NPDGamma Experiment:
from LANSCE to the SNS

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University of Kentucky

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Outline

- Hadronic Weak Interaction
  - DDH couplings
  - EFT couplings
  - Danilov parameters
  - existing data

- NPDGamma @ LANSCE
  - experimental setup
  - results

- NPDGamma @ SNS
  - upgrades
  - new sensitivity

- n-³He @ SNS
  - experimental setup
  - R&D at LANSCE

- NDTGamma
  - experimental setup
  - R&D at LANSCE

- Conclusion
Motivation

The Hadronic Weak Interaction is weak, but can be isolated due to parity violation.

- $W,Z$ range = 0.002 fm – probe short-range quark correlations in QCD nonperturbative regime
- Nuclear PV – test of nuclear structure models
- Test of EFT in $\Delta S = 0$ sector ($\Delta I = 1/2$ rule not understood)
- Physics input to PV electron scattering experiments
- $0\nu\beta\beta$ decay – matrix elements of 4-quark operators

$$\frac{e^2}{M_W^2} / \frac{g^2}{m_\pi^2} \approx 10^{-7}$$
EFT approach

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

\[ V_{-1,LR}^{\text{PV}}(r) = \frac{2}{\Lambda^3_\chi} \tilde{C}_6 \tau^z_\times \sigma_+ \cdot y_{\pi-}(r) \sim h^{1}_\pi \]

\[ V_{1,MR}^{\text{PV}}(r) = \frac{2}{\Lambda^3_\chi} \left\{ \tilde{C}_2 \tau^z_+ \sigma_\times \cdot y_{2\pi}^L(r) + \tilde{C}_6 \tau^z_\times \sigma_+ \cdot \left[ (1 - 1/(3 g^2_A)) y_{2\pi}^L(r) - 1/3 y_{2\pi}^H(r) \right] \right\} \]

\[ V_{1,SR}^{\text{PV}}(r) = V_{1,SR}^{\text{PV}}(r) = \frac{2}{\Lambda^3_\chi} \left\{ \left[ C_1 + (C_2 + C_4) \tau^z_+ + C_3 \tau_+ + C_5 \tau^{zz} \right] \sigma_- \cdot y_{m+}(r) \sim h^{0}_\omega \ h^{1}_\omega \ h^{1}_\rho \ h^{0}_\rho \ h^{2}_\rho \right. \]
\[ + \left[ \tilde{C}_1 + (\tilde{C}_2 + \tilde{C}_4) \tau^z_+ + \tilde{C}_3 \tau_+ + \tilde{C}_5 \tau^{zz} \right] \sigma_\times \cdot y_{m-}(r) \]
\[ + (C_2 - C_4) \tau^z_- \sigma_+ \cdot y_{m+}(r) + \tilde{C}_6 \tau^z_\times \sigma_+ \cdot y_{m-}(r) \right\}, \sim h^{1'}_\rho \sim h^{1}_\pi \]

C.-P. Liu, PRC 75, 065501 (2007)
Danilov parameters

- elastic NN scattering
- $S = 1/2 + 1/2 \quad I = 1/2 + 1/2$
- equivalent to EFT in very low energy limit (generally much more complicated)

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

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

C.-P. Liu, PRC 75, 065501 (2007)
# Pion-less EFT Couplings

<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>
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</thead>
<tbody>
<tr>
<td>$A_{2p}^p(k)$</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>$A_{2p}'$</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>$A_{\gamma}'$</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>$A_{\gamma}'$</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>


$$A_L^{np}(13.6 \text{ MeV}) \approx -0.45 m_N \lambda_s^{np},$$

$$A_L^{np}(45 \text{ MeV}) \approx -0.78 m_N \lambda_s^{np},$$

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

$$P_{\gamma}^{np}(\text{th.}) \approx -0.16 m_N \lambda_s^{np} + 0.57 m_N \lambda_t \approx A_L^{zd}(1.32 \text{ keV}^+),$$

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

Liu, PRC 75, 065501 (2007)

Hyun, Ando, Desplanques, nucl-th/0611018
Nuclear PV experiments

Existing data

- $^{18}$F asym. $\Delta l = 1$
- $^{19}$F, $^{41}$K, $^{175}$Lu, $^{181}$Ta asym.
- $^{133}$Cs, $^{205}$Tl anapole moment
- $^{21}$Ne (even-odd)

GOAL – resolve coupling constants from few-body PV experiments only
NPDGamma Collaboration


1Arizona State University
2Universidad Nacional Autonoma de Mexico
3University of Virginia
4Oak Ridge National Laboratory
5Thomas Jefferson National Laboratory
6National Institute of Standards and Technology
7University of Michigan, Ann Arbor
8University of Kentucky
9University of New Hampshire
10Los Alamos National Laboratory
11Indiana University
12University of Tennessee
13University of California at Berkeley
14University of Manitoba, Canada
15High Energy Accelerator Research Organization (KEK), Japan
16Hamilton College
17Paul Scherer Institute, Switzerland
18Spallation Neutron Source
19University of California at Davis
20TRIUMF, Canada
21Bhabha Atomic Research Center, India
22Duke University
23Joint Institute of Nuclear Research, Dubna, Russia
24University of Dayton
NPDGamma parity-violating observable $A_\gamma$
Spallation neutron source – cold moderator

- Spallation sources: LANL, SNS
- Pulsed -> TOF -> energy
- LH2 moderator: cold neutrons
- Thermal equilibrium in ~30 interactions
Frame overlap chopper

- Pulsed beam: time-of-flight determines neutron velocity, energy
- PV asymmetry is independent of energy
- Very slow neutrons can overlap with faster neutrons from later pulse
- Chopper rotor coated with Gd$_2$O$_3$ absorbs slow neutrons, opens window for faster ones
3He neutron polarizer

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

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

Steps to polarize neutrons:

1. Optically pump Rb vapor with circular polarized laser
2. Polarize $^3\text{He}$ atoms via spin-exchange collisions
3. Polarize $^3\text{He}$ 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

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

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

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

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

![Image of neutron beam monitors with equations and graph showing neutron polarization as a function of neutron time of flight at 21 meters (ms)].
Neutron Polarization

![Graph showing neutron polarization over time.](image-url)
RF spin rotator

- essential to reduce instrumental systematics
  - spin sequence: ↑↓↓↑ ↓↑↑↓ cancels drift to 2nd 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 for all energies
  - compact, no static field gradients
Beam stability
16L liquid para-hydrogen target

- 30 cm long $\rightarrow$ 1 interaction length
- 99.97% para $\rightarrow$ 1% depolarization
- super-cooled to reduce bubbles
- SAFETY !!

\[ \Delta E = 15 \text{ meV} \]
16L liquid para-hydrogen target
CsI(Tl) Detector Array

- 4 rings of 12 detectors each
  - 15 x 15 x 15 cm$^3$ each
- VPD’s insensitive to B field
- detection efficiency: 95%
- current-mode operation
  - 5 x 10$^7$ gammas/pulse
  - counting statistics limited
Asymmetry analysis

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

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

\[
\langle G_{UD} \rangle = \langle \cos \theta \rangle
\]
Engineering Runs

Calibration asymmetry

$A_\gamma = (-21.0 \pm 1.6) \times 10^{-6}$

<table>
<thead>
<tr>
<th>Material</th>
<th>yrk runs</th>
<th>$A_\gamma \times 10^{-6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cl</td>
<td>53</td>
<td>-21.0 ± 1.6</td>
</tr>
<tr>
<td>Cu</td>
<td>17</td>
<td>-1.0 ± 3.0</td>
</tr>
<tr>
<td>B$_4$C</td>
<td>11</td>
<td>-1.0 ± 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>2864</td>
<td>-0.0477 ± 0.0603</td>
</tr>
<tr>
<td>Noise</td>
<td></td>
<td>~ 0.001</td>
</tr>
<tr>
<td>Physics:</td>
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<td></td>
</tr>
<tr>
<td>Mn</td>
<td>1529</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>2864</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>
LH$_2$ run – Fall 2006

- Number of good runs
  5401 / 750 h

- Average delivered proton current
  89 A at 80 kW

- Average beam pol. (3He spin filter)
  55 +/- 7.5 %

- Spin-flip efficiency
  98 +/- 0.8%

- Para-hydrogen fraction in LH2 target
  99.98 %

- Beam depolarization in target
  2 %

- Data loss (cuts, bad events)
  ~1 %
Preliminary results

Total statistical error: \[ A_{\gamma,UD} = \left(-1.1 \pm 2.1\right) \times 10^{-7} \quad A_{\gamma,LR} = \left(-1.9 \pm 2.0\right) \times 10^{-7} \]

Total systematic error: a (very) conservative 10% mostly due to polarization
Preliminary results

\[ \bar{n} + p \rightarrow d + \gamma \]
Cavaignac, et al.
Phys. Lett. 67B (1977) 148

\[ ^{18}\text{F} \]
Evans, et al.; Bini et al.

\[ ^{133}\text{Cs} \]
Wood, et al.
Science 275 (1997) 1641
Flambaum and Murray

Compund Nuclei, Bowman et al.
LANL 2002

NPDGamma Proposed

\[ H_\pi^1 \quad [\text{ppm}] \]

DDH Range
Gain in sensitivity at the SNS

- 12.0 x brighter at the end of the SNS guide
- 4.1 x gain by new SM polarizer
- 6.5 x longer running time
- Higher duty factor at SNS
- Projected sensitivity: \( \delta A = 1 \times 10^{-8} \) in 10^{7}s
- Installation: currently underway
- Commissioning: mid 2009
- Data-taking: early 2010
Experimental setup at the FnPB

- Supermirror polarizer
- CsI Detector Array
- Liquid H₂ Target
- H₂ Vent Line
- H₂ Manifold Enclosure
- Magnetic Shielding
- Magnetic Field Coils
- FNPB guide
- Magnetic Field Coils
- Beam Stop
- H₂ Manifold Enclosure
NPDGamma cave and shielding
n-³He collaboration

- J.D. Bowman (PI), S.I. Penttilä  
  Oak Ridge National Laboratory
- M.T. Gericke (PI), S.A. Page, Mark McCrea  
  University of Manitoba
- C.B. Crawford (PI), Y. Shin, E. Martin  
  University of Kentucky
- C. Gillis, J. Mei  
  Indiana University
- J. Martin  
  University of Winnipeg
- V. Gudkov  
  University of South Carolina
- M. Viviani  
  INFN, Sezione di Pisa
- A. Klein, A. Salas-Bacci, A. Hayes, G. Hale  
  Los Alamos National Lab
- R. Mahurin  
  University of Tennessee
- P.-N. Seo  
  Triangle Universities Nuclear Lab
- L. Barron  
  Universidad Nacional Autónoma de México
n-$^3$He PV Asymmetry

\[ \vec{n} + ^3\text{He} \rightarrow p + t + 764 \text{ keV} \]

\[ S(I) : \quad \frac{1}{2} \left( \frac{1}{2} \right) + \frac{1}{2} \left( \frac{1}{2} \right) \rightarrow \frac{1}{2} \left( \frac{1}{2} \right) + \frac{1}{2} \left( \frac{1}{2} \right) \]

PV observables:

- \[ \sigma_n \cdot k_n \sim k_n \text{ very small for low-energy neutrons} \]
- \[ \sigma_n \cdot k_p, \sigma_n \cdot k_t \] - essentially the same asym.
- must discriminate between back-to-back proton-triton

- \[ ^4\text{He} J^{\pi} = 0^+ \text{ resonance} \]
  \[ ^1S_0(I = 0) \leftrightarrow ^3P_0(I = 0) \]

- sensitive to EFT coupling or DDH couplings \[ h_0^0, h_0^0 \]
  \[ \lambda_0^{I=0} \]

- \[ \sim 10\% \Delta I=1 \text{ contribution} \]
  (Gerry Hale, qualitative)

- \[ A \sim 3 \times 10^{-7} \] (M. Viviani, PISA)

Extraction of DDH couplings

<table>
<thead>
<tr>
<th></th>
<th>np A_γ</th>
<th>nD A_γ</th>
<th>n^3He A_p</th>
<th>np φ</th>
<th>nα φ</th>
<th>pp A_z</th>
<th>pα A_z</th>
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<tr>
<td>f_π</td>
<td>-0.11</td>
<td>0.92</td>
<td>-0.18</td>
<td>-3.12</td>
<td>-0.97</td>
<td>-0.34</td>
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<tr>
<td>h_ρ^0</td>
<td>-0.50</td>
<td>-0.14</td>
<td>-0.23</td>
<td>-0.32</td>
<td>0.08</td>
<td>0.14</td>
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<tr>
<td>h_ρ^1</td>
<td>-0.001</td>
<td>0.10</td>
<td>0.027</td>
<td>0.11</td>
<td>0.08</td>
<td>0.05</td>
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<tr>
<td>h_ρ^2</td>
<td>0.05</td>
<td>0.0012</td>
<td>-0.25</td>
<td>0.03</td>
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<tr>
<td>h_ω^0</td>
<td>-0.16</td>
<td>-0.13</td>
<td>-0.23</td>
<td>-0.22</td>
<td>0.07</td>
<td>0.06</td>
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<tr>
<td>h_ω^1</td>
<td>-0.003</td>
<td>-0.002</td>
<td>0.05</td>
<td>0.22</td>
<td>0.07</td>
<td>0.06</td>
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n-^3He: M. Viviani
(PISA)

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<th></th>
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<th>h_ρ^2</th>
<th>h_ω^0</th>
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<td>4.6</td>
<td>-11.4</td>
<td>-9.5</td>
<td>-1.9</td>
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<tr>
<td>range</td>
<td>0.0–11.4</td>
<td>-30.8–11.4</td>
<td>-11.7.6</td>
<td>-10.3–5.7</td>
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<tr>
<td></td>
<td>8.1%</td>
<td>15.8%</td>
<td>77.2%</td>
<td>36.4%</td>
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<tr>
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<td>5.8</td>
<td>14.0</td>
<td>64.7</td>
<td>36.4</td>
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<td>3.3</td>
<td>13.8</td>
<td>30.6</td>
<td>35.0</td>
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<td>3.1</td>
<td>13.4</td>
<td>30.3</td>
<td>34.0</td>
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<td>8.2</td>
<td>24.6</td>
<td>132.6</td>
<td>36.4</td>
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<tr>
<td></td>
<td>6.7</td>
<td>14.9</td>
<td>33.0</td>
<td>35.8</td>
</tr>
</tbody>
</table>

DDH Best Value

DDH Reasonable Range (%)

- present / DDH Range (%)
- present + npdγ
- present + n^3He
- present + npdγ + n^3He
- present few body + npdγ
- present few body + npdγ + n^3He
Experimental setup

- longitudinal holding field – suppressed PC asymmetry
- RF spin flipper – negligible spin-dependent neutron velocity
- $^3$He ion chamber – both target and detector
Solenoid holding field

- **uniformity requirements**
  - $\delta B \sim 0.3 \text{ G}$
  - $\mu \phi \delta B / 2E_n = 10^{-10} < \delta A_z$
  - $\theta_z \sim 0.1^{\pm} + \text{alignment of wires}$

- **preliminary design**
  - solenoid with compensation coils at end for uniformity
  - $\mu$-metal shield for residual earth’s field
  - 1010 steel flux return to prevent saturation of $\mu$-metal

- **design parameters**
  - 3 m length x 50 cm diameter
  - $B = 10 \text{ G}$ for spin flipper
  - $j = 9 \text{ A/cm}$ winding density
  - $I_0 = 1560 \text{ A}$ (or end-cap windings)

- **simulation using COMSOL**

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10 Gauss solenoid

1010 steel flux return

3 m £ 50 cm diam.

4 m £ 55 cm diam.

$I_0 = 1500+60 \text{ A turns}$

$j = 8+1 \text{ A/cm}$
Radio frequency spin rotator

- extension of design for NPDGamma

- new resonator for n-3He experiment
  - transverse horizontal RF B-field
  - longitudinal / transverse flipping
  - no fringe field - 100% efficiency
  - compact geometry - efficient
    - small diameter solenoid
  - matched to driver electronics for NPDGamma spin flipper

- prototype design
  - parasitic with similar design for nEDM guide field near cryostat
  - fabrication and testing at UKy – 2009

\[ \nabla^2 \Phi_M = 0 \quad \frac{\partial \Phi_M}{\partial n} = H_n \]
\[ \hat{n} \times H = j \quad -\nabla \Phi_M = H \]
\[ \nabla \Phi_M \cdot j = 0 \quad \Delta \Phi_M = \int j \cdot dl \]
**3He target / ion chamber**

- MC simulations of sensitivity to proton asymmetry
  - including wire correlations
  - $\delta A \sim 6 \mu$N
- tests at LANSCE FP12
  - fission chamber flux calibration
  - prototype drift chamber R&D
  - new beam monitors for SNS
- design of new ion chamber for NPDGamma, test at LANL

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M. Gericke, U. Manitoba

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**Diagram Description:**

- Neutron beam enters the target chamber.
- Protons and tritons are produced in the reaction.
- Ionization distribution is shown with proton and triton tracks.
- Energy and position distributions are displayed.

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UNIVERSITY OF KENTUCKY
NDPGamma vs. NDTGamma

- **capture cross section**
  - 1000x smaller in D$_2$O
  - $\sigma_H = .3326$ b, $\sigma_D = .000519$ b

- **neutron polarization**
  - para-hydrogen: no depolarization
  - D$_2$O: spin-flip scattering

- **expected asymmetry**
  - 20 times larger than NPDGamma
  - previous measurement (ILL)
  - goal: measure $\delta A_\gamma = 4\times10^{-7}$ at the SNS
Neutron Depolarization in D$_2$O

- Compton Polarimetry test run at LANSCE: 2008, 2009
NDT$_{\gamma}$ Target Design

- need extremely low background
- conflict with D$_2$ safety requirement of thick vacuum chamber
- must shield gammas from all windows
- D$_2$O ice needs cooled from outside shielding
- target thickness optimization: 13 cm

Indiana Univ.
Conclusion

- there is a viable program to measure the HWI with PV reactions in few-body systems
- $p-p$, $p-\alpha$ elastic scattering complete
- $n-\alpha$ spin rotation has taken data
- $n + p \rightarrow d + \gamma$ will run at the SNS in 2010
- $n + ^3He \rightarrow t + p$ will run at the SNS in 2011
- $n + p \rightarrow d + \gamma$ and others are in planning stage
- we will soon have significant tests of EFT in the $\Delta S = 0$ sector using few-body reactions only