The Interpretation of Atomic Electric Dipole Moments [1]

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JUN 05, 2007

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[1] LA-UR-07-2262, arXiv:0705.1681

New-Generation EDM Searches

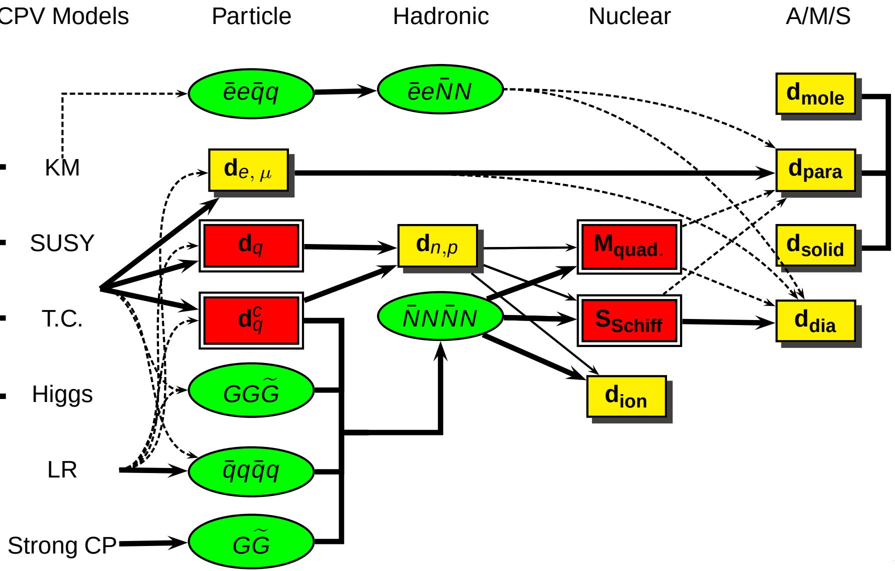
A non-exhaustive list:

Leptonic EDMs		Hadronic EDMs	
System	Group	System	Group
Cs (trapped)	Penn St.	n (UCN)	SNS
Cs (trapped)	Texas	n (UCN)	ILL
Cs (fountain)	LBNL	n (UCN)	PSI
YbF (beam)	Imperial	n (UCN)	Munich
PbO (cell)	Yale	^{199}Hg (cell)	Seattle
HBr^+ (trapped)	JILA	^{129}Xe (liquid)	Princeton
PbF (trapped)	Oklahoma	^{225}Ra (trapped)	Argonne
GdIG (solid)	Amherst	^{213,225}Ra (trapped)	KVI
GGG (solid)	Yale/Indiana	^{223}Rn (trapped)	TRIUMF
muon (ring)	J-PARC	deuteron (ring)	BNL?

- All leptonic searches except μ target at d_e (indirectly inferred).
- Most of them are subject to the shielding effects.

With the new-generation exps. hopefully increasing the EDM sensitivity by few orders of magnitude, the theoretical interpretation needs to be refined, too!

The Road Map



CPV Models
Particle
Hadronic
Nuclear
A/M/S
KM
SUSY
T.C.
Higgs
LR
Strong CP
$\bar{e}e\bar{q}q$
$\bar{e}e\bar{N}N$
$\mathbf{d}_{e,\mu}$
$\mathbf{d}_q$
$\mathbf{d}_q^c$
$G G\tilde{G}$
$\bar{q}q\bar{q}q$
$G\tilde{G}$
$\mathbf{d}_{n,p}$
$\bar{N}N\bar{N}N$
$\mathbf{M}_{\mathbf{quad.}}$
$\mathbf{S}_{\mathbf{Schiff}}$
$\mathbf{d}_{\mathbf{ion}}$
$\mathbf{d}_{\mathbf{mole}}$
$\mathbf{d}_{\mathbf{para}}$
$\mathbf{d}_{\mathbf{solid}}$
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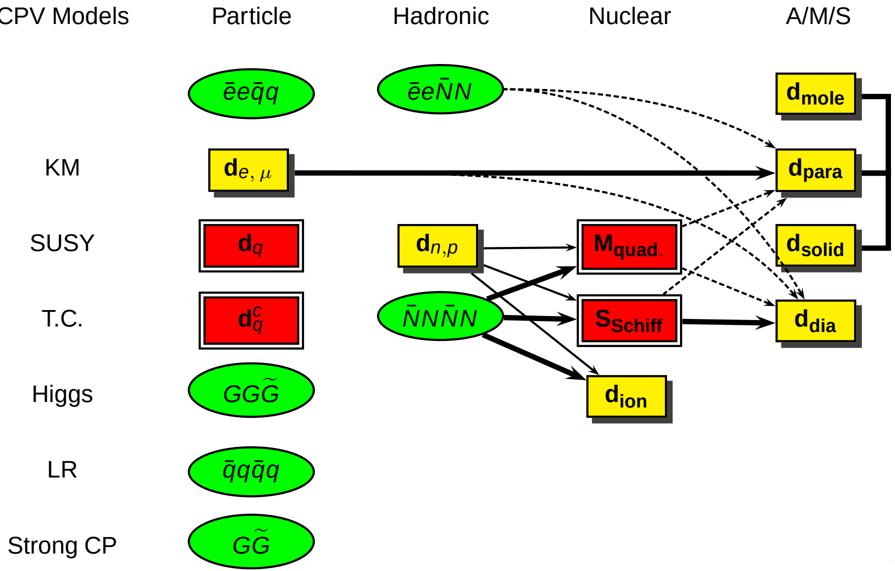
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LR
$\bar{q}q\bar{q}q$
Strong CP
$G\tilde{G}$

Theorem

For a NR system made up of point, charged particles which interact electrostatically with each other and with an arbitrary external field, the shielding is complete. (Schiff, 63)

- Classical picture: The re-arrangement of constituent charged particles in order to keep the whole system stationary.
- Quantum-Mechanical description: Schiff (63), Sandars (68), Feinberg (77), Sushkov, Flambaum, and Khriplovich (84), Engel, Friar, and Hayes (00), Flambaum and Ginges (02) ...

What this implies for atoms? (molecules? solids? neutron?)

- The measurability of atomic EDMs is severely constrained.
- One has to look for the loopholes (Schiff ff 63, Sandars 68) in
  - relativistic effects (electron)
  - finite-size effects (nucleus)
  - magnetic interactions (electron–nucleus)
  - non-EM exotica such as $\not{P}\not{T}$ electron-nucleon interaction

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The Atom under Detection (weak $\boldsymbol{E}^{(\mathrm{ext})}$)

The whole atomic EDM consists of:

1. Intrinsic EDMs of electrons and nucleus
   - d_e is elementary.
   - d_{nuc} has contributions from $d_{n,p}$ and $\not{P}\not{T}$ NN interaction, parametrized by $\tilde{C}^{\mathrm{had}}$.
2. Polarization effects by the $\not{P}\not{T}$ electron–nucleus interactions $\tilde{V}_{e-\mathrm{nuc}}$
   - Nuclear excitations are much less effective since $\Delta E_e / \Delta E_{\mathrm{nuc}} \sim 10^{-6}$.
   - $\tilde{V}_{e-\mathrm{nuc}}$ contains leptonic, semi-leptonic, and hadronic $\not{P}\not{T}$ sources.

The main task is determing the residual EDM responses that surive the cancellation of (1) and (2).

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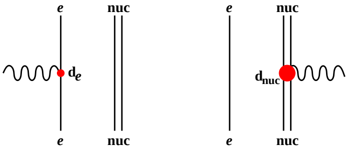

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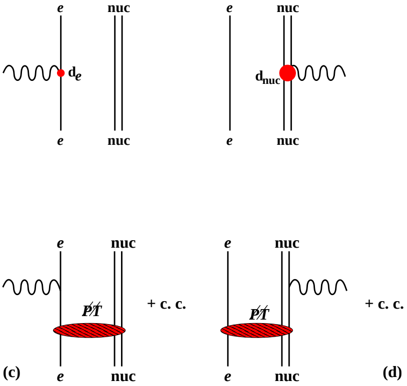

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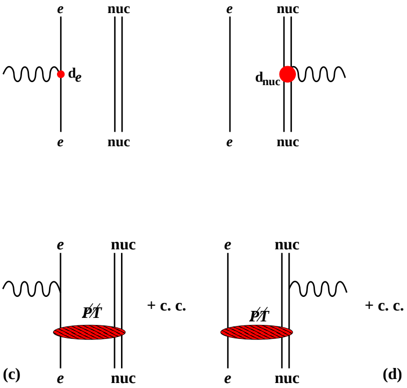

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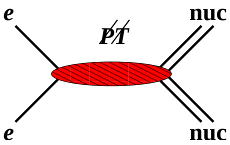
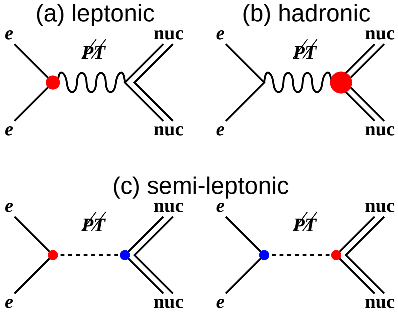
Contributions to $\not{P}\not{T}$ Electron–Nucleus Interaction

- Red vertices denote the $\not{P}\not{T}$ couplings: (a) d_e, (b) $d_{\rm nuc}$, (c) $\kappa_e^{\rm PS}$, $\kappa_N^{\rm PS}$ etc.





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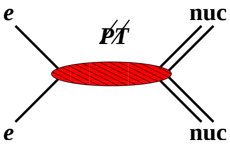
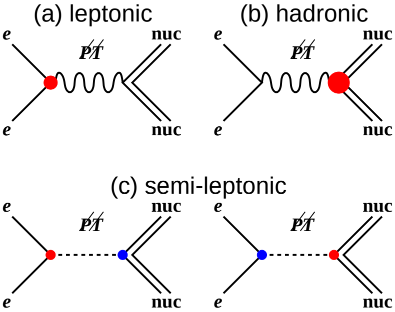
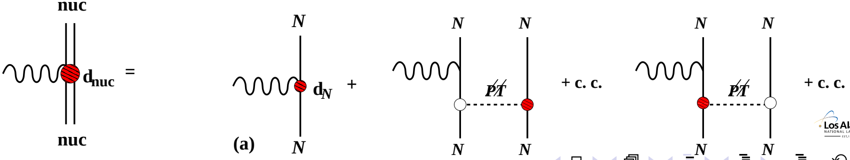




- What is inside of diagram (b) which involves nuclear EDM?



Fact

As the Schiff theorem is a quantum-mechanical description of the screening effect, the nuclear degrees of freedom (in terms of multipoles) are treated as q-numbers, instead of c-numbers (static distribution).

The Most Striking Difference from Literature: The Schiff Moment

In the leading approximation:

$$\langle \vec{S}^{(old)} \rangle = \frac{1}{10}\left\{ \langle y^2\, \vec{y} \rangle - \frac{5}{3Z} \langle \vec{d}_{\mathrm{nuc}} \rangle \otimes \langle y^2 \rangle \right\}$$

$$\langle \vec{S}^{(new)} \rangle = \frac{1}{10}\left\{ \langle y^2\, \vec{y} \rangle - \frac{5}{3Z} \left(\langle \vec{d}_{\mathrm{nuc}} \otimes y^2 \rangle - \frac{4\sqrt{2\pi}}{5} \langle [\vec{d}_{\mathrm{nuc}} \otimes y^2\, Y_2(\hat{y})]_1 \rangle \right) \right\} + \ldots$$

- The quadrupole operator appears (not quadrupole moment)
- For deuteron (1-body): 1:-5/3:-4/3 (Y_2 makes difference: -2 vs. -2/3)
- Evaluated in the old way (g.s. saturates the complete sum): 1:-0.59 : -0.071
- "…" contains many terms only show up in the operator formulation
- How about heavy diamagnetic atoms like Hg, Xe, Ra, Rn? (in progress)

The New Formulation (I)

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The New Formulation (II)

Also worth pointing out: the magnetic *e*–nuc interaction

$$\hat{\mathcal{O}}^{(\mathrm{int,mag})}_{\mathrm{nuc}} = -\frac{4\,\pi\,\alpha}{Z\,x^3}[Y_1(\hat{x})\otimes\boldsymbol{\alpha}]_1 \odot \left[\vec{d}_{\mathrm{nuc}}\,,\,\frac{1}{3}\left(M_1+\mathcal{M}_1(x)\right)\right]\cdot(x\,\boldsymbol{\nabla}^{\mathrm{sym}})+\ldots$$

- Schiff had this term for H ($I = 1/2$). If $\vec{d}_{\mathrm{nuc}}$ were a c-number, he would not have gotten this term
- Magnetic contributions are typically suppressed by the hyperfine scale $\alpha^2\,m_e/m_N \sim 10^{-7}$, might not be less important than the finite-size scale $\mathrm{fm}^2/a_0^2 \sim 10^{-9}$.

The competition in H-like paramagnetic atoms (real cases in progress):

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- (1) from the atomic structure calculation ($\sim Z^2$ for normal heavy atoms)
- (2) from the nuclear charge, (3) from the coherent contributions from nucleons
- (4) from $y^2\,\vec{y}$ in $\vec{S}$, scale $\sim A^{2/3}$, (5) from M_2 in $\vec{S}^{\mathrm{mag}}$, also scale $\sim A^{2/3}$

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In conclusion:

- The Schiff theorem is derived at the operator level in the most general fashion. The Schiff operator we got is different from existing literature. For a deuteron, the difference is huge, and check on nuclei of great interests like Hg, Xe, Ra, Rn, etc. should be carried out.
- The hadronic contributions to atomic EDMs of paramagnetic atoms Cs, Tl, etc. should also be considered for a better interpretation of such measurements.

Thank You!