Electric dipole moment of nuclei

Nodoka Yamanaka
(iTHES Group, RIKEN)

In collaboration with
E. Hiyama (RIKEN), T. Yamada (Kanto Gakuin Univ.),
Y. Funaki (RIKEN)
CP violation of Standard model is not sufficient to explain matter/antimatter asymmetry ...

Prediction of Standard model: $10^{28} : 1$
Real observed data: $10^{10} : 1$

We need new source(s) of large CP violation beyond the standard model!

How to search?

Electric dipole moment: $\langle d \rangle = \langle \psi | e\vec{r} | \psi \rangle$

EDM is CP-odd!
Sensitivity to new physics beyond standard model

If the EDM of light nuclei can be measured at $O(10^{-29})$e cm:

- **Supersymmetric model:**
  - Can probe 10 TeV scale SUSY breaking

- **Models with 4-quark interactions:**
  - Can probe PeV scale physics
    (Left-right symmetric model, ...)

- **Models with Barr-Zee type diagrams:**
  - Can probe PeV scale physics
    (Higgs doublet models, RPV SUSY, ...)

EDM is an attractive observable in the search for BSM physics!
Nuclear EDM from nucleon level CP violation

Paramagnetic Atom / Molecule EDM

Diamagnetic Atom EDM

Energy scale

Atomic Nuclear Hadron QCD TeV

observable : Observable available at experiment

: Sizable dependence

: Weak dependence

Nuclear EDM from nucleon level CP violation

Paramagnetic Atom / Molecule EDM

Diamagnetic Atom EDM

Nuclear EDM

Energy scale

Atomic  Nuclear

observable: Observable available at experiment

: Sizable dependence

: Weak dependence

Nuclear EDM (or ion)

Left-Right

Leptoquark

Composite models

SUSY

Extradimension

Standard Model

TeV

Need the calculation of nuclear structure:

⇒ Many-body method!!

Why the nuclear EDM?

- **Nuclear EDM is sensitive to hadron level CP violation**
  (hadron level CP violation is generated by CP violating operator with gluons and quarks)

- **Standard model contribution is very small**: $O(10^{-31})e\ cm$
  NY and E. Hiyama, JHEP 02 (2016) 067.

- **Nuclear EDM may enhance the CP violation through many-body effect**
  (Cluster, deformation make the parity violation easier)
  V. V. Flambaum, I. B. Khriplovich and O. P. Sushkov, Phys. Lett. B162, 213 (1985);

- **Nuclear EDM does not suffer from Schiff’s screening encountered in atomic EDM**
  (No electron to screen the nucleus)

- **Very accurate measurement of EDM is possible using storage rings**
  $\Rightarrow O(10^{-29})e\ cm$ !

**Nuclear EDM is a very good probe of BSM**
EDM of charged particles using storage rings

Rotating particles in a storage ring feel very strong central effective electric field

The spin precession of the charged particle can be measured if magnetic moment is kept collinear to the particle momentum. (strong electric field normal to the precession plane)

Measurements of the EDMs of muon, proton, deuteron, $^3$He are planned.

Prospective sensitivity:

$O(10^{-29})$ e cm!!

EDM of light nuclei is accurately measurable!

Better Experiment possible: $d\mu < 10^{-24}$ ecm

Essence: Cancel counteracting effects of g-2 precession!

Can work also for any charged particle

(prepared at FermiLab)
Two leading contributions to be evaluated:

1) Nucleon’s intrinsic EDM:

Contribution from the nucleon EDM

\[
D^{(1)} = \langle \psi | \sum_{i=1}^{A} \frac{1}{2} [(d_p + d_n) + (d_p - d_n) \tau_i^z] \sigma_i^z | \psi \rangle
\]

⇒ Spin expectation value (CP-even)

2) Polarization of the nucleus:

Contribution from the P, CP-odd nuclear force

\[
D^{(pol)} = \langle 0 | \hat{D}_z | 0 \rangle + \text{c.c.}, \quad \hat{D}_z = \frac{e}{2} \sum_{i=1}^{A} (1 + \tau_i^z) z_i
\]

⇒ EDM generated by the CP-even ⇔ CP-odd mixing
Nuclear EDM from nucleon level CP violation

Two leading contributions to be evaluated:

1) Nucleon’s intrinsic EDM:

Contribution from the nucleon EDM

\[ D^{(1)} = \langle \psi | \sum_{i=1}^{A} \frac{1}{2} \left[ (d_p + d_n) + (d_p - d_n) \tau_i^z \right] \sigma_i^z | \psi \rangle \]

⇒ Spin expectation value (CP-even)

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⇒ EDM generated by the CP-even ⇔ CP-odd mixing

May be enhanced by many-body effect!
A sophisticated method to calculate few-body system


Basis function:

$$\phi_{lm}(r) = \sum_n N_{nl} \sum_k C_{lm,k} e^{-\nu_n(r-D_{lm,k})^2}$$

Variational method

Successful in the benchmark calculation of $^4$He binding energy


It is applied in many subjects:
Nuclei, Hypernuclei, atoms, hadrons, astrophysics, ...

We expect accurate calculation of nuclear EDM!
Nuclear EDM (polarization) from CP-odd nuclear force

Electric dipole operator requires CP mixing to have finite expectation value

**Total hamiltonian:**

\[
H = \begin{pmatrix}
H_{\text{realistic}} & H_{P\mathcal{T}} \\
H_{P\mathcal{T}} & H_{\text{realistic}}
\end{pmatrix}
\]

CP-odd N-N interactions mixes opposite parity states

Parity mixing ⇒ Polarized ground state!
P, CP-odd nuclear force from one pion exchange

P, CP-odd nuclear force: we assume one-pion exchange process

\[ \sim \frac{1}{q^2 - m_\pi^2} \bar{N}N \bar{N}i\gamma_5 N \]

P, CP-odd Hamiltonian (3-types):

\[ H_{\text{PT}} = -\frac{g_{\pi NN}}{8\pi m_p} \left[ (g_{\pi NN}^{(0)} \tau_a \cdot \tau_b + g_{\pi NN}^{(2)}(\tau_a \cdot \tau_b - 3\tau_z^a \tau_z^b)) (\vec{\sigma}_a - \vec{\sigma}_b) + g_{\pi NN}^{(1)}(\tau_z^a \vec{\sigma}_a - \tau_z^b \vec{\sigma}_b) \right] \cdot \nabla_a \frac{e^{-m_\pi r_{ab}}}{r_{ab}}, \]

4 important properties:

- Coherence in nuclear scalar density: enhanced in nucleon number
- One-pion exchange: suppress long distance contribution
- Spin dependent interaction: closed shell has no EDM
- Derivative: contribution from the surface

What is expected:

- Polarization effect grows in \( A \) for small nuclei
- May have additional enhancements with cluster, deformation, ...
Physics of nuclear EDM: light and heavy nuclei

Light nuclei

Heavy nuclei

Core
Light nuclei have cluster structure
→ Larger “surface”
→ May enhance CPV effect??
What we want to do

⇒ Nucleon level CPV is unknown and small : linear dependence

⇒ Linear coefficients depends on the nuclear structure

⇒ We want to find nuclei with large enhancement factors

⇒ We must calculate the nuclear structure with nucleon level CPV

Dependence of nuclear EDM on nucleon level CP violation must be written as:

\[ d_A = (a^{(0)}_\pi \bar{G}^{(0)}_\pi + a^{(1)}_\pi \bar{G}^{(1)}_\pi + a^{(2)}_\pi \bar{G}^{(2)}_\pi) \ e \ fm \]

⇒ We want to evaluate red factors and find interesting nuclei!
Integrate the CP-odd N-N interaction with the $^4\text{He}$ nucleon density

(a cluster is indestructible)

Gaussian approximation of density:

$$\rho_\alpha(r) = Ae^{-\frac{r^2}{b}}$$

Spread: $b = (1.358 \text{ fm})^2$

Only isovector CP-odd nuclear force is relevant in N-\(\alpha\) interaction

(Isoscalar and isotensor CP-odd nuclear forces cancel by folding)

\[ \Rightarrow \text{Can reduce the calculation of p-shell nuclei to few-body problem} \]

Result: $^6$Li EDM

$^6$Li is well described with $\alpha+d$

Binding energy: 3.7 MeV

$^6$Li EDM is made of 2 comparable components:

- Deuteron cluster polarization: slightly smaller than deuteron EDM
- CP-odd $\alpha$-N interaction effect

Compare with deuteron EDM ($c_1 = 0.0145 \text{ e fm}$):

$\Rightarrow$ $^6$Li enhances the CP-odd effect! (twice deuteron EDM)
Result: $^9$Be EDM

![Diagram of $^9$Be with a neutron and two alpha particles]

- Binding energy: $1.57$ MeV

<table>
<thead>
<tr>
<th>Nuclear force</th>
<th>$\langle \sigma \rangle$</th>
<th>$\langle \sigma_\tau \rangle$</th>
<th>isoscalar ($c_0$)</th>
<th>isovector ($c_1$)</th>
<th>isotensor ($c_2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cluster model</td>
<td>0.38</td>
<td>-0.38</td>
<td>$-$</td>
<td>0.014 e fm</td>
<td>$-$</td>
</tr>
</tbody>
</table>

- Sensitivity to isovector CP-odd nuclear force comparable to deuteron

- Polarization due to the CP-odd $\alpha$-N interaction

(No polarization from $\alpha$-$\alpha$ system)
Result: $^{13}$C EDM

- Nuclear force:
  - $<\sigma>$: -0.17
  - $<\sigma_T>$: 0.17
  - Isoscalar ($c_0$): —
  - Isovector ($c_1$): -0.0012 $\text{e fm}$
  - Isotensor ($c_2$): —

- Opposite sign: orbital angular momentum and spin are antiparallel

- Smaller sensitivity than lighter nuclei

- Bad overlap with $1/2^+$ excited state?
  - Ground state is shell like, but $1/2^+$ is neutron halo like.
  - Bad core overlap between Ground and $1/2^+$ states.

- Energy levels of $^{13}$C:
  - $4.94635 \text{MeV} \quad ^{12}\text{C} + n$
  - $3.089 \text{MeV} \quad 1/2^+$
  - Ground $1/2^-$
Parity-odd transitions in $^{13}\text{C}$

$^{13}\text{C}^{1/2}_{1/2} + n$ $^{12}\text{C}(0^+) + n$ $^{12}\text{C}(0^+) + n$ $^{12}\text{C}(2^+) + n$

$E(\text{MeV})$

$P = -1$ $P = +1$ $P = -1$

$1/2^-_1$ $1/2^+_1$ $1/2^-_1$

$H_{PT}$ EDM
Parity-odd transitions in $^{13}\text{C}$

$^{13}\text{C} \rightarrow ^{12}\text{C} + ^{1}\text{H}$

$P = -1$

$J_{^{13}\text{C}} = 1/2^-$

$L = 1$

$L \times S = 3/2$

$(\text{Strong LS})$

$J_{^{12}\text{C}} = 2$

$S = 1/2$

$E(\text{MeV})$

$0 \quad 1/2^-_1$

$1/2^-_1$

$P = -1$

$P = -1$

$^{12}\text{C}(0^+) + ^{1}\text{n}$

$^{12}\text{C}(2^+) + ^{1}\text{n}$

$^{12}\text{C}(0^+) + ^{1}\text{n}$

$^{12}\text{C}(0^+) + ^{1}\text{n}$
Parity-odd transitions in $^{13}$C

$^{12}$C$(0^+)$+n

$^{12}$C$(2^+)$+n

$^{12}$C$(0^+)$+n

EDM

P = +1

P = −1

$L = 1, S = 1/2$

$L \times S = 3/2$

(Strong LS)

$J_{^{12}C} = 2$

$J_{^{13}C} = 1/2^-$
Parity-odd transitions in $^{13}$C

$J_{12C} = 2 \quad L = 1 \quad S = 1/2$

$J_{13C} = 1/2^-$

$L \times S = 3/2$

(Strong LS)

$P = +1$

$^{12}$C($0^+)+n$

$^{12}$C($2^+)+n$

Bad overlap with $1/2^-$

$E$(MeV)

$L\times S = 3/2$

$J_{12C} = 0 \quad L = 0 \quad S = 1/2$

$J_{13C} = 1/2^+$

$^{12}$C($0^+)+n$

$^{12}$C($0^+)+n$

$^{12}$C($0^+)+n$
Parity-odd transitions in $^{13}$C

$^{12}$C(0$^+$)+n

$^{12}$C(2$^+$)+n

$P = -1$

$P = +1$

$E$(MeV)

5

7

9

$L_x S = 3/2$

(Strong LS)

$L = 1$

$S = 1/2$

$L = 0$

$S = 1/2$

Bad overlap with 1/2$^-$

$J_{12C} = 2$

$J_{13C} = 1/2^-$

$J_{12C} = 0$

$J_{13C} = 1/2^+$

$P = +1$

$P = -1$

1/2
Parity-odd transitions in $^{13}\text{C}$

$^{13}\text{C}(0^+) + n \rightarrow \frac{1}{2}^+ \rightarrow \frac{1}{2}^+$

$L > 2, S = 1/2$

$J_{12c} = 2, L = 1, S = 1/2$

Good overlap with $1/2^-\text{n}$, but far energetically.

$J_{13c} = 1/2^+$

$E(\text{MeV})$
Parity-odd transitions in $^{13}\text{C}$

$^{12}\text{C}(0^+) + n$

$J_{12C} = 2 \quad L = 1 \quad S = 1/2$

$L \times S = 3/2$ (Strong LS)

$J_{13C} = 1/2^-$

$P = +1$

$J_{12C} = 2 \quad L > 2 \quad S = 1/2$

$n$

$P = -1$

Good overlap with $1/2^-$, but far energetically

$\Rightarrow$ Bad overlap of the core suppresses the EDM!
## Results

<table>
<thead>
<tr>
<th>EDM</th>
<th>isoscalar (c₀)</th>
<th>isovector (c₁)</th>
<th>isotensor (c₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>129Xe atom</strong></td>
<td>1.0x10⁻⁷ e fm</td>
<td>3.0x10⁻⁸ e fm</td>
<td>7.6x10⁻⁸ e fm</td>
</tr>
<tr>
<td>N. Yoshinaga et al., talk of this conference</td>
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<td></td>
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<tr>
<td>Dzuba et al., PRA 80, 032120 (2009)</td>
<td></td>
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</tr>
<tr>
<td><strong>199Hg atom</strong></td>
<td>4.7x10⁻⁶ e fm</td>
<td>-1.8x10⁻⁶ e fm</td>
<td>7.5x10⁻⁶ e fm</td>
</tr>
<tr>
<td>Ban et al., PRC 82, 015501 (2010)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Dzuba et al., PRA 80, 032120 (2009)</td>
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</tr>
<tr>
<td><strong>225Ra atom</strong></td>
<td>0.00088 e fm</td>
<td>-0.0052 e fm</td>
<td>0.0035 e fm</td>
</tr>
<tr>
<td>Dobaczewski et al., PRL 94, 232502 (2005)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dzuba et al., PRA 80, 032120 (2009)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutron (Chiral analysis)</td>
<td>0.01 e fm</td>
<td>–</td>
<td>– 0.01 e fm</td>
</tr>
<tr>
<td><strong>Deuteron</strong></td>
<td>–</td>
<td>0.0145 e fm</td>
<td>–</td>
</tr>
<tr>
<td>Liu et al., PRC 70, 055501 (2004)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>NY and EH, PRC 91, 054005 (2015)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>3He nucleus</strong></td>
<td>0.0060 e fm</td>
<td>0.0108 e fm</td>
<td>0.0168 e fm</td>
</tr>
<tr>
<td>Baisou et al., JHEP 1503 (2015) 104</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NY and EH, PRC 91, 054005 (2015)</td>
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</tr>
<tr>
<td><strong>6Li nucleus</strong></td>
<td>–</td>
<td>0.028 e fm</td>
<td>–</td>
</tr>
<tr>
<td>NY and EH, PRC 91, 054005 (2015)</td>
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<td><strong>9Be nucleus</strong></td>
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<td>NY and EH, PRC 91, 054005 (2015)</td>
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<tr>
<td><strong>13C nucleus</strong></td>
<td>–</td>
<td>-0.0012 e fm</td>
<td>–</td>
</tr>
<tr>
<td>NY et al., in preparation</td>
<td></td>
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</tr>
</tbody>
</table>

*Our result*
7Li:

- Have $\alpha+3N$ cluster structure
  - Can be treated as 4-body system
- Closest $^3\text{He}+\alpha$ continuum threshold at 2.5 MeV
  - Large overlap with closest continuum?
- $g-2 = +1.256$

19F:

- Coupled channel $^{15}\text{N}+\alpha - ^{16}\text{O}+^3\text{H}$ cluster structure
- $1/2^+ - 1/2^-$ energy splitting: Only 110 keV!
- $g-2 = +0.629$
Summary:

- We have studied the EDM of light nuclei using the Gaussian Expansion Method.
- Large EDM for $^6$Li: suggest enhancement of EDM due to cluster structure.
- Small EDM for $^{13}$C EDM: may be understood by the small overlap between the cores of $1/2^-$ and $1/2^+$ states.
- Our results are a very good guide to search for nuclei with large enhancement factors.

Future subjects:

- Further study of EDM of light nuclei:
  - EDM of $^{19}$F and $^7$Li?
- We are waiting for experiments!