Hadronic Weak Interaction

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David Bowman, ORNL
Early Study of the weak interaction and HWI

Question of Parity Conservation in Weak Interactions
T. D. Lee and C. N. Yang

“Experimental Tests of Parity Conservation in Beta Decay”, C. S. Wu and E. Ambler
P.R. 1957

“Observations of the Failure of Conservation of Parity in Meson Decays”
Garwin and Lederman P.R. 1957

Beta decay of polarized $^{60}\text{Co}$.

Fig. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.
In this pioneering experiment Haas et al. took advantage of CN enhancement of PV due to small level spacing. Their negative result was PV admixture $< 4 \times 10^{-5}$ in $^{113}$Cd.
Feynman and Gell-Mann predict that HWI is first order in $G_F$ in contrast to the Fermi theory. Phys. Rev. 109, 193 (1958)

$\beta$ decay

Fermi

$\beta$ Decay $\sim G \sim 10^{-7}$

HWI

$\text{HWI} \sim G^2 \sim 10^{-14}$
10 years later, Lobashov et al. Observe Circular Polarization in 482 KeV γ in $^{181}$Ta


$P_\gamma = (-6 \pm 1) \times 10^{-8}$

Brilliant experimental innovation: Current-Mode detection.
Most subsequent PV experiments used CM Jlab PV
Rate~2 $10^{12}$ Hz
HWI provided confirmation that the Standard Model (then Intermediate Vector Boson) picture was correct

- The HWI between nucleons produces small odd-parity admixtures in nuclear wave functions.
- In the standard-model picture, the admixtures are $10^7$ larger than in the Fermi picture.
- Lobashov result provided strong support for the Current-Current model of the weak interaction and IVB hypothesis; now a cornerstone of the Standard Model.
Quantitative study of HWI in nuclear states and scattering

Between 1967 and 1990 circular polarization (units of $10^{-7}$) was observed in

4 odd-proton nuclei

\[ ^{181}\text{Ta} \quad -52 \pm 5 \]
\[ ^{175}\text{Lu} \quad 550 \pm 50 \]
\[ ^{41}\text{K} \quad 200 \pm 40 \]
\[ ^{19}\text{F} \quad 730 \pm 150 \]

1 even-even nucleus

\[ ^{18}\text{F} \quad 0 \pm 4100 \]

5 measurements

Change in rate of progress
Apparatus for longitudinal asymmetry measurement

\[ A_L = \frac{+}{++} \]
Longitudinal cross-section asymmetries were observed in

P-P at 15 MeV       -.93 ± .20
P-P at 45 MeV       -1.57 ± .22
P-P at 220 MeV      +0.84 ± .34
P-α at 45 MeV       -3.34 ± .93

4 measurements
Anapole Current Distribution

anapole odd-parity operator mixes opposite-parity states into $^{133}$Cs nuclear ground state.

Parity Mixing Produces Intensity Changes in Hyperfine Intensities of $^{133}$Cs

Experiment: $A = 800 \pm 140$

10 Experiments Total
1980 Deplanques, Donoghue, and Holstein published meson-exchange model of HWI

The Compton wave length of a massive W in the nucleus is .002 Fm. Nucleons are separated by 1 Fm. Mesons bridge the gap. The HWI is expected to be more complex than the semi-leptonic WI.
The HWI potential between two nucleons involves their separation, spins, and isospins. The potential conserves $I_z$, but changes, $I$, the isospin of the pair.

6 $P_{vodd}$ operators: For example: $\pi$, $\Delta I=1$:

$$f(r_{12}) = \frac{\text{Exp}(m r_{12})}{4 r_{12}}$$

$$V(r_{12}) = f_{,1} \frac{i g_{NN}}{2\sqrt{2}} \frac{\text{Exp}(m r_{12})}{4 r_{12}} \left( \begin{array}{c} 1 \\ 2 \end{array} \right)^z \left( \begin{array}{c} 1 \\ 1+ \end{array} \right) \frac{P_1 P_2}{2M}, f(r_{12})$$

The subscripts on the couplings, $f_{\pi,1}$, indicate the meson exchanged and $\Delta I$

The ratio of the weak to strong potentials is

$$G_F \frac{P_F}{nuc \frac{M}{U_0}} 10^7$$
DDH Theory

- 6 couplings to be determined from experiment
- DDH give reasonable ranges based on hyperon decays and SU(6)$_w$. $h_{\rho,1}$ and $h_{\omega,1}$ are too small to influence asymmetries.
- There are 4 independent data sets.
- adopt the reasonable ranges as a working hypothesis

<table>
<thead>
<tr>
<th>Coupling</th>
<th>“Reasonable range”</th>
<th>“Best value”</th>
<th>DZ [28]</th>
<th>FCDH [29]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_\pi$</td>
<td>0.0$\leftrightarrow$11.4</td>
<td>4.6</td>
<td>1.1</td>
<td>2.7</td>
</tr>
<tr>
<td>$h_{\rho}^0$</td>
<td>$-30.8$</td>
<td>$-11.4$</td>
<td>$-8.4$</td>
<td>$-3.8$</td>
</tr>
<tr>
<td>$h_{\rho}^1$</td>
<td>$-0.38$</td>
<td>$-0.19$</td>
<td>0.4</td>
<td>$-0.4$</td>
</tr>
<tr>
<td>$h_{\rho}^2$</td>
<td>$-11.0$</td>
<td>$-9.5$</td>
<td>$-6.8$</td>
<td>$-6.8$</td>
</tr>
<tr>
<td>$h_{\sigma}^0$</td>
<td>$-10.3$</td>
<td>$-1.9$</td>
<td>$-3.8$</td>
<td>$-4.9$</td>
</tr>
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<td>$h_{\sigma}^1$</td>
<td>$-1.9$</td>
<td>$-1.1$</td>
<td>$-2.3$</td>
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</tr>
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Can the 10 data be described by 4 couplings?
Linear combinations of couplings for experiments

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<thead>
<tr>
<th>Coup/Exp</th>
<th>$f_{\pi,1}$</th>
<th>$f_{\rho,0}$</th>
<th>$f_{\rho,2}$</th>
<th>$f_{\omega,0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>odd p</td>
<td>5.5</td>
<td>-1.13</td>
<td>0</td>
<td>-0.91</td>
</tr>
<tr>
<td>$^{18}$F</td>
<td>5.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>p-p 45</td>
<td>0</td>
<td>0.095</td>
<td>0.040</td>
<td>0.090</td>
</tr>
<tr>
<td>p-p 220</td>
<td>0</td>
<td>-0.029</td>
<td>-0.012</td>
<td>0.009</td>
</tr>
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Fit Results $\chi^2 = 5.8/6$

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<th>Meson, $\Delta I$</th>
<th>Fit</th>
<th>DDH range</th>
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<td>$\pi, 1$</td>
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<td>$\omega, 0$</td>
<td>14 ± 9</td>
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The data are well described by 4 couplings. Agrees with Haxton and Holstein $h_{\rho, 2} = 0$

Non-zero $h_{\rho, 2}$ is important because QCD Calculations are most accurate for large $\Delta I$. 

2013)
Paradigm for TR violation. The description of low-energy hadronic phenomena involves TR-odd meson-nucleon couplings.
Meson nucleon couplings describe PV and PVT TV phenomena

Both P-T+ and P-T- involve sums over meson couplings. Need measure and learn how to calculate P-T+ and apply method to unknown P-T- couplings. (QCD matrix elements)
NPDG experiment will report results on $f_{\pi,1}$
n-\(^{3}\)He Experiment will report results

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

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

10 Gauss Holding field

FNPB cold neutron guide
Super-mirror polarizer

\(^{3}\)He Beam Monitor
RF spin rotator
Collimator \(^{3}\)He target / ion chamber

\(3\)He Experiment will report results
The goal of these experiments is to constrain DDH couplings by measuring asymmetries in exactly calculable few-body systems. Test DDH reasonable range hypothesis. Provide benchmark for QCD calculations of HWI couplings NPD\(_\gamma\) 2-body n-\(^3\)He 4-body Hyper-Spherical cord. Vivani

Other exactly calculable systems p-\(^2\)d A\(_L\) : Fadeyev and H-S n-\(\alpha\): Spin rotation Greens-function MC, H-S p-\(\alpha\) A\(_L\): H-S (experiment done)
PV in Compound-Nuclear Resonances and a new test of TR

TRIPLE apparatus for measuring PV asymmetries in CN resonances

TRIPLE Collaboration measured 80 $\sigma \cdot K$ asymmetries in 20 nuclei
Neutron transmission through In target

Absorption spectrum shows closely spaced strong L=0 and weak L=1 resonances
Level spacing of a few eV
Compound nucleus as a laboratory for Symmetry studies.

States in $^{139}$La+n system
PV in $^{139}$La .734 eV
$\Delta \sigma/\sigma = 0.097 \pm 0.005$. **$10^6$ amplification!**
Largest PV asymmetry in n-n interaction is $10^{-7}$. 
The compound-nuclear system as a laboratory for symmetry violation

- Neutron kinetic energy $T = E_x - E_t$. Neutron ToF provides a window on nuclear structure at excitation energies from 0 to few KeV above neutron threshold $\sim 7$ MeV.
- Small level spacings – large mixing.
- PV and TR are enhanced $(10^6)$ by mixing of strong (s-wave) resonances into weak opposite parity (p-wave) resonances.
- $\frac{\sigma_s}{\sigma_p} \sim \frac{1}{k}$
Theory of PV and TR in CN resonances

Low-energy neutrons propagate through matter according to a spin-dependent index of refraction. If the matter is polarized the index depends on $I$

$$n \sim A_0 + A_1 k + A_2 s \cdot I \cdot k$$

The second term is Podd and Teven. The third term is Podd and Todd
Near a CN resonance the longitudinal asymmetry shows a parity-violating resonance behavior

\[ \Delta \sigma_p = \frac{2\pi G^p_J}{k^2} \frac{v(\Gamma^n_s \Gamma^n_p)^{1/2}}{[s][p]} [(E - E_s)\Gamma_p + (E - E_p)\Gamma_s]. \]

If the medium is polarized the longitudinal asymmetry is time reversal violating

\[ \Delta \sigma_{p\bar{\gamma}} = -\frac{2\pi G^T_J}{k^2} \frac{w(\Gamma^n_s \Gamma^n_p(S))^{1/2}}{[s][p]} [(E - E_s)\Gamma_p + (E - E_p)\Gamma_s], \]

The amplification (kinematical factors) are identical for PV and PVTR!
False TR asymmetries caused by TRI interactions

Ideally, the spin is along $y$ such that $\sigma \cdot \mathbf{x} \cdot \mathbf{k}$ is maximal and $\sigma \cdot \mathbf{k}$ is zero. $\sigma$ is shown making a small angle, $+/-\theta$, in the $y$-$z$ plane. Because $\sigma \cdot \mathbf{k}$ is non-zero there is a PV asymmetry $\sim \sin(\theta)$. 
For neutron optics $K_i = K_f$. Reverse all magnetic fields and polarization. Rotation causes order of Interactions to reverse. If $A_2 = 0$, transmission is Unchanged.
Constraints on $\lambda$ from EDM’s

From $n$ EDM $^{(1)}$

$$g^{(0)}_\pi < 2.5 \cdot 10^{-10}$$

From $^{199}Hg$ EDM $^{(2)}$

$$g^{(1)}_\pi < 0.5 \cdot 10^{-10}$$

$$\frac{\mathcal{P}P}{\mathcal{P}^P} \sim 10^{-3}$$ from the current EDMs

$\equiv$ "discovery potential" $10^2$ (nucl) -- $10^4$ (nucl & "weak")

- M. Pospelov and A. Ritz (2005)
(Aggressive) Independent evaluations of experiments by TREX Collaboration and Shimizu at JPARK

Podd-Todd uncertainty $\sim 10^{-5}$
Discovery potential 100 time existing EDM measurements

The experiments are non-trivial
  Polarized La target (has been done at JPARC)
  Current-Mode detector
  Rotating Apparatus for False Asymmetries
  ...

Requires a multi-year effort at
  spallation source – neutron absorption on resonance
  reactor – spin-rotation at thermal energies
**DDH Meson-exchange potential**

- **PV meson exchange**
- **STRONG (PC)**
- **WEAK (PV)**

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


1st Lattice QCD result of \( f_\pi \) !!

- **Isospin**
  - \( \Delta I = 0 \)
  - \( \Delta I = 1 \)
  - \( \Delta I = 2 \)

- **Meson exchange**
  - **STRONG (PC)**
  - **WEAK (PV)**

- **1st Lattice QCD result of \( f_\pi \) !!**

\[
\begin{align*}
\frac{i}{2} (\tau_1 \times \tau_2)^3 & = \frac{1}{2} (\tau_1 \pm \tau_2)^3 \\
& \pm \frac{1}{2\sqrt{6}} (3\tau_1^3 \tau_2^3 - \tau_1 \cdot \tau_2)
\end{align*}
\]

**Range and “Best” Estimate of Weinberg–Salam Model Parameters**

- Amplitudes are in units of \( g_\pi = 3.8 \times 10^{-4} \).

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<th>“Best” value</th>
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<td>( f_\pi )</td>
<td>( 0 \to 30 )</td>
<td>12</td>
</tr>
<tr>
<td>( h_\rho^0 )</td>
<td>( 30 \to -81 )</td>
<td>-30</td>
</tr>
<tr>
<td>( h_\rho^1 )</td>
<td>( -1 \to 0 )</td>
<td>-0.5</td>
</tr>
<tr>
<td>( h_\phi^0 )</td>
<td>( -20 \to -29 )</td>
<td>-25</td>
</tr>
<tr>
<td>( h_\phi^1 )</td>
<td>( -15 \to -27 )</td>
<td>-5</td>
</tr>
<tr>
<td>( h_\omega^0 )</td>
<td>( -5 \to -2 )</td>
<td>-3</td>
</tr>
<tr>
<td>( h_\omega^1 )</td>
<td>( 0.4 \to 0.2 )</td>
<td>0.3</td>
</tr>
<tr>
<td>( h_\phi^1 )</td>
<td>( -20 \to -13 )</td>
<td>-13</td>
</tr>
</tbody>
</table>
PV occurs when S and P resonances mix

$^{115}\text{In}$ neutron resonances in TRIPLE transmission data:

P-wave: 86., 85., 78., 73., 66., 59, 41. ... (eV).

S-wave: 83., 81., 69., 63., 48., 46., 40. ... (eV)
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PV Neutron Spin Rotation

\[ \phi_{PV} = \phi_{PC} \]

\[ PNC = 2 \]

- PV rotation angle / unit length \((d\phi_{PV}/dx)\) approaches a finite limit for zero neutron energy:
  \[ d\phi_{PV}/dx \sim 10^{-6} \text{ rad/m} \] based on dimensional analysis
- \(d\phi_{PC}/dx\) (due to B field) can be much larger than \(d\phi_{PV}/dx\), and is \(v_n\) dependent