Nuclear electric dipole moment in the Gaussian expansion method

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Introduction

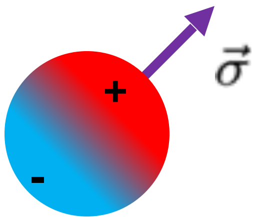
CP violation of Standard model is not sufficient to explain matter/antimatter asymmetry …

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

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

How to search ?

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



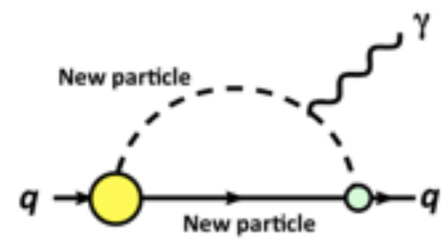
EDM is CP-odd !

$$\begin{cases} \vec{E} \xrightarrow{\mathrm{T}} \vec{E} \\ \vec{\sigma} \xrightarrow{\mathrm{T}} -\vec{\sigma} \end{cases}$$

EDM as a sensitive probe of BSM physics

Naïve estimation of neutron EDM:

- Coupling of new physics ~ O(1) (naturalness assumption)
- Contribute from one-loop graph
- 1 Yukawa coupling (required for chirality flip)
- d_n/d_q ~ O(1) (hadron level analysis)



$$d_n = \frac{Y_q e}{4\pi^2 M_{\rm NP}} \sim \frac{10^{-21}}{M_{\rm NP}/{\rm GeV}} e\,cm$$

Exp data: $d_n < 2.9 \times 10^{-26}$ e cm

C. A. Baker *et al.*, Phys. Rev. Lett. **97**, 131801 (2006).

⇒ Current exp data of Neutron EDM can probe M_{NP} ~ 10TeV!

(for $d_n < 10^{-28}$ e cm , M_{NP} ~ 1000TeV can be probed: well beyond reach of LHC!)

➡ EDM is an attractive observable!

Nuclear EDM

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)

- **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. B**162**, 213 (1985);
NY and E. Hiyama, Phys. Rev. C **91**, 054005 (2015).

- **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**

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

EDM of charged particles using storage rings

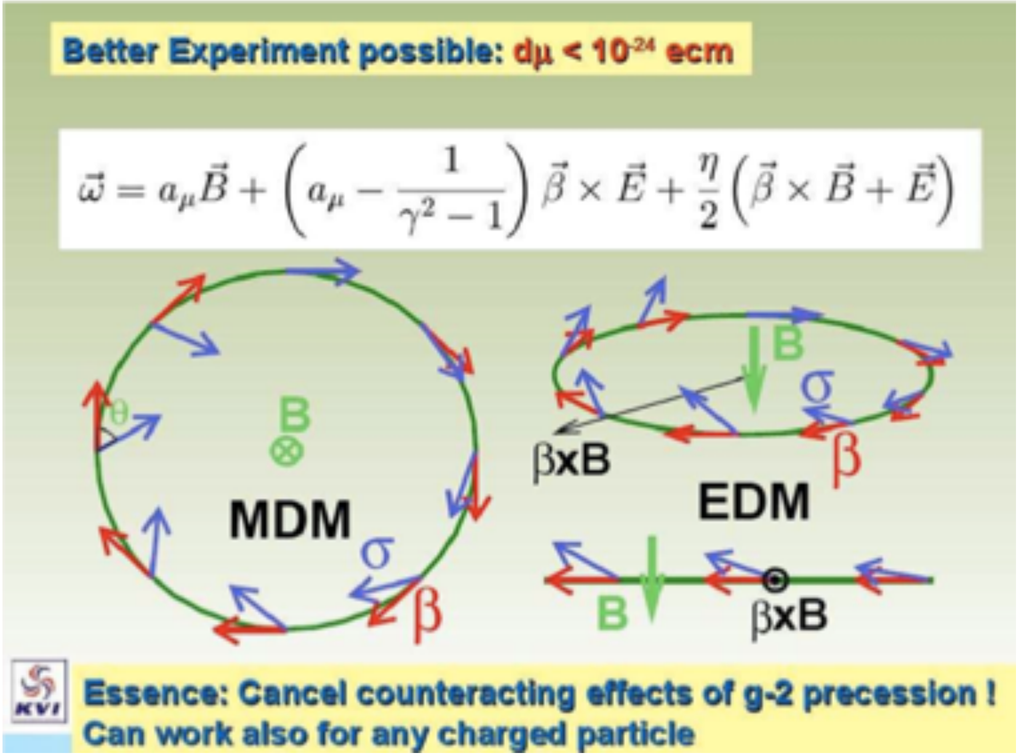
Rotating particles in a storage ring feel very strong central effective electric field

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!!



(prepared at BNL)

➡ EDM of light nuclei is accurately measurable!

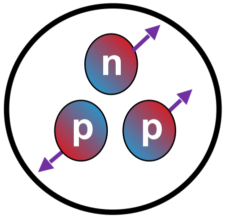
Nuclear EDM from nucleon level CP violation

Two leading contributions to be evaluated:

1) Nucleon's intrinsic EDM:

Contribution from the nucleon EDM

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

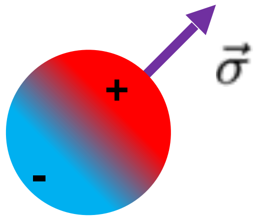


⇒ Spin expectation value (CP-even)

2) Polarization of the nucleus:

Contribution from the P, CP-odd nuclear force

$$D^{(\mathrm{pol})} = \langle 0 | \hat{D}_z | \tilde{0} \rangle + \mathrm{c.c.}, \qquad \hat{D}_z = \frac{e}{2} \sum_{i=1}^{A} (1 + \tau_i^z) z_i$$



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

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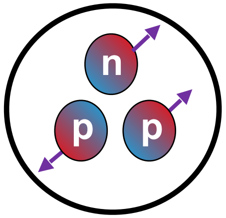

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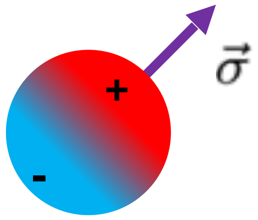


⇒ EDM generated by the CP-even ⇄ CP-odd mixing

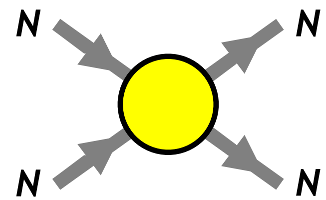
May be enhanced by many-body effect!

Nuclear EDM (polarization) from CP-odd nuclear force

Electric dipole operator requires CP mixing to have finite expectation value

Total hamiltonian:

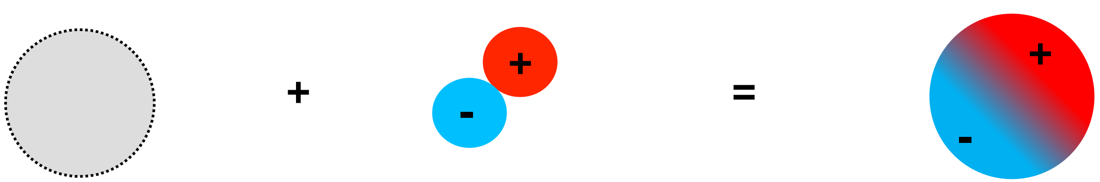
$$H = \begin{pmatrix} H_{\text{realistic}} & H_{\not P \not T} \\ H_{\not P \not T} & H_{\text{realistic}} \end{pmatrix}$$



P, CP-odd
nuclear force

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

CP-odd N-N interactions mixes opposite parity states

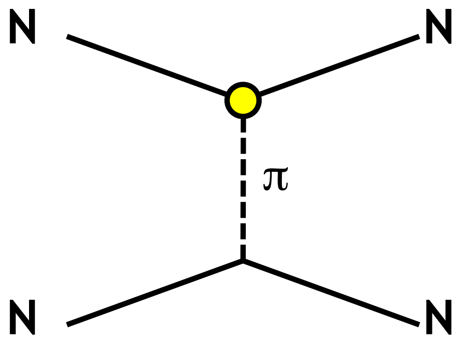


s-wave p-wave polarized system

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):

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

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, …

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:

Unknown parameter of CP violation beyond standard model

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

Depends on the nuclear structure!

⇒ We want to evaluate red factors and find interesting nuclei!

Previous works
(^{2}H, ^{3}He, ^{3}H, ^{6}Li, ^{9}Be EDM)

Our previous work

We have previously evaluated the EDM of light nuclei

⇒ EDM of ^{2}H, ^{3}He, ^{3}H, ^{6}Li, and ^{9}Be nuclei

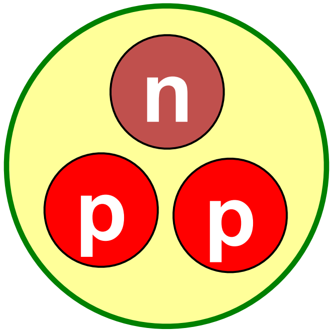
NY and E. Hiyama, Phys. Rev. C **91**, 054005 (2015).

Using Infinitesimally shifted Gaussian expansion method

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

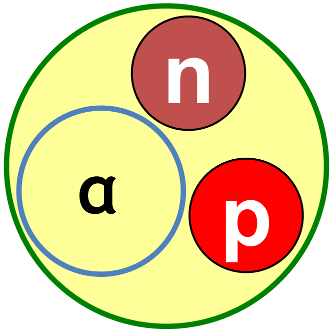
- ^{2}H, ^{3}He, ^{3}H in ab initio evaluation (Av18)

  ⇒ Good agreement with other works!



- ^{6}Li, ^{9}Be in cluster approximation +Orthogonality Condition Model (OCM)

  ⇒ Cluster structure may enhance EDM!



Infinitesimally shifted Gaussian expansion method

A sophisticated method to calculate few-body system

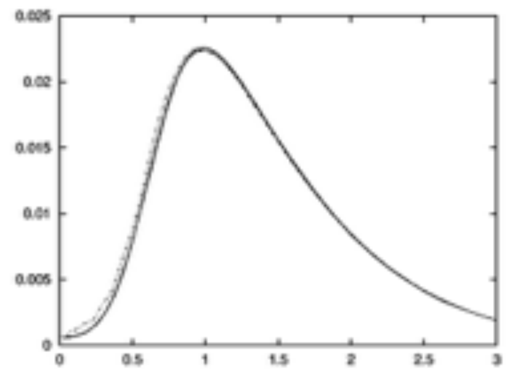
E. Hiyama *et al.*, Prog. Part. Nucl. Phys. **51**, 223 (2003).

- **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).



^{4}He Density distribution

- **It is applied in many subjects:**
  Nuclei, Hypernuclei, atoms, hadrons, astrophysics, …

We expect accurate calculation of nuclear EDM!

Ab initio evaluations (^2H, ^3He)

- **Deuteron EDM:**

Group	Nuclear force	c_0	c_1	c_2
Liu & Timmermans Liu et al., PRC **70**, 055501 (2004)	Av18	0	1.43×10^{-2}e fm	0
GEM (our work)	Av18	0	1.45×10^{-2}e fm	0

- **^{3}He EDM:**

Group	Nuclear force	isoscalar (c_0)	isovector (c_1)	isotensor (c_2)
Faddeev Bsaisou et al., JHEP **1503** (2015) 104	N^{2}LO chiral EFT	0.0079 *e* fm	0.0101 *e* fm	0.0169 *e* fm
GEM (our work) 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 and ^{9}Be EDM

- ^{6}Li EDM:

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)

- ^{9}Be EDM:

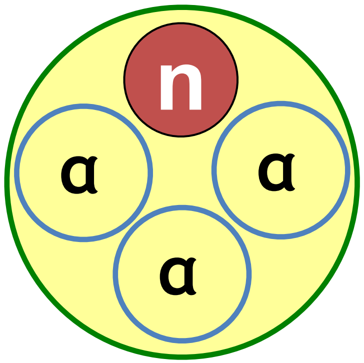
Nuclear force	<σ>	<στ>	isoscalar (c_0)	isovector (c_1)	isotensor (c_2)
Cluster model	0.38	-0.38	–	0.014 *e* fm	–

Similar contribution as ^{6}Li for the polarization due to CP-odd α-N interaction

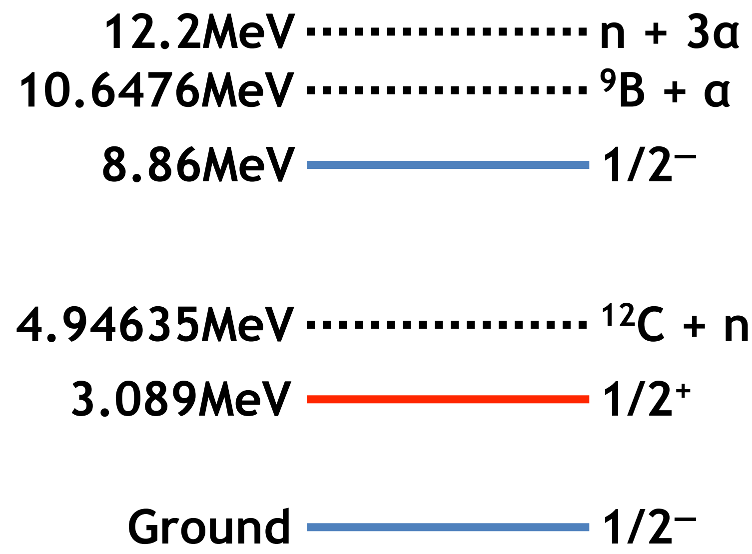
N. Yamanaka, E. Hiyama, Phys. Rev. C **91**, 054005 (2015).

^{13}C EDM

Structure of ^{13}C



^{13}C : 4-body in cluster approximation



Energy levels of ^{13}C

Study of ^{13}C EDM has many motivations:

- 1/2+ state is close to ground state (3.1 MeV, bound)
- Ground state has shell structure, but 1/2+ state is neutron halo
- Ground state is dominated by l=1 state (core+valence picture)

➡ Object of study : Let us study the EDM of ^{13}C!

Setup of the cluster model

We treat the ^{13}C nucleus as a 4-body system of nucleons and α clusters (^{4}He nucleus).

T. Yamada, Y. Funaki, to appear in Phys. Rev. C (2015) [arXiv:1503.04261].

- **α-α interaction:**

  Folding of Schmid-Wildermuth *NN* force (include Coulomb)

  Pauli exclusion taken into account via OCM

  E. W. Schmid and K. Wildermuth, Nucl. Phys. **26**, 462 (1961).

- **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).

- **3-,4-body interactions:**

  Phenomenological 3-α force with angular momentum dependence

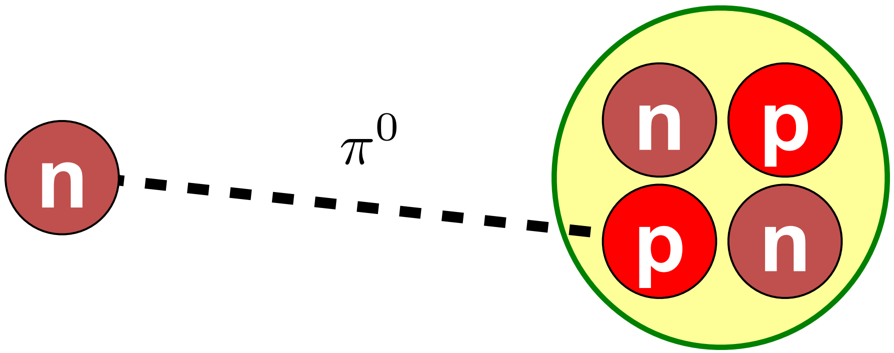
  Phenomenological α*αN* force to fit ^{9}Be ground-state energy

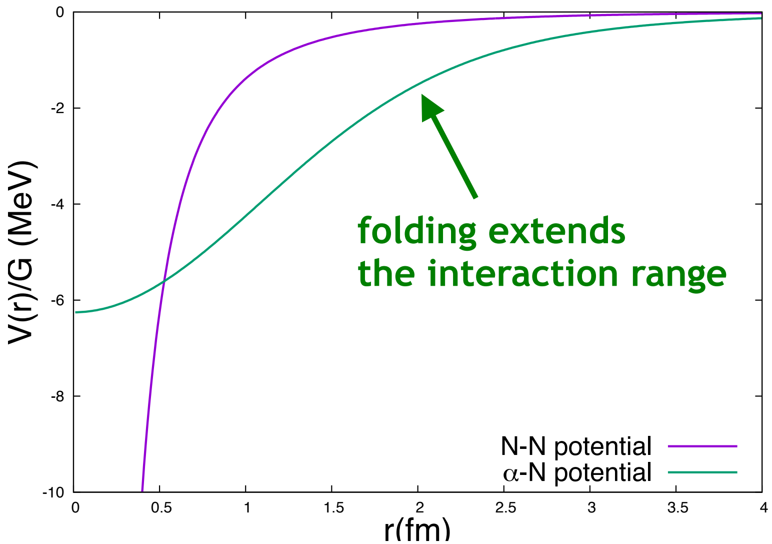
  Phenomenological 3α-*N* force to fit ^{13}C ground-state energy

CP-odd nuclear force (CP-odd α-N interaction)

Integrate the CP-odd N-N interaction with the ^{4}He nucleon density

(α cluster is indestructible)





Gaussian approximation of density:

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

Spread : b = (1.358 fm)^2

Only isovector CP-odd nuclear force is relevant in N-α interaction

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

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

Calculation of ^{13}C EDM

- We have used 120 channels, with 343 bases for each.

  Total number of bases : 41160

- Reproduce the binding energy of ^{13}C:

  1/2- (Ground) : 12.4 MeV

  1/2+ : 9.4 MeV Energy difference: E(GS)-E(1/2+) = 3 MeV

- Reproduce the root mean square radius of ^{13}C:

  1/2- (Ground) : $<\sqrt{r^2}> = 2.4$ fm

- Root mean square radius of core-valence distance:

  1/2- (Ground) : $<\sqrt{r_1^2}> = 2.81$ fm ⇒ Compact

  1/2+ : $<\sqrt{r_1^2}> = 3.95$ fm ⇒ Neutron-halo

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 Bsaisou et al., JHEP **1503** (2015) 104 NY and EH, PRC **91**, 054005 (2015)	0.0060 *e* fm	0.0108 *e* fm	0.0168 *e* fm
^{6}Li nucleus NY and EH, PRC **91**, 054005 (2015)	–	0.028 *e* fm	–
^{9}Be nucleus NY and EH, PRC **91**, 054005 (2015)	–	0.014 *e* fm	–
^{13}C nucleus	–	–0.00085 *e* fm Preliminary	–

Our result

Why small ^{13}C EDM?

- Small overlap between shell-like 1/2- state and neutron halo like 1/2+ state

  (EDM is larger for large overlap between opposite parity states)

- Orbital angular momentum and spin are antiparallel:
  ⇒ Suppresses the EDM

➡ This is a very good guide for searching nuclei with large EDM

A sensitive nucleus must have:

- Ground and opposite parity excited states with large overlap
- Same sign orbital angular momentum and spin in ground state
- Cluster structure : low opposite parity excitation energy

Summary:

- We have studied the EDM of the ^{13}C nucleus in the cluster approximation, using the Gaussian Expansion Method.
- Result : $d_{13C} = -8.5 \times 10^{-4} G_{\pi}^{(1)}$ e fm
  Relatively small EDM: may be understood by the small overlap between shell-like 1/2- state and neutron halo like 1/2+ state.

Future subjects:

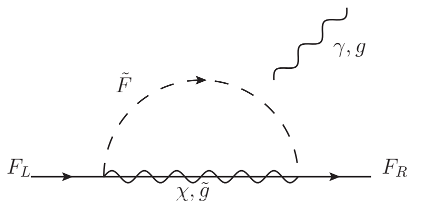
- Study of ^{13}N EDM.
- Further study of EDM of light nuclei: find sensitive nuclei respecting the analysis of this work.
- We are waiting for experiments!

Sensitivity to new physics beyond standard model

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

- **Supersymmetric model:**

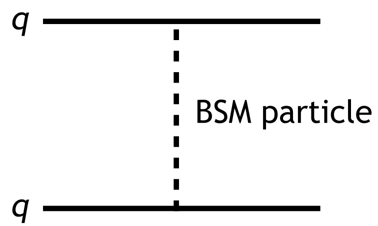
  ⇒ Can probe 10 TeV scale SUSY breaking



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

  ⇒ Can probe PeV scale physics

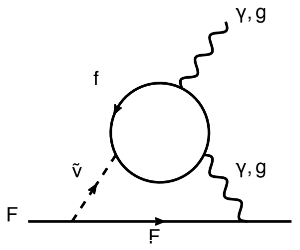
  (Left-right symmetric model, …)



- **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!**

End

Orthogonality condition model (OCM)

Simple way to include the effect of antisymmetrization (Pauli exclusion) in cluster model

N-α interaction:

Repulsion of the 0s state:

$$V_{\text{Pauli}} = \lim_{\lambda\to\infty} \sum_{\text{f}=0s} |\phi_{\text{f}}(\mathbf{r}_{\alpha\alpha})\rangle\langle\phi_{\text{f}}(\mathbf{r}'_{\alpha\alpha})|\, \boldsymbol{\lambda}$$

α-α interaction:

Repulsion of the 0s, 1s, 0d states.

$$V_{\text{Pauli}} = \lim_{\lambda\to\infty} \sum_{\text{f}=0s,1s,0d} \boldsymbol{\lambda}\, |\phi_{\text{f}}(\mathbf{r}_{\alpha\alpha})\rangle\langle\phi_{\text{f}}(\mathbf{r}'_{\alpha\alpha})|$$

In our calculation, we have taken λ ~ 10^4 MeV

S. Saito, Prog. Theor. Phys. **41**, 705 (1969).