Physics of NN parity violation

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1. Theoretical background/present experimental status
2. Neutron experiment in progress: NPDGamma
3. Proposed neutron experiments: (a) n+3He, (b) n+4He
4. Experimental bounds on “long-range” neutron parity violation
NN Weak Interaction: the nucleons are the “problem”

In the Standard Model, the structure of the quark-quark weak interaction is known from the electroweak sector.

However, quarks in both the initial and final states are confined by QCD.

QCD confines/correlates the quarks, thereby making perturbative calculation of the amplitude impossible.

Furthermore, the physical picture for the interaction mechanism above is wrong.
N-N Weak Interaction: Size and Mechanism

NN repulsive core $\rightarrow 1$ fm range for NN strong force

$$|N\rangle = |qqq\rangle + |qqqq\overline{q}\rangle + \cdots = \text{valence} + \text{sea quarks} + \text{gluons} + \cdots$$

NN strong force at low energy mediated by mesons

$$|m\rangle = |q\overline{q}\rangle + |q\overline{q}qq\overline{q}\rangle + \cdots$$

QCD possesses only vector quark-gluon couplings $\rightarrow$ conserves parity

Both W and Z exchange possess much smaller range [\sim 1/100 fm]

Relative strength of weak / strong amplitudes:

$$\left(\frac{e^2}{m_W^2}\right) / \left(\frac{g^2}{m^2}\right) \approx 10^{-6}$$

NN weak amplitudes first-order sensitive to $qq$ correlations

Weak interaction violates parity. Use parity violation to isolate the weak contribution to the NN interaction.
There is no quantitative theory for NN parity violation.

The reason why there is no theory is because such a theory would need to understand subnucleon-range quark-quark correlation effects and their long-range manifestation in a two nucleon system. We have no such understanding at present.

From all of our previous experience with strongly interacting many-body systems, we know that it is very important to understand the ground state of the theory and build excitations upon it. In QCD the first part is equivalent to understanding the mechanism of confinement and chiral symmetry breaking.

If the (strongly interacting) ground state is not boring it is typically highly correlated. The QCD ground state is not boring.

Lattice gauge theory? There is hope…

What to do in the meantime? Classify
NN Weak Interaction: Isospin Dependence

The quark-quark weak interaction at energies below the W and Z mass can be written in a current-current form, with contributions from charged and neutral currents

\[ M_{CC} = \frac{g^2}{2M_W^2} J_{\mu,CC}^\dagger J_{\mu,CC}^\mu; M_{NC} = \frac{g^2}{\cos^2\theta_W M_Z^2} J_{\mu,NC}^\dagger J_{\mu,NC}^\mu \]

\[ J_{\mu,CC}^\mu = u \frac{1}{2} \gamma^\mu (1 - \gamma^5) \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}; J_{\mu,NC}^\mu = \sum_{q=u,d} q^{-1} \gamma^\mu (c_V^q - c_A^q \gamma^5)q \]

Possible isospin changes from qq weak interactions:

Charged current: \( \Delta I=0,2 \) (~ \( V_{ud}^2 \)), \( \Delta I=1 \) (~ \( V_{us}^2 \))

Neutral current: \( \Delta I=0,1,2 \).

The \( \Delta I=1 \) terms comes only from the quark-quark neutral currents in the absence of strange quarks due to small size of \( V_{us} \)

These terms are about the same size, so any large differences in different isospin channels presumably would come from QCD dynamics.

Between electroweak scale and QCD scale one can perturbatively calculate RG evolution of the 4-quark operators; DONE at LO (Dai91) and for \( \Delta I=1 \) at NLO (Tiburzi 2012)
Theoretical Approaches to NN Weak Interaction

- **Kinematic**: 5 S→P transition amplitudes in elastic NN scattering (*Danilov*)

- **QCD effective field theory**: $\chi$ perturbation theory, incorporates low energy symmetries of QCD (Kaplan, Savage, Wise, *Liu*, Holstein, Musolf, Zhu, Phillips, Springer, Schindler, …)

- **Dynamical models**: meson exchange model for NN weak interaction (effect of $qq$ weak interactions parametrized by ~6 couplings), QCD sum rules, Skyrme models, chiral quark models, ADS/CFT-based models (*Desplanques*, Donoghue, Holstein, Meissner, Hwang, Gazit, …)

- **Standard Model; lattice gauge theory**: a target for exoscale computing (*Beane & Savage, Wasem*)

Strong NN amplitudes are now well-enough known to relate parity violation measurements in few body systems to the weak NN interaction (Pieper, Wiringa, Nollett, Schiavilla, Carlson, Paris, Kievsky, Viviani…).

It is also known that, as expected, P-odd NNN interactions are small compared to P-odd NN interactions (Schindler)
Meson Exchange/NN Weak Effective Field Theories

Meson exchange model: exchange of light mesons ($\pi$, $\rho$, $\omega$) with one strong interaction vertex and one weak interaction vertex (Desplanques, Donoghue, Holstein 1980)

Effective Field Theory approach: most general formulation for NN weak interaction consistent with QCD symmetries (Zhu et al 2005)


<table>
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<th>Partial wave transition</th>
<th>$I \leftrightarrow I'$</th>
<th>$\Delta I$</th>
<th>n-n</th>
<th>n-p</th>
<th>p-p</th>
<th>Hybrid EFT coupling</th>
<th>Pionless EFT coupling</th>
<th>Exchanged Meson</th>
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<td>$\rho$</td>
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Weak NN interaction: a target for petascale computing (S. Beane)

- High-impact NP from petascale computing (in Pflop-yrs)

1. The emergence of two-body forces from QCD (LRP,ch2,p31)
   Two-body interactions: $NN$, $YN$ and $YY$ ($\sim 1$)

2. Hadronic parity violation (LRP,ch2,p91)
   Parity-violating $\pi N$ coupling constant ($\sim 1$)

3. Deuteron axial charge (LRP,ch2,p91)
   Two-body with currents: axial charge, E&M properties etc. ($\sim 10$)

4. The hadron spectrum (LRP,ch2,p30) ★
   $\pi N$ phase shifts!, $\sigma$-terms, etc. ($\sim 1$)

★ more later in this session!
Lattice Calculations of NN Weak Amplitudes from Standard Model Now Becoming Possible


• Calculation of NN weak amplitudes is just now becoming possible using lattice gauge theory

• Result: $h_{\pi} = (1.1 \pm 0.5) \times 10^{-7}$

• Prospects for lattice calculation for $\Delta l=2$ from the lattice: next talk?
Haxton and Holstein 2013: reanalysis of pp parity violation

Corrected pp analysis for inconsistent treatment of strong NN couplings
Result: isoscalar linear combination goes up by \(~50\%\)
NIST Center for Neutron Research
Gaithersburg MD
Most intense reactor-based US slow neutron source, new beam #2 intensity in the world in 2014

Spallation Neutron Source
Oak Ridge National Lab (TN)
Most intense pulsed spallation neutron source in the world.
Now in operation

~X10 increase in polarized slow neutron flux relative to previous comparable beams.
The NPDGamma collaboration

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The NPDGamma experiment

\[ \frac{d\sigma}{d\Omega} \propto \frac{1}{4\pi} \left( 1 + A_\gamma \cos \theta \right) \]

\( A_\gamma \) – P-odd asymmetry in the gammas emitted from polarized slow neutron capture on protons.
GOAL: 10 ppb stat error on \( A_\gamma \), <1 ppb sys error

Helmholtz coils provide uniform vertical magnetic field.
Hadronic Weak Interaction Models

1. **DDH model** – uses valence quarks to calculate effective PV meson-nucleon coupling directly from SM via 7 weak meson coupling constants

\[
\begin{align*}
&f_\pi^1, h_\rho^0, h_\rho^1, h_\rho^1, h_\omega^0, h_\omega^1 \\
&f_\pi \approx 4.5 \times 10^{-7}
\end{align*}
\]

- Observables can be written as their combinations

\[
A = a_\pi f_\pi^1 + a_\rho h_\rho^0 + a_\rho h_\rho^1 + a_\omega h_\omega^0 + a_\omega h_\omega^1
\]

\[
A_\gamma \approx -0.11 f_\pi^1
\]

2. **Lattice QCD** [J. Wasem, PRC (2012)]

- Result: \( f_\pi = (1.1 \pm 0.5) \times 10^{-7} \)

3. **Effective Field Theory** (hybrid and pure)

   - Model-independent
     - Connect to 5 parity-odd S-P NN amplitudes

\[
A_{\gamma}^{\tilde{np}} \approx -0.27 \tilde{C}_6 - 0.09 m_N \rho_t \quad \text{hybrid}
\]

\[
A_{\gamma}^{np} \approx \tilde{C}^{3S1 \rightarrow 3P1} \quad \text{pionless}
\]
Pulsed neutron source important for control of systematic errors

Liquid parahydrogen target (16 liters), current mode CsI array

Goal at SNS: $1 \times 10^{-8}$ for $A_\gamma$ in $n+p\rightarrow D+\gamma$

STATUS: now taking data at SNS: statistical error of better than 20 ppb with data in hand.

Need to separately measure $P$-odd asymmetry from aluminum

Scheduled to end in ~mid-2014
NPDGamma Apparatus at SNS
H1 Asymmetries, after cuts

Det 0

Det 12

Det 24

Det 36
Ability of apparatus to measure parity violation confirmed using n capture on 35Cl (possesses ~20 ppm P-odd asymmetry)

CsI gamma array operated in current mode

Systematic errors bounded from several auxiliary measurements at LANSCE and SNS

Need to measure and correct for possible aluminum P-odd asymmetry
n-3He and n-4He Parity Violation: ~orthogonal to p-4He

The PV longitudinal analyzing power in p-4He scattering at 40 MeV has been measured:

$$A_L(p,4He) = [-3.3 + / -0.9] \times 10^{-7}$$

*Lang et al. PRC 34 1545 (1986)*

It was calculated in the DDH framework:

$$A_L(p,^4He) = -(0.34f_\pi - 0.06h_0^0 - 0.06h_1^0 - 0.14h_0^1 - 0.05h_1^1)$$

The calculation for the n-4He spin rotation (*isospin mirror system*):

$$\phi_{PV}(\bar{n},^4He) = -(0.97f_\pi + 0.22h_0^0 - 0.22h_1^0 + 0.32h_0^1 - 0.11h_1^1) \text{rad/m}$$

*Dmitriev et al. Phys Lett 125 1 (1983)*

The calculation for the n-3He correlation:

$$A_{PV}(\bar{n},^3He) = (0.19f_\pi - 0.023h_0^0 - 0.038h_0^1 + 0.023h_1^1 + 0.05h_1^1)$$

*Vivani et al. PRC 82 044001 (2010)*

These expressions are proportional (up to signs of coefficients) from isospin. Also n-3He and n-4He observables constrain a similar linear combination of amplitudes. This makes n-3He/n-4He and p-4He combination more powerful in constraining weak NN
Constraints from n-3He and n-4He experiments
n-\textsuperscript{3}He PV Asymmetry

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

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

PV observables:

\[ \sigma_n \cdot k_n \sim k_n \text{ very small for low-energy neutrons} \]

\[ \begin{array}{c}
\sigma_n \cdot k_p \\
\sigma_n \cdot k_t
\end{array} \]

- the same asymmetry
- must discriminate between back-to-back proton-triton

\[ N = N_0 \frac{d\Omega}{4\pi} (1 \pm P_n A_p \cos \theta) \]

\[ \text{Tilley, Weller, Hale, Nucl. Phys. A541, 1 (1992)} \]

\[ \begin{array}{c}
\text{20.578} \\
\text{19.815}
\end{array} \]

- sensitive to I=0 and I=1 couplings
- PV A \sim 1.1 \times 10^{-7} \text{ (Viviani)}
- PC A \sim 1.7 \times 10^{-6} \text{ (Hale)}

**GOAL:** \( \delta A = 1.3 \times 10^{-8} \)
Theoretical calculations

- **Gerry Hale (LANL)**
  - PC $A_y(90) = -1.7 \pm 0.3 \times 10^{-6}$
  - R matrix calculation of PC asymmetry, nuclear structure, and resonance properties

- **Vladimir Gudkov (USC)**
  - PV $A = -(1 - 4) \times 10^{-7}$
  - PV reaction theory
  - Gudkov, PRC 82, 065502 (2010)

- **Michele Viviani et al. (INFN Pisa)**
  - PV $A = -1.14 \times 10^{-7}$
  - Full 4-body calc. of strong scattering wave functions $J^\pi = 0^+, 0^-, 1^+, 1^-$
  - Eval. of weak $<J^-|V_{PV}|J^+>$ matrix elements in terms of DDH potential
  - Work in progress on calculation of EFT low energy coefficients
  - Viviani, Schiavilla, Girlanda, Kievsky, Marcucci, PRC 82, 044001 (2010)

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<th>$C_\pi^1$</th>
<th>$C_\rho^0$</th>
<th>$C_\rho^1$</th>
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<th>$C_\omega^0$</th>
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<td>AV18</td>
<td>-0.1892(86)</td>
<td>-0.0364(40)</td>
<td>+0.0193(9)</td>
<td>-0.0006(1)</td>
<td>-0.0334(29)</td>
<td>+0.0413(10)</td>
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<tr>
<td>AV18/UIX</td>
<td>-0.1853(150)</td>
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<td>+0.0230(18)</td>
<td>-0.0011(1)</td>
<td>-0.0231(56)</td>
<td>+0.0500(20)</td>
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$$a_z = h_\pi^1 C_\pi^1 + h_\rho^0 C_\rho^0 + h_\rho^1 C_\rho^1 + h_\rho^2 C_\rho^2 + h_\omega^0 C_\omega^0 + h_\omega^1 C_\omega^1$$
Experimental setup

- FnPB cold neutron guide
- Supermirror bender polarizer (transverse)
- 3He Beam Monitor
- Transition field (not shown)
- RF spin rotator
- 3He target / ion chamber
- 10 Gauss solenoid
- Shim coils (not shown)

FNPB (already exists)

- Longitudinal holding field – suppressed PC asymmetry
- RF spin flipper – negligible spin-dependent neutron velocity
- 3He ion chamber – both target and detector
- Record ionization signal in each wire; spin asymmetry \( \rightarrow A_p \)
n-^4^He Spin Rotation Collaboration

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DOE
A Parity-Violating Observable: Neutron Spin Rotation

transversely-polarized neutrons corkscrew due to the NN weak interaction

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

neutron index of refraction in target dependent on incident neutron helicity

\[ |+y\rangle = \frac{1}{\sqrt{2}}(|+z\rangle + |−z\rangle) \quad \rightarrow \quad \frac{1}{\sqrt{2}} \left( e^{-i(\phi_{PC}+\phi_{PNC})}|+z\rangle + e^{-i(\phi_{PC}-\phi_{PNC})}|−z\rangle \right) \]

PNC spin rotation angle is independent of incident neutron energy

\[ \phi_{PNC} = \phi_+ - \phi_- = 2\phi_{PNC} = 4\pi l \rho f_{PNC} \]
Parity Violation in Neutron Spin Rotation

Apparatus measures the horizontal component of neutron spin generated in the liquid target starting from a vertically-polarized beam.

\[ |\uparrow> = \frac{1}{\sqrt{2}} (|+> + |->) \rightarrow \frac{1}{\sqrt{2}} (e^{i\phi+} |+) + e^{i\phi-} |->) \]
• Nonmagnetic movement of liquid helium.

• Cryogenic target of 4K helium, volume~10 liters

Transversely polarized neutrons corkscrew due to weak interaction

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


PLAN: experiment to be repeated at NIST, \( \sim 1 \times 10^{-7} \text{ rad/m goal} \)
New interactions with ranges from millimeters to microns... “Who ordered that?”

1. Weakly-coupled, long-range interactions are a generic consequence of spontaneously broken continuous symmetries (Goldstone theorem)
2. Specific theoretical ideas (axions, extra dimensions for gravity) imply new interactions at ~mm-μm scales
3. Dimensional analysis: dark energy->100 microns

Not so many precision experiments have been conducted to search for new interactions over “mesoscopic” ranges, esp. spin-dependent ones

Comptes Rendus Physique 12, 755-778 (2011)
Example of a nonstandard P-odd interaction from spin 1 boson exchange:

[Dobrescu/Mocioiu 06, general construction of interaction between nonrelativistic fermions]

\[ V(\vec{\sigma}, \vec{r}, \vec{v}) = \frac{\hbar}{8\pi mc^2} g_A g_V \vec{\sigma} \cdot \vec{v} \frac{1}{r} e^{-\frac{r}{\lambda}} \]

- Induces an interaction between polarized and unpolarized matter
- Violates P symmetry
- Not very well constrained over “mesoscopic” ranges (millimeters to microns)
- Best investigated using a beam of polarized particles
Neutron Spin Rotation: A Parity-Odd Observable in Neutron Optics

$$f(0) = f_{\text{strong}} + f_{P-\text{odd}} (\vec{\sigma} \cdot \vec{p})$$

$$f_{P-\text{odd}} = g_A g_V \lambda^2$$

$$\phi_\pm = \phi_{\text{strong}} \pm \phi_{P-\text{odd}}$$

$$\frac{d\phi_{P-\text{odd}}}{dL} = 4g_A g_V \rho \lambda^2$$

Forward scattering amplitude of neutron in matter sensitive to all neutron-matter interactions

Parity violation gives helicity-dependent phase shift and therefore rotation of plane of polarization vector

An upper bound on $f_{P-\text{odd}}$ places a constraint on possible new P-odd interactions between nucleons over a broad set of distance scales
Constraints on exotic V-A interactions

Also: much stronger constraints now above ~1 cm from Eot_Wash+ other data [E. G. Adelberger and T. A. Wagner, PRD 88, 031101 (2013)]
NN parity violation: experiment summary

NPDGamma: on track to get ~10 ppb error on P-odd asymmetry

n-3He P-odd asymmetry and n-4He P-odd spin rotation: ~orthogonal to already-measured p-4He in isoscalar/isovector coupling space

Status:

n-3He parity violation experiment at SNS: “readiness review” in ~Jan. 2014
n-4He parity violation experiment at NIST: “readiness review” in ~Jan. 2014

γ-D P-odd photodisintegration: under analysis for HiGS2
Outlook for NN Weak Interaction Theory+Experiment

Only one NN weak EFT coupling is determined from existing experiments from p-p

Asymmetry measurement in n+p->D+gamma will fix a second NN weak EFT coupling( $^3S_1 \leftrightarrow ^3P_1, \Delta l=1$)

Asymmetry in n+p->D+gamma/weak isovector NN coupling a goal for lattice gauge theory/exoscale computing

Beams at NIST and SNS can be used to see parity violation in spin rotation experiments [~1E-7 rad/m statistical accuracy in n-4He] and in inelastic asymmetries and analyzing powers [~1E-8 in n+p->D+gamma and n+3He->3H+p]

Theoretical work is needed to extend weak NN calculations to few nucleon systems (n-D, n-3He, n-4He, p-4He), investigate region of EFT validity, and make use of existing data in p-4He and experiments planned in n-3He and n-4He
Simple Level Diagram of $n$-$p$ System

- 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 $^3S_1$ -$^3P_1$ mixing and interference of $E1$-$M1$ transitions in $\Delta I = 1$ channel.

$\widetilde{n} + p \rightarrow d + \gamma$ is primarily sensitive to the $\Delta I = 1$ component of the weak interaction.
Using isospin symmetry applied to NN elastic scattering we get the usual Pauli-allowed L,S,J combinations:

\[ I_{\text{tot}} = 1 \text{ (isospin-S):} \]

- Space-S (even L) \( \otimes \) spin-A (\( S_{\text{tot}} = 0 \)) \( \Rightarrow \) \( ^1S_0, ^1D_2, ^1G_4, \ldots \)
- or Space-A (odd L) \( \otimes \) spin-S (\( S_{\text{tot}} = 1 \)) \( \Rightarrow \) \( ^3P_{0,1,2}, ^3F_{2,3,4}, \ldots \)

\[ I_{\text{tot}} = 0 \text{ (isospin-A):} \]

- Space-A (odd L) \( \otimes \) spin-A (\( S_{\text{tot}} = 0 \)) \( \Rightarrow \) \( ^1P_1, ^1F_3, \ldots \)
- Space-S (even L) \( \otimes \) spin-S (\( S_{\text{tot}} = 1 \)) \( \Rightarrow \) \( ^3S_1, ^3D_{1,2,3}, ^3G_{3,4,5}, \ldots \)

If we use energies low enough that only S-waves are important for strong interaction, parity violation is dominated by S- P interference,

Then we have 5 independent NN parity-violating transition amplitudes:

\[ ^3S_1 \leftrightarrow ^1P_1(\Delta l=0, \text{ np}); \quad ^3S_1 \leftrightarrow ^3P_1(\Delta l=1, \text{ np}); \quad ^1S_0 \leftrightarrow ^3P_0(\Delta l=0,1,2; \text{ nn,pp,np}) \]
Spin-dependent macroscopic interactions between nonrelativistic fermions mediated by light bosons

\[ \mathcal{O}_1 = 1, \]
\[ \mathcal{O}_2 = \mathbf{\sigma} \cdot \mathbf{\sigma}', \]
\[ \mathcal{O}_3 = \frac{1}{m^2} (\mathbf{\sigma} \cdot \mathbf{q}) (\mathbf{\sigma}' \cdot \mathbf{q}) , \]
\[ \mathcal{O}_{4,5} = \frac{i}{2m^2} (\mathbf{\sigma} \pm \mathbf{\sigma}') \cdot (\mathbf{P} \times \mathbf{q}) , \]
\[ \mathcal{O}_{6,7} = \frac{i}{2m^2} \left[ (\mathbf{\sigma} \cdot \mathbf{P}) (\mathbf{\sigma}' \cdot \mathbf{q}) \pm (\mathbf{\sigma} \cdot \mathbf{q}) (\mathbf{\sigma}' \cdot \mathbf{P}) \right] , \]
\[ \mathcal{O}_8 = \frac{1}{m^2} (\mathbf{\sigma} \cdot \mathbf{P}) (\mathbf{\sigma}' \cdot \mathbf{P}) . \]

- 16 independent scalars can be formed: 8 P-even, 8 P-odd
- 15/16 depend on spin
- Traditional “fifth force” searches constrain \( O_1 \)

Parity-odd Nonrelativistic Potentials between Fermions

\[ \mathcal{V}_{9,10} = -\frac{1}{2mr^2} (\vec{\sigma} \pm \vec{\sigma}') \cdot \hat{r} \left( 1 - r \frac{d}{dr} \right) y(r) , \]

\[ \mathcal{V}_{11} = -\frac{1}{mr^2} (\vec{\sigma} \times \vec{\sigma}') \cdot \hat{r} \left( 1 - r \frac{d}{dr} \right) y(r) , \]

\[ \mathcal{V}_{12,13} = \frac{1}{2r} (\vec{\sigma} \pm \vec{\sigma}') \cdot \vec{v} y(r) , \]

\[ \mathcal{V}_{14} = \frac{1}{r} (\vec{\sigma} \times \vec{\sigma}') \cdot \vec{v} y(r) , \]

\[ \mathcal{V}_{15} = -\frac{3}{2m^2 r^3} \left\{ \left[ \vec{\sigma} \cdot (\vec{v} \times \hat{r}) \right] \left( \vec{\sigma}' \cdot \hat{r} \right) + \left( \vec{\sigma} \cdot \hat{r} \right) \left[ \vec{\sigma}' \cdot (\vec{v} \times \hat{r}) \right] \right\} \]

\[ \times \left( 1 - r \frac{d}{dr} + \frac{1}{3} r^2 \frac{d^2}{dr^2} \right) y(r) , \]

\[ \mathcal{V}_{16} = -\frac{1}{2mr^2} \left\{ \left[ \vec{\sigma} \cdot (\vec{v} \times \hat{r}) \right] (\vec{\sigma}' \cdot \vec{v}) + (\vec{\sigma} \cdot \vec{v}) \left[ \vec{\sigma}' \cdot (\vec{v} \times \hat{r}) \right] \right\} \left( 1 - r \frac{d}{dr} \right) y(r) \]

Comparison with \((p,^4\text{He})\) PV in EFT

In terms of pionless EFT couplings:

\[
\phi_{pv}(n^4\text{He}) = (0.85\lambda_s^{nn} - 0.43\lambda_s^{np} + 0.95\lambda_t - 1.89\rho_t) = (1.7 + / - 8.3) \times 10^{-7}
\]
\[
A_L(p^4\text{He}) = -0.48\lambda_s^{pp} - 0.24\lambda_s^{np} - 0.54\lambda_t - 1.07\rho_t = -(3.3 + / - 0.9) \times 10^{-7}
\]

\[
A_L(pp,13\text{MeV}) = -0.48\lambda_s^{pp} = -(0.9 + / - 0.2) \times 10^{-7}
\]


\[
P_\gamma(np) = 0.63\lambda_t - 0.16\lambda_s^{np} = (1.8 + / - 1.8) \times 10^{-7}
\]

The same constraint expressed in terms of the Danilov parameters:

\[1.95\lambda_t + 0.85\lambda_s^{nn} = (6.0 + / - 8.3) \times 10^{-7}\]
q-q Weak Interaction: Isospin Dependence

At energies below the $W^\pm$ and $Z^0$ mass, the q-q weak interaction can be written in a current-current form, with contributions from charged currents and neutral currents.

$$M_{CC} = \frac{g^2}{2M_w^2} J_{\mu,CC}^\dagger J_{CC}^\mu; M_{NC} = \frac{g^2}{\cos^2 \theta_w M_Z^2} J_{\mu,NC}^\dagger J_{NC}^\mu$$

$$J_{CC}^\mu = u \frac{1}{2} \gamma^\mu (1 - \gamma^5) \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}; J_{NC}^\mu = \sum_{q=u,d} \frac{1}{2} \gamma^\mu (c_V^q - c_A^q \gamma^5) q$$

Looks like neutral currents dominate $\Delta I=1$

Between electroweak scale and QCD scale one can perturbatively calculate RG evolution of the 4-quark operators

DONE at LO (Dai91) and for $\Delta I=1$ at NLO (Tiburzi 2012)

<table>
<thead>
<tr>
<th>possible isospin changes from q-q weak interactions</th>
<th>$\Delta I$</th>
</tr>
</thead>
<tbody>
<tr>
<td>charged current</td>
<td>$0, 2 : (\sim V_{ud}^2) \ 1 : (\sim V_{us}^2)$</td>
</tr>
<tr>
<td>neutral current</td>
<td>$0, 1, 2$</td>
</tr>
</tbody>
</table>
The PV longitudinal analyzing power in \( p^{-4}\text{He} \) scattering at 40 MeV (isospin mirror system!) has been measured:

\[
\phi_{PV}(\vec{n}, ^4\text{He}) = -(0.97 f_\pi + 0.22 h_\omega^0 - 0.22 h_\omega^1 + 0.32 h_\rho^0 - 0.11 h_\rho^1) \text{ rad/m}
\]

It was also calculated in the DDH framework:

\[
A_L(p, ^4\text{He}) = \left[-3.3 + / - 0.9\right] \times 10^{-7}
\]

\[
A_L(p, ^4\text{He}) = -(0.34 f_\pi - 0.06 h_\omega^0 - 0.06 h_\omega^1 - 0.14 h_\rho^0 - 0.05 h_\rho^1)
\]

Calculations are old and in DDH framework; need GFMC methods/conversion to EFT. Can EFT treatment even be applied to \( p^{-4}\text{He} \)? Is 40 MeV too high? New calculations in progress (Carlson, Wiringa, Nollett, Schiavilla, Pieper)
Transversely polarized neutrons corkscrew due to parity violation

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


Sets upper bound on any P-odd neutron coupling to protons, neutrons, electrons in 4He
If we stay with 5 cm x 5 cm beam, can reuse B shields, target, cryostat, ion chamber, motion control, and (maybe) coils

Pi-coil: measure/reconstruct?
Input/output guides: glass->supermirrors (IU $$$ exists)
New polarizer/analyzer (NIST?)
Target motion improved
Change location of cryo shield (IU $$$ exists)
Continuous liquid helium fill of cryostat/target (IU $$$ exists)
Better B shielding/compensation

Chris will discuss