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 ...

	ratio photon : matter
Prediction of Standard model:	10^{28} : 1
Real observed data:	10^{10} : 1

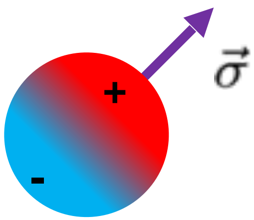
➡ **CP violation of standard model is in great deficit!**

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

Electric dipole moment:

Permanent polarization of internal charge of a particle.

$$\langle \vec{d} \rangle = \langle \psi | \, e\vec{r} \, | \psi \rangle$$



Odd under time reversal: $\begin{cases} \vec{E} \xrightarrow{\mathrm{T}} \vec{E} \\ \vec{\sigma} \xrightarrow{\mathrm{T}} -\vec{\sigma} \end{cases}$ → 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

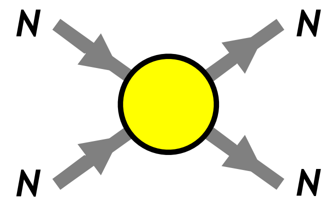
➡ **Nuclear EDM is a very good probe of BSM**

Nuclear EDM (polarization) from CP-odd nuclear force

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

Total hamiltonian:

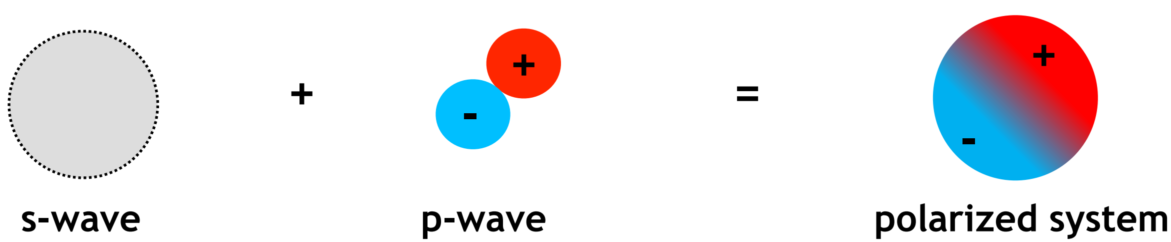
$$H = \begin{pmatrix} H_{\text{realistic}} & H_{\not{P}\not{T}} \\ H_{\not{P}\not{T}} & H_{\text{realistic}} \end{pmatrix}$$



P, CP-odd nuclear force

P, CP-even realistic nuclear force (e.g. Av18,xEFT,...)

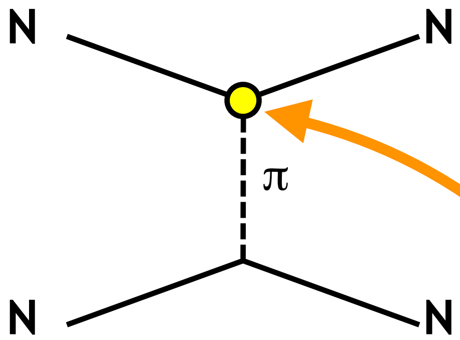
CP-odd N-N interactions mixes opposite parity states



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



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

CPV πNN 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):

$$H_{\not P \not T} = -\frac{g_{\pi NN}}{8\pi m_p}\left[\left(\bar{g}^{(0)}_{\pi NN}\tau_a\cdot\tau_b + \bar{g}^{(2)}_{\pi NN}(\tau_a\cdot\tau_b - 3\tau_a^z\tau_b^z)\right)(\vec{\sigma}_a-\vec{\sigma}_b) + \bar{g}^{(1)}_{\pi NN}(\tau_a^z\vec{\sigma}_a - \tau_b^z\vec{\sigma}_b)\right]\cdot\vec{\nabla}_a \frac{e^{-m_\pi r_{ab}}}{r_{ab}} ,$$

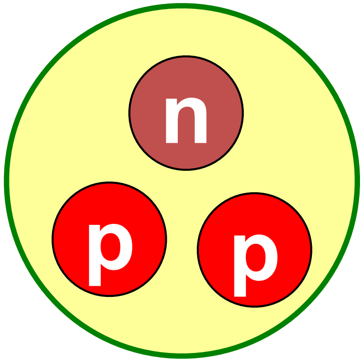
Isoscalar ($\bar{g}^{(0)}_{\pi NN}$) Isotensor ($\bar{g}^{(2)}_{\pi NN}$) Isovector ($\bar{g}^{(1)}_{\pi NN}$)

Object of study

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

⇒ 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?

Infinitesimally shifted Gaussian expansion method

E. Hiyama *et al.*, Prog. Part. Nucl. Phys. **51**, 223 (2003).

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.

N. Yamanaka and E. Hiyama, Phys. Rev. C 91, 054005 (2015).

Infinitesimally shifted Gaussian expansion method

A sophisticated method to calculate few-body system

E. Hiyama *et al.*, Prog. Part. Nucl. Phys. **51**, 223 (2003).

- **Basis function:** $\phi_{lm}(\mathbf{r}) = \sum_n N_{nl} \sum_k C_{lm,k} e^{-\nu_n (\mathbf{r}-\mathbf{D}_{lm,k})^2}$
- **Variational method**
- **Successful in the benchmark calculation of ^{4}He binding energy**

  H. Kamada et al., Phys. Rev. C **64**, 044001 (2001).
- **Binding energies of 3-nucleon systems in this work:**

  B(^{3}H) = 7.63 MeV
  B(^{3}He) = 6.93 MeV **(Using Av18 potential, 3-body forces neglected)**

Accurate calculation of nuclear EDM is possible!

Ab initio calculation:
^3He, ^3H EDM

Result of ab initio calculations (deuteron, ^{3}H, ^{3}He EDMs)

$$d_A = \left(c_0 \bar{g}^{(0)}_{\pi NN} + c_1 \bar{g}^{(1)}_{\pi NN} + c_2 \bar{g}^{(2)}_{\pi NN} \right) \times 10^{-13} e\,\mathrm{cm} \times g_{\pi NN}$$

Deuteron EDM:

Group	Nuclear force	c_0	c_1	c_2
Liu & Timmermans	Av18	0	1.43×10^{-2}e fm	0
Song, Lazauskaus, Gudkov Song et al., PRC 87, 015501 (2013)	Av18	0	1.45×10^{-2}e fm	0
Our result NY, E. Hiyama, PRC **91**, 054005 (2015)	Av18	0	1.45×10^{-2}e fm	0

^{3}He EDM:

Group	Nuclear force	isoscalar (c_0)	isovector (c_1)	isotensor (c_2)
Bsaisou et al. Bsaisou et al., JHEP 1503 (2015) 104 Ann. Phys. 359, 317 (2015)	N^{2}LO chiral EFT	0.0079 *e* fm	0.0101 *e* fm	0.0169 *e* fm
Our result NY, E. Hiyama, PRC **91**, 054005 (2015)	Av18	0.0060 *e* fm	0.0108 *e* fm	0.0168 *e* fm

⇒ **Consistent with previous works!**

Cluster approximation: ^{6}Li, ^{9}Be EDM

Setup of cluster model

We treat ^{6}Li and ^{9}Be nuclei as 3-body systems of nucleons and α clusters (^{4}He nucleus).

CP-even sector:

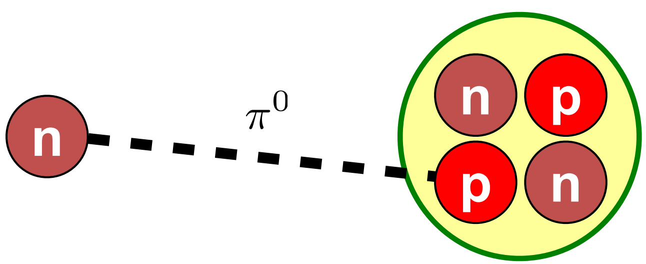
Realistic nuclear force (Av8') for N-N

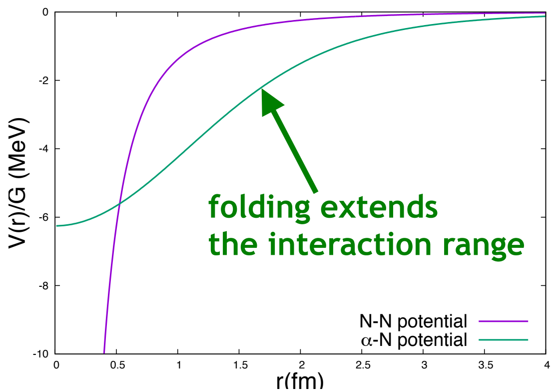
Effective interactions for cluster (α-N, α-α) given by fitting the scattering phase shift + Pauli exclusion with OCM.

CP-odd sector:

Standard one-pion exchange for N-N

Folding of CP-odd N-N interaction for α-N



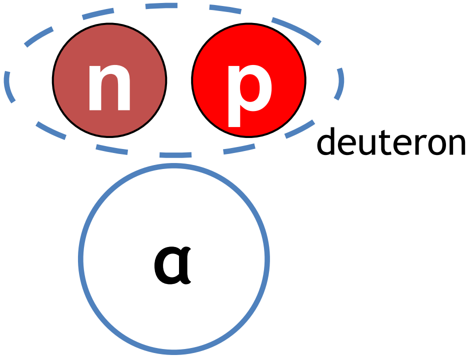


Gaussian approximation of density:

$$\rho_\alpha(r) = Ae^{-\frac{r^2}{b}} \qquad \text{Spread : } b = (1.358 \text{ fm})^2$$

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

Result : ^{6}Li EDM (polarization contribution)



Binding energy : 3.7 MeV

^{6}Li is well described with α+d

Nuclear force	<σ>	<στ>	isoscalar (c_0)	isovector (c_1)	isotensor (c_2)
Av8'+cluster model	0.88	–	–	0.028 *e* fm	–

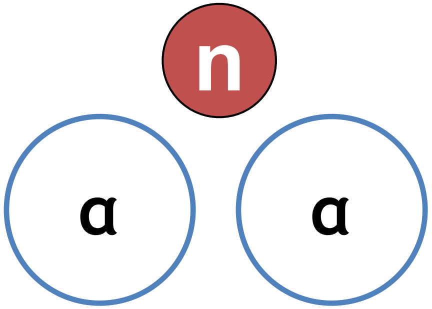
^{6}Li EDM is made of 2 comparable components:

- Deuteron cluster polarization : slightly smaller than deuteron EDM
- CP-odd α-N interaction effect

Compare with deuteron EDM (c_1 = 0.0145 *e* fm) :

⇒ ^{6}Li enhances the CP-odd effect ! (twice deuteron EDM)

Result : ^{9}Be EDM (polarization contribution)



Binding energy : 1.57 MeV

Nuclear force	<σ>	<στ>	isoscalar (c_0)	isovector (c_1)	isotensor (c_2)
Cluster model	0.22	-0.22	–	0.014 *e* fm	–

Sensitivity to isovector CP-odd nuclear force comparable to deuteron

Polarization due to the CP-odd α-N interaction

How nuclear EDM is sensitive to CP violation??

EDM	isoscalar (c_0)	isovector (c_1)	isotensor (c_2)
^{199}Hg atom Ban et al., PRC 82, , 015501 (2010) Dzuba et al., PRA 80, 032120 (2009)	4.7×10^{-6} e fm	-1.8×10^{-6} e fm	7.5×10^{-6} e fm
^{225}Ra atom Dobaczewski et al., PRL 94, 232502 (2005) Dzuba et al., PRA 80, 032120 (2009)	0.00088 e fm	-0.0052 e fm	0.0035 e fm
Neutron (Chiral analysis)	0.01 e fm	–	- 0.01 e fm
Deuteron Liu et al., PRC **70**, 055501 (2004)	–	0.0145 e fm	–
^{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

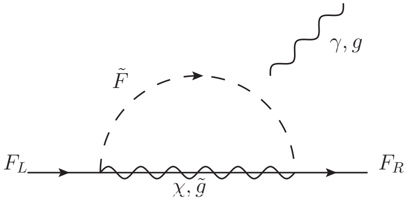
N. Yamanaka, E. Hiyama, PRC 91, 054005 (2015)

Sensitivity to new physics beyond standard model

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

- **Supersymmetric model:**

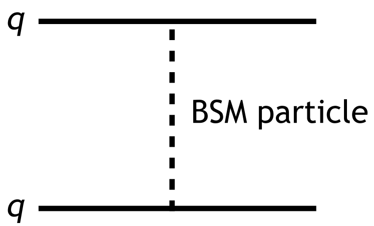
  ⇒ Can probe 10 TeV scale SUSY breaking



- **Models with 4-quark interactions:**

  ⇒ Can probe PeV scale physics

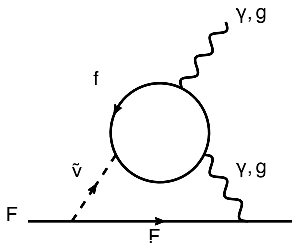
  (Left-right symmetric model, …)



- **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!

Summary:

- We have studied the EDM of deuteron, ^{3}He and ^{3}H nuclei with the Gaussian expansion method: we have found consistency with previous works.
- We have studied the EDM of ^{6}Li and ^{9}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

Setup of the cluster model

We treat ^{6}Li and ^{9}Be nuclei as 3-body systems of nucleons and α clusters (^{4}He nucleus).

N-N interaction:

Av8'

R. B. Wiringa *et al.*, Phys. Rev. C **51**, 38 (1995).

N-α interaction:

Fitted to reproduce the α-N scattering phase shift at low energy

Pauli exclusion taken into account via OCM (0s excluded)

H. Kanada *et al.*, Prog. Theor. Phys. **61**, 1327 (1979).

α-α interaction:

Fitted to reproduce the α-α scattering phase shift at low energy

Pauli exclusion taken into account via OCM (0s,1s, 0d excluded)

A. Hasegawa and S. Nagata, Prog. Theor. Phys. **45**, 1786 (1971).