Final Results from the n3He experiment:
Parity violation in cold neutron capture on $^3$He.

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The n\(^3\)He Observable

The experiment measures the parity violating directional asymmetry in the number of emitted protons, as a function of neutron spin, in the reaction

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

\[
\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_c \left(1 + A_{PV} \cos \theta_{\vec{s}_n\cdot\vec{k}_p} + A_{PC} \cos \phi_{\vec{s}_n\times\vec{k}_n\cdot\vec{k}_p}\right)
\]

\[ A_{PV}^{exp} = f_{exp} \left(A_{PV} \cos \theta_{\vec{s}_n\cdot\vec{k}_p} + A_{PC} \cos \phi_{\vec{s}_n\times\vec{k}_n\cdot\vec{k}_p}\right) \]

Proposal Goal:

- Measure the up-down PV spin asymmetry to \(~2\times10^{-8}\)
- Measure the left right PC spin asymmetry to \(~5\times10^{-8}\)
The $n^3$He Setup
**n³He Motivation**

Parity violating processes between nucleons can be used as a tool to study the hadronic weak interaction (HWI) as well as how it is modified by the strong interactions from the Standard Model prediction.

1. Study 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

2. Shed light on the puzzles in the ΔS=1 sector of the HWI
Hadronic Weak Interaction

Basic dynamic picture:

For the pion:

\[ H_{PC} = ig_{\pi NN} \int d^3x \bar{\psi}_i(x) \gamma^5 \psi_j(x) (\bar{\tau} \cdot \bar{\phi}(x)) \]

\[ H_{PNC} = \frac{h^1_\pi}{\sqrt{2}} \int d^3x' \bar{\psi}_i(x') \psi_j(x') (\bar{\tau} \times \bar{\phi}(x')) \]

\[ \langle f \mid V_{PNC} \mid i \rangle = \langle N_f N_f \mid H_{PC} \frac{1}{E_0 - H_0 + i\varepsilon} H_{PNC} \mid N_i N_i \rangle \]

\[ \frac{ig_{\pi NN} h^1_\pi}{\sqrt{32M}} \left[ \bar{\sigma}_1 \times \bar{\sigma}_2 \right] \left[ \bar{\sigma}_1 + \bar{\sigma}_2 \right] \cdot \left[ \vec{p}, \frac{e^{-mr}}{4\pi r} \right] \]

Weak \( \pi \)-Nucleon Coupling potential

Problem: We don’t know how to form nucleon wavefunctions based on fundamental degrees of freedom (except maybe now from LQCD - talk by Andre Walker-Loud) ...
n³He Effective Theory

- Full four-body calculation of strong scattering wave functions
- Evaluation of the weak matrix elements in terms of the DDH potential:

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

\[ A_{PV}^{(th.)} \approx (-9.4 \rightarrow 2.5) \times 10^{-8} \]

<table>
<thead>
<tr>
<th>DDH Weak Coupling</th>
<th>((A_{PV}^{P})\ n³He \rightarrow tp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a_{\pi}^{1})</td>
<td>-0.189</td>
</tr>
<tr>
<td>(a_{\rho}^{0})</td>
<td>-0.036</td>
</tr>
<tr>
<td>(a_{\rho}^{1})</td>
<td>0.019</td>
</tr>
<tr>
<td>(a_{\rho}^{2})</td>
<td>-0.0006</td>
</tr>
<tr>
<td>(a_{\omega}^{0})</td>
<td>-0.0334</td>
</tr>
<tr>
<td>(a_{\omega}^{1})</td>
<td>0.0413</td>
</tr>
</tbody>
</table>

n\textsuperscript{3}He Effective Theory

- Full four-body calculation of strong scattering wave functions
- Evaluation of the weak matrix elements in terms of $\chi$PT EFT:

$$A_{PV} = a_0 h_\pi^1 + a_1 C_1 + a_2 C_2 + a_3 C_3 + a_4 C_4 + a_5 C_5$$

$A_{PV}$ (th.) $\approx 1.7 \times 10^{-8}$, $\Lambda = 500$ MeV

$A_{PV}$ (th.) $\approx 3.5 \times 10^{-8}$, $\Lambda = 600$ MeV

<table>
<thead>
<tr>
<th>EFT coefficients</th>
<th>$\Lambda = 500$ MeV</th>
<th>$\Lambda = 600$ MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_0$</td>
<td>-0.1444</td>
<td>-0.1293</td>
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<tr>
<td>$a_1$</td>
<td>0.0061</td>
<td>0.0081</td>
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<tr>
<td>$a_2$</td>
<td>0.0226</td>
<td>0.0320</td>
</tr>
<tr>
<td>$a_3$</td>
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<tr>
<td>$a_4$</td>
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<td>-0.0156</td>
</tr>
<tr>
<td>$a_5$</td>
<td>-0.0005</td>
<td>-0.0001</td>
</tr>
</tbody>
</table>

n³He Effective Theory

- New approach to HWI: Large Nc expansion formalism

Susan Gardner, Wick Haxton, Barry Holstein:

Wick's talk next ...
The Fundamental Neutron Physics Beam (FnPB)

- 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
Measure the asymmetry in the number of outgoing protons in a $^3$He wire chamber as a function of neutron spin:

\[ \hat{\sigma}_n \cdot \vec{k}_T \quad \text{Directional PV asymmetry in the number of tritons} \]

\[ \hat{\sigma}_n \cdot \vec{k}_p \quad \text{Directional PV asymmetry in the number of protons} \]

- Active target
- Exploit the much larger track length of the protons
- Wires run vertical or horizontal

\[ n + ^3\text{He} \rightarrow p + t + 764 \text{ keV} \]
Chamber filled with Helium 3
Want to let protons range out
Proton range $r_p \sim 10$ cm
Neutron mfp should be $< r_p / 2$
Optimize wavelength range
Maximize neutron beam intensity
n³He Principle of Measurement

Split the $^3$He target volume into 144 equally spaced cells using wires:

The asymmetry is determined either from the yield of a single wire for two different spin states, or from the yield of two opposite (conjugate) wire pairs in the same spin state.

$$A_{raw} = \left( \frac{y^\uparrow - y^\downarrow}{y^\uparrow + y^\downarrow} \right)$$

From Mark McCrea Ph.D. thesis.
n³He Principle of Measurement

Target-Detector Chamber:

From Mark McCrea Ph.D. thesis.
The size of the wire frame was designed to cover the beam profile including beam divergence.
Each neutron pulse window signal yield is divided into 49 TOF bins of 0.32 ms width.

We usually integrate over the a TOF range within each pulse to get the wire yield.
Parity Violating measurement (Up-Down) setup:

Neutron polarization up or down

Beam direction into page

\[ A_{PV}^{exp} = f_{exp} \left( A_{PV} \cos \theta \hat{s}_n \cdot \hat{k}_p + A_{PC} \cos \phi \hat{s}_n \times \hat{k}_n \cdot \hat{k}_p \right) \]
Parity Conserving (Left-Right) measurement setup:

Neutron polarization up or down

Beam direction into page

\[ A_{PV}^{\text{exp}} = f_{\text{exp}} \left( A_{PV} \cos \theta \hat{s}_n \cdot \hat{k}_p + A_{PC} \cos \phi \frac{\hat{s}_n \times \hat{k}_n \cdot \hat{k}_p}{k_n} \right) \]
Comparisons between data and Simulation were used to verify the geometry effect of the chamber and the beam.

\[
\cos \theta \frac{s_n \cdot k_p}{G_{UD}}
\]

\[
\cos \phi \frac{s_n \times k_n \cdot k_p}{G_{LR}}
\]
Finite geometry correction factors:

\[ A_{PV}^{\text{exp}} = f_{\text{exp}} \left( A_{PV} G_{UD} + A_{PC} G_{LR} \right) \]
n³He Analysis

Detector wire yield:
\[
\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_c \left(1 + A_{pV} \cos \theta_{\bar{s}_n k_p} + A_{pC} \cos \phi_{\bar{s}_n \bar{k}_n \cdot k_p}\right)
\]

\[\Rightarrow Y^\pm = Y_0 \left(1 \pm \varepsilon P A_{pV} G_{UD} \pm \varepsilon P A_{pC} G_{LR}\right) \text{ per wire}\]

Raw asymmetry:
\[
A_{raw} = \left(\frac{Y^+ - Y^-}{Y^+ + Y^-}\right) \quad (\text{theoretically: } \varepsilon P A_{pC/pV} = \left(\frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}\right))
\]

Things that one has to take care off:

- Pedestals and possible electronic false asymmetries
  \[Y_i^\pm \rightarrow Y_i^\pm + p_i^\pm\]
- Beam fluctuations and associated false asymmetries
  \[Y_i^o \rightarrow g_i I^\pm\]
- Correlations between wires
Incorporating the pedestal and neutron beam intensity variations in the analysis:

**Single wire asymmetry (with normalized yields):**

\[
A_{i,\text{raw}} = \varepsilon PG_i A_{PV} + \frac{1}{2} \left( \frac{p_i^+}{Y_i^{o+}} - \frac{p_i^-}{Y_i^{o-}} \right)
\]

**Wire pair asymmetry (un-normalized yields):**

\[
A_{u-d,\text{raw}} = \frac{Y_u^- - Y_u^-}{Y_u^- + Y_u^-} - \frac{Y_d^- - Y_d^-}{Y_d^- + Y_d^-} \approx 2\varepsilon PG_u A_{PV} + \frac{\tilde{p}_u^+ - \tilde{p}_u^-}{Y_u^{o+} + Y_u^{o-}} - \frac{\tilde{p}_d^+ - \tilde{p}_d^-}{Y_d^{o+} + Y_d^{o-}}
\]

We can measure the beam intensity asymmetry and the pedestal asymmetry:

\[
A_{i,\text{ped}} = \frac{p_i^+ - p_i^-}{Y_i^{o+} + Y_i^{o-}} \quad A_{\text{Beam}} = \frac{Y_i^{o+} - Y_i^{o-}}{Y_i^{o+} + Y_i^{o-}} = \frac{I^+ - I^-}{I^+ + I^-}
\]
n³He Analysis

Incorporating the pedestal and neutron beam intensity variations in the analysis:

**Single wire asymmetry (with normalized yields):**

\[ A_{i,\text{raw}} = \varepsilon P G_i A_{PV} - \frac{\tilde{p}_i^+}{Y_i^0} A_{\text{Beam}} + A_{i,\text{ped}} + A_{i,\text{ped}} A_{\text{Beam}} + \mathcal{O}(A_{\text{Beam}}^2) + \ldots \]

\[ A_{i,\text{raw}} \approx \varepsilon P G_i A_{PV} - \frac{\tilde{p}_i^+}{Y_i^0} A_{\text{Beam}} + A_{i,\text{ped}} \]

**Wire pair asymmetry (un-normalized yields):**

\[ A_{u-d,\text{raw}} \approx 2\varepsilon P G_u A_{PV} + A_{u,\text{ped}} - A_{d,\text{ped}} \]

The wire pair asymmetry should be less sensitive to beam intensity variations.
n³He Analysis

Some data statistics:

- **PV asymmetry**
  
  31854 runs (~8 minute long)
  
  Number of good pulses: 690937760
  
  Number of pulses cut: 78335992 (10%)

- **PC asymmetry**

  1110 runs

  Number of good pulses: 22529520

  Number of pulses cut: 4468923 (17%)

Right: Example of asymmetry distributions for specific wires.
Corrected PV (UD) asymmetry:

Final UD Wire Pair Asymmetry

Unregressed

Regressed
Corrected PC (LR) asymmetry:

Final Wire Pair Asymmetry

Unregressed

Regressed
\[ A_{u+d,raw} = \frac{Y_u^- - Y_u^-}{Y_u^- + Y_u^-} + \frac{Y_d^- - Y_d^-}{Y_d^- + Y_d^-} \]

\[ A_{u+d,raw} \approx 2A_{Beam} + A_{u,ped} - A_{d,ped} \]
n$^3$He Analysis

Uncorrected PC (LR) asymmetry:

Compare with simulated form factor structure:
### n³He Systematic Effects / background

<table>
<thead>
<tr>
<th>Source</th>
<th>Comment</th>
<th>PV Correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>beta/gamma background</td>
<td>Simulated signal fraction &lt; 0.5%</td>
<td>&lt; $10^{-10}$</td>
</tr>
<tr>
<td>from capture</td>
<td>Small dE/dx (~ 100 times smaller)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Interaction prob. $10^{-4}$ relative to capture</td>
<td></td>
</tr>
<tr>
<td>In flight beta decay</td>
<td>(using NPDGamma estimate)</td>
<td>&lt; $10^{-11}$</td>
</tr>
<tr>
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<tr>
<td>Stern-Gerlach steering</td>
<td>2 mG/cm field grad., small chamber volume</td>
<td>&lt; $10^{-10}$</td>
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<tr>
<td>Chamber-field</td>
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</tr>
<tr>
<td>alignment</td>
<td>3 mrad field to vertical, 0-20 mrad frame twist (leakage of PC into PV)</td>
<td>~1 $\times$ 10^{-9}</td>
</tr>
<tr>
<td>Mott-Schwinger</td>
<td>next slide</td>
<td>&lt; $10^{-11}$</td>
</tr>
<tr>
<td>Polarization</td>
<td></td>
<td>0.936 ± 0.002</td>
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<tr>
<td>Spin-flip efficiency</td>
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<td>0.998 ± 0.001</td>
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<tr>
<td>Electronic false</td>
<td>Measured from beam-off runs every week</td>
<td>&lt; $10^{-9}$</td>
</tr>
<tr>
<td>asymmetry</td>
<td></td>
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</tbody>
</table>
**n^3\text{He Systematic Effects}**


E&M spin-orbit and strong elastic (parity conserving) left-right asymmetry

\[ H = V_s - \vec{\mu}_n \cdot \left( \vec{E} \times \vec{v}/c^2 \right) \]

Integration over energy and angle range.

Weighted by the Detector spectrum.

\[ \sigma_c = \frac{(5327 \pm 10)v_o}{\nu} \text{ barn} \]

\[ \sigma_s \approx 1.0 \pm 0.7 \text{ barn} \]
$n^3\text{He}$ Final Results

**PV asymmetry:**

Corrected asymmetry: $A_{PV} = 11.7 \pm 9.3\,(\text{stat}) \pm 1.0\,(\text{sys})$ ppb
PC asymmetry:

Corrected asymmetry: \( A_{PC} = -394 \pm 51 \text{(stat)} \pm 3.0 \text{(sys)} \text{ ppb} \)
n^3He Final Results

Constraints from this experiment:

\[-(h_0^0 + 0.7h_\omega^0)\]

\[h_\pi^1 - 0.12h_\rho^1 - 0.18h_\omega^1\]
Summary

• Proposal 2008
• Development and Construction 2010 - 2014
• Installation Fall 2014
• Commissioning Fall 2014 - January 2015
• Production Data Taking February - December 2015
• Analysis Completed
• Publications In progress

Thank you