T-violation in nucleons and nuclei: an effective field theory approach

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Main purpose of this talk

1. How to describe T-violating hadronic interactions in a systematic fashion? What interactions to include for ‘leading order’ calculations?

2. Using these interactions to calculate T-odd nuclear observables (EDMs, Schiff moments, Magnetic quadrupole, neutron spin rotation, analyzing powers …). I will focus on PVT in not on PCTV (but happy to discuss)

3. Focus on simple observables that capture main ideas (analogue of program of hadronic PV) → extension to complicated observables in heavy nuclei is far from trivial.
Main purpose of this talk

1. How to describe T-violating hadronic interactions in a systematic fashion? What interactions to include for ‘leading order’ calculations?

2. Using these interactions to calculate T-odd nuclear observables (EDMs, Schiff moments, Magnetic quadrupole, neutron spin rotation, analyzing powers …). I will focus on PVTV not on PCTV (but happy to discuss)

3. Focus on simple observables that capture main ideas (analogue of program of hadronic PV) → extension to complicated observables in heavy nuclei is far from trivial.

4. **Very important:** measurable T-violating signals require BSM physics (or nonzero theta term). Need some sort of link between hadronic T-violation and particle physics to be able to do 1) and then 2) and 3).

5. Will **not** discuss in detail specific BSM models or implications or baryogenesis motivations → talks by Kaori and Michael on Saturday.
EDMs in the SM

- CP is broken in the CM via the Kobayashi-Maskawa mechanism
- CP-odd phase in the off-diagonal CKM matrix
- Manifests in flavor-diagonal (our goal) at 3 loops (electron 4 loops)

- Very very suppressed SM electroweak contributions to EDMs

Hoogeveen '90, Khriplovich, Zhitnitsky '82, Czarnecki, Krause '97, Uraltsev '13, Seng '14
5 to 6 orders **below** upper bound → **Out of reach!**

With linear extrapolation: CKM neutron EDM in 2075….
The strong CP problem

If $\theta \sim 1$

Sets $\theta$ upper bound: $\theta < 10^{-10}$

Reason for this suppression? Axions? Nelson-Barr?
All solutions have problems....

Dine/Draper '15
Measurement of a nonzero EDM

Standard Model: \( \theta \) -term

BSM sources of CP-violation
- SUSY, Left-Right, 2HDM, ...

For the foreseeable future: EDMs are ‘background-free’ searches for new physics
Comparing to hadronic parity violation

Energy

>100 GeV

Full Standard Model

Integrate out heavy W, Z fields

~ 1 GeV

Effective Fermi interactions

< 1 GeV

Hadronic PV-violation (DDH or EFT)

$G_F \sim \frac{1}{M_W^2}$
Comparing to hadronic parity violation

Energy

>~ 1 TeV

Full Beyond the Standard Model

Integrate out heavy BSM fields

~ 1 GeV

We need to figure out the form of the CP-odd analogous ‘Fermi interactions’

< 1 GeV

Hadronic CP-violation
The form of the CP-odd ‘Fermi’ interactions

- To stay model independent: add all EFT operators (infinite…)

1) Degrees of freedom: Full SM field content
2) Symmetries: Lorentz, \( \text{SU}(3) \times \text{SU}(2) \times \text{U}(1) \)

\[
L_{\text{new}} = L_{\text{SM}} + \frac{1}{\Lambda} L_5 + \frac{1}{\Lambda^2} L_6 + \cdots
\]

- Effects at low energy (E) suppressed by powers of \( (E/\Lambda) \)

Buchmuller & Wyler ‘86
Gradzkowski et al ’10
Many others
The form of the CP-odd ‘Fermi’ interactions

- To stay **model independent**: add all EFT operators (infinite…)

1) Degrees of freedom: Full SM field content
2) Symmetries: Lorentz, SU(3)xSU(2)xU(1)

\[ L_{new} = L_{SM} + \frac{1}{\Lambda} L_5 + \frac{1}{\Lambda^2} L_6 + \cdots \]

- Effects at low energy (E) suppressed by powers of \((E/\Lambda)\)

- Focus on all CP-odd operators at dimension-six
- Run down \(\Rightarrow\) Integrate out \(H, W, Z, t\) \(\Rightarrow\) Run down \(\Rightarrow\) integrate out \(b, c\) \(\Rightarrow\)

Obtain form of the ‘CP-odd’ Fermi interactions

- Can be easily matched to specific BSM models
- CPV unlikely to arise from light BSM fields but loopholes exist!

Buchmuller & Wyler ’86
Gradkowski et al ’10
Many others

Dekens & JdV, ’13
Cirigliano et al’ 15,’16’17
Fuyuto et al ‘17
Le Dall, Pospelov, Ritz ‘15
When the dust settles.....

Different beyond-the-SM models predict different dominant operator(s)

EFT p.o.v: just look at these low-energy structures

I am mostly neglecting (semi-)leptonic CPV for this talk
Intermediate summary I

- Parametrized BSM CP violation in terms of \textbf{dim6} operators
- Several operators at low energy: theta, (C)EDMs, Weinberg, Four-fermion
- \textbf{Important:} different BSM models $\rightarrow$ different EFT operators

1. Standard Model: only \textbf{theta} has a chance to be measured
2. 2-Higgs doublet model: \textbf{quark+electron EDM}, \textbf{CEDMs}, \textbf{Weinberg}
   (exact hierarchy depends on detail of models)
3. Split SUSY: only \textbf{electron} + \textbf{quark EDMs} (ratio fixed)
4. Left-right symmetric: \textbf{Four-quark LR operators}, small (C)EDMs
5. Leptoquarks: Semi-leptonic four-fermion and four-quark (tree-level)

- But we neglect these ‘high-energy details’ in this talk and focus on the EFT operators around 1 GeV

Mohapatra et al ’75 Giudice et al ’06 Dekens et al ’14 ‘18
Pich & Jung ’14 Fuyuto et al ’18
When the dust settles......

Few GeV

QCD (θ-term) + Quark EDM + Quark chromo-EDM + Gluon chromo-EDM

4quark operators

'Hadronization'

100 MeV

π°,±

N N

N N
CPV in hadrons and nuclei

Goal is to calculate CPV properties of **hadrons** and **nuclei**
- Electric dipole + higher moments (Schiff, magnetic quadrupole…)
- CP-odd scattering observables

Wishlist
- **Link** to underlying theory (QCD + CPV operators)
- **Power counting of nuclear forces and currents**
- **General** (several observables in one framework)
General CP-violating NN force

- Parametrize the CPV nuclear force with one-meson exchange
- CP-odd analogue of the PV DDH model with O(10) CPV couplings

\[ N \xleftarrow{\pi, \rho, \omega} N \]

Strong vertex

\[ N \xrightarrow{\text{CPV vertex}} N \]

Or in EFT with just contact terms: five \( S \leftrightarrow P \) transitions

\[ \begin{align*}
{^3}S_1 & \leftrightarrow {^1}P_1 & \text{np} \\
{^3}S_1 & \leftrightarrow {^3}P_1 & \text{np} \\
{^1}S_0 & \leftrightarrow {^3}P_0 & \text{np, nn, pp}
\end{align*} \]
General CP-violating NN force

- Parametrize the CPV nuclear force with one-meson exchange
- CP-odd analogue of the PV DDH model with O(10) CPV couplings

Or in EFT with just contact terms: five $S \leftrightarrow P$ transitions

Here we use chiral EFT: startpoint QCD + CPV dim-6 operators

1. Systematic derivation of CPV potential + CPV 3-body forces
2. Direct connection between forces and currents (for EDMs!)
3. Link to lattice QCD
An ultrashort intro to Chiral EFT

- Use the symmetries of QCD to obtain **chiral Lagrangian**

\[ L_{QCD} \rightarrow L_{\text{chiPT}} = L_{\pi\pi} + L_{\pi N} + L_{NN} + \cdots \]

- Quark masses = 0 \( \rightarrow \) SU(2)_L \times SU(2)_R symmetry
  - Spontaneously broken to SU(2)-isospin (pions = Goldstone)
  - Explicit breaking (quark mass) \( \rightarrow \) pion mass

- ChPT has systematic expansion in \( Q/\Lambda_\chi \sim m_\pi/\Lambda_\chi \) \( \Lambda_\chi \approx 1 \text{ GeV} \)

Weinberg, Gasser, Leutwyler, and many many others
An ultrashort intro to Chiral EFT

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  ▪ Explicit breaking (quark mass) \(\rightarrow\) pion mass

• ChPT has systematic expansion in \(Q/\Lambda_\chi \sim m_\pi/\Lambda_\chi\) \(\Lambda_\chi \approx 1 \text{ GeV}\)
  ▪ **Form of interactions fixed by symmetries**
  ▪ Each interactions comes with an unknown constant (LEC)
  ▪ Can be used to derive a nucleon-nucleon potential (chiral EFT)

• **Extended to include CP violation** Mereghetti et al’ 10, JdV et al ’12, Bsaisou et al ’14

Weinberg, Gasser, Leutwyler, and many many others
ChiPT with CP violation

QCD \ + \ \begin{array}{c}
\gamma \\
q \rightarrow q
\end{array} \ + \ \begin{array}{c}
g \\
q \rightarrow g \rightarrow q
\end{array} \ + \ \begin{array}{c}
g \\
g \rightarrow g
\end{array} \ + \ \begin{array}{c}
\text{q}
\end{array}

- They all break CP....

- But transform **differently** under chiral/isospin symmetry

**Different** CP-odd chiral Lagrangians

**Different** hierarchy of CP-odd moments and scattering observables
The magnificent seven

- 2 pion-nucleon (no $g_2$!)
- 1 pion-pion-pion
- 2 nucleon-nucleon
- 2 nucleon-photon (EDM)

- Up to NLO, **seven** interactions for all CP-odd dim4-6 sources
- Each hadronic/nuclear CPV observables probes a linear combination
- More terms if leptons are included!

Mereghetti et al ’10, JdV et al ’12, Bsaisou et al ’14, Chupp/Ramsey-Musolf ‘13
Hierarchy of CPV nuclear forces

CP-even

\[ \frac{g_A}{2F_\pi} \bar{N}(\vec{\sigma} \cdot \vec{D}\pi^a)\tau^a N \]

\[ \approx \left( \frac{g_A Q}{Q^2} \right)^2 \approx Q^0 \]

\[ \bar{N}N \bar{N}N \]

\[ \sim Q^0 \]
Hierarchy of CPV nuclear forces

- **CP-even**
  \[
  \frac{g_A}{2F_\pi} \bar{N}(\bar{\sigma} \cdot \bar{D}\pi^a)\tau^a N
  \]
  \[
  \pi^{\pm,0} \sim \frac{(g_A Q)^2}{Q^2} \sim Q^0
  \]
  \[
  \bar{NN} \bar{NN}
  \]
  \[
  \sim Q^0
  \]

- **CP-odd**
  \[
  \bar{g}_0 \bar{N}(\bar{\tau} \cdot \bar{\pi})N
  \]
  \[
  \pi^\pm \sim \frac{(g_A Q)\bar{g}_0}{Q^2} \sim Q^{-1}
  \]
  \[
  (\bar{NN}) \partial^i (\bar{N}\sigma^i N)
  \]
  \[
  \sim Q^1
  \]

- In general: short-range CPV appear at next-to-next-to-leading order
- Unless symmetries forbid pion-nucleon interactions!
An explicit example: the theta term

U(1) and SU(2) rotations + vacuum alignments:  **CP-odd quark mass:**

\[ \mathcal{L}_{\text{QCD}} = \mathcal{L}_{\text{kin}} - \bar{m}\bar{q}q - \varepsilon \bar{m}\bar{q}\tau^3 q + m_\star \bar{q}i\gamma^5 q \]

Easy to include in ChPT  \[ \chi = 2B(\bar{m} + \varepsilon \bar{m}\tau^3) \rightarrow 2B(\bar{m} + \varepsilon \bar{m}\tau^3 + im_\star \bar{\theta}) \]
Theta and chiral perturbation theory

\[ \mathcal{L}_{\text{QCD}} = \mathcal{L}_{\text{kin}} - \bar{m}qq - \varepsilon \bar{m} \bar{q} \tau^3 q + m_\star \bar{\theta} \bar{q}i \gamma^5 q \]

U(1) and SU(2) rotations + vacuum alignments: **CP-odd quark mass:**

\[ \varepsilon = \frac{m_u - m_d}{m_u + m_d} \]

\[ \mathcal{L}' = \mathcal{L}_\chi - \frac{m^2_\pi}{2} \pi^2 - \delta m_N \bar{N} \tau^3 N + \bar{g}_0 \bar{N} \tau \cdot \pi N \]

Strong proton-neutron mass splitting

Crewther et al’ 79
Baluni ‘79
Theta and chiral perturbation theory

U(1) and SU(2) rotations + vacuum alignments: **CP-odd quark mass:**

\[
\mathcal{L}_{\text{QCD}} = \mathcal{L}_{\text{kin}} - \bar{m} \bar{q} q - \varepsilon \bar{m} \bar{q} \tau^3 q + m_\star \bar{\Theta} \bar{q} i \gamma^5 q
\]

\[
\varepsilon = \frac{m_u - m_d}{m_u + m_d}
\]

\[
\mathcal{L}'_\chi = \mathcal{L}_\chi - \frac{m_\pi^2}{2} \pi^2 - \delta m_N \bar{N} \tau^3 N + \bar{g}_0 \bar{N} \tau \cdot \pi N
\]

\[
m_\star = \frac{m_u m_d}{m_u + m_d}
\]

**CP-odd pion-nucleon vertex**

\[
\pi^\pm
\]

\[
\bar{g}_0
\]

\[
\bar{g}_1
\]

\[
\bar{C}_{1,2}
\]
Theta and chiral perturbation theory

After axial U(1) and SU(2) rotations, complex CP-odd quark mass:

\[ \mathcal{L}_{\text{QCD}} = \mathcal{L}_{\text{kin}} - \bar{m}\bar{q}q - \varepsilon \bar{m} \bar{q} \tau^3 q + m \bar{\theta} \bar{q} i \gamma^5 q \]

\[ \varepsilon = \frac{m_u - m_d}{m_u + m_d} \]

Linked via SU\(_A\)(2) rotation

\[ \mathcal{L}'_\chi = \mathcal{L}_\chi - \frac{m^2 \pi}{2} \pi^2 - \delta m_N \bar{N} \tau^3 N + \bar{g}_0 \bar{N} \tau \cdot \pi N \]

Nucleon mass splitting
(strong part, no EM!)

Walker-Loud ‘14, Borsanyi ’14, Aoki (FLAG) ’13

Use lattice for mass splitting

\[ g_0 = \delta m_N \frac{1 - \varepsilon^2}{2\varepsilon} \bar{\theta} = (15.5 \pm 2.5) \times 10^{-3} \bar{\theta} \]
Wrap-up

- Identify protected relations for various couplings

\[
g_1 = -(3 \pm 2) \cdot 10^{-3} \bar{\theta}
\]

Small due to isospin symmetry

- Used to estimate short-range CPV NN forces from theta term

Confirms power counting expectation!
Back to pion-nucleon couplings

- Dominant CPV force from:

\[ L = g_0 \bar{N}\pi \cdot \tau N + g_1 \bar{N}\pi^0 N \]

- Dimension-six qCEDMs have isospin-odd component!

- ChPT gives no direct info about size. Both \( g_{0,1} \) are LO

- QCD sum rules to the rescue

\[ \bar{g}_0 = (5 \pm 10)(\tilde{d}_u + \tilde{d}_d) \text{ fm}^{-1} \quad \bar{g}_1 = (20^{+20}_{-10})(\tilde{d}_u - \tilde{d}_d) \text{ fm}^{-1} \]

- Large uncertainties. But generally: \( |\bar{g}_1| \geq |\bar{g}_0| \)

- Lattice in progress (CALLAT)
Back to pion-nucleon couplings

- 2 CP-odd structures

\[ L = g_0 \bar{N} \pi \cdot \tau N + g_1 \bar{N} \pi^0 N \]

- Four-quark left-right operator breaks isospin!

\[ L = i \Xi (\bar{u}_R \gamma_\mu d_R) (\bar{u}_L \gamma_\mu d_L) + \text{h.c.} \]

- ChPT gives ratio of couplings

\[ \frac{\bar{g}_1}{\bar{g}_0} = \frac{8c_1 m_\pi^2}{(m_n - m_p)_{\text{strong}}} = -(68 \pm 25) \]

Mohapatra, Senjanovic, Pati ’75
Maiezza et al ‘14
Back to pion-nucleon couplings

- 2 CP-odd structures

\[ L = g_0 \bar{N} \pi \cdot \tau N + g_1 \bar{N} \pi^0 N \]

- Four-quark left-right operator breaks isospin!

\[ L = i \Xi (\bar{u}_R \gamma_\mu d_R)(\bar{u}_L \gamma_\mu d_L) + \text{h.c.} \]

- Due to current-current form: more complicated chiral Lagrangian

- Unique CPV pion-pion-pion interaction

Mohapatra, Senjanovic, Pati ’75
Maiezza et al , 14
JdV et al ‘12

\[ \bar{\Delta}_\pi \]

enters at NLO
Back to pion-nucleon couplings

• 2 CP-odd structures

\[ L = g_0 \, \bar{N} \pi \cdot \tau N + g_1 \, \bar{N} \pi^0 N \]

• Finally: CPV operators that are chiral invariant: e.g. Weinberg operator

\[ L = C_w \, f^{abc} \epsilon^{\mu\nu\alpha\beta} \, G_\alpha^a \, G_\beta^b \, G_\gamma^c \,

\frac{m_\pi^2}{\Lambda_\chi^2} \]

• CPV pion-nucleon operators forbidden at LO

\[ \sim \]

\[ \bar{C}_{1,2} \]

\[ \bar{g}_0, \bar{g}_1 \]

• Short-range are important but only for 2 out of 5 S-P transitions

\[ ^3S_1 \leftrightarrow ^1P_1 \quad ^1S_0 \leftrightarrow ^3P_0 \quad (np = nn = pp) \]
The CPV NN + NNN potential

For all dim4 + dim6 sources, NN + NNN CPV potential is subset of

\[ \cdots \bar{g}_0, \bar{g}_1 \]

- Long-range (pions): \( \bar{g}_0 \quad ^3S_1 \leftrightarrow ^1P_1 + \ ^1S_0 \leftrightarrow ^3P_0 \quad np = nn = pp \)
  \( \bar{g}_1 \quad ^3S_1 \leftrightarrow ^3P_1 + \ ^1S_0 \leftrightarrow ^3P_0 \quad nn = -pp \)

- Short range \( C_{1,2} \quad ^3S_1 \leftrightarrow ^1P_1 \quad & \quad ^1S_0 \leftrightarrow ^3P_0 \quad np = nn = pp \)

- Quite different (simpler) from general boson-exchange model:
  3 long-range + 5 short-range transitions and no 3-body
The CPV NN +NNN potential

For all dim4 + dim6 sources, NN + NNN CPV potential is subset of

\[ \Delta \pi \]

These 5 interactions can form the starting point for CP-violating scattering and transmission experiments.

They can be linked to CPV at quark level and to BSM models.

Existing/future calculations for CPV reactions can be matched to this framework and then compared to EDMs.

For EDMs we also need currents!
The problem of the nucleon EDMs

- Lowest-order interactions: CPV pion-nucleon couplings (2x)
The strong CP problem

Nucleon EDM

\[ d_n = \bar{d}_0(\mu) - \bar{d}_1(\mu) - \frac{eg_A \bar{g}_0}{4\pi^2 F_\pi} \left( \ln \frac{m_\pi^2}{\mu^2} - \frac{\pi}{2} \frac{m_\pi}{m_N} \right) \]

\[ d_p = \bar{d}_0(\mu) + \bar{d}_1(\mu) + \frac{eg_A \bar{g}_0}{4\pi^2 F_\pi} \left( \ln \frac{m_\pi^2}{\mu^2} - 2\pi \frac{m_\pi}{m_N} \right) - \frac{eg_A \bar{g}_1}{8\pi F_\pi} \frac{m_\pi}{m_N} \]

- Loop enhanced by chiral logarithm (long-range physics)
- But depends on renormalization-scale \( \mu \)

- Counter terms absorb \( \mu \): no direct link between EDMs and CPV potential at the hadronic level (but there is one at the quark level)
The strong CP problem

Nucleon EDM

\[ d_n = \bar{d}_0(\mu) - \bar{d}_1(\mu) - \frac{e g A \bar{g}_0}{4\pi^2 F_\pi} \left( \ln \frac{m_\pi^2}{\mu^2} - \frac{\pi}{2} \frac{m_\pi}{m_N} \right) \]

\[ d_p = \bar{d}_0(\mu) + \bar{d}_1(\mu) + \frac{e g A \bar{g}_0}{4\pi^2 F_\pi} \left( \ln \frac{m_\pi^2}{\mu^2} - 2\pi \frac{m_\pi}{m_N} \right) - \frac{e g A \bar{g}_1}{8\pi F_\pi} \frac{m_\pi}{m_N} \]

\[
\bar{g}_0 = -(15.5 \pm 2.5) \cdot 10^{-3} \bar{\theta} \\
\mu = m_N \\
\Rightarrow d_n \simeq -2.5 \cdot 10^{-16} \bar{\theta} \text{ e cm}
\]

- Experimental constraint: \[ \bar{\theta} < 10^{-10} \]
- Lattice + ChPT \[ d_n = -(3.9 \pm 1.0) \cdot 10^{-16} \bar{\theta} \text{ e cm} \]
- But: BNL group criticizes the lattice extraction \[ d_n \simeq -2.5 \cdot 10^{-16} \bar{\theta} \text{ e cm} \]

See also: Shindler et al ‘15, Shintani et al ‘15, Alexandrou et al ‘15

Crewther ‘79  Borasoy ‘02  Guo et al, ’10 ’12 ’14, JdV et al ‘10 ’11  Abramczyk et al ‘17
The strong CP problem

Nucleon EDM

Lattice results contaminated by spurious signal
Corrected EDM signal consistent with zero within errors
No sign for strong CP problem on the lattice yet
Neutron \( \frac{\tilde{F}_3(Q^2 = 0)}{2m_N} \), \( d_n(a, m_\pi) \) Fit

- \( R \) Improved
- \( m_\pi = m_\pi^{\text{phys}}, \ d_n = 0.00190(68) \ efm \)
- \( m_\pi = m_\pi^{\text{phys}}, \ d_n = 0.0023(16) \ efm \)

Fit at \( a = 0.0907 \text{ fm} \)

Fit at \( a = 0 \)

Preliminary: A. Shindler, T. Luu, J. Dragos, A. Yousif, jav
And dim-6 sources?

- Quark EDM accurately determined
  \[ d_n = -(0.22 \pm 0.03)d_u + (0.74 \pm 0.07)d_d + (0.008 \pm 0.01)d_s \]

- Quark CEDM no lattice calculations yet. **But in progress.**

  **QCD sum rules:** nucleon EDMs \( \sim 50\text{-}75\% \) uncertainty

- Weinberg (and four-quark) only **estimates**
  \[ d_n \sim d_p \sim \pm (50 \pm 40)\text{MeV} \]

- Not easy to unravel source from nucleon EDMs
The CPV NN force and nuclear EDMs

- Tree-level: **no loop** suppression
- Orthogonal to nucleon EDMs, sensitive to different CPV structures

\[
d_A = < \Psi_A \| \vec{J}_{CP} \| \Psi_A > + 2 < \Psi_A \| \vec{J}_{CP} \| \tilde{\Psi}_A >
\]

\[
(E - H_{PT}) |\Psi_A> = 0 \quad \quad (E - H_{PT}) |\Psi_A> = V_{CP} |\Psi_A>
\]

- Solve Schrodinger eq. with CP-even NN potential
- **Perturb** with CPV nuclear force we derived before
EDM of the deuteron

- Example: the simplest nucleus $^2\text{H}$
- Target of storage ring measurement and interesting theoretical laboratory

Deuteron

\[ \bullet \quad \text{Use a perturbative pion approach (Kaplan, Savage, Wise (1996))} \]

- **S-wave NN** interactions are **resummed** and generate deuteron

- Pion exchange treated in perturbation theory (for now)
- Fails for denser nuclei/higher momenta but useful to get some insight

Expansion parameter:

\[ m_\pi \left( \frac{g_A^2 m_N}{4\pi F^2_\pi} \right) \equiv \frac{m_\pi}{M_{NN}} \approx 0.4 \]
EDM of the deuteron

Target of storage ring measurement

- Three contributions (NLO)
  1. Sum of nucleon EDMs
  2. CP-odd pion exchange
  3. CP-odd NN interactions
  4. No three-body force obviously

- Deuteron is a special case due to N=Z

\[ ^3 \overline{S}_1 \rightarrow ^1 P_1 \rightarrow \gamma \rightarrow ^3 \overline{S}_1 \]

\[ ^3 S_1 \rightarrow ^3 P_1 \rightarrow \gamma \rightarrow ^3 S_1 \]
EDM of the deuteron

Target of storage ring measurement

- Three contributions (NLO)
  1. Sum of nucleon EDMs
  2. CP-odd pion exchange
  3. CP-odd NN interactions
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- Deuteron is a special case due to \( N=Z \)

\[
F_D(q^2) = (d_n + d_p) \left( 1 - \frac{1}{3} \left( \frac{q}{4\gamma} \right)^2 + \ldots \right)
\]

\[
F_D(q^2) = g_1 \frac{2eg_A}{3m_\pi M_{NN}} \frac{1 + \gamma/m_\pi}{(1 + 2\gamma/m_\pi)^2} \left( 1 - 0.48 \left( \frac{q}{4\gamma} \right)^2 + \ldots \right)
\]

- Get the full form factor: extract EDM and Schiff Moment
Deuteron as a chiral filter

- Deuteron EDM results \[ d_D = (d_n + d_p) + 0.23 \bar{g}_1 e \text{ fm} \]

- Do the nucleon EDMs or the CPV NN force dominate?
- Depends on the source of CP violation! \( JdV \) et al. PRL 11

<table>
<thead>
<tr>
<th></th>
<th>Theta term</th>
<th>Quark CEDMs</th>
<th>Four-quark operator</th>
<th>Quark EDM and Weinberg</th>
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<tbody>
<tr>
<td>[d_D - d_n - d_p] [d_n]</td>
<td>0.5 ± 0.2</td>
<td>5 ± 3</td>
<td>20 ± 10</td>
<td>≅ 0</td>
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- Ratio suffers from hadronic uncertainties (need lattice)
- EFT approach connects different measurements
**Deuteron as a chiral filter**

- Deuteron EDM results: \( d_D = (d_n + d_p) + 0.23 \, \bar{g}_1 e \, fm \)

- Do the nucleon EDMs or the CPV NN force dominate?
- **Depends on the source of CP violation!**

  - Ratio suffers from hadronic uncertainties (need lattice)
  - Using a realistic NN potential and solving Schrodinger equation:
    \[
    d_D = 0.9(d_n + d_p) + \left[ (0.18 \pm 0.02) \, \bar{g}_1 + (0.0028 \pm 0.0003) \, \bar{g}_0 \right] e \, fm
    \]

  - Analytic approach works up to 20% (for \(^2\)H)

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<td>( \left</td>
<td>\frac{d_D - d_n - d_p}{d_n} \right</td>
<td>)</td>
<td>0.5 ± 0.2</td>
<td>5 ± 3</td>
</tr>
</tbody>
</table>

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JdV et al PRL 11

Liu+Timmermans PRC ’04

Bsaisou et al ‘15
The magnetic quadrupole moment

- A spin 1 particle has a Magnetic Quadrupole Moment

\[ H = \frac{\overline{M}_d}{4} \varepsilon^i \varepsilon^j \nabla^i B^j \]

- There is no one-body contribution

Sensitive to both \( \overline{g}_0 \) and \( \overline{g}_1 \) exchange

For chromo-EDM

\[ \frac{\overline{M}_d}{d_d} m_d = 1.6 (\mu_p - \mu_n) + 2.2 \frac{\overline{g}_0}{\overline{g}_1} (\mu_p + \mu_n) \]
The magnetic quadrupole moment

For theta:

\[ \frac{\bar{M}_d}{d_d} m_d = 0.22 (\mu_p + \mu_n) \left| \frac{\bar{g}_0}{F_\pi d_0} \right| e \text{ fm} \propto 20 (\mu_p + \mu_n) \]

- Higher moments like MQMs can provide additional input
- Deuteron MQM is not a realistic target
- But nuclear MQMs can be important in atoms and molecules

Liu et al, PLB ‘12
Flambaum et al 17 ‘18
EDMs of the tri-nucleon system

- $^3$He can be put in a ring as well ($^3$H too but radioactive...)
- More contributions than deuteron:
  1. Nucleon EDMs
  2. Both $g_0$ and $g_1$ pion exchange

\[
d_{^3\text{He}} = 0.9 \, d_n - 0.05 \, d_p + \left[ (0.14 \pm 0.04) \, \bar{g}_1 + (0.10 \pm 0.03) \, \bar{g}_0 \right] \, e \, fm + ....
\]

- Error estimate from cut-off variations + higher-order terms

Stetcu et al ‘08
JdV et al ’11
Song et al ‘13
Bsaisou et al ‘14
EDMs of the tri-nucleon system

- 3He can be put in a ring as well (3H too but radioactive...)
- More contributions than deuteron:
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d_{3He} = 0.9 \, d_n - 0.05 \, d_p + \left[ (0.14 \pm 0.04) \, \bar{g}_1 + (0.10 \pm 0.03) \, \bar{g}_0 \right] \text{e fm} + \ldots
\]

- Found to give small contributions (smaller than expectations)  
  Bsaisou et al ‘14
- Unclear why, related to 3He structure?
- Viviani + Gnech reinvestigated this and found a larger and significant contribution! (talk at CD ’18)
- No calculations include this for heavier nuclei

Stetcu et al ‘08  
JdV et al ’11  
Song et al ‘13  
Bsaisou et al ‘14
Cut-off dependence

\[
\frac{m_1^2 \overline{C}_1}{4\pi r} e^{-m_1 r} \rightarrow \overline{C}_1 \delta^{(3)}(\vec{r})
\]

Av18

CD-Bonn

Chiral EFT

Cut-off variation

Plot from Bsaisou et al JHEP ‘14

- Quite a large spread ….
- Only 10-20% for most CPV sources but leading for Weinberg operator
- How to understand this?
Cut-off dependence

\[ \frac{m_1^2 C_1}{4\pi r} e^{-m_1 r} \rightarrow C_1 \delta^{(3)}(\vec{r}) \]

- Av18
- CD-Bonn
- Chiral EFT
- Cut-off variation

- Spread for different wave functions \( \rightarrow \) different short-range NN force
- No consistent renormalization of CP-even + CP-odd force
- For a given regulator \( \Lambda \) : fit \( C_1(\Lambda) \) to data. Requires nonzero EDMs…
- Better: calculate S \( \leftrightarrow \) P transitions on lattice \( \rightarrow \) fit \( C_1(\Lambda) \)

Plot from Bsaisou et al JHEP '14
Towards denser systems....

- Yamanaka and collaborators started a program for larger EDMs
- Focus only one pion-exchange + nucleon EDMs
- So far: $^6\text{Li}$, $^7\text{Li}$, $^9\text{Be}$, $^{11}\text{B}$, $^{13}\text{C}$ and $^{19}\text{F}$ is in progress

- $^6\text{Li}$ described as $\alpha + n + p$
- Use phenomenological $\alpha$-$N$ and $\alpha$-$\alpha$ interaction
- Use ‘folding’ to describe CPV nucleon-$\alpha$ interaction

\[ V_{\alpha-N}(r) = \int d^3r' \, V_{\varphi T}(r - r') \rho_\alpha(r'), \]

\[ \rho_\alpha(r) = \frac{4}{b^3 \pi^{3/2}} e^{-r^2/b^2}. \]
Towards denser systems…..

Yamanaka et al ’15 ’16 ‘17 ‘18

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$$V_{\alpha-N}(r) = \int d^3r' V_{\mathcal{P}T}(r-r')\rho_{\alpha}(r'),$$

$$\rho_{\alpha}(r) = \frac{4}{b^3\pi^{3/2}}e^{-r^2/b^2}$$

$$d_{6Li} = 0.86(d_n + d_p) + 0.28 \bar{g}_1 e \text{ fm}$$

$$d_D = 0.9(d_n + d_p) + [(0.18 \pm 0.02) \bar{g}_1 + (0.0028 \pm 0.0003) \bar{g}_0] e \text{ fm}$$

- Accuracy: I don’t know…..
- Main point: no light nuclei with significant enhancements over $^2$H
Onwards to heavy systems

**Strongest bound** on atomic EDM: \[ d_{199\text{Hg}} < 8.7 \cdot 10^{-30} \text{ e cm} \]

New measurements expected: Ra, Xe, ….

**Schiff Theorem:** EDM of nucleus is screened by electron cloud if:

1. Non-relativistic kinematics
2. Point particles
3. Electrostatic interactions

Schiff, ‘63
Onwards to heavy systems

Graner et al, ‘16

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Screening incomplete: nuclear finite size (Schiff moment \( S \))

Typical suppression:
\[
\frac{d_{\text{Atom}}}{d_{\text{nucleus}}} \propto 10^Z \left( \frac{R_N}{R_A} \right)^2 \approx 10^{-3}
\]

Atomic part well under control

\[
d_{199\text{Hg}} = (2.8 \pm 0.6) \cdot 10^{-4} \ S_{\text{Hg}} \ e \text{ fm}^2
\]

Dzuba et al, ’02, ‘09

Sing et al, ’15

Jung, Fleig ‘18
Onwards to heavy systems

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**Schiff Theorem:** EDM of nucleus is screened by electron cloud if:

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Screening incomplete: nuclear finite size (Schiff moment \( S \))

\[
S \equiv \left\langle \Psi_0 \left| \hat{S}_0 \right| \Psi_0 \right\rangle \equiv \sum_{i \neq 0} \frac{\left\langle \Psi_0 \left| \hat{S}_0 \right| \Psi_i \right\rangle \left\langle \Psi_i \left| V_{PT} \right| \Psi_0 \right\rangle}{E_0 - E_i}
\]

**Schiff operator** \( S_0 \sim \sum_i \left( r_i^3 - \frac{5}{3} r_{ch}^2 r_i \right) Y_0^1 \)

CPV potential
EFT and many-body problems

- Need to calculate Schiff Moment (or MQM) of Hg, Ra, Xe....
- **Issue**: does chiral power counting hold? Do pions dominate?
- Say we assume so:

\[ S = g(a_0 \bar{g}_0 + a_1 \bar{g}_1) \text{ e fm}^3 \]

\[ g = 13.5 \]

<table>
<thead>
<tr>
<th></th>
<th>( a_0 ) range (best)</th>
<th>( a_1 ) range (best)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{199}\text{Hg})</td>
<td>0.03(\pm)0.025 (0.01)</td>
<td>0.030(\pm)0.060 ((\pm)0.02)</td>
</tr>
<tr>
<td>(^{225}\text{Ra})</td>
<td>-3.5(\pm)3.5 (-1.5)</td>
<td>14(\pm)12 (6)</td>
</tr>
<tr>
<td>(^{129}\text{Xe})</td>
<td>-0.03(\pm)0.025 (-0.008)</td>
<td>-0.03(\pm)0.025 (-0.009)</td>
</tr>
</tbody>
</table>

Flambaum, de Jesus, Engel, Dobaczewski,.....

- Uncertainties make interpretation more difficult
- **Great challenge**: connect EFT approach to heavier nuclei

Table from review: Engel et al, '13
Recent progress

- In nuclei like $^{225}\text{Ra}$ there is a low-lying state with opposite parity

$$S \equiv -2 \frac{\langle \Psi_0 | \hat{S}_0 | \bar{\Psi}_0 \rangle \langle \bar{\Psi}_0 | V_{PT} | \Psi_0 \rangle}{\Delta E}$$

- Schiff operator closely related to the octupole charge operator

$$\hat{Q}_0^3 \sim e \sum_i (r_i^3) Y_0^3 \quad \rightarrow \quad \langle \hat{Q}_0^3 \rangle = (940 \pm 30)e \text{ fm}^3$$

Note: measurement is for $^{224}\text{Ra}$
Recent progress

\[ S = g(a_0 \bar{g}_0 + a_1 \bar{g}_1) + b_1 \bar{C}_1 + b_2 \bar{C}_2 \]

- CPV potential from EFT
- Observe relation between \( a_i \), \( b_i \) and octupole moment
Recent progress

Correlating Schiff Moments in the Light Actinides with Octupole Moments

Jacek Dobaczewski, 1,2,3,4 Jonathan Engel, 5 Markus Kortelainen, 2,4 and Pierre Becker 1

- CPV potential from EFT
  \[ S = g(a_0 \bar{g}_0 + a_1 \bar{g}_1) + b_1 \bar{C}_1 + b_2 \bar{C}_2 \]
- Significant improvement for matrix elements!

<table>
<thead>
<tr>
<th>Element</th>
<th>(a_0)</th>
<th>(a_1)</th>
<th>(a_2)</th>
<th>(b_1)</th>
<th>(b_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{221}\text{Rn})</td>
<td>0.04(10)</td>
<td>-1.7(3)</td>
<td>0.67(10)</td>
<td>-0.015(5)</td>
<td>-0.007(4)</td>
</tr>
<tr>
<td>(^{223}\text{Rn})</td>
<td>0.08(8)</td>
<td>-2.4(4)</td>
<td>0.86(10)</td>
<td>-0.031(9)</td>
<td>-0.008(8)</td>
</tr>
<tr>
<td>(^{223}\text{Fr})</td>
<td>0.07(20)</td>
<td>-0.8(7)</td>
<td>0.05(40)</td>
<td>0.018(8)</td>
<td>-0.016(10)</td>
</tr>
<tr>
<td>(^{225}\text{Ra})</td>
<td>0.2(6)</td>
<td>-5(3)</td>
<td>3.3(1.5)</td>
<td>-0.01(3)</td>
<td>0.03(2)</td>
</tr>
<tr>
<td>(^{229}\text{Pa})</td>
<td>-1.2(3)</td>
<td>-0.9(9)</td>
<td>-0.3(5)</td>
<td><strong>0.036(8)</strong></td>
<td>0.032(18)</td>
</tr>
</tbody>
</table>
Recap

- Each hadronic/nuclear CPV observables probes a linear combination
- Compare EDMs and scattering experiments in a single framework
- Link to particle physics exists

- 2 pion-nucleon (no $g_2$!)
- 1 pion-pion-pion
- 2 nucleon-nucleon
- 2 nucleon-photon (EDM)
The EDM metromap
EDMs are important for particle physics

- Connected to open questions like matter/antimatter asymmetry (see Michaels talk) and existence of axions (Kaori’s talk)
- Strong limits on specific BSM scenarios
- Strong limits on CP-violation in top-Higgs sector
- Testing explanations of B- and K-anomalies

Dekens et al ‘18

Brod et al ‘13
Cirigliano et al ‘15’16
Fuyuto et al ‘17
Conclusion/Summary/Outlook

EDMs
✓ Very powerful search for BSM physics (probe the highest scales)
✓ Heroic experimental effort and great outlook
✓ Theory needed to interpret measurements and constraints

EFT framework
✓ Framework exists for CP-violation (EDMs) from 1\textsuperscript{st} principles
✓ Keep track of \textit{symmetries} (gauge/CP/chiral) from multi-Tev to atomic scales

The chiral filter
✓ Chiral symmetry determines form of hadronic interactions
✓ Different models \(\rightarrow\) different dim6 \(\rightarrow\) different EDM hierarchy

✓ Need theory improvement to fully exploit the experimental program