

# **Electric dipole moments of light nuclei**

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In collaboration with

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

ratio photon : matter

Prediction of Standard model:  $10^{20} : 1$

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 !**

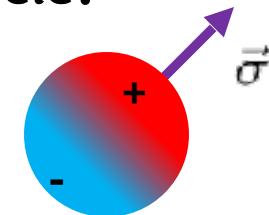
# Electric dipole moment (EDM)

## Electric dipole moment:

Permanent polarization of internal charge of a particle.

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

⇒ This is what will be evaluated!



- Direction:  $\vec{d} \propto \vec{\sigma}$   
(Spin is the only vector quantity in spin  $1/2$  particle )

- Interaction:  $H_{\text{EDM}} = -d \langle \vec{\sigma} \rangle \cdot \vec{E}$

- Transformation properties:

- Under parity tr.:

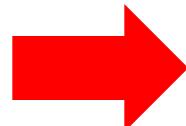
$$\begin{cases} \vec{E} & \xrightarrow{P} -\vec{E} \\ \vec{\sigma} & \xrightarrow{P} \vec{\sigma} \end{cases} \quad \rightarrow H_{\text{EDM}} \text{ is P-odd}$$

- Under time reversal:

$$\begin{cases} \vec{E} & \xrightarrow{T} \vec{E} \\ \vec{\sigma} & \xrightarrow{T} -\vec{\sigma} \end{cases} \quad \rightarrow H_{\text{EDM}} \text{ is CP-odd !}$$

# 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 :  $O(10^{-31})e\text{ cm}$   
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);  
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  
 $\Rightarrow O(10^{-29})e\text{ cm} !$

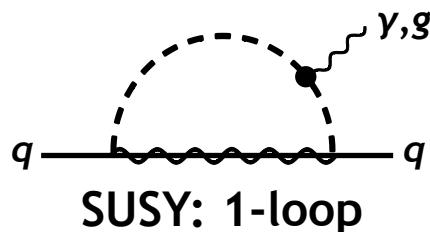


Nuclear EDM is a very good probe of BSM

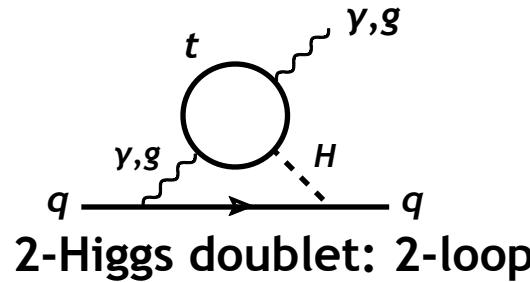
# *CP violating contribution from new physics*

CP violating processes scale as  $1/M_{NP}^2$

## ● Quark EDM, chromo-EDM:



SUSY: 1-loop

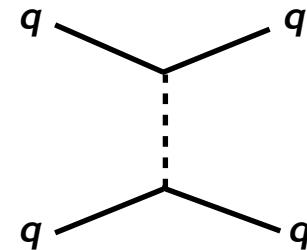
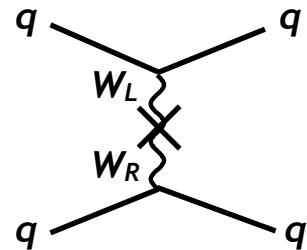


2-Higgs doublet: 2-loop

## ● CP-odd 4-quark interaction:

Tree level:

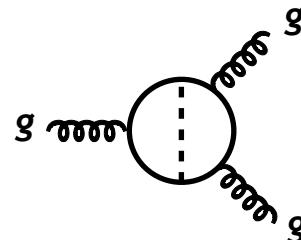
- \* Left-right sym.
- \* Scalar exchange



## ● Weinberg operator:

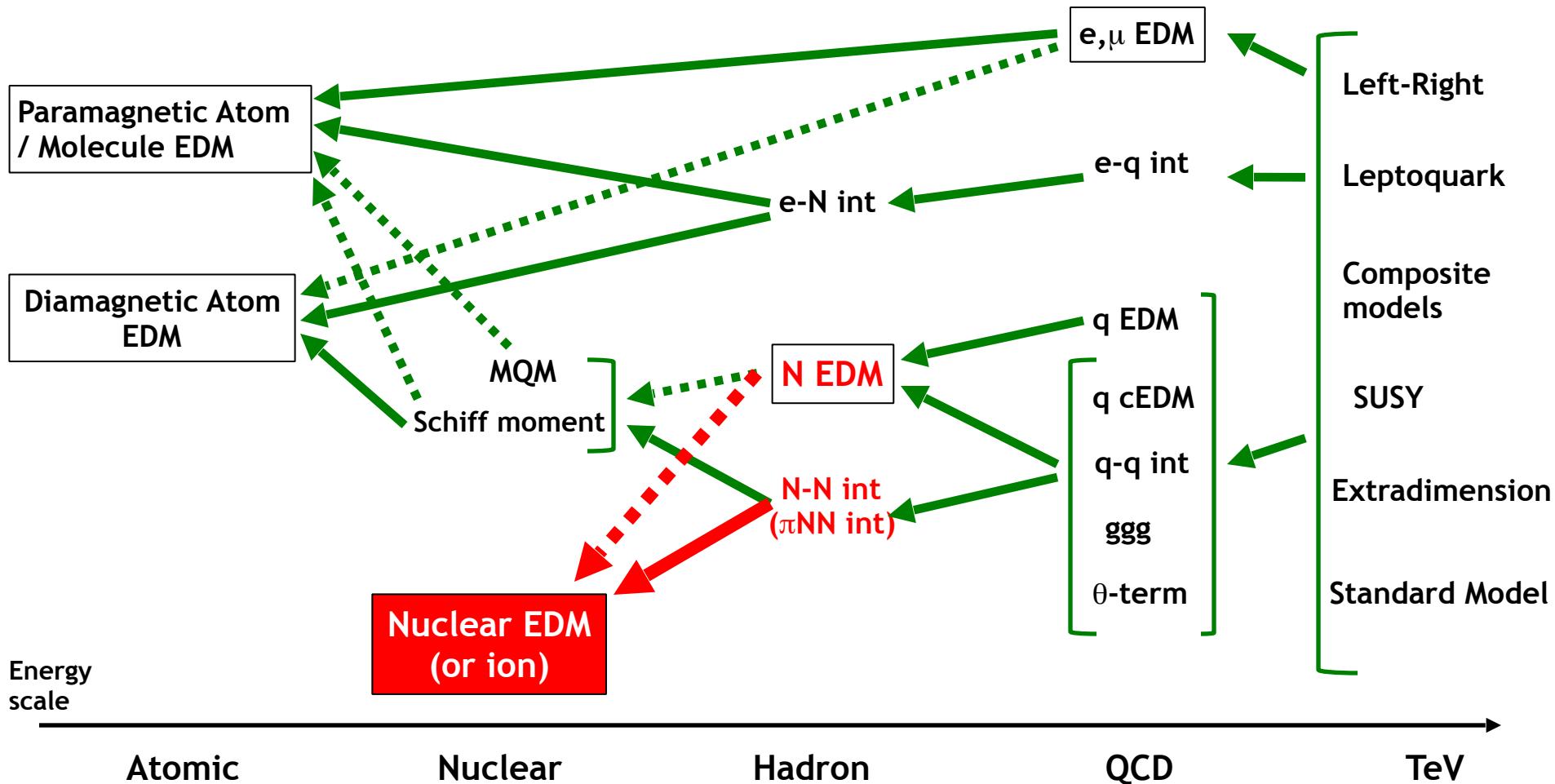
2-loop diagram:

- \* 2-Higgs doublet model
- \* Vectorlike quark model



Probe BSM sectors  
without mixing  
with light quarks

# Nuclear EDM from nucleon level CP violation

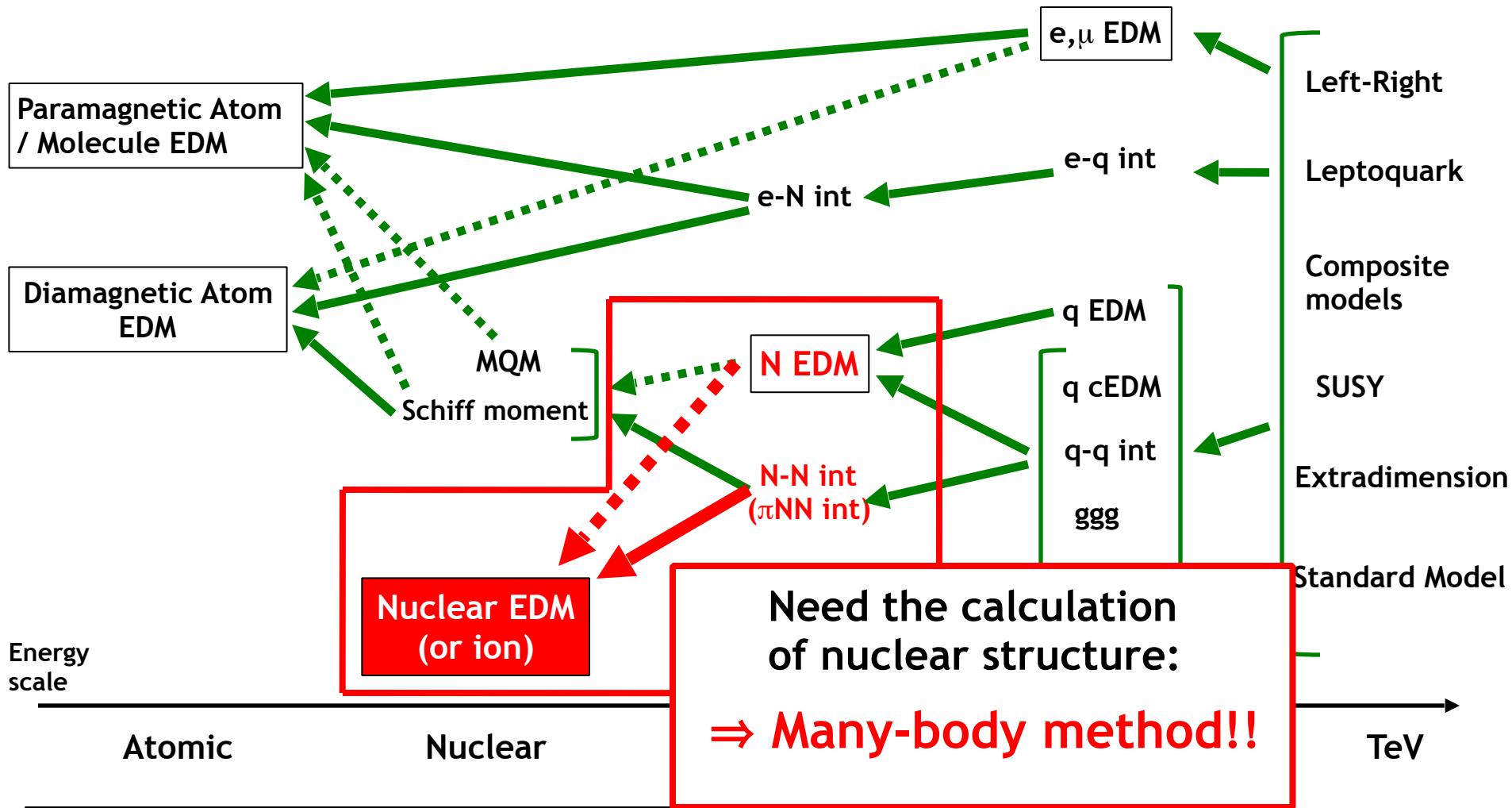


**observable** : Observable available at experiment

← : Sizable dependence

↔ : Weak dependence

# Nuclear EDM from nucleon level CP violation



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# Nuclear EDM from nucleon level CP violation

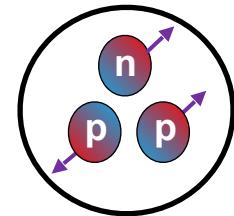
Two leading contributions to be evaluated:

## 1) Nucleon's intrinsic EDM:

Contribution from the **nucleon EDM**

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

⇒ Spin expectation value (CP-even)

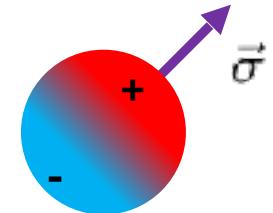


## 2) Polarization of the nucleus:

Contribution from the P, CP-odd nuclear force

$$D^{(\text{pol})} = \frac{e}{2} \sum_{i=1}^A \langle \psi | (1 + \tau_i^z) z_i | \tilde{\psi} \rangle + (\text{c.c.})$$

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



# Nuclear EDM from nucleon level CP violation

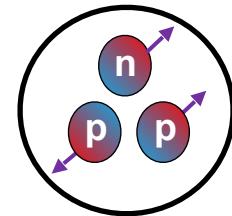
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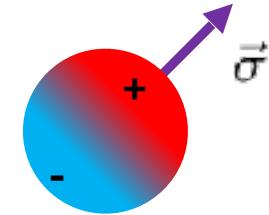


## 2) Polarization of the nucleus:

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$$D^{(\text{pol})} = \frac{e}{2} \sum_{i=1}^A \langle \psi | (1 + \tau_i^z) z_i | \tilde{\psi} \rangle + (\text{c.c.})$$

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



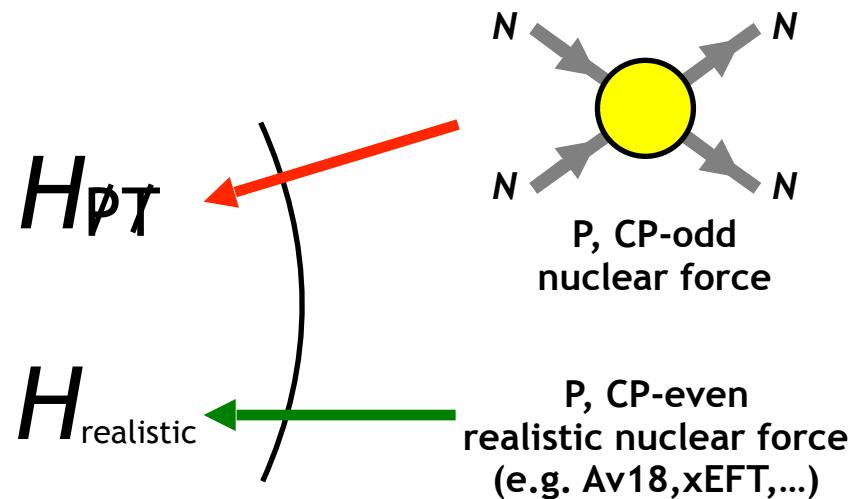
May be enhanced by many-body effect!

# Nuclear EDM (polarization) from CP-odd nuclear force

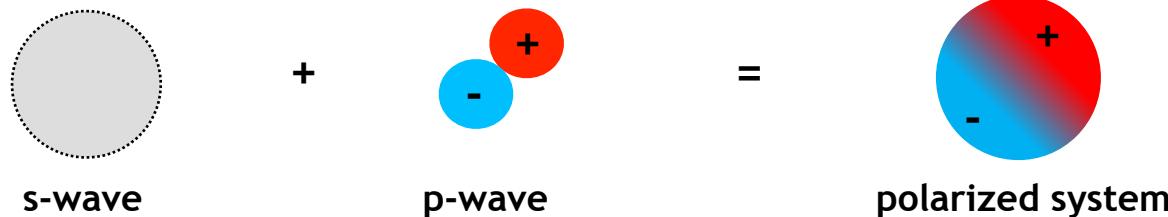
Electric dipole operator requires CP mixing to have finite expectation value

Total hamiltonian:

$$H = \begin{pmatrix} H_{\text{realistic}} & H_{\text{P}\bar{T}} \\ H_{\text{P}\bar{T}} & H_{\text{realistic}} \end{pmatrix}$$



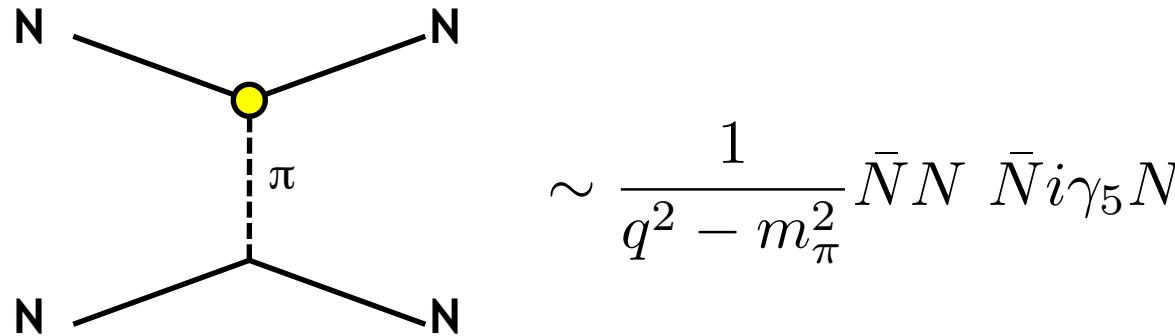
CP-odd N-N interactions mixes opposite parity states



Parity mixing  $\Rightarrow$  Polarized ground state!

# P, CP-odd nuclear force from one pion exchange

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



## ● P, CP-odd Hamiltonian (3-types):

$$H_{P\chi} = -\frac{g_{\pi NN}}{8\pi^2 n_p} \left[ \underbrace{\mathcal{G}_{\pi NN}^{(0)} \tau_a \cdot \tau_b}_{\text{Isoscalar}} + \underbrace{\mathcal{G}_{\pi NN}^{(2)} (\tau_a \cdot \tau_b - 3\tau_a^z \tau_b^z)}_{\text{Isotensor}} \right] (\vec{\sigma}_a - \vec{\sigma}_b) + \underbrace{\mathcal{G}_{\pi NN}^{(1)} (\tau_a^z \vec{\sigma}_a - \tau_b^z \vec{\sigma}_b)}_{\text{Isovector}} \cdot \vec{\nabla}_a \frac{e^{-m_\pi r_{ab}}}{r_{ab}},$$

## ● 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:

$$d_A^{(\text{pol})} = (a_{\pi}^{(0)} \bar{G}_{\pi}^{(0)} + a_{\pi}^{(1)} \bar{G}_{\pi}^{(1)} + a_{\pi}^{(2)} \bar{G}_{\pi}^{(2)}) e \text{ fm}$$

Unknown CP violating nuclear couplings beyond the standard model

↓      ↓      ↓

$a_{\pi}^{(0)}$      $\bar{G}_{\pi}^{(0)}$      $a_{\pi}^{(1)}$      $\bar{G}_{\pi}^{(1)}$      $a_{\pi}^{(2)}$      $\bar{G}_{\pi}^{(2)}$

↑      ↑      ↑

Depends on the nuclear structure!

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

# How to calculate: Gaussian expansion method

## A sophisticated method to calculate few-body system

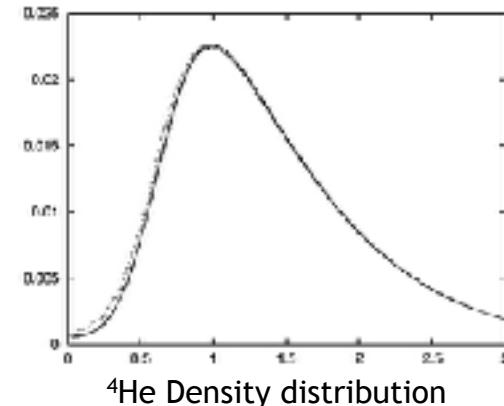
E. Hiyama *et al.*, Prog. Part. Nucl. Phys. **51**, 223 (2003).

- Basis function:  $\phi_{lm}(\mathbf{r}) = \sum_n N_{nl} \sum_k C_{lm,k} e^{-\nu_n(\mathbf{r}-\mathbf{D}_{lm,k})^2}$

- Solve Schroedinger eq. with variational method

- Successful in the benchmark calculation of  ${}^4\text{He}$  binding energy

H. Kamada et al., Phys. Rev. C **64**, 044001 (2001).



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

We expect accurate calculation of nuclear EDM!

# Ab initio tests ( $^2\text{H}$ , $^3\text{He}$ )

## Ab initio:

Solve the full many-body Schroedinger equation with realistic nuclear force.

### Deuteron EDM:

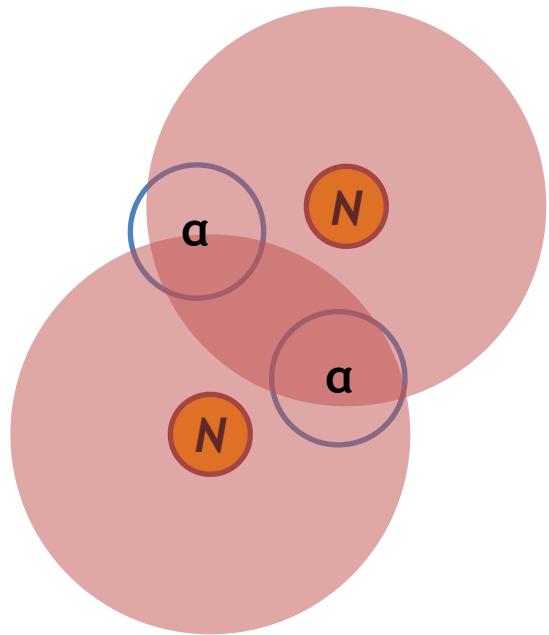
Group	Nuclear force	$a_0$	$a_1$	$a_2$
Liu & Timmermans Liu et al., PRC 70, 055501 (2004)	Av18	0	$1.43 \times 10^{-2} e \text{ fm}$	0
GEM (our work) NY, E. Hiyama, PRC 91, 054005 (2015)	Av18	0	$1.45 \times 10^{-2} e \text{ fm}$	0

### $^3\text{He}$ EDM:

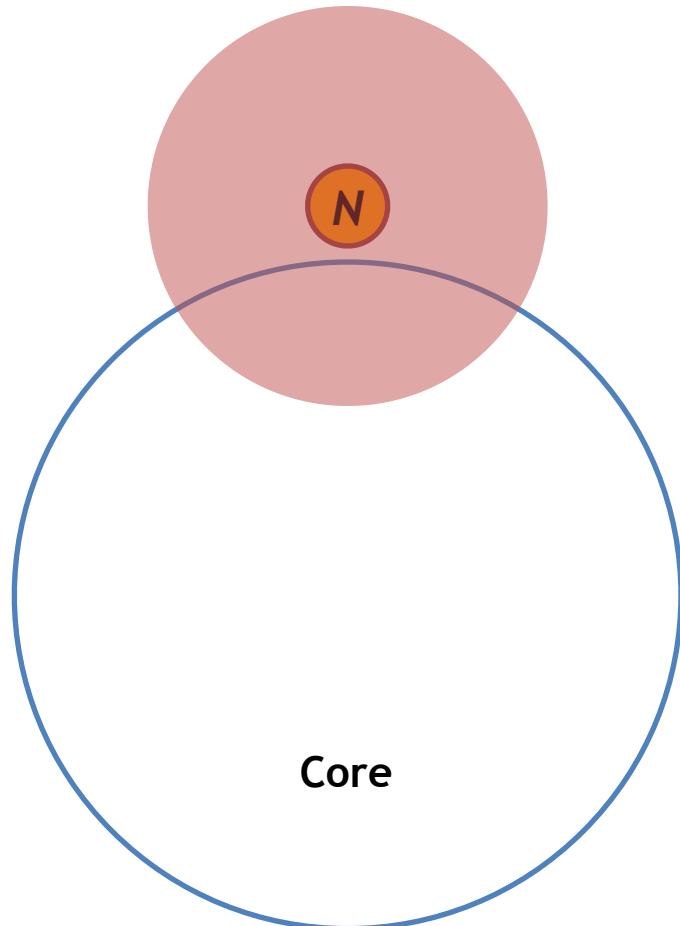
Group	Nuclear force	$a_0$	$a_1$	$a_2$
Faddeev Bsaisou et al., JHEP 1503 (2015) 104	$\text{N}^2\text{LO}$ chiral EFT	0.0079 $e \text{ fm}$	0.0101 $e \text{ fm}$	0.0169 $e \text{ fm}$
GEM (our work) NY, E. Hiyama, PRC 91, 054005 (2015)	Av18	0.0060 $e \text{ fm}$	0.0108 $e \text{ fm}$	0.0168 $e \text{ fm}$

**Ab initio results are consistent!**

# Physics of nuclear EDM: light and heavy nuclei

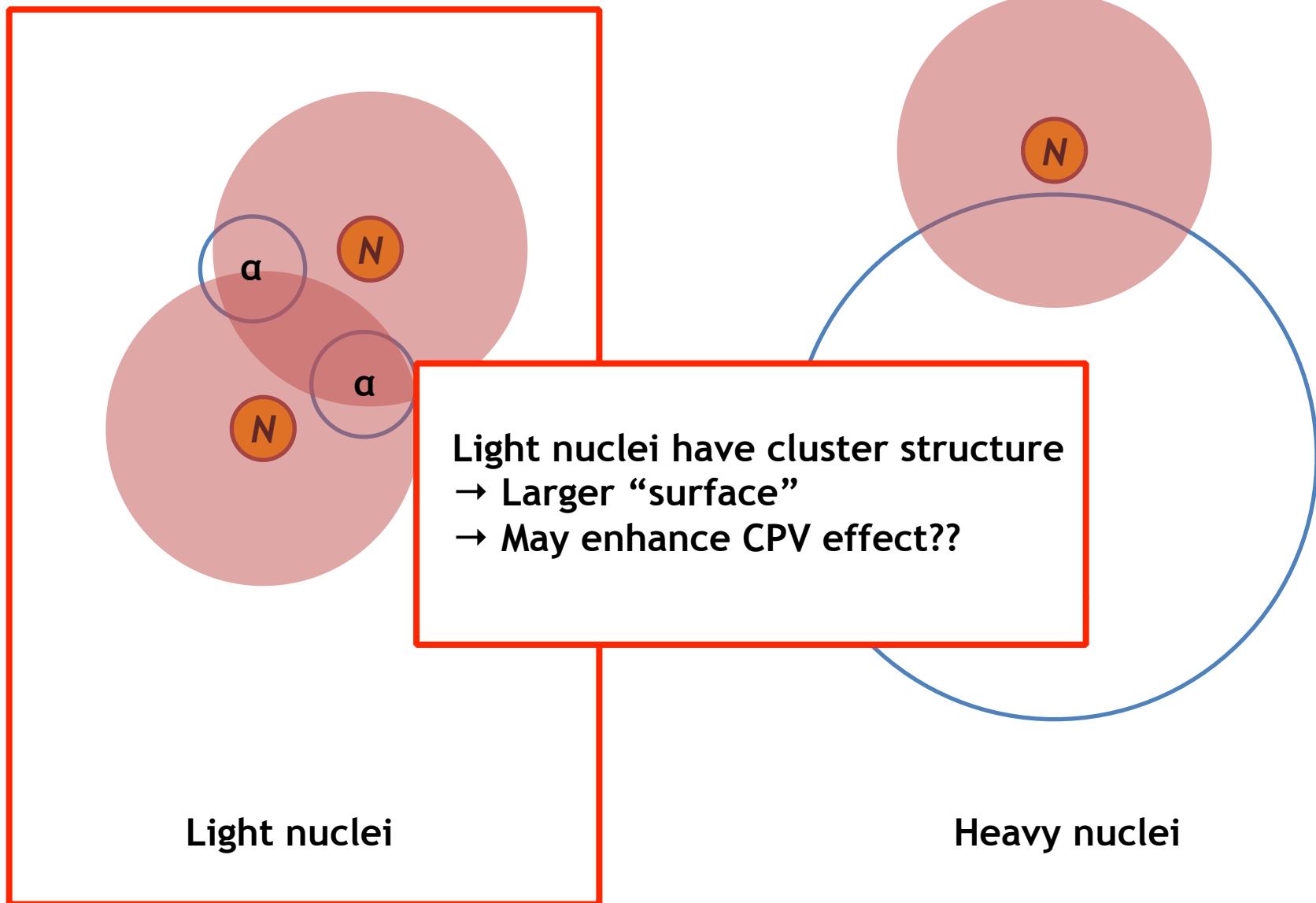


Light nuclei



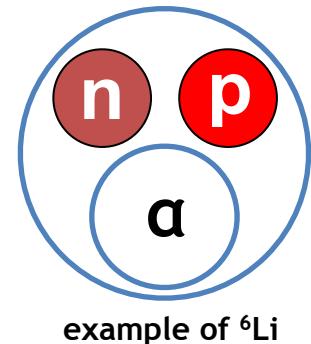
Heavy nuclei

# Physics of nuclear EDM: light and heavy nuclei



# Setup of the cluster model

We treat light nuclei in the cluster model



## ● N-N interaction:

Av8'

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

## ● N- $\alpha$ interaction:

Fitted to reproduce the  $\alpha$ -N scattering phase shift at low energy

Pauli exclusion taken into account via OCM

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

## ● $\alpha$ - $\alpha$ interaction:

Fitted to reproduce the  $\alpha$ - $\alpha$  scattering phase shift at low energy

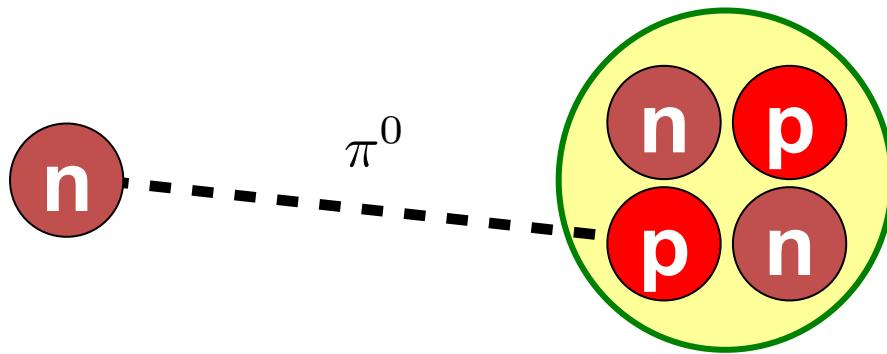
Pauli exclusion taken into account via OCM

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

# CP-odd nuclear force with cluster (CP-odd $\alpha$ -N interaction)

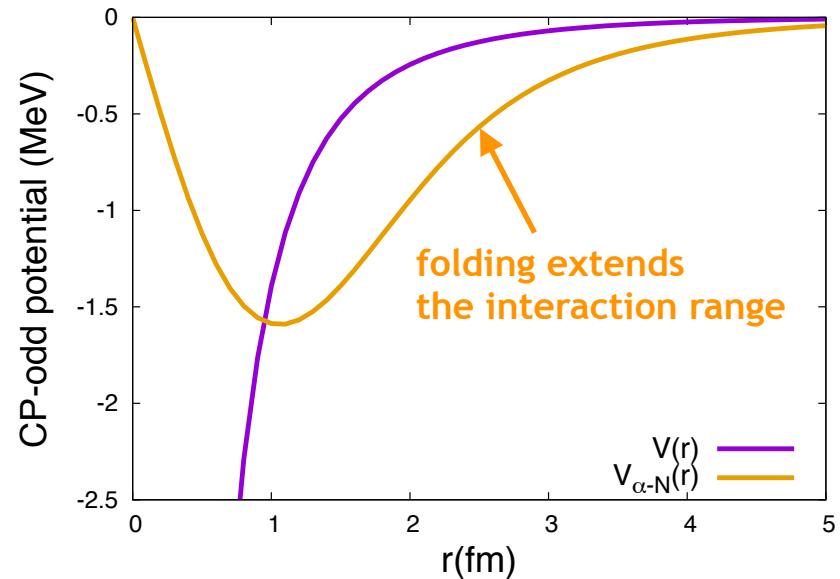
Integrate the CP-odd N-N interaction with the  ${}^4\text{He}$  nucleon density

(a cluster is indestructible)



Gaussian approximation of density:

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



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

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

# Results

EDM	isoscalar ( $a_0$ )	isovector ( $a_1$ )	isotensor ( $a_2$ )
<b><math>^{129}\text{Xe}</math> atom</b> E. Teruya et al., to appear in PRC Y. Singh et al., PRA <b>89</b> , 030502 (2014)	<b><math>1.1 \times 10^{-7} \text{ e fm}</math></b>	<b><math>4.0 \times 10^{-8} \text{ e fm}</math></b>	<b><math>1.4 \times 10^{-7} \text{ e fm}</math></b>
<b><math>^{199}\text{Hg}</math> atom</b> Ban et al., PRC <b>82</b> , , 015501 (2010) Y. Singh et al., PRA <b>91</b> , 030501 (2015)	<b><math>3.2 \times 10^{-6} \text{ e fm}</math></b>	<b><math>-1.3 \times 10^{-6} \text{ e fm}</math></b>	<b><math>5.2 \times 10^{-6} \text{ e fm}</math></b>
<b><math>^{225}\text{Ra}</math> atom</b> Dobaczewski et al., PRL <b>94</b> , 232502 (2005) Y. Singh et al., PRA <b>92</b> , 022502 (2015)	<b><math>0.00093 \text{ e fm}</math></b>	<b><math>-0.0037 \text{ e fm}</math></b>	<b><math>0.0025 \text{ e fm}</math></b>
<b>Neutron</b> Crewther et al. , PLB 88,123 (1979) Mereghetti et al., PLB 696, 97 (2011)	<b><math>0.01 \text{ e fm}</math></b>	—	— <b><math>0.01 \text{ e fm}</math></b>
<b>Deuteron</b> Liu et al., PRC <b>70</b> , 055501 (2004) NY and EH, PRC <b>91</b> , 054005 (2015)	—	<b><math>0.0145 \text{ e fm}</math></b>	—
<b><math>^3\text{He}</math> nucleus</b> Bsaisou et al., JHEP <b>1503</b> (2015) 104 NY and EH, PRC <b>91</b> , 054005 (2015)	<b><math>0.0060 \text{ e fm}</math></b>	<b><math>0.0108 \text{ e fm}</math></b>	<b><math>0.0168 \text{ e fm}</math></b>
<b><math>^6\text{Li}</math> nucleus</b> NY and EH, PRC <b>91</b> , 054005 (2015)	—	<b><math>0.022 \text{ e fm}</math></b>	—
<b><math>^9\text{Be}</math> nucleus</b> NY and EH, PRC <b>91</b> , 054005 (2015)	—	<b><math>0.014 \text{ e fm}</math></b>	—
<b><math>^7\text{Li}</math> nucleus</b> NY, in preparation	<b><math>-0.0060 \text{ e fm}</math></b>	<b><math>0.016 \text{ e fm}</math></b>	<b><math>-0.017 \text{ e fm}</math></b>
<b><math>^{13}\text{C}</math> nucleus</b> NY et al., arXiv:1603.03136 [nucl-th]	—	<b><math>-0.0020 \text{ e fm}</math></b>	—
<b><math>^{129}\text{Xe}</math> nucleus</b> N. Yoshinaga et al., PRC <b>89</b> , 045501 (2014)	<b><math>7.0 \times 10^{-5} \text{ e fm}</math></b>	<b><math>7.4 \times 10^{-5} \text{ e fm}</math></b>	<b><math>3.7 \times 10^{-4} \text{ e fm}</math></b>

Preliminary

# Results

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<b><math>^6\text{Li}</math> nucleus</b> NY and EH, PRC <b>91</b> , 054005 (2015)	—	<b><math>0.022 \text{ e fm}</math></b>	—
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<b><math>^{13}\text{C}</math> nucleus</b> NY et al., arXiv:1603.03136 [nucl-th]	—	<b><math>-0.0020 \text{ e fm}</math></b>	—
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Preliminary

Enhanced!

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<b>Neutron</b> Crewther et al. , PLB <b>88</b> , 123 (1979) Mereghetti et al., PLB <b>696</b> , 97 (2011)	<b><math>0.01 \text{ e fm}</math></b>	—	— <b><math>0.01 \text{ e fm}</math></b>
<b>Deuteron</b> Liu et al., PRC <b>70</b> , 055501 (2004) NY and EH, PRC <b>91</b> , 054005 (2015)	—	<b><math>0.0145 \text{ e fm}</math></b>	—
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<b><math>^6\text{Li}</math> nucleus</b> NY and EH, PRC <b>91</b> , 054005 (2015)	—	<b><math>0.022 \text{ e fm}</math></b>	—
<b><math>^9\text{Be}</math> nucleus</b> NY and EH, PRC <b>91</b> , 054005 (2015)	—	<b><math>0.014 \text{ e fm}</math></b>	—
<b><math>^7\text{Li}</math> nucleus</b> NY, in preparation	<b><math>-0.0060 \text{ e fm}</math></b>	<b><math>0.016 \text{ e fm}</math></b>	<b><math>-0.017 \text{ e fm}</math></b>
<b><math>^{13}\text{C}</math> nucleus</b> NY et al., arXiv:1603.03136 [nucl-th]	—	<b><math>-0.0020 \text{ e fm}</math></b>	<b>Suppressed!</b>
<b><math>^{129}\text{Xe}</math> nucleus</b> N. Yoshinaga et al., PRC <b>89</b> , 045501 (2014)	<b><math>7.0 \times 10^{-5} \text{ e fm}</math></b>	<b><math>7.4 \times 10^{-5} \text{ e fm}</math></b>	<b><math>3.7 \times 10^{-4} \text{ e fm}</math></b>

Preliminary

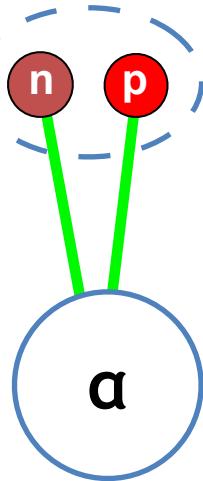
Enhanced!

Suppressed!

# Isovector CP-odd nuclear force: a counting rule?

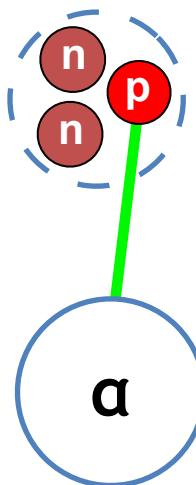
$^6\text{Li}$  EDM

deuteron  
cluster

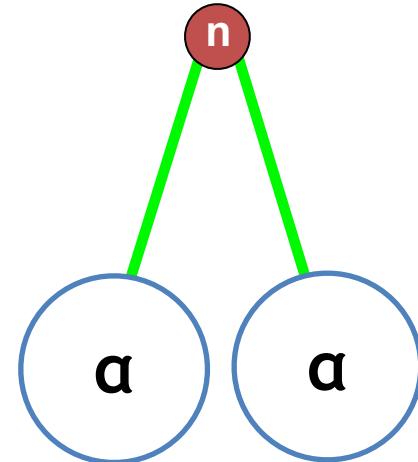


$^7\text{Li}$  EDM

$^3\text{H}$  cluster



$^9\text{Be}$  EDM

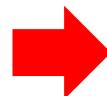


$$d_{^6\text{Li}} = 0.022 \text{ } G_{\pi}^{(1)} e \text{ fm}$$

$$d_{^7\text{Li}} = 0.016 \text{ } G_{\pi}^{(1)} e \text{ fm}$$

$$d_{^9\text{Be}} = 0.014 \text{ } G_{\pi}^{(1)} e \text{ fm}$$

$$\left\{ \begin{array}{ll} ^6\text{Li} : & a_1 = 0.022 \text{ } G_{\pi}^{(1)} e \text{ fm} \\ ^7\text{Li} : & a_1 = 0.016 \text{ } G_{\pi}^{(1)} e \text{ fm} \\ ^9\text{Be} : & a_1 = 0.014 \text{ } G_{\pi}^{(1)} e \text{ fm} \end{array} \right. \quad \begin{array}{l} {}^2\text{H EDM} + 2 \times (\text{alpha}-\text{N polarization}) \\ {}^3\text{H EDM} + 1 \times (\text{alpha}-\text{N polarization}) \\ 2 \times (\text{alpha}-\text{N polarization}) \end{array}$$

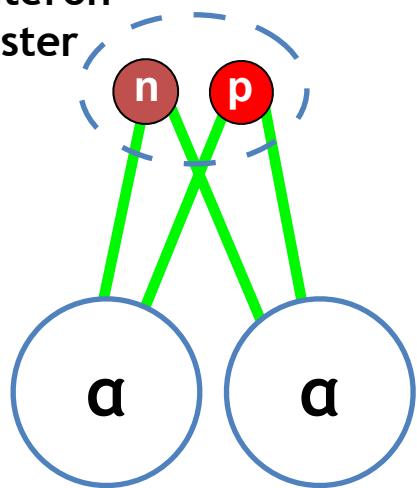


$$\text{alpha-N polarization} : \quad a_1 = (0.005 \sim 0.007) \text{ } G_{\pi}^{(1)} e \text{ fm}$$

# Predictions

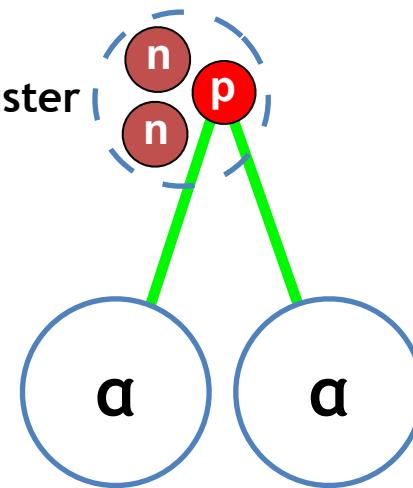
$^{10}\text{B} :$

deuteron  
cluster



$^{11}\text{B} :$

$^3\text{H}$  cluster



$^2\text{H}$  EDM + 4 x ( $\alpha$ -N polarization)

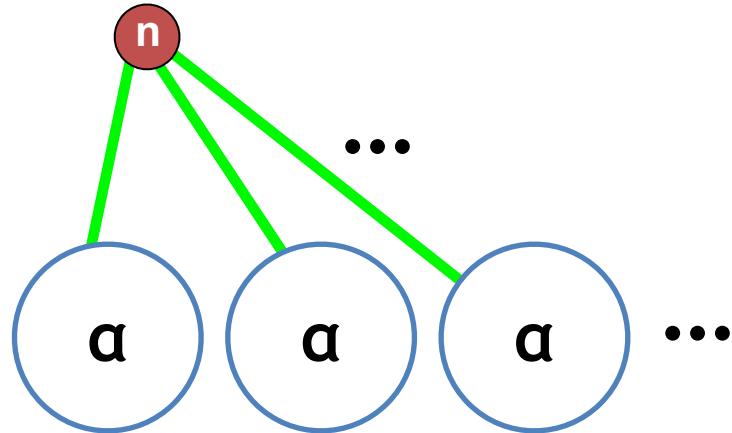
$$d_{^{10}\text{B}} \sim 0.03 G_{\pi}^{(1)} e \text{ fm}$$

$^3\text{H}$  EDM + 2 x ( $\alpha$ -N polarization)

$$d_{^{11}\text{B}} \sim 0.02 G_{\pi}^{(1)} e \text{ fm}$$

# Nuclear EDM of heavier nuclei?

EDM of larger nuclei is larger?



$$d_A = (A/4) \times (\alpha\text{-N polarization}) ??$$

$\doteq$  (Simple shell model picture)

→ No!

Large nuclei have configuration mixing

$$|\Psi\rangle = |\dots\dots\dots\rangle + |\dots\dots\dots\rangle + |\dots\dots\dots\rangle + \dots$$

→ EDM of large nuclei is quenched due to destructive interference of the spin of valence nucleon(s).

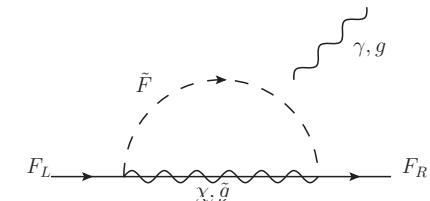
e.g.  $^{129}\text{Xe}$  EDM :  $d_{^{129}\text{Xe}} \sim 0.000074 \text{ G}_\pi^{(1)} \text{ e fm}$

# Sensitivity to new physics beyond standard model

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

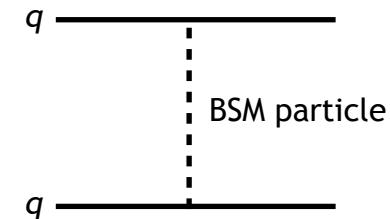
## ● Supersymmetric model:

⇒ Can probe 10 TeV scale SUSY breaking



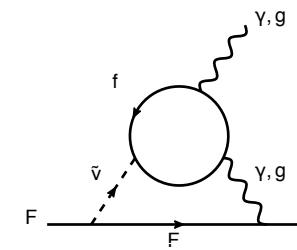
## ● Models with 4-quark interactions:

⇒ Can probe PeV scale physics  
(Left-right symmetric model, ...)



## ● Models with Barr-Zee type diagrams:

⇒ Can probe TeV scale physics  
(Higgs doublet models, RPV SUSY, ...)



**→ EDM is an attractive observable  
in the search for BSM physics!**

## Summary

### Summary:

- We have studied the EDM of several light nuclei in the cluster model: can unveil beyond TeV scale BSM with future experiments?
- Enhancement due to many-body effect is suggested for EDM of light nuclei.
- Heavy nuclei are not more sensitive than light nuclei due to the configuration mixing (exception may be the octuple deformed or easily deformable nuclei).

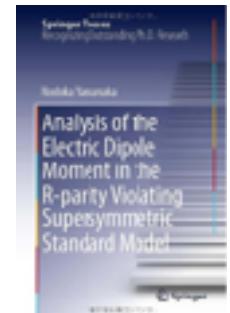
### Future subjects:

- Evaluation of the effective CP-odd interactions required.
- Further study of EDM of light nuclei:  
-> EDM of  $^{10}\text{B}$ ,  $^{11}\text{B}$ ,  $^{19}\text{F}$ ?
- We are waiting for experiments!

# Advertisement

Please also see:

- N. Yamanaka, B. K. Sahoo, N. Yoshinaga, T. Sato, K. Asahi and B. P. Das,  
Probing exotic phenomena at the interface of nuclear and particle physics  
with the electric dipole moments of diamagnetic atoms ,  
European Physical Journal A 53, 54 (2017)  
arXiv:1609.04759 [nucl-th].
  
- N. Yamanaka,  
Review of the electric dipole moment of light nuclei,  
International Journal of Modern Physics E 26, 1730002 (2017)  
arXiv:1609.04759 [nucl-th].
  
- N. Yamanaka,  
Analysis of the Electric Dipole Moment  
in the R-parity Violating Supersymmetric Standard Model,  
Springer, 2014.



→ EDM Physics is reviewed !!

**End**

## Backup slides

# EDM of charged particles using storage rings

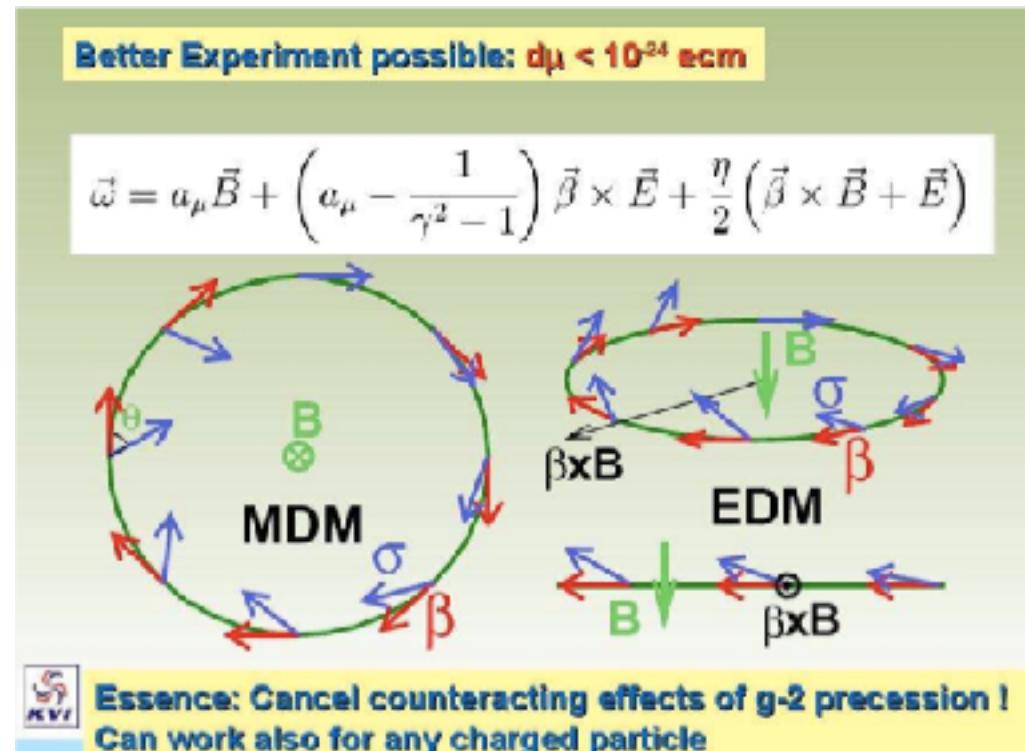
Rotating particles in a storage ring feel very strong **central effective electric field**

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,  ${}^3\text{He}$  are planned.

Prospective sensitivity:

→  $O(10^{-29}) \text{ e cm}!!$



→ **EDM of light nuclei is accurately measurable!**

# Flow of EDM calculation of Gaussian expansion method

## 1) Prepare interaction hamiltonian

Realistic nuclear force + CP-odd nuclear force (nonrela.)

Repeat to find  
the lowest  
binding energy  
(variational method)

## 2) Set Gaussian basis

Choose Gaussian basis with geometric series of range parameters

## 3) Calculate matrix elements in the gaussian basis

Integral is simple due to the gaussian basis

## 4) Diagonalization

Becomes exponentially difficult with growing nucleon number ( $A$ )

## 5) Calculation of observables (EDM)

$$D^{(\text{pol})} = \frac{e}{2} \sum_{i=1}^A \langle \psi | (1 + \tau_i^z) z_i | \tilde{\psi} \rangle + (\text{c.c.})$$



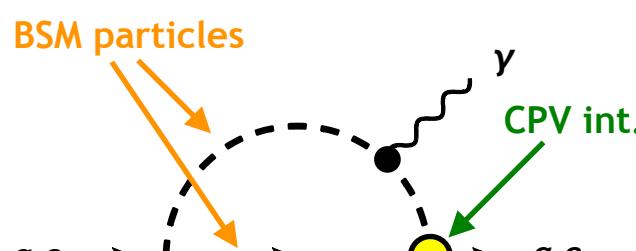
# EDM from physics beyond Standard model

EDM operator in relativistic field theory: dimension five-5 operator

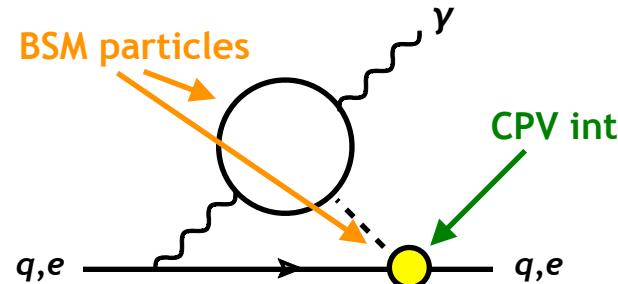
$$-\frac{i}{2} d_\psi \bar{\psi} \sigma_{\mu\nu} F^{\mu\nu} \gamma_5 \psi \quad \xrightarrow{\text{Nonrela. lim.}} \quad -d_\psi \sigma \cdot \mathbf{E}$$

EDM is generated by **CP violating interactions**.

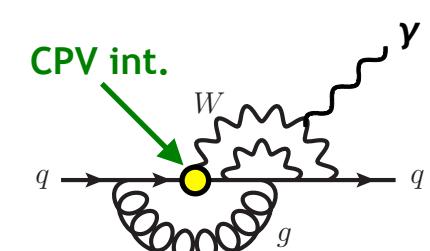
Can be calculated using Feynman diagrams:



1-loop diagram  
(e.g. SUSY)



2-loop diagram  
(e.g. 2-Higgs models)



3-loop diagram  
(e.g. Standard model)

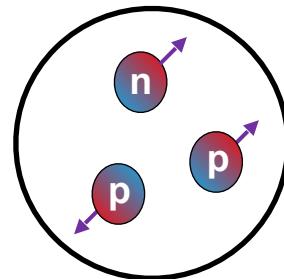
EDM receives very small contribution from SM,  
whereas BSM new physics may contribute with low loop level :

→ **EDM is a very good probe of BSM new physics!**

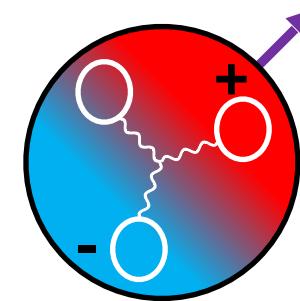
## EDM of composite systems

The EDM are usually measured in composite systems (neutron, atoms, ...)

The EDM of composite systems is  
not only generated by the EDM of the components,  
but also **by CP violating many-body interactions.**

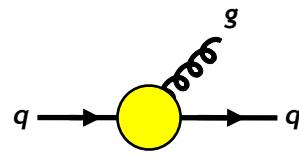


EDM of constituents

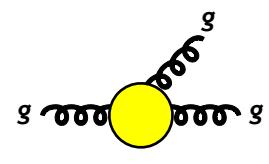


CP-odd many-body  
interaction

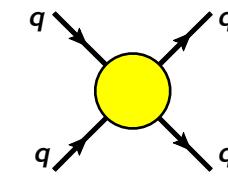
Example of QCD level many-body interactions inducing neutron EDM:



quark chromo-EDM



Weinberg operator



P, CP-odd 4-quark  
interaction

Note : Effect of CPV many-body interaction **may be enhanced!**

# Orthogonality condition model (OCM)

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

## ● N- $\alpha$ interaction:

Repulsion of the 0s state:

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

## ● $\alpha$ - $\alpha$ interaction:

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

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

In our calculation, we have taken  $\lambda \sim 10^4 \text{ MeV}$