Theoretical study of the parity-violating asymmetry in the $^3\mathrm{He}(\vec{n}, p)^3\mathrm{H}$ reaction

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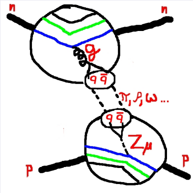
Outline

Study of PV in few-nucleon systems



- Interest: quark-quark weak interaction
- $\Delta T = 1$ component: dominated by neutral currents see, for example, [Haxton & Holstein, 2013]
- Several discrepancies theory-experiment in hyperon non-leptonic decays $\Lambda \to p + \pi^-$, etc.

Experiments in few-nucleon systems

- Longitudinal asymmetries $\vec{p}p$, $\vec{p}^4\mathrm{He}$, $\vec{n}^3\mathrm{He}$
- Neutron spin rotation $\vec{n}p$, $\vec{n}d$, $\vec{n}\,^4\mathrm{He}$
- Longitudinal asymmetries in EM capture $n + p \to \gamma + d$, $n + d \to \gamma + {}^3\mathrm{H}$
- γ polarization $\vec{n} + p \to \gamma d$
- Nuclear dynamics under control – the "theoretical uncertainties" can be estimated

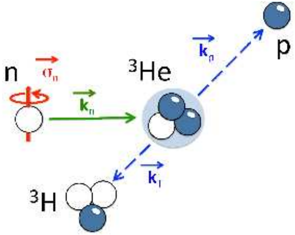
Theoretical frameworks

- meson-exchanges: DDH [Desplanques, Donoghue, & Holstein, 1980]
- Pionless EFT [Schindler & Springer, 2013],[Haxton & Holstein, 2013]
- Pionfull EFT [Kaplan & Savage, 1993], [Zhu *et al.*, 2005], [De Vries *et al.*, 2014] [MV *et al.*, 2014]
  - derived up to N2LO [De Vries *et al.*, 2014], [Gnech & MV, 2016]

Longitudinal asymmetry in $\vec{n} + {}^3\mathrm{He} \rightarrow p + {}^3\mathrm{H}$

Interest

- $A_z(\theta) = a_z \cos\theta$
- Sensitive to different combination of LEC'S?



Studies already published

- [MV *et al.*, PRC **82**, 044001 (2010)] AV18/UIX + DDH PV pot.
- [MV *et al.*, PRC **89**, 064004 (2014)] N3LO/N2LO + NLO χEFT PV pot.
- A. Gnech, Master Thesis (2016)] N2LO χEFT PV pot.

Contributing waves

- initial state $(n - {}^3\mathrm{He})$ $q \approx 0$: ${}^1S_0$, ${}^3S_1$
- final state $(p - {}^3\mathrm{H})$ $q = 0.165$ fm^{-1}:
  - $J = 0$: ${}^1S_0$, ${}^3P_0$
  - $J = 1$: ${}^3S_1 - {}^3D_1$, ${}^1P_1 - {}^3P_1$

Neglecting ${}^3D_1$, we have to compute the matrix elements $T^{(nh,pt),J}_{LS,L'S'}$

PC	
${}^1S_0 \to {}^1S_0$	$T^{(nh,pt),0}_{00,00}$
${}^3S_1 \to {}^3S_1$	$T^{(nh,pt),1}_{01,01}$

PV	
${}^1S_0 \to {}^3P_0$	$T^{(nh,pt),0}_{00,11}$
${}^3S_1 \to {}^1P_1$	$T^{(nh,pt),1}_{01,10}$
${}^3S_1 \to {}^3P_1$	$T^{(nh,pt),1}_{01,11}$

- PC T-matrix elements + Ψ^J_{LS}: using the KVP+HH method, starting from a NN+3N interaction model (neglecting the PV potential)
- PV T-matrix elements: $T^{(nh,pt),J}_{0J,1S} = \langle \mathcal{T}\Psi^{J-}_{1S} | V_{PV} | \Psi^{J+}_{0J} \rangle$ (Monte Carlo code by R. Schiavilla)

4N wave functions

$n^3\mathrm{He} \to n^3\mathrm{He} + p^3\mathrm{H}$ process

$$\Omega^{\pm}_{AB,LS} = \sqrt{\frac{1}{N}} \sum_{perm.=1}^{N} \left[Y_L(\hat{\mathbf{y}}_p) \otimes [\phi_A \otimes \phi_B]_S \right]_{JJ_z} \left(f_L(y_p) \frac{G_L(\eta, q_{AB} y_p)}{q_{AB} y_p} \pm \mathrm{i} \frac{F_L(\eta, q_{AB} y_p)}{q_{AB} y_p} \right)$$

$$|\Psi_{nh,LS}\rangle = \sum_{n,[K]} a_{nh,LS,[K]} |n,[K]\rangle + |\Omega^{-}_{nh,LS}\rangle - \sum_{L'S'} \mathcal{S}^{(nh,nh),J}_{LS,L'S'} |\Omega^{+}_{nh,L'S'}\rangle - \sum_{L'S'} \mathcal{S}^{(nh,pt),J}_{LS,L'S'} |\Omega^{+}_{pt,L'S'}\rangle$$

- $|n,[K]\rangle$ HH states – essentially, homegeneous polynomials of degree K
- $\mathcal{S}^{(AB,a'B'),J}_{LS,L'S'}$ = S-matrix ($T = (\mathcal{S} - I)2\pi$)
- $a_{AB,LS,[K]}$ and $\mathcal{S}^{(AB,A'B'),J}_{LS,L'S'}$ computed using the Kohn variational principle
- For a review, see [J. Phys. G: Nucl. Part. Phys. **35**, 063101 (2008)]

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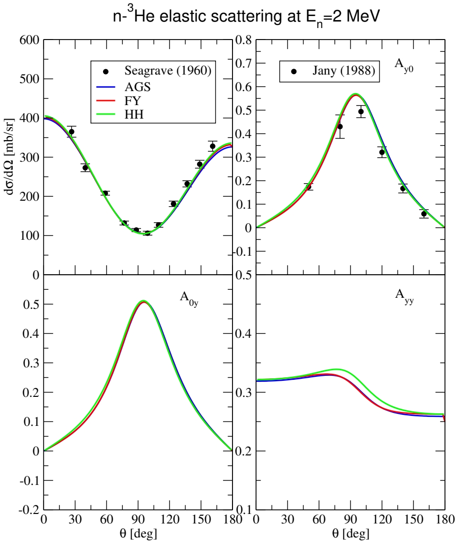
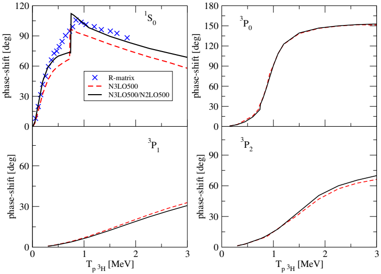
Benchmark test of 4N scattering calculations



AGS= Deltuva & Fonseca – FY= Lazauskas & Carbonell – HH= present work

Extraction of the resonance parameters (1)

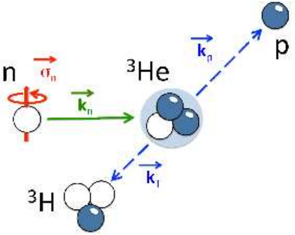
- $p - {}^3\mathrm{H}$ phase-shifts (deg)
- $\mathcal{S}^{(pt,pt),J}_{LS,LS} = \eta e^{2i\delta}$
- PC potential N3LO [Entem & Machleidt, 2003]
- Extraction of the resonance parameters from the S matrix elements [Rakityansky, Sofianos, & Elander (2011)]



Interaction	$^1S_0$ E_R (MeV)	Γ (MeV)	$^3P_0$ E_R (MeV)	Γ (MeV)
N3LO500	0.080	0.40	0.96	0.42
N3LO500/N2LO500	0.085	0.28	0.96	0.44
Expt.	0.39	0.50	1.20	0.84

Interaction	$^3P_1$ E_R (MeV)	Γ (MeV)	$^3P_2$ E_R (MeV)	Γ (MeV)
N3LO500	1.02	4.60	1.28	2.00
N3LO500/N2LO500	1.26	4.72	1.93	2.56
Expt.	4.43	6.10	2.02	2.01

Results for the PC asymmetry



PC asymmetry at $E_n = 4.9$ meV – N3LO pot. by Entem & Machleidt + 3N force at N2LO

	including contribution of the $J = 2^-\ {}^3P_2$ wave		
	$\Lambda_F = 500$ MeV	$\Lambda_F = 600$ MeV	Expt.
$A_y(90\,\text{deg})$	$-3.1 \cdot 10^{-7}$	$-2.7 \cdot 10^{-7}$	$-(4.4 \pm 0.7) \cdot 10^{-7}$

Results for the AV18/UIX + DDH potential

From [MV *et al.*, (2010)]

$$|\Psi_{nh,LS}\rangle = \sum_{n,[K]} a_{nh,LS,[K]}|n,[K]\rangle + |\Omega^-_{nh,LS}\rangle - \sum_{L'S'} \mathcal{S}^{(nh,nh),J}_{LS,L'S'}|\Omega^+_{nh,L'S'}\rangle - \sum_{L'S'} \mathcal{S}^{(nh,pt),J}_{LS,L'S'}|\Omega^+_{pt,L'S'}\rangle$$

Contribution of $h^1\pi$ coming from $\langle\Psi|(\boldsymbol{\tau}_i \times \boldsymbol{\tau}_j)_z|\Psi\rangle$
mainly due to the difference between $n + {}^3\mathrm{He}$ and $p + {}^3\mathrm{H}$ wave functions

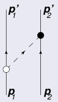
$$A_z = \underbrace{\left[h^1_\pi C^1_\pi + h^0_\rho C^0_\rho + h^1_\rho C^1_\rho + h^2_\rho C^2_\rho + h^0_\omega C^0_\omega + h^1_\omega C^1_\omega\right]}_{a_z} \cos\theta$$

Inter.	C^1_π	C^0_ρ	C^1_ρ	C^2_ρ	C^0_ω	C^1_ω
AV18	-0.189	-0.036	0.019	-0.001	-0.033	0.041
AV18/UIX	-0.185	-0.038	0.023	-0.001	-0.023	0.050

- For the allowed ranges of the DDH coupling constants
- $a_z \times 10^8 = -30 \leftrightarrow +10$

The PV potential in χEFT

$\sim Q^{-1}$
Leading order (LO)

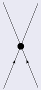


One Pion Exchange

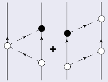
$$V_{PV}^{(-1)}(\text{OPE}) = \frac{g_A h_\pi^1}{2\sqrt{2} f_\pi} (\boldsymbol{\tau}_1 \times \boldsymbol{\tau}_2)_z \frac{i\boldsymbol{k} \cdot (\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2)}{\omega_k^2}$$

$$\boldsymbol{k} = \boldsymbol{p}_1' - \boldsymbol{p}_1 = \boldsymbol{p}_2 - \boldsymbol{p}_2' \quad \omega_k = \sqrt{m_\pi^2 + k^2} \quad g_A = 1.267 \quad f_\pi = 92.4 \text{ MeV} \quad \Lambda_\chi = 4\pi f_\pi$$

$\sim Q$
next-to-leading order (NLO)



Contact Terms
5 LECs C_i, $i = 1, \ldots, 5$



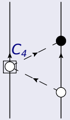
Two Pion Exchange (TPE) diagrams depending on h_π^1

- 5 LECS

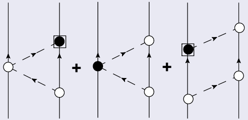
- [Zhu *et al.*, 2005], [Hyun *et al.*, 2008], [De Vries *et al.*, 2014]
- [MV *et al.*, (2014)] (independent PV Lagrangian terms allowed at order Q^2)

The PV potential in χEFT at N2LO

$\sim Q^2$ next-to-next-to-leading order (N2LO)



no new LECS, c_4 fixed using πN scattering



subleading PV $\pi - N$ vertices $h_V^{0,1,2}$
+ PV $\pi\pi - N$ vertices $h_A^{1,2}$

- 5 new LECs

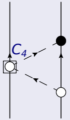
- First derived at N2LO by [De Vries *et al.*, 2014]
- Rederived using our approach by A. Gnech for his Master Thesis

- To be used in the Schroedinger equation, the potential has to be regularized
- Each term is multiplied by
$$f_\Lambda(k) = e^{-\left(\frac{k}{\Lambda_F}\right)^4}$$
- Dependence on Λ_F taken as measure of the theoretical uncertainty

Results presented at the DNP16 (Vancouver) – 11 LECs!

The PV potential in χEFT at N2LO

$\sim Q^2$ next-to-next-to-leading order (N2LO)



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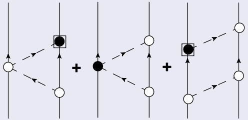

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Pionless PV contact potential

[Gardner, Haxton, Holstein (GHH), 2017]

$$
\begin{aligned}
V_{CT}^{PV}(\boldsymbol{r}) &= \Lambda_0^{^1S_0-^3P_0}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)+\frac{1}{i}\frac{\boldsymbol{\nabla}}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot i(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\right)\\
&+ \Lambda_0^{^3S_1-^1P_1}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)-\frac{1}{i}\frac{\boldsymbol{\nabla}}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot i(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\right)\\
&+ \Lambda_1^{^1S_0-^3P_0}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)(\tau_{1\,z}+\tau_{2\,z})\right)\\
&+ \Lambda_1^{^3S_1-^3P_1}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)(\tau_{1\,z}-\tau_{2\,z})\right)\\
&+ \Lambda_2^{^1S_0-^3P_0}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)(\boldsymbol{\tau}_1\otimes\boldsymbol{\tau}_2)_{20}\right)
\end{aligned}
$$

$\Lambda_0^{^1S_0-^3P_0}, \ldots$: LECs to be determined

$S-P$ transitions: [Danilov, 1965] – From general properties of the Lagrangian: [Girlanda, 2008]

Large N_c analysis

[Schindler, Springer, & Vanasse, 2016]

$$
\begin{aligned}
\Lambda_0^+ \equiv \frac{3}{4}\Lambda_0^{{}^3S_1-{}^1P_1} + \frac{1}{4}\Lambda_0^{{}^1S_0-{}^3P_0} &\sim N_c \\
\Lambda_2^{{}^1S_0-{}^3P_0} &\sim N_c, \\
\Lambda_0^- \equiv \frac{1}{4}\Lambda_0^{{}^3S_1-{}^1P_1} - \frac{3}{4}\Lambda_0^{{}^1S_0-{}^3P_0} &\sim 1/N_c \\
\Lambda_1^{{}^1S_0-{}^3P_0} &\sim \sin^2\theta_W \\
\Lambda_1^{{}^3S_1-{}^3P_1} &\sim \sin^2\theta_W
\end{aligned}
$$

$1/N_c^2 = 1/9$, $\sin^2\theta_W/N_c \sim 1/12$ 3 LECs suppressed

LQCD calculation of $\Lambda_2^{{}^1S_0-{}^3P_0}$ in progress [Tiburzi, 2012], [Kurth *et al.*, 2016], [Walker-Loud, this workshop], ...

In the following all the coupling constants are given in units of 10^{-7}

Calculation of $A_L(\vec{n}^3\mathrm{He})$

Two difficulties

- Treatment of the δ?

$$\delta(\mathbf{r}) \to \frac{\Lambda^3}{(2\pi)^{\frac{3}{2}}} e^{-\frac{1}{2}(\Lambda r)^2}$$

- Which PC interaction one should use?

pp longitudinal asymmetry

- At low energies only the ${}^1S_0 \to {}^3P_0$ transition
- The isospin state is $|T=1, T_z=+1\rangle$

$$\langle pp|V_{CT}^{PV}|pp\rangle = \left(\Lambda_0^{{}^1S_0-{}^3P_0} + \Lambda_1^{{}^1S_0-{}^3P_0} + \frac{\Lambda_0^{{}^1S_0-{}^3P_0}}{\sqrt{6}}\right)\langle \frac{1}{i}\frac{\overleftrightarrow{\nabla}}{2\,m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)\rangle$$

$$\langle pp|V_{CT}^{PV}|pp\rangle = a_1\Lambda_0^{{}^1S_0-{}^3P_0} + a_2\Lambda_0^{{}^3S_1-{}^3P_1} + a_3\Lambda_1^{{}^1S_0-{}^3P_0} + a_4\Lambda_1^{{}^3S_1-{}^3P_1} + a_5\frac{\Lambda_0^{{}^1S_0-{}^3P_0}}{\sqrt{6}}$$

Dependence on Λ [N3LO potential – $E_p = 45$ MeV]

Λ (GeV)	a_1	a_2	a_3	a_4	a_5
5.0	-0.01121	0.00002	-0.01118	0	-0.01118
0.5	-0.01493	0.00070	-0.01423	0	-0.011423
0.138	-0.00804	0.00411	-0.01251	0	-0.01251

Dependence on the PC interaction [$\Lambda = 5$ GeV – $E_p = 45$ MeV]

Int.	a_1	a_2	a_3	a_4	a_5
AV18	-0.00029	0.00001	-0.00028	0	-0.00028
N3LO500(2003)	-0.01121	0.00002	-0.01118	0	-0.01118
N3LO500(2017)	-0.01860	0.00004	-0.01856	0	-0.01856
N4LO500	-0.01980	0.00003	-0.01978	0	-0.01978

[Haxton and Holstein, 2013], [GHH, 2017]

Int. (GeV)	a_1	a_2	a_3	a_4	a_5
	-0.00375	0	-0.00375	0	-0.00375

Results for $A_L(\vec{n}^3\mathrm{He})$ with the GHH PV potential

PV asymmetry

$$A_L(\vec{n}^3\mathrm{He}) = a_+\Lambda_0^+ + a_2\Lambda_2^{^1S_0-^3P_0} + \left[a_-\Lambda_0^- + a_1\Lambda_1^{^1S_0-^3P_0} + \tilde{a}_1\Lambda_1^{^3S_1-^3P_1}\right]$$

N3LO500/N2LO500 PC interaction
PRELIMINARY

Λ (GeV)	a_+	a_2
5.0	7.1×10^{-4}	9.3×10^{-6}
0.5	1.4×10^{-3}	3.8×10^{-6}

a_+ & a_2 extracted from [MV *et al.*, (2010)]
PC interaction AV18/UIX, $\Lambda = 0.138$ GeV
$\delta \to$ Yukawian

	a_+	a_2
GHH paper	-2.7×10^{-4}	6.2×10^{-5}

Using the best-values $\Lambda_0^+ = 717$ and $\Lambda_2 = 324$ from [GHH, 2017]

$$A_L(\vec{n}^3\mathrm{He}) = (0.5 \pm 0.1) \times 10^{-7} \qquad \Lambda = 5\ \mathrm{GeV}$$

However, it is not correct to use the values extracted using the pionless theory....

Results for $A_L(\vec{n}^3\mathrm{He})$ with the GHH PV potential

PV asymmetry

$$A_L(\vec{n}^3\mathrm{He}) = a_+\Lambda_0^+ + a_2\Lambda_2^{{}^1S_0-{}^3P_0} + \left[a_-\Lambda_0^- + a_1\Lambda_1^{{}^1S_0-{}^3P_0} + \tilde{a}_1\Lambda_1^{{}^3S_1-{}^3P_1}\right]$$

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Using the *pp* data to fix the two LO LECs

Measurements

E_p (MeV)	$A_L(\vec{p}p)$	(θ_1, θ_2)	Lab. (year)
13.6	$(-0.97 \pm 0.20) \times 10^{-7}$	$(20°, 78°)$	Bonn Germany (1991)
45	$(-1.53 \pm 0.21) \times 10^{-7}$	$(23°, 52°)$	PSI Switzerland (1987)
221	$(+0.84 \pm 0.34) \times 10^{-7}$	$(5°, 90°)$	TRIUMF Canada (2003)

- Problem: The two data at lower energies are not independent $A_L \sim \sqrt{E_p}$
- Question: Is possible to use also the TRIUMF datum at $E_P = 221$ MeV?
- Take into account of the two scales in NP: $\epsilon = a^{-1} \approx 10 - 40$ MeV and m_π, f_π
- Contact interactions are promoted with respect to pion vertices by a factor f_π/ϵ

$$\mathcal{L} = c_{\ell mn} \left(\frac{\bar{N}...N}{f_\pi \Lambda_\chi \epsilon}\right)^\ell \left(\frac{\pi}{f_\pi}\right)^m \left(\frac{\partial_\mu, m_\pi}{\Lambda_\chi}\right)^n \Lambda_\chi^2 f_\pi \epsilon \qquad \Lambda_\chi \approx 1\ \mathrm{GeV}$$

- [Kievsky, MV, Gattobigio, & Girlanda, 2016]
- The GHH contact interactions could be the LO up to pion threshold (??)

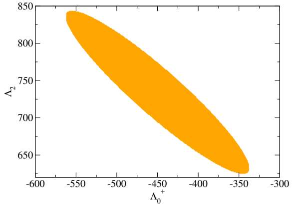
Fit of all three $\vec{p}p$ data

$A_L(\vec{p}p)$ asymmetry

$$A_L(\vec{p}p) = a_+ \Lambda_0^+ + a_2 \Lambda_2^{{}^1S_0 - {}^3P_0}$$

Exploratory study!! – N3LO500(2003) PC interaction – $\Lambda = 0.5$ GeV

E_p (MeV)	a_+	a_2
13.6	-0.002036	-0.002404
45	-0.003747	-0.004478
221	-0.004342	-0.001521



"central values"

$$\Lambda_0^+ = -450 \quad \Lambda_2 = +734$$

Results for $A_L(\vec{n}\,^3\mathrm{He})$

$$A_L(\vec{n}\,^3\mathrm{He}) = -(0.61 \pm 0.20) \times 10^{-7}$$

Error estimated using the "Hessian" method

Covariance matrix $\mathcal{C} = 2\mathcal{H}^{-1}$

Conclusions

Study of PV observables witht he GHH PV potential

- Longitudinal asymmetry in $\vec{p}\,p$ scattering
- Longitudinal asymmetries in $n + {}^3\mathrm{He} \to p + {}^3\mathrm{H}$ scattering
- $A_L(\vec{n}^3\mathrm{He}) = -(0.61 \pm 0.20) \times 10^{-7} \ldots$
- ... but what I should do?

Future work

- $\vec{n}\alpha$ spin rotation
- $\vec{p}d$ longitudinal asymmetry at several energies
- Extension to time-reversal violation: EDMs & $\vec{n}A$ spin rotation along the y direction [Kabir, 1982], [Gudkov, 1992]
  - $\vec{n}p$: $d\phi_y/dz \approx (-6.0 \times \bar{\theta})$ rad m^{-1} $\lesssim 10^{-11}$ Rad m^{-1} $\Rightarrow$ too small ...
  - but it may be enhanced in medium heavy nuclei [Gudkov, 1992]
  - beyond standard model contributions? see, for example, [Mereghetti & van Kolck, 2015], [Bsaisou *et al.* , 2015]

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Thank you!