The $n^{-3}\text{He}$ Experiment: A new era in Hadronic Parity Violation

Christopher Crawford, Univ. Kentucky, for the $n^{-3}\text{He}$ collaboration

Physics of Fundamental Symmetries and Interactions - PSI2019

PSI, Villigen, Switzerland 2019-10-22
Overview

• Hadronic Parity Violation
  – Hadronic Weak Interaction (HWI) formalisms
• $n$-$^3$He Experimental Setup
  – RF spin rotator, active target/ion chamber
• Data analysis
  – Results, global fit, next steps

$$A_p \approx \vec{s}_n \cdot \vec{k}_p$$

Is a parity odd pseudoscalar!
Motivation the studying the HWI

• Least understood weak interaction
  – EW: Quarks & Leptons, Semileptonic, Hadronic
  – Complicated by nuclear structure
  – Strongly suppressed by \( \frac{M_\pi^2}{M_W^2} \sim 10^{-7} \)
  – Unique PV signature

• Orthogonal probe of QCD structure
  – test of QCD structure in \( \Delta S = 0 \) sector
    \((\Delta I=1/2 \) rule not understood)\)
  – Study the NC in hadronic systems – forbidden by \( \Delta S = 1 \) by GIM mechanism
  – \( W,Z \) range = 0.002 fm – probe of short-range quark correlations in QCD nonperturbative regime
  – Nuclear and atomic PV test of nuclear structure models
  – physics input to PV electron scattering experiments
  – \( 0\nu\beta\beta \) decay – matrix elements of 4-quark operators
  – Same formalism used for Hadronic TRIV (complementary to EDM)
Relation between HPV and EDMs

• Tree level diagrams

Bowman, Gudkov, PRC 90, 065503 (2014)

\[
\frac{d\sigma_{TP}}{d\sigma_P} = k_0 \frac{g_0^0}{h_1^1} + k_1 \frac{\bar{g}_{\pi}^1}{h_1^1}
\]

- P even T even
- P odd T even
- P odd T odd

Fig. 2: “Reverse” Configuration
DDH Meson-exchange potential

PV meson exchange

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

isospin

\[
\begin{align*}
\Delta I &= 0 & f_\pi & \hbar_\rho^1 & \hbar_{\rho,0,1,2}^0 & \hbar_{\omega,0,1}^0 \\
\Delta I &= 1 & \frac{i}{2}(\mathbf{T}_1 \times \mathbf{T}_2)^3 & \frac{1}{2}(\mathbf{T}_1 \pm \mathbf{T}_2)^3 & \frac{1}{2}(\mathbf{T}_1 \pm \mathbf{T}_2)^3 \\
\Delta I &= 2 & \frac{1}{2\sqrt{6}}(3\mathbf{T}_1^3 \mathbf{T}_2^3 - \mathbf{T}_1 \cdot \mathbf{T}_2) & \\
J &= 0 & & & \\
J &= 1 & \quad & \text{(1)} \\
J &= 1 & \end{align*}
\]

range

\[
\begin{align*}
\mathbf{m}_\pi & \quad (\mathbf{\sigma}_1 + \mathbf{\sigma}_2) \left[ \frac{p_1-p_2}{2M}, \frac{e^{-m_\rho r}}{4\pi r} \right] \\
\mathbf{m}_\rho &= \mathbf{m}_\omega & (\mathbf{\sigma}_1 + \mathbf{\sigma}_2) & (\mathbf{\sigma}_1 \pm \mathbf{\sigma}_2) \left[ \frac{p_1-p_2}{2M}, \frac{e^{-m_\rho r}}{4\pi r} \right] \\
& & i(\mathbf{\sigma}_1 \times \mathbf{\sigma}_2) & \end{align*}
\]


1st Lattice QCD result of \( f_\pi \) !!
Few-body HWI PV Observables

- Long. analyzing power in elastic scattering
  - pp (15,45, 220 MeV), pd, pα
- Circular polarization, n + p → d + γ
- Gamma asymmetry, n + p → d + γ
  - Desplanques, NP A 335, 147 (1980)
  - PV mixing in final bound state
    + PV transition amplitudes
  - Dominated by long range $h_\pi^1$
- $n + ^3\text{He} \rightarrow p + ^3\text{H}$ reaction
  - 4-body wave functions + $P_{\text{odd}}$ operators
  - Sensitive to $h_\pi^1, h_\rho^0, h_\omega^0$
- $n + ^4\text{He}$ spin rotation
  - Observables are LINEAR in weak couplings

n-3He collaboration
Danilov parameters / EFT

- Elastic NN scattering
  S-P transition amplitudes
  \( S_z = \pm 1/2 \quad I_3 = \pm 1/2 \)
  antisymmetric in \( L, S, I \)
  conservation of \( J \)

- Equivalent to pion-less
  Effective Field Theory (EFT)
  in the low energy limit

<table>
<thead>
<tr>
<th>Coeff</th>
<th>DDH</th>
<th>Girlanda</th>
<th>Zhu</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Lambda_0^{1S_0-3P_1} )</td>
<td>(-g_\rho h^0_\rho(2+\chi_V) - g_\omega h^0_\omega(2+\chi_S))</td>
<td>(2(\mathcal{G}_1+\tilde{\mathcal{G}}_1))</td>
<td>(2(C_1+C_3))</td>
</tr>
<tr>
<td>( \Lambda_0^{3S_1-1P_1} )</td>
<td>(g_\omega h^0_\omega(\chi_S) - 3g_\rho h^0_\rho(2\chi_V))</td>
<td>(2(\mathcal{G}_1-\tilde{\mathcal{G}}_1))</td>
<td>(2(C_1-3\mathcal{C}_3))</td>
</tr>
<tr>
<td>( \Lambda_1^{1S_0-3P_1} )</td>
<td>(-g_\rho h^1_\rho(2+\chi_V) - g_\omega h^1_\omega(2+\chi_S))</td>
<td>(\mathcal{G}_2)</td>
<td>((\mathcal{C}_2+\mathcal{C}_1))</td>
</tr>
<tr>
<td>( \Lambda_1^{3S_1-1P_1} )</td>
<td>(\frac{1}{\sqrt{2}}g_{\pi N N}h^1_\pi\left(\frac{m_\rho}{m_\pi}\right)^2 + g_\rho(h^1_\rho-h^1_\pi) - g_\omega h^1_\omega)</td>
<td>(2\mathcal{G}_6)</td>
<td>((2\tilde{\mathcal{C}}_6+C_2))</td>
</tr>
<tr>
<td>( \Lambda_2^{1S_0-3P_1} )</td>
<td>(-g_\rho h^2_\rho(2+\chi_V))</td>
<td>(-2\sqrt{6}\mathcal{G}_5)</td>
<td>(2\sqrt{6}(\mathcal{C}_5+\tilde{\mathcal{C}}_5))</td>
</tr>
</tbody>
</table>

C.-P. Liu, P.R.C. 75, 065501 (2007)

Haxton & Holstein, P.P.N.P. 7, 1851 (2013)
Large $N_c$ expansion

- Two leading order amplitudes
  \[ \Lambda_0^+ = \frac{3}{4} \Lambda_0^3 S_1^{-1} P_1 + \frac{1}{4} \Lambda_0^1 S_0^{-3} P_0 \sim N_c \]
  \[ \Lambda_2^1 S_0^{-3} P_0 \sim N_c \sin^2 \theta_w \]

- Others suppressed by $N_c^2$
  \[ \Lambda_0^- = \frac{1}{4} \Lambda_0^3 S_1^{-1} P_1 - \frac{3}{4} \Lambda_0^1 S_0^{-3} P_0 \sim 1/N_c \]
  \[ \Lambda_1^1 S_0^{-3} P_0 \sim \sin^2 \theta_w \]
  \[ \Lambda_1^3 S_1^{-3} P_1 \sim \sin^2 \theta_w \]

- New paradigm for experiments
  - NPDG tests the smallness of $\Lambda_1^1 S_0^{-3} P_0$
  - $n^3\text{He}$ an orthogonal constraint on $\Lambda_0^+ \Lambda_0^1 S_0^{-3} P_0$.

Schindler, Springer, Vanasse, PRC 93, 025502 (2016)
n-^3^He Experimental setup

\[ \sigma_\pm = \sigma_0 (1 \pm A_{PC} \hat{k}_n \times \hat{\sigma}_n \cdot \hat{k}_p) \pm A_{PV} \]

\[ P_n \frac{A_{PC}}{G_{LR}} G_{UD} = \frac{Y_+ - Y_-}{Y_+ + Y_-} \]

- **FnPB cold neutron guide**
- **Supermirror polarizer**
- **3^He Beam Monitor**
- **RF spin rotator**
- **Collimator** (3^He target / ion chamber)
- **10 Gauss Holding field**
Transverse RF spin rotator

• Double-cosine-theta coil
  – Fringeless transverse RF field
  – Longitudinal OR transverse
  – Designed using scalar potential

Univ. Kentucky / Univ. Tennessee
3^He transmission polarimetry

Larmor Resonance

Rabi Oscillation

Polarization of 3^He Cell

Beam Polarization

Spin Flip Efficiency

\[ \langle P_n \rangle = 0.936 \pm 0.002 \]

\[ \langle \epsilon_{sf} \rangle = 0.998 \pm 0.001 \]
Active target / ion chamber

- $^3$He serves as both target and ionization gas
- 16 mCi tritium over life of experiment

University of Manitoba

- Macor frames with 9 x 16 sense wires, 8 x 17 HV wires
- 12” x 0.9 mm CF aluminum windows
- All aluminum chamber except for knife edges
Ion chamber yield from neutron beam

- Detector yield in individual wire cells
n\textsuperscript{-3}He in the FnPB
Asymmetry extraction

- PV physics asymmetry
  - Extracted from weighted average of single-wire spin asymmetries

\[
Y_{\pm} = Y_0 (1 \pm P A_p \langle \cos \theta \rangle)
\]

\[
A_p = \frac{1}{P \langle \cos \theta \rangle} \frac{Y_+ - Y_-}{Y_+ + Y_-}
\]

Geometry Factors \( G = \langle \cos \theta \rangle \)
Data selection

- cut on time-of-flight
  - chopper opening/closing, RFSF ramping

- cut on dropped pulses
  - require complete 600 pulse sequence + previous
Individual raw wire asymmetries

Example 600-pulse sequence asymmetry distributions.

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

**PC asymmetry**
- 1110 runs
- # good pulses: 22529520
- # pulses cut: 4468923 (17%)
Final Results

- $A_{PV} = 15.3 \pm 9.7 \text{ (stat)} \pm 2.5 \text{ (sys)} \text{ ppb}$ (goal: 20 ppb)
- $A_{PC} = -437 \pm 59 \text{ (stat)} \pm 4.3 \text{ (sys)} \text{ ppb}$
## Systematic Effects

### Corrections

<table>
<thead>
<tr>
<th>Source</th>
<th>Comment</th>
<th>PV Correction/uncert.</th>
<th>PC Correction/uncert.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame twist correction 0 to 20 mrad front to back of chamber</td>
<td>Additive correction due to measured twist in the frames. Implemented in the simulation geometry used to determine the geometry factors.</td>
<td>(~2 \times 10^{-9})</td>
<td>(~5 \times 10^{-9})</td>
</tr>
<tr>
<td>Residual 3He polarization</td>
<td>Additive correction estimate from thermal polarization and 3He removal</td>
<td>(&lt; 6 \times 10^{-11})</td>
<td>0</td>
</tr>
<tr>
<td>Beta/gamma background from capture</td>
<td>Additive correction, simulated signal fraction &lt; 0.5% Small dE/dx ((~100) times smaller) Ionization prob. (10^{-4}) relative to capture</td>
<td>(&lt; &lt; 10^{-10})</td>
<td>same</td>
</tr>
<tr>
<td>In flight beta decay</td>
<td>Additive correction (using NPDGamma estimate)</td>
<td>(&lt; &lt; 10^{-10})</td>
<td>same</td>
</tr>
<tr>
<td>Stern-Gerlach steering</td>
<td>Additive correction (2 mG/cm field grad., small chamber volume)</td>
<td>(&lt; 10^{-10})</td>
<td>same</td>
</tr>
<tr>
<td>Mott-Schwinger</td>
<td>Additive correction for left-right E&amp;M and Strong elastic scattering (published calculation)</td>
<td>(~6 \times 10^{-11})</td>
<td>(~3 \times 10^{-9})</td>
</tr>
<tr>
<td>Electronic false asymmetry</td>
<td>Additive correction, measured from beam-off runs every week</td>
<td>0</td>
<td>same</td>
</tr>
<tr>
<td>Polarization</td>
<td>Multiplicative correction from measured beam polarization.</td>
<td>(0.936 \pm 0.002)</td>
<td>same</td>
</tr>
<tr>
<td>Spin-flip efficiency</td>
<td>Multiplicative correction from measured spin flip efficiency</td>
<td>(0.998 \pm 0.001)</td>
<td>same</td>
</tr>
<tr>
<td><strong>Total Corrections (white fields only)</strong></td>
<td></td>
<td>(~2.1 \times 10^{-9})</td>
<td>(~8 \times 10^{-9})</td>
</tr>
</tbody>
</table>

### Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Comment</th>
<th>PV Correction/uncert.</th>
<th>PC Correction/uncert.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber-field alignment</td>
<td>3 mrad field to chamber vertical axis misalignment pitch, roll, yaw</td>
<td>(\pm 0.04 \times 10^{-9})</td>
<td>(1.25 \times 10^{-9})</td>
</tr>
<tr>
<td>Geometry Factor</td>
<td>Pressure and position uncertainty</td>
<td>(1.5 \times 10^{-9})</td>
<td>(3 \times 10^{-9})</td>
</tr>
<tr>
<td>Electronic false asymmetry</td>
<td>Measured from beam-off runs every week</td>
<td>(\pm 1.0 \times 10^{-9})</td>
<td>same</td>
</tr>
<tr>
<td><strong>Total systematic uncertainty (white fields only)</strong></td>
<td></td>
<td>(~2.54 \times 10^{-9})</td>
<td>(~4.25 \times 10^{-9})</td>
</tr>
</tbody>
</table>
Extraction of couplings

Global Fit to 10 Parity Violating Observables \([10^{-7}]\)

\[
\begin{align*}
\mathcal{f}_\pi &= 2.9 \pm 1.6 \\
\mathcal{f}_\rho^0 &= -14.1 \pm 11.7 \\
\mathcal{f}_\rho^1 &= 5.3 \pm 9.1 \\
\mathcal{f}_\rho^2 &= -21.5 \pm 27.9 \\
\mathcal{f}_\omega^0 &= 0.6 \pm 10.3 \\
\end{align*}
\]

\(\chi^2/\text{DOF} = 7.3471/5\)

(David Bowman)

DDH reasonable range:

\[
\begin{array}{ccc}
\text{min} & \text{'best'} & \text{max} \\
\mathcal{f}_\pi & 0 & 4.6 & 11.4 \\
\mathcal{f}_\rho^0 & -30.8 & -11.4 & 11.4 \\
\mathcal{f}_\rho^1 & -0.38 & -0.19 & 0 \\
\mathcal{f}_\rho^2 & -11 & -9.5 & 7.6 \\
\mathcal{f}_\omega^0 & -10.3 & -1.9 & 5.7 \\
\mathcal{f}_\omega^1 & -1.9 & -1.1 & -0.8 \\
\end{array}
\]

Conclusion

Hadronic Parity Violation

- We are close to a full complement of few-body HPV observables:
  - **old**: $pp$ (15, 45, 220 MeV), $p\alpha$
  - **new**: NPDGamma, $n^3He$
  - **upcoming**: $^4He$ NSR-III (NIST-NGC)
  - **future** possible measurements with low energy neutrons:
    - NPDGamma circular polarization
    - NDTGamma (counting mode)
- Tested newly proposed hierarchy in large $N_c$ limit
- An obtainable goal is to extract HWI couplings, AND to test the self-consistency of the HWI formalisms using only few-body observables

Thank you!
n-3He Collaboration

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  • Serpil Kucuker
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  • Chris Coppola
  • Irakli Garishvili
  • Eric Plemons
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  • Josh Hamblen
  • Caleb Wickersham
University of Virginia
  • S. Baessler
Sensitivities of few-body reactions

<table>
<thead>
<tr>
<th>Process</th>
<th>Observable</th>
<th>Expt ($\times 10^{-7}$)</th>
<th>$h_{\pi}^1$</th>
<th>$h_{\rho}^0$</th>
<th>$h_{\rho}^1$</th>
<th>$h_{\rho}^2$</th>
<th>$h_{\omega}^0$</th>
<th>$h_{\omega}^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{n} + p \rightarrow d + \gamma$</td>
<td>$A_\gamma \equiv \sigma_p \cdot K_\gamma$</td>
<td>$-1.2 \pm 2.1$</td>
<td>$-0.11$</td>
<td>$-0.001$</td>
<td>$-0.01$</td>
<td>$+0.004$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\bar{n} + d \rightarrow t + \gamma$</td>
<td>$A_\gamma \equiv \sigma_p \cdot K_\gamma$</td>
<td>$42 \pm 38$</td>
<td>$0.69$</td>
<td>$-0.33$</td>
<td>$0.09$</td>
<td>$0.05$</td>
<td>$-0.22$</td>
<td>$-0.05$</td>
</tr>
<tr>
<td>$\bar{n} + ^3\text{He} \rightarrow p + T$</td>
<td>$A_\gamma \equiv \sigma_p \cdot K_\gamma$</td>
<td>$-0.185$</td>
<td>$-0.038$</td>
<td>$0.023$</td>
<td>$-0.0011$</td>
<td>$-0.023$</td>
<td>$0.050$</td>
<td></td>
</tr>
<tr>
<td>$n + ^4\text{He} \rightarrow n + ^4\text{He}$</td>
<td>$\phi_{p\bar{p}}$</td>
<td>$1.7 \pm 0.2$</td>
<td>$-0.97$</td>
<td>$-0.32$</td>
<td>$0.11$</td>
<td>$-0.22$</td>
<td>$0.22$</td>
<td></td>
</tr>
<tr>
<td>$\bar{p} + p \rightarrow p + p$ (13.6 MeV)</td>
<td>$A_L \equiv \sigma_p \cdot K_\rho$</td>
<td>$-0.93 \pm 0.21$</td>
<td>$0.042$</td>
<td>$0.042$</td>
<td>$0.017$</td>
<td>$0.046$</td>
<td>$0.046$</td>
<td></td>
</tr>
<tr>
<td>$\bar{p} + p \rightarrow p + p$ (45 MeV)</td>
<td>$A_L \equiv \sigma_p \cdot K_\rho$</td>
<td>$-1.57 \pm 0.23$</td>
<td>$0.074$</td>
<td>$0.074$</td>
<td>$0.032$</td>
<td>$0.067$</td>
<td>$0.067$</td>
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<tr>
<td>$\bar{p} + p \rightarrow p + p$ (221 MeV)</td>
<td>$A_L \equiv \sigma_p \cdot K_\rho$</td>
<td>$0.84 \pm 0.34$</td>
<td>$-0.03$</td>
<td>$-0.03$</td>
<td>$-0.012$</td>
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<tr>
<td>$\bar{p} + ^4\text{He} \rightarrow p + ^4\text{He}$</td>
<td>$A_L$</td>
<td>$-3.34 \pm 0.93$</td>
<td>$-0.34$</td>
<td>$0.14$</td>
<td>$0.047$</td>
<td>$0.059$</td>
<td>$0.059$</td>
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<tr>
<td>$^{18}\text{F}$ decay</td>
<td>$P_{\gamma}$</td>
<td>$1200 \pm 3680$</td>
<td>$4385$</td>
<td>$-492$</td>
<td>$-833$</td>
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<tr>
<td>$^{19}\text{F}$ decay</td>
<td>$A_{\gamma}$</td>
<td>$-740 \pm 190$</td>
<td>$-94.2$</td>
<td>$34.1$</td>
<td>$-10.2$</td>
<td>$19.4$</td>
<td>$-16.9$</td>
<td></td>
</tr>
</tbody>
</table>

Adelberger, Haxton, 
P.R.C. 82, 044001 (2010)

Viviani (PISA), [n-3He]

n-\(^3\)He EFT calculation

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

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

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

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

<table>
<thead>
<tr>
<th>EFT coefficients</th>
<th>(\Lambda = 500 \text{ MeV})</th>
<th>(\Lambda = 600 \text{ MeV})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a_0)</td>
<td>-0.1444</td>
<td>-0.1293</td>
</tr>
<tr>
<td>(a_1)</td>
<td>0.0061</td>
<td>0.0081</td>
</tr>
<tr>
<td>(a_2)</td>
<td>0.0226</td>
<td>0.0320</td>
</tr>
<tr>
<td>(a_3)</td>
<td>-0.0199</td>
<td>-0.0161</td>
</tr>
<tr>
<td>(a_4)</td>
<td>-0.0174</td>
<td>-0.0156</td>
</tr>
<tr>
<td>(a_5)</td>
<td>-0.0005</td>
<td>-0.0001</td>
</tr>
</tbody>
</table>

FnPB supermirror polarizer

Transmission: 25.8%
Polarization: 95.3%
Output flux: $2.2 \times 10^{10}$ n/s

Simulations using McStas / ROOT ntuple

Readout electronics

- Ionization read out in current mode
  - 144 channels read out simultaneously
  - Low-noise I-V preamplifiers mounted on chamber
  - 24-bit, 100 kS/s, 48 channel Δ-Σ ADC FMC modules

Oak Ridge National Lab, Univ. Kentucky, Univ. Tennessee

Electronic Tests:
Instrumental false asymmetry measurements: $\delta A_{in} < 10^{-9}$
Covariance weighted averages

- Individual wire asymmetries are not independent
  - each proton/tritons ionizes gas in multiple cells in wire chamber

- Two identical methods of properly weighting for covariance
  - direct calculation: \( w_i = \text{Var}(A_i^p)^{-1} \rightarrow \sum_j \text{Cov}(A_i^p, A_j^p)^{-1} \)
  - diagonalization: \( S^T \cdot \text{Cov}(A_i^p, A_j^p) \cdot S = \text{diag}(\sigma_i) \)
    * asymmetry modes are statistically independent
Regression for Beam Asymmetry

- correlation between detector pair beam monitor asymmetries
- tested by beam asymmetry measured in individual wires
Corrected PV Wire Pair Asymmetries

![Graph showing unregressed and regressed data points across wire numbers from 0 to 140.](image)
Corrected PV Wire Pair Asymmetries

![Graph showing corrected PV wire pair asymmetries.](image)