Nuclear electric dipole moment of 3-body systems in the Gaussian expansion method

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CP violation of Standard model is not sufficient to explain matter/antimatter asymmetry ...

Prediction of Standard model: \(10^{28} : 1\)
Real observed data: \(10^{10} : 1\)

\[\text{ratio photon : matter}\]

\[\text{CP violation of standard model is in great deficit!}\]

We need new source(s) of large CP violation beyond the standard model!
Nuclear electric dipole moment (EDM)

Electric dipole moment:
Permanent polarization of internal charge of a particle.
\[
\langle d \rangle = \langle \psi | e \hat{r} | \psi \rangle
\]

Odd under time reversal:
\[
\begin{align*}
\bar{E} & \xrightarrow{T} E \\
\bar{\sigma} & \xrightarrow{T} -\bar{\sigma}
\end{align*}
\]
→ EDM is sensitive to CPV!

Nuclear EDM has many advantages:
- Nuclear EDM is enhanced due to many-body effect
- Nuclear EDM does not suffer from Schiff’s screening encountered in atomic EDM
- Very accurate measurement of EDM is possible using storage rings

Nuclear EDM is a very good probe of BSM
Nuclear EDM (polarization) from CP-odd nuclear force

Nuclear EDM is generated by P, CP-odd nuclear force

Total hamiltonian:

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

CP-odd N-N interactions mixes opposite parity states

\[
\begin{align*}
\text{s-wave} & \quad + \\
\text{p-wave} & \quad - \\
\text{polarized system} & \quad =
\end{align*}
\]

Parity mixing \( \Rightarrow \) Polarized ground state!
P, CP-odd nuclear force: we assume one-pion exchange process

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

CPV \( \pi N N \) interaction:
Generated by BSM CP violation: SUSY, extended Higgs, etc.
In this work, we assume a very small CPV coupling

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

\[ H_{\piNN} = -\frac{g_{\pi NN}}{8\pi m_p} \left[ \left( \tilde{g}^{(0)}_{\pi NN} \tau_a \cdot \tau_b + \tilde{g}^{(2)}_{\pi NN} (\tau_a \cdot \tau_b - 3\tau_a^z \tau_b^z) \right) (\vec{\sigma}_a - \vec{\sigma}_b) + \tilde{g}^{(1)}_{\pi NN} (\tau_a^z \vec{\sigma}_a - \tau_b^z \vec{\sigma}_b) \right] \cdot \vec{\nabla}_a \frac{e^{-m_\pi r_{ab}}}{r_{ab}}, \]

Isoscalar \hspace{1cm} Isotensor \hspace{1cm} Isovector
Object of study

To start, let us evaluate light few-body nuclei:

$\Rightarrow$ EDM of $^2$H, $^3$He, $^3$H, $^6$Li and $^9$Be nuclei

They can be treated as 3-body systems

How to do?

$\Rightarrow$ Infinitesimally shifted Gaussian expansion method


Object of our research:

Study the sensitivity of $^2$H, $^3$He, $^3$H, $^6$Li, $^9$Be nuclear EDM to CP violation using the Gaussian expansion method.

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 \(^4\text{He}\) binding energy

- Binding energies of 3-nucleon systems in this work:
  \[ \begin{align*}
  B(\text{\(^3\text{H}\)}) &= 7.63 \text{ MeV} \\
  B(\text{\(^3\text{He}\)}) &= 6.93 \text{ MeV}
  \end{align*} \] (Using Av18 potential, 3-body forces neglected)

Accurate calculation of nuclear EDM is possible!
Ab initio calculation: $^3\text{He}$, $^3\text{H}$ EDM
### Result of ab initio calculations (deuteron, $^3$H, $^3$He EDMs)

\[
d_A = \left( c_0 g_{\pi NN}^{(0)} + c_1 g_{\pi NN}^{(1)} + c_2 g_{\pi NN}^{(2)} \right) \times 10^{-13} \text{e cm} \times g_{\pi NN}
\]

#### Deuteron EDM:

<table>
<thead>
<tr>
<th>Group</th>
<th>Nuclear force</th>
<th>$c_0$</th>
<th>$c_1$</th>
<th>$c_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liu &amp; Timmermans</td>
<td>Av18</td>
<td>0</td>
<td>1.43x10^{-2}e fm</td>
<td>0</td>
</tr>
<tr>
<td>Song, Lazauskaus, Gudkov</td>
<td>Av18</td>
<td>0</td>
<td>1.45x10^{-2}e fm</td>
<td>0</td>
</tr>
<tr>
<td>Our result</td>
<td>Av18</td>
<td>0</td>
<td>1.45x10^{-2}e fm</td>
<td>0</td>
</tr>
</tbody>
</table>

Song et al., PRC 87, 015501 (2013)


#### $^3$He EDM:

<table>
<thead>
<tr>
<th>Group</th>
<th>Nuclear force</th>
<th>$c_0$ (isoscalar)</th>
<th>$c_1$ (isovector)</th>
<th>$c_2$ (isotensor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bsaisou et al.</td>
<td>N$^2$LO chiral EFT</td>
<td>0.0079 e fm</td>
<td>0.0101 e fm</td>
<td>0.0169 e fm</td>
</tr>
<tr>
<td></td>
<td>Av18</td>
<td>0.0060 e fm</td>
<td>0.0108 e fm</td>
<td>0.0168 e fm</td>
</tr>
</tbody>
</table>


\[\Rightarrow\text{Consistent with previous works!}\]
Cluster approximation: $^6\text{Li}$, $^9\text{Be}$ EDM
Setup of cluster model

We treat $^6$Li and $^9$Be nuclei as 3-body systems of nucleons and $\alpha$ clusters ($^4$He nucleus).

**CP-even sector:**

Realistic nuclear force (Av8’) for N-N

Effective interactions for cluster ($\alpha$-N, $\alpha$-$\alpha$) given by fitting the scattering phase shift + Pauli exclusion with OCM.

**CP-odd sector:**

Standard one-pion exchange for N-N

Folding of CP-odd N-N interaction for $\alpha$-N

Gaussian approximation of density:

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

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

(Isoscalar and isotensor CP-odd nuclear forces cancel by folding)
**Result: ** $^6$Li EDM (polarization contribution)

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

**Binding energy:** 3.7 MeV

<table>
<thead>
<tr>
<th>Nuclear force</th>
<th>$&lt;\sigma&gt;$</th>
<th>$&lt;\sigma_T&gt;$</th>
<th>isoscalar ($c_0$)</th>
<th>isovector ($c_1$)</th>
<th>isotensor ($c_2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Av8’+cluster model</td>
<td>0.88</td>
<td>—</td>
<td>—</td>
<td>0.028 e fm</td>
<td>—</td>
</tr>
</tbody>
</table>

$^6$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 ($c_1 = 0.0145$ e fm):

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

Binding energy: 1.57 MeV

<table>
<thead>
<tr>
<th>Nuclear force</th>
<th>$&lt;\sigma&gt;$</th>
<th>$&lt;\sigma_\tau&gt;$</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>0.22</td>
<td>-0.22</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
**How nuclear EDM is sensitive to CP violation?**

<table>
<thead>
<tr>
<th>EDM</th>
<th>isoscalar (c₀)</th>
<th>isovector (c₁)</th>
<th>isotensor (c₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{199}$Hg atom</td>
<td>$4.7 \times 10^{-6}$ e fm</td>
<td>$-1.8 \times 10^{-6}$ e fm</td>
<td>$7.5 \times 10^{-6}$ e fm</td>
</tr>
</tbody>
</table>
| Ban et al., PRC 82, 015501 (2010)  
Dzuba et al., PRA 80, 032120 (2009) | | | |
| $^{225}$Ra atom | $0.00088$ e fm | $-0.0052$ e fm | $0.0035$ e fm |
| Dobaczewski et al., PRL 94, 232502 (2005)  
Dzuba et al., PRA 80, 032120 (2009) | | | |
| Neutron | $0.01$ e fm | — | $-0.01$ e fm |
| (Chiral analysis) | | | |
| Deuteron | — | $0.0145$ e fm | — |
| Liu et al., PRC 70, 055501 (2004) | | | |
| $^{3}$He nucleus | $0.0060$ e fm | $0.0108$ e fm | $0.0168$ e fm |
| $^{6}$Li nucleus | — | $0.028$ e fm | — |
| $^{9}$Be nucleus | — | $0.014$ e fm | — |

**Our result**

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!**
Summary:

- We have studied the EDM of deuteron, $^{3}\text{He}$ and $^{3}\text{H}$ nuclei with the Gaussian expansion method: we have found consistency with previous works.
- We have studied the EDM of $^{6}\text{Li}$ and $^{9}\text{Be}$ nuclei in the Gaussian expansion method with the cluster approximation: an enhancement of the EDM due to the many-body effect is suggested.

Future subjects:

- Further study of EDM of light nuclei: find sensitive nuclei.
- Study of nuclear EDM beyond cluster approximation.
- We are waiting for experiments to unveil BSM CPV!
End
We treat $^6$Li and $^9$Be nuclei as 3-body systems of nucleons and $\alpha$ clusters ($^4$He nucleus).

- **N-N interaction:**
  
  $\text{Av8}'$
  

- **N-$\alpha$ interaction:**
  
  Fitted to reproduce the $\alpha$-N scattering phase shift at low energy
  Pauli exclusion taken into account via OCM (0s excluded)
  

- **$\alpha$-$\alpha$ interaction:**
  
  Fitted to reproduce the $\alpha$-$\alpha$ scattering phase shift at low energy
  Pauli exclusion taken into account via OCM (0s, 1s, 0d excluded)
  