Hadronic parity violation in $d\gamma \to np$ at low energies

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Outline

- Current Status
- What and How
- Results
- Conclusion

Current Status

- Parity-violating (PV) nuclear forces: believed to be originated from weak interactions
- Understanding the interactions from the first principles: QCD, standard model
- Follow the tradition : meson exchange picture
- Or rely on new methods: effective field theory (EFT)

Meson exchange PV potential: DDH potential

$$
\begin{aligned}
V_{\mathrm{PV}}(\boldsymbol{r}) &= V_{\mathrm{PV}}^{\pi}(\boldsymbol{r}) + V_{\mathrm{PV}}^{\rho}(\boldsymbol{r}) + V_{\mathrm{PV}}^{\omega}(\boldsymbol{r}), \\
V_{\mathrm{PV}}^{\pi}(\boldsymbol{r}) &= i\frac{g_{\pi NN} h_{\pi}^{1}}{2\sqrt{2}m_N}(\boldsymbol{\tau}_1 \times \boldsymbol{\tau}_2)^z (\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2)\cdot[\boldsymbol{p},\, f_{\pi}(r)], \\
V_{\mathrm{PV}}^{\rho}(\boldsymbol{r}) &= -\frac{g_{\rho NN}}{m_N}\left[\left(h_{\rho}^{0}\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2 + \frac{1}{2}h_{\rho}^{1}(\tau_1^z + \tau_2^z) + \frac{h_{\rho}^{2}}{2\sqrt{6}}(3\tau_1^z\tau_2^z - \boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)\right)\times\right. \\
&\qquad ((\boldsymbol{\sigma}_1 - \boldsymbol{\sigma}_2)\cdot\{\boldsymbol{p},\, f_{\rho}(r)\} + i(1+\chi_{\rho})(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\cdot[\boldsymbol{p},\, f_{\rho}(r)]) \\
&+ \left. i\frac{h_{\rho}^{1'}}{2}(\boldsymbol{\tau}_1\times\boldsymbol{\tau}_2)^z(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)\cdot[\boldsymbol{p},\, f_{\rho}(r)] - \frac{h_{\rho}^{1}}{2}(\tau_1^z - \tau_2^z)(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)\cdot\{\boldsymbol{p},\, f_{\rho}(r)\}\right], \\
V_{\mathrm{PV}}^{\omega}(\boldsymbol{r}) &= -\frac{g_{\omega NN}}{m_N}\left[\left(h_{\omega}^{0} + \frac{1}{2}h_{\omega}^{1}(\tau_1^z + \tau_2^z)\right)\times\right. \\
&\qquad ((\boldsymbol{\sigma}_1 - \boldsymbol{\sigma}_2)\cdot\{\boldsymbol{p},\, f_{\omega}(r)\} + i(1+\chi_{\omega})(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\cdot[\boldsymbol{p},\, f_{\omega}(r)]) \\
&\qquad \left. + \frac{h_{\omega}^{1}}{2}(\tau_1^z - \tau_2^z)(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)\cdot\{\boldsymbol{p},\, f_{\omega}(r)\}\right]
\end{aligned}
$$

Issues with DDH potential

- Correct form?
- Missing term?
- Value of the coupling constants?

Predicted values for the PV coupling constants

$h_i \times 10^7$	h^1_π	h^0_ρ	h^1_ρ	h^2_ρ	h^0_ω	h^1_ω
DDH	4.6	-11.4	-0.2	-9.5	-1.9	-1.1
Skyrme	1.0	-3.7	-0.1	-3.3	-1.4	-1.0
Sum rule	3.0	·	·	·	·	·
Lattice	1.0±0.5	·	·	·	·	·
Chiral quark	0.1	·	·	·	·	·

PV observables and data in the few-nucleon systems

Process (MeV)	Observable	Exp. ($\times 10^7$)
pp scat. (13.6)	Longitudinal asymmetry	-0.93 ± 0.21
pp scat. (45)	Longitudinal asymmetry	-1.57 ± 0.23
pα scat. (46)	Longitudinal asymmetry	-3.34 ± 0.93
np capture	Polarization	1.8 ± 1.8
pol(n)p capture	Asymmetry	$-(0.15 \pm 0.48)$
pol(n)d capture	Asymmetry	42 ± 38

PV coupling constants can be determined from data, e.g.

Asymmetry in pol(n)p capture

$$A_\gamma = a_\pi h_\pi^1 + a_\rho h_\rho^1 + a_\omega h_\omega^1$$

	a_π	a_ρ	a_ω
Paris	-0.148	-0.001	0.003
Av18	-0.117	-0.001	0.002

Polarization in np capture

$$P_\gamma = p_{\rho 0} h_\rho^0 + p_{\rho 2} h_\rho^2 + p_{\omega 0} h_\omega^0$$

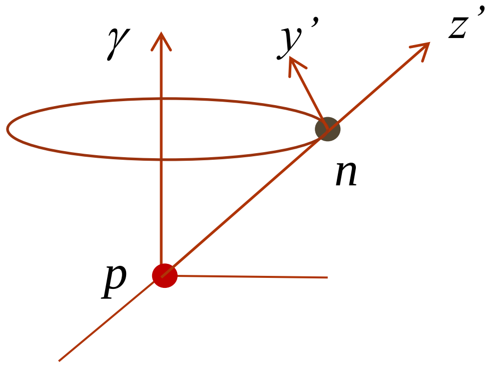
	$p_{\rho 0}$	$p_{\rho 2}$	$p_{\omega 0}$
Bonn	-0.0890	-0.0214	0.0088
Av18	-0.0088	-0.0175	0.0034

New experiments

- NPDGamma collaboration at SNS
- Anapole moments of exotic nuclei at RI facilities
- Parity violation group in High Intensity Gamma Source (HIGS) facility: $d\gamma \rightarrow np$
- Others

What and How

- Polarization $P_{i'}$ in $d\gamma \rightarrow np$ (i=x, y, z)



$$
\begin{aligned}
\hat{k} &= (0,\ 0,\ 1) \\
\hat{p} &= (\sin\theta\cos\phi,\ \sin\theta\sin\phi,\ 0) \\
\hat{z}' &= \hat{p} \\
\hat{y}' &= (-\sin\phi,\ \cos\phi,\ 0) \\
\hat{x}' &= \hat{y}' \times \hat{z}'
\end{aligned}
$$

$$P_{i'} = \frac{\sigma_i(+) - \sigma_i(-)}{\sigma_i(+) + \sigma_i(-)}$$

$\sigma_i(\pm)$: differential cross section with neutron spin parallel and anti-parallel along the axis i

- With parity-conserving interactions only

$$S^{-1}\sum_{spin}^{P}|A|^2 = 4\left[|X_{MS}|^2+|Y_{MV}|^2-(X^*_{MS}Y_{MV}+Y^*_{MV}X_{MS})\right]$$
$$+2\left[|X_{MV}|^2+|Y_{MS}|^2-(X^*_{MV}Y_{MS}+Y^*_{MS}X_{MV})\right]$$
$$+3\left[1-(\hat{k}\cdot\hat{p})^2\right]\left[|X_E|^2+|Y_E|^2-(X^*_EY_E+Y^*_EX_E)\right]$$
$$\mp i\hat{n}\cdot(\hat{k}\times\hat{p})[(X^*_EX_{MV}-X^*_{MV}X_E)+(Y^*_EY_{MS}-Y^*_{MS}Y_E)$$
$$-(Y^*_EX_{MV}-X^*_{MV}Y_E)-(Y^*_{MV}Y_{MS}-Y^*_{MS}Y_{MV})]\ .$$

- Including PV interactions

$$S^{-1}\sum_{spin}^{P}|A|^2 = 4(|X_{MS}|^2+|Y_{MV}|^2-2Y_{MV}ReX_{MS})$$
$$+2(|X_{MV}|^2+|Y_{MS}|^2-2Y_{MS}ReX_{MV})+3[1-(\hat{k}\cdot\hat{p})^2](|X_E|^2+|Y_E|^2-2X_EY_X)$$
$$\mp 2\hat{n}\cdot(\hat{k}\times\hat{p})(X_E-Y_E)ImX_{MV}\mp 2(\hat{k}\cdot\hat{n})Imf(pv1)\mp 2(\hat{p}\cdot\hat{k})(\hat{k}\cdot\hat{n})Imf(pv2)$$
$$\mp 2(\hat{p}\cdot\hat{n})Imf(pv3)\mp 2(\hat{p}\cdot\hat{k})(\hat{p}\cdot\hat{n})Imf(pv4).$$

Effective field theory

- Nuclear interactions at low energies on systematic ground
- Perturbative expansion with counting rules
- Many effective field theories with different counting rules

EFT for PV interactions with pions (pionful theory)

- Leading order: one-pion exchange
- Next-to-next leading order: two-pion exchange, four-nucleon contact

EFT for PV interactions without pions and with dibaryons (dEFT)

- Very low energy: scale even smaller than the pion mass
- Integrate out the pion and heavier degrees: all the interactions become contact type
- Dibaryon: an auxiliary field treating two-nucleon states in terms of a single field
- Advantage of dibaryon formalism: treat non-perturbative properties of the deuteron easily

PV interactions in the dEFT

$$\mathcal{L}^0_{\rm PV} = \frac{h^{0s}_{\rm dNN}}{2\sqrt{2\,\rho_d\, r_0}\, m_N^{5/2}} s_a^\dagger\, N^T \sigma_2 \sigma_i \tau_2 \tau_a \frac{i}{2} \overset{\leftrightarrow}{\nabla}_i\, N + \frac{h^{0t}_{\rm dNN}}{2\sqrt{2}\rho_d\, m_N^{5/2}}\, t_i^\dagger\, N^T \sigma_2 \tau_2 \frac{i}{2} \overset{\leftrightarrow}{\nabla}_i\, N,$$

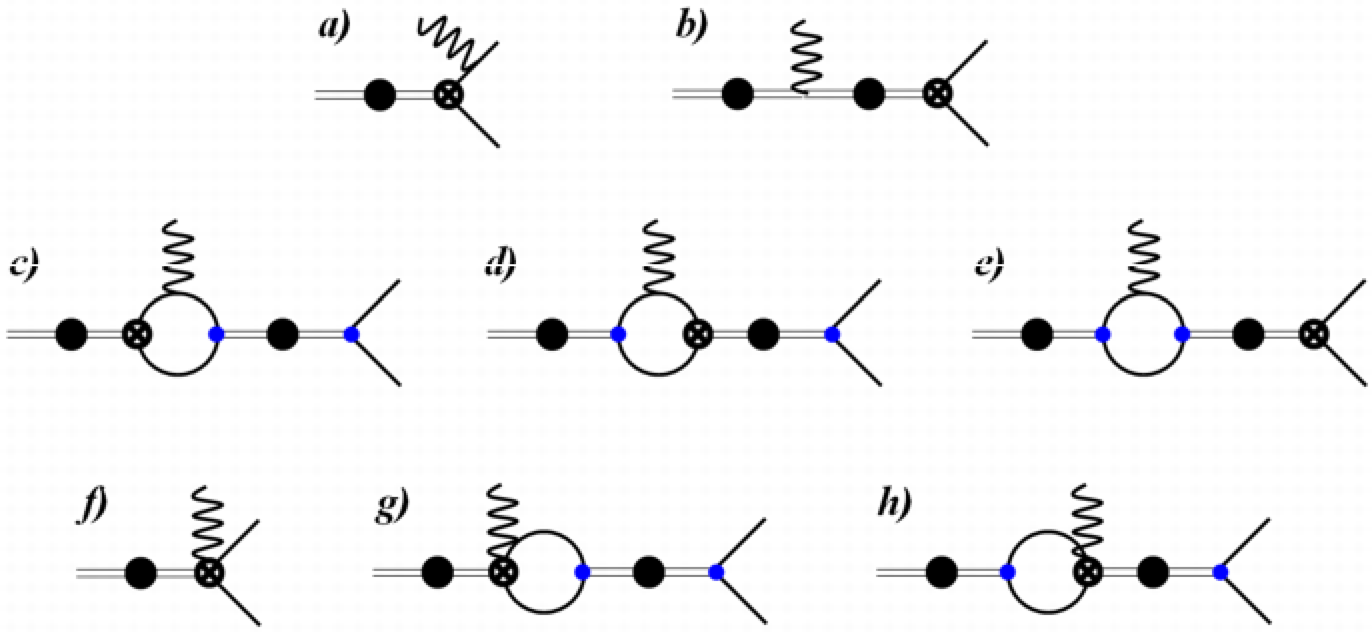
$$\mathcal{L}^1_{\rm PV} = i \frac{h^{1}_{\rm dNN}}{2\sqrt{2}\rho_d\, m_N^{5/2}}\, \epsilon_{ijk}\, t_i^\dagger\, N^T \sigma_2 \sigma_j \tau_2 \tau_3 \frac{i}{2} \overset{\leftrightarrow}{\nabla}_k\, N$$

- $h^{0s}{}_{\rm dNN}$: ${}^1S_0$-${}^3P_0$ mixing, ΔI = 0 or 2, ρ, ω exchange
- $h^{0t}{}_{\rm dNN}$: ${}^3S_1$-${}^1P_1$ mixing, ΔI = 0 or 2, ρ, ω exchange
- $h^{1}{}_{\rm dNN}$: ${}^3S_1$-${}^3P_1$ mixing, ΔI = 1, π, ρ, ω exchange

Calculate PV observables and obtain them in terms of weak dNN coupling constants

Results

Leading order diagrams



Amplitude

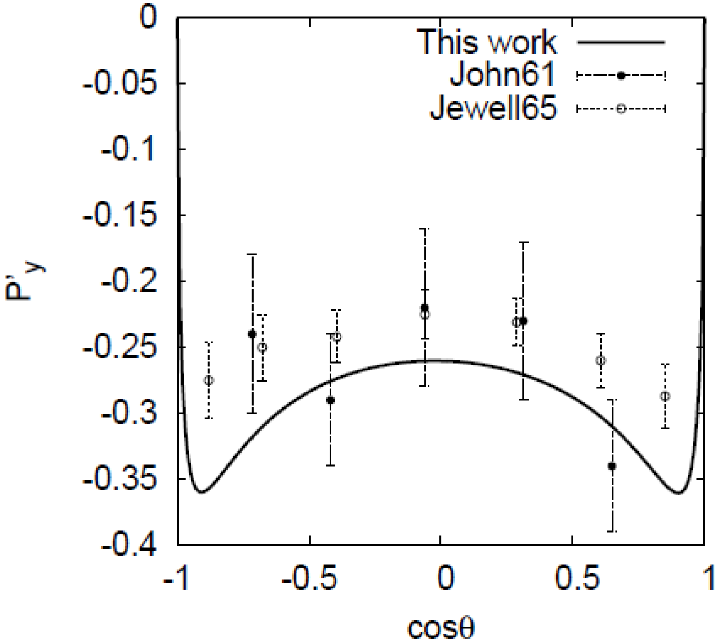
$$iA^{PV} = i(h^{0t}A^{PV}_{0t} + h^{0s}A^{PV}_{0s} + h^1 A^{PV}_1)$$

$$\begin{aligned}
iA^{PV}_{0t} &= i\chi_1^\dagger\sigma_2\tau_2\chi_2^{T\dagger}\left[\vec{\epsilon}_{(d)}\cdot\vec{\epsilon}_{(\gamma)}\hat{p}\cdot\hat{k}\,Z^{PVpg}_{MS} + \vec{\epsilon}_{(d)}\cdot\hat{k}\vec{\epsilon}_{(\gamma)}\cdot\hat{p}(X^{PV}_{pg} - Z^{PVpg}_{MS}) - \vec{\epsilon}_{(d)}\cdot\hat{p}\vec{\epsilon}_{(\gamma)}\cdot\hat{p}\,Y^{PV}_{pp}\right] \\
&+i\chi_1^\dagger\sigma_2\tau_3\tau_2\chi_2^{T\dagger}\left[\vec{\epsilon}_{(d)}\cdot\vec{\epsilon}_{(\gamma)}Z^{PV0t}_E + \vec{\epsilon}_{(d)}\cdot\hat{k}\vec{\epsilon}_{(\gamma)}\cdot\hat{p}\,Y^{PV}_{pg} - \vec{\epsilon}_{(d)}\cdot\hat{p}\vec{\epsilon}_{(\gamma)}\cdot\hat{p}X^{PV}_{pp}\right] \\
&+\chi_1^\dagger\vec{\sigma}\sigma_2\tau_2\chi_2^{T\dagger}\cdot\left\{(\hat{k}\times\vec{\epsilon}_{(\gamma)})\left[\vec{\epsilon}_{(d)}\cdot\hat{p}\,\mu_S Y^{PV}_{pg} - \vec{\epsilon}_{(d)}\cdot\hat{k}(\mu_S X^{PV}_{gg} + \mu_S Z^{PVt})\right]\right. \\
&\left.+\hat{k}\,\vec{\epsilon}_{(d)}\cdot(\hat{k}\times\vec{\epsilon}_{(\gamma)})\mu_S Z^{PVtg}\right\} + \chi_1^\dagger\vec{\sigma}\sigma_2\tau_3\tau_2\chi_2^{T\dagger}\cdot(\hat{k}\times\vec{\epsilon}_{(\gamma)})\left[\vec{\epsilon}_{(d)}\cdot\hat{p}\mu_V X^{PV}_{pg} - \vec{\epsilon}_{(d)}\cdot\hat{k}\mu_V Y^{PV}_{gg}\right], \qquad (13)
\end{aligned}$$

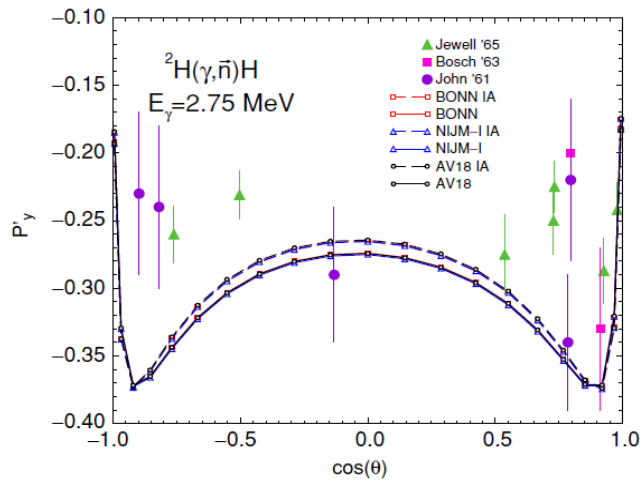
$$iA^{PV}_{0s} = i\chi_1^\dagger\sigma_2\tau_3\tau_2\chi_2^{T\dagger}\vec{\epsilon}_{(d)}\cdot\vec{\epsilon}_{(\gamma)}\left(Z^{PV0s}_E + \mu_V Z^{PVsg}\right) + \chi_1^\dagger\vec{\sigma}\sigma_2\tau_3\tau_2\chi_2^{T\dagger}\cdot\hat{p}\,\vec{\epsilon}_{(d)}\cdot(\hat{k}\times\vec{\epsilon}_{(\gamma)})Z^{PVpg}_{MV}, \qquad (14)$$

$$\begin{aligned}
iA^{PV}_1 &= i\chi_1^\dagger\sigma_2\tau_2\chi_2^{T\dagger}\left[\vec{\epsilon}_{(d)}\cdot\vec{\epsilon}_{(\gamma)}\left(\mu_V Y^{PV}_{gg} - \hat{p}\cdot\hat{k}\,\mu_V X^{PV}_{pg}\right) + \vec{\epsilon}_{(d)}\cdot\hat{k}\vec{\epsilon}_{(\gamma)}\hat{p}\,\mu_V X^{PV}_{pg}\right] \\
&+i\chi_1^\dagger\sigma_2\tau_3\tau_2\chi_2^{T\dagger}\left[\vec{\epsilon}_{(d)}\cdot\vec{\epsilon}_{(\gamma)}\left(\mu_S X^{PV}_{gg} + \mu_S Z^{PVs} - \hat{p}\cdot\hat{k}\mu_S Y^{PV}_{pg}\right) + \vec{\epsilon}_{(d)}\cdot\hat{k}\vec{\epsilon}_{(\gamma)}\cdot\hat{p}\mu_S Y^{PV}_{pg}\right] \\
&+\chi_1^\dagger\vec{\sigma}\sigma_2\tau_2\chi_2^{T\dagger}\cdot\left\{(\vec{\epsilon}_{(d)}\times\vec{\epsilon}_{(\gamma)})Z^{PV1}_E - (\hat{k}\times\vec{\epsilon}_{(\gamma)})\vec{\epsilon}_{(d)}\cdot\hat{k}\mu_V Z^{PVtg} + (\vec{\epsilon}_{(d)}\times\hat{p})\vec{\epsilon}_{(\gamma)}\cdot\hat{p}X^{PV}_{pp}\right. \\
&-(\vec{\epsilon}_{(d)}\times\hat{k})\vec{\epsilon}_{(\gamma)}\cdot\hat{p}Y^{PV}_{pg} + \hat{k}\left[\vec{\epsilon}_{(\gamma)}\cdot(\hat{k}\times\vec{\epsilon}_{(d)})\left(\mu_V X^{PV}_{gg} + \mu_V Z^{PVt}\right) - \vec{\epsilon}_{(\gamma)}\cdot(\hat{p}\times\vec{\epsilon}_{(d)})\mu_V Y^{PV}_{pg}\right] \\
&\left.+\vec{\epsilon}_{(\gamma)}\hat{k}\cdot(\hat{p}\times\vec{\epsilon}_{(d)})\mu_V Y^{PV}_{pg}\right\} + \chi_1^\dagger\vec{\sigma}\sigma_2\tau_3\tau_2\chi_2^{T\dagger}\cdot\left\{(\vec{\epsilon}_{(d)}\times\hat{p})\vec{\epsilon}_{(\gamma)}\cdot\hat{p}Y^{PV}_{pp} - (\vec{\epsilon}_{(d)}\times\hat{k})\vec{\epsilon}_{(\gamma)}\cdot\hat{p}X^{PV}_{pg}\right. \\
&+(\hat{p}\times\hat{k})\vec{\epsilon}_{(d)}\cdot\vec{\epsilon}_{(\gamma)}Z^{PVpg}_{MS} + (\vec{\epsilon}_{(\gamma)}\times\hat{p})\vec{\epsilon}_{(d)}\cdot\hat{k}Z^{PVpg}_{MS} + \hat{k}\left[\vec{\epsilon}_{(\gamma)}\cdot(\hat{k}\times\vec{\epsilon}_{(d)})Y^{PV}_{gg}\right. \\
&\left.\left.-\vec{\epsilon}_{(\gamma)}\cdot(\hat{p}\times\vec{\epsilon}_{(d)})\mu_S X^{PV}_{pg}\right] + \vec{\epsilon}_{(\gamma)}\hat{k}\cdot(\hat{p}\times\vec{\epsilon}_{(d)})\mu_S X^{PV}_{pg}\right\}, \qquad (15)
\end{aligned}$$

$P_{y'}$ at E_γ = 2.75 MeV: check for a parity-conserving quantity



Our work

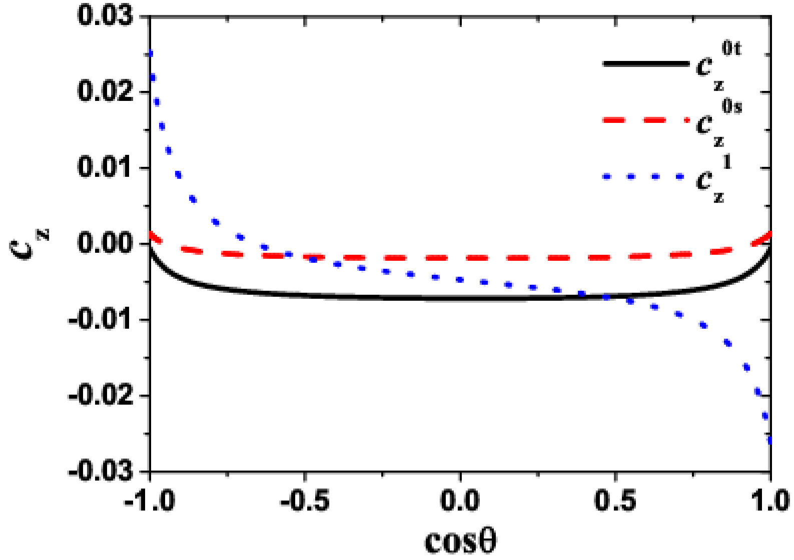


Modern potential

R. Schiavilla, PRC2005

$P_{z'}$ at $E_\gamma = 2.75$ MeV

$$P_{z'} \equiv c_z^{0t} h_d^{0t} + c_z^{0s} h_d^{0s} + c_z^1 h_d^1.$$



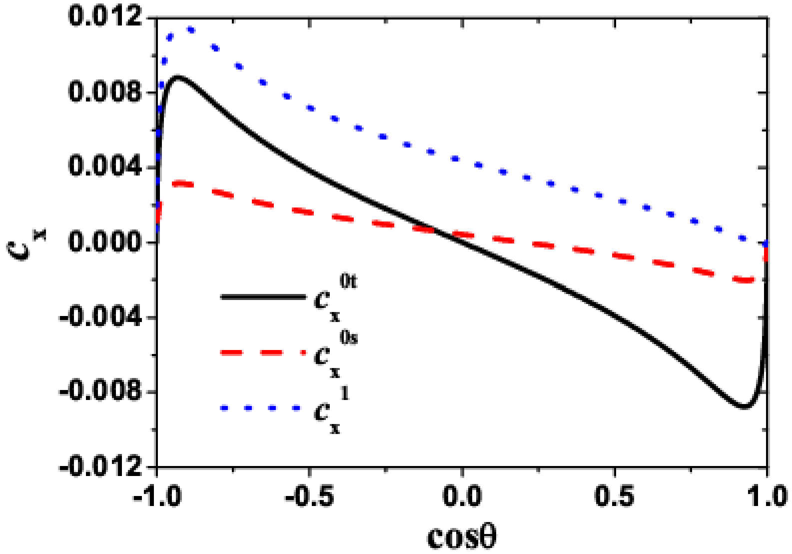
How large? Compare to the asymmetry in pol(n)p capture

dEFT: $$A_\gamma = -\frac{h^1_{\rm dNN}}{\sqrt{2\pi m_N \rho_d}} \frac{1 - \frac{2}{3}\gamma a_3}{(1+\kappa_V)(1-\gamma a_0) - \gamma^2 a_0 L_1} = -9.03 \times 10^{-4} h^1_{\rm dNN}.$$

$A_\gamma = -(0.15 \pm 0.48) \times 10^{-7}$

$P_{x'}$ at $E_\gamma = 2.75$ MeV

$$P_{x'} \equiv c_x^{0t} h_d^{0t} + c_x^{0s} h_d^{0s} + c_x^{1} h_d^{1}$$



How large? Compare to the polarization in np capture

dEFT: $$P_\gamma = -\frac{1}{\sqrt{2\pi m_N \rho_d}} \frac{h^{0t}_{\mathrm{dNN}} + \frac{5}{3}\gamma a_0 \left(h^{0s}_{\mathrm{dNN}} + h^{0t}_{\mathrm{dNN}}\right)}{(1+\kappa_V)(1-\gamma a_0) - \gamma^2 a_0 L_1}$$
$$= 0.051 h^{0s}_{\mathrm{dNN}} + 0.045 h^{0t}_{\mathrm{dNN}}.$$

$P_\gamma = (1.8 \pm 1.8) \times 10^{-7}$

Summary

- Large P_z, non-negligible P_x
- Counter calculations: DDH, other EFT's
- As many observables as possible: e.g. $\gamma\ {}^3He \rightarrow p\ d$