Problem:

Parity violating effects in strong

and electromagnetic hadronic interactions.

Examples:

First experiment—PV in pp by Tanner (1957)

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

$A_\gamma = -(1.66 \pm 0.18) \times 10^{-2}$ 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 $\longrightarrow$ 2007

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 $J_\mu^{\rm hadron} \times J^\mu_{\rm hadron}$

Theoretical Picture

$$\mathcal{H}_w = \frac{G_F}{\sqrt{2}} J_\mu^\dagger J^\mu$$

with

$$J_\mu = J_\mu^{\rm hadron} + J_\mu^{\rm lepton}$$

Then

i) $J_\mu^{\rm lepton} \times J_{\rm lepton}^{\mu} \longrightarrow \mu^- \to e^- + \bar{\nu}_e + \nu_\mu$

ii) $J_\mu^{\rm lepton} \times J_{\rm hadron}^{\mu\dagger} \longrightarrow n \to p + e^- + \bar{\nu}_e$

iii) $J_\mu^{\rm hadron} \times J_{\rm hadron}^{\mu\dagger} \longrightarrow$ hadronic PV

Canonical size: $\mathcal{H}_w/\mathcal{H}_{str} \sim G_F m_\pi^2 \sim 10^{-7}$

Isolate via PV effects in strong and/or EM processes

Standard Model Picture

$$\boxed{\mathcal{H}_w = \frac{G_F}{\sqrt{2}}(J_c^\dagger \times J_c + \frac{1}{2} J_n^\dagger \times J_n)}$$

with

$$J_\mu^c = \bar{u}\gamma_\mu(1+\gamma_5)(\cos\theta_c d + \sin\theta_c s)$$

$$J_\mu^n = \bar{u}\gamma_\mu(1+\gamma_5)u - \bar{d}\gamma_\mu(1+\gamma_5)d - \bar{s}\gamma_\mu(1+\gamma_5)s$$

$$-4\sin^2\theta_w J_\mu^{em}$$

Then

$\mathcal{H}_w(\Delta S = 0)$ carries $\Delta I = 0, 1, 2$

leads to

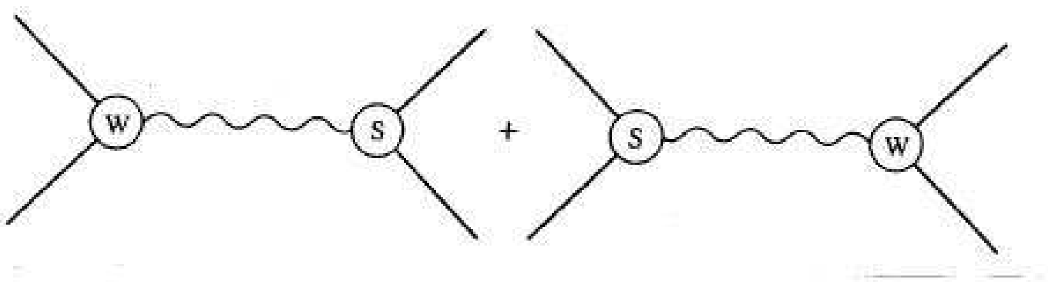
1980: DDH Approach

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 need PV weak couplings:

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

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

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

Gives two-body PV NN potential

$$V^{\rm PNC}=i\frac{f_\pi g_{\pi NN}}{\sqrt{2}}\left(\frac{\tau_1\times\tau_2}{2}\right)_3(\sigma_1+\sigma_2)\cdot\left[\frac{\mathbf{p}_1-\mathbf{p}_2}{2M},f_\pi(r)\right]$$

$$-g_\rho\left(h_\rho^0\tau_1\cdot\tau_2+h_\rho^1\left(\frac{\tau_1+\tau_2}{2}\right)_3+h_\rho^2\frac{(3\tau_1^3\tau_2^3-\tau_1\cdot\tau_2)}{2\sqrt{6}}\right)$$

$$\times((\sigma_1-\sigma_2)\cdot\left\{\frac{\mathbf{p}_1-\mathbf{p}_2}{2M},f_\rho(r)\right\}$$

$$+i(1+\chi_V)\sigma_1\times\sigma_2\cdot\left[\frac{\mathbf{p}_1-\mathbf{p}_2}{2M},f_\rho(r)\right])$$

$$-g_\omega\left(h_\omega^0+h_\omega^1\left(\frac{\tau_1+\tau_2}{2}\right)_3\right)$$

$$\times((\sigma_1-\sigma_2)\cdot\left\{\frac{\mathbf{p}_1-\mathbf{p}_2}{2M},f_\omega(r)\right\}$$

$$+i(1+\chi_S)\sigma_1\times\sigma_2\cdot\left[\frac{\mathbf{p}_1-\mathbf{p}_2}{2M},f_\omega(r)\right])$$

$$-(g_\omega h^1_\omega - g_\rho h^1_\rho)\left(\frac{\tau_1 - \tau_2}{2}\right)_3 (\sigma_1 + \sigma_2)\cdot\left\{\frac{\mathbf{p}_1 - \mathbf{p}_2}{2M}, f_\rho(r)\right\}$$

$$-g_\rho h^{1'}_\rho i\left(\frac{\tau_1 \times \tau_2}{2}\right)_3 (\sigma_1 + \sigma_2)\cdot\left[\frac{\mathbf{p}_1 - \mathbf{p}_2}{2M}, f_\rho(r)\right]$$

where

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

Problem is to calculate seven weak couplings

Historical Approaches

Theoretical

1964: Michel—Factorization

$$< \rho^+ n|\mathcal{H}^c_{\rm wk}|p >= \frac{G}{\sqrt{2}}\cos^2\theta_c < \rho^+ n|V^\mu_+ A^-_\mu|p >$$

$$\approx \frac{G}{\sqrt{2}}\cos^2\theta_c < \rho^+|V^\mu_+|0 >< n|A^-_\mu|p >$$

1968: Tadic, Fischbach, McKeller—SU(3) Sum Rule

$$< \pi^+ n|\mathcal{H}^c_{\rm wk}|p >= -\sqrt{\frac{2}{3}}\tan\theta_c(2 < \pi^- p|\mathcal{H}_{\rm wk}|\Lambda^0 >$$

$$- < \pi^-\Lambda^0|\mathcal{H}_{\rm wk}|\Xi^- >)$$

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

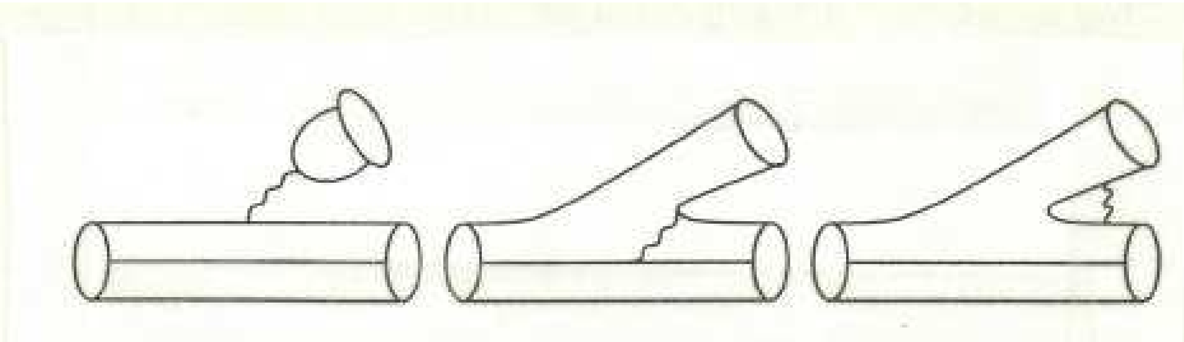
$$<MN|\mathcal{H}_{\rm wk}|N>=\frac{G}{\sqrt{2}}<0|(b_{qs}b_{q's'}b_{q``s"})(b_{qs}d_{q's'})$$

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

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
h_π	$0 \rightarrow 30$	12
h_ρ^0	$30 \rightarrow -81$	-30
h_ρ^1	$-1 \rightarrow 0$	-0.5
h_ρ^2	$-20 \rightarrow -29$	-25
h_ω^0	$15 \rightarrow -27$	-5
h_ω^1	$-5 \rightarrow -2$	-3

all times sum rule value 3.8×10^{-8}

Experimental

Can use nucleus as amplifier—first order perturbation theory

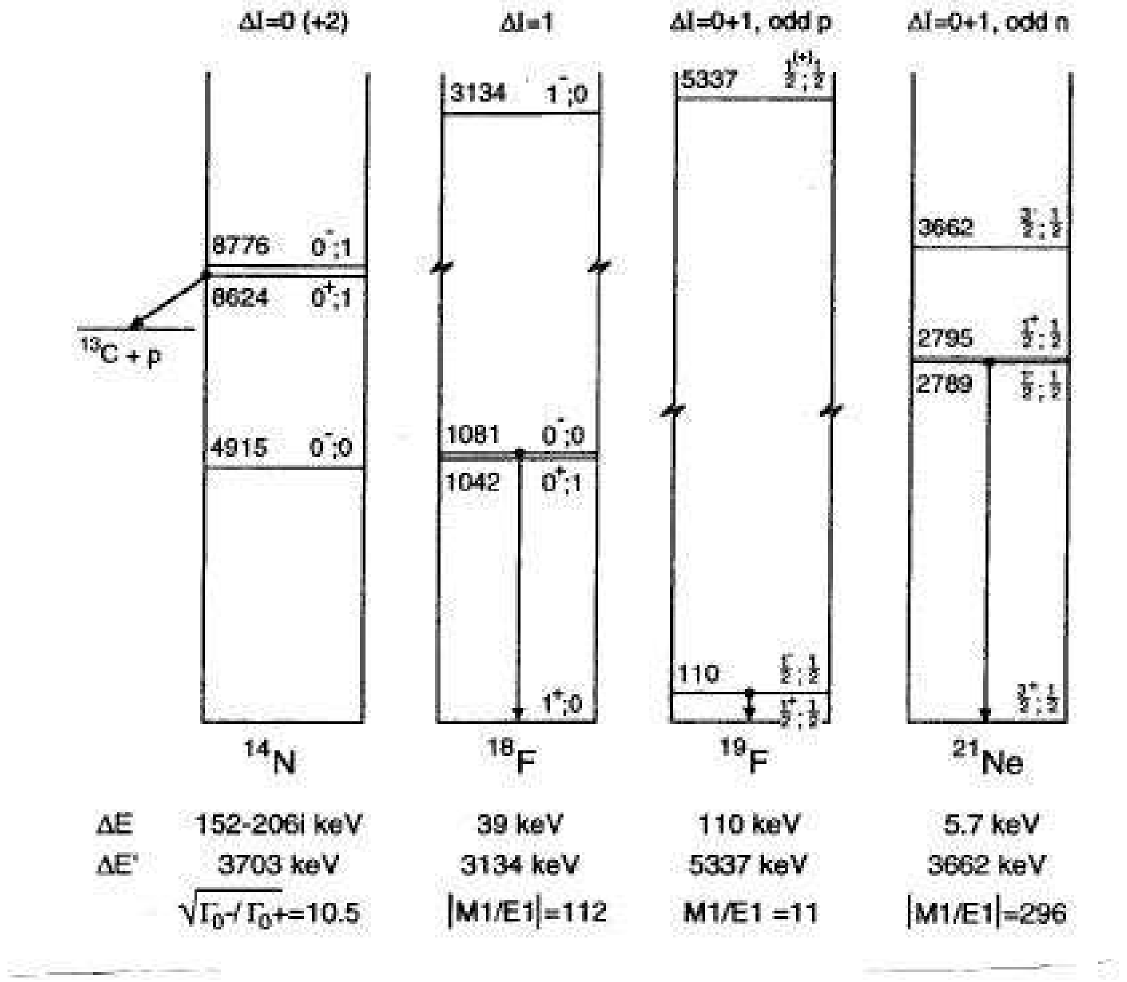
$$|\psi_{J^+}> \simeq |\phi_{J^+}> + \frac{|\phi_{J^-}><\phi_{J^-}|\mathcal{H}_{\rm wk}|\phi_{J^+}>}{E_+ - E_-}$$

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

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

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

Then enhancement if $\Delta E << $ typical spacing. Examples are



ΔI=0 (+2)
ΔI=1
ΔI=0+1, odd p
ΔI=0+1, odd n
8776 0⁻;1
8624 0⁺;1
13C + p
4915 0⁻;0
3134 1⁻;0
1081 0⁻;0
1042 0⁺;1
1⁺;0
5337
110
3662
2795
2789
14N
18F
19F
21Ne
ΔE
ΔE'
152-206i keV
3703 keV
39 keV
3134 keV
|M1/E1|=112
110 keV
5337 keV
M1/E1 =11
5.7 keV
3662 keV
|M1/E1|=296

Typical results: Circular polarization in ^{18}F E1 decay of 0^- 1.081 MeV excited state

$$|P_\gamma(1081)| = \left\{ \begin{array}{cc} (-7 \pm 20) \times 10^{-4} & \text{Caltech/Seattle} \\ (3 \pm 6) \times 10^{-4} & \text{Florence} \\ (-10 \pm 18) \times 10^{-4} & \text{Mainz} \\ (2 \pm 6) \times 10^{-4} & \text{Queens} \\ (-4 \pm 30) \times 10^{-4} & \text{Florence} \end{array} \right.$$

Asymmetry in decay of polarized $\frac{1}{2}^-$ 110 KeV excited state of ^{19}F

$$A_\gamma = \left\{ \begin{array}{cc} (-8.5 \pm 2.6) \times 10^{-5} & \text{Seattle} \\ (-6.8 \pm 1.8) \times 10^{-5} & \text{Mainz} \end{array} \right.$$

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

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

Also results on NN systems which are not enhanced:

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

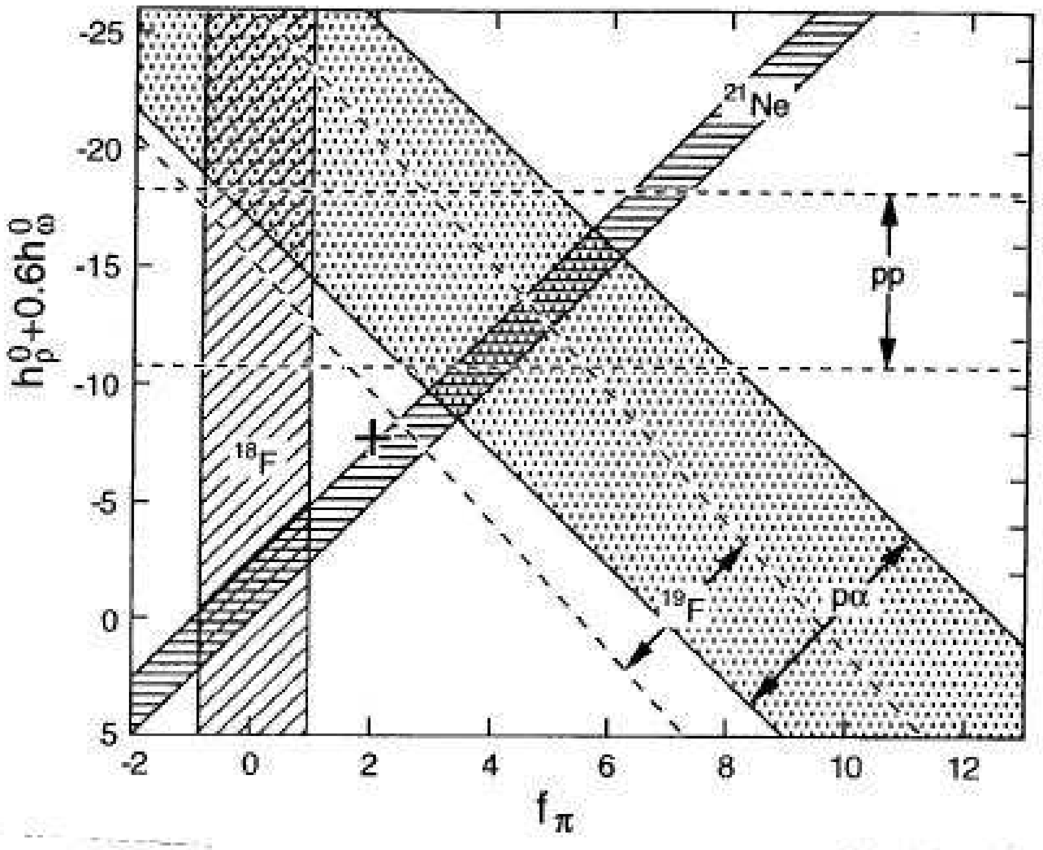
pp: Bonn $A_z(13.6\,MeV) = -(0.93 \pm 0.20 \pm 0.05) \times 10^{-7}$

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

Summary of present results in nuclei:

Reaction	Excited State	Measured Quantity	Experiment ($\times 10^{-5}$)	Theory ($\times 10^{-5}$)
^{13}C(p, α)^{14}N	J=0^+, T=1 8.264 MeV J=0^-, T=1 8.802 MeV	$[A_z(35^\circ)$ $-A_z(155^\circ)]$	0.9 ± 0.6	-2.8
^{19}F(p, α)^{20}Ne	J=1^+, T=1 13.482 MeV J=1^-, T=0 13.462 MeV	$A_z(90^\circ)$ A_z A_x	150 ± 76 660 ± 240 100 ± 100	
^{18}F	J=0^-, T=0 1.081 MeV	P_γ mean	-70 ± 200 -40 ± 300 -100 ± 180 17 ± 58 27 ± 57 12 ± 38	208 ± 49
^{19}F	J=$\frac{1}{2}^-, T + \frac{1}{2}$ 0.110 MeV	A_γ mean	-8.5 ± 2.6 -6.8 ± 2.1 -7.4 ± 1.9	-8.9 ± 1.6
^{21}Ne	J=$\frac{1}{2}^-, T = \frac{1}{2}$ 2.789 MeV	P_γ	80 ± 140	46

Graphical Summary

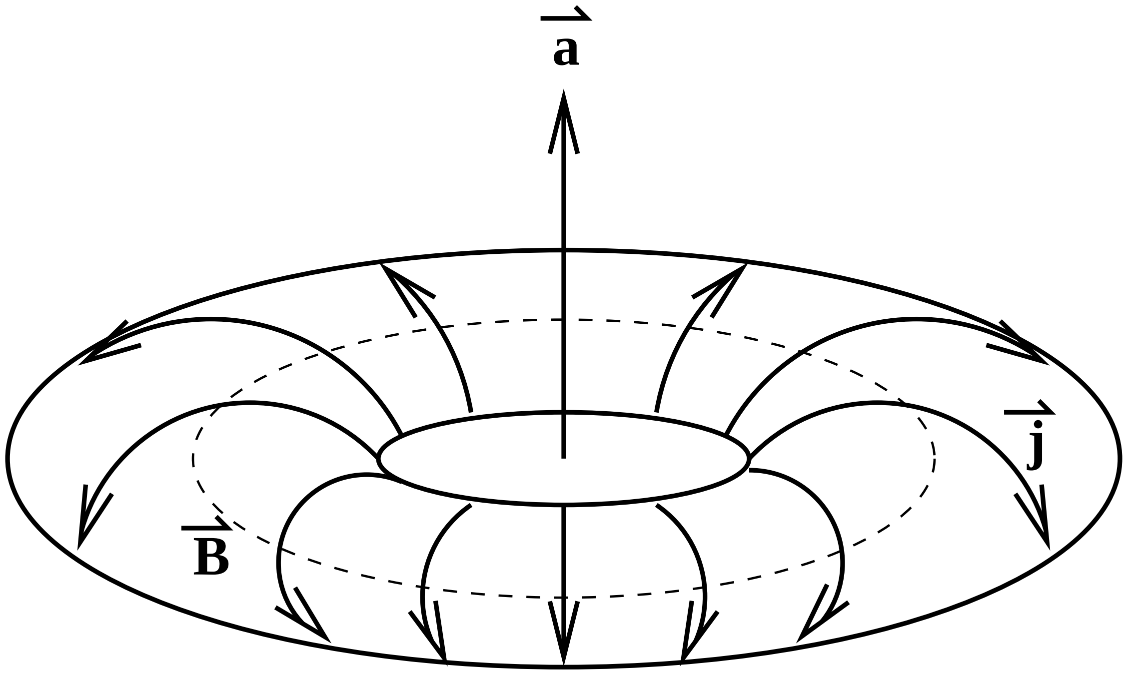


Recent Additions

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

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

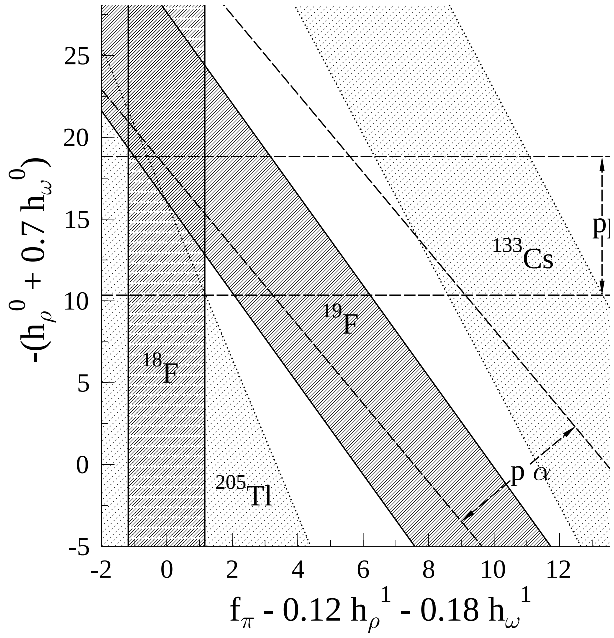
Here $\kappa_Z = 0.013$ is direct Z-exchange term and

$$\kappa_a = 0.112 \pm 0.016$$

is anapole moment

In terms of DDH

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



Now What?

A Vision

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

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

so

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

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

i) $\vec{p}p$ scattering

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

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

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 : $A_\gamma = -0.11 M\rho_t$

iv) Neutron spin rotation in He

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

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)	$P_\gamma(np)$	Athens, Duke, ???
e)	$A_\gamma(np)$	done at Lansce; scheduled and moved t
f)	$\phi^{n\alpha}$	scheduled at NIST; move to SNS?

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.....

iii) Use Effective field theory ideas

BH, Ramsey-Musolf, van Kolck, etc.

Effective potential is (pionless theory)

$$\frac{2}{\Lambda_\chi^3}\{[C_1 + (C_2 + C_4)\left(\frac{\tau_1 + \tau_2}{2}\right)_3$$

$$
\begin{aligned}
+ \quad & C_3\tau_1\cdot\tau_2 + \mathcal{I}_{ab}C_5\tau_1^a\tau_2^b] \\
& \qquad (\vec{\sigma}_1 - \vec{\sigma}_2)\cdot\{-i\vec{\nabla}, f_m(r)\} \\
& \quad +[\tilde{C}_1 + (\tilde{C}_2 + \tilde{C}_4)\left(\frac{\tau_1+\tau_2}{2}\right)_3 \\
+ \quad & \tilde{C}_3\tau_1\cdot\tau_2 + \mathcal{I}_{ab}\tilde{C}_5\tau_1^a\tau_2^b] \\
\times \quad & \qquad i\,(\vec{\sigma}_1 \times \vec{\sigma}_2)\cdot[-i\vec{\nabla}, f_m(r)] \\
& \quad +(C_2 - C_4)\left(\frac{\tau_1-\tau_2}{2}\right)_3 \\
\times \quad & (\vec{\sigma}_1 + \vec{\sigma}_2)\cdot\{-i\vec{\nabla}, f_m(r)\} \\
& \quad +C_6 i\epsilon^{ab3}\tau_1^a\tau_2^b\,(\vec{\sigma}_1 + \vec{\sigma}_2)\cdot[-i\vec{\nabla}, f_m(r)]\Big\}
\end{aligned}
\tag{1}
$$

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.,

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

Check counting in pionless theory in point approximation—p-wavefunction vanishes:

$$\begin{gathered}
\lambda_t \propto (C_1 - C_3) - (\tilde{C}_1 - 3\tilde{C}_3) \\
\lambda_s^0 \propto (C_1 + C_3) + (\tilde{C}_1 + \tilde{C}_3) \\
\lambda_s^1 \propto (C_2 + C_4) + (\tilde{C}_2 + \tilde{C}_4) \\
\lambda_s^2 \propto -\sqrt{\frac{8}{3}}(C_5 + \tilde{C}_5) \\
\rho_t \propto (C_2 - C_4) + 2C_6
\end{gathered}$$

Using finite size corrections find corrections, e.g.

$$M_N \rho_t = -\frac{2}{\Lambda^3}[B_2(\frac{1}{2}C_2 - \frac{1}{2}C_4 + C_6) + B_3(\frac{1}{2}C_2 - \frac{1}{2}C_4 - C_6)]$$

with $B_2 = -0.0043$ and $B_3 = 0.0005$.

Connect with DDH via

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

$$C_3^{DDH} = -\frac{1}{2}\bar{\Lambda}_\rho^3 g_\rho h_\rho^0 \qquad C_4^{DDH} = -\frac{1}{2}\bar{\Lambda}_\rho^3 g_\rho h_\rho^1$$

$$C_5^{DDH} = \frac{1}{4\sqrt{6}}\bar{\Lambda}_\rho^3 g_\rho h_\rho^2 \qquad C_6^{DDH} = -\frac{1}{2}\bar{\Lambda}_\rho^3 g_\rho h_\rho^{1'}$$

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 and $\tilde{C}_i$ are 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—h_π and a PV analog of Kroll-Ruderman term—as well as the addition of medium range two-pion-exchange effects. Now require *seven* independent experiments!

Result is understanding of PVNN by ??

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