Time Reversal Violation in two Nucleons Systems

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TNPI2017 - XVI Conference on Theoretical Nuclear Physics in Italy
Cortona, October 5

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Table of contents

Introduction

The Time Reversal Violation in Nuclei

- In the Standard Model (SM) it is possible to introduce *P*-violating and *C*-conserving terms and therefore time reversal violating (TRV):
  - phase of the CKM matrix
  - phase of the neutrino's mixing matrix
  - θ-term
- The effects of the CKM and neutrino's mixing matrix phases give small contributions in observables which do not involve flavour changes
- Light nuclei can be good candidates to investigate TRV effects from θ:
  - Permanent Electric Dipole Moment (EDM)
  - Spin rotation
- Related issues:
  - "Strong CP" problem ($\bar{\theta} < 10^{-10}$ from neutron EDM)
  - possible effects beyond the SM [J. Bsaisou, *et al.*, 2015; E. Mereghetti and U. van Kolck, 2015]
  - matter-antimatter asymmetry [G. Steigman, 1976]

The TRV Lagrangian in the χEFT [J. Bsaisou, *et al.*, 2015]

$$\overline{\mathcal{L}}_{\rm QCD} = \overline{q} i\gamma^\mu D_\mu q - \frac{1}{4}\mathcal{G}_{\mu\nu,a}\mathcal{G}^{\mu\nu}_a - \overbrace{\overline{q}\mathcal{M}q}^{\mathcal{L}^{\mathcal{M}}_{\rm QCD}} - \theta\frac{g^2}{64\,\pi^2}\epsilon^{\mu\nu\rho\sigma}\mathcal{G}^a_{\mu\nu}\mathcal{G}^a_{\rho\sigma}$$

$$\mathcal{M} = e^{i\rho}\begin{pmatrix} m_u & 0 \\ 0 & m_d \end{pmatrix}$$

$$\Downarrow \quad U(1)_A$$

$$\mathcal{L}^{\mathcal{M}}_{\rm QCD} = -\overline{q}(\overline{m}1 + \epsilon\,\overline{m}\,\tau_3 - i\frac{\overline{\theta}\,\overline{m}}{2}(1-\epsilon^2)\gamma^5 1)q$$

$$\overline{m} = (m_u + m_d)/2 \qquad \epsilon = \frac{m_u - m_d}{m_u + m_d} \qquad \overline{\theta} = 2\rho - \theta$$

$\Downarrow$ χEFT ($\overline{\theta}$ as external source)

The TRV Lagrangian in the χEFT [J. Bsaisou, *et al.*, 2015]

At nuclear level $N = (n, p)$

$$\mathcal{L}^{(\text{TRV})} = \underbrace{\overline{N}(\overline{g_0}^{\theta}\, \vec{\tau}\cdot\vec{\pi} + \overline{g_1}^{\theta}\pi_3)N + M\overline{\Delta}^{\theta}\pi_3\pi^2}_{\text{Bsaisou pionfull Lagrangian}}$$

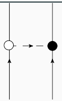
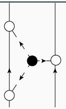
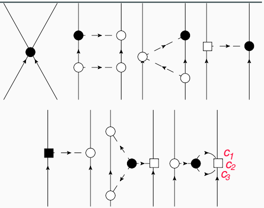
$$\underbrace{+\frac{\overline{C_1}^{\theta}}{2\Lambda_\chi^2 f_\pi}\overline{N}N\partial_\mu\left(\overline{N}\gamma^\mu\gamma^5 N\right) + \frac{\overline{C_2}^{\theta}}{2\Lambda_\chi^2 f_\pi}\overline{N}\vec{\tau}N\partial_\mu\left(\overline{N}\vec{\tau}\gamma^\mu\gamma^5 N\right)}_{\text{Bsaisou contact Lagrnagian}}$$

$$\underbrace{-d_n\overline{N}(1-\tau_z)i\gamma_5\sigma^{\mu\nu}NF_{\mu\nu} - d_p\overline{N}(1+\tau_z)i\gamma_5\sigma^{\mu\nu}NF_{\mu\nu}}_{\text{Coupling with the photons}}$$

$$+\underbrace{\frac{\overline{C_3}^{\theta}}{2\Lambda_\chi^2 f_\pi}\overline{N}\tau_3 N\partial_\mu\left(\overline{N}\gamma^\mu\gamma^5 N\right)}_{\text{“New” contact term}}$$

Construction of TRV potential

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 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

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

- The observables should not depend on Λ_F

The $\vec{n} - \vec{p}$ spin rotation

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]

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

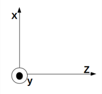
$$|\chi\rangle = \text{intial spin state}$$

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

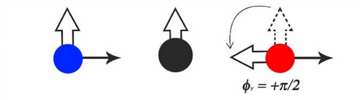
- $f(0)$ forward scattering amplitude
- p_n neutron momentum
- σ spin operator of the incoming neutron
- S spin operator of the proton
- $N = 0.4 \cdot 10^{23}$ cm^{-1} gas density

TRV spin rotation

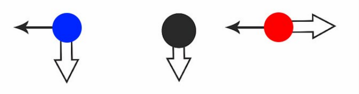
- initial state:
  $\Uparrow \vec{p}, \Uparrow \vec{n} \parallel x-$axis
- final state: $\Uparrow \vec{p} \parallel x-$axis



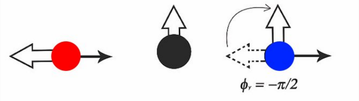
Original process
(we suppose that the spin rotates
counterclokwise around the y-axis)



Time-reversal



Rotation of 180° around the y-axis



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

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

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

Results

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

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

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 $\overline{g}_1^\theta$, $\overline{\Delta}^\theta$ and $\overline{C}_3^\theta$.

Results

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

$$\begin{aligned}
\overline{\Delta}^{\theta} &= (0.37 \pm 0.09) \cdot 10^{-3}\overline{\theta} \\
\overline{g_0}^{\theta} &= (0.0155 \pm 0.0019)\overline{\theta} \\
\overline{g_1}^{\theta} &= (0.0034 \pm 0.0011)\overline{\theta} \\
\overline{C}^{\theta}_{1,2,3} &\simeq (3 \cdot 10^{-2})\overline{\theta}
\end{aligned}$$

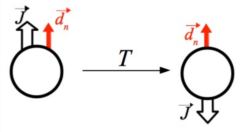
Λ_F(MeV)	$\mathrm{d}\phi_y/\mathrm{d}z$(rad/m)
450	$(6.62 \pm 0.81) \cdot 10^{-2}\,\overline{\theta}$
500	$(6.80 \pm 0.83) \cdot 10^{-2}\,\overline{\theta}$
600	$(6.91 \pm 0.85) \cdot 10^{-2}\,\overline{\theta}$

- Only $\overline{g}_1^{\theta}$ contribution ($\overline{C}_1^{\theta}$, $\overline{C}_2^{\theta}$ not considered)
- The estimated value of $\overline{\theta} \lesssim 10^{-10}$ 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

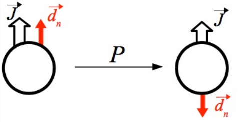
The deuteron EDM

Permanent Electric Dipole Moment

Not degenrate 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:

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

- $e > 0$
- d_p proton EDM
- d_n neutron EDM
- $\hat{D}_{\mathrm{PC}}$ standard operator

The Deuteron EDM

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

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

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 $\overline{g}_0^\theta$, $\overline{C}_1^\theta$ and $\overline{C}_2^\theta$.
- The contribution from $\overline{\Delta}^\theta$ (NLO) seems bigger than the $\overline{g}_1^\theta$ contribution, but $\overline{\Delta}^\theta / \overline{g}_1^\theta \simeq 0.1$.

The Deuteron EDM

Convergence of the coefficients 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 & Mechleidt
- $\Lambda_F = 500$ MeV
- The correction due to N2LO TRV potential is $\sim$ 20%

The Deuteron EDM

- This work (PC potential [Entem & Machleidt, 2011])

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

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

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

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

- The contribution that comes from the pure TRV part of the operator is

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

where P_D is the percentage of D-wave in the deuteron wave function (as predicted by [Yamanaka & Hiyama, 2015])

Conclusions

Conclusions

- Independent derivation of the TRV *NN* potential at NLO + contact terms
- First derivation of the TRV potetnial at N2LO
- Explorative study of $\vec{n} - \vec{p}$ spin rotation
    - This effect could be enhanced in $\vec{n} - \vec{A}$ [V. Gudkov, 1992]

- Calculation of the deuteron EDM
    - Calculation of ^{3}H and ^{3}He are planned
    - Proposal for new storage-rings dedicated to the measurement of the d, ^{3}H, ^{3}He, ^{6}Li EDMs (estimated precision $\sim 10^{-16} e$ fm) [Y. K. Semertzidis, 2011]