Electric dipole moment of light nuclei

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

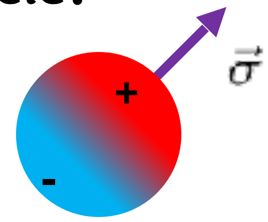
	ratio photon : matter
Prediction of Standard model:	10^{20} : 1
Real observed data:	10^{10} : 1

➡ **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:

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 !

EDM of charged particles using storage rings

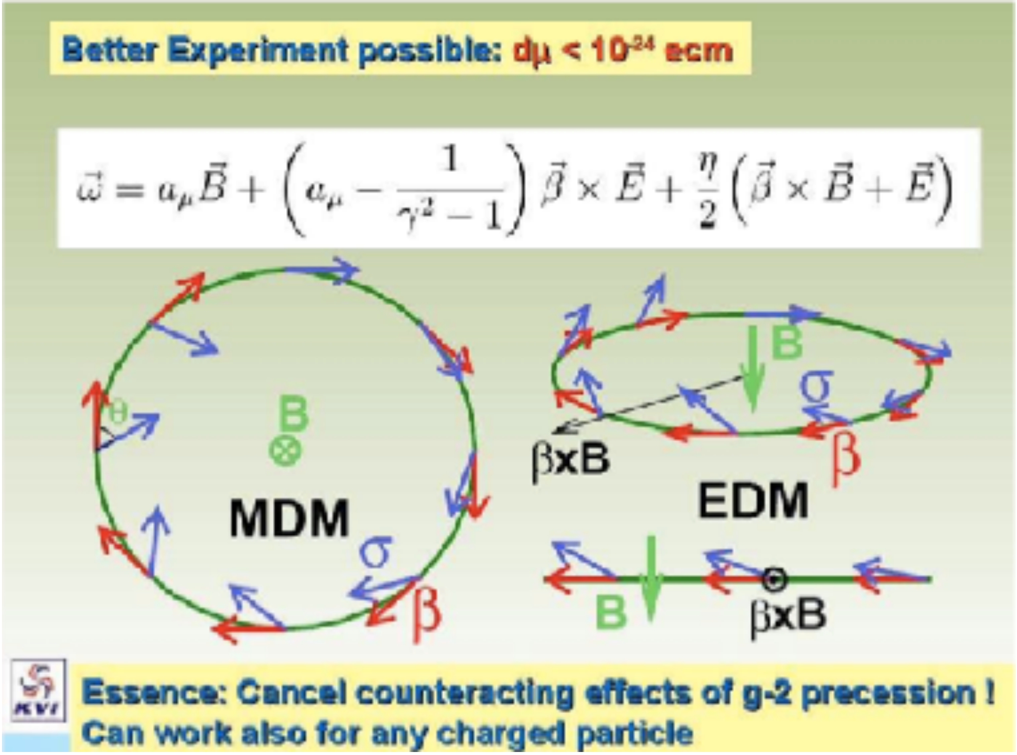
Rotating particles in a storage ring feel very strong central effective electric field

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.

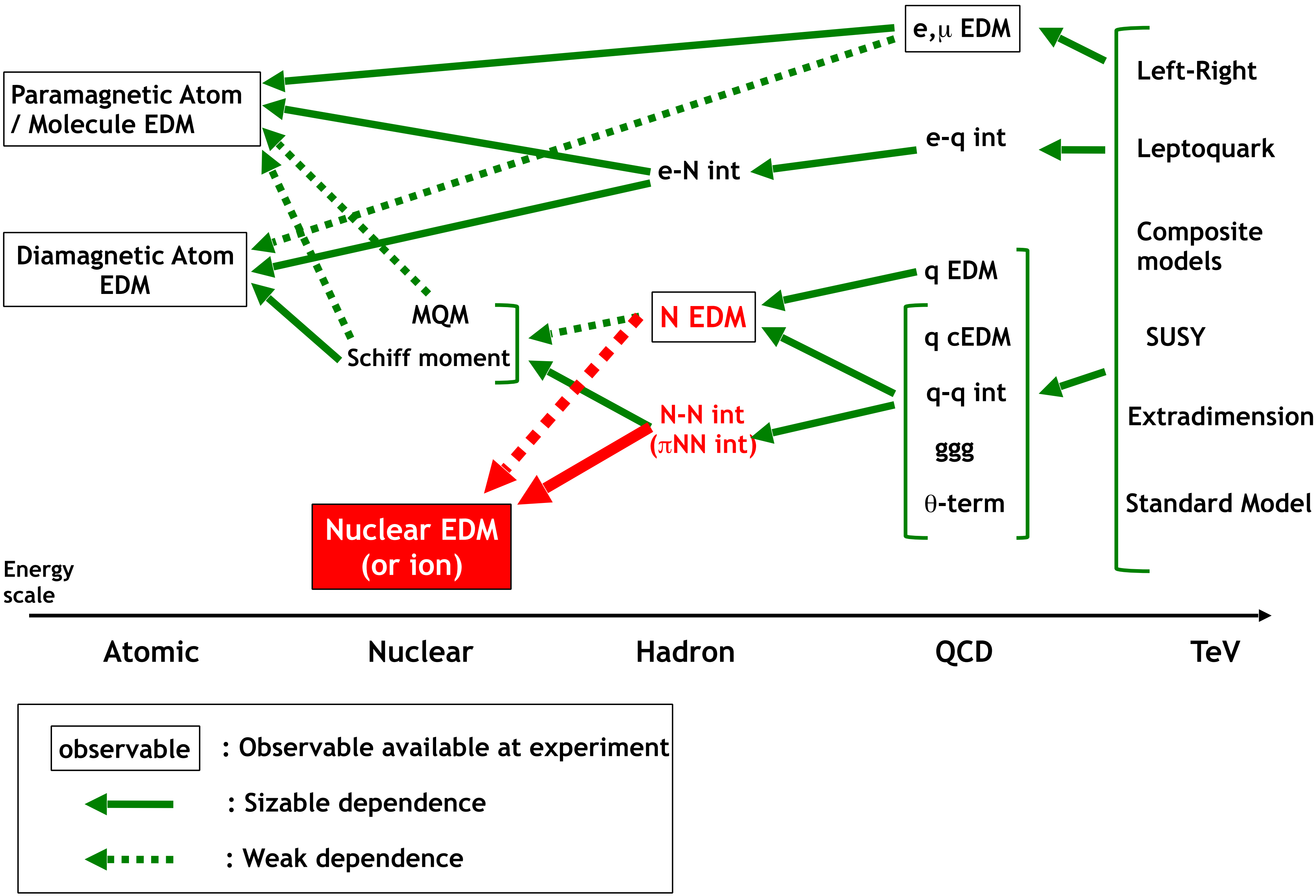
Prospective sensitivity:

➡ $O(10^{-29})$ e cm!!

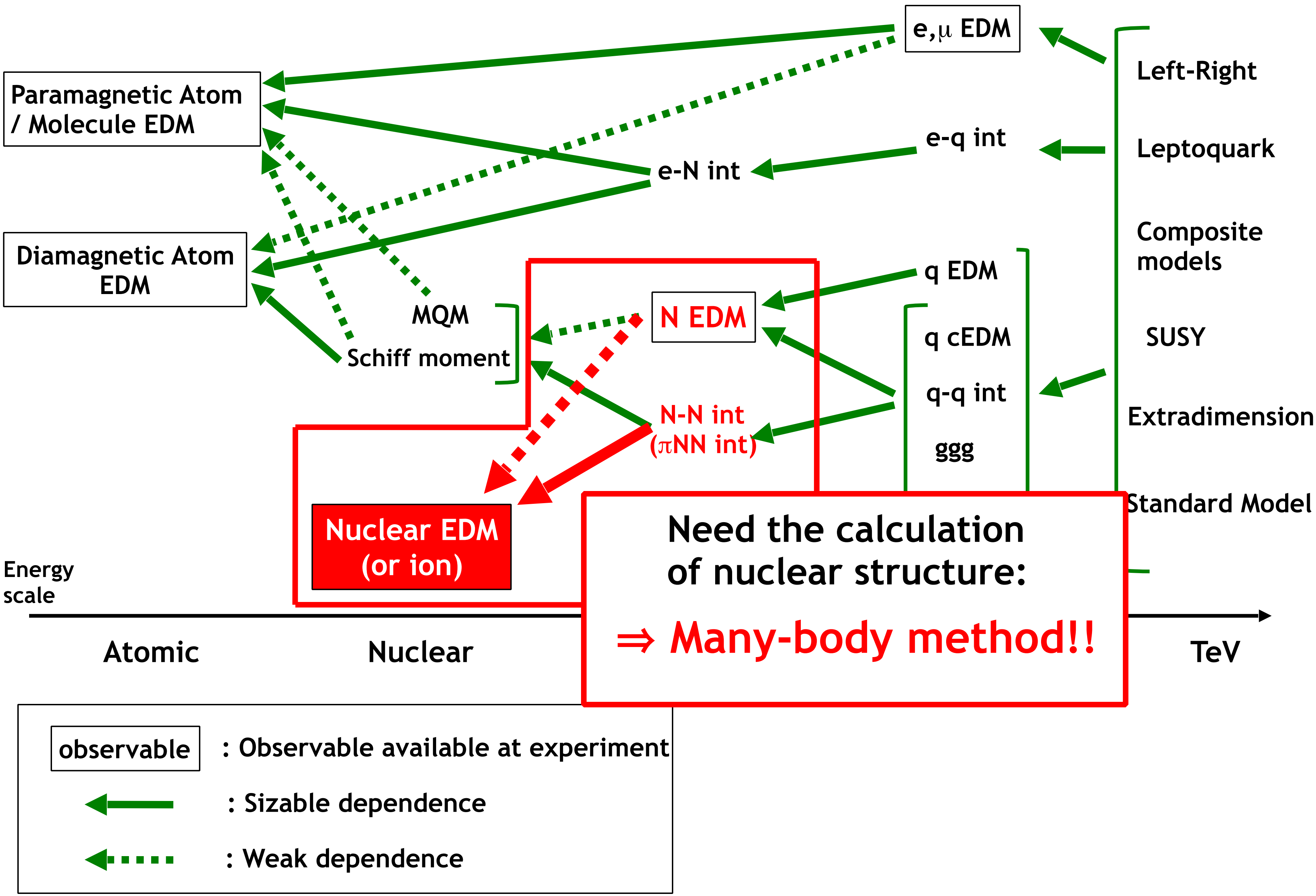


➡ **EDM of light nuclei is accurately measurable!**

Nuclear EDM from nucleon level CP violation



Nuclear EDM from nucleon level CP violation

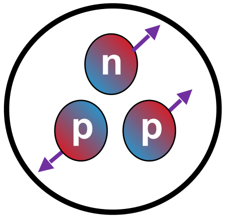


Nuclear EDM from nucleon level CP violation

Two leading contributions to be evaluated:

1) Nucleon's intrinsic EDM:

Contribution from the nucleon EDM

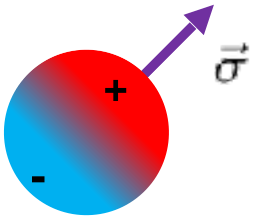


$$D^{(\mathrm{Nedm})} = \frac{1}{2}\sum_{i=1}^{A} \langle\psi| \left[(d_p + d_n) + (d_p - d_n)\tau_i^z\right]\sigma_i^z |\psi\rangle$$

⇒ 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

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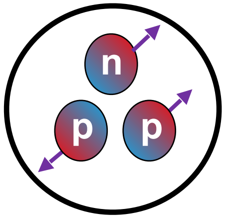

⇒ Spin expectation value (CP-even)

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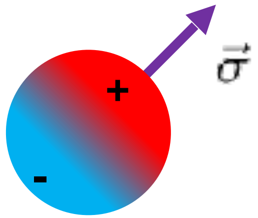


⇒ EDM generated by the CP-even ⇄ CP-odd mixing

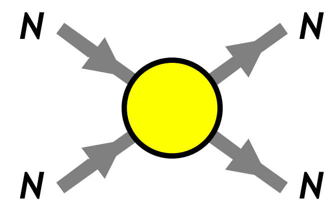
May be enhanced by many-body effect!

Nuclear EDM (polarization) from CP-odd nuclear force

Electric dipole operator requires CP mixing to have finite expectation value

Total hamiltonian:

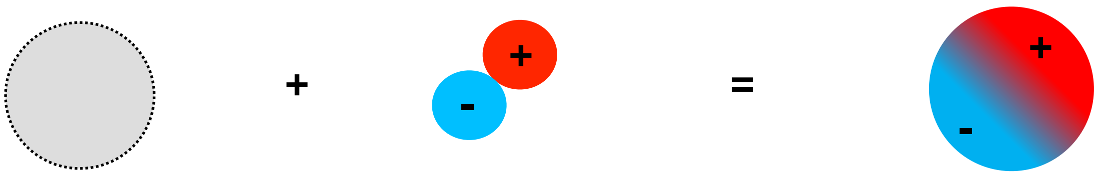
$$H = \begin{pmatrix} H_{\text{realistic}} & H_{\not{P}\not{T}} \\ H_{\not{P}\not{T}} & H_{\text{realistic}} \end{pmatrix}$$



P, CP-odd nuclear force

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

CP-odd N-N interactions mixes opposite parity states

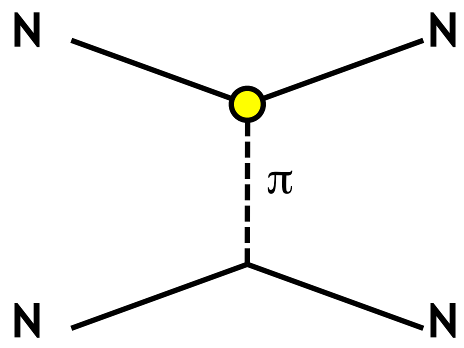


s-wave p-wave polarized system

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):

$$\mathcal{H}_{PT} = -\frac{1}{8\pi m_N} \Big[\big(\underbrace{\bar{G}_\pi^{(0)}}_{\text{Isoscalar}} \tau_a \cdot \tau_b + \underbrace{\bar{G}_\pi^{(2)}}_{\text{Isotensor}} (\tau_a \cdot \tau_b - 3\tau_a^z \tau_b^z) \big)(\sigma_a - \sigma_b) + \underbrace{\bar{G}_\pi^{(1)}}_{\text{Isovector}} (\tau_b^a \sigma_a - \tau_b^z \sigma_b) \Big] \cdot \frac{\nabla_{ab} e^{m_\pi r_{ab}}}{r_{ab}}$$

- 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 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 works (^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:**

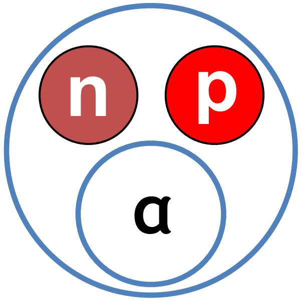
Group	Nuclear force	a_0	a_1	a_2
Faddeev Bsaisou et al., JHEP **1503** (2015) 104	N^{2}LO chiral EFT	0.0079 *e* fm	0.0101 *e* fm	0.0169 *e* fm
GEM (our work) NY, E. Hiyama, PRC **91**, 054005 (2015)	Av18	0.0060 *e* fm	0.0108 *e* fm	0.0168 *e* fm

Ab initio results are consistent!

Go beyond ^{6}Li : cluster model

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.



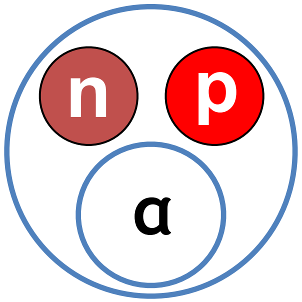
example of ^{6}Li

We evaluate light few-body nuclei
(^{6}Li, ^{7}Li, ^{9}Be, ^{11}B, ^{13}C) 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, t-α, α-α interactions:

Fitted to reproduce the scattering phase shifts at low energy

Pauli exclusion taken into account via Orthogonality condition model

N-α : H. Kanada *et al.*, Prog. Theor. Phys. **61**, 1327 (1979).

t-α : H. Nishioka *et al.*, Prog. Theor. Phys. **62**, 424 (1979).
T. Yamada and Y. Funaki, Phys. Rev. C **82**, 064315 (2010).

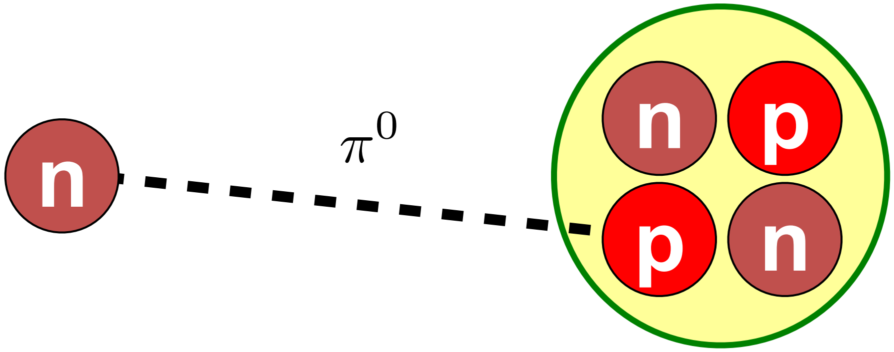
α-α : A. Hasegawa and S. Nagata, Prog. Theor. Phys. **45**, 1786 (1971).
E. W. Schmid and K. Wildermuth, Nucl. Phys. **26**, 462 (1961).

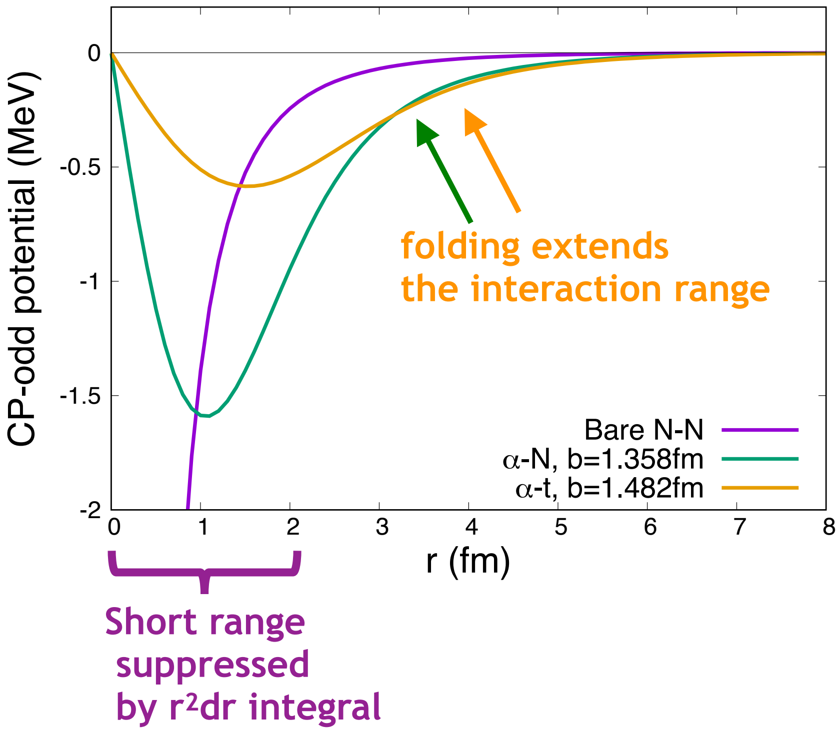
CP-odd α-N & α-t interactions

Folding the CP-odd N-N interaction with ^{4}He (α) and/or ^{3}H (*t*) cluster

(α & *t* cluster are indestructible)

Folding : direct part of RGM interaction kernel





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 & t-α interactions

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

Results

EDM	isoscalar (a_0)	isovector (a_1)	isotensor (a_2)
^{129}Xe atom E. Teruya et al., to appear in PRC Y. Singh et al., PRA **89**, 030502 (2014)	1.1×10^{-7} e fm	4.0×10^{-8} e fm	1.4×10^{-7} e fm
^{199}Hg atom Ban et al., PRC **82**, , 015501 (2010) Y. Singh et al., PRA **91**, 030501 (2015)	3.2×10^{-6} e fm	-1.3×10^{-6} e fm	5.2×10^{-6} e fm
^{225}Ra atom Dobaczewski et al., PRL **94**, 232502 (2005) Y. Singh et al., PRA **92**, 022502 (2015)	0.00093 e fm	-0.0037 e fm	0.0025 e fm
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 and EH, PRC **91**, 054005 (2015)	—	0.022 *e* fm	—
^{7}Li nucleus NY, arXiv:1712.06001 [nucl-th]	– 0.006 *e* fm	0.016 *e* fm	– 0.02 *e* fm
^{9}Be nucleus NY and EH, PRC **91**, 054005 (2015)	—	0.014 *e* fm	—
^{11}B nucleus	– 0.004 *e* fm	0.02 *e* fm	– 0.01 *e* fm
^{13}C nucleus NY et al., PRC 95,065503 (2017)	—	–0.0020 *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

} atom

Results

EDM	isoscalar (a_0)	isovector (a_1)	isotensor (a_2)
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Deuteron Liu et al., PRC **70**, 055501 (2004) NY et al., PRC **91**, 054005 (2015)	–	0.0145 e fm	–
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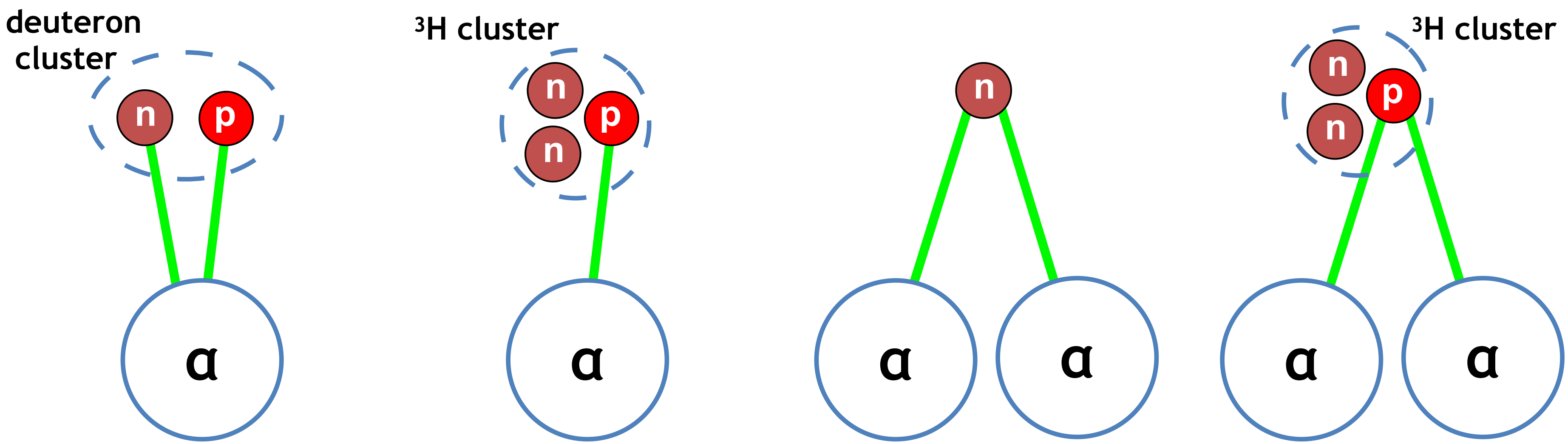
^{9}Be nucleus NY and EH, PRC **91**, 054005 (2015)	–	0.014 *e* fm	–
^{11}B nucleus	– 0.004 *e* fm	0.02 *e* fm	– 0.01 *e* fm
^{13}C nucleus NY et al., PRC 95,065503 (2017)	–	–0.0020 *e* fm	–
^{129}Xe nucleus N. Yoshinaga et al., PRC **89**, 045501 (2014)	7.0×10^{-5} e fm	7.4×10^{-5} e fm	3.7×10^{-4} e fm

atom

Preliminary

Isovector CP-odd nuclear force: a sum rule?

^{6}Li EDM | ^{7}Li EDM | ^{9}Be EDM | ^{11}B 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 $d_{^{11}B} = 0.02\, G^{(1)}_{\pi}\, e$ fm

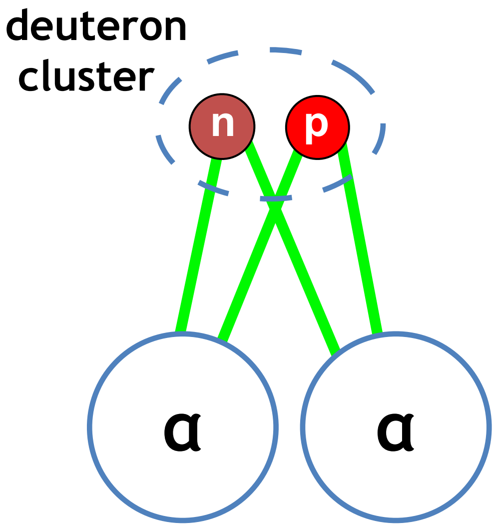
^{6}Li :	$a_1 = 0.022\, G_{\pi}^{(1)}$ e fm	^{2}H EDM + 2 x (α-N polarization)
^{7}Li :	$a_1 = 0.016\, G_{\pi}^{(1)}$ e fm	^{3}H EDM + 1 x (α-N polarization)
^{9}Be :	$a_1 = 0.014\, G_{\pi}^{(1)}$ e fm	2 x (α-N polarization)
^{11}B :	$a_1 = 0.02\, G_{\pi}^{(1)}$ e fm	^{3}H EDM + 2 x (α-N polarization)

➡ **Suggest a sum rule**

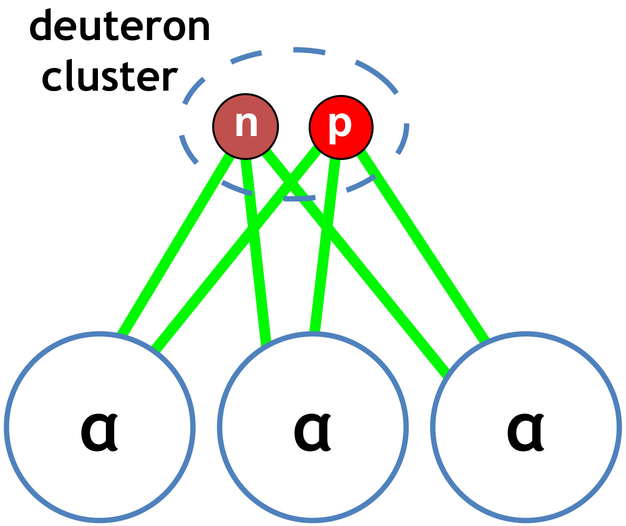
α-N polarization : $a_1 = (0.005\sim0.007)\, G_{\pi}^{(1)}$ e fm

Predictions based on the sum rule

^{10}B :



^{14}N :



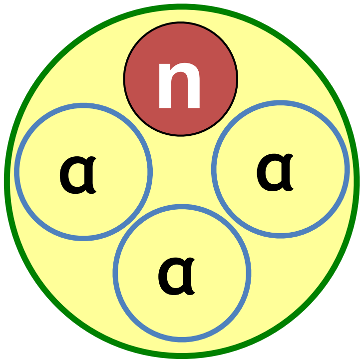
^{2}H EDM + 4 x (α-N polarization)

^{2}H EDM + 6 x (α-N polarization)

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

$d_{14N} \sim 0.04\, G_{\pi}^{(1)}$ 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

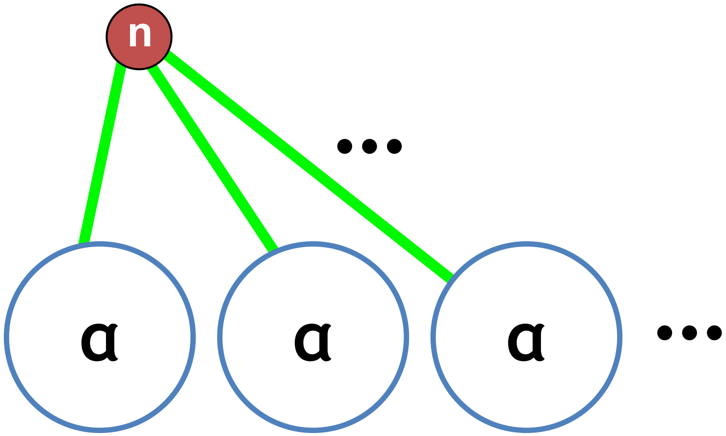
⇒ Larger nucleus does not imply larger EDM!

Aside 1 : ^{15}N may similarly be suppressed by this mechanism
Aside 2 : for 1/2+ state of ^{13}C, $a_1 = 0.024\ G_\pi^{(1)}$ e fm ⇒ obey sum rule

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

Nuclear EDM of heavier nuclei?

EDM of larger nuclei is larger?

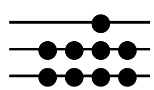
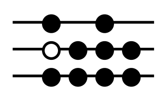
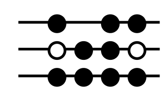


d_A = (A/4) x (α-N polarization) ??

≒ (Simple shell model picture)

➡ **No!**

Large nuclei have configuration mixing

$|\Psi\rangle = |$  $\rangle + |$  $\rangle + |$  $\rangle + \ldots$

➡ 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 (^{6}Li, ^{7}Li, ^{9}Be, ^{11}B, ^{13}C) in the cluster model.
- Results for ^{6}Li, ^{7}Li, ^{9}Be, and ^{11}B suggest a sum rule.
- Enhancement or suppression? This strongly depends on the nuclear structure. -> We have to study them one by one.
- 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.
- We are waiting for experiments!

Advertisement

- 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

Backup slides

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

  ⇒ $O(10^{-29})$e cm !

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

CP violation in the Standard model

CP violation in the Standard model:

Complex phase of Cabibbo-Kobayashi-Maskawa (CKM) matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

δ : CP violating phase

Relevant CP violation:

Jarlskog invariant (invariant in parametrization of CKM)

$$J = \mathrm{Im}[V_{ts}^{*}V_{td}V_{us}V_{ud}^{*}] = -\mathrm{Im}[V_{cs}^{*}V_{cd}V_{us}V_{ud}^{*}]$$

C. Jarlskog, Phys. Rev. Lett. **55**, 1039 (1985).

$$= (3.06 \pm 0.21)\times 10^{-5} \text{ (PDG value)}$$

Leading CP violation of CKM appears
through the Jarlskog combinations

Infinitesimally shifted Gaussian expansion method

How to solve few-body Schroedinger equation?

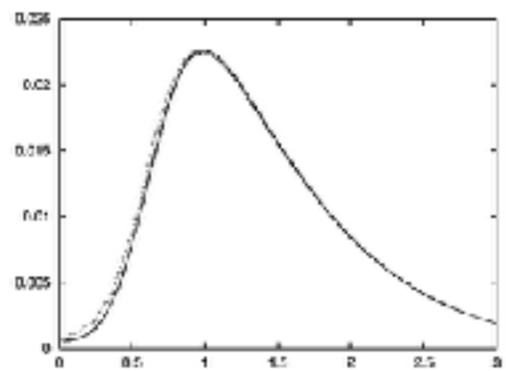
We use the Gaussian expansion method.

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!

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*)

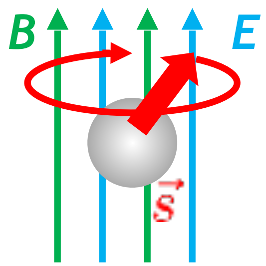
5) Calculation of observables (EDM)

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

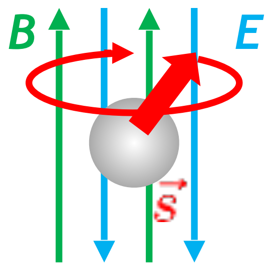
Experimental principle of EDM measurement (neutral sys.)

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!!



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



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

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
- …

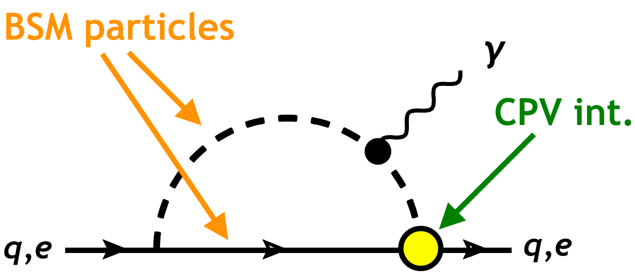
EDM from physics beyond Standard model

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

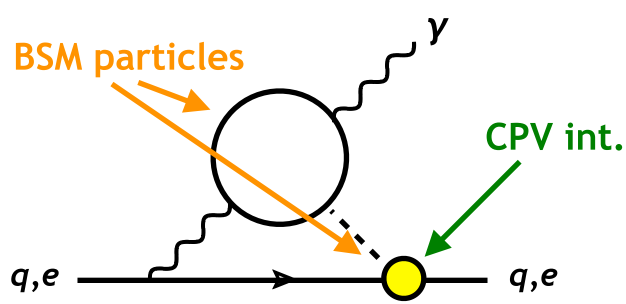
$$-\frac{i}{2} d_\psi \bar{\psi} \sigma_{\mu\nu} F^{\mu\nu} \gamma_5 \psi \quad \xrightarrow{\text{Nonrela. lim.}} \quad -d_\psi \sigma \cdot \mathbf{E}$$

EDM is generated by CP violating interactions.

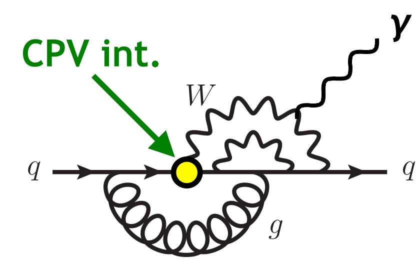
Can be calculated using Feynman diagrams:



1-loop diagram
(e.g. SUSY)



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



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

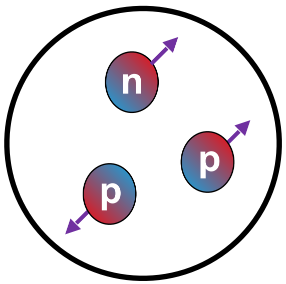
EDM receives very small contribution from SM, whereas BSM new physics may contribute with low loop level :

EDM is a very good probe of BSM new physics!

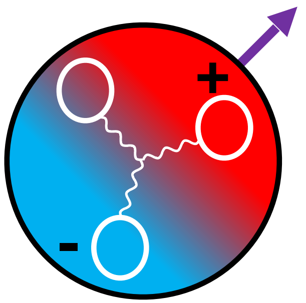
EDM of composite systems

The EDM 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.

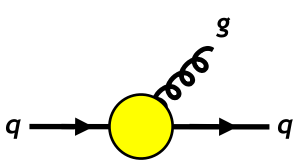


EDM of constituents

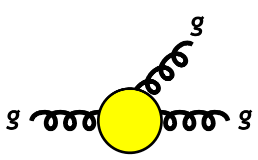


CP-odd many-body interaction

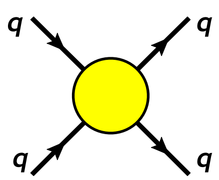
Example of QCD level many-body interactions inducing neutron EDM:



quark chromo-EDM



Weinberg operator



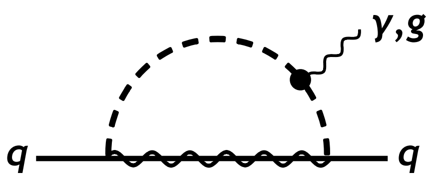
P, CP-odd 4-quark interaction

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

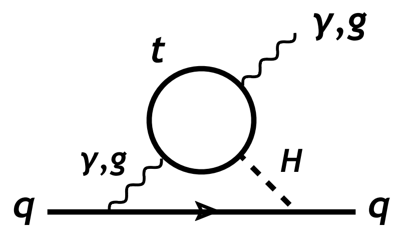
Dimension-6 QCD level interactions and their origin

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

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



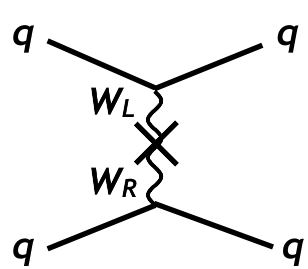
SUSY: 1-loop

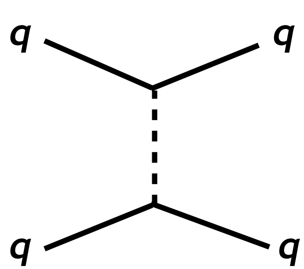


2-Higgs doublet: 2-loop

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

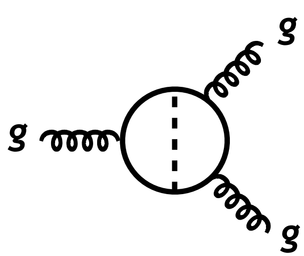
Tree level:
* Left-right sym.
* Scalar exchange





- **Weinberg operator:**

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



Probe BSM sectors
without mixing
with light quarks

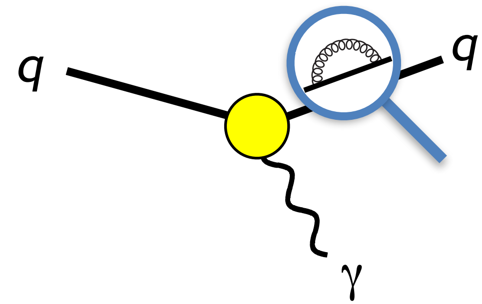
Renormalization group evolution

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

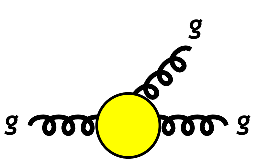
Note:
this analysis is perturbative, large uncertainty due to nonperturbative effect near μ = 1 GeV

1) Example 1: quark EDM

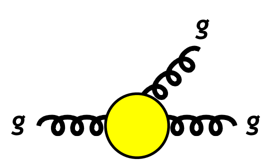
d_q → $0.8\ d_q$

μ = 1 TeV   μ = 1 GeV

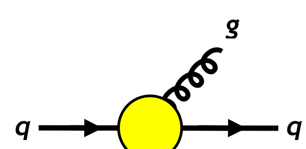
2) Example 2: Weinberg operator



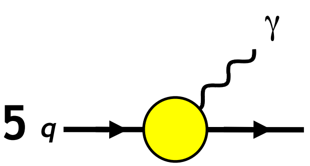
→ 0.17



+ 0.30

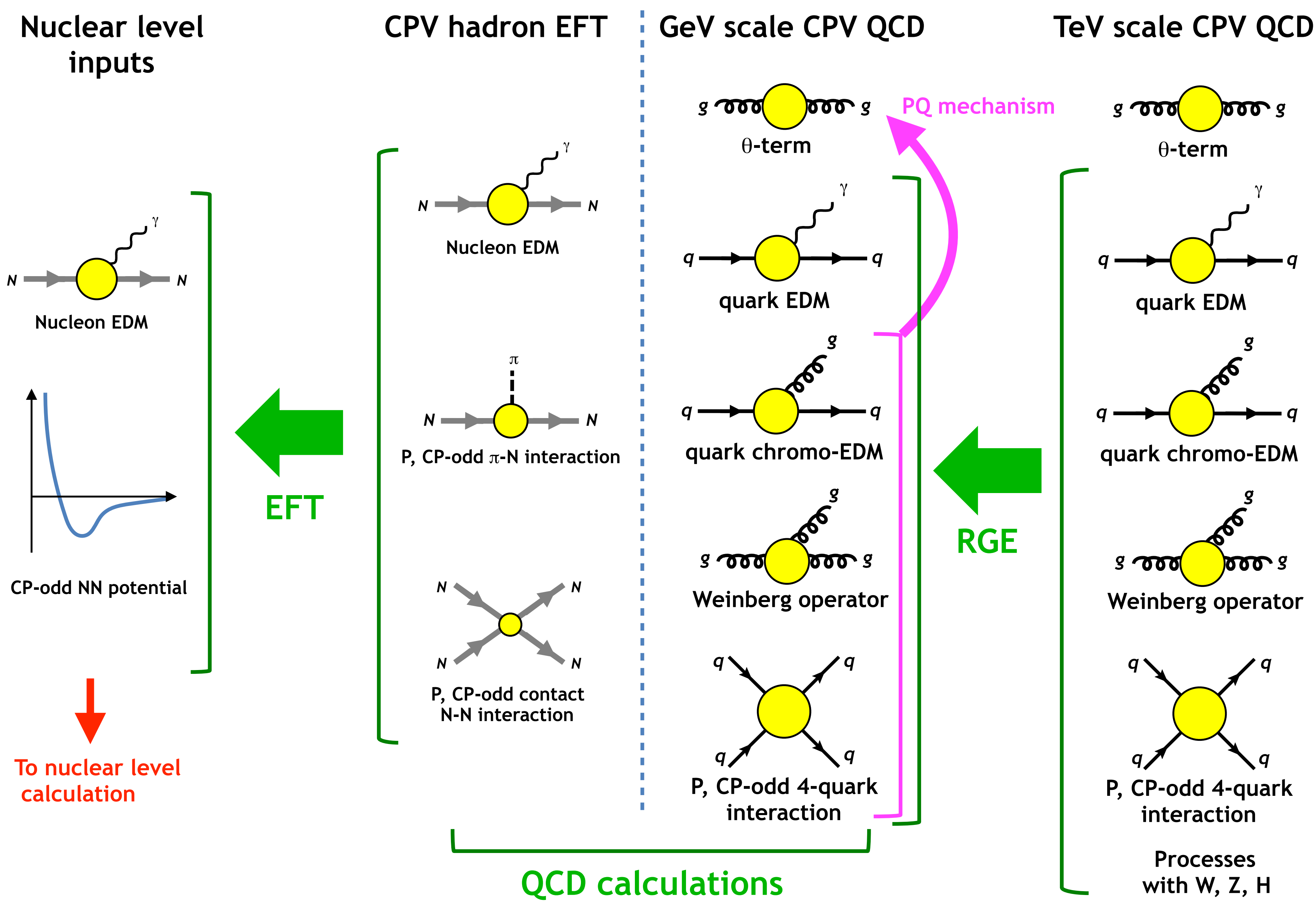


- 0.15



μ = 1 TeV   μ = 1 GeV

CP violation: from QCD to hadron level



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 $\lambda \sim 10^4$ MeV

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