Hadronic Parity Violation

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Parity IQ Question

When was weak interaction PV first seen?

Choices:

i) C.S. Wu et al., Phys. Rev. **105**, 1413 (1957).

ii) J.L. Friedman and V.L. Telegdi, Phys. Rev. **105**, 1681 (1957).

iii) R.T. Cox, C.G. McIlwraith, and B. Korrelmeyer, Proc. Natl. Acad. Sci. **14**, 544 (1928).

Our Problem:

Parity violating effects in strong

and electromagnetic hadronic interactions.

Examples:

First experiment—PV in ${}^{19}F(p,\alpha)^{16}O$ by Tanner (1957)—no effect seen

$$\boxed{{}^{180}Hf^*(8^-) \rightarrow {}^{180}Hf + \gamma}$$

$A_\gamma = -(1.66 \pm 0.18) \times 10^{-2}$ PRC4, 1906 (1971)

$$\boxed{\vec{n} + {}^{139}La}$$

$A_z = (9.55 \pm 0.35) \times 10^{-2}$ PRC44, 2187 (1991)

Theoretical Clues

Seminal paper: "Parity Nonconservation in Nuclei", F. Curtis Michel PR133B, 329 (1964)

1964 $\longrightarrow$ 2010

Great Progress in Particle/Nuclear Physics

Standard Model

BUT remain great unsolved problems at low energy:

i) $\Delta I = \frac{1}{2}$ Rule

ii) CP Violation

iii) Hypernuclear Weak Decay

iv) Hadronic Parity Violation

All deal with $J_\mu^{\mathrm{hadron}} \times J^\mu_{\mathrm{hadron}}$

1980: DDH Approach

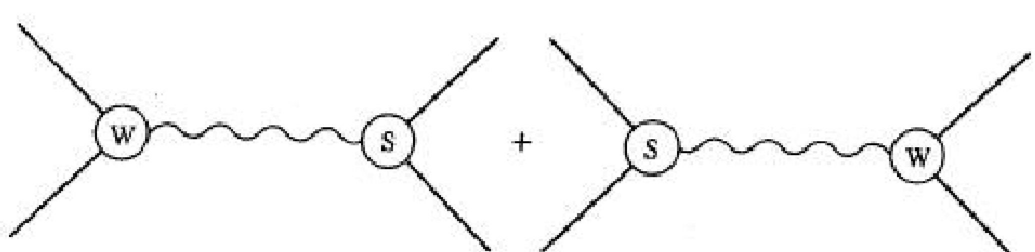
Basic idea:

Meson exchange gives good picture of PC NN interaction, with

$$\mathcal{H}_{\rm st} = ig_{\pi NN}\bar{N}\gamma_5\tau\cdot\pi N + g_\rho \bar{N}\left(\gamma_\mu + i\frac{\mu_V}{2M}\sigma_{\mu\nu}k^\nu\right)\tau\cdot\rho^\mu N$$

$$+g_\omega \bar{N}\left(\gamma_\mu + i\frac{\mu_S}{2M}\sigma_{\mu\nu}k^\nu\right)\omega^\mu N$$

so use for PV NN



Then define general PV weak couplings:

$$\mathcal{H}_{\rm wk} = \frac{f_\pi^1}{\sqrt{2}}\bar{N}(\tau\times\pi)_3 N$$

$$+\bar{N}\left(h_\rho^0\tau\cdot\rho^\mu + h_\rho^1\rho_3^\mu + \frac{h_\rho^2}{2\sqrt{6}}(3\tau_3\rho_3^\mu - \tau\cdot\rho^\mu)\right)\gamma_\mu\gamma_5 N$$

$$+\bar{N}(h_\omega^0\omega^\mu + h_\omega^1\tau_3\omega^\mu)\gamma_\mu\gamma_5 N - h_\rho^{\prime 1}\bar{N}(\tau\times\rho^\mu)_3\frac{\sigma_{\mu\nu}k^\nu}{2M}\gamma_5 N$$

Yields two-body PV NN potential

$$
\begin{aligned}
V^{\mathrm{PNC}} = {} & i\frac{f_\pi^1 g_{\pi NN}}{\sqrt{2}}\left(\frac{\tau_1\times\tau_2}{2}\right)_3(\sigma_1+\sigma_2)\cdot\left[\frac{\mathbf{p}_1-\mathbf{p}_2}{2M}, f_\pi(r)\right] \\
& -g_\rho\left(h_\rho^0\tau_1\cdot\tau_2+h_\rho^1\left(\frac{\tau_1+\tau_2}{2}\right)_3+h_\rho^2\frac{(3\tau_1^3\tau_2^3-\tau_1\cdot\tau_2)}{2\sqrt{6}}\right) \\
& \times\left((\sigma_1-\sigma_2)\cdot\left\{\frac{\mathbf{p}_1-\mathbf{p}_2}{2M}, f_\rho(r)\right\}\right. \\
& \left.+i(1+\chi_V)\sigma_1\times\sigma_2\cdot\left[\frac{\mathbf{p}_1-\mathbf{p}_2}{2M}, f_\rho(r)\right]\right) \\
& -g_\omega\left(h_\omega^0+h_\omega^1\left(\frac{\tau_1+\tau_2}{2}\right)_3\right) \\
& \times\left((\sigma_1-\sigma_2)\cdot\left\{\frac{\mathbf{p}_1-\mathbf{p}_2}{2M}, f_\omega(r)\right\}\right. \\
& \left.+i(1+\chi_S)\sigma_1\times\sigma_2\cdot\left[\frac{\mathbf{p}_1-\mathbf{p}_2}{2M}, f_\omega(r)\right]\right) \\
& -(g_\omega h_\omega^1-g_\rho h_\rho^1)\left(\frac{\tau_1-\tau_2}{2}\right)_3(\sigma_1+\sigma_2)\cdot\left\{\frac{\mathbf{p}_1-\mathbf{p}_2}{2M}, f_\rho(r)\right\} \\
& -g_\rho h_\rho^{1'} i\left(\frac{\tau_1\times\tau_2}{2}\right)_3(\sigma_1+\sigma_2)\cdot\left[\frac{\mathbf{p}_1-\mathbf{p}_2}{2M}, f_\rho(r)\right]
\end{aligned}
$$

where

$$f_V(r) = \exp(-m_V r)/4\pi r$$

Key problem is to evaluate seven weak couplings

1980: DDH—Quark Model plus Symmetry

Represent states by

$$|N>\sim b^\dagger_{qs}b^\dagger_{q's'}b^\dagger_{q``s"}|0>$$

$$|M>\sim b^\dagger_{qs}d^\dagger_{q's'}|0>$$

and

$$\mathcal{H}_{\rm wk}\sim\frac{G}{\sqrt{2}}\bar\psi\mathcal{O}\psi\bar\psi\mathcal{O}'\psi$$

Then structure of weak matrix element is

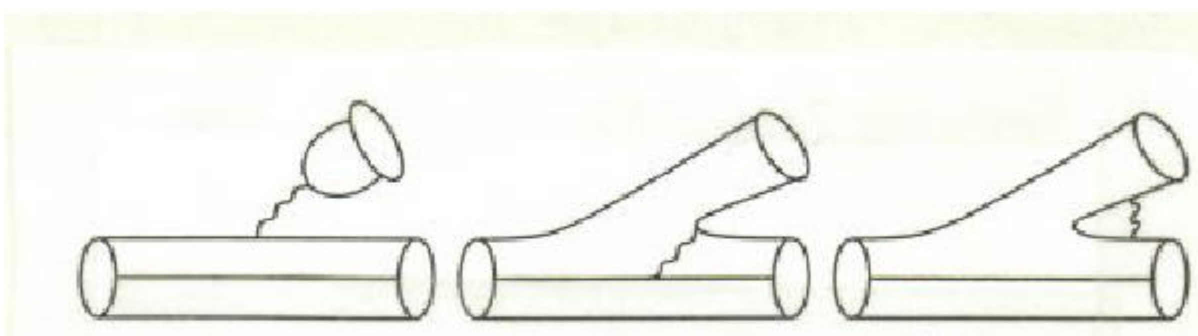
$$< MN|\mathcal{H}_{\rm wk}|N >= \frac{G}{\sqrt{2}} < 0|(b_{qs}b_{q's'}b_{q``s"})(b_{qs}d_{q's'})$$

$$\times\bar{\psi}\mathcal{O}\psi\bar{\psi}\mathcal{O}'\psi(b^\dagger_{qs}b^\dagger_{q's'}b^\dagger_{q``s"})|0 > \times R$$

with R a complicated radial integral—$i.e.$, a "Wigner-Eckart" theorem

$$< MN|\mathcal{H}_{\rm wk}|N >\sim \text{known "geometrical" factor} \times R$$

Find three basic structures



Here first is factorization, but two additional diagrams

Represent in terms of "Reasonable Range" and "Best Value"

Coupling	DDH Reasonable Range	DDH "Best" Value
f_π^1	$0 \to 30$	12
h_ρ^0	$30 \to -81$	-30
h_ρ^1	$-1 \to 0$	-0.5
h_ρ^2	$-20 \to -29$	-25
h_ω^0	$15 \to -27$	-5
h_ω^1	$-5 \to -2$	-3

all times "sum rule value" 3.8×10^{-8}

Others have also investigated PV couplings, e.g.:

Meissner and Kaiser used chiral methods to argue h_π^1 small.

Recent (2008) work by Hwang and Wen evaluated same using QCD sum rules. Results consistent with DDH except for h_ρ^2 and h_ω^1.

Experimental

Can use nucleus as amplifier—first order perturbation theory

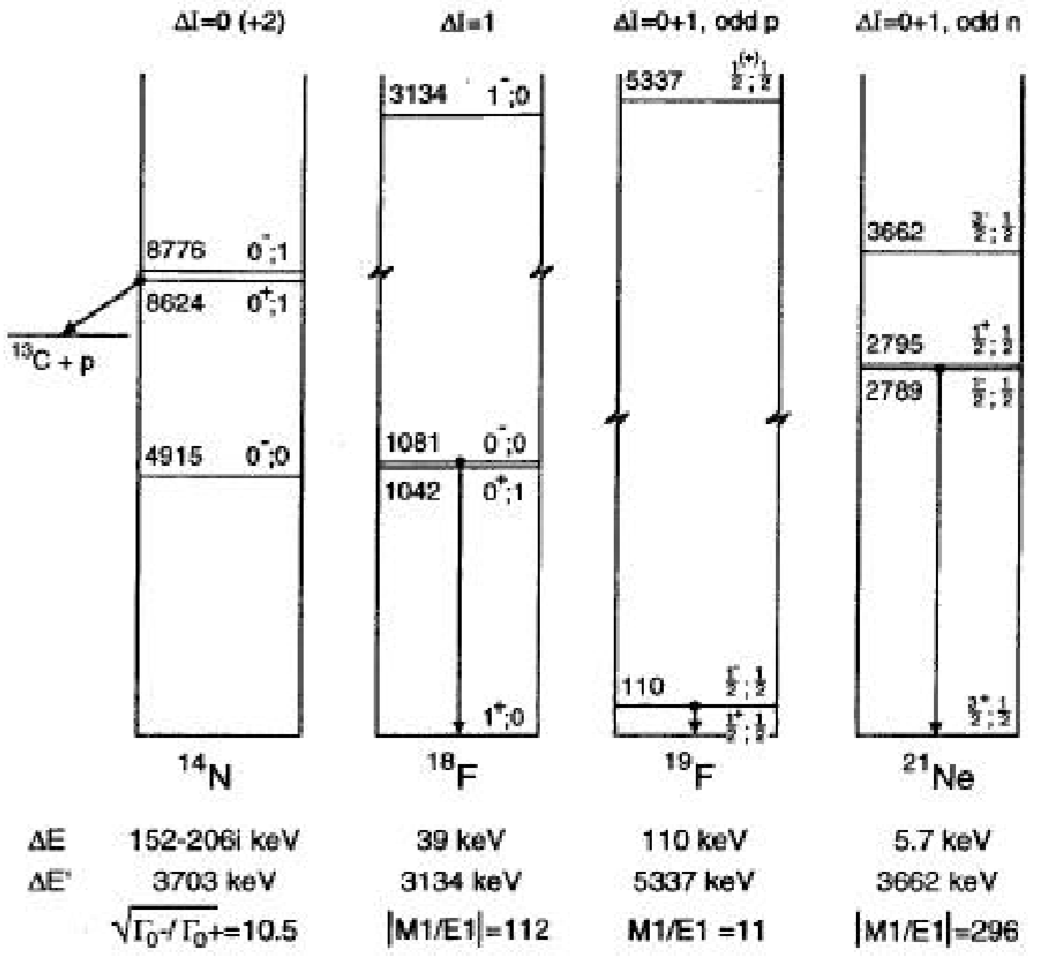
$$|\psi_{J^+}> \simeq |\phi_{J^+}> + \frac{|\phi_{J^-}><\phi_{J^-}|\mathcal{H}_{\rm wk}|\phi_{J^+}>}{E_+ - E_-}$$

$$= |\phi_{J^+}> + \epsilon|\phi_{J^-}>$$

$$|\psi_{J^-}> \simeq |\phi_{J^-}> + \frac{|\phi_{J^+}><\phi_{J^+}|\mathcal{H}_{\rm wk}|\phi_{J^-}>}{E_- - E_+}$$

$$= |\phi_{J^-}> - \epsilon|\phi_{J^+}>$$

Then enhancement if ΔE << typical spacing. Examples are



Circular Polarization in ^{21}Ne E1 decay of $\frac{1}{2}^-$ 2.789 Mev excited state

$$P_\gamma = \begin{cases} (24 \pm 24) \times 10^{-4} & \text{Seattle/Chalk River} \\ (3 \pm 16) \times 10^{-4} & \text{Chalk River/Seattle} \end{cases}$$

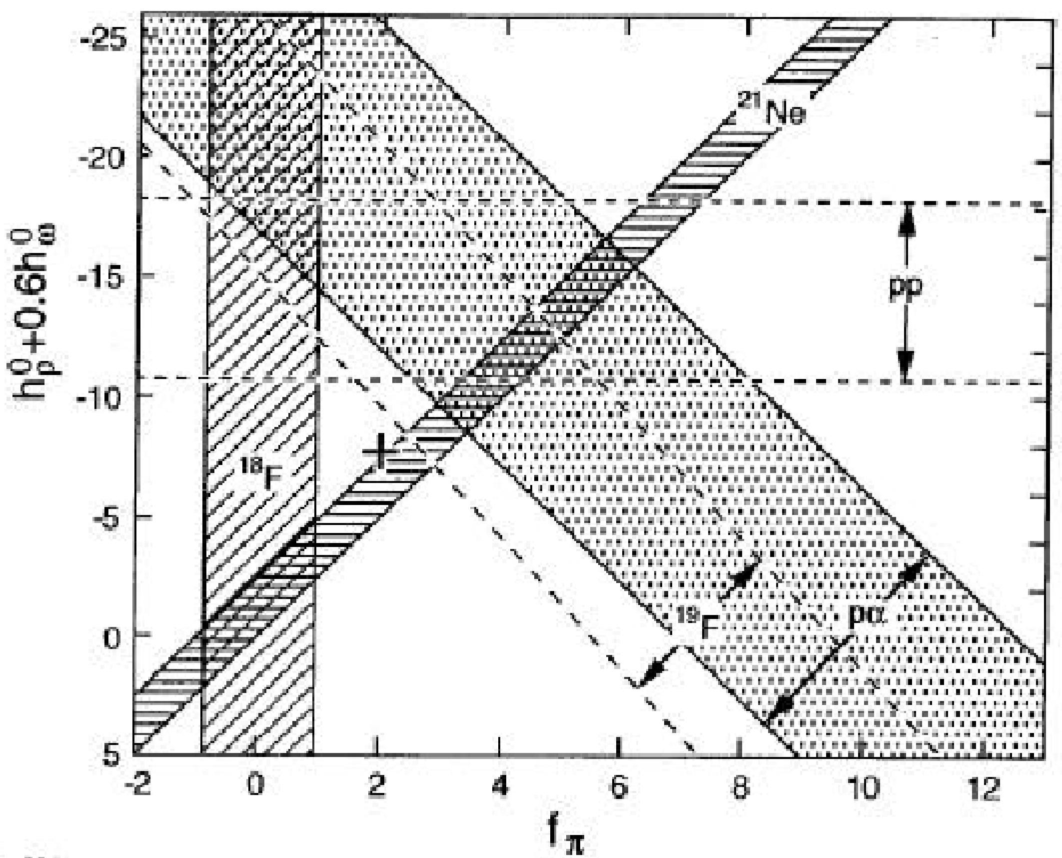
Also results on NN systems which are not enhanced:

pp: PSI $A_z^{tot}(45.0\,MeV) = -(1.57 \pm 0.23) \times 10^{-7}$

pp: Bonn $A_z(13.6\,MeV) = -(0.93 \pm 0.20 \pm 0.05) \times 10^{-7}$

pα: PSI $A_z(46.0\,MeV) = -(3.3 \pm 0.9) \times 10^{-7}$

Graphical Summary



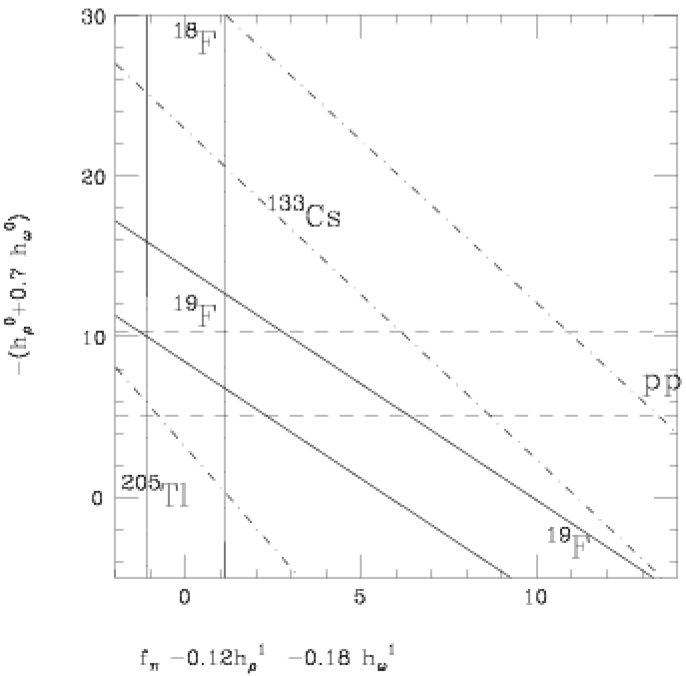
Wavefunction effects—Miller

J. Miller–Phys. Rev. **C67** 042501 (2003)–points out

i) correlations in pion exchange

ii) use of proper strong interaction couplings re: Bonn potential

yields changes in obtained couplings and possible consistency:

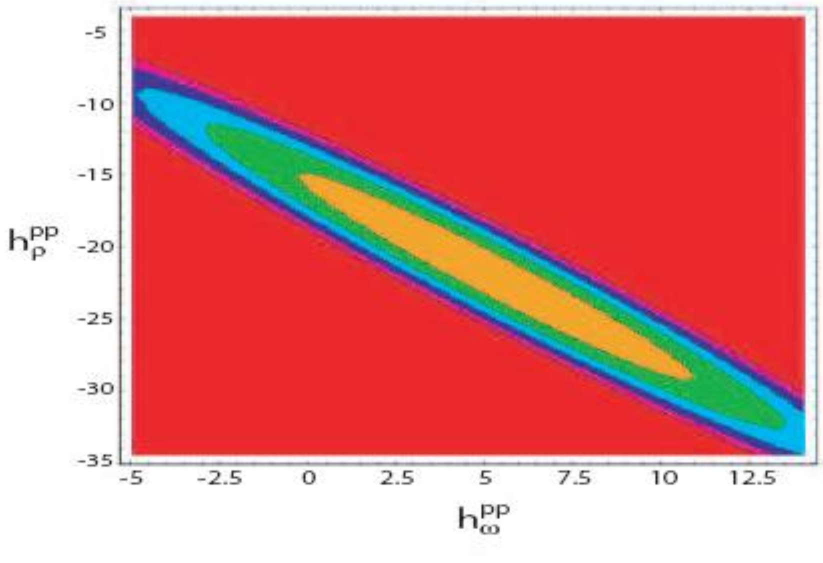


30
20
10
0
0
5
10
^{18}F
^{133}Cs
^{19}F
pp
^{205}Tl
^{19}F
$-(h_\rho^0+0.7\ h_\omega^0)$
$f_\pi\ -0.12h_\rho^1\ \ -0.18\ h_\omega^1$

TRIUMF E497

$\vec{p}p$ scattering at 221 MeV–special energy S-P vanishes–sensitive to P-D mixing

$$A_L = (0.84 \pm 0.29 \pm 0.27) \times 10^{-7}$$



PV n-scattering in heavy nuclei

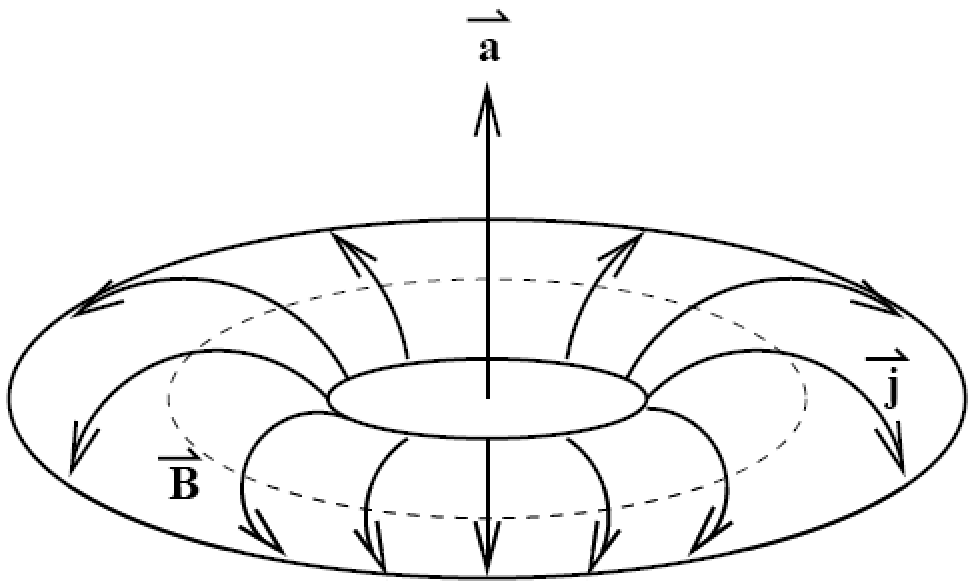
Series of experiments at LANL involving neutron scattering in heavy nuclei with nearby S-Pwave resonances by Bowman et al. was analyzed using statistical model by Johnson and Bowman. Results were found to be roughly consistent but somewhat larger than DDH best values.

Also Bowman has shown that consistent nuclear fit can be obtained if one goes outside DDH limits. I

A: Anapole Moment

Background—usual analysis of magnetic field away from currents involves multipole expansion—dipole, quadrupole, octupole, etc.

If parity violated a new possibility: toroidal current



Leads to *local* field! Another view: Consider matrix element of V_μ^{em} with parity violation:

$$< f|V_\mu^{em}|i >= \bar{u}(p_f)[F_1(q^2)\gamma_\mu - F_2(q^2)\frac{i\sigma_{\mu\nu}q^\nu}{2M}$$

$$+F_3(q^3)\frac{1}{4M^2}(\gamma_\mu\gamma_5 q^2 - q_\mu \not{q}\gamma_5) + F_4(q^2)\frac{i\sigma_{\mu\nu}q^\nu\gamma_5}{2M}]u(p_i)$$

Here $F_1(q^2)$, $F_2(q^2)$ usual charge, magnetic form factors.

$F_4(q^2)$ violates both P,T and is electric dipole moment.

$F_3(q^2)$ violates only T and is anapole moment—note q^2 dependence—local!

Since involves axial current—spin dependent—find via spin-dependent PV effect. Performed by Wieman et al. in 6S-7S ^{133}Cs transitions.

Effective interaction is

$$\mathcal{H}_w^{eff} = \frac{G_F}{\sqrt{2}}(\kappa_Z + \kappa_a)\vec{\alpha}_e \cdot \vec{J}_{nuc}\rho(r)$$

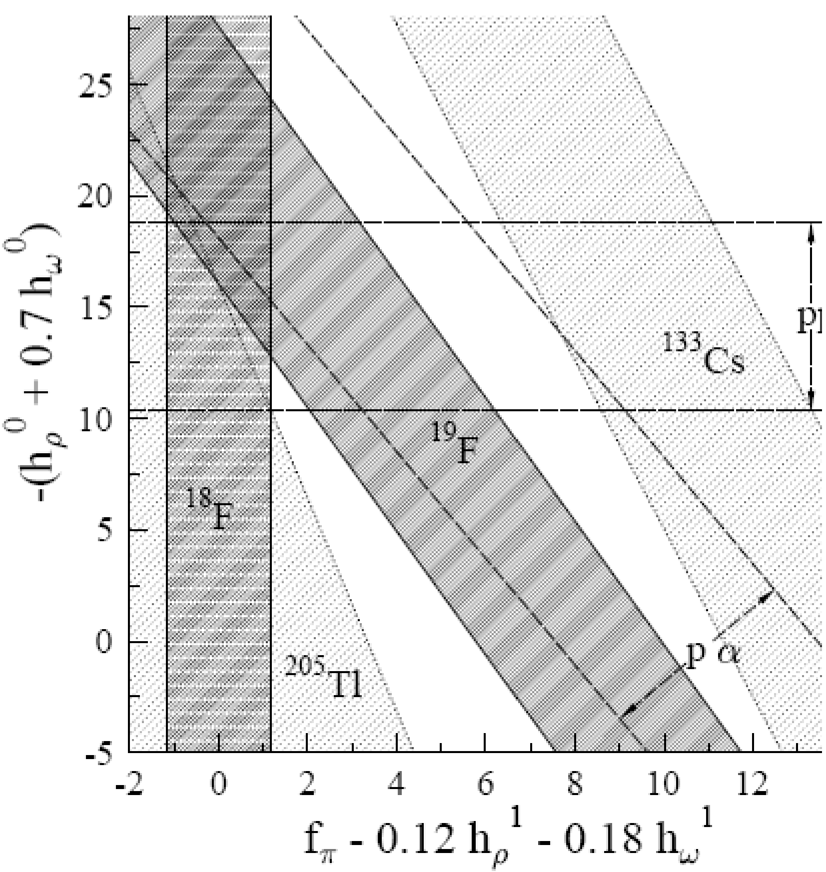
Here $\kappa_Z = 0.013$ is direct Z-exchange term and

$$\kappa_a = 0.112 \pm 0.016$$

is anapole moment

In terms of DDH

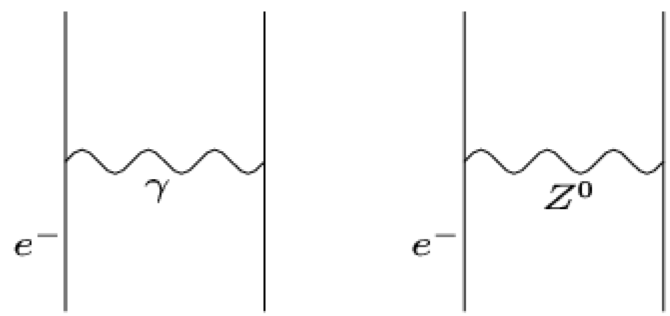
$$h_\pi - 0.21(h_\rho^0 + 0.6h_\omega^0) = (0.99 \pm 0.16) \times 10^{-6}$$



^{18}F
^{19}F
^{133}Cs
^{205}Tl
p p
p α
$-(h_\rho^0 + 0.7\, h_\omega^0)$
$f_\pi - 0.12\, h_\rho^1 - 0.18\, h_\omega^1$

B: SAMPLE Experiment

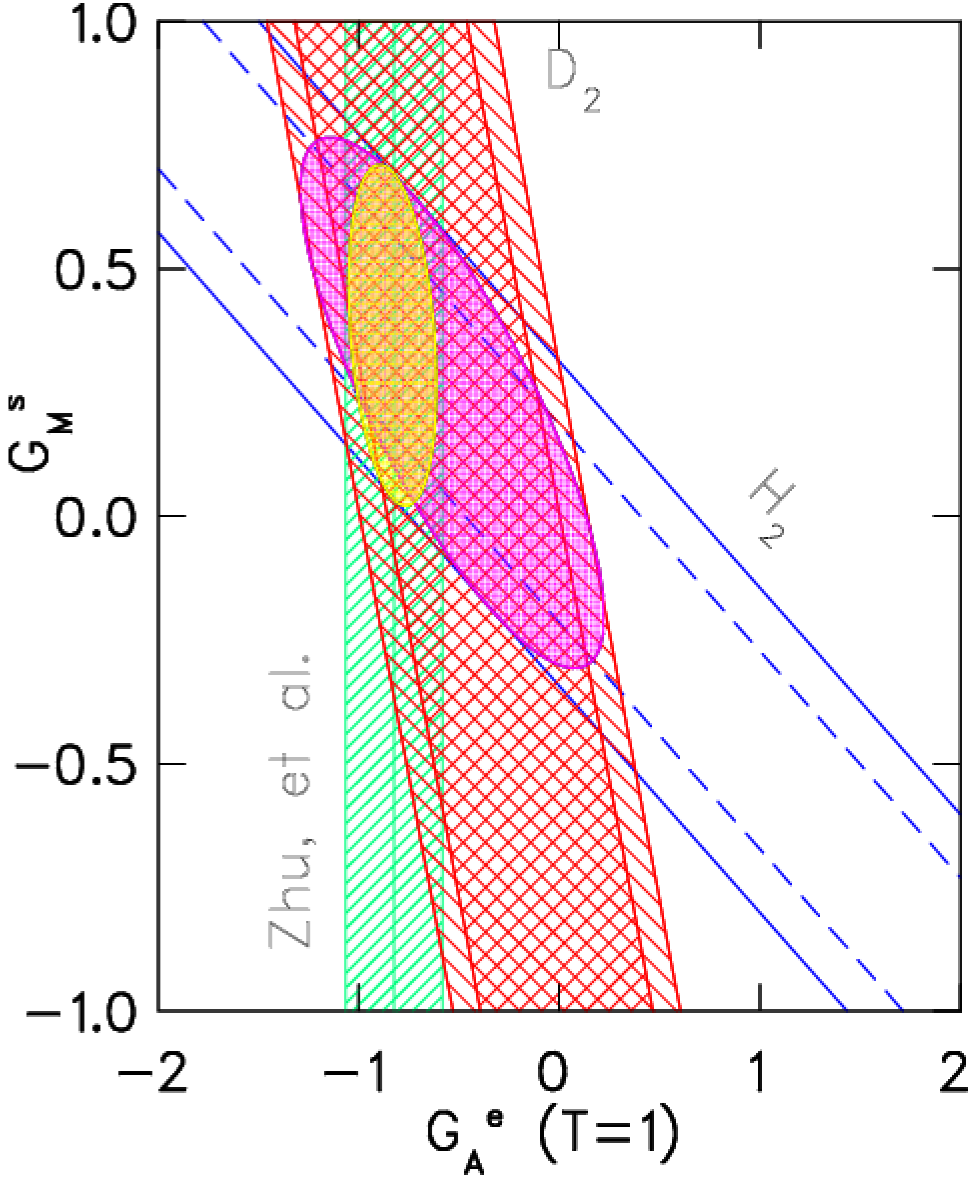
Looks for PV electron scattering in backward direction—interference of photon and Z-exchange



(a) (b)

Asymmetry given by

$$A =\sim G_F \frac{q^2}{\alpha}\left[\frac{\#G_E^{\gamma}G_E^{Z} + \#G_M^{\gamma}G_M^{Z} + \#(1-4\sin^2\theta_w)G_M^{\gamma}G_A^{Z}}{\#G_E^{\gamma 2} + \#G_M^{\gamma 2}}\right]$$



1.0
0.5
0.0
−0.5
−1.0
−2
−1
0
1
2
G_M^s
G_A^e (T=1)
D_2
H_2
Zhu, et al.

A New Approach:

Note low energy NN PV characterized by five amplitudes:

i) $d_t(k) - - - {}^3S_1 - -{}^1P_1$ mixing: $\Delta I = 0$

ii) $c_t(k) - - - {}^3S_1 - -{}^3P_1$ mixing: $\Delta I = 1$

iii) $d_s^{0,1,2}(k) - - - {}^1S_0 - - - {}^3P_0$ mixing: $\Delta I = 0, 1, 2$

Unitarity requires

$$d_{s,t}(k) = |d_{s,t}(k)| \exp i(\delta_S(k) + \delta_P(k))$$

Danilov suggests

$$d_i(k) \approx \lambda_i m_i(k)$$

with

$$m_i(k) = \frac{1}{k} e^{i\delta_i(k)} \sin\delta_i(k) \xrightarrow{k \longrightarrow 0} a_i$$

so

$$\lim_{k \longrightarrow 0} c_t(k), d_t(k), d_s^{0,1,2}(k) = \rho_t a_t, \lambda_t a_t, \lambda_s^{0,1,2} a_s$$

Need *five* independent experiments—use nuclei with $A \leq 4$. Interpret using Desplanques and Missimer

i) $\vec{p}p$ scattering

$$pp(13.6MeV) \quad A_L = -0.48 M\lambda_s^{pp}$$

$$pp(45MeV) \quad A_L = -0.82 M\lambda_s^{pp}$$

ii) $\vec{p}\alpha$ scattering

$$p\alpha(46MeV) \quad A_L = -M[0.48(\lambda_s^{pp}+\frac{1}{2}\lambda_s^{pn})+1.07(\frac{1}{2}\lambda_t+\rho_t)]$$

iii) Radiative Capture–$np \rightarrow d\gamma$

a) Circular Polarization : $P_\gamma = M(0.63\lambda_t - 0.16\lambda_s^{np})$

b) Photon asymmetry : $A_\gamma = -0.11M\rho_t$

iv) Neutron spin rotation in He

$$\frac{d\phi^{n\alpha}}{dz} = [0.85(\lambda_s^{nn} - \frac{1}{2}\lambda_s^{pn}) - 1.89(\rho_t - \frac{1}{2}\lambda_t)]m_N \ \mathrm{rad/m}$$

Status of experiments

a)	pp(13.6 MeV)	performed at Bonn
b)	pp(45 MeV)	performed at PSI
c)	pα(46 MeV)	performed at PSI
d)	$P_\gamma(np)$	Shanghai???
e)	$A_\gamma(np)$	done at LANSCE; moved to SNS
f)	$\phi^{n\alpha}$	done at NIST; move to SNS?

Use EFT ideas

Zhu, Maekawa, BRH, Ramsey-Musolf, van Kolck
Effective potential is (pionless theory)

$$
\begin{aligned}
V_{eff}(r) &= \frac{2}{\Lambda_\chi^3}\{[C_1 + (C_2 + C_4)\left(\frac{\tau_1+\tau_2}{2}\right)_3 \\
&+ C_3\tau_1\cdot\tau_2 + \mathcal{I}_{ab}C_5\tau_1^a\tau_2^b] \\
&\qquad (\vec{\sigma}_1 - \vec{\sigma}_2)\cdot\{-i\vec{\nabla}, f_m(r)\} \\
&\qquad +[\tilde{C}_1 + (\tilde{C}_2 + \tilde{C}_4)\left(\frac{\tau_1+\tau_2}{2}\right)_3 \\
&+ \tilde{C}_3\tau_1\cdot\tau_2 + \mathcal{I}_{ab}\tilde{C}_5\tau_1^a\tau_2^b] \\
&\times \qquad i\,(\vec{\sigma}_1\times\vec{\sigma}_2)\cdot[-i\vec{\nabla}, f_m(r)] \\
&\qquad + (C_2 - C_4)\left(\frac{\tau_1-\tau_2}{2}\right)_3 \\
&\times (\vec{\sigma}_1 + \vec{\sigma}_2)\cdot\{-i\vec{\nabla}, f_m(r)\} \\
&\qquad +\tilde{C}_6 i\epsilon^{ab3}\tau_1^a\tau_2^b\,(\vec{\sigma}_1 + \vec{\sigma}_2)\cdot[-i\vec{\nabla}, f_m(r)]\Big\}
\end{aligned}
$$

with

$$\mathcal{I} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

and $f_m(\vec{r})$ is function that

i) strongly peaked, with width $\sim 1/m$ about $r = 0$

ii) approaches $\delta^{(3)}(\vec{r})$ in zero-width ($m \to \infty$) limit.

e.g.,

$$f_m(r) = \frac{m^2}{4\pi r} \exp\left(-mr\right)$$

Then Liu gives

$$\lambda_t = -0.006((-2.23C_3+\tilde{C}_3)+0.333(-2.23\tilde{C}_1+\tilde{C}_1))M^{-1}$$

$$\lambda_s^{pp} = 0.0043((C_1+C_2+C_3+C_4-2C_5)+1.267(C_i \to \tilde{C}_i))M^{-1}$$
$$\lambda_s^{nn} = 0.0046((C_1-C_2+C_3-C_4-2C_5)+1.262(C_i \to \tilde{C}_i))M^{-1}$$
$$\lambda_s^{np} = 0.0047((C_1 + C_3 + 4C_5) + 1.236(C_i \to \tilde{C}_i))M^{-1}$$
$$\rho_t = 0.0019(1.656(C_2 - C_4) + \tilde{C}_6)M^{-1}$$

Connect with DDH via (with $\Lambda_M = \Lambda_\chi^3/2Mm_M^3$)

$$C_1^{DDH} = -\frac{1}{2}\bar{\Lambda}_\omega^3 g_\omega h_\omega^0 \qquad C_2^{DDH} = -\frac{1}{2}\bar{\Lambda}_\omega^3 g_\omega h_\omega^1$$

$$C_3^{DDH} = -\frac{1}{2}\bar{\Lambda}_\rho^3 g_\rho h_\rho^0 \qquad C_4^{DDH} = -\frac{1}{2}\bar{\Lambda}_\rho^3 g_\rho h_\rho^1$$
$$C_5^{DDH} = \frac{1}{4\sqrt{6}}\bar{\Lambda}_\rho^3 g_\rho h_\rho^2 \qquad \tilde{C}_6^{DDH} = -\frac{1}{2}\bar{\Lambda}_\rho^3 g_\rho h_\rho^{1'}$$

and

$$\tilde{C}_i^{DDH}/C_i^{DDH} = 1 + \chi_\omega \quad i = 1, 2$$
$$\tilde{C}_i^{DDH}/C_i^{DDH} = 1 + \chi_\rho \quad i = 3, 4, 5$$

Note that at threshold matrix elements of C_i (anticommutator) and $\tilde{C}_i$ (commutator) are closely connected so that there are only $five$ independent constants, as required by general principles.

At higher energy, must include pion as a degree of freedom. Then there are two additional constants—PV pion coupling f_π^1, and PV Kroll-Ruderman like term $\tilde{C}_\pi$—as well as medium range two-pion effects that must be added. Now require $seven$ independent experiments!

Recent Paper

See Schiavilla et al. arxiv:0805.3599
Write effective Lagrangian as (Girlanda form)

$$\mathcal{L} = \sum_{i=1}^{6} (C_i \mathcal{O}_i + \tilde{C}_i \tilde{\mathcal{O}}_i)$$

where

$$\begin{array}{ll}
\mathcal{O}_1 = \bar\psi\gamma^\mu\psi\bar\psi\gamma_\mu\gamma_5\psi & \tilde{\mathcal{O}}_1 = \bar\psi\gamma^\mu\gamma_5\psi\partial^\nu(\bar\psi\sigma_{\mu\nu}\psi) \\
\mathcal{O}_2 = \bar\psi\gamma^\mu\psi\bar\psi\tau_3\gamma_\mu\gamma_5\psi & \tilde{\mathcal{O}}_2 = \bar\psi\gamma^\mu\gamma_5\psi\partial^\nu(\bar\psi\tau_3\sigma_{\mu\nu}\psi) \\
\mathcal{O}_3 = \bar\psi\tau_a\gamma^\mu\psi\bar\psi\tau^a\gamma_\mu\gamma_5\psi & \tilde{\mathcal{O}}_3 = \bar\psi\tau_a\gamma^\mu\gamma_5\psi\partial^\nu(\bar\psi\tau^a\sigma_{\mu\nu}\psi) \\
\mathcal{O}_4 = \bar\psi\tau_3\gamma^\mu\psi\bar\psi\gamma_\mu\gamma_5\psi & \tilde{\mathcal{O}}_4 = \bar\psi\tau_3\gamma^\mu\gamma_5\psi\partial^\nu(\bar\psi\sigma_{\mu\nu}\psi) \\
\mathcal{O}_5 = \mathcal{I}_{ab}\bar\psi\tau_a\gamma^\mu\psi\bar\psi\tau_b\gamma_\mu\gamma_5\psi & \tilde{\mathcal{O}}_5 = \mathcal{I}_{ab}\bar\psi\tau_a\gamma^\mu\gamma_5\psi\partial^\nu(\bar\psi\tau_b\sigma_{\mu\nu}\psi) \\
\mathcal{O}_6 = i\epsilon_{ab3}\bar\psi\tau_a\gamma^\mu\psi\bar\psi\tau_b\gamma_\mu\gamma_5\psi & \tilde{\mathcal{O}}_6 = i\epsilon_{ab3}\bar\psi\tau_a\gamma^\mu\gamma_5\psi\partial^\nu(\bar\psi\tau_b\sigma_{\mu\nu}\psi)
\end{array}$$

With Fierz transformation and EOM find six conditions

$$\begin{aligned}
&\mathcal{O}_3 = \mathcal{O}_1 \\
&\mathcal{O}_2 - \mathcal{O}_4 = 2\mathcal{O}_6 \\
&\tilde{\mathcal{O}}_3 + 3\tilde{\mathcal{O}}_1 = 2M(\mathcal{O}_1 + \mathcal{O}_3) \\
&\tilde{\mathcal{O}}_2 + \tilde{\mathcal{O}}_4 = M(\mathcal{O}_2 + \mathcal{O}_4) \\
&\tilde{\mathcal{O}}_2 - \tilde{\mathcal{O}}_4 = -2M\mathcal{O}_6 - \tilde{\mathcal{O}}_6 \\
&\tilde{\mathcal{O}}_5 = \mathcal{O}_5
\end{aligned}$$

Find then effective (pionless) potential

$$V_{EFT} = \frac{2\mu^2}{\Lambda_\chi^3}[(C_1 + (C_2 + C_4)(\frac{\tau_1 + \tau_2}{2}) + C_5 \mathcal{I}_{ab}\tau_{1a}\tau_{2b})(\vec{\sigma}_1 - \vec{\sigma}_2)\cdot\{\vec{p}_{12}, f_\mu(r)\}$$

$$+ i\tilde{C}_1(\vec{\sigma}_1 \times \vec{\sigma}_2)\cdot[\vec{p}_{12}, f_\mu(r)] + iC_6\epsilon_{ab3}\tau_{1a}\tau_{2b}[\vec{p}_{12}, f_\mu(r)]]$$

with only five terms.

Schiavilla et al. calculates nd spin rotation as

$$\frac{1}{\rho}\frac{d\phi}{dz} = \frac{1}{2M}\sum_{i=1}^{12} c_n I_n$$

with for "DDH" (with variable $\kappa_\rho, \kappa_\omega$)

Total is ($\times 10^{-7}$ rad/cm)

$$0.457(\pi) + 0.063(\rho + \omega) = 0.520$$

Lesson: Whether using Girlanda or Zhu et al form of PV potential, ALL calculations of observables should be calculated and quoted in SAME consistent framework.

What's needed?

i) Precision Experiments

a) Bowman et al.—LANSCE, SNS
b) Snow et al.—NIST, SNS
c) HIγS, Shanghai?

ii) State of the art NN theory:

Carlson, Wiringa, Schiavilla, etc.

i) Apply to $\vec{p}^4He$ and n^4He
ii) Apply to $\vec{p}d$ and nd
iii) Others.....

Predicting the Future

After reliable set of couplings obtained

a) Confirm via other experiments in $A < 4$ systems

b) Use these to analyze previous results in heavier nuclei

c) Confront measured numbers with fundamental theory via lattice and/or other methods

d) Reliably predict effects in other experiments

Summary

i) Much work done but still much to do.

ii) On theory side, need all observables expressed in (the same) consistent theoretical picture.

iii) On experimental side need careful and definitive numbers on nucleons and light nuclei

After fifty years, time to put this problem to rest!