) + A_1 R sin(θ) with data points and error bars for Ring 1 to Ring 4.]

<table>
<thead>
<tr>
<th>Material</th>
<th>runs</th>
<th>A_γ (×10^{-6})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cl</td>
<td>53</td>
<td>-21 ± 1.6</td>
</tr>
<tr>
<td>Cu</td>
<td>17</td>
<td>-1 ± 3.0</td>
</tr>
<tr>
<td>B_4C</td>
<td>11</td>
<td>-1 ± 2.0</td>
</tr>
<tr>
<td>Al</td>
<td>1057</td>
<td>-0.00 ± 0.30</td>
</tr>
<tr>
<td>In</td>
<td>716</td>
<td>-0.68 ± 0.30</td>
</tr>
<tr>
<td>LEDs</td>
<td>2064</td>
<td>-0.0477 ± 0.0603</td>
</tr>
<tr>
<td>Noise</td>
<td>~</td>
<td>0.001</td>
</tr>
<tr>
<td>Physics:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mn</td>
<td>529</td>
<td>0.53 ± 0.78</td>
</tr>
<tr>
<td>V</td>
<td>2313</td>
<td>0.24 ± 0.45</td>
</tr>
<tr>
<td>Ti</td>
<td>2064</td>
<td>0.41 ± 0.36</td>
</tr>
<tr>
<td>Co</td>
<td>744</td>
<td>0.61 ± 0.31</td>
</tr>
<tr>
<td>Sc</td>
<td>2179</td>
<td>-1.04 ± 0.25</td>
</tr>
</tbody>
</table>

NPDGamma LED Asymmetry, runs 47675-47906 (31 hrs)

NPDGamma Pedestal Asymmetry, runs 47907-48002 (13 hrs)
NPDG Asymmetry (Stat. Error)

NPDGamma PV Asymmetry, runs 41550-44800, 45800-47623 (424 hr)

\[ \delta A_y = 2.1 \times 10^{-7} \]
Spallation Neutron Source (SNS)

Oak Ridge National Laboratory, Tennessee
Spallation Neutron Source (SNS)

- Spallation sources: LANL, SNS
- Pulsed -> TOF -> energy
- LH2 moderator: cold neutrons
- Thermal equilibrium in ~30 interactions
FnPB Cold Neutron Beamline

Improvements for SNS:
- curved beamline
- 2 choppers (+ 2 unused)
- new shielding hut
- SM bender polarizer
- new LH₂ vent line
- 60 Hz DAQ system
Timeline

- move NPDG to the SNS to achieve goal of $\delta A_\gamma = 1 \times 10^{-8}$
- possible follow-up experiment: $n + d \rightarrow t + \gamma$
Conclusion

• the NPDG experiment had a successful first phase at LANSCE

• project to determine $A_\gamma$ to $1 \times 10^{-8}$ at the SNS
  – possible follow-up experiment: $n + d \rightarrow t + \gamma$

• hadronic parity violation is a unique probe of short-distance nuclear interactions and QCD
  – neutron capture is an important key to mapping the long-range component of the hadronic weak interaction