Parity-odd Neutron Spin Rotation

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for the NSR collaboration

Physics of Fundamental Symmetries and Interactions
PSI, September 10, 2013
Why Hadronic Weak Interactions?

We know there is a quark-quark Weak interaction:

\[ A_\gamma(^{180}\text{Hf}^* \rightarrow ^{180}\text{Hf} + \gamma) = -(1.66 \pm 0.18) \times 10^{-2} \]
\[ A_h(\vec{n} + ^{139}\text{La}) = (9.55 \pm 0.35) \times 10^{-2} \]

…but we don’t fully understand observations because the low-energy (non-perturbative) limit of QCD controls how the HWI manifests itself. Need to study simpler systems:

Non-leptonic Flavor-changing

meson decays: EFT is effective, but, e.g., \( \Delta I = 1/2 \) rule not fully understood

baryon decays: \( \Delta S = 1 \) hyperon decay properties don’t follow from QCD symmetries

Evidence of non-trivial QCD ground state dynamical phenomena?

\[
\frac{M_{\text{weak}}}{M_{\text{strong}}} \sim \frac{e^2}{M_W^2} \frac{g^2}{M_\pi^2} \sim 10^{-7}
\]

Hallmark is use of PV to single out weak part of interaction

- \( \Delta S = 0 \) : is strange quark or light quark dynamics in general responsible for hyperon decay?
- Sensitive to NC effects at low energy, probes the QCD ground state
- NN and few-body systems
**SM Framework for HWI**

**Current-current form at low energy ($\Lambda_{\text{QCD}} < q < v$)**

$$H_{\text{weak}} = \frac{G_F}{\sqrt{2}} \left( J^{(C)}_\mu J^{(C)\mu} + \frac{1}{2} J^{(N)}_\mu J^{(N)\mu} \right) + \text{h.c.}$$

- $J^{(C)}_\mu = U_{ud} \bar{u} \gamma_\mu (1 + \gamma_5) d + U_{us} \bar{u} \gamma_\mu (1 + \gamma_5) s$
- $J^{(N)}_\mu = \bar{u} \gamma_\mu (1 + \gamma_5) u - \bar{d} \gamma_\mu (1 + \gamma_5) d - \bar{s} \gamma_\mu (1 + \gamma_5) s - 4 \sin^2 \theta_W J^{\text{em}}_\mu$

**Delta I Calculations**

- $\Delta I = 2 \rightarrow J^{(C)}_{I=1} J^{(C)}_{I=1}$
- $\Delta I = 1 \rightarrow J^{(C)}_{I=1/2} J^{(C)}_{I=1/2} + J^{(N)}_{I=1} J^{(N)}_{I=1}$
- $\Delta I = 0 \rightarrow J^{(C)}_{I=0} J^{(C)}_{I=0} + J^{(N)}_{I=0} J^{(N)}_{I=0} + J^{(N)}_{I=1} J^{(N)}_{I=1}$

**Calculation of the NN Weak Interaction ($q < \Lambda_{\text{QCD}}$)**

**DDH:** Model dependent, seven (non-elementary) meson-nucleon couplings: $h^1_{\pi}, h^{0,1,2}_{\rho}, h^{1'}_{\rho}, h^0_{\omega}$

**EFT:** Model-independent, QCD symmetries built in, perturbative expansion in $q/\Lambda$, pionful ($q \sim 140 \text{ MeV}$) theory has six parameters

$$\lambda^0_{s,1,2}, \lambda_t, \rho_t, \tilde{C}_6 \propto h^1_{\pi}$$

- $(I = 1)^+ \otimes L^+ \otimes (S = 0)^- \rightarrow \frac{1}{2} S_0, \ldots$
- $(I = 1)^+ \otimes L^- \otimes (S = 1)^+ \rightarrow 3 P_{0,1,2}, \ldots$
- $(I = 0)^- \otimes L^- \otimes (S = 0)^- \rightarrow \frac{1}{2} P_1, \ldots$
- $(I = 0)^- \otimes L^+ \otimes (S = 1)^+ \rightarrow 3 S_1, \ldots$

**Lattice QCD:** Gold standard

$v \sim 246 \text{ GeV}$

$\Lambda_{\text{HAD}} \sim 1 \text{ GeV}$

$\Lambda_{\text{QCD}} \sim 200 \text{ MeV}$

$m_\pi \sim 140 \text{ MeV}$
### PV Observables in terms of DDH Parameters

<table>
<thead>
<tr>
<th>Observables</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>
<th>Status</th>
</tr>
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<tbody>
<tr>
<td>( \phi_{PV}, n^4\text{He} )</td>
<td>-0.97</td>
<td>-0.32</td>
<td>0.11</td>
<td>0</td>
<td>-0.22</td>
<td>0.22</td>
<td>will run at NIST</td>
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<tr>
<td>( \sigma_n \cdot k_n )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( A_\gamma, npd\gamma )</td>
<td>-0.107</td>
<td>0</td>
<td>-0.001</td>
<td>0</td>
<td>0</td>
<td>0.004</td>
<td>running at SNS</td>
</tr>
<tr>
<td>( \sigma_n \cdot k_{\gamma} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( A_p, n^3\text{He} )</td>
<td>-0.189</td>
<td>-0.036</td>
<td>0.019</td>
<td>-0.001</td>
<td>-0.033</td>
<td>0.041</td>
<td>proposed at SNS</td>
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<tr>
<td>( \sigma_n \cdot k_p )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>( A_L, p\alpha )</td>
<td>-0.333</td>
<td>0.140</td>
<td>0.047</td>
<td>0</td>
<td>0.059</td>
<td>0.059</td>
<td>1982-1985</td>
</tr>
<tr>
<td>( \sigma_p \cdot k_p )</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>( A_L, pp )</td>
<td>0</td>
<td>0.074</td>
<td>0.074</td>
<td>0.030</td>
<td>0.067</td>
<td>0.067</td>
<td>1991-2003</td>
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<tr>
<td>( \sigma_p \cdot k_p )</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( (45 \text{ MeV}) )</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>( P_\gamma, ^{18}\text{F} )</td>
<td>4385</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1978-1987</td>
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<tr>
<td>( \cdot k_p )</td>
<td></td>
<td></td>
<td></td>
<td></td>
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- Recent experiments focus on simple NN and few-nucleon systems
- Many-body systems are also beginning to contribute via measurements of the nuclear anapole moment
The Current Experimental Landscape, DDH-Style

Weak NN iso-scalar, iso-vector coupling subspace

- $(-h_0^1 + 0.7 h^0_\omega)$

- $f_\pi - 0.12 h^1_\rho - 0.18 h^1_\omega$

Recent re-analysis of pp data by Haxton and Holstein presets a clearer picture… but where are the $\Delta I=1$ contributions?

Plot by J. Fry
PV Spin Rotation in $^4$He

\[ f(0) = f_{PC} + f_{PV}(\vec{\sigma}_n \cdot \vec{k}_n) \]

\[ \langle \vec{S}_{4\text{He}} \rangle = 0 \]

\[ \psi_n \sim \exp \left\{ i \left[ 1 + \frac{2\pi \rho f(0)}{k^2} \right] \vec{k}_0 \cdot \vec{z} \right\} \]

Passage through the $^4$He optical potential results in a helicity-dependent total phase

\[ \phi_{\pm} = k z \left( 1 + \frac{2\pi \rho f_{PC}}{k^2} \right) \pm 2\pi \rho z f_{PV} \]

which causes rotation of the neutron polarization

\[ |\uparrow\rangle = \frac{1}{\sqrt{2}} \left[ |+\rangle + |-\rangle \right] \rightarrow \frac{1}{\sqrt{2}} \left[ e^{i(\varphi_{PC} + \varphi_{PV})} |+\rangle + e^{i(\varphi_{PC} - \varphi_{PV})} |-\rangle \right] \]

\[ \varphi_{PC} \quad \varphi_{PV} \]

constant in the low-energy limit

DDH prediction is $[-16,12] \times 10^{-7}$ rad/m
PV Spin Rotation Measurement Technique

Two measurements produce a spin rotation angle $PA \sin \phi = \frac{I_+ - I_-}{I_+ + I_-}$

PV rotation $\sim 10^{-7}$ rad/m, but earth’s field would produce a rotation $\sim 10$ rad/m!
PV Spin Rotation Measurement Technique

\[ +B_y \]
\[ -B_y \]

\( \pi \)-coil tuned to produce 180° rotation around y-direction for average neutron wavelength

PV rotation rotation from stray B-fields

Spin rotation from stray fields as well as left/right field asymmetries cancel

\[ (\phi_L - \phi_R)_A - (\phi_L - \phi_R)_B = 4\phi_{PV} \]
Application of a horizontal B-field gradient causes output guide field to rotate by ±90° before reaching the vertical analyzer field.
NSR-III: NIST NG-C Beam Line

- NG-C beam line completed
- NG-C end station ready early 2014
- SM polarizer and analyzer arriving Oct.
The Neutron Spin Rotation Experiment

CN from NIST fundamental physics beam line NG-C
AFP spin flipper
supermirror polarizer

Application of a horizontal B-field gradient causes output guide field to rotate by ±90° before reaching the vertical analyzer field.
NSR-III Neutron Guides

- 10cm x 10cm, 1.25 and 2.0 non-magnetic supermirror (NiMo/T) neutron guides
- 1cm thick borofloat glass
- $M = 2.0$, $R > 90\%$
- depolarization probability per bounce $< 1\%$
The Neutron Spin Rotation Experiment

Application of a horizontal B-field gradient causes output guide field to rotate by ±90° before reaching the vertical analyzer field.
• New ionization chamber constructed and will be tested at Indiana University in October
• Based on the radially and longitudinally segmented detector used for NSR-II
The Neutron Spin Rotation Experiment

Application of a horizontal B-field gradient causes output guide field to rotate by $\pm 90^\circ$ before reaching the vertical analyzer field.
\[
\frac{d\phi_{PV}}{dz} = [1.7 \pm 9.1 \text{ (stat)} \pm 1.4 \text{ (sys)}] \times 10^{-7} \text{ rad/m}
\]
\[
\frac{d\phi_{PV}}{dz} = [1.7 \pm 9.1 \text{ (stat)} \pm 1.4 \text{ (sys)}] \times 10^{-7} \text{ rad/m}
\]

### NSR-II

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (rad/m)</th>
<th>Method</th>
<th>NSR-II</th>
<th>NSR-III</th>
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<tbody>
<tr>
<td>L 4He diamagnetism</td>
<td>$2 \times 10^{-9}$</td>
<td>calc</td>
<td>$2 \times 10^{-10}$</td>
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</tr>
<tr>
<td>L 4He optical potential</td>
<td>$3 \times 10^{-9}$</td>
<td>calc</td>
<td>$3 \times 10^{-10}$</td>
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<tr>
<td>Neutron E spectrum shift</td>
<td>$8 \times 10^{-9}$</td>
<td>calc</td>
<td>$8 \times 10^{-10}$</td>
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<tr>
<td>Refraction/reflection</td>
<td>$3 \times 10^{-10}$</td>
<td>calc</td>
<td>$3 \times 10^{-11}$</td>
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</tr>
<tr>
<td>Non-forward scattering</td>
<td>$2 \times 10^{-8}$</td>
<td>calc</td>
<td>$2 \times 10^{-9}$</td>
<td></td>
</tr>
<tr>
<td>Polarimeter non-uniformity</td>
<td>$1 \times 10^{-8}$</td>
<td>meas</td>
<td>$&lt;1 \times 10^{-8}$</td>
<td></td>
</tr>
<tr>
<td>B amplification</td>
<td>$&lt;4 \times 10^{-8}$</td>
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<td>$&lt;4 \times 10^{-9}$</td>
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<tr>
<td>B gradient amplification</td>
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<td>meas</td>
<td>$&lt;3 \times 10^{-9}$</td>
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<td>PA/target nonuniformity</td>
<td>$&lt;6 \times 10^{-8}$</td>
<td>meas</td>
<td>$&lt;6 \times 10^{-8}$</td>
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<tr>
<td>Total</td>
<td>$1.4 \times 10^{-7}$</td>
<td></td>
<td>$\leq 1 \times 10^{-7}$</td>
<td></td>
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NSR-II : 5cm x 5cm

NSR-III : 10cm x 10cm

- x 10 in neutron flux
- x 40 effective increase in polarized cold neutron flux from enhanced neutron transport
NSR-III Magnetic Shielding

- Three nested layers of μ metal shielding (two external and one internal); demonstrated to reduce B-field in target region to <10μG, a factor of ten improvement from NSR-II.
- In-situ de-gaussing, internal fluxgate magnetometers, trim coils, and active field cancelation supplement the passive shields.

![Magnetic field measurement graph](image)

Magnetic field is responsible for a majority of systematic effects...

Suppression of B field:

Magnetic shields, fluxgates, trim coils, active feedback

Isolating the PV signal: B shielding

There are three nested layers of magnetic shielding (metal) to reduce the residual magnetic fields in the target region to less than 10 μG. Changes in the residual magnetic fields are small and take place over time that is larger than a target measurement time. Shielding needed to be degaussed periodically since the shielding acquires a magnetization over time.
The expression for the differential cross-section is given as:

\[
\frac{d\phi_{PV}}{dz} = [1.7 \pm 9.1 \text{ (stat)} \pm 1.4 \text{ (sys)}] \times 10^{-7} \text{ rad/m}
\]

### Table: Uncertainty Sources

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### Footnotes:

- **NSR-II** : 5cm x 5cm
- **NSR-III** : 10cm x 10cm
- x 10 in neutron flux
- x 40 effective increase in polarized cold neutron flux from enhanced neutron transport
**NSR-III Cryogenics**

- Improved cryogenic design for reduced heat load, simpler assembly/disassembly, and more robust operation
- He re-liquefier removes necessity of LHe fills
- R&D on new LHe pump to reduce target change time
Re-Liquefier

- Cryomech pulse tube re-liquefier tested for three months of continuous operation
- Observed a liquefaction rate from warm gas of 12L/day
- Demonstrated ability to continuously maintain LHe volume comparable to spin rotation cryostat with little intervention under a heat load of ~600mW

R&D on New LHe Pump

- Bellows pump demonstrated equivalent of 100 days of data-taking in water
- Pumping rate in water is ten times larger than previous centrifugal pump
- Cryogenics tests are underway
There is vigorous interest in placing constraints on spin- and momentum-dependent mesoscopic exotic forces:

A New Limit on Possible Long-Range Parity-odd Interactions of the Neutron from Neutron Spin Rotation in Liquid $^4$He

H. Yan and W. M. Snow*  
Indiana University, Bloomington, Indiana 47408, USA  
Center for Exploration of Energy and Matter, Indiana University, Bloomington, IN 47408  
(Dated: November 23, 2012)

Improved Limits on Long-Range Parity-odd Interactions of the Neutron

E. G. Adelberger and T. A. Wagner  
Center for Experimental Nuclear Physics and Astrophysics,  
Box 554290, University of Washington, Seattle, WA 98195-4290  
(Dated: July 26, 2013)


Such interactions can be generated by a new light vector boson $X_\mu$ coupling to a fermion

$$\mathcal{L} = \bar{\psi}(g_V \gamma^\mu + g_A \gamma^\mu \gamma_5)\psi X_\mu$$

Examples of the interaction potentials generated by such a coupling include

$$V \sim g_V g_A \vec{\sigma} \cdot \vec{v}$$

$$V \sim g_A^2 \vec{\sigma} \cdot (\vec{v} \times \hat{r})$$
NSR Collaboration

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S. van Sciver
Pi-Coil design by Chris Crawford (University of Kentucky)

Input and output by Libertad Barrón Palos (Universidad Nacional Autónoma de México Instituto de Física)