Enhancements and suppressions of CP violating effect in the nucleons, nuclei, and atoms: role of the spin

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(IPN Orsay)

2018/09/12

Spin 2018

Ferrara

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

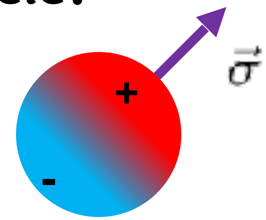
	ratio photon : matter
Prediction of Standard model:	$10^{20} : 1$
Real observed data:	$10^{10} : 1$

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:** $\vec{d} \propto \vec{\sigma}$ ⇒ Parallel with the spin (angular momentum)
  (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 !

Aim of this talk

The EDM can experimentally be measured in many systems

(Neutron, atoms, muon, electron in molecules, etc)

There are also much experimental R & D, with new techniques

(Proton, nuclei, heavy hadrons, tau, electrons in other systems,...)

We must know how the elementary level CP violation and the EDM of the above systems are related in theory

Are there enhancements, suppressions, specific sensitivity...?

This is a disorganized review of mechanisms of enhancement and suppression of hadronic, nuclear and atomic CP violating contributions to the EDM

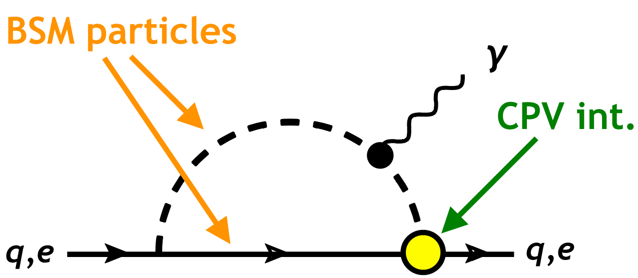
EDM from physics beyond Standard model

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

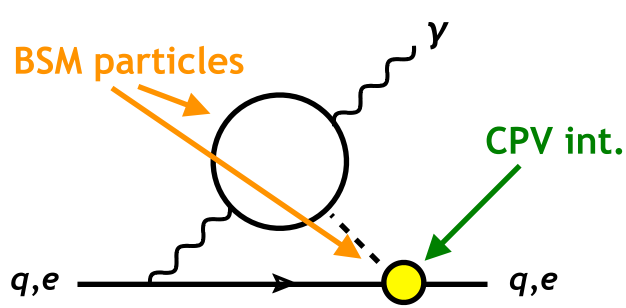
$$-\frac{i}{2} d_\psi \bar{\psi} \sigma_{\mu\nu} F^{\mu\nu} \gamma_5 \psi \quad \xrightarrow[\text{Nonrela. lim.}]{} \quad -d_\psi \sigma \cdot \mathbf{E}$$

EDM is generated by CP violating interactions.

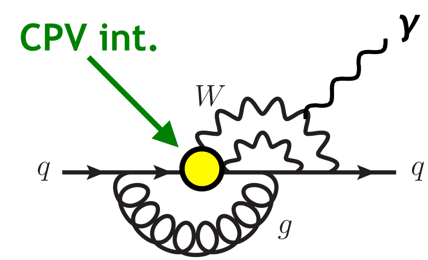
Can be calculated using Feynman diagrams:



1-loop diagram
(e.g. SUSY)



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



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

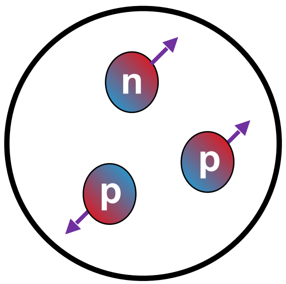
EDM receives very small contribution from SM,
whereas BSM new physics may contribute with low loop level :

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

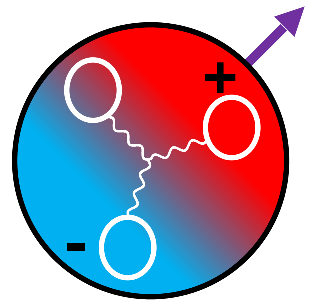
EDM of composite systems

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

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

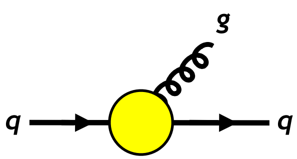


EDM of constituents

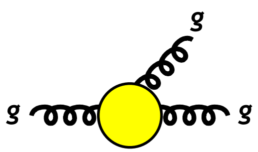


CP-odd many-body interaction

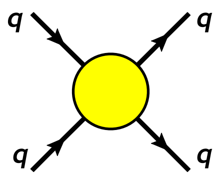
Example of QCD level many-body interactions inducing neutron EDM:



quark chromo-EDM



Weinberg operator



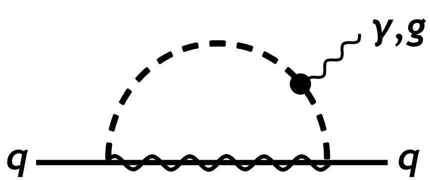
P, CP-odd 4-quark interaction

Effect of CPV many-body interaction may be enhanced/suppressed!

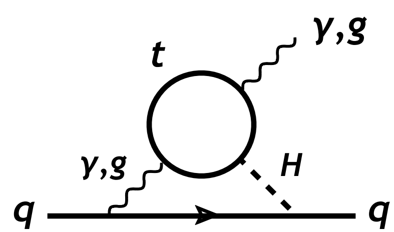
Elementary level CP violation and its origin

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

Quark EDM, chromo-EDM:



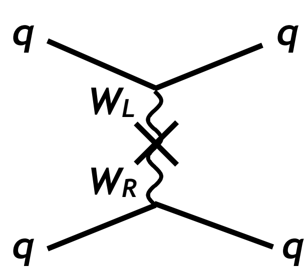
SUSY: 1-loop

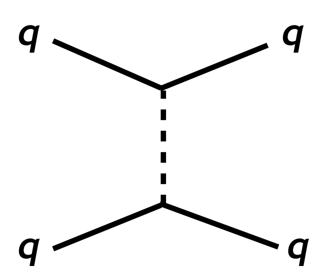


2-Higgs doublet: 2-loop

CP-odd 4-quark interaction:

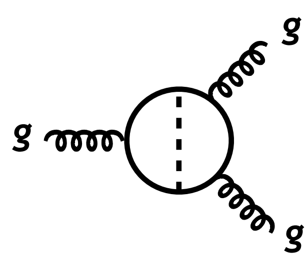
Tree level:
* Left-right sym.
* Scalar exchange





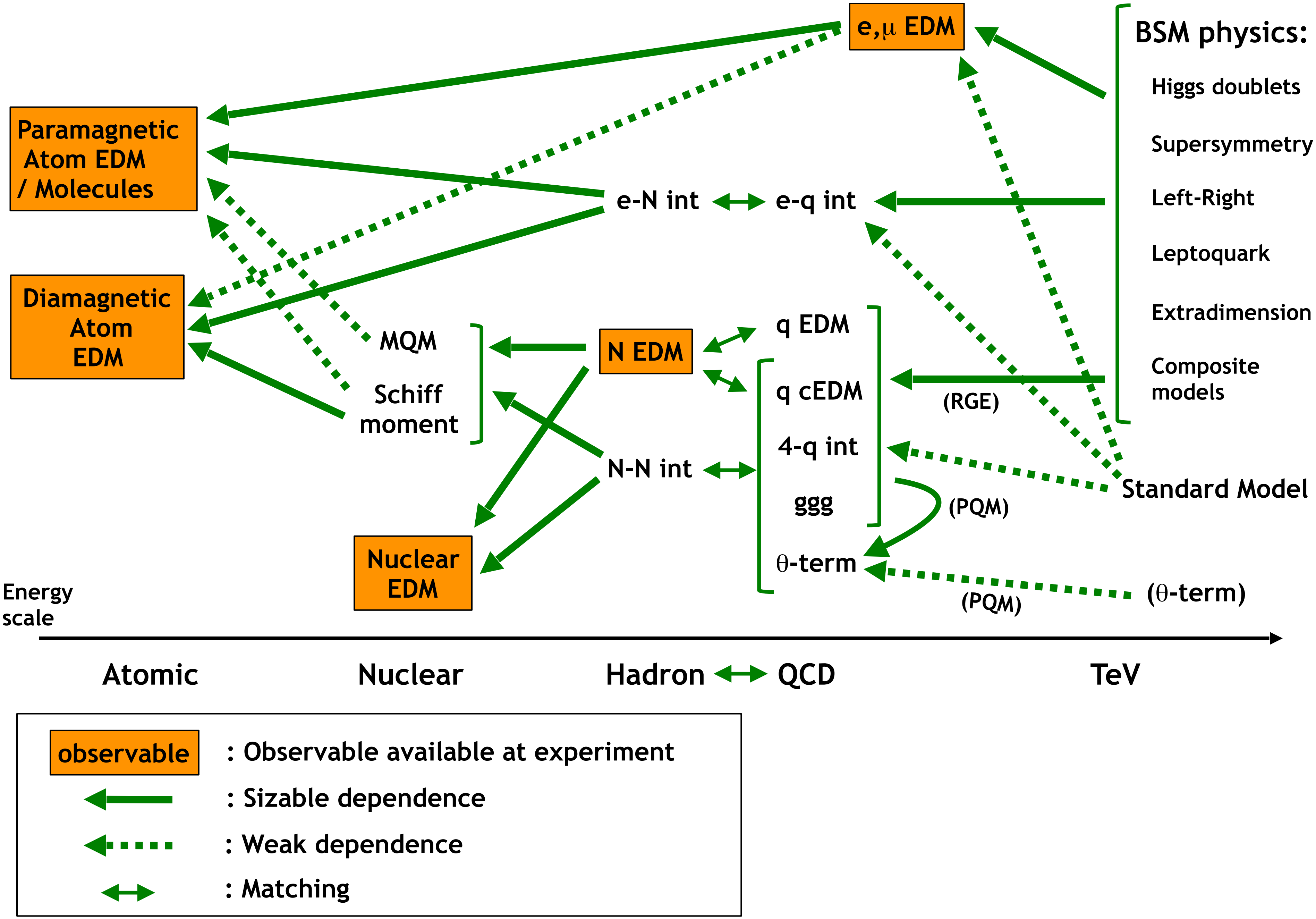
Weinberg operator:

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



Probe BSM sectors
without LO interaction
with light quarks

EDM from elementary level CP violation



What we want to find

⇒ Elementary level CPV is unknown and small : can be factorized

Unknown CP violating couplings beyond the standard model

$$d_A = (a_\pi^{(0)}\,\bar{G}_\pi^{(0)} + a_\pi^{(1)}\,\bar{G}_\pi^{(1)})\ e\ \mathrm{cm} + K_e\, d_e + \ldots$$

Depends on the structure of the system!

⇒ Linear coefficients depends only on the structure of the system, not in NP

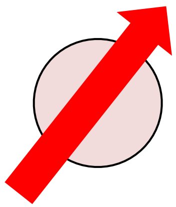
⇒ We want to evaluate coefficients and find interesting systems!

⇒ We want to find systems with large enhancement factors

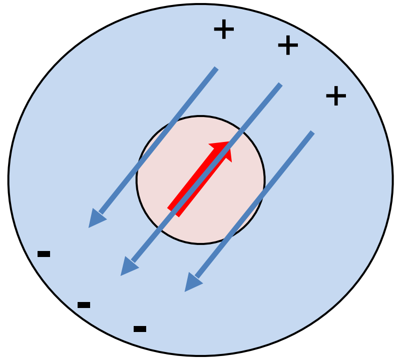
(or understand and avoid suppression)

Atomic EDM and Schiff's screening

In atoms, EDM of nonrelativistic constituents suffers Schiff's screening



EDM of bare constituent



Atomic EDM :
screening via rearrangement

Typically, looses sensitivity by α_{QED}^2 ~ 10^{-4}

3 leading P, CP-odd processes in atoms :

- **Relativistic effect of constituents** (electrons in heavy atoms)
- **CP-odd electron-nucleon interaction**
- **Schiff moment** (residual nuclear moment due to nuclear finite size)

$$S = \sum_i \frac{\langle \Psi_0 | \hat{S} | \Psi_i \rangle \langle \Psi_i | W | \Psi_0 \rangle}{E_0 - E_i} + \mathrm{c.c.}$$

Schiff moment operator: $\hat{S} \equiv \frac{e}{2} \sum_{p=1}^{Z} \left(\frac{1}{5} r_p^2 - \frac{1}{3} \langle r^2 \rangle_{\mathrm{ch}} \right) r_p$

W: P, CP-odd N-N interaction

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

Electron EDM in atoms/molecules : relativistic enhancement

Electron EDM is enhanced in heavy paramagnetic atoms/molecules due to the relativistic effect

P. G. H. Sandars, Phys. Lett. 14, 194 (1965); Phys. Lett. 22, 290 (1966).

$$d_A = \sum_n \frac{\langle \Psi_0 | -e\sum_i^Z z_i | \Psi_n \rangle \langle \Psi_n | d_e \sum_j^Z \underline{(1-\beta_j)} \boldsymbol{\sigma}_j \cdot \mathbf{E}_j | \Psi_0 \rangle}{E_n - E_0} = K_e d_e$$

Relativistic effect :
Not canceled by Schiff theorem

Paramagnetic atoms:

	K_e	Limit to d_e	
Tl atom	-585	1.6×10^{-27}e cm	Regan et al., PRL **88**, 071805 (2002)
Fr atom	-910	–	Sakemi et al., on-going

Paramagnetic polar molecules : enhancement due to parity doubling

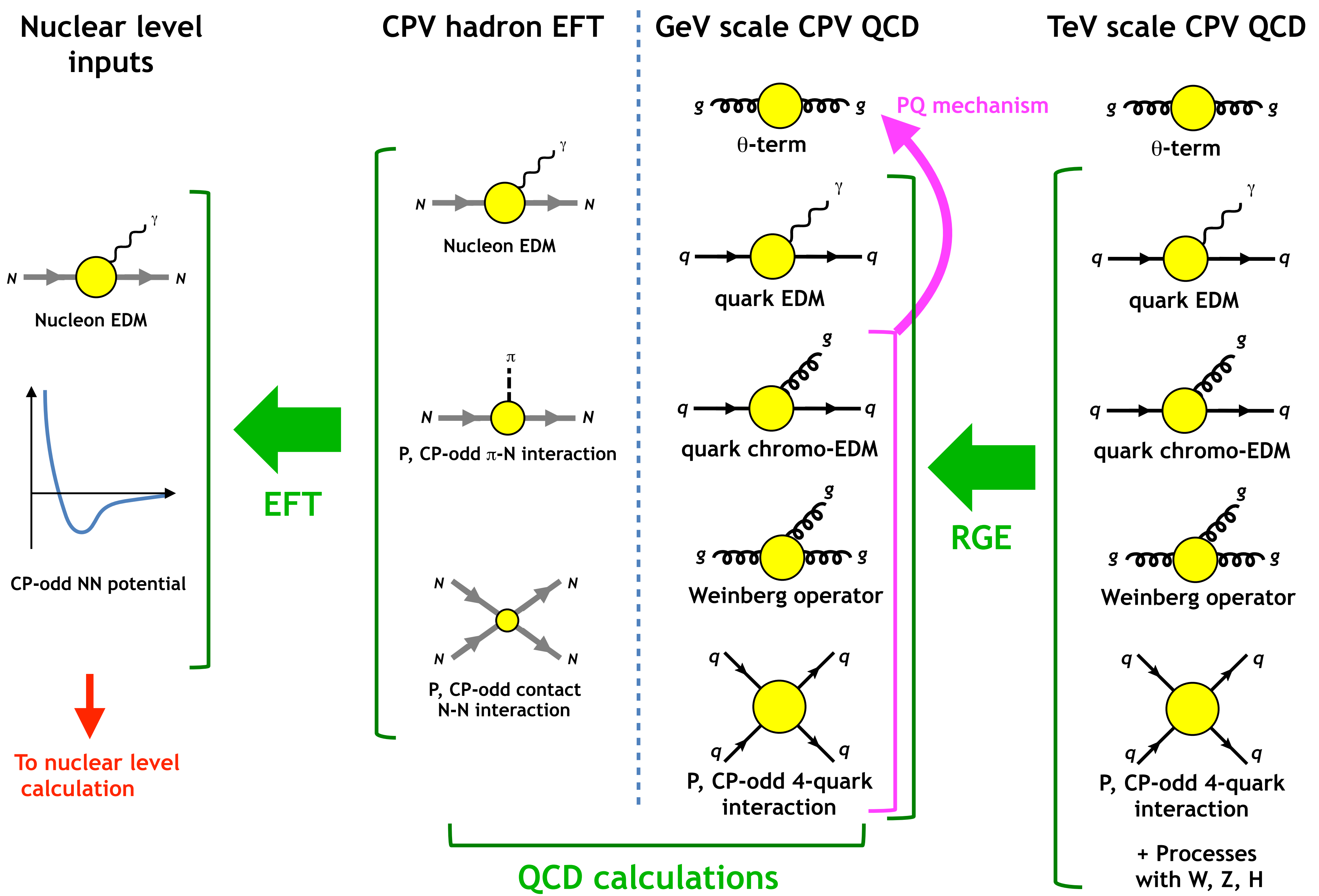
	Limit to d_e	
YbF molecule	1×10^{-27}e cm	Hudson et al., Nature **473** (2011) 493
ThO molecule	9×10^{-29}e cm	Baron et al., Science **343** (2014) 269

d_e's effect is now accurate thanks to the well established atomic level physics

(Relativistic Hartree-Fock, Relativistic coupled-cluster)

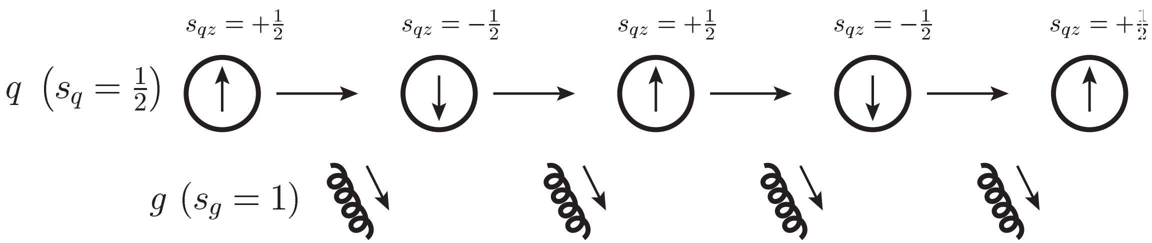
Ginges et al., Phys. Rep. **397** (2004) 63
B. P. Das et al., Handbook of Relativistic Quantum Chemistry 1-26 (2015)

Hadronic CP violation: from QCD to hadron level



Quark-gluon level enhancement/suppression

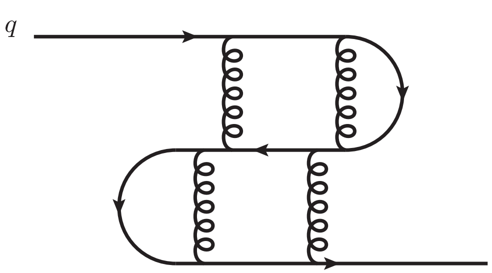
- Quark spin (tensor, axial charges) : suppression



Quark EDM is a superposition of flipping after gluon emissions/absorptions

$\Rightarrow$ Quark EDM is suppressed after QCD corrections!

- Quark scalar density : enhancement



Relativistic effect : Z graph

Scalar density of particles and antiparticles has the same sign

$\Rightarrow$ Becomes large with long worldline

$\Rightarrow$ Enhancement by relativistic effect

NY, T. M. Doi, S. Imai, H. Suganuma, Phys. Rev. D **88**, 074036 (2013).
NY, S. Imai, T. M. Doi, H. Suganuma, Phys. Rev. D **89**, 074017 (2014).

Renormalization group evolution of CPV QCD operators

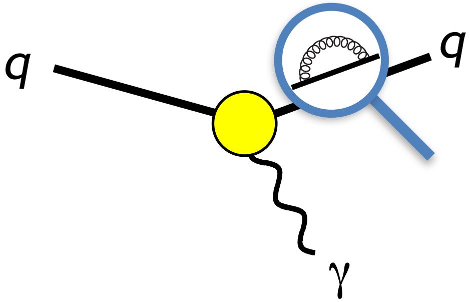
Change of energy scale modifies the coupling constants, mixes operators

Significant changes for quark/gluon operators due to QCD

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
Dekens et al. JHEP**1305**(2013)149

- **Renormalization = resummation of perturbative QCD corrections**
- **Large uncertainty due to nonperturbative effect below μ = 1 GeV**

⇒ We have to stop (perturbative) RG evolution and calculate the hadronic processes with nonperturbative methods

Renormalization group evolution of CPV QCD operators

- **Scalar density:**

$\bar{q}q \rightarrow 2\,\bar{q}q$

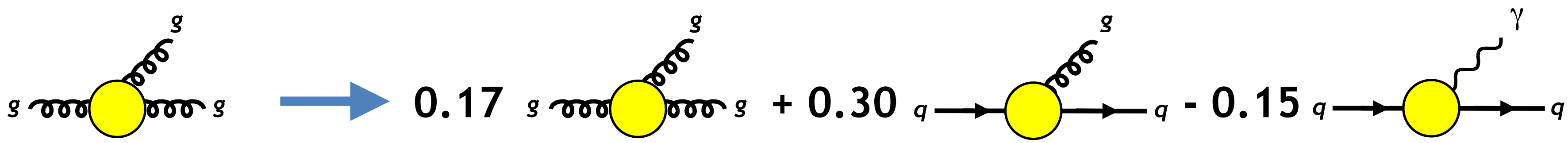
μ = 1 TeV → μ = 1 GeV

- **Quark EDM:**

$d_q \rightarrow 0.8\, d_q$

μ = 1 TeV → μ = 1 GeV

- **Weinberg operator:**



μ = 1 TeV → μ = 1 GeV

Roughly, scalar increases and spin decreases when scale goes down

Well-known nucleon matrix elements

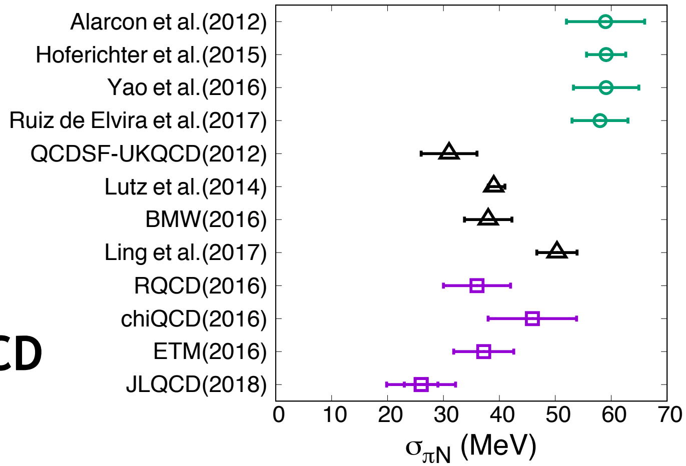
- **Nucleon scalar density:** $\langle N|\bar{q}q|N\rangle$

  Important input in EDM related ChPT

  Input of CP-odd electron-nucleon interaction

  Phenomenological extractions (ChPT), lattice QCD

  ⇒ Visible disagreement



$\langle N|\bar{q}q|N\rangle$ ~ 10 ⇒ enhanced ➡ **Obey the rough rule**

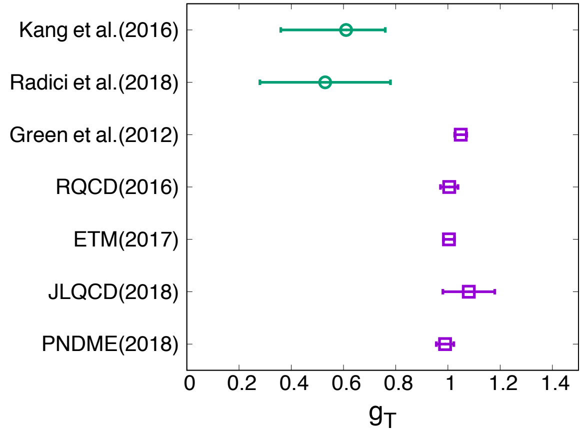
- **Nucleon tensor charge:** $\langle N|\bar{q}\sigma_{\mu\nu}q|N\rangle$

  Contribution of the quark EDM to the nucleon EDM

  Input of CP-odd electron-nucleon interaction

  Lattice QCD, phenomenological extractions (pQCD)

  ⇒ Birth of a puzzle?



$\langle N|\bar{q}\sigma_{\mu\nu}q|N\rangle$ ~ 1 < 5/3 (quark model) ⇒ suppressed ➡ **Obey the rough rule**

Pion-nucleon level enhancement/suppression

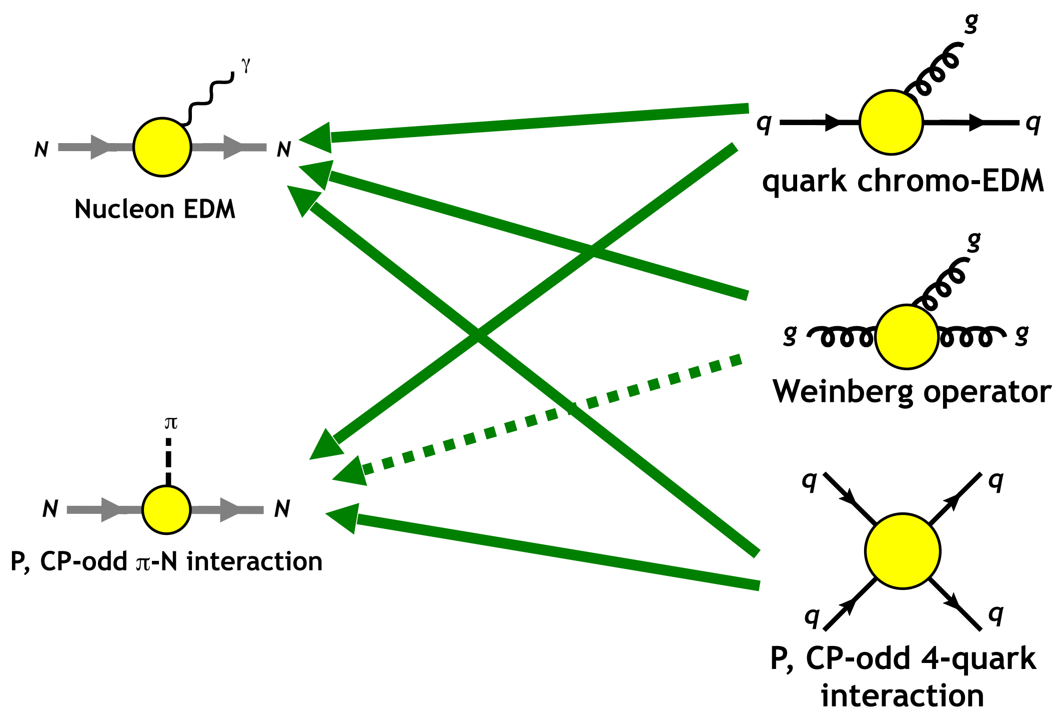
Unfortunately, not all hadron matrix elements are available from lattice QCD

Use chiral EFT to relate unknown ones with known ones

A rough rule of ChEFT :

Count the power of m_π^2 (or m_q) and match operators between QCD and pion-nucleon physics

Evidently, if the chiral representations of the CP-odd operators at the QCD and hadron levels do not match, we have a suppression by at least m_π^2.



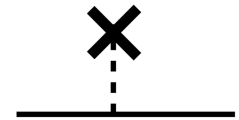
J. de Vries et al., PRC **84**, 065501 (2011)

Less known nucleon matrix elements in ChEFT

- **Nucleon pseudoscalar density:** $\langle N|\bar{q}i\gamma_5 q|N\rangle$

  Use nucleon axial charge $\langle N|\bar{q}\gamma_\mu\gamma_5 q|N\rangle$ as input (anomalous Ward identity)

  ⇒ Pion pole dominance $\propto \frac{1}{m_\pi^2}$ $\sim$ 100 !!

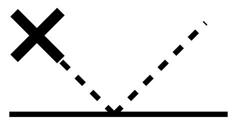


- **πNN interaction from quark chromo-EDM:** $\langle N|\bar{q}i\sigma_{\mu\nu}G_a^{\mu\nu}\gamma_5 t_a q|\pi N\rangle$

  Vacuum alignment contribution, may be enhanced by scalar density
  Contact term rather small from high energy QCD input

J. de Vries et al, PLB**766**, 254 (2017)
C.-Y. Seng, arXiv:1809.00307 [hep-ph]

$\langle\pi^0|O_{\mathrm{CP}}|0\rangle$



$\sim$ O(1-10)

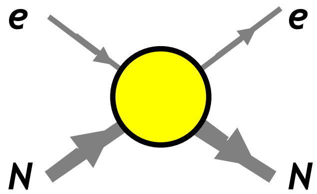
- **πNN interaction from four-quark interaction:** $\langle N|\bar{q}q\cdot\bar{q}'i\gamma_5 q'|\pi N\rangle$

  Vacuum alignment, but may cancel by chiral symmetry arguments

  Contact interaction is important in factorization model (scalar density)

➡ Chiral EFT plays an important role in the control of errorbars

CP-odd electron-nucleon interaction : purely atomic effect



P, CP-odd e-N interaction have specific sensitivity to some NP

Extended Higgs, leptoquark, R-parity violation, etc.

- **Scalar-pseudoscalar type:** $C_{SP}\bar{N}N\,\bar{e}i\gamma_5 e$

  Atomic level : enhanced for paramagnetic atoms, like for d_e
  very suppressed by close electron spin shell (diamagnetic)

  Hadron level : enhanced by quark scalar density $\langle N|\bar{q}q|N\rangle$

  Nuclear level : enhanced by nucleon number

- **Tensor type:** $C_T\bar{N}\sigma_{\mu\nu}N\,\bar{e}i\sigma^{\mu\nu}\gamma_5 e$

  Hadron level : not enhanced by tensor charge (spin) $\langle N|\bar{q}\sigma_{\mu\nu}q|N\rangle$

  Nuclear level : suppressed by configuration mixing (depends on nuclei)

- **Pseudoscalar-scalar type:** $C_{PS}\bar{N}i\gamma_5 N\,\bar{e}e$

  Hadron level : enhanced by pion pole $\langle N|\bar{q}i\gamma_5 q|N\rangle$

  Nuclear level : suppressed due to nonrelativistic nucleons

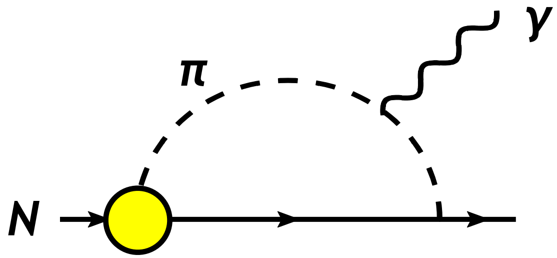
  Compensation!

K. Yanase et al., arXiv:1805.00419 [nucl-th]

Nucleon EDM : status

Experimental limit : $d_n < 3 \times 10^{-26}$e cm J. M. Pendlebury et al., PRD **92**,092003 (2015)

- **Chiral loop:**



$\theta < 10^{-10}$

⇒ Strong CP problem

R. J. Crewther et al., PLB**88**, 123 (1979)
J. de Vries et al., PRC**92**, 045201 (2015)

$\tilde{d}_q < 10^{-26}$cm

⇒ CP problems for 1-loop level EDM (e.g. SUSY)

J. Ellis et al., PLB**112**, 231 (1982)

- **Quark EDM:**

Not enhanced, $d_n \sim d_q$, but

nucleon EDM has specific sensitivity to quark EDM generated by some NP

⇒ Constrain Split SUSY, R-parity violation, leptoquarks, ...

- Single nucleon EDM has low sensitivity to isovector couplings

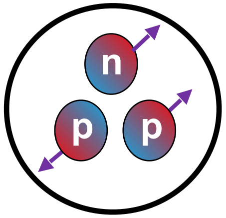
Nuclear EDM / Schiff moment from nucleon level CP violation

Two leading contributions to nuclear EDM/Schiff moment:

1) Nucleon's intrinsic EDM:

Contribution from the nucleon EDM (spin)

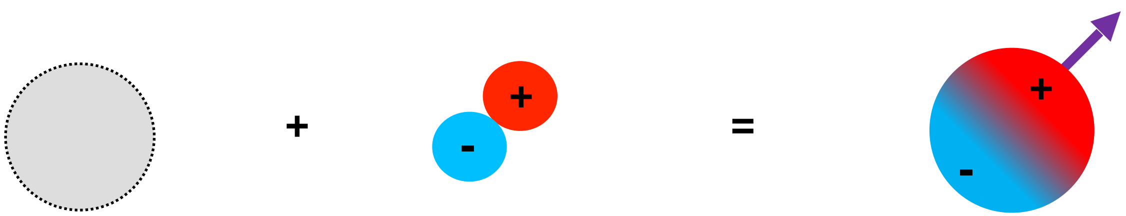
- Strong pairing force : only unpaired nucleon(s) contribute
- Nucleons are nonrelativisitic in nuclei



$\Rightarrow$ **Nucleon EDM is not enhanced in nuclei**

2) Polarization of the nucleus:

Polarize the whole system by the parity and CP mixing due to CP-odd nuclear force

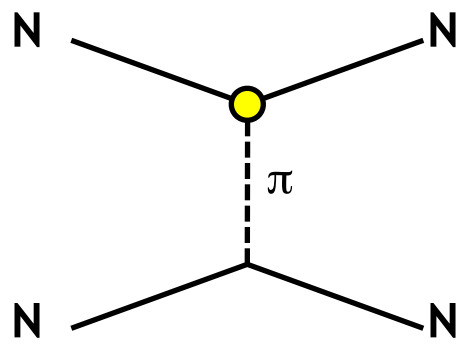


s-wave p-wave polarized system

May be enhanced by the many-body effect?

P, CP-odd nuclear force

P, CP-odd nuclear force : pion exchange is dominant



$$\sim \frac{1}{q^2 - m_\pi^2} \bar{N}N \; \bar{N} i \gamma_5 N$$

- 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 interaction : contribution from the surface

- What is expected:
  - Polarization effect grows in *A* for small nuclei ?
  - May have additional enhancements with cluster structure, deformation, …

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

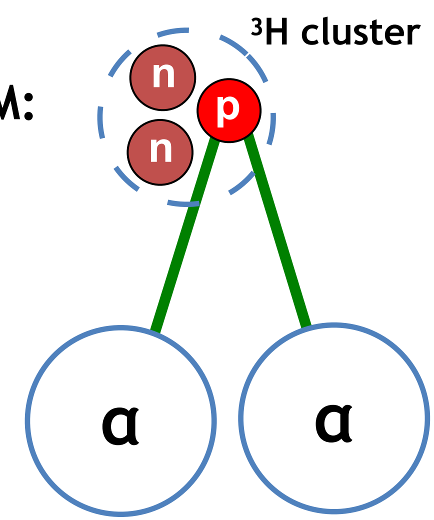
- **Isovector** coupling obeys a **counting rule**

$$d_A^{(pol)} \sim \underbrace{d({}^{2/3}H)}_{\text{EDM of cluster with open shell}} + \underbrace{n \times 0.005\, G_\pi^{(1)}\, e\,\mathrm{fm}}_{\alpha\text{-N polarization (times \# }\alpha\text{-N combinations)}}$$

⇒ Explained by the cluster structure

NY, T. Yamada, Y. Funaki, in preparation

Example of ^{11}B EDM:

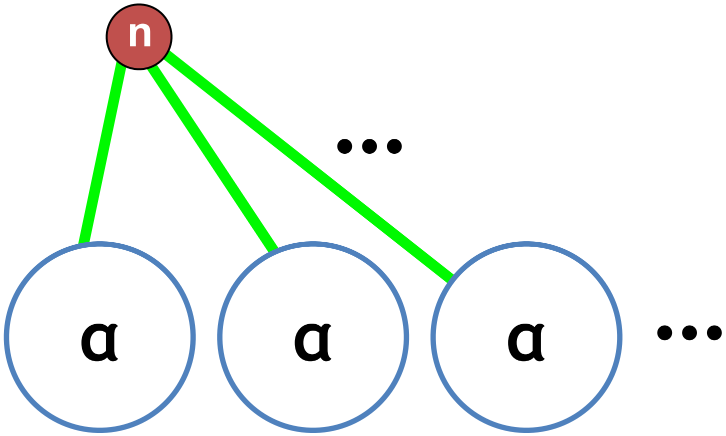


$d_{11B} = 0.02\ G^{(1)}_\pi\ e$ fm

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

Nuclear EDM / Schiff moment of heavy nuclei: suppression

EDM of larger nuclei is larger?

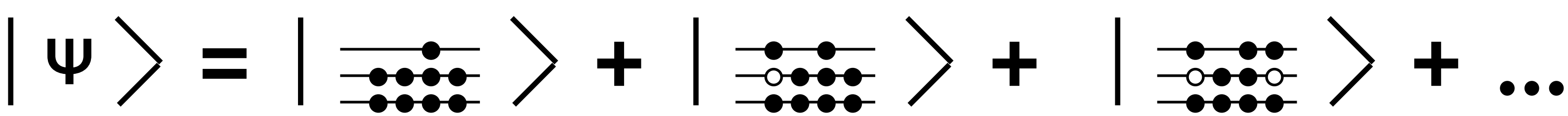


d_A = (A/4) x (α-N polarization) ??

≒ (Simple shell model picture)

No!

Large nuclei have configuration mixing

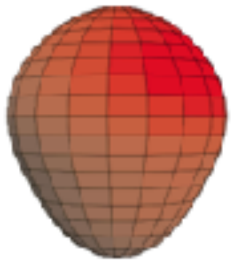


EDM of large nuclei is quenched due to destructive interference of the spin of valence nucleon(s).

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).

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:

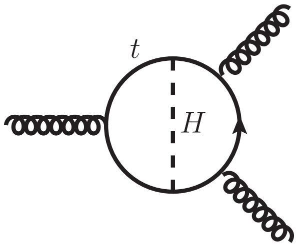
	a_0(isoscalar)	a_1(isovector)	a_2(isotensor)
^{225}Ra	-1.5 e fm^3	6.0 e fm^3	-4.0 e fm^3
^{199}Hg	0.02 e fm^3	-0.007 e fm^3	0.03 e fm^3

J. Dobaczewski and J. Engel, Phys. Rev. Lett. **94**, 232502 (2005)
J. Dobaczewski et al., arXiv:1807.09581 [nucl-th].
(Comparison ^{199}Hg result of S. Ban et al., Phys. Rev. C **82**, 015501 (2010))

➡ Octupole deformation enhances by O(1000) times!!

Weinberg operator : a very unknown contribution

Weinberg operator is generated in many interesting models
(2HDM, vectorlike quark, …)



Its contribution to the EDM is however very obscure

S. Weinberg, Phys. Rev. Lett. **63**, 2333 (1990).

Summary of problems in the study of WO:

- Hadron level : no reliable calculations

  WO is gluonic ⇒ low energy constant in chiral EFT not known

  Only model calculation of intermediate quantity exists

  M. Pospelov et al., PRD **67**, 015007 (2003)

  Lattice calculation needs high statistics

  J. Dragos et al., EPJ Web Conf. **175**, 06018 (2018)

- Nuclear level : large uncertainty due to the short distance wave function

  J. Bsaisou et al., JHEP **1503** (2015) 104

  Possible approach : Lattice QCD calculation of nuclear force?
  High energy QCD experiments?

At least, an order estimation of the relative size with chromo-EDM is necessary
(recall that WO mixes with quark chromo-EDM in RGE)

EDM from CKM matrix

We consider the complex phase of CKM matrix as the CP violation in the Standard model:

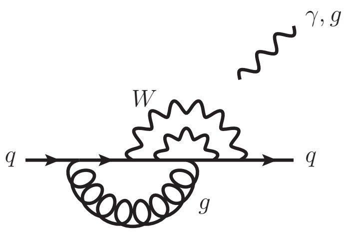
Leading CP violation from Jarlskog invariant

$$J = \mathrm{Im}[V_{ts}^{*}V_{td}V_{us}V_{ud}^{*}] = -\mathrm{Im}[V_{cs}^{*}V_{cd}V_{us}V_{ud}^{*}]$$
$$= (3.06 \pm 0.21)\times 10^{-5} \text{ (PDG value)}$$

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

- **Short distance processes :**

EDM in the Standard model starts from
* 3-loop diagram for quark ~10^{-35}e cm
* 4-loop diagram for electron ~10^{-40}e cm



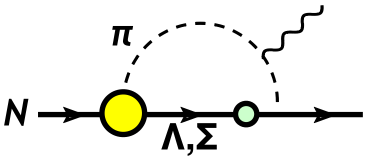
A. Czarnecki et al., PRL **78**, 4339 (1997)
M. Pospelov et al., Sov. J. Nucl. Phys. **53** (1991) 638

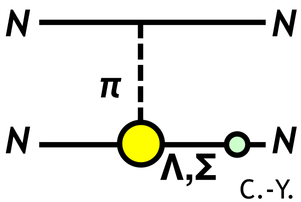
Very small due to GIM cancellation

- **Long distance processes (hadronic level):**

Generated by hadron level $|\Delta S|=1$ interaction

* Neutron EDM ~10^{-32}e cm
* Deuteron EDM ~10^{-31}e cm





C.-Y. Seng, PRC **91**, 025502 (2015)
NY et al., JHEP02(2016)067

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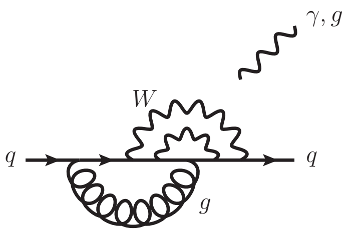

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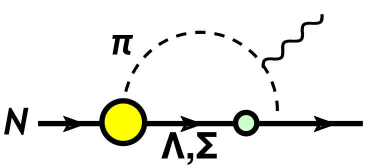

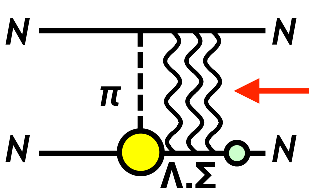

C.-Y. Seng, PRC **91**, 025502 (2015)
NY et al., JHEP02(2016)067

Caution :
Unknown systematics due to mixing of hypernuclear states for larger nuclei

Summary:

- A review of enhancement/suppression in EDM.
- Schiff's screening in atoms damps the leading CPV.
- Scalar is enhanced, spin is suppressed, but O(1).
- Notable enhancement : relativistic electron in atoms/ molecules, octuple deformation of nuclei, and maybe scalar density.
- Suppression : nuclear configuration mixing
- We have to note that experimentally measurable systems are not numerous : limited # of cases to be studied.

Future subjects:

- Still unknown mechanisms : Weinberg operator, but important for Higgs sector.
- We are waiting for new 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