Hadronic Weak Interaction Theory

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First Summer School on Fundamental Neutron Physics
Univ. of Tennessee, Knoxville, TN
June 7, 2006
Outline

1 Introduction
   - The Standard Model
   - Why Difficult?
   - Why Important?
   - The Search Program

2 S–P Amps.
   - S-P Amplitudes
   - General Structure of S–P Amplitudes

3 Meson Exchange
   - Meson-Exchange Model
   - PV Meson-Nucleon Couplings
   - Current Status

4 EFT
   - EFT Formulation
   - Analysis

5 Outlook and Summary
   - Outlook
   - Summary
   - Further Reading

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Hadronic Weak Interaction Theory
Introduction

The Standard Model

Why Difficult?

Why Important?

The Search Program

S–P Amps.

S-P Amplitudes

General Structure of S–P Amplitudes

Meson Exchange

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The question of parity conservation in $\beta$ decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.
Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, Columbia University, New York, New York

AND


(Received January 15, 1957)
Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

Richard L. Garwin,† Leon M. Lederman, and Marcel Weinrich

Physics Department, Nevis Cyclotron Laboratories, Columbia University, Irvington-on-Hudson, New York, New York

(Received January 15, 1957)
Nuclear Emulsion Evidence for Parity Nonconservation in the Decay Chain
\[ \pi^+ \rightarrow \mu^+ \rightarrow e^{+*} \]

JEROME I. FRIEDMAN AND V. L. TELEGDI

Enrico Fermi Institute for Nuclear Studies, University of Chicago,
Chicago, Illinois

(Received January 17, 1957)
Parity in Nuclear Reactions*

Neil Tanner

Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California

(Received June 26, 1957)
PARITY NON-CONSERVATION IN THE GAMMA DECAY OF $^{181}$Ta

V. M. LOBASHOV, V. A. NAZARENKO, L. F. SAENKO, L. M. SMOTRITSKY and G. I. KHARKEVITCH
A. F. Ioffe Physico-Technical Institute, Leningrad, USSR

Received 7 June 1967

A method of integral detection of $\gamma$ quanta with subsequent resonance separation and storage of a periodic signal was used to measure the circular polarization of $\gamma$ quanta in $^{181}$Ta (a transition of 482 keV). The value of the polarization obtained is $P_\gamma = -(6 \pm 1) \times 10^{-6}$. This result agrees with the data obtained by the authors earlier, $P_\gamma < 2 \times 10^{-5}$, and is at variance with the value reported by Boehm and Kankeleit, $P_\gamma = -(2 \pm 0.4) \times 10^{-4}$. The amplitude of the nucleon-nucleon weak interaction estimated from a comparison with experimental data on $^{175}$Lu is $F \approx (2 \pm 4) \times 10^{-7}$. 
PARITY NON-CONSERVATION
IN RADIATIVE THERMAL NEUTRON CAPTURE BY PROTONS

V. M. LOBASHOV, D. M. KAMINKER, G. I. KHARKEVICH, V. A. KNIAZKOV,
N. A. LOZOVoy, V. A. NAZARENKO, L. F. SAYENKO, L. M. SMOTRITSKY
and A. I. YEGOROV

Leningrad Nuclear Physics Institute, Academy of Sciences, USSR

Received 21 April 1972

Abstract: The circular polarization of γ-quanta from the reaction \( n + p \rightarrow d + \gamma \) has been measured using a light-water neutron trap in the reactor active zone as a γ-ray source. The trap was shielded from the γ-radiation of the active zone by lead and bismuth screens. The effective source activity was \( 10^{16} \gamma \)-quanta/sec. For the γ-ray circular polarization measurements use was made of a transmission-type polarimeter and of integral current detection with the separation and accumulation of a periodic signal. Zero control experiments were carried out using γ-quanta from the \( ^{24}\text{Mg} \) and \( ^{48}\text{Ti}(n,\gamma)^{49}\text{Ti} \) reaction as non-polarized γ-ray sources. The circular polarization of γ-rays from the reaction \( n + p \rightarrow d + \gamma \) was found to be \( P = -(1.30 \pm 0.45) \times 10^{-6} \).
A NEW EXPERIMENTAL STUDY OF THE CIRCULAR POLARIZATION OF np CAPTURE $\gamma$-RAYS

V.A. KNYAZ’KOV, E.A. KOLOMENSKII, V.M. LOBASHOV, V.A. NAZARENKO, A.N. PIROZHKOV, A.I. SHABLII, E.V. SHUL’GINA, Y.V. SOBOLEV and A.I. YEGOROV

Leningrad Nuclear Physics Institute, Academy of Sciences of the USSR, Leningrad, USSR

Received 1 August 1983

Abstract: An installation using a light-water neutron trap in the reactor core as a proton target is described. Results of the main and control measurements are presented which permit one to conclude that the parity-violating circular polarization of the $\gamma$-rays from the np$\to$d$\gamma$ reaction is $P_\gamma = (1.8 \pm 1.8) \times 10^{-7}$. 
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The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is generally included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

**Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS**

The Standard Model is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

**PROPERTY OF THE INTERACTIONS**

**Gravitational**
- Mass
- Energy
- Flavor
- Electric Charge
- Strong, Electrically charged

**Weak**
- Mass
- Energy
- Flavor
- Electric Charge
- Quarks, Leptons
- Electrively charged

**Electromagnetic**
- Mass
- Energy
- Flavor
- Electric Charge
- Quarks, Gluons
- Hadrons

**GO FERMIONS**

**Baryons**
- spin = 1/2
- Protons
- Neutrons
- Up
- Down
- Strange
- Lambda
- Omega

**Mesons**
- spin = 0
- Protons
- Antiprotons
- Up
- Down
- Strangeness

**GO BOSONS**

**Unified Electroweak**
- Photon
- W
- Z

**Strong**
- Gluon
- G

**Color Charge**
- Each quark carries one of three types of "strong charge" (color). These charges have nothing to do with the color of visible light. There are eight possible types of color charge for gluons, but as electrically charged particles interact by exchanging photons, only strong-color-neutral color-charged particles interact by exchanging gluons. Leptons, photons, and W and Z bosons have no strong interaction and hence no color charge.

**Residual Strong Interaction**
- The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions. These interactions are known as hadronic interactions, and the total energy of the reaction depends on the additional quark-antiquark pair (see figure below).

**Matter and Antimatter**
- There are 136 types of baryons.

**The Particle Adventure**
- Visit the award-winning website The Particle Adventure at http://TheParticleAdventure.org

This chart has been made possible by the generous support of:
- U.S. Department of Energy
- U.S. National Science Foundation
- Lawrence Berkeley National Laboratory
- Stanford Linear Accelerator Center
- Los Alamos National Laboratory
- American Physical Society, Division of Particles and Fields

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### Classification of Weak Interactions

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Charged</th>
<th>Neutral</th>
<th>Charged+Neutral</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Leptonic</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1)</td>
<td>$\mu \rightarrow e\nu\nu$ ($2 \times 10^{-5}$)</td>
<td></td>
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<tr>
<td>(2)</td>
<td>$\nu_\mu e \rightarrow \mu\nu e$</td>
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<tr>
<td>(3)</td>
<td>$\tau \rightarrow l\nu\nu$</td>
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<tr>
<td>(4)</td>
<td>$\nu_\mu e \rightarrow \nu_\mu e$</td>
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<tr>
<td>(5)</td>
<td>$\bar{\nu}<em>\mu e \rightarrow \bar{\nu}</em>\mu e$</td>
<td></td>
<td></td>
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<tr>
<td>(7)</td>
<td>$\nu_e e \rightarrow \nu_e e$ (10%)</td>
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</tr>
<tr>
<td>(8)</td>
<td>$\bar{\nu}_e e \rightarrow \bar{\nu}_e e$</td>
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<td></td>
</tr>
<tr>
<td>(9)</td>
<td>$e^+ e^- \rightarrow \nu_e \bar{\nu}_e$</td>
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<td></td>
</tr>
<tr>
<td><strong>Semileptonic Meson</strong></td>
<td>(10)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(10)</td>
<td>$\pi^+ \rightarrow \mu\nu, \ e\nu$ ($2 \times 10^{-4}$)</td>
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<tr>
<td>(11)</td>
<td>$K^+ \rightarrow \mu\nu, \ e\nu$</td>
<td></td>
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</tr>
<tr>
<td>(12)</td>
<td>$F^+ \rightarrow \tau^+\nu$</td>
<td></td>
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<tr>
<td>(11)</td>
<td>$\pi^+ \rightarrow \pi^0\nu$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(12)</td>
<td>$K^+ \rightarrow \pi^0\nu$</td>
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<tr>
<td></td>
<td>$K_L^0 \rightarrow \pi^\pm\nu$</td>
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<tr>
<td>(13)</td>
<td>$D \rightarrow \begin{pmatrix} \pi \ K \ K^* \end{pmatrix}$</td>
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</tr>
<tr>
<td><strong>Baryon</strong></td>
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<tr>
<td>(14)</td>
<td>$\mu^-B \rightarrow B'\nu$</td>
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<tr>
<td>(15)</td>
<td>$B \rightarrow B'\nu$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(16)</td>
<td>$\nu B \rightarrow B'\nu$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(17)</td>
<td>$\nu N \rightarrow \nu N, \nu N\pi, \nu X$</td>
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<td></td>
</tr>
<tr>
<td>(18)</td>
<td>$\bar{\nu}_e + D \rightarrow n + p + \bar{\nu}_e$</td>
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<tr>
<td>(19)</td>
<td>$eN \rightarrow eN, eX$ (10%)</td>
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<tr>
<td><strong>Hadronic Meson</strong></td>
<td>(20)</td>
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<tr>
<td>(20)</td>
<td>$K \rightarrow \pi\pi$ ($1 \times 10^{-3}$)</td>
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<tr>
<td>(21)</td>
<td>$K \rightarrow 3\pi$ ($8 \times 10^{-3}$)</td>
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<tr>
<td>(22)</td>
<td>$D \rightarrow KK, K\pi, K2\pi, K3\pi$</td>
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</tr>
<tr>
<td>(23)</td>
<td>$B^{0,\pm}_{\pi\pi} \rightarrow D\pi, DK$</td>
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</tr>
<tr>
<td><strong>Baryon</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(24)</td>
<td>$\Lambda \rightarrow N\pi$</td>
<td></td>
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<tr>
<td>(25)</td>
<td>$\Sigma \rightarrow N\pi$</td>
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<tr>
<td></td>
<td>$\Xi \rightarrow N\pi$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(25)</td>
<td>$\Lambda^- \rightarrow pK^-\pi^+$</td>
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<tr>
<td>(26)</td>
<td>$NN \rightarrow NN$ (10%)</td>
<td></td>
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</tr>
</tbody>
</table>
Fact

Strong (and EM, too) interaction is omnipresent!

- **Experimentally:**
  - The signal-to-noise ratio \( S/N \sim \frac{g_w^2}{M_W^2} / \frac{g_s^2}{m_{\pi}^2} \sim G_F m_{\pi}^2 \approx 10^{-7} \)
    
    \[
    A_{L}^{\tilde{p}+p}(45 \text{ MeV}) = (-1.57 \pm 0.23) \times 10^{-7}
    
    A_{L}^{\tilde{p}+\alpha}(46 \text{ MeV}) = (-3.34 \pm 0.93) \times 10^{-7}
    
    P_{\gamma}^{18}\text{F}(1081 \text{ keV}) = (12 \pm 38) \times 10^{-5}
    
    A_{\gamma}^{19}\text{F}(110 \text{ keV}) = (-7.4 \pm 1.9) \times 10^{-5}
    
    A_{L}^{\tilde{n}+137}\text{La}(0.734 \text{ eV}) = (9.8 \pm 0.3) \times 10^{-2}
    
    A_{\gamma}^{180}\text{Hf}(501 \text{ keV}) = (-1.66 \pm 0.18) \times 10^{-2}
    
- **Theoretically:**
  - The non-perturbative QCD at low energies
  - The difficult nuclear many-body problems
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Fundamental Weak Current in Flavor $SU(3)$

\[ J_W = \cos \theta_C \bar{u} \gamma_\mu (1 - \gamma_5) d + \sin \theta_C \bar{u} \gamma_\mu (1 - \gamma_5) s \]
\[ J_Z = \bar{u} \gamma_\mu (1 - \gamma_5) u - \bar{d} \gamma_\mu (1 - \gamma_5) d - \bar{s} \gamma_\mu (1 - \gamma_5) s \]

Fundamental $\Delta S = 0$ $q-q$ Interaction in Flavor $SU(3)$

\[
\frac{G_F}{\sqrt{2}} \left[ \cos^2 \theta_C J_W^{l=1} J_W^{l=1} + \sin^2 \theta_C J_W^{l=1/2} J_W^{l=1/2} + J_Z^{l=0,1} J_Z^{l=0,1} \right] + \text{H.c.}
\]

1. $\Delta l = 0$: from $J_W^{1^+} J_W^{1^+}$, $J_Z^{0^+} J_Z^{0^+}$ and $J_Z^{1^+} J_Z^{1^+}$
2. $\Delta l = 1$: from $J_W^{1/2^+} J_W^{1/2^+}$, $J_Z^{0^+} J_Z^{1^+}$ and $J_Z^{1^+} J_Z^{0^+}$
3. $\Delta l = 2$: from $J_W^{1^+} J_W^{1^+}$ and $J_Z^{1^+} J_Z^{1^+}$

Charged $\Delta l = 1$ is suppress by $\sin^2 \theta \sim 1/25$, therefore $\Delta l = 1$ is dominated by NC (may not be the case for dressed quarks)
The Importance of $\Delta S = 0$ Hadronic Weak Interaction

- The only viable venue to observe the hadronic neutral current effect: FCNC is GIM suppressed
- Provide other touchstones for strong dynamics: How the strong interaction modify the above interaction?
- Complementary to the $\Delta S = 1$ sector: Any similar thing to the $\Delta I = 1/2$ rule?
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The Search Program

1. **Experiments:** $O_1...N$
   - Find nuclear PV observables, such as $A_L(\vec{x}, x)$, $\phi_{\text{spin}}(\vec{x}, \vec{x}')$, $P_\gamma(X, \vec{y})$, $A_\gamma(\vec{X}, \gamma)$, or $P$-odd nuclear moments, such as anapole (measured in atomic PV).

2. **Nuclear Theory:** $O_1...N = O_1...N(C_1...M) \rightarrow C_1...M = C_1...M(O_1...N)$
   - Identify the parameters (model-dep. or model-indep.) which determine the $P$-odd $NN$ interaction
   - Need good nuclear structure and reaction calculations (few- and many-body) to interpret the experimental data

3. **Hadronic Theory:** $C_1...M = C_1...M(G_F)$
   - Link the nuclear parameters to the fundamental $P$-odd $q-q$ interaction
   - Need good non-perturbative calculations (quark model, QCD sum rules, lattice QCD) to get theoretical predictions

If $C_i...M(O_1...N)|_{\text{phenomenology}} \cong C_i...M(G_F)|_{\text{theory}}$

Consistency is reached and the SM gains further success in $\Delta S = 0$ sector!
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**Basic idea:** At low energies, only S-wave and its P-wave admixture substantially contribute to observables (Danilov 65, 71), and there are 5 independent ones:

<table>
<thead>
<tr>
<th>Transition</th>
<th>$I \leftrightarrow I'$</th>
<th>$\Delta I$</th>
<th>$n-n$</th>
<th>$n-p$</th>
<th>$p-p$</th>
<th>Amp.</th>
<th>$E \rightarrow 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3S_1 \leftrightarrow^1 P_1$</td>
<td>0 $\leftrightarrow$ 0</td>
<td>0</td>
<td>✓</td>
<td>✓</td>
<td>u</td>
<td>$\lambda_t$</td>
<td></td>
</tr>
<tr>
<td>$^1S_0 \leftrightarrow^3 P_0$</td>
<td>1 $\leftrightarrow$ 1</td>
<td>0</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>$v^0$</td>
<td>$\lambda_s^0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>$v^1$</td>
<td>$\lambda_s^1$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>$v^2$</td>
<td>$\lambda_s^2$</td>
</tr>
<tr>
<td>$^3S_1 \leftrightarrow^3 P_1$</td>
<td>0 $\leftrightarrow$ 1</td>
<td>1</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>w</td>
<td>$\rho_t$</td>
</tr>
</tbody>
</table>

**Note:** The energy dependence is determined by strong phase shifts

**Generalization:** Approximate finite nuclei as nuclear matter, and applying the Bethe-Goldstone eqn. to obtain an effective PV interaction for many-body problems (Desplanques and Missimer 78, 80)
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General Structure of $S$–$P$ Amplitudes

The building blocks:

- **Isospin**: $1, \tilde{\tau}_1 \cdot \tilde{\tau}_2, \tau^z_+ = (\tau^z_1 + \tau^z_2)/2, \tau^z_- = (\tau^z_1 - \tau^z_2)/2, \tau^z_x = i(\tilde{\tau}_1 \times \tilde{\tau}_2)^z$, and $\tau^{zz} = (3\tau^z_1 \tau^z_2 - \tilde{\tau}_1 \cdot \tilde{\tau}_2)/2\sqrt{6}$
- **Spin**: $\tilde{\sigma}_+ = \tilde{\sigma}_1 + \tilde{\sigma}_2, \tilde{\sigma}_- = \tilde{\sigma}_1 - \tilde{\sigma}_2, \tilde{\sigma}_x = i(\tilde{\sigma}_1 \times \tilde{\sigma}_2)$
- **Spatial**: $\vec{p}_{1,2}$ and $\vec{p'}_{1,2}$

The symmetry considerations:

- **Pseudoscalar**: $\vec{\sigma} \cdot \vec{k}$ form (Hermitian, PV, ignore higher order in $k$)
- **Permutation symmetry**: $f(1,2) = f(2,1)$
- **Translational invariance**: out of three independent momenta from $\vec{p}_{1,2}$ and $\vec{p'}_{1,2}$, only $\vec{q} \equiv \vec{p'}_1 - \vec{p}_1 = \vec{p}_2 - \vec{p'}_2$ and $\vec{Q} = (\vec{p'}_1 + \vec{p}_1 - \vec{p'}_2 - \vec{p}_2)/2$ are allowed
- **Time-reversal invariance**: $\vec{q} \rightarrow \vec{q}, \vec{Q} \rightarrow -\vec{Q}; \langle \tilde{\sigma}_{+,x} \rangle \rightarrow \langle \tilde{\sigma}_{+,x} \rangle, \langle \tilde{\sigma}_{-} \rangle \rightarrow -\langle \tilde{\sigma}_{-} \rangle$

Note

5 amplitudes, each one has 2 independent structures ($5 \times 2 = 10$)
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**Building blocks**: nucleon, mesons (pseudo-scalar and vector), and their couplings

**Basic assumption**: the \( \mathcal{P} \) physics, which is short-ranged, is buried inside the \( \mathcal{P} \) meson-nucleon couplings

**Low-Energy**: light mesons with \( m_x < 1 \text{ GeV} \)

**Barton’s Thm.**: \( CP \) conservation excludes scalar coupling to neutral pseudoscalar mesons (\( C \)-even \( P \)-odd)

---

### Meson Exchange Picture

- **Building blocks**: nucleon, mesons (pseudo-scalar and vector), and their couplings
- **Basic assumption**: the \( \mathcal{P} \) physics, which is short-ranged, is buried inside the \( \mathcal{P} \) meson-nucleon couplings
- **Low-Energy**: light mesons with \( m_x < 1 \text{ GeV} \)
- **Barton’s Thm.**: \( CP \) conservation excludes scalar coupling to neutral pseudoscalar mesons (\( C \)-even \( P \)-odd)

---

**OME with \( \pi^\pm, \rho, \omega \)**

![Diagram of OME with \( \pi^\pm, \rho, \omega \)](image)

**2 \( m_N \times H_\mathcal{P} \) based on OME**

\[
\begin{align*}
g_\pi h_\pi^1/(2 \sqrt{2}) \; &\tau_+^z \; \bar{\sigma} \cdot \vec{y}_{\pi^-} (\vec{r}) \\
&- g_\rho \left( h_\rho^0 \; \bar{\tau}_1 \cdot \bar{\tau}_2 + h_\rho^1 \; \tau_+^z + h_\rho^2 \; \tau_{zz} \right) \left( \bar{\sigma} \cdot \vec{y}_{\rho^+} + \mu_\rho \; \bar{\sigma} \times \vec{y}_{\rho^-} \right) \\
&- g_\omega \left( h_\omega^0 \; 1 + h_\omega^1 \; \tau_+^z \right) \left( \bar{\sigma} \cdot \vec{y}_{\omega^+} + \mu_\omega \; \bar{\sigma} \times \vec{y}_{\omega^-} \right) \\
&- (g_\omega h_\omega^1 - g_\rho h_\rho^1) \; \tau_-^z \; \bar{\sigma} + \vec{y}_{\rho^+} - g_\rho h_\rho^1 \; \bar{\sigma} + \vec{y}_{\rho^-}
\end{align*}
\]

with \( \vec{y}_{x^\pm}(\vec{r}) \equiv [\vec{p}_1 - \vec{p}_2 \cdot e^{-m_x r} / (4 \pi r)]^\pm \)
Outline

1. Introduction
   - The Standard Model
   - Why Difficult?
   - Why Important?
   - The Search Program

2. S–P Amps.
   - S-P Amplitudes
   - General Structure of S–P Amplitudes

3. Meson Exchange
   - Meson-Exchange Model
   - **PV Meson-Nucleon Couplings**
   - Current Status

4. EFT
   - EFT Formulation
   - Analysis

5. Outlook and Summary
   - Outlook
   - Summary
   - Further Reading
### Predictions for $\not{P}$ Meson-Nucleon Couplings

<table>
<thead>
<tr>
<th>$\times 10^7$</th>
<th>DDH Range</th>
<th>Best</th>
<th>DZ</th>
<th>FCDH</th>
<th>KM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_\pi^1$</td>
<td>0.0 $\leftrightarrow$ 11.4</td>
<td>4.6</td>
<td>1.1</td>
<td>2.7</td>
<td>0.2</td>
</tr>
<tr>
<td>$h_\rho^0$</td>
<td>-30.8 $\leftrightarrow$ 11.4</td>
<td>-11.4</td>
<td>-8.4</td>
<td>-3.8</td>
<td>-3.7</td>
</tr>
<tr>
<td>$h_\rho^1$</td>
<td>-0.4 $\leftrightarrow$ 100.0</td>
<td>-0.2</td>
<td>0.4</td>
<td>-0.4</td>
<td>-0.1</td>
</tr>
<tr>
<td>$h_\rho^2$</td>
<td>-11.0 $\leftrightarrow$ 107.6</td>
<td>-9.5</td>
<td>-6.8</td>
<td>-6.8</td>
<td>-3.3</td>
</tr>
<tr>
<td>$h_\omega^0$</td>
<td>-10.3 $\leftrightarrow$ 105.7</td>
<td>-1.9</td>
<td>-3.8</td>
<td>-4.9</td>
<td>-6.2</td>
</tr>
<tr>
<td>$h_\omega^1$</td>
<td>-1.9 $\leftrightarrow$ 110.8</td>
<td>-1.1</td>
<td>-2.3</td>
<td>-2.3</td>
<td>-1.0</td>
</tr>
<tr>
<td>$h_\rho^1$</td>
<td>0.0 $\leftrightarrow$ 10.8</td>
<td>0.0</td>
<td></td>
<td></td>
<td>-2.2</td>
</tr>
</tbody>
</table>

- Calculations by DDH, DZ, FCDH are based on quark models, KM used the chiral soliton model.
- $h_\rho^1$ term is usually ignored, so leaving 6 $\not{P}$ couplings to be checked by exps.
- QCD sum rule calculations of $h_\pi^1$ give $3 \times 10^{-7}$ (HHK 98, formerly $2 \times 10^{-8}$) and $3.4 \times 10^{-7}$ (Lobov 02).
- Lattice QCD calculations of $h_\pi^1$ (should be similar to $g_\pi$ but with a shorter range) are proposed (e.g. Beane and Savage: matching PQQCD to PQChPT).
Two Major Puzzles

Is $h^1_\pi$ small?

The $^{18}\text{F}$ is performed by five different groups, the theoretical calculation (Haxton 85) is thought to be reliable.

Is $h_\omega \equiv h^0_\omega + h^1_\omega$ positive?

$p\bar{p}$ scattering @ 13.6, 45, and 221 MeV where $A_L$ depends on a linear combination of $h_\rho$ and $h_\omega$ (Carlson et al. 02)
In parallel to the success in the PC sector, the ChPT is extended to the PV sector at $O(Q)$ (Zhu et al. 04) 
The benefits over or cure to the meson-exchange version include:

1. It’s model-independent
2. It’s completely general and exhibits the underlying symmetries
3. It has a systematic expansion scheme (power counting) and improvable

Basic ingredients:

- **Chiral symmetry**: $SU(2)_L \times SU(2)_R$ (massless quarks)
- **SSB**: $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$ (eight massless Goldstone bosons: $\pi$, $K$, and $\eta$)
- **Scales**: $\Lambda_{\chi SB} \sim m_N \sim m_\rho \sim 1 \text{ GeV}$, $m_\pi \sim f_\pi \sim 100 \text{ MeV}$, so expansions in terms of $Q/\Lambda_{\chi SB}$ and $m_\pi/m_N$ converges well
The proposed form has two versions:

**Pionless**: pions are integrated out, i.e. only (b)
- Good for low energies, interaction is short-ranged
- Has $10$ LECs

**Pionful**: pions are dynamical
- OPE provides some long-ranged interaction, (b)+(c)+(d)+...
- Introduces additional $3$ couplings
H_p in Pionless EFT

\[ V_{PV}^\pi = V_{1,SR}^{PV} = \frac{2}{\Lambda_\chi^3} \]
\[ \times \left\{ \left[ C_1 + (C_2 + C_4) \tau_+^Z + C_3 \bar{\tau}_1 \cdot \bar{\tau}_2 + C_5 \tau^{ZZ} \right] \bar{\sigma} \cdot \bar{y}_{m+} \right. \\
+ \left[ \tilde{C}_1 + (\tilde{C}_2 + \tilde{C}_4) \tau_+^Z + \tilde{C}_3 \bar{\tau}_1 \cdot \bar{\tau}_2 + \tilde{C}_5 \tau^{ZZ} \right] \bar{\sigma} \times \bar{y}_{m-} \right. \\
+ \left. (C_2 - C_4) \tau_+^Z \bar{\sigma} \cdot \bar{y}_{m+} + \tilde{C}_6 \tau_+^Z \bar{\sigma} \cdot \bar{y}_{m-} \right\} \\

- Overall, there are 10 LECs (too many!)
- In ZRA, \( \langle \bar{y}_{m+} \rangle = \langle \bar{y}_{m-} \rangle \), the 10 LECs can be effectively reduced into 5
- If \( \langle \bar{y}_{m+} \rangle / \langle \bar{y}_{m-} \rangle \equiv R(E) \approx R \), the 10-to-5 reduction can still be valid
- When \( m \to \infty \), \( \bar{y}_{m\pm} \to [\bar{p}_1 - \bar{p}_2, \delta(r)/r^2]_\pm \) : the contact form
- For calculations using realistic w.fs., \( \delta(r) \) is softened (hybrid EFT, EFT*)
- Taking \( m = m_\rho \) and \( \tilde{C}_{1,2,3,4,5} / C_{1,2,3,4,5} = \mu_\omega / \rho \), \( V_{PV}^{1,SR} \equiv V_{\rho + \omega}^{OME} \), both have 6 independent parameters
$H_P$ in Pionful EFT

\[ V_{\pi-ful}^{PV} = V_{-1,LR}^{PV} + V_{1,LR}^{PV} + V_{1,MR}^{PV} + V_{1,SR}^{PV} \]

- $V_{-1,LR}^{PV}$: the normal OPE one, depends on $h_{\pi}^1$
- $V_{1,LR}^{PV}$: from vertex corrections in both PC and PV parts with one new coupling $k_{\pi}^{1a}$
- $V_{1,MR}^{PV}$: from TPE, depends on $h_{\pi}^1$, has non-analytic $\ln q/m_\pi$ terms
- $V_{1,SR}^{PV}$: similar structure to the pionless version, but LECs bear different meaning
- $V_{\pi-ful}^{PV}$ depends on the regularization scheme which shuffles some pion-exchange contributions into $V_{1,SR}^{PV}$.

Most MECs are constrained by gauging the potential, with a transverse piece depending one a new coupling constant $\bar{c}_\pi$.

---

1 Redundant (Liu and Ramsey-Musolf)
2 Suppressed by $k/m_N$ (Liu)
Reduction of 10-to-5 LECs

Fact

The condition $\frac{\langle \vec{y}_{m+} \rangle}{\langle \vec{y}_{m} \rangle} \equiv R(E) \approx R$ has to be satisfied.

The results are (PRELIMINARY!):

- For all $v$’s and $w$, the constancy is excellent
- For $u$, if constrained to $E_{\text{Lab}} \lesssim 40\text{MeV}$, the variation is about 10% (acceptable)
Limit of 10-to-5 Reduction

Fact

*At low energies, S-P amplitudes dominate which makes the reduction valid. But when D-P and F-P ones come into play, this will no longer be the case.*

The results are (PRELIMINARY!):

- For ν’s, the 10% correction enters at $E_{\text{Lab}} \approx 90\text{MeV}$ for $np$ and $nn$, and even higher for $pp$ (Coulomb barrier).
- The 10% correction enters at $E_{\text{Lab}} \approx 40, 60\text{MeV}$ for $u$ and $w$ respectively.
Fact

It depends on whether pion contributions have roughly similar energy-dependence to the short-ranged interaction.

The results are (PRELIMINARY!):

Conclusion

- While TPE tracks with the SR interaction very well, OPE does not.
- The OPE part has to be singled out independently.
- Overall, six parameters are needed for low energies.
- As long as S-P amps. dominate, EFT=OME?
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### Few-body PV Observables

**Goal**

Have at least 6 low-energy measurements which are linearly-independent enough, and apply the analysis in the EFT framework

<table>
<thead>
<tr>
<th>Observables</th>
<th>Theory (PRELIMINARY!) ★</th>
<th>Experiment ($\times 10^7$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A^{\bar{p}p}_L$ (13.6 MeV)</td>
<td>$-2.48 \tilde{\lambda}^{\bar{p}p}_S$</td>
<td>$-0.93 \pm 0.21$</td>
</tr>
<tr>
<td>$A^{pp}_L$ (45 MeV)</td>
<td>$-4.48 \tilde{\lambda}^{pp}_S$</td>
<td>$-1.57 \pm 0.23$</td>
</tr>
<tr>
<td>$\frac{d}{dz} \phi^{np}_n$ (th.)</td>
<td>$1.44 \tilde{\lambda}^{np}_S + 0.08 \tilde{\lambda}_t + 0.36 \bar{\rho}_t + 0.57 C^{1\pi}$</td>
<td>SNS</td>
</tr>
<tr>
<td>$P^{np}_\gamma$ (th.)</td>
<td>$-0.93 \tilde{\lambda}^{np}_S - 0.98 \lambda_t$</td>
<td>$(1.8 \pm 1.8)$, SNS?</td>
</tr>
<tr>
<td>$A^{\tilde{d}d}_L$ (1.32 keV)</td>
<td>Same as above</td>
<td>HIGS? IASA? Spring-8?</td>
</tr>
<tr>
<td>$A^{np}_\gamma$ (th.)***</td>
<td>$-0.29 \bar{\rho}_t - 0.57 C^{1\pi}$</td>
<td>LANSCE, SNS</td>
</tr>
<tr>
<td>$A^{nd}_\gamma$ (th.)</td>
<td>To be improved</td>
<td>$(0.6 \pm 2.1)$, SNS?</td>
</tr>
<tr>
<td>$A^{\bar{p}\alpha}_L$ (46 MeV)</td>
<td>To be improved</td>
<td>$-3.3 \pm 0.9$</td>
</tr>
<tr>
<td>$\frac{d}{dz} \phi^{n\alpha}_n$ (th.)</td>
<td>To be improved</td>
<td>$(8 \pm 14)$, NIST, SNS</td>
</tr>
</tbody>
</table>

*** Will be a unique determination of $h^{1\pi}_1$?
★ All LECs are not in usual convention!
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In Conclusion:

- The strangeness-conserving hadronic weak interaction is the last piece of the jigsaw for a complete test of the standard electroweak theory; at the same time, it provides another window for examining strong interaction dynamics which is complementary to purely PC observables or its strangeness-non-conserving counterpart.

- An EFT formulation of PV nucleon-nucleon interaction anticipates six independent parameters for the low-energy processes in which $S$-$P$ amplitudes dominate the observables.

- Theory and experiment of nuclear few-body physics are mature enough to make new progress, and one will see if a more consistent picture will result from these efforts.
Introduction

- The Standard Model
- Why Difficult?
- Why Important?
- The Search Program

S–P Amps.

- S-P Amplitudes
- General Structure of S–P Amplitudes

Meson Exchange

- Meson-Exchange Model
- PV Meson-Nucleon Couplings
- Current Status

EFT

- EFT Formulation
- Analysis

Outlook and Summary

- Outlook
- Summary
- Further Reading
For More Details and References:

E.G. Adelberger and W.C. Haxton

W. Haeberli and B.R. Holstein

B. Desplanques

M.J. Ramsey-Musolf and S.A. Page

B.R. Holstein
<table>
<thead>
<tr>
<th>Leptons</th>
<th>spin = 1/2</th>
<th>Quarks</th>
<th>spin = 1/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flavor</td>
<td>Mass GeV/c²</td>
<td>Electric charge</td>
<td>Flavor</td>
</tr>
<tr>
<td>νₑ</td>
<td>&lt;1×10⁻⁸</td>
<td>0</td>
<td>U up</td>
</tr>
<tr>
<td>e</td>
<td>0.000511</td>
<td>-1</td>
<td>d down</td>
</tr>
<tr>
<td>νₘ</td>
<td>&lt;0.0002</td>
<td>0</td>
<td>C charm</td>
</tr>
<tr>
<td>μ</td>
<td>0.106</td>
<td>-1</td>
<td>S strange</td>
</tr>
<tr>
<td>νₜ</td>
<td>&lt;0.02</td>
<td>0</td>
<td>t top</td>
</tr>
<tr>
<td>τ</td>
<td>1.7771</td>
<td>-1</td>
<td>b bottom</td>
</tr>
</tbody>
</table>
### BOSONS

**Force Carriers**

**Spin** = 0, 1, 2, ...

<table>
<thead>
<tr>
<th>Unified Electroweak</th>
<th>Spin = 1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Name</strong></td>
<td><strong>Mass GeV/c^2</strong></td>
</tr>
<tr>
<td>(\gamma) (Photon)</td>
<td>0</td>
</tr>
<tr>
<td>(W^-)</td>
<td>80.4</td>
</tr>
<tr>
<td>(W^+)</td>
<td>80.4</td>
</tr>
<tr>
<td>(Z^0)</td>
<td>91.187</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Strong (Color)</th>
<th>Spin = 1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Name</strong></td>
<td><strong>Mass GeV/c^2</strong></td>
</tr>
<tr>
<td>(g) (Gluon)</td>
<td>0</td>
</tr>
</tbody>
</table>
## Properties of the Interactions

<table>
<thead>
<tr>
<th>Property</th>
<th>Gravitational</th>
<th>Weak (Electroweak)</th>
<th>Electromagnetic</th>
<th>Strong</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Acts on:</strong></td>
<td>Mass – Energy</td>
<td>Flavor</td>
<td>Electric Charge</td>
<td>Color Charge</td>
</tr>
<tr>
<td><strong>Particles experiencing:</strong></td>
<td>All</td>
<td>Quarks, Leptons</td>
<td>Electrically charged</td>
<td>Quarks, Gluons</td>
</tr>
<tr>
<td><strong>Particles mediating:</strong></td>
<td>Graviton (not yet observed)</td>
<td>W⁺, W⁻, Z⁰</td>
<td>γ</td>
<td>Gluons</td>
</tr>
<tr>
<td><strong>Strength relative to electromag</strong></td>
<td>10⁻¹⁸ m</td>
<td>0.8</td>
<td>1</td>
<td>25</td>
</tr>
<tr>
<td><strong>for two u quarks at:</strong></td>
<td>10⁻⁴¹</td>
<td>10⁻⁴</td>
<td>1</td>
<td>60</td>
</tr>
<tr>
<td><strong>for two protons in nucleus</strong></td>
<td>10⁻³⁶</td>
<td>10⁻⁷</td>
<td>1</td>
<td>Not applicable to hadrons</td>
</tr>
</tbody>
</table>

See Residual Strong Interaction Note

Not applicable to quarks

Mesons
Generic Parity-Violating Observables

Longitudinal Asymmetry

Circular Polarization

Photon Asymmetry

EM Moments

\[
\begin{array}{cccc}
J & C_J & E_J & M_J \\
0 & PT & PT & PT \\
1 & PT & PT & PT \\
2 & PT & PT & PT \\
\vdots & \vdots & \vdots & \vdots \\
\end{array}
\]

* C1: EDM, M2: MQM
* E1: Anapole
How to calculate $\langle n, p | V_{NN} | p, n \rangle = \langle n, p | (\bar{q}_1' \Gamma_1 q_1) G(q) (\bar{q}_2' \Gamma_2 q_2) | n, p \rangle$?
How to calculate $\langle n, p | V_{NN} | p, n \rangle = \langle n, p | (\bar{q}_1' \Gamma_1 q_1) G(q) (\bar{q}_2' \Gamma_2 q_2) | n, p \rangle$?
How to calculate \( \langle n, p | V_{NN} | p, n \rangle = \langle n, p | (\bar{q}'_1 \Gamma_1 q_1) G(q) (\bar{q}'_2 \Gamma_2 q_2) | n, p \rangle \)?
Figure 2  Total cross section of $^{232}\text{Th} + \nu$ as a function of neutron energy (8a).
Glashow–Iliopoulos–Maiani Mechanism

\[ (a) + (b) \propto \sin \theta_C \cos \theta_C - \cos \theta_C \sin \theta_C = 0, \] anticipate the charm quark!
\[ \Delta I = 1/2 \text{ Rule} \]

Example (\( \Lambda \to N + \pi \) decay)

- \( \Gamma(p + \pi^-)/\Gamma_{tot} = (63.9 \pm 0.5)\% \), \( \Gamma(n + \pi^0)/\Gamma_{tot} = (35.8 \pm 0.5)\% \)
- \( \langle (\frac{1}{2}, \frac{1}{2}), (1, -1)|\frac{1}{2}, -\frac{1}{2}\rangle^2 / \langle (\frac{1}{2}, -\frac{1}{2}), (1, 0)|\frac{1}{2}, -\frac{1}{2}\rangle^2 = 2 \)
- \( \langle (\frac{1}{2}, \frac{1}{2}), (1, -1)|\frac{3}{2}, -\frac{1}{2}\rangle^2 / \langle (\frac{1}{2}, -\frac{1}{2}), (1, 0)|\frac{3}{2}, -\frac{1}{2}\rangle^2 = 1/2 \)

Therefore, \( \Delta I = 1/2 \) channel dominates the transition

Qualitatively understood, but not fully from the first principle
Fig. 4. Corrections to the long-range PV $NN$ potential from insertions of (a), (b) higher-order PC $\pi NN$ terms, which are denoted by the unfilled circle, and (c) loops.

Fig. 5. Corrections to the long-range PV $NN$ potential from insertions of (a), (b) higher-order PV $\pi NN$ terms, which are denoted by the circled filled circle, and (c) loops.
Fig. 8. PV TPE triangle diagrams that contribute to the medium-range PV N N interaction at $\mathcal{O}(Q)$.

Fig. 9. PV TPE crossed diagrams that contribute to the medium-range PV N N interaction at $\mathcal{O}(Q)$.
Fig. 6. PV $NN$ contact interactions that contribute to the PV short-range potential.

Fig. 7. Possible PV chiral corrections to PC $NN$ couplings $C_{S,T}$. 
Fig. 12. Long-range PV meson-exchange currents in leading order. A wavy lines represents a photon.

Fig. 13. Corrections to PV meson-exchange currents: OPE from minimal substitution in the sub-leading (a) PC and (b) PV $\pi N N$ vertices, (c) TPE, (d) short-range contribution from minimal substitution in the PV contact interaction, and (e) OPE from new $\gamma \pi N N$ vertex. Not all ordering and topologies are displayed.