Hadronic CP violation and CP-odd nuclear moments

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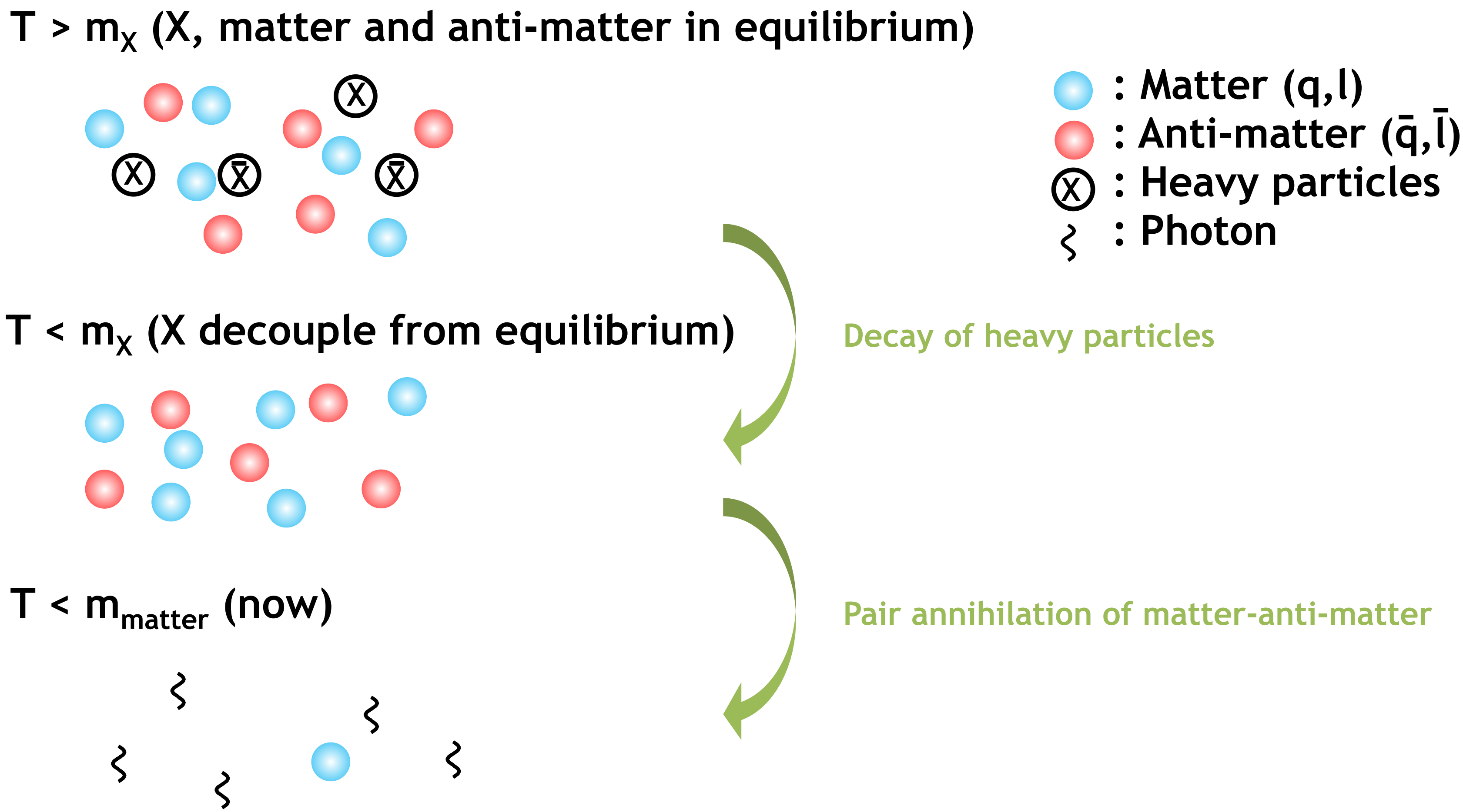
核力に基づいた原子核の構造と反応

Baryon number asymmetry of the Universe

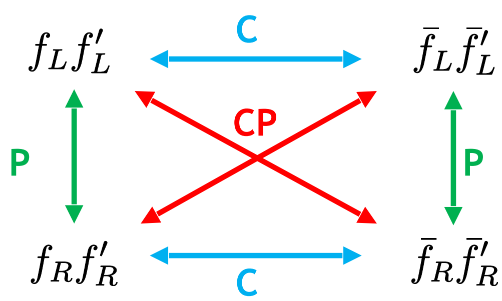
Asymmetric decays generates excess of matters in the early Universe



➡ **Matter/photon ratio is a direct signature of baryon number asymmetry**

C, CP violations and baryon number asymmetry

P, C and CP transformation of initial & final states:



Baryon number asymmetry:

$$\epsilon \propto \Gamma(X \to f_L f'_L) + \Gamma(X \to f_R f'_R) - \Gamma(\bar{X} \to \bar{f}_L \bar{f}'_L) - \Gamma(\bar{X} \to \bar{f}_R \bar{f}'_R)$$

Similar relations hold for decays of other particles, other interactions

➡ **C & CP violations are both needed for baryon number asymmetric decays**

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:	$10^{10} : 1$

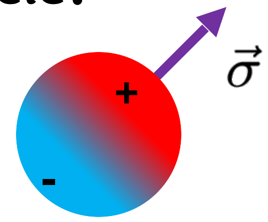
➡ **CP violation of standard model is in great deficit!**

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

Electric dipole moment:

Permanent polarization of internal charge of a particle.

$$\vec{d}_\psi = \sum_i \langle \psi | Q_i e \vec{r}_i | \psi \rangle$$



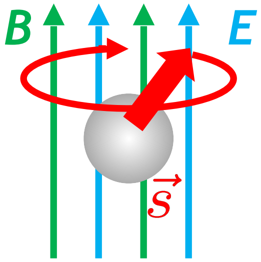
⇒ This is what will be evaluated!

- 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 !

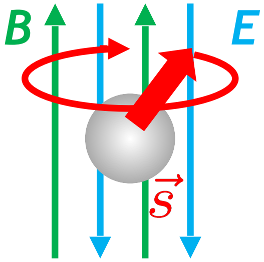
Experimental principle of EDM measurement (neutral sys.)

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:

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

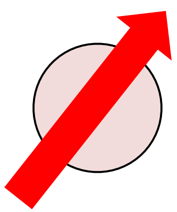
Required Skills:
- Particle density
- Polarization of particles
- Long coherence time
- Strong electric field
- …

Nuclear CP violation contribution in atomic EDM

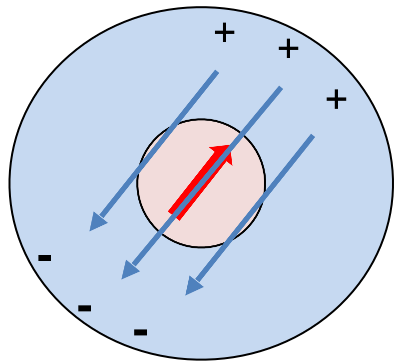
Atoms are the most convenient system to handle in EDM experiments, but nuclear EDM is damped due to Schiff's screening

Schiff's screening theorem:

EDM of nonrelativistic point-like particles is completely screened in neutral electromagnetically bound system



Nuclear EDM



Nuclear EDM screened by atomic electron

Electrically neutral bound system rearranges itself to suppress EDM of components

There are ways to generate EDM:

- Relativistic particles
- Non-point-like (finite volume) effect
- CP-odd interactions among particles
- Oscillating EDM of particles

EDM of charged particles using storage rings

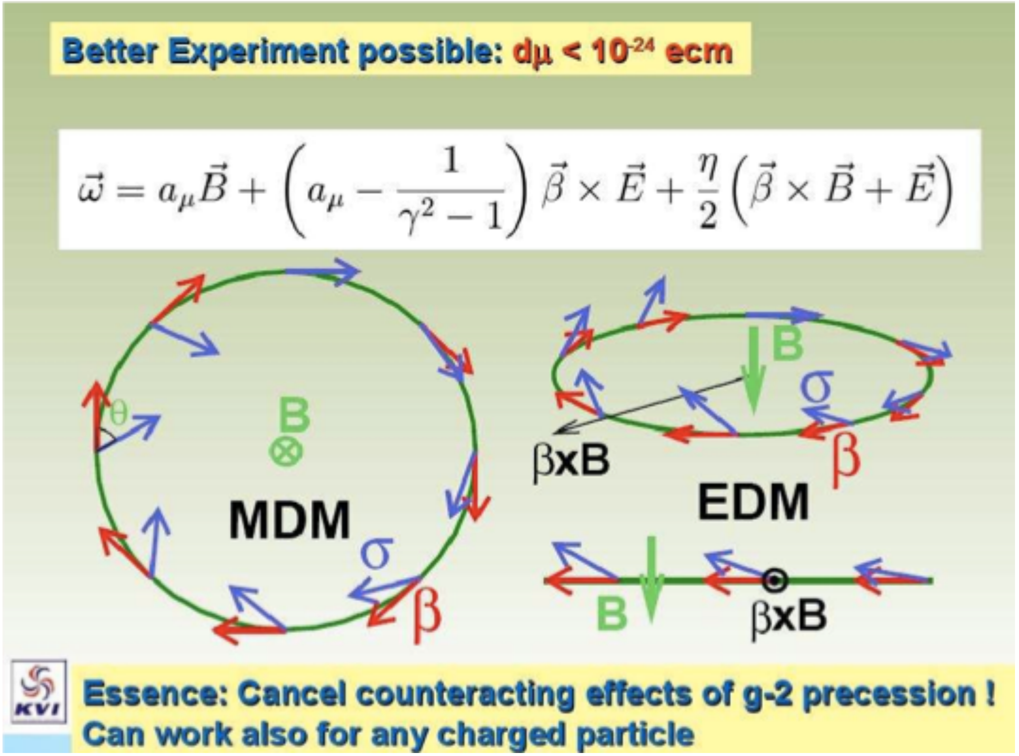
Rotating particles in a storage ring feel very strong central effective electric field

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 <u>light nuclei</u> is accurately measurable!**

(experiment currently under preparation)

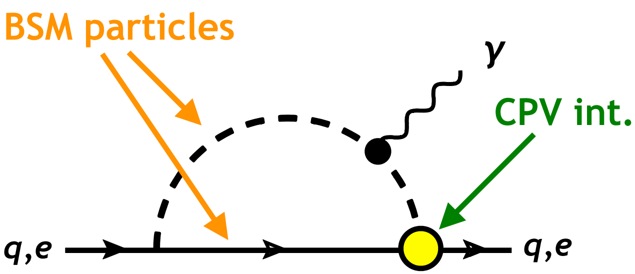
EDM from physics beyond Standard model

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

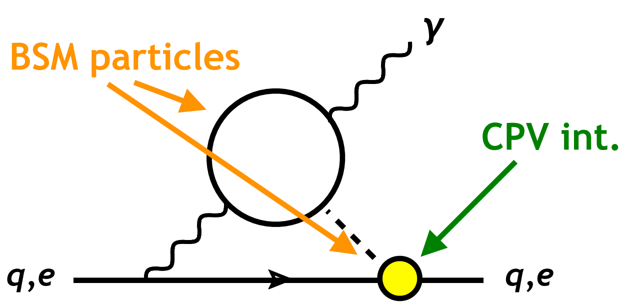
$$-\frac{i}{2} d_\psi \bar{\psi} \sigma_{\mu\nu} F^{\mu\nu} \gamma_5 \psi \quad \xrightarrow{\text{Nonrela. lim.}} \quad d_\psi \vec{\sigma} \cdot \vec{E}$$

EDM is generated by CP violating interactions.

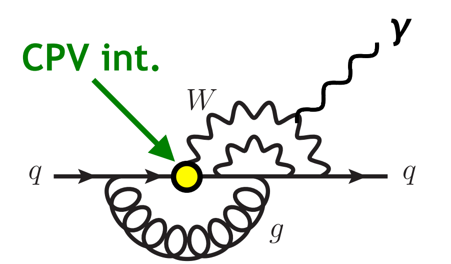
Can be calculated using Feynman diagrams:



1-loop diagram
(e.g. SUSY)



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



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

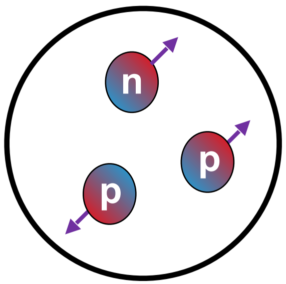
EDM receives very small contribution from SM,
whereas BSM new physics may contribute at low loop level :

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

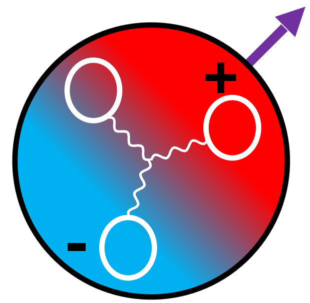
EDM of composite systems

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.

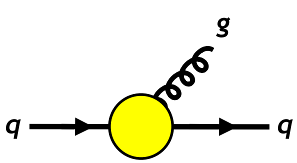


EDM of constituents

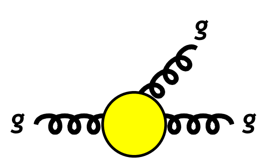


CP-odd many-body interaction

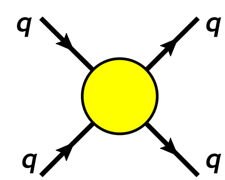
Example of QCD level many-body interactions inducing nucleon EDM:



quark chromo-EDM



Weinberg operator



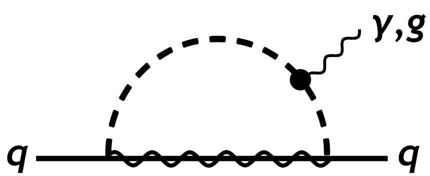
P, CP-odd 4-quark interaction

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

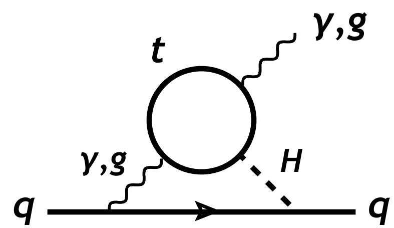
Dimension-6 QCD level interactions and their origin

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

Quark EDM, chromo-EDM:



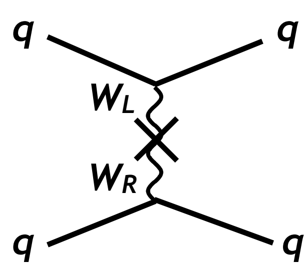
SUSY: 1-loop

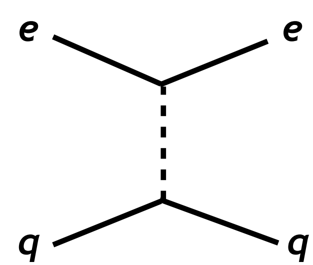


2-Higgs doublet: 2-loop

CP-odd 4-fermion interaction:

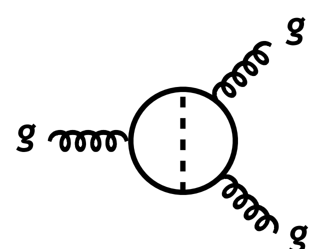
Tree level:
* Left-right sym.
* Scalar exchange





Weinberg operator:

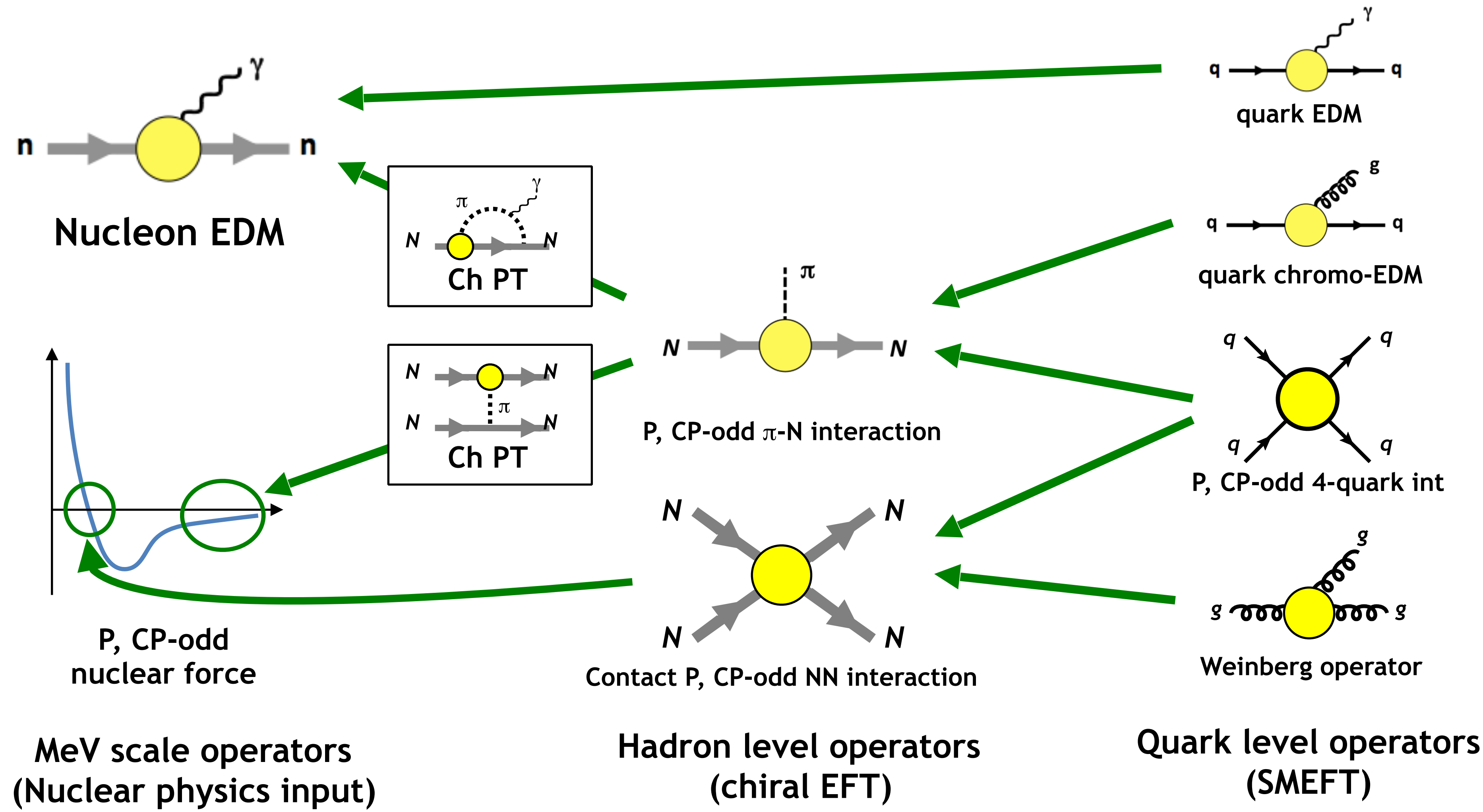
2-loop diagram:
* 2-Higgs doublet model
* Vectorlike quark model



Probe BSM sectors
without mixing
with light quarks

Nucleon level CP violation from subhadronic physics

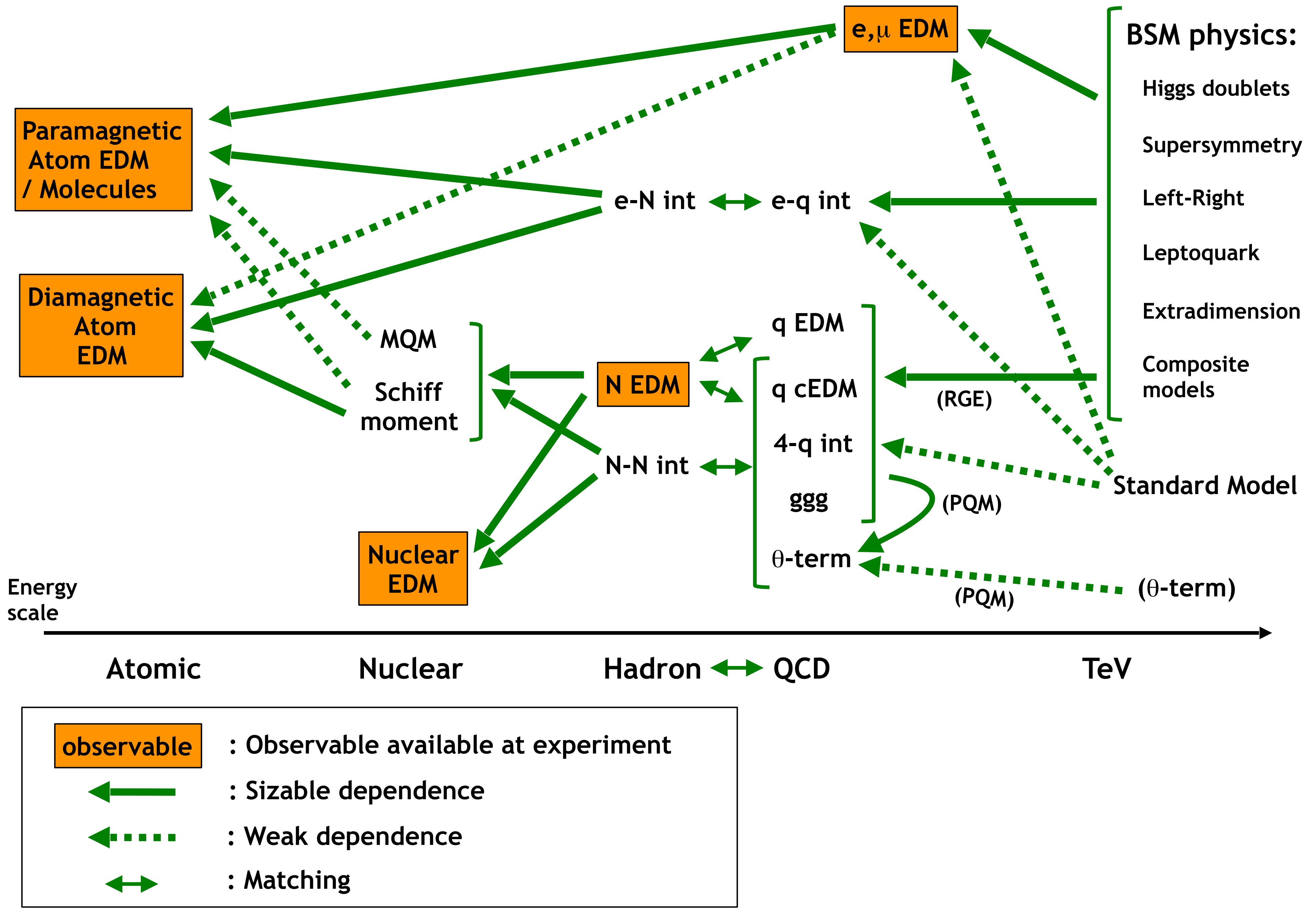
Much chiral EFT / lattice QCD works in the past. Current understanding is like



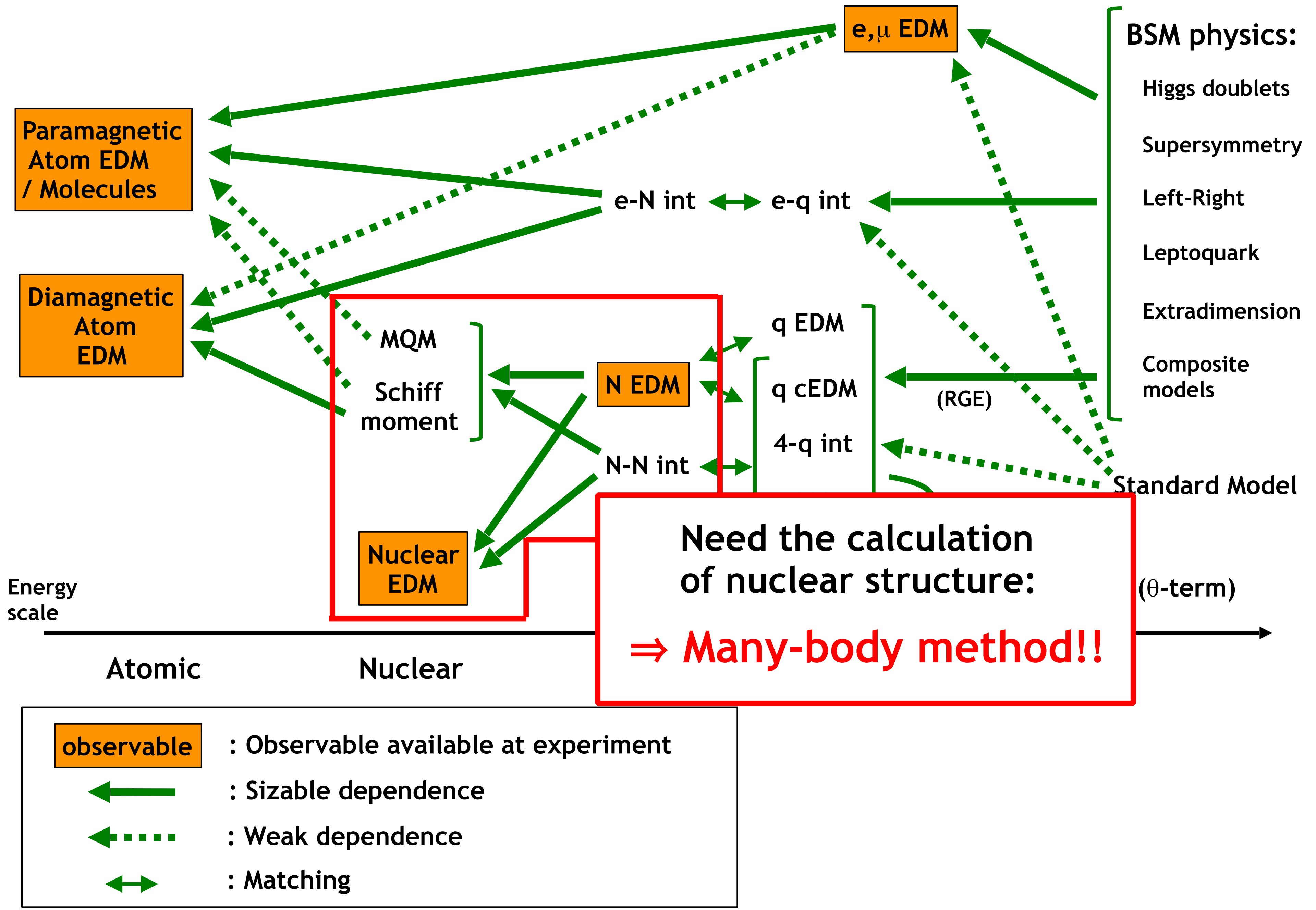
In this talk, we do not go in the detail of the subhadronic CP violation.

We treat nucleon EDM and CP-odd N-N couplings as small variables

EDM from elementary level CP violation



EDM from elementary level CP violation



What we want to do

⇒ Nucleon level CPV is unknown and small : linear dependence

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!

⇒ Linear coefficients depend only on the nuclear structure

⇒ We must calculate the nuclear structure with nucleon level CPV

Important goals:

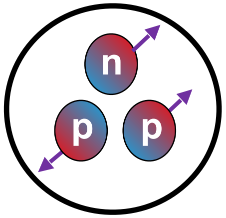
- We want to find sensitive nuclei i.e. with large linear coefficients
- Calculating coefficients for several nuclei is required to disentangle unknown new physics couplings : system of linear equations cannot be solved with only one nuclear EDM experimental data!

Nuclear EDM from nucleon level CP violation

Two leading contributions:

1) Nucleon's intrinsic EDM:

Contribution from the nucleon EDM

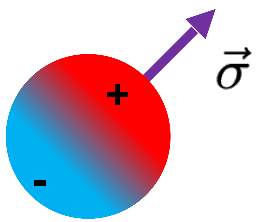


$$D^{(\mathrm{Nedm})} = \frac{1}{2}\sum_{i=1}^{A}\langle\psi|\,[(d_p+d_n)+(d_p-d_n)\tau_i^z]\sigma_i^z\,|\psi\rangle$$

⇒ 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

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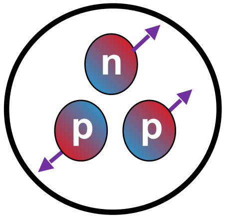
1) Nucleon's intrinsic EDM:

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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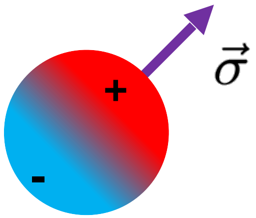
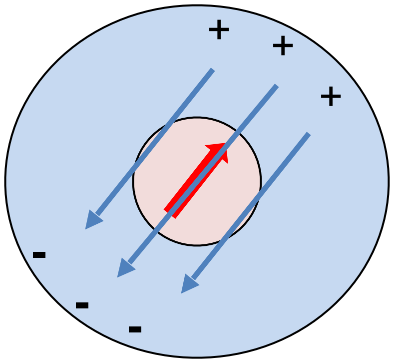


$$D^{(\mathrm{pol})} = \frac{e}{2}\sum_{i=1}^{A} \langle\psi| \,(1+\tau_i^z) z_i \,|\tilde{\psi}\rangle + (\mathrm{c.c.})$$

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

May be enhanced by many-body effect!

Nuclear EDM in atoms : Schiff moment



Nuclear EDM screened by rearrangement of atomic electrons, but not completely!

⇒ Residual effect : nuclear Schiff moment

Schiff moment operator:

$$\hat{S} \equiv \frac{e}{2}\sum_{p=1}^{Z}\left(\frac{1}{5}r_p^2 - \frac{1}{3}\langle r^2\rangle_{\rm ch}\right) r_p + \sum_{N=1}^{A}\left\{\frac{1}{6}\left(r_N^2 - \langle r^2\rangle_{\rm ch}\right)\mathbf{d}_N + \frac{1}{5}\left((\mathbf{r}_N\cdot\mathbf{d}_N)\mathbf{r}_N - \frac{r_N^2}{3}\mathbf{d}_N\right)\right\}$$

Polarization due to CP-odd nuclear force: Need mixing of s-p waves

Contribution of intrinsic nucleon EDM

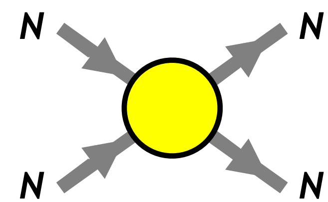
L. I. Schiff, Phys. Rev. **132**, 2194 (1963).

Nuclear moment (polarization) from CP-odd nuclear force

Electric dipole operator requires CP mixing to have finite expectation value

Total hamiltonian:

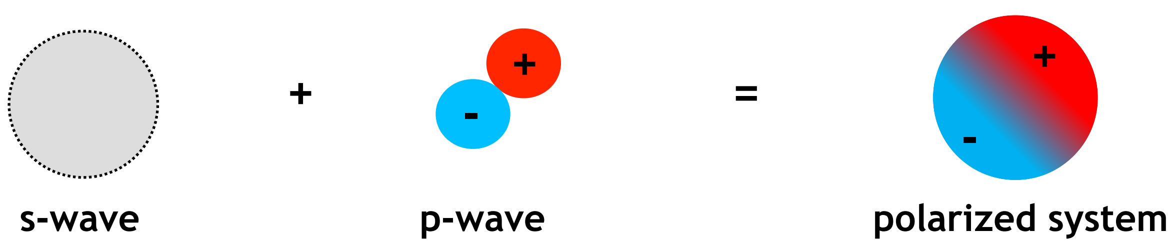
$$H = \begin{pmatrix} H_{\text{realistic}} & H_{\not{P}\not{T}} \\ H_{\not{P}\not{T}} & H_{\text{realistic}} \end{pmatrix}$$



P, CP-odd nuclear force

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

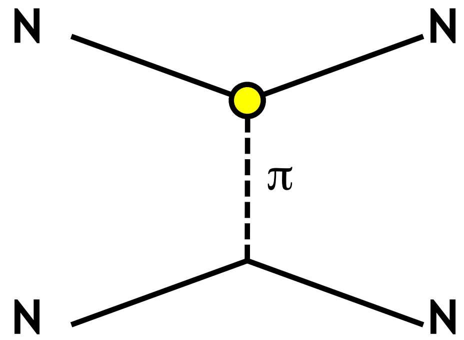
CP-odd N-N interactions mixes opposite parity states



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):**

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

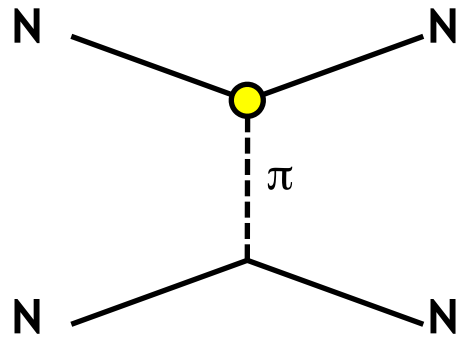
Isoscalar — Isotensor — Isovector

- **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, …

P, CP-odd nuclear force from one pion exchange

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



Isocalar CPV NN-int. :

Axion DM, SUSY,...

$i\gamma_5 N$

- P, CP-odd Hamiltonian (3-types):

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

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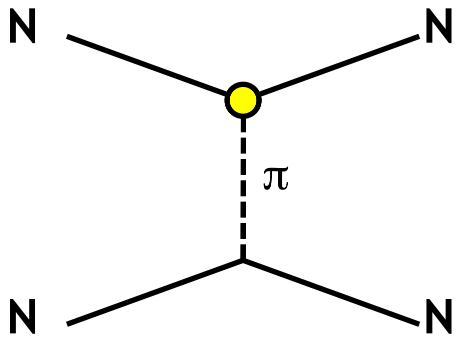

Isocalar CPV NN-int. :
Axion DM, SUSY,...

$i\gamma_5$

Isovector CPV NN-int. :
Higgs, SUSY, ...

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

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Results

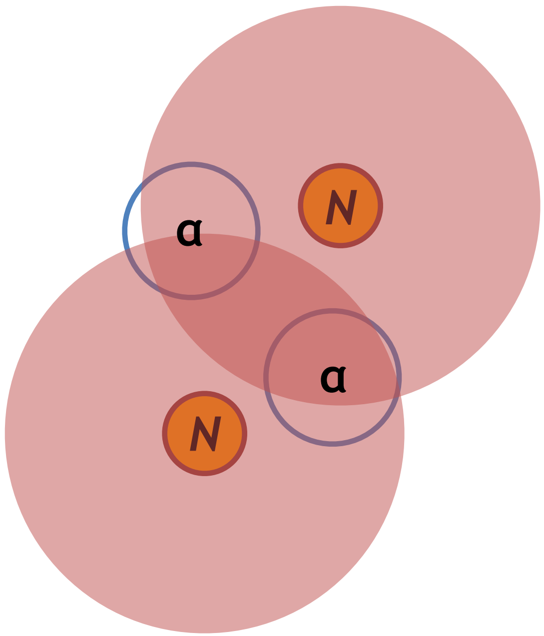
EDM	isoscalar (a_0)	isovector (a_1)	isotensor (a_2)	
^{129}Xe atom K. Yanase et al., PRC **102**, 065502 (2020) A. Sakurai et al., PRA **100**, 0320502 (2019)	-1.2×10^{-6} *e* fm	-1.3×10^{-6} *e* fm	-2.6×10^{-6} *e* fm	atoms
^{199}Hg atom K. Yanase et al., PRC **102**, 065502 (2020) B. K. Sahoo et al., PRL **120**, 203001 (2018)	-1.4×10^{-5} *e* fm	-1.3×10^{-5} *e* fm	-2.6×10^{-5} *e* fm	atoms
^{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	atoms
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	–	nuclei
^{3}He nucleus Bsaisou et al., JHEP **1503** (2015) 104 NY et al., PRC **91**, 054005 (2015)	0.015 *e* fm	0.0108 *e* fm	0.026 *e* fm	nuclei
^{6}Li nucleus NY et al., PRC **91**, 054005 (2015)	–	0.022 *e* fm	–	nuclei
^{7}Li nucleus NY et al., PRC **100**, 055501 (2019)	– 0.015 *e* fm	0.016 *e* fm	– 0.026 *e* fm	nuclei
^{9}Be nucleus NY et al., PRC **91**, 054005 (2015)	0.01 *e* fm	0.014 *e* fm	0.01 *e* fm	nuclei
^{11}B nucleus NY et al., PRC **100**, 055501 (2019)	– 0.01 *e* fm	0.016 *e* fm	– 0.02 *e* fm	nuclei
^{13}C nucleus NY et al., PRC 95,065503 (2017)	– 0.003 *e* fm	–0.0020 *e* fm	– 0.003 *e* fm	nuclei
^{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	nuclei
Simple shell model O. P. Sushkov et al., Sov. JETP **60**, 873 (1984)	O(0.01) *e* fm	0.07 *e* fm	O(0.01) *e* fm	nuclei

Results

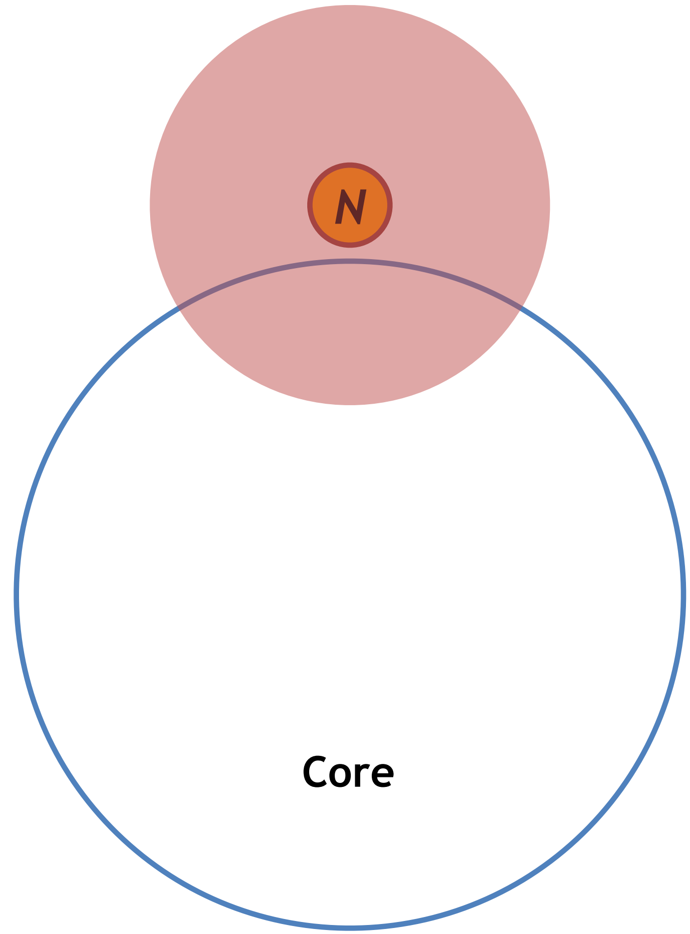
EDM	isoscalar (a_0)	isovector (a_1)	isotensor (a_2)	
^{129}Xe atom K. Yanase et al., PRC **102**, 065502 (2020) A. Sakurai et al., PRA **100**, 0320502 (2019)	-1.2×10^{-6} *e* fm	-1.3×10^{-6} *e* fm	-2.6×10^{-6} *e* fm	atoms
^{199}Hg atom K. Yanase et al., PRC **102**, 065502 (2020) B. K. Sahoo et al., PRL **120**, 203001 (2018)	-1.4×10^{-5} *e* fm	-1.3×10^{-5} *e* fm	-2.6×10^{-5} *e* fm	atoms
^{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	atoms
Neutron Crewther et al. , PLB 88,123 (1979) Mereghetti et al., PLB 696, 97 (2011)	0.01 *e* fm	–		nuclei
Deuteron Liu et al., PRC **70**, 055501 (2004) NY et al., PRC **91**, 054005 (2015)	–	0.0145 *e* fm		nuclei
^{3}He nucleus Bsaisou et al., JHEP **1503** (2015) 104 NY et al., PRC **91**, 054005 (2015)	0.015 *e* fm	0.0108 *e* fm	0.026 *e* fm	nuclei
^{6}Li nucleus NY et al., PRC **91**, 054005 (2015)	–	0.022 *e* fm	–	nuclei
^{7}Li nucleus NY et al., PRC **100**, 055501 (2019)	– 0.015 *e* fm	0.016 *e* fm	– 0.026 *e* fm	nuclei
^{9}Be nucleus NY et al., PRC **91**, 054005 (2015)	0.01 *e* fm	0.014 *e* fm	0.01 *e* fm	nuclei
^{11}B nucleus NY et al., PRC **100**, 055501 (2019)	– 0.01 *e* fm	0.016 *e* fm	– 0.02 *e* fm	nuclei
^{13}C nucleus NY et al., PRC 95,065503 (2017)	– 0.003 *e* fm	–0.0020 *e* fm	– 0.003 *e* fm	nuclei
^{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	nuclei
Simple shell model O. P. Sushkov et al., Sov. JETP **60**, 873 (1984)	O(0.01) *e* fm	0.07 *e* fm	O(0.01) *e* fm	nuclei

Consistent with recent ab initio calculations!
Froese, Navratil, PRC **104**, 025502 (2021).

Physics of nuclear EDM: light and heavy nuclei

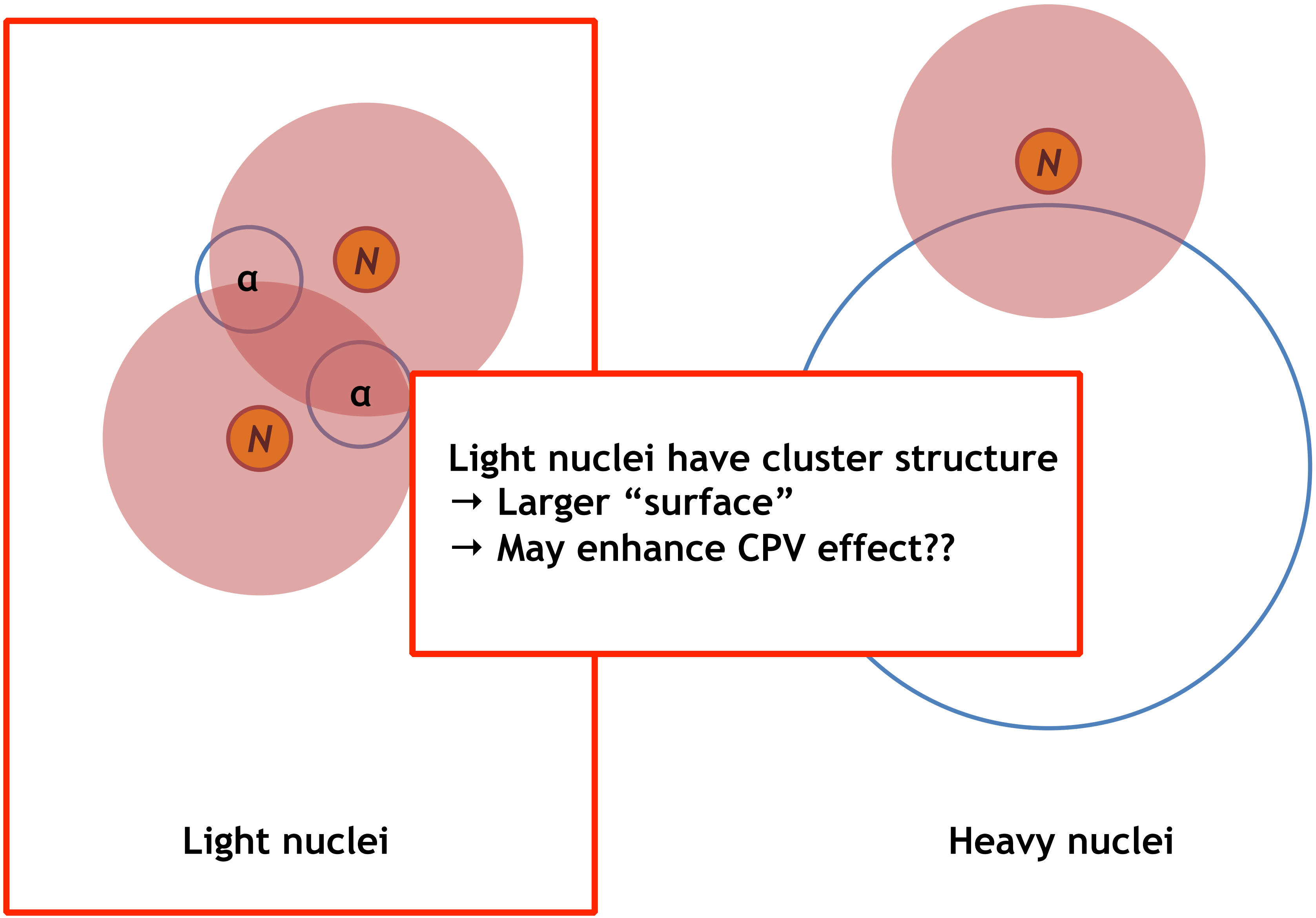


Light nuclei



Heavy nuclei

Physics of nuclear EDM: light and heavy nuclei



Light nuclei have cluster structure
→ Larger "surface"
→ May enhance CPV effect??

Light nuclei

Heavy nuclei

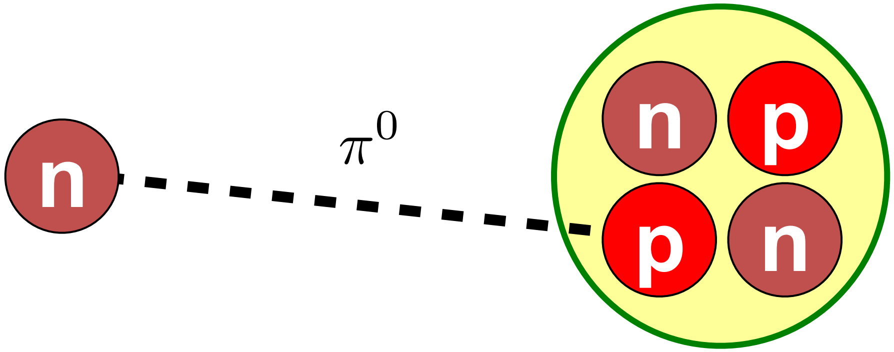
CP-odd α-N & α-t interactions

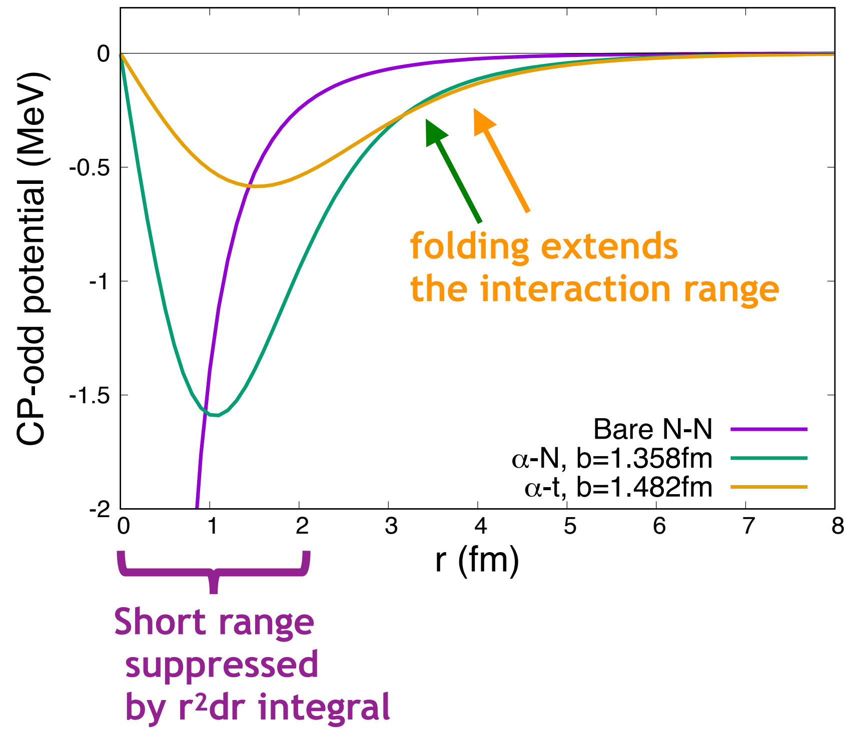
Folding the CP-odd N-N interaction with ^{4}He (α) and/or ^{3}H (*t*) cluster

(α & *t* cluster are indestructible)

Folding : direct part of RGM interaction kernel

H. Horiuchi, PTP Suppl. **62**, 90 (1977).





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)

NY, Int. J. Mod. Phys. E **26**, 1730002 (2017).

EDM of light nuclei and counting rule

EDM of light nuclei can be measured using storage rings
⇒ No Schiff's screening
⇒ Very high sensitivity to new physics expected

- Isovector coupling obeys a counting rule

$$d_A^{(pol)} \sim d(^{2/3}H) + n \times 0.005\, G_\pi^{(1)}\, e\ \mathrm{fm}$$

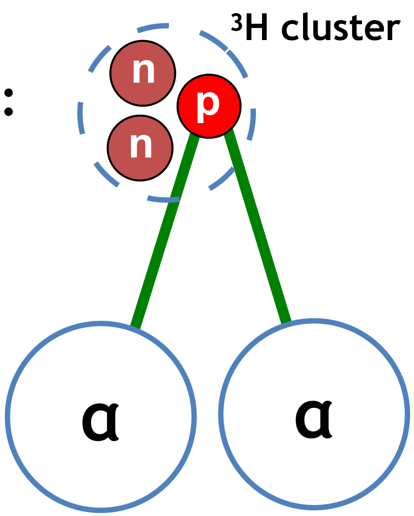
EDM of cluster with open shell

α-N polarization (times # α-N combinations)

⇒ Explained by the cluster structure

NY, T. Yamada, Y. Funaki, PRC **100**, 055501 (2019)

Example of ^{11}B EDM:



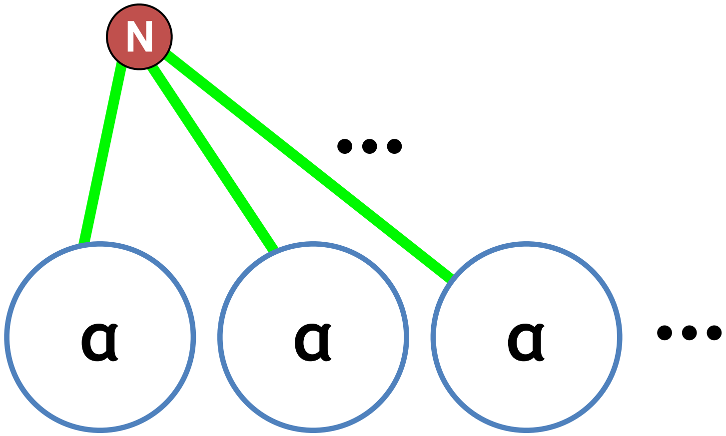
$d_{^{11}B} = 0.02\, G^{(1)}_\pi\, e$ fm

- Isoscalar and isotensor appears from single valence nucleon and ^{3}H cluster (vanish for α-N polarization)

NY, Int. J. Mod. Phys. E **26**, 1730002 (2017).

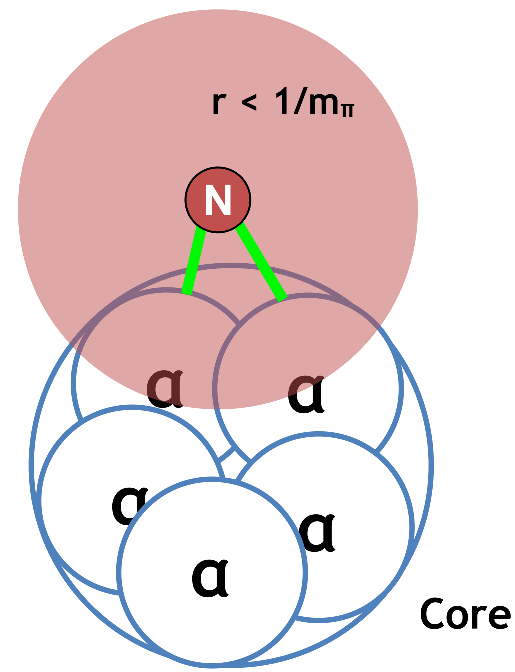
EDM of heavy nuclei : simple shell model

EDM of larger nuclei is larger?



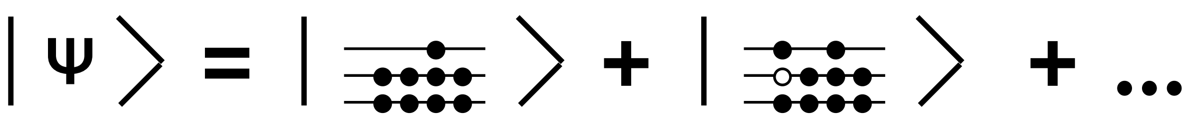
d_A = (A/4) x (α-N polarization) ??

No!



Problems:

- pion is massive, nucleon cannot interact with the other side of the nucleus
- CP-odd nuclear force is a derivative interaction, interact with the surface
- Large nuclei have configuration mixings (destructive interference of angular momentum of valence nucleons)



We should have some upper limit in the sensitivity $d_A \sim 0.07\, G_\pi^{(1)}$ e fm

EDM diamagnetic atoms: ^{129}Xe and ^{199}Hg

EDMs (Schiff moments) of ^{129}Xe and ^{199}Hg are experimentally interesting:
⇒ Recently calculated in large scale shell-model

- ^{129}Xe (atomic) EDM:

$$d_{Xe} = -\,1.0 \times 10^{-5}\, d_n + (-1.2\, \bar{G}_\pi^{(0)} - 1.3\, \bar{G}_\pi^{(1)} - 2.6\, \bar{G}_\pi^{(2)}) \times 10^{-6}\ e\ \mathrm{fm}$$

[Used the atomic level calculation of A. Sakurai et al., PRA **100**, 020502 (2019)]

- ^{199}Hg (atomic) EDM:

$$d_{Hg} = -\,4.7 \times 10^{-4}\, d_n + (-1.4\, \bar{G}_\pi^{(0)} - 1.3\, \bar{G}_\pi^{(1)} - 2.6\, \bar{G}_\pi^{(2)}) \times 10^{-5}\ e\ \mathrm{fm}$$

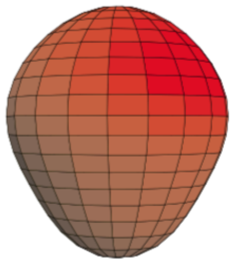
[Used the atomic level calculation of B. K. Sahoo et al., PRL **120**, 203001 (2018)]

Some notable points:

- Atomic EDM looses sensitivity due Schiff's screening, but the very high experimental sensitivity covers this loss (limit to neutron EDM from ^{199}Hg EDM experiment comparable to direct neutron EDM experiment).
- Valence proton EDM effect is small, but may be large in octuple deformed nuclei (e.g. ^{225}Ra).
- Isoscalar CPV NN force also contributes to the valence neutron EDM, but the polarization effect is larger (nuclear enhancement).

N. Yoshinaga et al., PTP **124**, 1115 (2010);
K. Yanase and N. Shimizu, PRC **102**, 065502 (2020);
K. Yanase, PRC **103**, 035501 (2021)

Schiff moment of octuple deformed nuclei: enhancement



Octupole deformation

⇒ parity doubling due to axially asymmetric shape

⇒ close opposite parity levels

⇒ enhance nuclear Schiff moment

Octupole deformation occurs in heavy nuclei (^{225}Ra, ^{223}Rn, ^{223}Fr, etc)

Comparison of Schiff moment with ^{199}Hg:

	a_0(isoscalar)	a_1(isovector)	a_2(isotensor)
^{225}Ra	-1.5 e fm^3	6.0 e fm^3	-4.0 e fm^3
^{199}Hg	0.08 e fm^3	0.08 e fm^3	0.14 e fm^3

J. Dobaczewski and J. Engel, Phys. Rev. Lett. **94**, 232502 (2005)
J. Dobaczewski et al., Phys. Rev. Lett. **121**, 232501 (2018).
(Comparison ^{199}Hg result of Yanase and Shimizu, PRC **102**, 065502 (2020)

➡ Octupole deformation enhances by O(100) times!!

^{19}F EDM

^{19}F has several interesting features:

- $1/2^+_1$ - $1/2^-_1$ energy splitting : Only 110 keV!

  ⇒ Enhancement of EDM??

- g-2 = +0.629

  Positive g-2 ⇒ Easy to measure in storage ring experiment

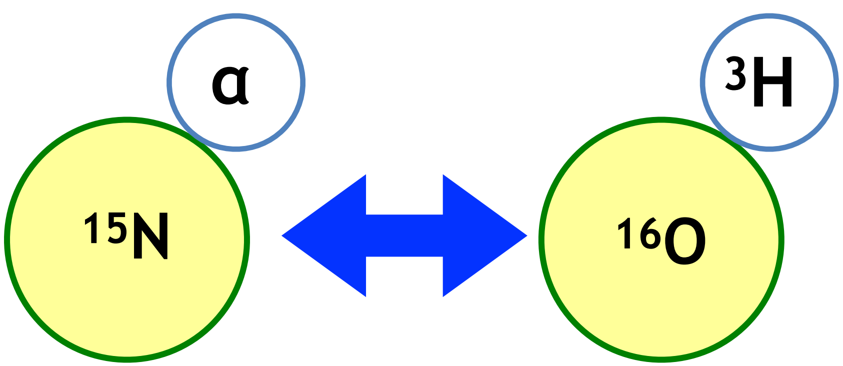
- May also be used in diatomic molecule beam experiments

- Difficult to handle in shell model (calculated ab initio, but…)

  Froese, Navratil, PRC **104**, 025502 (2021).

- Coupled channel ^{15}N+α -^{16}O+^{3}H cluster structure

  T. Sakuda et al., Prog. Theor. Phys. **62**, 1274 (1979.)



Interesting as next target of study!

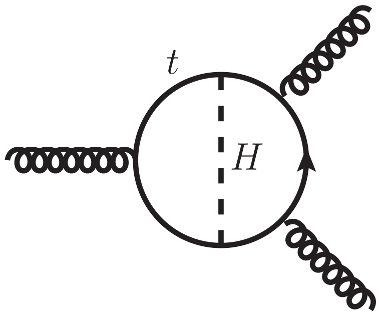
Weinberg operator

$$\mathcal{L}_w = \frac{1}{3!} w f^{abc} \epsilon^{\alpha\beta\gamma\delta} G^a_{\mu\alpha} G^b_{\beta\gamma} G^{\mu,c}_{\delta}$$ (= gluon chromo-EDM)

Induced in many candidates of BSM physics,

especially in extended Higgs models

S. Weinberg, Phys. Rev. Lett. **63**, 2333 (1989).



⇒ Unveiling Higgs is the most important homework in particle physics phenomenology!

The Weinberg operator contributes to the neutron and atomic EDMs, already measured in experiment (e.g. $d_n < 1.8 \times 10^{-26}$ e cm)

C. Abel et al., Phys. Rev. Lett. **124**, 081803 (2020).

Due to the gluonic structure, it is difficult to quantify its effect

⇒ This is the last frontier of EDM study !

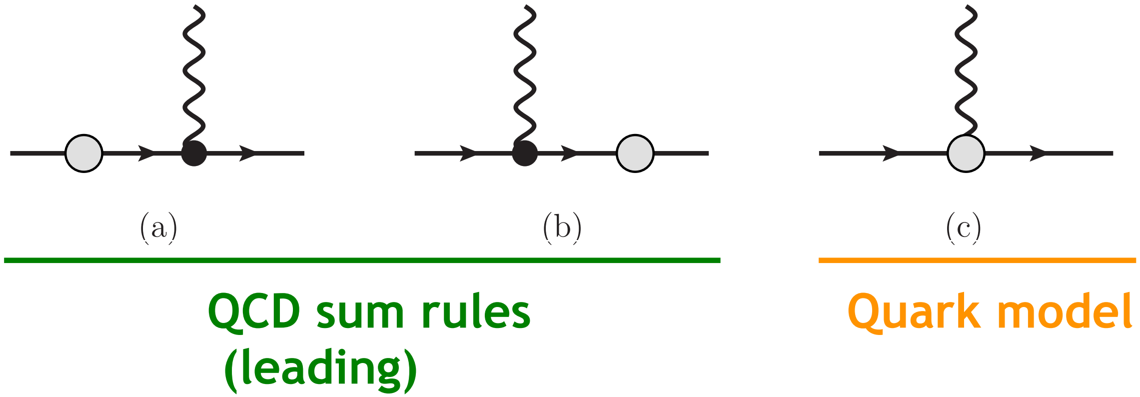
Valence nucleon EDM generated by Weinberg operator

Nucleon EDM:

$$d_N = \begin{cases} w \times (20 \pm 12)\, e\,\mathrm{MeV} & (N = n) \\ -w \times (18 \pm 11)\, e\,\mathrm{MeV} & (N = p) \end{cases}$$

(w : Weinberg operator coupling)

➡ **Combination of results using QCD sum rules and quark model**



Chiral rotation contribution (QCD sum rules, (a) and (b)) is leading

NY and E. Hiyama, Phys. Rev. D **103**, 035023 (2021) .

Summary

- Standard model cannot explain the matter abundance of the Universe: new physics with large CP violation is needed.
- EDM is a very good probe of BSM CP violation.
- CP violation may be enhanced by many-body effect.
- EDM of light nuclei (j=l+1/2) obeys counting rule.
- Heavy nuclei are not more sensitive than light nuclei due to the range of pion exchange, surface, and configuration mixing
  ⇒ Light nuclei are maybe the best probe of CPV for EDM exp.

  (exception may be the octuple deformed or easily deformable nuclei)

Future studies:

- Study ^{19}F EDM.
- Quantification of Weinberg operator contribution to nuclear CP-odd moments : enhanced in nuclei?
- We are waiting for storage ring EDM experiments!

Advertisement

- For details of nuclear EDM calculation, see

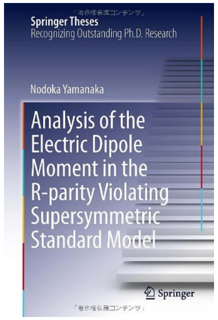
  N. Yamanaka,
  Review of the electric dipole moment of light nuclei,
  International Journal of Modern Physics E 26, 1730002 (2017)
  arXiv:1609.04759 [nucl-th].

- 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 !!