Parity Violation in Two-Nucleon Systems

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Outline

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Why is low-energy hadronic weak interaction still of interest?

- The only viable venue to observe the hadronic neutral current interaction:
  - FCNC is GIM suppressed
- 4-quark short-range correlation is of fundamental interest:
  - How the strong interaction modify the above interaction?
  - Exchange of other exotic bosons?
- Complementary to the $\Delta S = 1$ sector:
  - Any similar thing to the $\Delta I = 1/2$ rule?
  - So far, exps. seems to indicate $\Delta I = 1$ is suppressed in $\Delta S = 0$ sector.
- Needed for better interpretation of semi-leptonic processes:
  - PV electron-nucleon/nucleus scattering: probing nucleon structure, in particular strangeness
  - Atomic PV experiments: probing $\sin^2\theta_W$ at extremely low Q^2

Current status: still fuzzy after 50+ years...

- Experimentally:
  - The signal-to-noise ratio $S/N \sim \frac{g_W^2}{M_W^2} / \frac{g_S^2}{m_\pi^2} \sim G_F\, m_\pi^2 \approx 10^{-7}$

$$A_L^{\vec{p}+p}(45\,\text{MeV}) = (-1.57 \pm 0.23) \times 10^{-7}$$
$$A_L^{\vec{p}+\alpha}(46\,\text{MeV}) = (-3.34 \pm 0.93) \times 10^{-7}$$
$$P_\gamma^{18\text{F}}(1081\,\text{keV}) = (12 \pm 38) \times 10^{-5}$$
$$A_\gamma^{19\text{F}}(110\,\text{keV}) = (-7.4 \pm 1.9) \times 10^{-5}$$
$$A_L^{\vec{n}+{}^{137}\text{La}}(0.734\,\text{eV}) = (9.8 \pm 0.3) \times 10^{-2}$$
$$A_\gamma^{180\text{Hf}}(501\,\text{keV}) = (-1.66 \pm 0.18) \times 10^{-2}$$

- Theoretically:
  - The non-perturbative QCD at low energies
  - The difficult nuclear many-body problems

- Can we understand the PV *NN* interaction as we do for the PC one?
- Wish list: $h^{(1)}_{\pi NN}$ (as $g_{\pi NN}$), PV scattering lengths ($a_s^{pp,nn,np}$, a_t), etc. (Have to be very economic!)

Outline

S–P Amplitudes: $\langle P|H_{\not P}|S\rangle$ (1st-order Born Approx.)

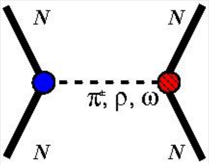
- **Basic idea:** At low energies, only S-waves and their P-wave admixtures substantially contribute to PV observables (Danilov 65, 71), and there are 5 independent ones:

Transition	$I \leftrightarrow I'$	ΔI	n-n	n-p	p-p	Amp.
${}^3S_1 \leftrightarrow {}^1P_1$	$0 \leftrightarrow 0$	0		$\surd$		u
${}^1S_0 \leftrightarrow {}^3P_0$	$1 \leftrightarrow 1$	0	$\surd$	$\surd$	$\surd$	v^0
		1	$\surd$		$\surd$	v^1
		2	$\surd$	$\surd$	$\surd$	v^2
${}^3S_1 \leftrightarrow {}^3P_1$	$0 \leftrightarrow 1$	1		$\surd$		w

- **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)
- **Note:** Single out pion exchange from the ${}^3S_1 \leftrightarrow {}^3P_1$ amplitude provides a better fit.

Meson Exchange Picture

OME with $\pi^\pm$, ρ, and ω



$H_{\not p}$ based on OME (DDH potential)

$$
\begin{aligned}
H_{\not p} = \frac{1}{2\,m_N}\Big\{ & g_\pi\, h_\pi^1/(2\sqrt{2})\,\tau_\times^z\,\vec{\sigma}_+\cdot\vec{y}_{\pi-}(\vec{r}) \\
& - g_\rho\,(h_\rho^0\,\vec{\tau}_1\cdot\vec{\tau}_2 + h_\rho^1\,\tau_+^z + h_\rho^2\,\tau^{zz})\,(\vec{\sigma}_-\cdot\vec{y}_{\rho+} + \mu_\rho\,\vec{\sigma}_\times\cdot\vec{y}_{\rho-}) \\
& - g_\omega\,(h_\omega^0\,1 + h_\omega^1\,\tau_+^z)\,(\vec{\sigma}_-\cdot\vec{y}_{\rho+} + \mu_\omega\,\vec{\sigma}_\times\cdot\vec{y}_{\rho-}) \\
& - (g_\omega\,h_\omega^1 - g_\rho\,h_\rho^1)\,\tau_-^z\,\vec{\sigma}_+\cdot\vec{y}_{\rho+} - g_\rho\,h_\rho^{\prime 1}\,\vec{\sigma}_+\cdot\vec{y}_{\rho-}\Big\}
\end{aligned}
$$

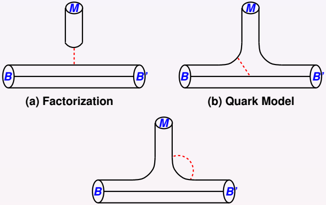
with $\vec{y}_{x\pm}(\vec{r}) \equiv [\vec{p}_1 - \vec{p}_2\,,\, f_{m,\Lambda_m}(r)]_\pm$

Note: Two commonly-used sets of strong parameters:

	g_π	g_ρ	g_ω	μ_ρ	μ_ω	$f_{m,\Lambda_m}(r)$
DDH-best	13.45	2.79	8.37	4.70	0.88	Bare Yukawa ($\Lambda_m \to \infty$)
DDH-adj.	13.22	3.25	15.85	7.10	1.00	Modified Yukawa

Predictions for $\not{P}$ Meson-Nucleon Couplings (7 in total)

$\times 10^7$	DDH Range	Best	DZ	FCDH	KM
h_π^1	0.0↔ 11.4	4.6	1.1	2.7	0.2
h_ρ^0	-30.8↔ 11.4	-11.4	-8.4	-3.8	-3.7
h_ρ^1	-0.4↔ 0.0	-0.2	0.4	-0.4	-0.1
h_ρ^2	-11.0↔ 7.6	-9.5	-6.8	-6.8	-3.3
h_ω^0	-10.3↔ 5.7	-1.9	-3.8	-4.9	-6.2
h_ω^1	-1.9↔ 0.8	-1.1	-2.3	-2.3	-1.0
$h_\rho^{\prime 1}$		0.0			-2.2

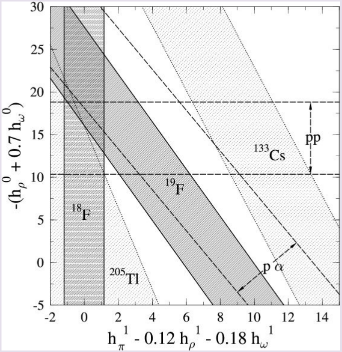


(a) Factorization (b) Quark Model (c) Sum Rule

- Calculations by DDH (Desplanques, Donoghue, and Holstein, '80), DZ (Dubovik and Zenkin, '86), FCDH (Feldman, Crawford, Dubach, and Holstein, '91) are based on quark models, KM (Kaiser and Meissner, '88-'89) used the chiral soliton model
- $h_\rho^{\prime 1}$ term is usually ignored, so leaving 6 $\not{P}$ couplings to be checked by exps.
- QCD sum rule calculations of h_π^1 give 3×10^{-7} (Henley, Hwang, and Kisslinger, '98, formerly 2×10^{-8}) and 3.4×10^{-7} (Lobov, '02)
- Lattice QCD calculations of h_π^1 (should be similar to g_π but with a shorter range) are proposed (Beane and Savage, '02: matching PQQCD to PQChPT)

Two Major Puzzles

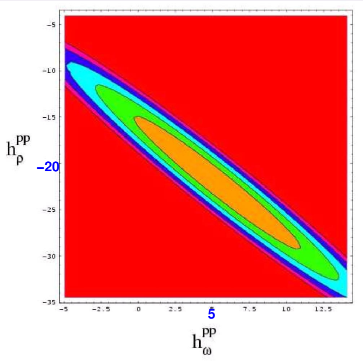
Is h_π^1 small?



Haxton, CPL, and Ramsey–Musolf, '01

- The ^{18}F is performed by five different groups, the theoretical calculation (Haxton, '85) is thought to be reliable (?)
- Anapole constraints worsen the consistency.

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



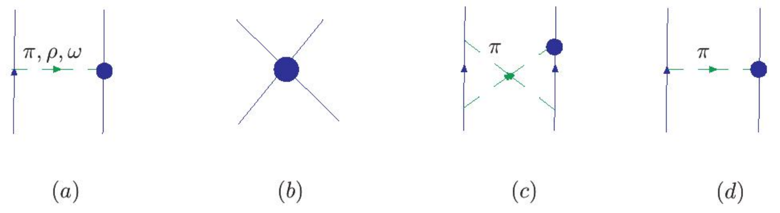
Carlson, Schiavilla, Brown, and Gibson, '02

- $\vec{p}p$ scattering @ 13.6, 45, and 221 MeV where A_L depends on a linear combination of h_ρ and h_ω
- h_ω is marginally consistent with the DDH range $[-12.2, 6.5]$ (CPL, Hyun, and Desplanques, '06)

Effective Field Theory

ChPT is extended to the PV sector at $O(Q)$ (Zhu, Maekawa, Holstein, Ramsey-Musolf, and van Kolck, '05) and the proposed form is characterized by:

- (b) SR: 4F contact int. for integrating out heavy degrees of freedom
  Has 5 genuine LECs (superficially has 10) which correspond to the 5 S–P amplitudes.
- (c&d) MR&LR: Due to TPE and OPE
  Introduces the PV π–N coupling, h_π^1, and a two-body current term $\bar{c}_\pi$.



The hope is too carry out a series of low-energy experiments so that these LO parameters can be well constrained!

Outline

Solving Wave Functions and Calculating Observables

- PC wave functions are obtained by solving the Lippman-Schwinger or Schrödinger equations for scattering or bound states

$$(E - H_0 + V^{\mathrm{PC}} \mp i\varepsilon)\,|\psi\rangle^{(\pm)} = 0\,,$$
$$(E_B + H_0 + V^{\mathrm{PC}})\,|\psi\rangle_B = 0\,.$$

- PV admixtures are obtained by 1st-order Born approximation (solving the inhomogeneous differential equations)

$$(E - H_0 - V^{\mathrm{PC}} \mp i\varepsilon)\widetilde{|\psi\rangle}^{(\pm)} = V^{\mathrm{PV}}\,|\psi\rangle^{(\pm)}\,,$$
$$(E_B + H_0 + V^{\mathrm{PC}})\widetilde{|\psi\rangle}_B = -V^{\mathrm{PV}}\,|\psi\rangle_B\,,$$

Different Calculation Schemes

1. Phenomenological V^{PC} (AV18, CD-Bonn, Nijmegen etc.) and V^{PV} (DDH etc.)
   - Most state-of-the-arts few- and many-body calculations are still performed in such ways
   - Still do not reach a consistent phenomenological V^{PV}
2. Phenomenological V^{PC} and EFT V^{PV} (hybrid approach)
   - Have quality wave functions, general operators, and link of V_m^{OME}–V_{SR}^{EFT} (by $\lim_{m\to\infty} m^2 e^{-mr}/(4\pi r) = \delta(r)/r^2$).
   - Not fully consistent
3. EFT V^{PC} and V^{PV}
   - Treat pions perturbatively: no regulator needed but with limited range of applicability (p/m_π)
   - Treat pions nonperturbatively: larger range of applicability (p/Λ) but involve high-momentum cut-off

Depending on schemes, the results may have model and/or cutoff dependence. Can they be put on the same page?

Determining the Danilov Parameters

The dimensionless Danilov parameters are extracted from the zero-energy S–P amplitudes by:

$$\bar{\lambda}_s^{(pp,nn,np)} \propto \frac{1}{p} e^{-i(\delta_1+\delta_0)} \langle {}^3P_0 | V^{\mathrm{PV}} | {}^1S_0 \rangle_{E\to 0}^{(pp,nn,np)}$$

$$\bar{\lambda}_t \propto \frac{1}{p} e^{-i(\delta_1+\delta_0)} \langle {}^1P_1 | V^{\mathrm{PV}} | {}^3S_1 \rangle_{E\to 0}$$

$$\bar{\rho}_t \propto \frac{1}{p} e^{-i(\delta_1+\delta_0)} \langle {}^3P_1 | V^{\mathrm{PV}} | {}^3S_1 \rangle_{E\to 0} \quad (\text{without OPE})$$

- At low energy, the energy dependence of S–P amplitudes is well approximated by $p\, e^{i(\delta_0+\delta_1)}$.
- The long-ranged OPE only contributes to the ${}^3P_1$–${}^3S_1$ transition, and this is not included in $\bar{\rho}_t$.
- These parameters are physical, i.e., model- and/or cutoff-independent.
- In a typical calculation which specifies some model (AV18, CD-Bonn, etc) and/or cutoffs (bare/modified Yukawa in meson exchange models, mass cutoffs in EFT potential), its expression is model- and/or cutoff-dependent.

Expressing Observables in a Physical Way

Step 1 Recast an observable in terms of the Danilov parameters.

Step 2 Examine if the error is small.

Yes This implies:

1. *S*–*P* transitions dominate the observables.
2. Energy dependence is in the coefficients.

No This usually implies higher partial waves can not be ignored and higher orders in EFT are needed (which we try to avoid, at least for the moment).

Step 3 Vary model and/or cutoff to see if consistency is reached.

Yes The observable is reliably expressed in terms of Danilov parameters and h_π^1.

Example1: Longitudinal Asymmetry A_L in $\vec{p}p$ Scattering

- At 13.6 and 45 MeV, the hybrid calculations (CPL, 2007) give

		$A_L \times 10^3$		
		D_v^{pp}	$\widetilde{D}_v^{pp}$	$\widetilde{C}_2^{2\pi}$
13.6	bare	-1.984	-2.471	4.000
	mod	-1.402	-1.614	1.876
45	bare	-3.781	-4.377	6.847
	mod	-2.652	-2.797	2.712

- Danilov parameter $\bar{\lambda}_s^{pp}$ is

$$\bar{\lambda}_s^{pp} = 5.507 \times 10^{-3} (\widetilde{D}_v^{pp} + 0.789\, D_v^{pp} - 1.655\, \widetilde{C}_2^{2\pi}) \quad \text{(bare)}$$
$$= 3.628 \times 10^{-3} (\widetilde{D}_v^{pp'} + 0.849\, D_v^{pp'} - 1.260\, \widetilde{C}_2^{2\pi'}) \quad \text{(mod)}$$

- The physical expression is

$$A_L^{\vec{p}p}(13.6\,\text{MeV}) = -0.449\, \bar{\lambda}_s^{pp} + (-0.035\, D_v^{pp} - 0.088\, \widetilde{C}_2^{2\pi}) \times 10^{-3} \qquad \text{(bare)}$$
$$= -0.445\, \bar{\lambda}_s^{pp'} + (-0.032\, D_v^{pp'} - 0.157\, \widetilde{C}_2^{2\pi'}) \times 10^{-3} \qquad \text{(mod)}$$
$$A_L^{\vec{p}p}(45\,\text{MeV}) = -0.795\, \bar{\lambda}_s^{pp} + (-0.329\, D_v^{pp} - 0.395\, \widetilde{C}_2^{2\pi}) \times 10^{-3} \qquad \text{(bare)}$$
$$= -0.771\, \bar{\lambda}_s^{pp'} + (-0.276\, D_v^{pp'} - 0.813\, \widetilde{C}_2^{2\pi'}) \times 10^{-3} \qquad \text{(mod)}$$

Example2: Photon Asymmetry A_γ in $\vec{n}+p\to d+\gamma$

- For NPDGamma with thermal neutron ($E\cong 0.025\,\mathrm{eV}$), the hybrid calculations (CPL, 2007) give

	$^3S_1$–$^3P_1(\times 10^{-3})$				$\mathscr{D}$–$^3P_1(\times 10^{-3})$			
	D_w	$\widetilde{D}_w$	$\widetilde{C}_6^{\pi}$	$\widetilde{C}_2^{2\pi}$	D_v^{pp}	$\widetilde{D}_v^{pp}$	$\widetilde{C}_6^{\pi}$	$\widetilde{C}_2^{2\pi}$
bare	−0.108	−0.185	−0.133	0.321	−0.066	−0.103	−0.139	0.193
mod	−0.076	−0.118	−0.132	0.172	−0.048	−0.069	−0.138	0.128

- Danilov parameter $\bar{\rho}_t$ is

$$\bar{\rho}_t = 3.108\times 10^{-3}\,(\widetilde{D}_w + 0.604\,D_w - 1.771\,\widetilde{C}_6^{2\pi}) \quad \text{(bare)}$$
$$= 2.003\times 10^{-3}\,(\widetilde{D}_w' + 0.664\,D_w' - 1.586\,\widetilde{C}_6^{2\pi'}) \quad \text{(mod)}$$

- The physical expression is

$$A_\gamma^{\vec{n}p}(\text{th.}) = -0.093\,\bar{\rho}_t - 0.272\,\widetilde{C}_6^{\pi} + (0.003\,\widetilde{C}_6^{2\pi})\times 10^{-3} \qquad (\text{bare})$$
$$= -0.093\,\bar{\rho}_t' - 0.270\,\widetilde{C}_6^{\pi'} + (0.004\,\widetilde{C}_6^{2\pi'})\times 10^{-3} \qquad (\text{mod})$$

- Assuming naturalness, $\bar{\rho}_t/\widetilde{C}_6^{\pi}\sim 0.1$, $A_\gamma^{\vec{n}p}(\text{th.})\sim -0.1\,h_\pi^1$.

Outline

1. Background
2. PV *NN* Interaction
3. 2N Observables
4. Summary

The Search Program in Few-Nucleon Systems

The non-exhaustive candidate list and database:

Observables	Theory	Experiment ($\times 10^7$)
$A_L^{\vec{p}p}(13.6\,\text{MeV})$	$-0.45\,\lambda_s^{pp}$	-0.93 ± 0.21 (Bonn)
$A_L^{\vec{p}p}(45\,\text{MeV})$	$-0.78\,\lambda_s^{pp}$	-1.57 ± 0.23 (SIN)
$\frac{d}{dz}\,\phi_n^{\vec{n}p}(\text{th.})\vert_{\text{rad/m}}$	$2.50\,\lambda_s^{np}-0.57\,\lambda_t+1.41\,\rho_t+0.29\,\widetilde{C}_6^{\pi}$	SNS?
$P_\gamma^{np}(\text{th.})$	$-0.16\,\lambda_s^{np}+0.67\,\lambda_t$	(1.8 ± 1.8), SNS?
$A_L^{\vec{\gamma}d}(1.32\,\text{keV})$	Same as above	HIGS2?
$A_\gamma^{\vec{n}p}(\text{th.})$	$-0.09\,\rho_t-0.27\,\widetilde{C}_6^{\pi}$	(-1.8 ± 1.9) SNS
$A_\gamma^{\vec{n}d}(\text{th.})$	$(0.59\,\lambda_s^{nn}+0.51\,\lambda_s^{np}+1.18\,\lambda_t+1.42\,\rho_t)$ [1]	(0.6 ± 2.1), SNS?
$A_L^{\vec{p}\alpha}(46\,\text{MeV})$	$(-0.48\,\lambda_s^{pp}-0.24\,\lambda_s^{np}-0.54\,\lambda_t-1.07\,\rho_t)$ [1]	-3.3 ± 0.9 (SIN)
$\frac{d}{dz}\,\phi_n^{\vec{n}\alpha}(\text{th.})\vert_{\text{rad/m}}$	$(1.2\,\lambda_s^{nn}+0.6\,\lambda_s^{np}+1.34\,\lambda_t-2.68\,\rho_t)$ [1]	(1.7 ± 9.2) NIST
⋮ [2]	⋮ [2]	⋮ [2]

1. Expressions should be updated.
2. Other processes like $\vec{n}+d$, $\vec{n}+d\to t+\gamma$, $\vec{n}+t$, $\vec{n}+t\to\alpha+\gamma$, $\vec{\gamma}+t\to n+2p$, $\vec{\gamma}+{}^3\text{He}\to n+d$, $\vec{\gamma}+\alpha\to 2d$ etc. are also considered and/or calculated in certain schemes.