Interpretation of Electric Dipole Moments of Complex Systems

Jordy de Vries

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Outline of this talk

- **Part I:** What are EDMs and why are they interesting in the first place?
- **Part II:** Effective field theory framework
- **Part III:** Chiral perturbation theory and CP violation
  - EDMs of nucleons, nuclei, and diamagnetic atoms
- **Part IV:** Semi-leptonic CP violation
  - Paramagnetic atoms and polar molecules
EDMs 101

• Electric and Magnetic Dipole Moment (EDM and MDM)

\[
\mathcal{L}_d = -\frac{d_e}{2} \bar{\Psi} \sigma^{\mu\nu} \gamma^5 \Psi F_{\mu\nu} - \frac{d_m}{2} \bar{\Psi} \sigma^{\mu\nu} \Psi F_{\mu\nu}
\]

\[
\mathcal{H}_d = -d_e \bar{\sigma} \cdot E - d_m \bar{\sigma} \cdot B
\]
EDMs 101

- Electric and Magnetic Dipole Moment (EDM and MDM)

\[ \mathcal{L}_d = -\frac{d_e}{2} \bar{\Psi} \sigma^{\mu\nu} \gamma^5 \Psi F_{\mu\nu} - \frac{d_m}{2} \bar{\Psi} \sigma^{\mu\nu} \Psi F_{\mu\nu} \]

\[ \mathcal{H}_d = \pm d_e \bar{\sigma} \cdot E - d_m \bar{\sigma} \cdot B \]
EDMs in the Standard Model

- Electroweak CP-violation very ineffective

- Quark EDMs = 0 at 2-loops, Electron EDM = 0 at 3-loops
- Dominant neutron from four-quark operators

Hoogeveen ’90, Khriplovich, Zhitnitsky ‘82, Czarnecki, Krause ’97, Mannel, Uraltsev ’12, Seng ‘14
Neutron EDM from CKM

5 to 6 orders below upper bound → Out of reach!

With linear extrapolation: CKM neutron EDM in 2075....

Neutron EDM from theta term

If $\theta \sim 1$

More details on calculation later

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

- Measurement of a nonzero EDM
- Standard Model: $\theta$-term
- BSM sources of CP-violation

For the foreseeable future: EDMs are 'background-free' searches for new physics
### Active experimental field

See next talk by M. Chupp!

<table>
<thead>
<tr>
<th>System</th>
<th>Group</th>
<th>Limit</th>
<th>C.L.</th>
<th>Value</th>
<th>Year</th>
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<tbody>
<tr>
<td>$^{205}$Tl</td>
<td>Berkeley</td>
<td>$1.6 \times 10^{-27}$</td>
<td>90%</td>
<td>$6.9(7.4) \times 10^{-28}$</td>
<td>2002</td>
</tr>
<tr>
<td>YbF</td>
<td>Imperial</td>
<td>$10.5 \times 10^{-28}$</td>
<td>90%</td>
<td>$-2.4(5.7)(1.5) \times 10^{-28}$</td>
<td>2011</td>
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<td>$\text{Eu}<em>{0.5}\text{Ba}</em>{0.5}\text{TiO}_3$</td>
<td>Yale</td>
<td>$6.05 \times 10^{-25}$</td>
<td>90%</td>
<td>$-1.07(3.06)(1.74) \times 10^{-25}$</td>
<td>2012</td>
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<td>PbO</td>
<td>Yale</td>
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<td>90%</td>
<td>$-4.4(9.5)(1.8) \times 10^{-27}$</td>
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<tr>
<td>ThO</td>
<td>ACME</td>
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<td>90%</td>
<td>$-2.1(3.7)(2.5) \times 10^{-29}$</td>
<td>2014</td>
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<td>$n$</td>
<td>Sussex-RAL-ILL</td>
<td>$2.9 \times 10^{-26}$</td>
<td>90%</td>
<td>$0.2(1.5)(0.7) \times 10^{-26}$</td>
<td>2006</td>
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<tr>
<td>$^{129}$Xe</td>
<td>UMich</td>
<td>$6.6 \times 10^{-27}$</td>
<td>95%</td>
<td>$0.7(3.3)(0.1) \times 10^{-27}$</td>
<td>2001</td>
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<tr>
<td>$^{199}$Hg</td>
<td>UWash</td>
<td>$3.1 \times 10^{-29}$</td>
<td>95%</td>
<td>$0.49(1.29)(0.76) \times 10^{-29}$</td>
<td>2009</td>
</tr>
<tr>
<td>muon</td>
<td>E821 BNL g−2</td>
<td>$1.8 \times 10^{-19}$</td>
<td>95%</td>
<td>$0.0(0.2)(0.9) \times 10^{-19}$</td>
<td>2009</td>
</tr>
</tbody>
</table>

Current EDM null results $\rightarrow$ **probe few TeV scale** or $\phi_{CP} \leq O(10^{-2,-3})$

*(model dependent!)*
The EDM landscape

- Neutron
- Nuclei: p, $^2$H, $^3$He
- Diamagnetic atoms: Hg, Xe, Ra
- Paramagnetic atoms: Tl, Cs
- Molecules: YbF, PbO, HfF$^+$
- Leptons

- Quark EDM
- Quark chromo-EDM
- Gluon chromo-EDM
- Four-quark operators
- Lepton-quark operators
- Lepton EDM

Energy scales:
yeV, keV, MeV, GeV, TeV, ?
Unraveling the source

Measurement of a Hadronic/nuclear EDM

Standard Model: θ-term

BSM source of CP-violation

Not in this talk

Baryo/Leptogenesis ?

High-energy model ?
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Separation of scales

**Energy**

$M_{CP}$

$M_{EW} \sim \nu \sim M_{Z,W,H,t}$

100 GeV

$\Lambda_\chi \sim 2\pi F_\pi \sim M_N$

1 GeV

**BSM physics**

$\mathcal{L}_{\text{EFF}}$

Renormalization-group evolution

Integrate out heavy SM degrees of freedom

$\mathcal{L}_{\text{EFF}}'$

Renormalization-group evolution

Nonperturbative QCD regimes
Separation of scales

**Energy**

- $M_{CP}$: TeV
- $M_{EW} \sim \nu \sim M_{Z,W,H,t}$: 100 GeV
- $\Lambda_{\chi} \sim 2\pi F_{\pi} \sim M_{N}$: 1 GeV
- $F_{\pi} \sim m_{\pi}$: 100 MeV
- $\alpha_{em} m_{e}$: 1 keV

**BSM physics**

- $L'_{EFF}$: Renormalization-group evolution
- $L_{EFF}$: Renormalization-group evolution

**Integrate out heavy**

- heavy degrees of freedom
- heavy SM degrees of freedom

**Nonperturbative**

- QCD regimes
- methods: Lattice + chiral EFT
- Hadronic and nuclear EDMs

**Chiral EFT**

**Schiff theorem**

**Atomic/Molecular observables**
Step 1: SM as an EFT

- Assume any BSM physics lives at scales \( \gg M_{EW} \)
- Match to full set of CP-odd operators (model independent **)

1) Degrees of freedom: Full SM field content

2) Symmetries: Lorentz, \( SU(3) \times SU(2) \times U(1) \)

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

dim-5 generates neutrino masses/mixing, neglected here

** Big assumption: ** no new light fields
Does not cover for instance light axion DM, Graham et al ‘13

Buchmuller & Wyler ‘86
Gradzkowski et al ‘10
Dipole operators

Requires Higgs: \[ \Gamma_X \bar{\Psi}_L \sigma^{\mu\nu} \Psi_R X_{\mu\nu} \phi + h.c. \]

In most models: \[ \Gamma_X \propto \frac{m_{\psi}}{\nu M_{CP}^2} \]

X = W, B, G quarks
X = W, B leptons

EDMs typically scale with mass!

\( M_{CP} \) ? TeV

1 GeV
Dipole operators

Requires Higgs: \[ \Gamma_X \bar{\Psi}_L \sigma^{\mu\nu} \Psi_R X_{\mu\nu} \varphi + h.c. \]

In most models: \[ \Gamma_X \propto \frac{m_\Psi}{v M_{CP}^2} \]

EDMs typically scale with mass!

\( M_{CP} \) ? TeV

1 GeV

X=W,B,G quarks
X=W,B leptons

Quark chromo-EDM
Quark EDM
electron EDM
Gluon chromo-EDM

Weinberg operator

\[ d_w \mathbf{f}_{abc} \varepsilon^{\mu \nu \alpha \beta} G_{\alpha \beta}^a G_{\mu \lambda}^b G_{\nu \lambda}^c \]

\[ M_{CP} \quad ? \text{ TeV} \]

\[ 1 \text{ GeV} \]

Weinberg PRL ’89
Braaten et al PRL ’90

Gluon chromo-EDM

Quark chromo-EDM

Quark EDM
Four-quark operators

Fermion-Higgs interactions

\[ \Xi \bar{u}_R \gamma^\mu d_R (\bar{\phi}^\dagger i D_\mu \phi) + h.c. \rightarrow \Xi v^2 g (\bar{u}_R \gamma^\mu d_R W_\mu^\pm + h.c.) \]

A right-handed quark-W coupling

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

QCD RGE induces another operator

Two four-quarks terms (FQLR operators)

Ng & Tulin ’12
JdV et al ’12
An et al ’10
Anomalous gauge/higgs couplings

\[ M_{CP} \] 

> 1 TeV

100 GeV

> 100 GeV

1 GeV

Search at the same time at LHC.

One example:

\[ \frac{g_s^2}{M_{CP}^2} H^2 G \tilde{G} \]

a) Gluon fusion at LHC

b) Induces quark CEDM \( \rightarrow \) neutron EDM

\[ M_{CP} > 11 \text{ TeV}^* \] (ATLAS/CMS)

\[ M_{CP} > 20 \text{ TeV}^* \] (neutron EDM**)

* Loop suppression reduces scales
** depends on hadronic matrix element
When the dust settles....

**Hadronic interactions**

- QCD (\(\theta\)-term)
- Quark EDM
- Quark chromo-EDM
- Gluon chromo-EDM
- 4\*4 quark operators

\(~ 1 \text{ GeV}\)

**1 GeV**

**Electron EDM**

**(semi-)leptonic interactions**

- Electron EDM
- (4 coupling constants)
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  - Chiral Perturbation Theory
  - EDMs of nucleons, nuclei, and diamagnetic atoms

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  - Paramagnetic atoms and polar molecules
Crossing the barrier

Few GeV

\[ \text{QCD (\theta-term)} + \text{Quark EDM} + \text{Quark chromo-EDM} + \text{Gluon chromo-EDM} + \text{3*4quark operators} \]

\[ \text{100 MeV} \]

\[ N \rightarrow \pi + N \rightarrow N \]

\[ N \rightarrow \gamma + N \rightarrow N \]

\[ N \rightarrow \gamma + N \rightarrow N \]

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**Chiral Perturbation Theory**
The next 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 QCD has SU(2)_L \times SU(2)_R symmetry
  - Spontaneously broken to SU(2)-isospin
  - Pions are Goldstone bosons
  - Explicit breaking (quark mass) \rightarrow pion mass

- ChPT gives systematic expansion in \[ Q/\Lambda_\chi \sim m_\pi/\Lambda_\chi \quad \Lambda_\chi \equiv 1 \text{ GeV} \]
  - Form of interactions fixed by symmetries
  - Each interactions comes with an unknown constant (LEC)
  - Successful nucleon-nucleon potential (chiral EFT)

Weinberg, Gasser, Leutwyler, Meißner, van Kolck, Epelbaum, …
ChiPT with CP violation

QCD (θ-term) + $\gamma$ + $g$ +

- They all break CP....

- But transform differently under chiral and isospin symmetry

Different CP-odd chiral Lagrangians

Different hierarchy of EDMs
CP violation at nuclear level

- 2 pion-nucleon
- 1 pion-pion-pion
- 2 nucleon-nucleon
- 2 nucleon-photon (EDM)

- Up to NLO seven interactions for all CP-odd dim4-6 sources
- Different models (SUSY, left-right, multi-Higgs) $\rightarrow$ different hierarchies

Mereghetti et al ’10, JdV et al ’12, Bsaisou et al ’14
An example of the hierarchy

- Example: CP-odd pion-nucleon interactions
- Traditionally expected to dominate nuclear EDMs

\[ L = \bar{g}_0 \bar{N} (\bar{\pi} \cdot \bar{\tau}) N + \bar{g}_1 \bar{N} \pi_3 N \]
An example of the hierarchy

- Example: CP-odd pion-nucleon interactions
- Traditionally expected to dominate nuclear EDMs

\[ L = \bar{g}_0 \bar{N} (\bar{\pi} \cdot \bar{\tau}) N + \bar{g}_1 \bar{N} \pi_3 N \]

- \( \theta \)-term \( L = im^* \theta \bar{q} i \gamma^5 q \) transforms as quark mass

\[ \bar{g}_0 = \frac{(m_n - m_p)^{\text{strong}}}{4F_\pi \varepsilon} \bar{\theta} = -0.018(7) \bar{\theta} \]
\[ \bar{g}_1 = \frac{8c_1 (\delta m_{\pi}^2)^{\text{strong}}}{F_\pi} \frac{1 - \varepsilon^2}{2\varepsilon} \bar{\theta} = 0.003(2) \bar{\theta} \]

- \( \varepsilon = \frac{m_u + m_d}{m_u - m_d} = -0.35(10) \)
- \( \frac{\bar{g}_1}{\bar{g}_0} = -(0.2 \pm 0.1) \)

- Input from lattice QCD \( (m_n - m_p) \) and pion-nucleon scattering \( (c_1) \)
- \( g_0 > g_1 \) due to isospin conservation of theta term

Crewther et al’ 79, Lebedev et al’ 04, Mereghetti et al’ 10, Bsaisou et al’ 12 ‘14
An example of the hierarchy

- Example: CP-odd pion-nucleon interactions
- Traditionally expected to dominate nuclear EDMs

\[
L = \bar{g}_0 \bar{N}(\bar{\pi} \cdot \bar{\tau})N + \bar{g}_1 \bar{N}\pi_3 N
\]

- Four-quark operators (left-right symmetric models)

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

- \( \bar{g}_0, \bar{g}_1 \) both poorly known
- ChPT gives ratio:

\[
\frac{\bar{g}_1}{\bar{g}_0} = \frac{8c_1m_\pi^2}{(m_n - m_p)^{\text{strong}}} = -(68 \pm 25)
\]

\[
\frac{\theta\text{-term}}{\bar{g}_0} = -(0.2 \pm 0.1)
\]

Mohapatra, Senjanovic, Pati

Seng et al’ 14
Maiezza, Nemevsek ‘14
An example of the hierarchy

- Example: CP-odd pion-nucleon interactions
- Traditionally expected to dominate nuclear EDMs

\[ L = \bar{g}_0 \bar{N} (\bar{\pi} \cdot \bar{\tau}) N + \bar{g}_1 \bar{N} \pi_3 N \]

- Quark chromo-EDM: (MSSM, 2HDM, ....)
  \[ |\bar{g}_0| \approx |\bar{g}_1| \]
  Relatively large uncertainty in LECs e.g. from QCD sum rules
  Pospelov, Ritz ’02 ’05
  Hisano et al ’12 ’13

- Weinberg operator, LECs suppressed due to chiral symmetry.
  Leading contributions from CP-odd NN interactions.

\[ L = \bar{C} (\bar{N} \bar{\sigma} N) \cdot \bar{\partial}(\bar{N}N) \]

JdV et al ‘11
The Nucleon EDM

Nucleon EDM

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

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

• absorb UV divergences in \( \bar{d}_0, \bar{d}_1 \)

Crewther et al., '79, Pich, Rafael, '91, Guo et al, '10 '12 '14, Mereghetti et al ‘10 ‘11 ‘14
The Nucleon EDM

Nucleon EDM

\[
\begin{align*}
    d_n &= \bar{d}_0 - \bar{d}_1 - \frac{e g_A \overline{g}_0}{4\pi^2 F_\pi} \left( \ln \frac{m_\pi^2}{M_N^2} - \frac{\pi}{2} \frac{m_\pi}{M_N} \right) \\
    d_p &= \bar{d}_0 + \bar{d}_1 + \frac{e g_A}{4\pi^2 F_\pi} \left[ \overline{g}_0 \left( \ln \frac{m_\pi^2}{M_N^2} - 2\pi \frac{m_\pi}{M_N} \right) - \overline{g}_1 \frac{\pi}{2} \frac{m_\pi}{M_N} \right]
\end{align*}
\]

- absorb UV divergences in \( \bar{d}_0, \bar{d}_1 \)

- 3 (4) LECs at LO (NLO).... Can be fitted by any source

- For all sources, neutron and proton EDM of same order

No hierarchy!

Lattice QCD to the rescue

- With QCD lattice input:
  
  \[ d_n = (2.7 \pm 1.2) \cdot 10^{-16} \ \bar{\theta} \ e \ cm \]
  \[ d_p = -(2.1 \pm 1.2) \cdot 10^{-16} \ \bar{\theta} \ e \ cm \]

- ChPT extrapolation to **physical pion mass and infinite volume**
Lattice QCD to the rescue

- With QCD lattice input:
  
  $$d_n = (2.7 \pm 1.2) \cdot 10^{-16} \bar{\theta} \, e \, cm$$
  $$d_p = -(2.1 \pm 1.2) \cdot 10^{-16} \bar{\theta} \, e \, cm$$

- ChPT extrapolation to **physical pion mass** and **infinite volume**

- Less known for dimension-six sources (≈100% uncertainties)

- **Dedicated Amherst workshop, January ’15 → road map**
  “**Hadronic Matrix Elements for Probes for CP-violation**”

- Lattice qEDM and qCEDM in progress (**difficult!**)  
  Bhattacharya et al ’12 ’15

**In any case: Need more observables to unravel sources!**
Experiments on charged particles

See talk by Yannis Semertzidis

• New kid on the block: **Charged particle in storage ring**

![Image of COSY Jülich](image_url)

• Limit on muon EDM
  \[ d_\mu \leq 1.8 \cdot 10^{-19} \text{ e cm} \]

  *Anastassopoulos et al ‘15*

• **Proposals to measure EDMs of light nuclei (p, 2H, 3He, ...)**

• Precursor experiment at COSY at Jülich

  *Eversmann et al ‘15*

• High final accuracy (aimed at $10^{-27-29}$ e cm)

  *Farley et al PRL ’04*

  *Bennett et al (BNL g-2) PRL ‘09*
Why light nuclei?

- Tree-level contributions: no loop suppression

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

- Input: 1) CP-even potential from **chiral EFT (N2LO)**
  2) **CP-odd** potentials derived for each source

- Numerical solution requires **regulator**, check **cut-off independence**

Epelbaum et al ‘05
Maekawa et al ‘11
Example: deuteron EDM

Target of storage ring measurement

- Three contributions (NLO)
  1. Sum of nucleon EDMs
  2. CP-odd pion exchange
  3. CP-odd NN interactions
Example: deuteron EDM

Target of storage ring measurement

- Three contributions (NLO)
  1. Sum of nucleon EDMs
  2. CP-odd pion exchange
  3. CP-odd NN interactions

- Deuteron is a special case due to N=Z

\[ ^3S_1 \xrightarrow{\bar{g}_0} ^1P_1 \xrightarrow{\gamma} ^3S_1 \]

\[ ^3S_1 \xrightarrow{\bar{g}_1} ^3P_1 \xrightarrow{\gamma} ^3S_1 \]
Example: deuteron EDM

- Three contributions
  1. Sum of nucleon EDMs
  2. CP-odd pion exchange

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

Theoretical accuracy is very good
(chiral corrections + cut-off dependence)

Strong isospin filter

Errors from Dekens et al JHEP `14, Bsaisou et al JHEP `14
**Example: deuteron EDM**

**Filtering the sources**

<table>
<thead>
<tr>
<th>Theta</th>
<th>Four-quark left-right</th>
<th>Quark chromo-EDM</th>
<th>Quark EDM</th>
<th>Weinberg Operator</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_D - d_n - d_p \over d_n$</td>
<td>0.5 ± 0.2</td>
<td>≈ 7 – 20</td>
<td>≈ 5 – 10</td>
<td>= 0 *</td>
</tr>
</tbody>
</table>

- Ratio suffers from **hadronic uncertainties** (need lattice)
- Nevertheless: EDM ratio hint towards **underlying source**!

* For quark EDM + Weinberg: $d_D \equiv (d_n + d_p)$

Lebedev et al ’04, JdV et al ’11, Bsaisou et al ’12,’14
Similar for $^3\text{He}$ (and $^3\text{H}$)

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

- **No isospin filter, complementary** to deuteron
- **Good nuclear accuracy** (25%)
- **With deuteron** $\rightarrow$ give $g_0/g_1$ ratio

Stetcu et al, ’08, JdV et al, ’11 ’14, Song et al, ’13, Yamanaka ’15
Similar for $^3$He (and $^3$H)

\[ d_{^3He} = 0.9 \, d_n - 0.05 \, d_p + \left[ (0.14 \pm 0.03) \, g_1 + (0.10 \pm 0.03) \, g_0 \right] e \, fm \]

- **No isospin filter, complementary** to deuteron
- **Good nuclear accuracy** (25%)

**But...**
- Dependence on CP-odd NN operators
- N2LO for most sources (~10%)
- **But LO for Weinberg operator** (*SUSY, 2HDM*)

Contact NN term described by ‘heavy meson’ exchange

\[ \frac{m^2 \bar{C}}{4\pi r} e^{-mr} \rightarrow \bar{C} \, \delta^{(3)}(\vec{r}) \]

Stetcu et al., ’08, JdV et al., ’11 ‘14, Song et al., ’13, Yamanaka ‘15
Not so clear....

EDM contribution (some units)

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

-0.12 -0.10 -0.08 -0.06 -0.04 -0.02 0.00 0.02

0 1 2 3 4 5 6 7 8

Heavy meson mass (GeV)

- Convergence..... but not to the same value......
- Av18 very repulsive at short distances (not best estimate)
- Large nuclear uncertainty (for Weinberg operator)
Onwards to heavy systems

Strongest bound on atomic EDM: \[ d_{199\,\text{Hg}} < 3.1 \cdot 10^{-29} \, e \, cm \]

New measurements expected: Hg, Ra, Xe, ...

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

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

Schiff, ‘63

Griffiths et al, ‘09
Onwards to heavy systems

Strongest bound on atomic EDM: \( d_{199\text{Hg}} < 3.1 \cdot 10^{-29} \, e \, cm \)

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

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3. Electrostatic forces

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

Typical suppression:

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

- Atomic part well under control

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

\[
d_{225\text{Ra}} = (7.2 \pm 1.5) \cdot 10^{-4} \, S_{\text{Ra}} \, e \, fm^2
\]

Dzuba et al., '02, '09

Sing et al., '15
Calculating Schiff Moments

**Task:** Calculate Schiff Moments of Hg, Ra, Xe, ...

- Typically only one-pion exchange (sometimes nucleon EDMs)  
  Dmitriev, Sen’kov ’03  

- **Very complicated** many-body calculation  
- Cannot solve Schrodinger equation directly  
- Use nuclear model and mean-field theory (Skyrme interactions)
Assessment of uncertainties

\[ S = g(a_0 g_0 + a_1 g_1) e fm^3 \]
\[ g = 13.5 \]

<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±0.025 (0.01)</td>
<td>0.030±0.060 (±0.02)</td>
</tr>
<tr>
<td>(^{225}\text{Ra})</td>
<td>-3.5±2.5 (-1.5)</td>
<td>14±10 (6)</td>
</tr>
<tr>
<td>(^{129}\text{Xe})</td>
<td>-0.03±0.025 (-0.008)</td>
<td>-0.03±0.025 (-0.009)</td>
</tr>
</tbody>
</table>

- Based on calculations from various groups
- Hg & Xe: spread \(\sim>100\%\) (unclear why, difficult ‘soft’ nuclei)
- Ra enhanced (\(\sim 100x\)) due to octopole deformation and theory better under control.

Flambaum, de Jesus, Engel, Dobaczewski, Dmitriev, Sen’kov,.....
Comparison of sensitivities

Now include **Schiff screening**: 
\[ d = g(b_0 \bar{g}_0 + b_1 \bar{g}_1) \ e \ fm \]

<table>
<thead>
<tr>
<th></th>
<th>( b_0 ) (best values)</th>
<th>( b_1 ) (best values)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{199})Hg</td>
<td>3 x 10^{-6}</td>
<td>6 x 10^{-6}</td>
</tr>
<tr>
<td>(^{225})Ra</td>
<td>-1 x 10^{-3}</td>
<td>4 x 10^{-3}</td>
</tr>
<tr>
<td>(^{129})Xe</td>
<td>-2 x 10^{-7}</td>
<td>-2 x 10^{-7}</td>
</tr>
<tr>
<td>(^2)H (ion)</td>
<td>2 x 10^{-4}</td>
<td>1 x 10^{-2}</td>
</tr>
<tr>
<td>(^3)He (ion)</td>
<td>1 x 10^{-2}</td>
<td>7 x 10^{-3}</td>
</tr>
</tbody>
</table>

- Radium almost **overcomes** Schiff screening
- \(^2\)H or \(^3\)He EDM @ 10^{-24,25} competitive with Hg bound
- **But:** large nuclear uncertainty and missing CP-odd interactions
Outline of this talk

- **Part I:** What are EDMs and why are they interesting in the first place?
- **Part II:** Effective field theory framework
- **Part III:** Hadronic and nuclear CP-violation
  - Chiral Perturbation Theory
  - EDMs of nucleons, nuclei, and diamagnetic atoms
- **Part IV:** Semi-leptonic CP violation
  - Paramagnetic atoms and polar molecules
Probing the leptonic interactions

(semi-)leptonic interactions (4 operators)

\[ \gamma \rightarrow e + e \]

Electron EDM

\[ C_S(\bar{e} i\gamma^5 e \bar{q}q) \]

\[ C_P \quad C_T \]

\[ \sim 1 \text{ GeV} \]
Probing the leptonic interactions

(semi-)leptonic interactions (4 operators)

\[ C_S(\bar{e} i\gamma^5 e \bar{q}q) \]

Focus on these

~1 GeV

Electron EDM

\[ C_P \quad C_T \]

Suppressed (best bounds from Hg EDM)

0.1 GeV

Electron EDM

\[ C_S(\bar{e} i\gamma^5 e \bar{N}N) \]

hadronic matrix elements relatively well known
Probing the leptonic interactions

Bound on Tl EDM \[ d_{205\text{Tl}} < 9 \cdot 10^{-25} \text{ e cm} \] Regan et al ’02

What about screening? Schiff theorem violated by \textit{relativity}

\[ d_A(d_e) = K_A d_e \quad K_A \propto Z^3 \alpha_{em}^2 \]

Sandars ’65
Probing the leptonic interactions

Bound on Tl EDM

\[ d_{205\text{Tl}} < 9 \cdot 10^{-25} \text{ e cm} \]

Regan et al ’02

What about screening? Schiff theorem violated by \textit{relativity}

\[ d_A(d_e) = K_A d_e \quad K_A \propto Z^3 \alpha_{em}^2 \]

Sandars ’65

Strong enhancement!

\[ K_{\text{Tl}} = -(570 \pm 20) \quad \rightarrow \quad d_e < 1.6 \cdot 10^{-27} \text{ e cm} \]

Additional dependence on electron-nucleon interactions

\[ d_{\text{Tl}} = -(570 \pm 20) d_e - (7.0 \pm 2.0) \cdot 10^{-18} \quad C_S \text{ e cm} \]

Liu,Kelly ’92, Dzuba, Flambaum ‘09, Porsev et al ‘12
Polar molecules: Convert small external to huge internal field

$\Delta E \approx E_{eff} (E_{ext}) d_e$

Nonlinear function of external field

Sandars '75
Sushkov, Flambaum '78

Plot from Hudson et al PRL '02

$YbF$
**Polar molecules**

**Polar molecules:** Convert small external to huge internal field

\[ \Delta E_{YbF} = (15 \pm 2) \cdot GeV \left( \frac{d_e}{e \ cm} \right) + O(C_S) \]

\[ \Delta E_{ThO} = (80 \pm 10) \cdot GeV \left( \frac{d_e}{e \ cm} \right) + O(C_S) \]

Meyer, Bohn ‘08, Skipnikov et al ‘13, Fleig, Nayak ‘14,

Assuming no cancellation with \( O(C_S) \): \( d_e < 8.7 \cdot 10^{-29} \ e \ cm \)

Or no cancellation with eEDM: \( C_S < 5.9 \cdot 10^{-9} \)

Baron et al ‘13
Finding the source.

- Find a signal: what is responsible? eEDM or Cs?
- Need at least two measurements

\[ \Delta E = \alpha d_e + \beta C_s \]

<table>
<thead>
<tr>
<th></th>
<th>Th</th>
<th>YbF</th>
<th>ThO</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\beta/\alpha)</td>
<td>1.15</td>
<td>0.85</td>
<td>1.25</td>
</tr>
</tbody>
</table>

\( \cdot 10^{-20} e cm \)

- Unfortunately: Probing roughly same combination
- Experiments on Fr, Rb could help in this case
- Same for diamagnetic systems (Hg, Ra, ...)

Dzuba et al ‘11
M. Jung ‘13
Chupp, Ramsey-Musolf ‘15
Cancellations?

Single source
\[ d_e < 8.7 \cdot 10^{-29} \text{ } e \text{ } cm \]
\[ C_S < 5.9 \cdot 10^{-9} \]

Allow for cancellations
\[ d_e < 5.4 \cdot 10^{-27} \text{ } e \text{ } cm \]
\[ C_S < 4.5 \cdot 10^{-7} \]

- Many models have one dominant source (e.g. eEDM in mLRSM)
- But good to keep in mind. Who knows...
- Experiments on Fr, Rb + diamagnetic would help

Plots and numbers from Chupp, Ramsey-Musolf PRC '15
The EDM landscape
Conclusion/Summary

- EDMs are great probes of new CP-odd physics
- Probe similar and higher energy scales as LHC

**EFT approach**
- Framework exists for CP-violation (EDMs) from 1st principles
- Keep track of symmetries from multi-Tev to atomic scales
- Specific models can be matched to EFT framework (not discussed here)

**The chiral filter**
- Chiral symmetry determines form of hadronic interactions
- Different models $\rightarrow$ different dim6 $\rightarrow$ different EDM hierarchy

**Uncertainties**
- Nucleon + light nuclei dominated by hadronic uncertainties (+ short-range)
- Heavy diamagnetic atoms suffer from additional nuclear uncertainties
- Atomic/Molecular theory in much better shape
Backup
Dipoles combined

Numerical solution of the three dipole operators (same for strange quarks)

\[ C_q(1 \text{ GeV}) = 0.39 C_q(1 \text{ TeV}) + 0.37 \tilde{C}_q(1 \text{ TeV}) - 0.072 C_W(1 \text{ TeV}) \]

\[ \tilde{C}_q(1 \text{ GeV}) = + 0.88 \tilde{C}_q(1 \text{ TeV}) - 0.29 C_W(1 \text{ TeV}) \]

\[ C_W(1 \text{ GeV}) = + 0.33 C_W(1 \text{ TeV}) \]

1) Diagonal terms are all suppressed

2) Suppressions are moderate

3) Mixing is important, e.g. if qCEDM at low energy then also qEDM (unless cancellations....)

* 2-loop running in Degrassi et al, JHEP '05 , O(10%) corrections to LO running
Bounds and scales

Use the neutron* EDM bound (big uncertainty for some operators: that’s why we are here!)

<table>
<thead>
<tr>
<th>Dimensionless couplings</th>
<th>$M_T = 1,\text{TeV}$</th>
<th>$M_T = 10,\text{TeV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(M_T^2)d_{u,d}(M_T)$</td>
<td>$\leq {1.8, 1.8} \cdot 10^{-3}$</td>
<td>$\leq {2.1, 2.1} \cdot 10^{-1}$</td>
</tr>
<tr>
<td>$(M_T^2)d_{u,d}(M_T)$</td>
<td>$\leq {1.9, 0.91} \cdot 10^{-3}$</td>
<td>$\leq {1.7, 0.94} \cdot 10^{-1}$</td>
</tr>
<tr>
<td>$(M_T^2)d_W(M_T)$</td>
<td>$\leq 5.6 \cdot 10^{-5}$</td>
<td>$\leq 7.0 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$(M_T^2)\text{Im}\Sigma_1(M_T)$</td>
<td>$\leq 3.2 \cdot 10^{-5}$</td>
<td>$\leq 2.3 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$(M_T^2)\text{Im}\Sigma_8(M_T)$</td>
<td>$\leq 3.3 \cdot 10^{-4}$</td>
<td>$\leq 2.4 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>$(M_T^2)\text{Im}\Xi_1(M_T)$</td>
<td>$\leq 1.7 \cdot 10^{-4}$</td>
<td>$\leq 1.7 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>$(M_T^2)\text{Im}Y_{nu,d}(M_T)$</td>
<td>$\leq {8.9, 8.9} \cdot 10^{-5}$</td>
<td>$\leq {7.9, 7.9} \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$(M_T^2)\theta'(M_T)$</td>
<td>$\leq 2.4 \cdot 10^{-3}$</td>
<td>$\leq 1.5 \cdot 10^{-1}$</td>
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</table>

* Hg EDM bound gives stronger limits for some operators (e.g. quark CEDM) but also suffers from larger theoretical uncertainty

Engel et al, PNPP ’13
Bounds and scales

Use the neutron EDM bound (**big uncertainty for some operators: that’s why we are here !**)

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</tr>
<tr>
<td>$(M_T^2)<em>{\tilde{d}</em>{u, d}}(M_T)$</td>
<td>$\leq {1.9, 0.91} \cdot 10^{-3}$</td>
<td>$\leq {1.7, 0.94} \cdot 10^{-1}$</td>
</tr>
<tr>
<td>$(M_T^2)_{d_W}(M_T)$</td>
<td>$\leq 5.6 \cdot 10^{-5}$</td>
<td>$\leq 7.0 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$(M_T^2)_{\text{Im} \Sigma_1}(M_T)$</td>
<td>$\leq 3.2 \cdot 10^{-5}$</td>
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</tr>
<tr>
<td>$(M_T^2)_{\text{Im} \Sigma_8}(M_T)$</td>
<td>$\leq 3.3 \cdot 10^{-4}$</td>
<td>$\leq 2.4 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>$(M_T^2)_{\text{Im} \Xi_1}(M_T)$</td>
<td>$\leq 1.7 \cdot 10^{-4}$</td>
<td>$\leq 1.7 \cdot 10^{-2}$</td>
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<tr>
<td>$(M_T^2)<em>{\text{Im} Y</em>{nu, d}}(M_T)$</td>
<td>$\leq {8.9, 8.9} \cdot 10^{-5}$</td>
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<tr>
<td>$(M_T^2)_{\theta'}(M_T)$</td>
<td>$\leq 2.4 \cdot 10^{-3}$</td>
<td>$\leq 1.5 \cdot 10^{-1}$</td>
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</table>

So 1 TeV seems ‘unnatural’ but note loop factors. For instance:

$$M_{CP}^2 \tilde{d}_q \sim \frac{\alpha_s}{4\pi} \sin \phi_{CP} \sim 10^{-2} \sin \phi_{CP} \quad \Rightarrow \quad \sin \phi_{CP} \leq 10^{-1}$$

The interpretation is model dependent.
# Bounds and scales

Use the neutron EDM bound (big uncertainty for some operators: that’s why we are here!)

Dekens, JdV JHEP ’13

## ‘electroweak suppressed operators’

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<th>$M_T = 10,\text{TeV}$</th>
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<tbody>
<tr>
<td>$(M_T^2)C_B (M_T)$</td>
<td>$\leq 8.1 \cdot 10^{-2}$</td>
<td>$\leq 4.6$</td>
</tr>
<tr>
<td>$(M_T^2)C_W (M_T)$</td>
<td>$\leq 1.9 \cdot 10^{-2}$</td>
<td>$\leq 1.1$</td>
</tr>
<tr>
<td>$(M_T^2)C_{WB} (M_T)$</td>
<td>$\leq 1.3 \cdot 10^{-2}$</td>
<td>$\leq 0.74$</td>
</tr>
<tr>
<td>$(M_T^2)C_{dw} (M_T)$</td>
<td>$\leq 0.11$</td>
<td>$\leq 11$</td>
</tr>
<tr>
<td>$(M_T^2)C_{Wu,d} (M_T)$</td>
<td>$\leq {1.0, 0.84} \cdot 10^{-2}$</td>
<td>$\leq {0.53, 0.45}$</td>
</tr>
<tr>
<td>$(M_T^2)C_{Zu,d} (M_T)$</td>
<td>$\leq {5.3, 2.8} \cdot 10^{-2}$</td>
<td>$\leq {2.7, 1.4}$</td>
</tr>
</tbody>
</table>

First 4 operators better bound by eEDM
Three-body force

- Gives rise to 3-body force in $A>2$ nuclei.
- But much smaller than power counting suggests in $^3$He/$^3$H EDMs
- Does renormalize $g_1$, 50% for theta term

Bsaisou et al ‘14