Study of time-reversal violation in the two-nucleon system

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Outline

Collaborators

- A. Gnech *GSSI, L'Aquila, (Italy) & INFN-Pisa (Italy)*
- A. Kievsky & L.E. Marcucci - *INFN & Pisa University, Pisa (Italy)*
- L. Girlanda *Lecce University, Lecce (Italy)*

Time reversal violation in hadrons: Current interest

- T-reversal violation (TRV) equivalent to CP violation (CPV)
  - needed to explain the matter/antimatter asymmetry [Sakharov, 1967]
  - $\rightarrow$ WMAP [Bennet *et al.*, 2013] & Planck [Ade *et al.*, 2014] results: $\eta_{BAU} = (n_B - n_{\overline{B}})/n_\gamma \sim 10^{-10}$
  - Expected from Standard Model (SM) $\sim 10^{-18}$
- Experimental observables
  - Electric dipole moment (EDM) of n, atoms, molecules
    - $|d_n| < 2.9\ 10^{-26} e$ cm [Baker *et al.*, 2006]
    - $|d_e| < 8.7\ 10^{-29} e$ cm [Baron *et al.*, 2014] (ThO molecule)
    - $|d_e| < 1.3\ 10^{-28} e$ cm [Cairncross *et al.*, 2017] (HfF molecule)
    - $|d_p| < 7.9\ 10^{-25} e$ cm [Griffith *et al.*, 2009] (^{199}Hg atom)
- Future: EDM of charge particles (p, ^{2}H, ^{3}H, ^{3}He, ... nuclei)
  - BNL: Pure electric ring (Storage Ring EDM Coll.)
    - `https://www.bnl.gov/edm/Proposal.asp`
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- Under exploration: TRV in neutron transmission [Bowman & Gudkov, 2014]

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SM & BSM contributions to TRV

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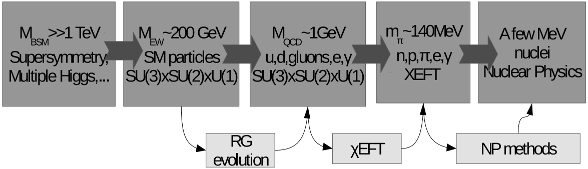
    - $d_n \sim 2.910^{-32} e$ [Pospelov & Ritz, 2005]
    - too small matter/antimatter asymmetry [Canetti *et al.*, 2012]
  - the "θ" term
    - $d_n \sim 4.5\ 10^{-15}\ \bar{\theta}$ e cm [Alexandrou *et al.*, 2016]
    - $\bar{\theta} < 10^{-10}$ "strong CP problem" $\rightarrow$ [Peccei & Quinn, 1977]
- . . . and beyond
  - Signal of new physics? At which scale?
  - CPV terms "beyond the SM" of dimension 6 [De Rujula *et al.*, 1991]
  - For a review, see [Chupp *et al.*, 2017]



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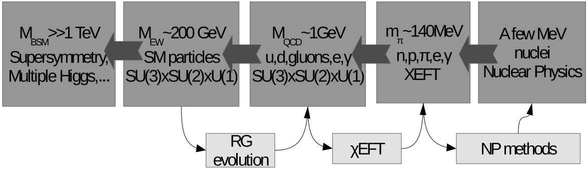

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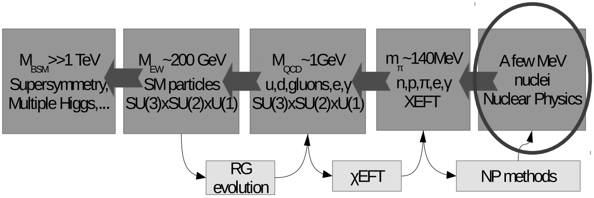


Step 1

At energies $M_{EW} \sim 200$ GeV

- SM as a low energy effective field theory
- Degrees of freedom: quarks, gluons, leptons, $W^{\pm}$, Z^0, γ
- Gauge symmetry $SU(3)_c \times SU(2)_L \times U(1)_Y$
- Dimension 4 terms $\rightarrow$ adimensional coupling constants

$$\mathcal{L}^{(4)}_{TRV} = \theta \frac{g_s^2}{64\pi^2} \epsilon^{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta}$$

- Dimension 5: one term responsible for neutrino mass and lepton number non-conservation [Weinberg, 1979] $\mathcal{O}(1/M_{BSM})$
  - Possible CPV from phases of the leptonic mixing matrix?
- Dimension 6: Several possible TRV terms [De Rujula *et al.*, 1991], [Grzadkowski *et al.*, 2010]
  - suppressed as $\mathcal{O}(1/M^2_{BSM})$, but maybe they could play a role

Step 2

At energies $= M_{QCD} \sim 1$ GeV

- Degrees of freedom: u, d, gluons, leptons, γ

$$q = \begin{pmatrix} u \\ d \end{pmatrix} \qquad q_{R,L} = \frac{1 \pm \gamma^5}{2} q \qquad \mathcal{M} = \begin{pmatrix} m_u & 0 \\ 0 & m_d \end{pmatrix}$$

$$\begin{aligned}
\mathcal{L}^{(4)}_{TRV} &= -\left(e^{i\rho}\bar{q}_L \mathcal{M} q_R + e^{-i\rho}\bar{q}_R \mathcal{M} q_L\right) - \theta \frac{g_s^2}{64\pi^2}\epsilon^{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta} \\
&\underbrace{\to}_{U(1)_A} \left(e^{i(\rho+\theta/2)}\bar{q}_L \mathcal{M} q_R + e^{-i(\rho+\theta/2)}\bar{q}_R \mathcal{M} q_L\right) \\
&\to \bar{q}(s_0 + s_3\tau_z - i\gamma_5 p_0 - i\gamma_5 p_3 \tau_3) q
\end{aligned}$$

$$\bar{m} = \frac{m_u + m_d}{2} \quad \epsilon = \frac{m_u - m_d}{m_u + m_d} \qquad p_0 = \bar{m}\bar{\theta}/2 \qquad p_3 = \bar{m}\bar{\theta}/2$$

$$\bar{\theta} = \theta + 2\rho$$

Step 2 (continued)

Evolved $D = 6$ TRV terms [de Vries *et al.*,2013], [Mereghetti & Van Kolck, 2015]

FQLR-term	$\nu_1 V_{ud} (\bar{u}_R \gamma_\mu d_R \bar{d}_L \gamma^\mu u_L - \bar{d}_R \gamma_\mu u_R \bar{u}_L \gamma^\mu d_L) +$
	$i\nu_8 y V_{ud} (\bar{u}_R \gamma_\mu \lambda^a d_R \bar{d}_L \gamma^\mu \lambda^a u_L - \bar{d}_R \gamma_\mu \lambda^a u_R \bar{u}_L \gamma^\mu \lambda^a d_L)$
qCEDM	$i\bar{q}\,(\,\tilde{\delta}^1_G + \tilde{\delta}^3_G \tau_3)\,\sigma^{\mu\nu}\gamma_5 \lambda^a q\, G^a_{\mu\nu}$
qEDM	$i\bar{q}\,(\,\tilde{\delta}^1_F + \tilde{\delta}^3_F \tau_3)\,\sigma^{\mu\nu}\gamma_5 q\, F_{\mu\nu}$
gCEDM	$\beta_G\, f^{abc} \epsilon^{\mu\nu\alpha\beta}\, G^a_{\alpha\beta} G^b_{\mu\rho} G^{c,\rho}_{\nu}$
4q-term	$i\mu_1\,(\bar{u}u\,\bar{d}\gamma_5 d + \bar{u}\gamma_5 u\,\bar{d}d - \bar{d}\gamma_5 u\,\bar{u}d - \bar{d}u\,\bar{u}\gamma_5 d) +$
	$i\mu_8\,(\bar{u}\lambda^a u\,\bar{d}\gamma_5\lambda^a d + \bar{u}\gamma_5\lambda^a u\,\bar{d}\lambda^a d - \bar{d}\gamma_5\lambda^a u\%, \bar{u}\lambda^a d - \bar{d}\lambda^a u\,\bar{u}\gamma_5\lambda^a d)$

Step 3

At energies $= m_\pi \sim 140$ MeV

- Degrees of freedom: nucleons, pions, leptons, γ
- χEFT [Weinberg, 1979, Gasser & Leutwyler, 1984]
- The QCD Lagrangian is (almost) invariant under $G = SU(2)_R \times SU(2)_L$

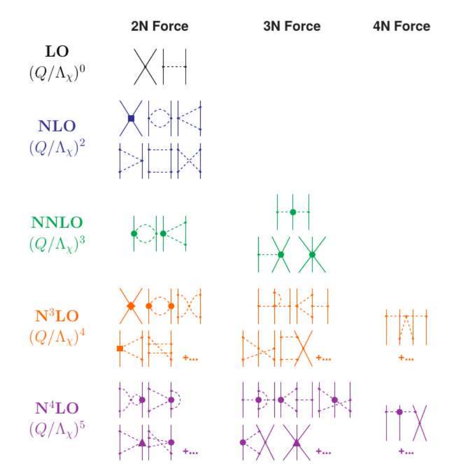
$$q = \begin{pmatrix} u \\ d \end{pmatrix} \qquad q_{R,L} = \frac{1 \pm \gamma^5}{2} q \qquad q_L \to R q_R \qquad q_L \to L q_L$$

- Strategy: write the most general Lagrangian in terms of nucleon and pion fields which transforms in the same way under G

Chiral counting

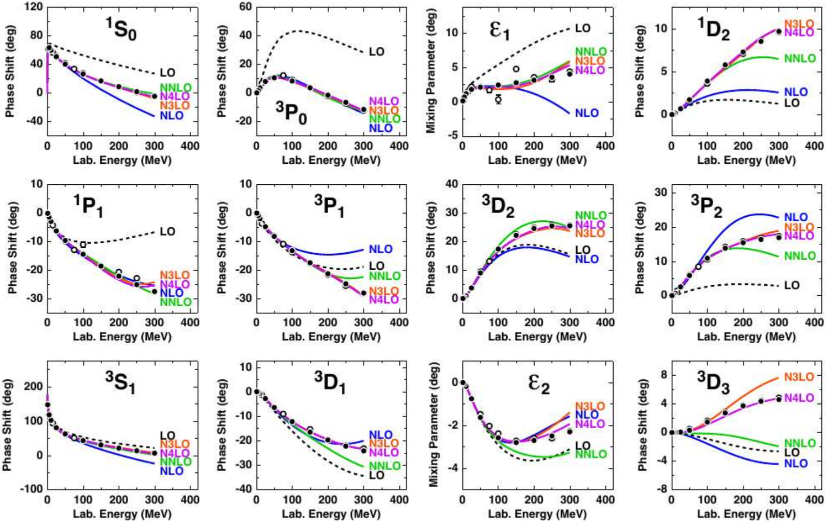
- Degrees of freedom at energy $> \Lambda_\chi \approx 1$ GeVintegrated out
- $\mathcal{L}$ useful for processes of energy $Q \ll \Lambda_\chi$
- Study low-energy processes: momenta $Q \leq m_\pi$
- $\to$ organize the expansion in powers of Q/Λ_χ (possible since the chiral symmetry imposes derivative couplings) $\to$ chiral perturbation theory (χPT)
- πN scattering, electromagnetic and weak interactions, . . .

NN & 3N forces from χPT



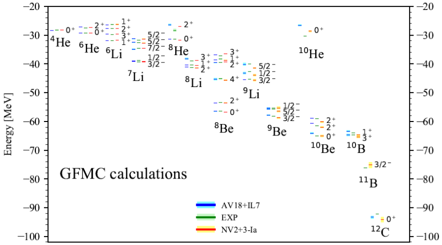
- NN & 3N force in the "Weinberg naive counting"
- [Bernard, Kaiser, & Meissner (1995)], [Ordonéz, Ray, & van Kolck (1996)], [Epelbaum, Meissner, & Gloeckle (1998)], [. . .]
- N4LO: [Epelbaum, Krebs, & Meissner, 2015], [Machleidt *et al.*, 2017]
- "N2LO+" with Δ dof: [Piarulli, Kievsky, Marcucci, MV *et al.*, 2016]
- Is this the correct (or more convenient) counting? Still debated . . .
- Coupling constants (LECs) fitted to NN and 3N database

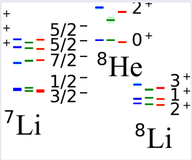
Comparison with NN data - convergence

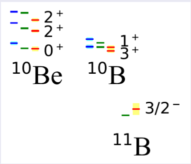


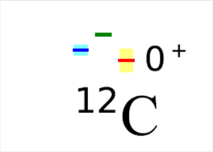
GFMC calculation of light nuclei

NV-Ia + 3NF – [Piarulli *et al.* , 2017]
GFMC calculation by the Argonne group





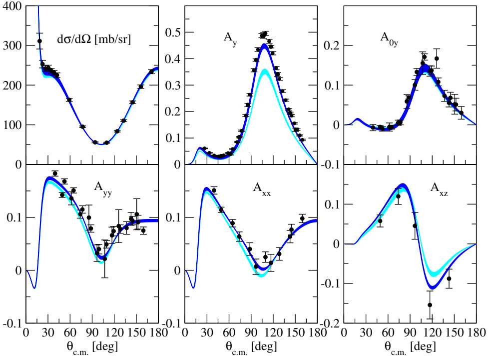




Nice reproduction of the energy levels – 3N force fitted using only $A = 3$ data!!!

$p - {}^3\mathrm{He}$ scattering at $E_p = 5.54$ MeV

Cyan band: NN only, blue band=nn+3N [MV *et al.* , 2014]



Width of the bands: theoretical uncertainty! Still in progress...

TRV Lagrangian for nucleons and pions

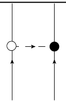
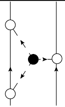
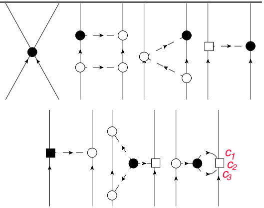
Heavy barion formalism $S^\mu = (0, \boldsymbol{\sigma}/2)$, $v^\mu = (1, \vec{0})$

$$\begin{aligned}\mathcal{L}_{TRV} &= N^\dagger\left(\bar{g}_0 \boldsymbol{\tau}\cdot\boldsymbol{\pi} + \bar{g}_1 \pi_3\right) N - 2N^\dagger\left(\bar{d}_0 + \bar{d}_1 \tau_3\right) S^\mu N v^\nu F_{\mu\nu} \\ &+ \bar{\Delta} M \pi_3 \boldsymbol{\pi}^2 + \bar{C}_1 N^\dagger N \partial_\mu \left(N^\dagger S^\mu N\right) + \bar{C}_2 N^\dagger \boldsymbol{\tau} N \cdot \partial_\mu \left(N^\dagger S^\mu \boldsymbol{\tau} N\right) + \cdots\end{aligned}$$

- Each LEC's can be put in correspondence with the coupling constants appearing in $\mathcal{L}_{QCD}$
- Example: Contribution of $\bar{\theta}$ to g_0, g_1, $\bar{\Delta}$, ... [Mereghetti *et al.*, 2010], [Bsaisou *et al.*, 2014]

$$\begin{aligned}\bar{g}_0^\theta &= -(0.0155 \pm 0.0019)\bar{\theta} \\ \bar{g}_1^\theta &= (0.0034 \pm 0.0015)\bar{\theta} \\ \bar{\Delta}^\theta &= -(0.00037 \pm 0.00009)\bar{\theta} \\ \ldots &= \ldots\end{aligned}$$

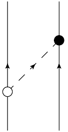
Chiral counting of the “Time-ordered” diagrams

Order	Chiral Power	TRV diagrams
LO	Q^{-1}	
NLO	Q^{0}	
N2LO	Q^{1}	

white=PC, black=TRV
dots=LO vertex, square=NLO vertex
First complete derivation of N2LO order

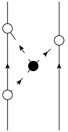
The TRV potential

Q^{-1}
(LO)



$$V^{(-1)}_{\rm TRV} = -\frac{g_A \bar{g}_0}{2f_\pi}(\vec{\tau}_1\cdot\vec{\tau}_2)\frac{i(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)\cdot\boldsymbol{k}}{k^2+m_\pi^2} - \frac{g_A\bar{g}_1}{4f_\pi}\Big[(\tau_{1z}+\tau_{2z}) \times \frac{i(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)\cdot\boldsymbol{k}}{k^2+m_\pi^2} + (\tau_{1z}-\tau_{2z})\frac{i(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)\cdot\boldsymbol{k}}{k^2+m_\pi^2}\Big]$$

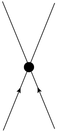
Q^0
(NLO)



$$V^{(0)}_{\rm TRV} = \frac{5g_A^3 M\bar{\Delta}}{4f_\pi}\frac{\pi}{\Lambda_\chi^2}\Big[(\tau_{1z}+\tau_{2z})\frac{i(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)\cdot\boldsymbol{k}}{k^2+m_\pi^2} + (\tau_{1z}-\tau_{2z}) \times \frac{i(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)\cdot\boldsymbol{k}}{k^2+m_\pi^2}\Big]\left(1-\frac{2m_\pi^2}{s^2}\right)s^2 A(k)$$

$$A(k) = \frac{1}{2k}\arctan\left(\frac{k}{2m_\pi}\right) \qquad s = \sqrt{4\,m_\pi^2 + k^2}$$

Q
(N2LO)



$$V^{(1)}_{\rm TRV} = -\frac{\bar{C}_1}{2\Lambda_\chi^2 f_\pi} i\boldsymbol{k}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2) - \frac{\bar{C}_2}{2\Lambda_\chi^2 f_\pi} i\boldsymbol{k}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)(\vec{\tau}_1\cdot\vec{\tau}_2) + \cdots$$

The potentials in configuration space

- The loop divergences are corrected through dimensional regularization
- To solve the Schröedinger equation we need the potential in configuration space

The potential is valid only for $Q \ll \Lambda_\chi$
$\Rightarrow$ we introduce a cut-off $C_{\Lambda_F}(k) = \exp(-(k/\Lambda_F)^4)$

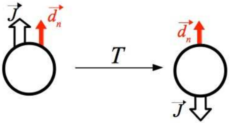
- The Fourier transform results

$$V(r) = \int \frac{\mathrm{d}^3 k}{(2\pi)^3} V(k) C_{\Lambda_F}(k) e^{i\boldsymbol{k}\cdot\boldsymbol{r}}$$

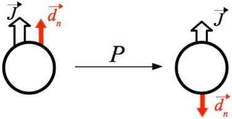
- The observables should not depend on Λ_F

The deuteron EDM

Not degenerate system $\Rightarrow \hat{D} = \beta\, \hat{J}$



Dipole $\Rightarrow \hat{D} = q\, \vec{r}$



if T is conserved $\Rightarrow \langle \hat{D} \rangle = 0$

The dipole operator is:

$$\hat{D} = \underbrace{e \sum_{i=1}^{A} \frac{(1+\tau_z(i))}{2} \vec{r}_i}_{\hat{D}_{\rm PC}} + \underbrace{\frac{1}{2} \sum_{i=1}^{A} \Big[(d_p + d_n) + (d_p - d_n)\tau_z(i) \Big] \sigma_z(i)}_{\hat{D}_{\rm TRV}}$$

- d_p, d_n proton & neutron EDM

$$\Psi_d = |^3S_1\rangle + |^3D_1\rangle + \underbrace{|^1P_1\rangle + |^3P_1\rangle}_{generated\ by\, V_{TRV}}$$

- $\langle D_{\rm TRV} \rangle_{^2{\rm H}} = (d_p + d_n)(1 - \frac{3}{2} P_D)$

The Deuteron EDM

- The contribution to the deuteron EDM that comes from $\hat{D}_{PC}$ is linearly dependent on TRV LECs

$$\langle \hat{D}_{PC} \rangle_{^2H} = \bar{g}_0 A_0 + \bar{g}_1 A_1 + \bar{\Delta} A_2 + \bar{C}_1 A_3 + \bar{C}_2 A_4 + \bar{C}_3 A_5$$

Λ_F(MeV)	A_0	A_1	A_2	A_3	A_4	A_5
450	0	0.1945	-0.6971	0	0	-0.0119
500	0	0.1966	-0.6914	0	0	-0.0132
600	0	0.1927	-0.6913	0	0	-0.0109

The coefficients A_i are in units of e fm

  - No contribution from the LECs $\bar{g}_0$, $\bar{C}_1$ and $\bar{C}_2$
  - The contribution from $\bar{\Delta}$ (NLO) seems bigger than the $\bar{g}_1$ contribution, but $\bar{\Delta}/\bar{g}_1 \simeq 0.1$

The Deuteron EDM

Convergence of the coefficient A_2

TRV/PC	LO	+NLO	+N2LO	+N3LO	+N4LO
LO	0	0	0	0	0
+NLO	-0.943	-0.906	-0.885	-0.895	-0.894
+N2LO	-0.696	-0.704	-0.689	-0.691	-0.698

- PC potential [Entem, Machleidt, & Nosyk, 2017]
- $\Lambda_F = 500$ MeV
- The correction due to N2LO TRV potential is $\sim$ 20%

The Deuteron EDM

$$\langle \hat{D} \rangle_{^2\mathrm{H}} = \langle \hat{D}_{\mathrm{PC}} \rangle_{^2\mathrm{H}} + \langle \hat{D}_{\mathrm{TRV}} \rangle_{^2\mathrm{H}} \qquad \langle \hat{D}_{\mathrm{TRV}} \rangle_{^2\mathrm{H}} = (d_p + d_n)(1 - \frac{3}{2} P_D)$$

-
- This work (PC potential [Entem, Machleidt, & Nosyk, 2017])

$$\text{NLO } \langle \hat{D}_{\mathrm{PC}} \rangle_{^2\mathrm{H}} = (0.994 \pm 0.331) \cdot 10^{-2} \bar{\theta} \, e \text{ fm}$$

$$\text{N2LO } \langle \hat{D}_{\mathrm{PC}} \rangle_{^2\mathrm{H}} = ((0.918 \pm 0.302) \cdot 10^{-2} \bar{\theta} - \bar{C}_3 (0.012 \pm 0.001) \, e \text{ fm}$$

- J. Bsaisou *et al.* result (PC potential [Epelbaum *et al.* , 2009])

$$\text{NLO } \langle \hat{D}_{\mathrm{PC}} \rangle_{^2\mathrm{H}} = (0.89 \pm 0.30) \cdot 10^{-2} \bar{\theta} \, e \text{ fm}$$

Spin rotation

Ultracold neutron beam ($E \simeq 0.0001$ MeV) which pass through an hydrogen gas layer of width d $\Rightarrow$ refraction index n [P. K. Kabir, 1982]

$$\psi_{in} = e^{ip_n z}|\chi\rangle \;\Rightarrow\; \psi_{out} = e^{ip_n(z-d)} e^{ip_n d n}|\chi\rangle$$

$$|\chi\rangle = \text{intial spin state}$$

$$n - 1 = \frac{2\pi N}{p_n^2} f(0) = \frac{2\pi N}{p_n^2}\Big(f_0 + \underbrace{f_M(\boldsymbol{\sigma}\cdot\boldsymbol{S})}_{\text{spin interaction}} + \overbrace{f_P(\boldsymbol{\sigma}\cdot\boldsymbol{p}_n)}^{\text{PV}} + \underbrace{f_T\boldsymbol{\sigma}\cdot(\boldsymbol{p}_n\times\boldsymbol{S})}_{\text{TRV}}\Big)$$

- $f(0)$ forward scattering amplitude
- p_n neutron momentum
- σ spin operator of the incoming neutron
- S spin operator of the proton
- $N = 0.4 \cdot 10^{23}$ cm^{-1} gas density

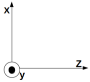
TRV spin rotation

$$f(0) = f_0 + f_M\sigma_x + f_P\sigma_z + f_T\sigma_y$$

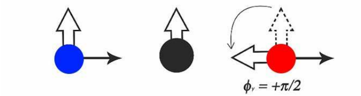
$\Rightarrow$ spin rotation term around the y-axis

$$\psi_{out} = e^{ip_n(z-d)} e^{i\frac{2\pi Nd}{p_n} f_T\sigma_y} |\chi\rangle$$

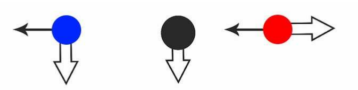
- initial state: $\Uparrow \vec{p}, \Uparrow \vec{n} \parallel x-$ axis
- final state: $\Uparrow \vec{p} \parallel x-$ axis



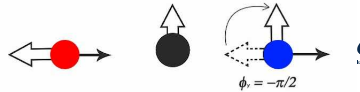
Original process
(we suppose that the spin rotates counterclokwise around the y-axis)



Time-reversal



Rotation of 180° around the y-axis



Results

The rotation around the y-axis is linearly dependent on TRV LECs

$$\frac{\mathrm{d}\phi_y}{\mathrm{d}z} = \bar{g}_0 d_0 + \bar{g}_1 d_1 + \bar{\Delta} d_2 + \bar{C}_1 d_3 + \bar{C}_2 d_4 + \bar{C}_3 d_5$$

Λ_F (MeV)	d_0	d_1	d_2	d_3	d_4	d_5
450	4.274	0	0	-0.126	-0.089	0
500	4.390	0	0	-0.128	-0.088	0
600	4.455	0	0	-0.118	-0.079	0

The coefficients d_i are in units of rad/m

- PC potential [Entem & Machleidt, 2011]
- No contribution from the LECs $\bar{g}_1$, $\bar{\Delta}$ and $\bar{C}_3$.

Results

Using the estimates of the LECs in term of $\bar{\theta}$ [J. Bsaisou *et al.*, 2015]

$$\begin{aligned} \bar{\Delta}^{\theta} &= (0.37 \pm 0.09) \cdot 10^{-3}\bar{\theta} \\ \bar{g}_0{}^{\theta} &= (0.0155 \pm 0.0019)\bar{\theta} \\ \bar{g}_1{}^{\theta} &= (0.0034 \pm 0.0011)\bar{\theta} \\ \bar{C}^{\theta}_{1,2,3} &\simeq (3 \cdot 10^{-2})\bar{\theta} \end{aligned}$$

Λ_F(MeV)	$\mathrm{d}\phi_y/\mathrm{d}z$(rad/m)
450	$(6.62 \pm 0.81) \cdot 10^{-2}\,\bar{\theta}$
500	$(6.80 \pm 0.83) \cdot 10^{-2}\,\bar{\theta}$
600	$(6.91 \pm 0.85) \cdot 10^{-2}\,\bar{\theta}$

- Only $\bar{g}_1^{\theta}$ contribution ($\bar{C}_1^{\theta}$, $\bar{C}_2^{\theta}$ not considered)
- The estimated value of $\bar{\theta} \lesssim 10^{-10}$ so we expect $\mathrm{d}\phi_y/\mathrm{d}z \lesssim 10^{-11}$ rad/m
- Any signal that $\mathrm{d}\phi_y/\mathrm{d}z \gtrsim 10^{-11}$ rad/m $\Rightarrow$ BSM effects

Summary & outlook

Summary

- Derivation of the TRV *NN* potential at N2LO
- Explorative study of $\vec{n} - \vec{p}$ spin rotation
  - This effect could be enhanced in $\vec{n} - \vec{A}$ [Bowman & Gudkov, 2014]
- Calculation of the deuteron EDM

Future work

- Calculation of $^3\mathrm{H}$ and $^3\mathrm{He}$ in progress (TRV 3N force!)
- EDM of dimagnetic atoms and the Shiff screening
  - Screening of nuclear and electron EDM by the electron cloud [Shiff, 1963], [Liu *et al.*, 2007]
  - "best limit" $d_{Hg} < 7.4\ 10^{-30}$ e cm [Graner *et al.*, 2016]
  - New experiments Ra, Xe, Hg, . . . [Chupp *et al.*, 2017]
  - Planned calculation in collaboration with colleagues of INFN-Napoli