Status of the theoretical calculation of nuclear electric dipole moment

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Nikhef
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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!**

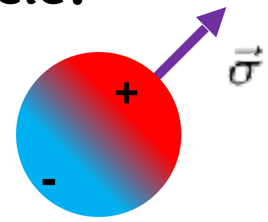
We need new source(s) of
large CP violation beyond the standard model !

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 ½ particle)
- Interaction: $H_{\mathrm{EDM}} = -d \langle \vec{\sigma} \rangle \cdot \vec{E}$
- Transformation properties:
  - Under parity tr.: $\begin{cases} \vec{E} \xrightarrow{\mathrm{P}} -\vec{E} \\ \vec{\sigma} \xrightarrow{\mathrm{P}} \vec{\sigma} \end{cases}$ → H_{EDM} is P-odd
  - Under time reversal: $\begin{cases} \vec{E} \xrightarrow{\mathrm{T}} \vec{E} \\ \vec{\sigma} \xrightarrow{\mathrm{T}} -\vec{\sigma} \end{cases}$ → H_{EDM} 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 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. 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
  $\Rightarrow$ $O(10^{-29})$e cm !

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

Experimental principle of EDM measurement (neutral sys.)

EDM and magnetic moment parallel to particle spin: $\vec{d}, \vec{\mu} \propto \vec{\sigma}$

➡ **Difference of spin precession frequency with parallel & opposite B and E in the presence of EDM!!**

$$\omega_{\uparrow\uparrow} = 2(\mu B + dE)/\hbar \qquad \omega_{\uparrow\downarrow} = 2(\mu B - dE)/\hbar$$

Measured EDM:

$$d = \frac{\hbar}{4E}(\omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow})$$

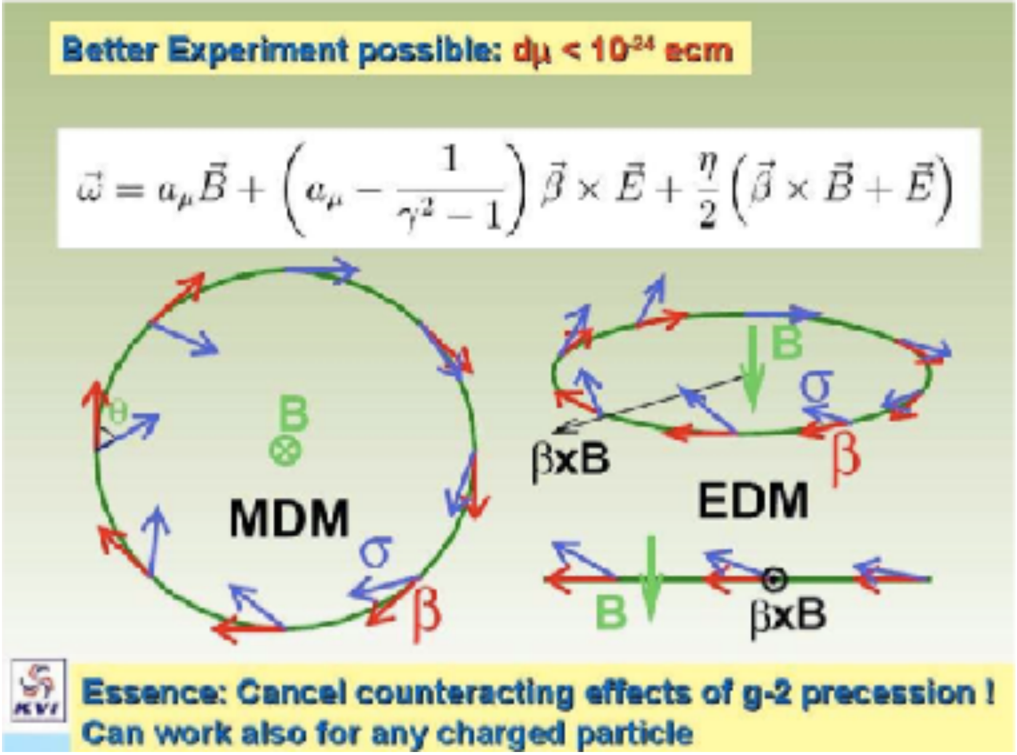
Required Skills:

- Particle density
- Polarization of particles
- Long coherence time
- Strong electric field
- …

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!

EDM from physics beyond Standard model

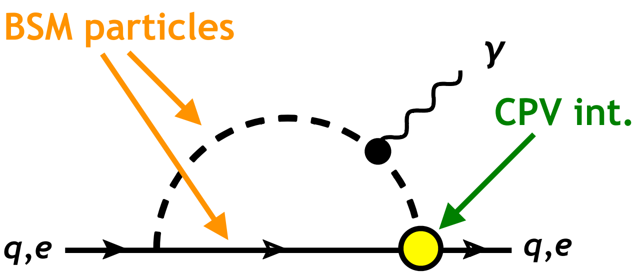
EDM operator in relativistic field theory: dimension five-5 operator

$$-\frac{i}{2} d_\psi \bar{\psi} \sigma_{\mu\nu} F^{\mu\nu} \gamma_5 \psi \quad \Longrightarrow \quad -d_\psi \sigma \cdot \mathbf{E}$$

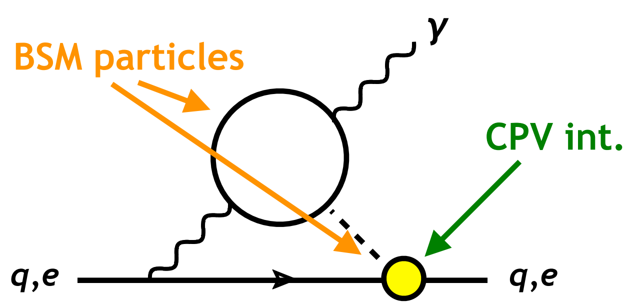
Nonrela. lim.

EDM is generated by CP violating interactions.

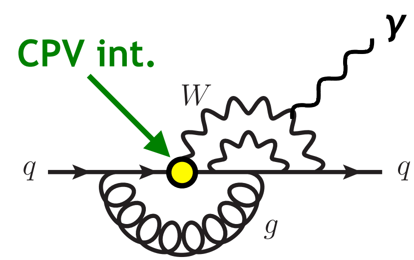
Can be calculated using Feynman diagrams:



1-loop diagram
(e.g. SUSY)



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



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

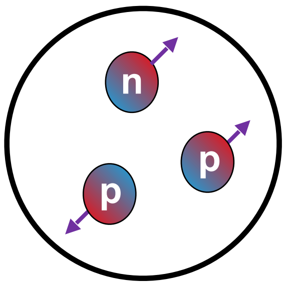
EDM receives very small contribution from SM,
whereas BSM new physics may contribute with low loop level :

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

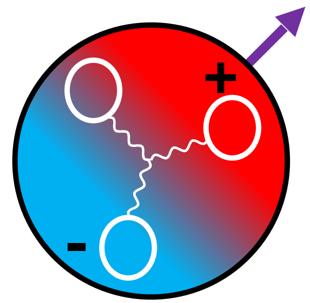
EDM of composite systems

The EDM is often measured in composite systems (neutron, atoms, nuclei)

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

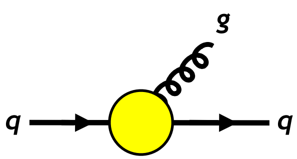


EDM of constituents

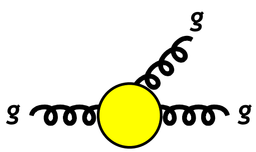


CP-odd many-body interaction

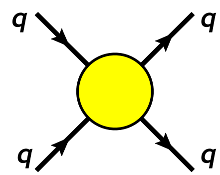
Example of QCD level many-body interactions inducing neutron EDM:



quark chromo-EDM



Weinberg operator



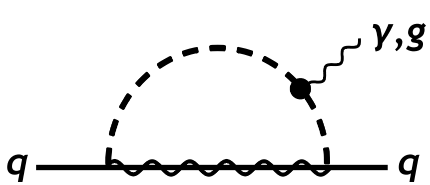
P, CP-odd 4-quark interaction

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

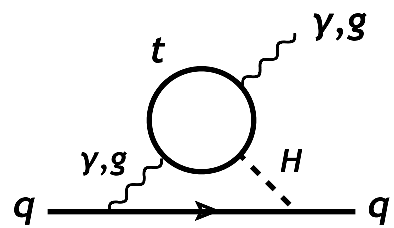
Dimension-6 QCD level interactions and their origin

All those processes scale as $1/M_{NP}^2$

- **Quark EDM, chromo-EDM:**



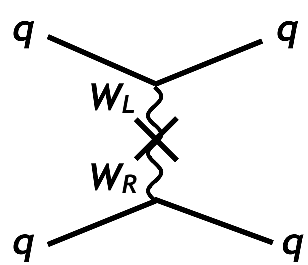
SUSY: 1-loop

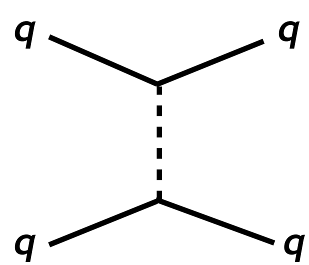


2-Higgs doublet: 2-loop

- **CP-odd 4-quark interaction:**

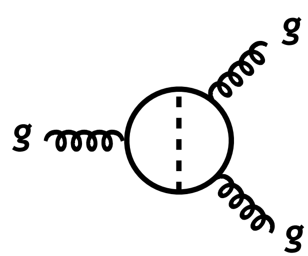
Tree level:
* Left-right sym.
* Scalar exchange





- **Weinberg operator:**

2-loop diagram:
* 2-Higgs doublet model
* Vectorlike quark model



Probe BSM sectors
without mixing
with light quarks

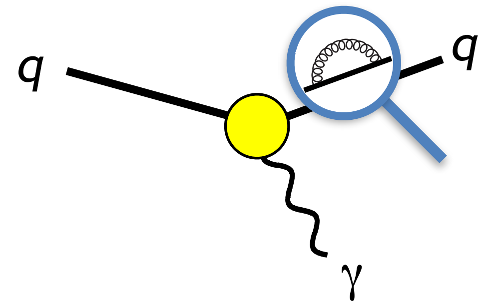
Renormalization group evolution

Change of energy scale modifies the coupling constants, mixes operators

Renormalization group equation:

$$\frac{d}{d\ln\mu}\mathbf{C}(\mu) = \hat{\gamma}^T(\alpha_s)\mathbf{C}(\mu)$$

C : Wilson coefficients of CPV operators



Anomalous dimension matrix:

$$\hat{\gamma}^{(0)} = \begin{pmatrix} 8C_F & 0 & 0 \\ 8C_F & 16C_F - 4n_c & 0 \\ 0 & 2n_c & n_c + 2n_f + \beta_0 \end{pmatrix}$$

Degrassi et al., JHEP **0511** (2005) 044
Yang et al., Phys. Lett. B **713** (2012) 473

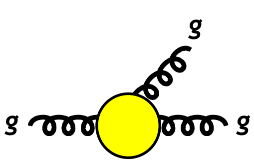
Note:
this analysis is perturbative, large uncertainty due to nonperturbative effect near μ = 1 GeV

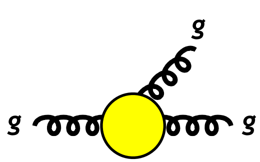
1) Example 1: quark EDM

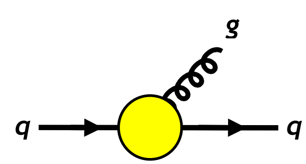
d_q → $0.8\ d_q$

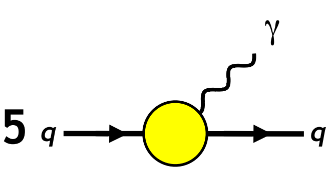
μ = 1 TeV   μ = 1 GeV

2) Example 2: Weinberg operator



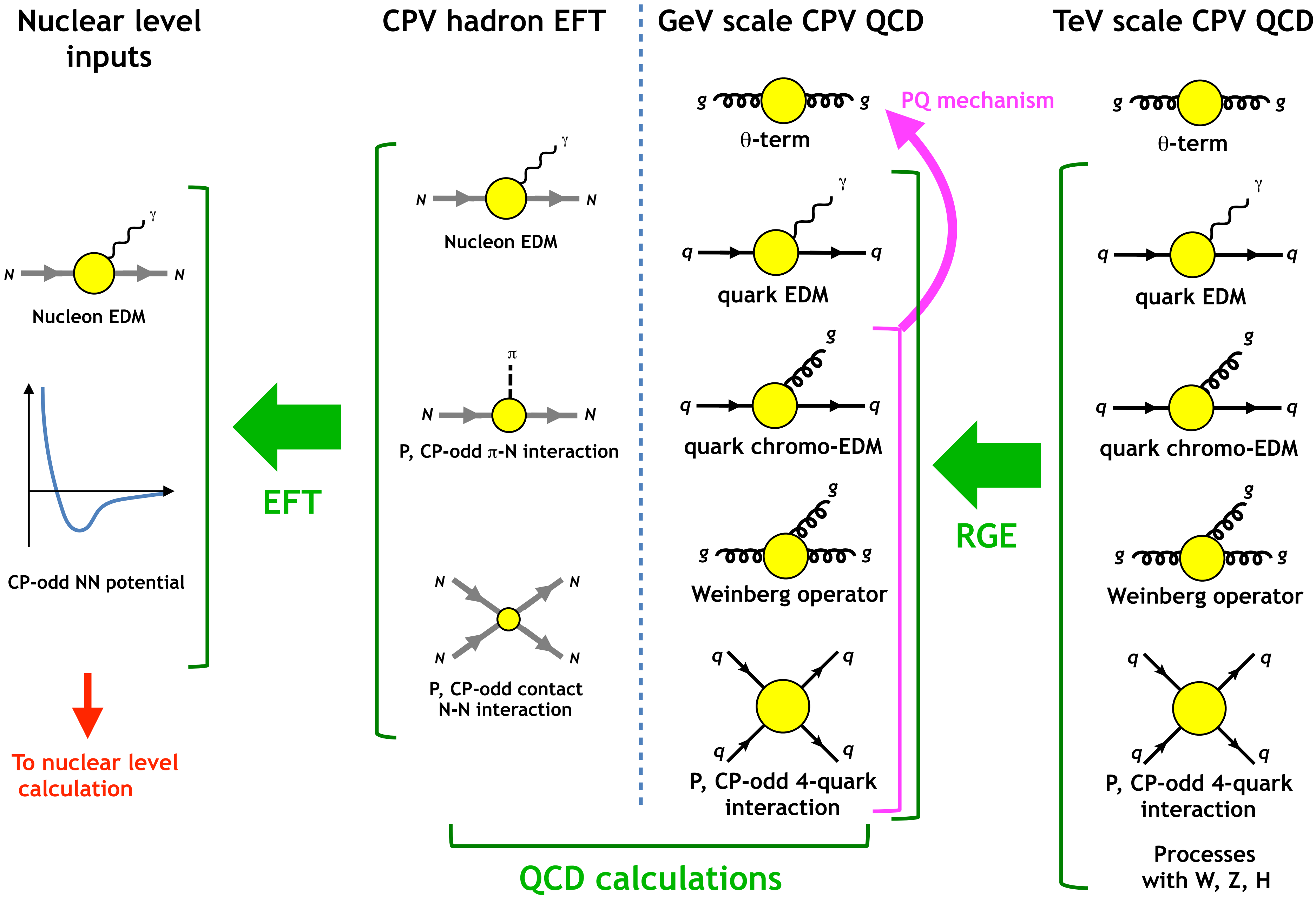
→ 0.17


+ 0.30


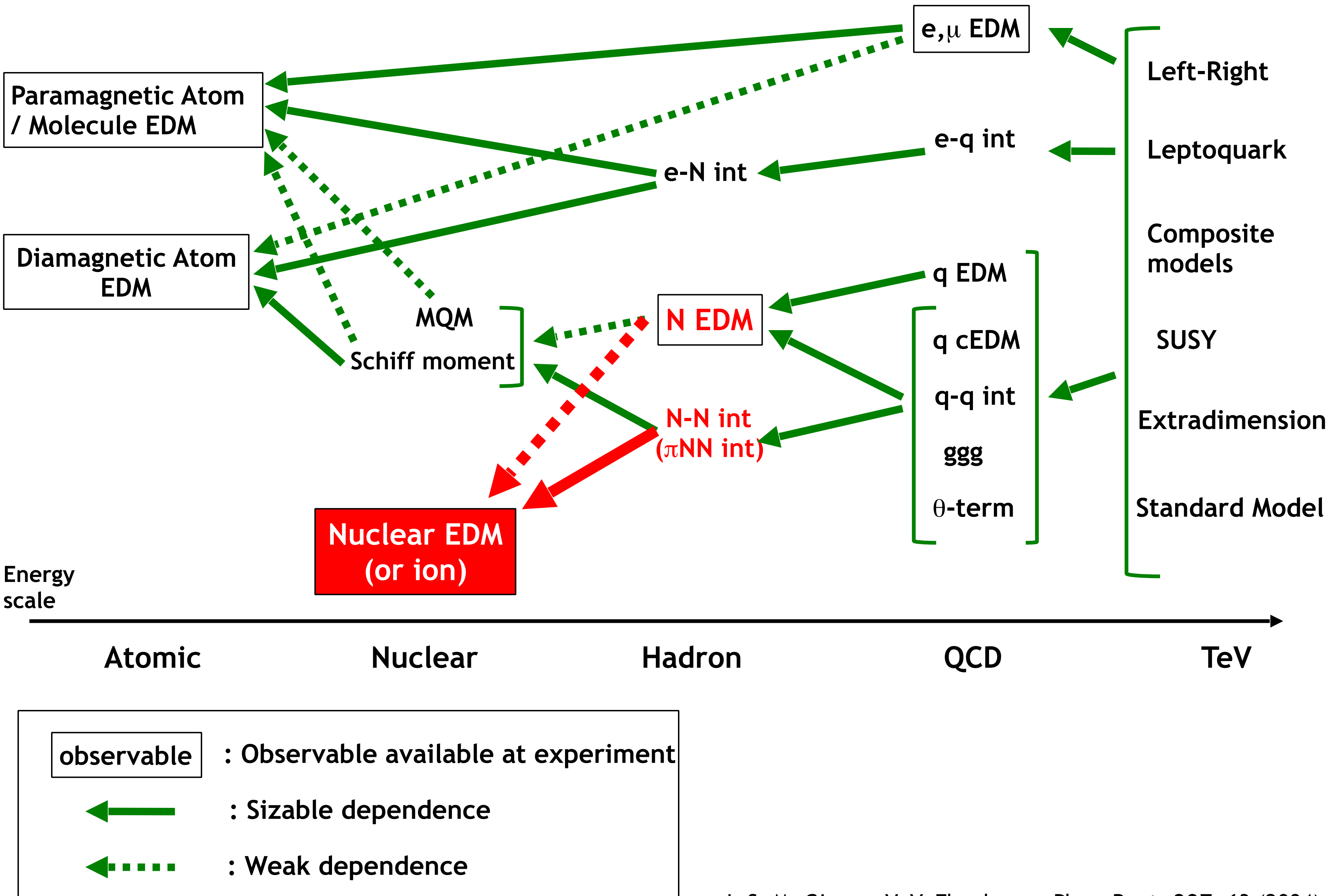
- 0.15


μ = 1 TeV   μ = 1 GeV

CP violation: from QCD to hadron level

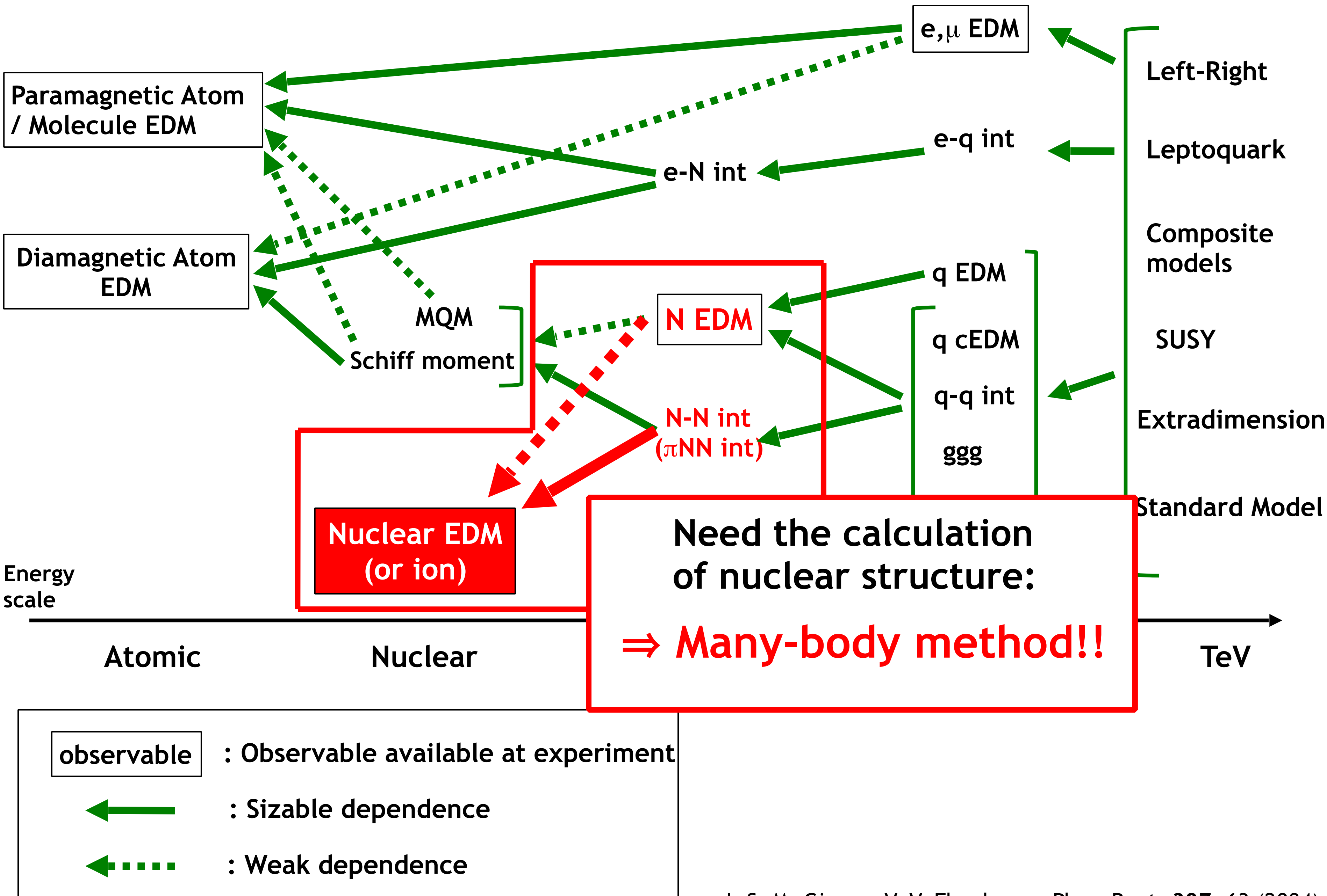


Nuclear EDM from nucleon level CP violation



J. S. M. Ginges, V. V. Flambaum, Phys. Rept. **397**, 63 (2004).

Nuclear EDM from nucleon level CP violation



Need the calculation of nuclear structure:

⇒ Many-body method!!

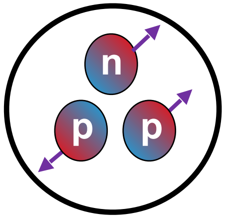
J. S. M. Ginges, V. V. Flambaum, Phys. Rept. **397**, 63 (2004).

Nuclear EDM from nucleon level CP violation

Two leading contributions to be evaluated:

1) Nucleon's intrinsic EDM:

Contribution from the nucleon EDM

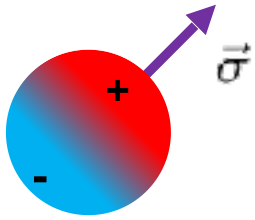


$$D^{(\mathrm{Nedm})} = \frac{1}{2}\sum_{i=1}^{A} \langle\psi|\,[(d_p + d_n) + (d_p - d_n)\tau_i^z]\sigma_i^z\,|\psi\rangle$$

⇒ Spin expectation value (CP-even)

2) Polarization of the nucleus:

Contribution from the P, CP-odd nuclear force



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

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

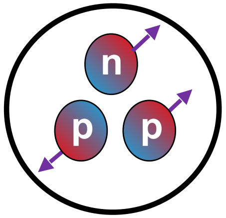
Nuclear EDM from nucleon level CP violation

Two leading contributions to be evaluated:

1) Nucleon's intrinsic EDM:

Contribution from the nucleon EDM

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



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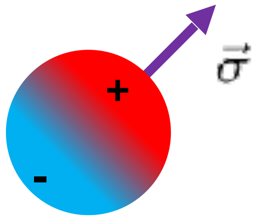


⇒ EDM generated by the CP-even ⇄ CP-odd mixing

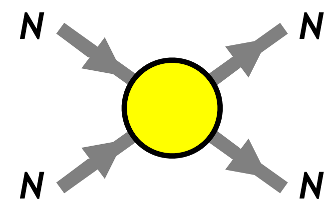
May be enhanced by many-body effect!

Nuclear EDM (polarization) from CP-odd nuclear force

Electric dipole operator requires CP mixing to have finite expectation value

Total hamiltonian:

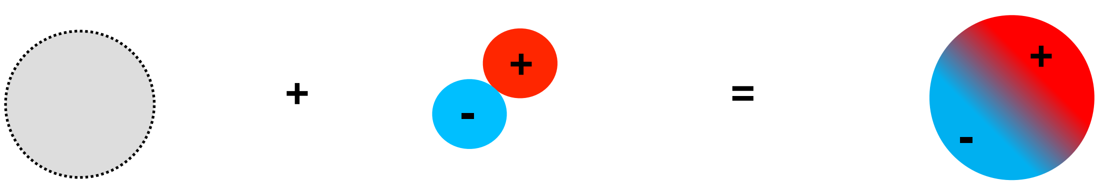
$$H = \begin{pmatrix} H_{realistic} & H_{\not{P}\not{T}} \\ H_{\not{P}\not{T}} & H_{realistic} \end{pmatrix}$$



P, CP-odd nuclear force → $H_{\not{P}\not{T}}$

P, CP-even realistic nuclear force (e.g. Av18,xEFT,...) → $H_{realistic}$

CP-odd N-N interactions mixes opposite parity states



s-wave

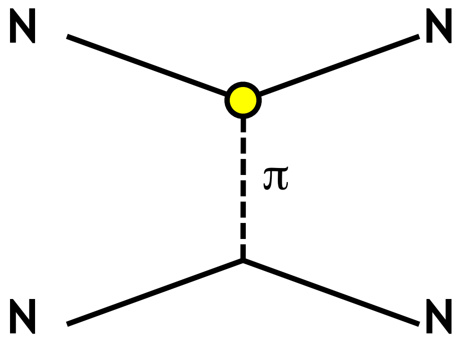
p-wave

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):**

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

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

- **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 only 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 CP violating nuclear couplings beyond the standard model

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

Depends on the nuclear structure!

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

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

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	$1.43 \times 10^{-2} e$ fm	0
GEM (our work) NY, E. Hiyama, PRC **91**, 054005 (2015)	Av18	0	$1.45 \times 10^{-2} e$ fm	0

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

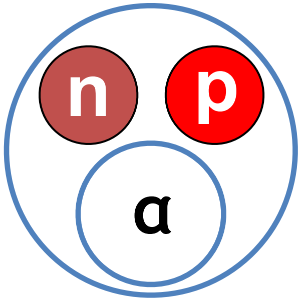
Group	Nuclear force	a_0	a_1	a_2
Faddeev Bsaisou et al., JHEP **1503** (2015) 104	N^{2}LO chiral EFT	0.0079 *e* fm	0.0101 *e* fm	0.0169 *e* fm
GEM (our work) NY, E. Hiyama, PRC **91**, 054005 (2015)	Av18	0.0060 *e* fm	0.0108 *e* fm	0.0168 *e* fm

Ab initio results are consistent!

Object of study

Calculation of nuclear wave functions becomes exponentially difficult when the nucleon number is increased.

Cluster model can reduce the degree of freedom, making the many-body problem easier, keeping the accuracy of the result with good choice of phenomenological parameters.



example of ^{6}Li

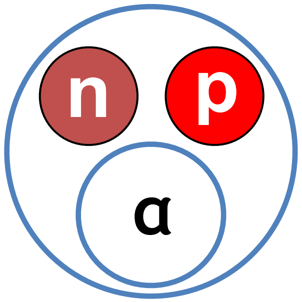
Object of our research:

We evaluate light few-body nuclei (^{6}Li, ^{7}Li, ^{9}Be, ^{13}C, ^{19}F) in cluster model

Are there sensitive nuclei on CP violation?

Setup of the cluster model

We treat light nuclei in the cluster model



example of ^{6}Li

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

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

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

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:

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

α-α interaction:

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

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

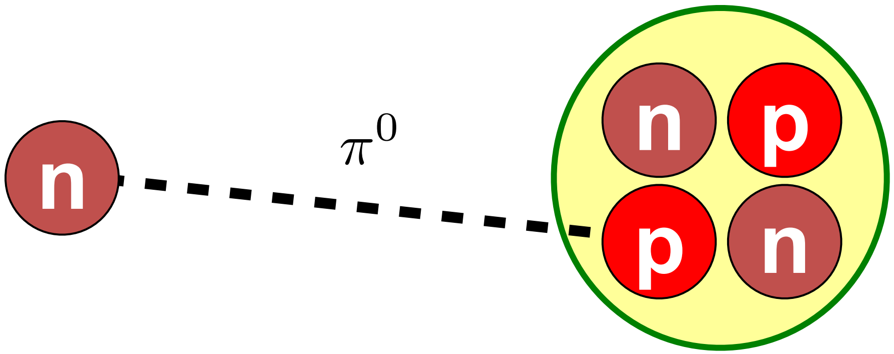
In our calculation, we have taken λ ~ 10^4 MeV

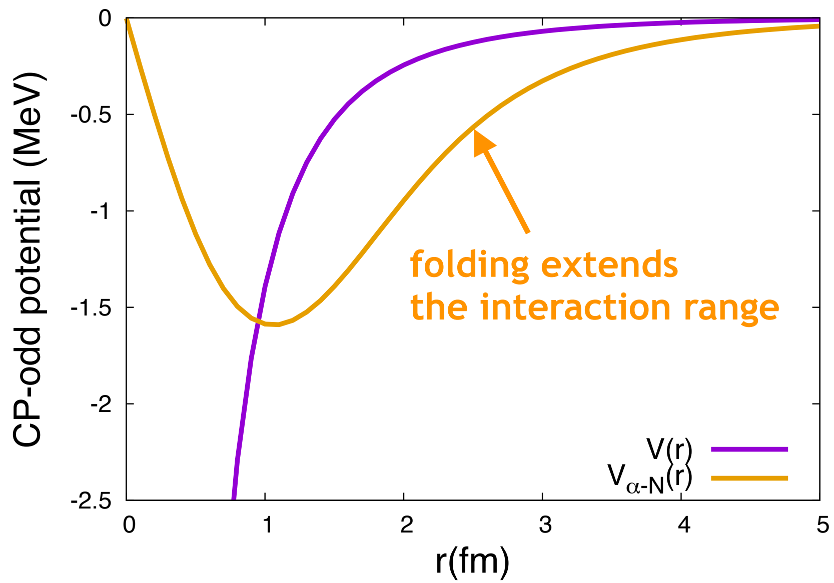
S. Saito, Prog. Theor. Phys. **41**, 705 (1969);
V. I. Kukulin et al., Nucl. Phys. A **586**, 151 (1995).

CP-odd nuclear force with cluster (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:

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

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)

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

Results : nuclear EDM

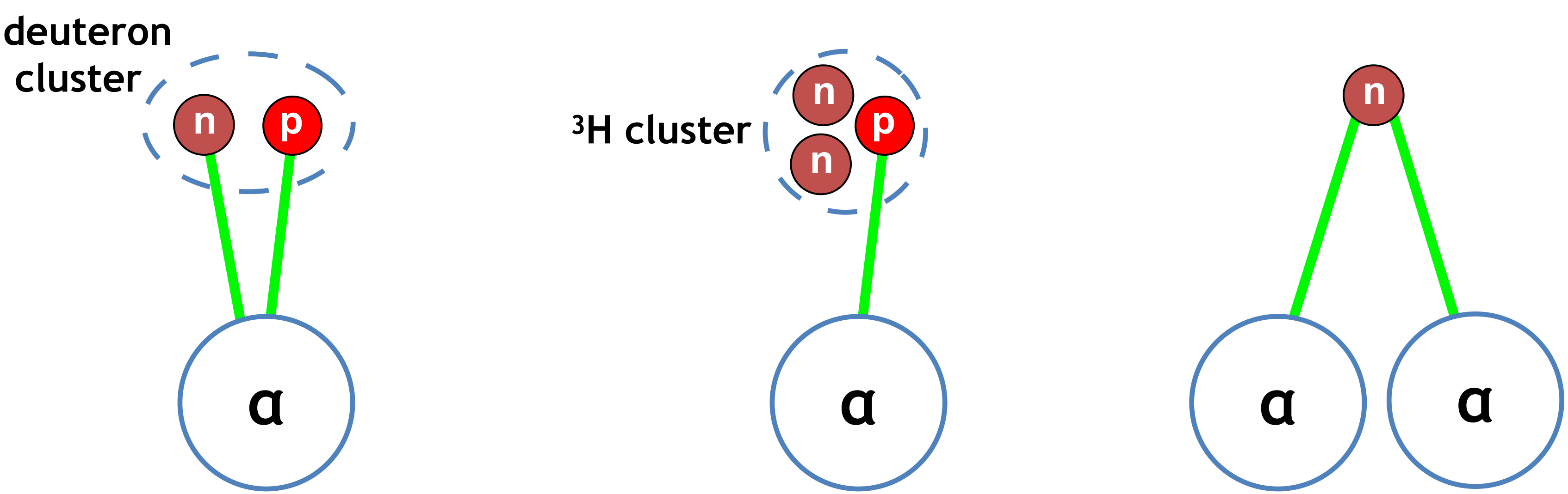
EDM	isoscalar (a_0)	isovector (a_1)	isotensor (a_2)
Neutron Crewther et al. , PLB 88,123 (1979) Mereghetti et al., PLB 696, 97 (2011)	0.01 e fm	—	— 0.01 e fm
Deuteron Liu et al., PRC **70**, 055501 (2004) NY et al., PRC **91**, 054005 (2015)	—	0.0145 e fm	—
^{3}He nucleus Bsaisou et al., JHEP **1503** (2015) 104 NY et al., PRC **91**, 054005 (2015)	0.0060 *e* fm	0.0108 *e* fm	0.0168 *e* fm
^{6}Li nucleus NY et al., PRC **91**, 054005 (2015)	—	0.022 *e* fm	—
^{9}Be nucleus NY et al., PRC **91**, 054005 (2015)	—	0.014 *e* fm	—
^{7}Li nucleus	-0.0060 *e* fm	0.016 *e* fm	-0.017 *e* fm
^{13}C nucleus NY et al., PRC 95,065503 (2017)	—	—0.0020 *e* fm	—
^{19}F nucleus	-0.006 *e* fm	0.1 *e* fm	-0.02 *e* fm
^{129}Xe nucleus N. Yoshinaga et al., PRC **89**, 045501 (2014)	7.0×10^{-5} e fm	7.4×10^{-5} e fm	3.7×10^{-4} e fm

Preliminary

Preliminary

Isovector CP-odd nuclear force: a counting rule?

^{6}Li EDM | ^{7}Li EDM | ^{9}Be EDM



$d_{6Li} = 0.022\ G^{(1)}_\pi\ e$ fm　　$d_{7Li} = 0.016\ G^{(1)}_\pi\ e$ fm　　$d_{9Be} = 0.014\ G^{(1)}_\pi\ e$ fm

^{6}Li :	$a_1 = 0.022\ G_\pi^{(1)}$ e fm	^{2}H EDM + 2 x (α-N polarization)
^{7}Li :	$a_1 = 0.016\ G_\pi^{(1)}$ e fm	^{3}H EDM + 1 x (α-N polarization)
^{9}Be :	$a_1 = 0.014\ G_\pi^{(1)}$ e fm	2 x (α-N polarization)

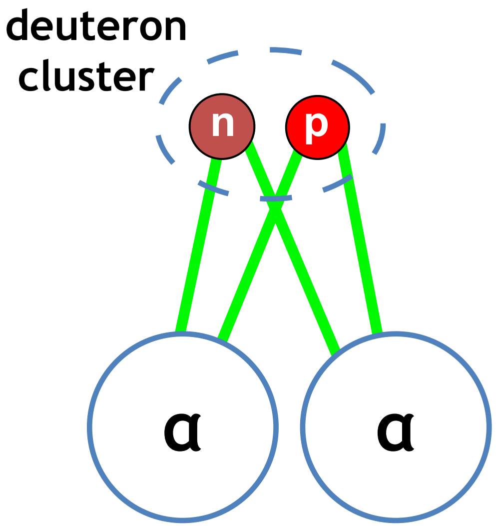
Preliminary

➡ Suggest a counting rule?

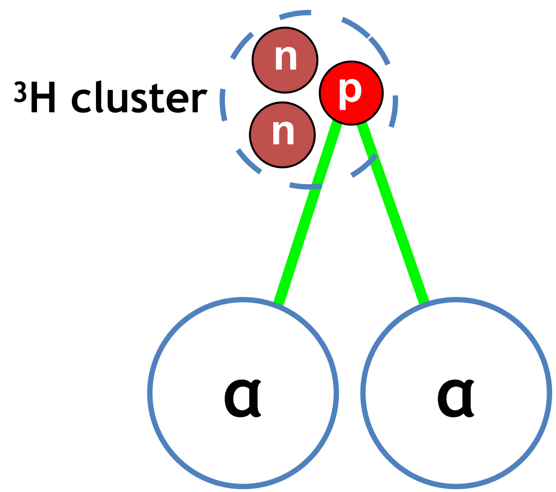
α-N polarization : $a_1 = (0.005{\sim}0.007)\ G_\pi^{(1)}$ e fm

Predictions based on counting rule

^{10}B :



^{11}B :



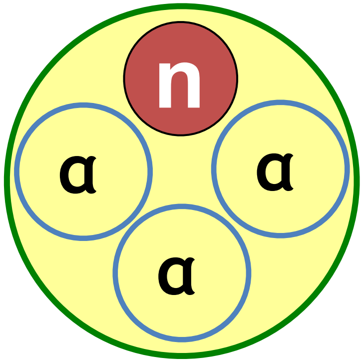
^{2}H EDM + 4 x (α-N polarization)

^{3}H EDM + 2 x (α-N polarization)

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

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

^{13}C EDM : suppression



Calculated in 3α+N (4-body) cluster model

Our result:

$$a_1 = -0.0020\, G_\pi^{(1)}\ e\ fm$$

⇒ Smaller EDM than other light nuclei

Why small?

⇒ Bad overlap of Ground state with 1/2+ excited state:

1/2- : n + $^{12}C(2+)$ ⟺ 1/2+ : n + $^{12}C(0+)$

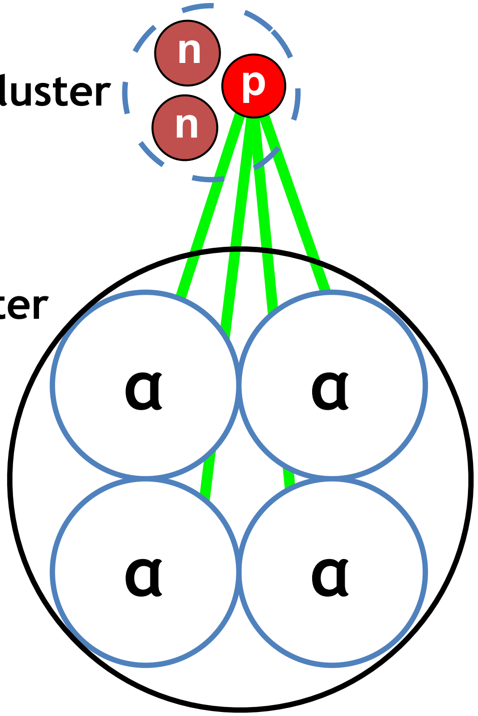
Bad transition

^{12}C core has not the same structure

⇒ Larger nucleus does not imply larger EDM!

NY, T. Yamada, E. Hiyama, Y. Funaki, Phys. Rev. C **95**, 065503 (2017)

^{19}F *EDM : enhancement*



Calculated in ^{3}H-^{16}O cluster model
(with Buck-Pilt potential)

B. Buck and A. A. Pilt, Nucl. Phys. A **280**, 133 (1977).

Our result: Preliminary

$a_1 = 0.1\, G_\pi^{(1)}$ e fm

⇒ Largest EDM !!

⇒ Constructive interference

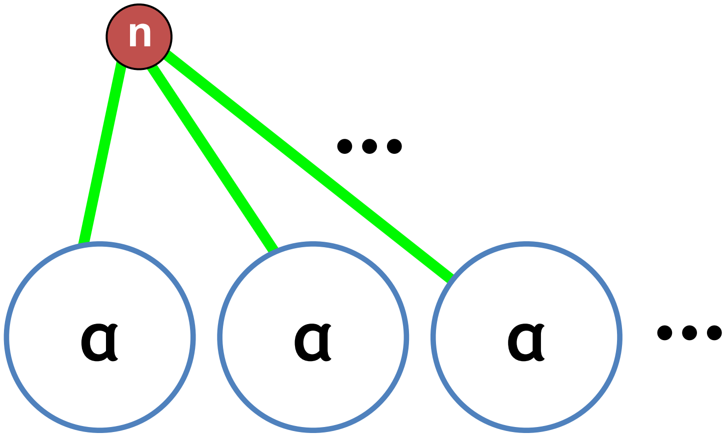
Larger than naive counting:

^{3}H EDM + 4 x (α-N polarization) ∼ $0.04\, G_\pi^{(1)}$ e fm

Shorter distance between clusters than other nuclei

Nuclear EDM of heavier nuclei?

EDM of larger nuclei is larger?

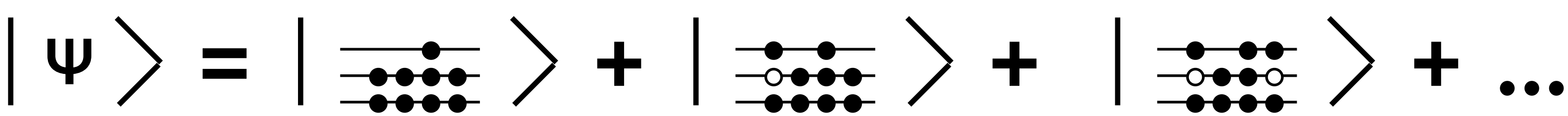


d_A = (A/4) x (α-N polarization) ??

≒ (Simple shell model picture)

No!

Large nuclei have configuration mixing



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

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

N. Yoshinaga, K. Higashiyama, R. Arai and E. Teruya, Phys. Rev. C **89**, 045501 (2014).

Summary:

- We have studied the EDM of several light nuclei in the cluster model.
- Enhancement or suppression? This strongly depends on the nuclear structure.
- 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:

- For quantitative analysis, evaluation of the effective CP-odd interactions (renormalization) is required.
- The most promising is ^{19}F, but we did not considered the cluster configuration mixing ⇒ next work.
- We are waiting for experiments!

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- For details of nuclear EDM calculation, see

  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].

- For values and error bars of hadron level CP violation, 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:1703.01570 [nucl-th].

- For details of particle physics level calculations, see

  N. Yamanaka,
  Analysis of the Electric Dipole Moment
  in the R-parity Violating Supersymmetric Standard Model,
  Springer, 2014.

EDM Physics is reviewed !!

End