Time reversal violation in light and heavy nuclei

M. Viviani

INFN, Sezione di Pisa &
Department of Physics, University of Pisa
Pisa (Italy)

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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 baryon/antibaryon asymmetry (BAU) [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
    - $|d_n| < 3.6\ 10^{-26} e$ cm [Pendlebury *et al.*, 2015]
    - $|d_e| < 9.7\ 10^{-29} e$ cm [Baron *et al.*, 2014] (ThO molecule)
    - $|d_A| < 7.4\ 10^{-30} e$ cm [Graner *et al.*, 2016] (^{199}Hg atom)
    - Paramagnetic systems: Cs, Tl, ThO, ... (more sensitive to d_e)
    - Diamagnetic systems: ^{199}Hg, ^{129}Xe, ^{223}Rn, ... more sensitive to nuclear TRV via the Schiff moment
- 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
  - Jülich: a new E/B ring or using the existing COSY ring (JEDI Coll.)
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- Under exploration: TRV in neutron transmission [Bowman & Gudkov, 2014]

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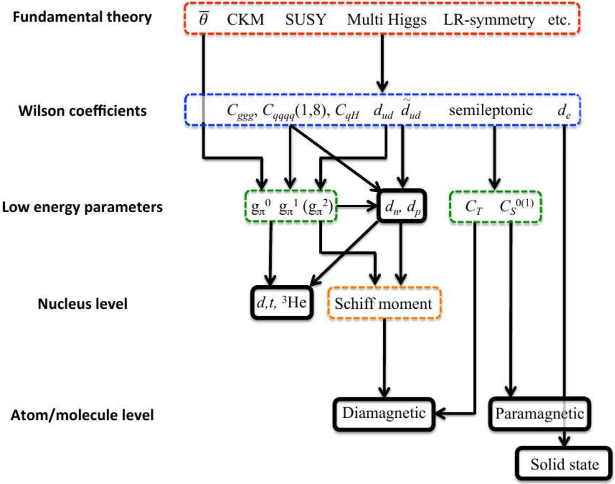
SM & BSM contributions to TRV

- Origin of TRV: in the Standard Model (SM) . . .
  - phase of the CKM matrix (very small effect in processes which do not involve flavour change)
    - $d_n \sim 2.9\ 10^{-32} e$ cm [Pospelov & Ritz, 2005]
    - too small matter/antimatter asymmetry [Canetti *et al.*, 2012]
  - the "θ" term
    - $d_n \sim 0.045\ \overline{\theta}$ e fm [Alexandrou *et al.*, 2016]
    - $\Rightarrow \bar{\theta} < 10^{-10}$ "strong CP problem" $\to$ axion? [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]

From BSM theories to observable quantities (and viceversa!)



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 the 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: a number of possible independent 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

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

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

$$\bar{m} = \frac{m_u + m_d}{2} \quad \epsilon = \frac{m_u - m_d}{m_u + m_d} \qquad s_0 = \bar{m} \qquad s_3 = \epsilon \bar{m} \qquad p_0 = \bar{m}\bar{\theta}/2 \qquad p_3 = \epsilon \bar{m}\bar{\theta}/2$$

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

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	$i\mu_1 \, (\bar{u}u \, \bar{d}\gamma_5 d + \bar{u}\gamma_5 u \, \bar{d}d - \bar{d}\gamma_5 u \, \bar{u}d - \bar{d}u \, \bar{u}\gamma_5 d) +$
	$i\mu_8 \, (\bar{u}\lambda^a u \, \bar{d}\gamma_5 \lambda^a d + \bar{u}\gamma_5 \lambda^a u \, \bar{d}\lambda^a d - \bar{d}\gamma_5 \lambda^a u\%, \bar{u}\lambda^a d - \bar{d}\lambda^a u \, \bar{u}\gamma_5 \lambda^a d)$

Summary: TRV at 1 GeV scale

10 coupling constants: $\bar{\theta}$ + $[\nu_1, \nu_8, \tilde{\delta}^1_G, \tilde{\delta}^3_G, \tilde{\delta}^1_F, \tilde{\delta}^3_F, \beta_G \; \mu_1, \mu_8]$
their values depend on the specific BSM theory

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 $G = SU(2)_R \times SU(2)_L$

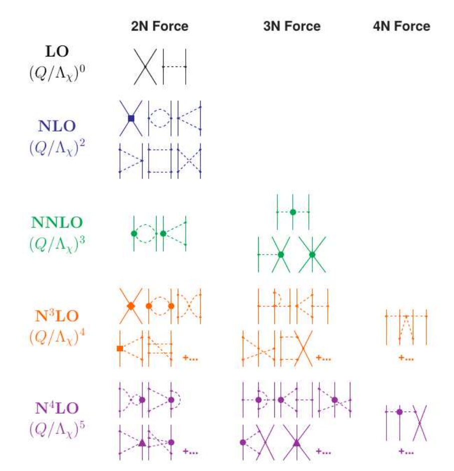
$$q = \begin{pmatrix} u \\ d \end{pmatrix} \qquad q_{R,L} = \frac{1 \pm \gamma^5}{2} q \qquad q_L \to R q_R \qquad q_L \to L q_L$$

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

Chiral counting

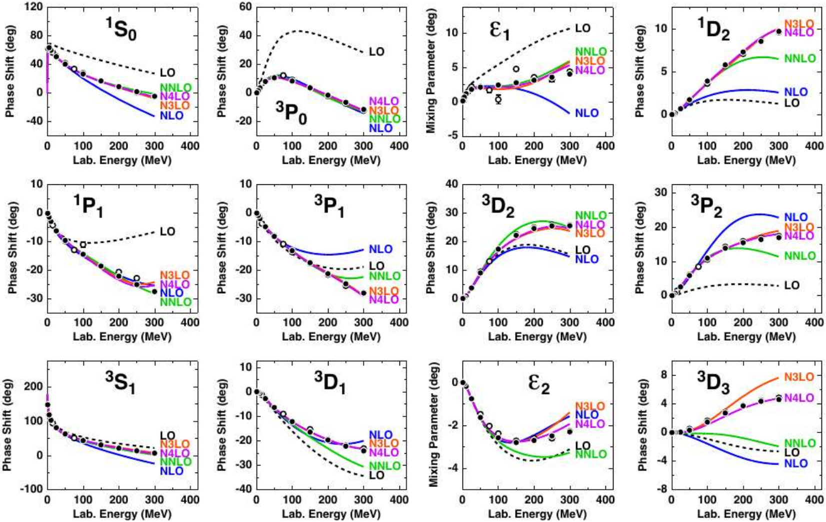
- Degrees of freedom at energy $> \Lambda_\chi \approx 1$ GeV integrated out
- $\mathcal{L}_{\chi\mathrm{EFT}}$ useful for processes of energy $Q \ll \Lambda_\chi$
- Study low-energy processes: momenta $Q \leq m_\pi$
- $\rightarrow$ organize the expansion in powers of Q/Λ_χ (possible since the chiral symmetry imposes derivative couplings) $\rightarrow$ chiral perturbation theory (χPT)

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 under debate!
- Coupling constants (LECs) fitted to NN and 3N database

Comparison with NN data - convergence



TRV Lagrangian for nucleons and pions

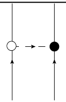
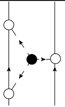
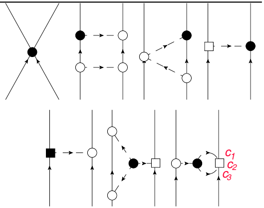
Heavy barion formalism $S^\mu = (0, \boldsymbol{\sigma}/2)$, $v^\mu = (1, \vec{0})$

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

- 10 LEC's: d_0, d_1 ($\equiv d_p$, d_n) + $\bar{g}_0$, $\bar{g}_1$, $\bar{\Delta}$, $\bar{C}_1$,. . ., $\bar{C}_5$
- Each LEC's can be put in correspondence with the coupling constants appearing in $\mathcal{L}_{QCD}$
- Example: Contribution of $\bar{\theta}$ to $\bar{g}_0$, $\bar{g}_1$, $\bar{\Delta}$, . . . [Mereghetti *et al.*, 2010], [Bsaisou *et al.*, 2014]

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

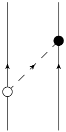
Chiral counting of the “Time-ordered” diagrams

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

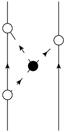
The TRV potential

Q^{-1} (LO)



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

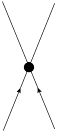
Q^0 (NLO)



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

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

Q (N2LO)



$$V_{\rm TRV}^{(1)} = -\frac{1}{2\Lambda_\chi^2 f_\pi}\Big[\bar{C}_1 i\boldsymbol{k}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2) + \bar{C}_2 i\boldsymbol{k}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)(\vec{\tau}_1\cdot\vec{\tau}_2) + \bar{C}_3 i\boldsymbol{k}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)(\tau_{1z}+\tau_{2z}) + \bar{C}_4 i\boldsymbol{k}\cdot(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)(\tau_{1z}-\tau_{2z}) + \bar{C}_5 i\boldsymbol{k}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)(3\tau_{1z}\tau_{2z}-\vec{\tau}_1\cdot\vec{\tau}_2)\Big]$$

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

EDM of the deuteron

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

$$\langle\hat{D}_{\rm PC}\rangle_{^2{\rm H}} = \bar{g}_0 a_0 + \bar{g}_1 a_1 + \bar{\Delta}A_\Delta + \sum_{i=1}^{5}\bar{C}_i A_i$$

Λ_F(MeV)	a_0	a_1	A_Δ	A_1	A_2	A_3	A_4	A_5
450	0	0.1945	-0.6971	0	0	0	-0.0119	0
500	0	0.1966	-0.6914	0	0	0	-0.0132	0
600	0	0.1927	-0.6913	0	0	0	-0.0109	0

The coefficients a_i, A_Δ, and A_i are in units of e fm

EDM of the deuteron

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

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

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

$$\text{N2LO } \langle \hat{D}_{PC} \rangle_{^2H} = (0.918 \pm 0.302) \cdot 10^{-2} \ \bar{\theta} - \bar{C}_4 (0.012 \pm 0.001) \ e \text{ fm}$$

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

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

- Uncertainties from variation of Λ_F and the the dependence of the LEC's on $\bar{\theta}$

EDM of heavy atoms and the Schiff moment

- EDM of diamagnetic atoms and molecules
  - sensitive primarily to nuclear TRV via the Schiff moment
  - Expected magnified effects in deformed nuclei
  - ^{129}Xe: $|d_A| < 6.6\ 10^{-27} e$ cm [Rosenberry & Chupp, 2001]
  - ^{199}Hg: $|d_A| < 7.4\ 10^{-30} e$ cm [Graner *et al.*, 2016]
  - ^{225}Ra: $|d_A| < 1.4\ 10^{-23} e$ cm [Parker *et al.*, 2015]; new possible experiment at FRIB?
  - ^{221,223}Rn: experiment at TRIUMF underway
- EDM of paramagnetic atoms & molecules
  - more sensitive to electron EDM
  - $|d_e| < 8.7\ 10^{-29} e$ cm [Baron *et al.*, 2014] (ThO molecule)
  - $|d_e| < 16\ 10^{-29} e$ cm [Cairncross *et al.*, 2016] (HfF molecule)
- EDM of the muon and other particles
  - $|d_\mu| < 1.9\ 10^{-19} e$ cm [Bennet *et al.*, 2009]
  - $|d_\Lambda| < 7.9\ 10^{-17} e$ cm [Pondrom *et al.*, 1987]

Schiff screening (1)

- A system of N particles with charge q_i and EDM $\boldsymbol{d}_i$
- Electrostatic energy $\mathcal{E}_i$ per each particle $\mathcal{E}_i = q_i\phi(\boldsymbol{r}_i) - \boldsymbol{E}(\boldsymbol{r}_i)\cdot\boldsymbol{d}_i$
- $\boldsymbol{E}_0$ external uniform electric field $\Rightarrow$ EDM of the system determined from $\Delta\mathcal{E} = -\boldsymbol{E}_0\cdot\boldsymbol{d}$
- Schiff displacement operator $A = \sum_i \boldsymbol{d}_i\cdot\boldsymbol{\nabla}_i/q_i = i\sum_i \boldsymbol{d}_i\cdot\boldsymbol{p}_i/q_i$
- Hamiltonian

$$H = \underbrace{T + V_{CC} + V_C^{ext}}_{H_0} + V_{CD} + V_D^{ext}$$

- charge-charge ($C-C$) and charge-dipole ($C-D$) interactions

$$V_{CC} = \frac{1}{2}\sum_{i\neq j}\frac{q_iq_j}{r_{ij}} \qquad V_{CD} = -\sum_i \boldsymbol{d}_i\cdot\left(-\boldsymbol{\nabla}_i\sum_{j\neq i}\frac{q_j}{r_{ij}}\right) = [A, V_{CC}]$$

- External field contribution $\phi_0 = -\boldsymbol{x}\cdot\boldsymbol{E}_0$

$$V_C^{ext} = -\sum_i q_i\boldsymbol{r}_i\cdot\boldsymbol{E}_0 \qquad V_D^{ext} = -\sum_i \boldsymbol{d}_i\cdot\boldsymbol{E}_0 = [A, V_C^{ext}]$$

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$$H = \underbrace{T + V_{CC} + V_C^{ext}}_{H_0} + V_{CD} + V_D^{ext}$$

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- [Schiff, PR**132**, 2194 (63)]
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Schiff moment

- The screening is “violated” if
  - the particles move relativistically $T = \sum_i \beta_i m_i + \boldsymbol{\alpha}_i \cdot \boldsymbol{p}_i$
  - The particles are not point-like
  - The interaction is not just the electrostatic one
- The effect of the finite size of the nucleus can be written as

$$H = -4\pi \boldsymbol{\nabla}\rho(0) \cdot \boldsymbol{S}$$

  - $\rho(0)$ electron density inside the nucleus
  - $\boldsymbol{S}$ Schiff momentum operator [Schiff, 1963], [Sanders, 1958], [Feinberg, 1977], [Sushkov *et al.*, 1984], [Liu *et al.*, 2007], [. . .]

$$\boldsymbol{S} = \frac{e}{10} \sum_{i=1}^{A} \boldsymbol{r}_i \frac{1 + \tau_z(i)}{2} \left[r_i^2 - \frac{5}{3} \langle r_{\rm ch}^2 \rangle \right]$$

- Exact form still under debate . . .
- In practice $d_A = \kappa_S \langle S \rangle$
  - $\kappa_S = \langle -4\pi \boldsymbol{\nabla}\rho(0) \rangle$ from atomic physics calculations
  - $\langle S \rangle$ from nuclear physics calculations
  - $\langle S \rangle = \bar{g}_0 a_0 + \bar{g}_1 a_1 + \cdots$

Examples of calculations

Coefficient κ_S

Atom	κ_S [cm/fm^3]	Ref.
^{129}Xe	$+(0.27-0.38)\ 10^{-17}$	*a*
^{199}Hg	$-(2.8-4.0)\ 10^{-17}$	*b*
^{225}Ra	$-(7.0-8.5)\ 10^{-17}$	*b*

[a] [Dzuba *et al.*, 2005]
[b] [Dzuba *et al.*, 2002]

Coefficient $\langle S \rangle$

^{129}Xe	a_0	a_1	a_2
Mean field[a]	$8\ 10^{-3}$	$6\ 10^{-3}$	$9\ 10^{-3}$
Shell model[b]	$5\ 10^{-4}$	$4\ 10^{-4}$	$2\ 10^{-3}$
Shell model[c]	$3\ 10^{-3}$	$8\ 10^{-4}$	$2\ 10^{-3}$

[a] [Dimitriev *et al.*, 2004]
[b] [Yoshinaga *et al.*, 2013]
[c] [Teruya *et al.*, 2015]

With the Colleagues of INFN-Napoli and Un. of Caserta we are planning shell-model calculations of the Schiff moment, starting from the χEFT TRV potential

Conclusions

- Derivation of the TRV *NN* potential at N2LO
- Calculation of the deuteron EDM

- In progress:
  - Derivation of the TRV 3N force up to N2LO
  - Calculation of the EDM of $^3\mathrm{H}$ and $^3\mathrm{He}$
  - Explorative study of $\vec{n}-\vec{p}$ & $\vec{n}-\vec{d}$ spin rotations
  - Preliminary estimate: $\mathrm{d}\phi_y/\mathrm{d}z \lesssim 10^{-11}$ rad/m
  - it could be enhanced in $\vec{n}-\vec{A}$ [Bowman & Gudkov, 2014]

- Planned:
  - EDM of heavy nuclei $\Rightarrow$ Schiff moment: shell-model calculations in collaboration with the Colleagues of INFN-Napoli and Un. of Caserta
  - Particular attention to nuclides produced by SPES!