Weinberg operator contribution to the hadronic CP violation

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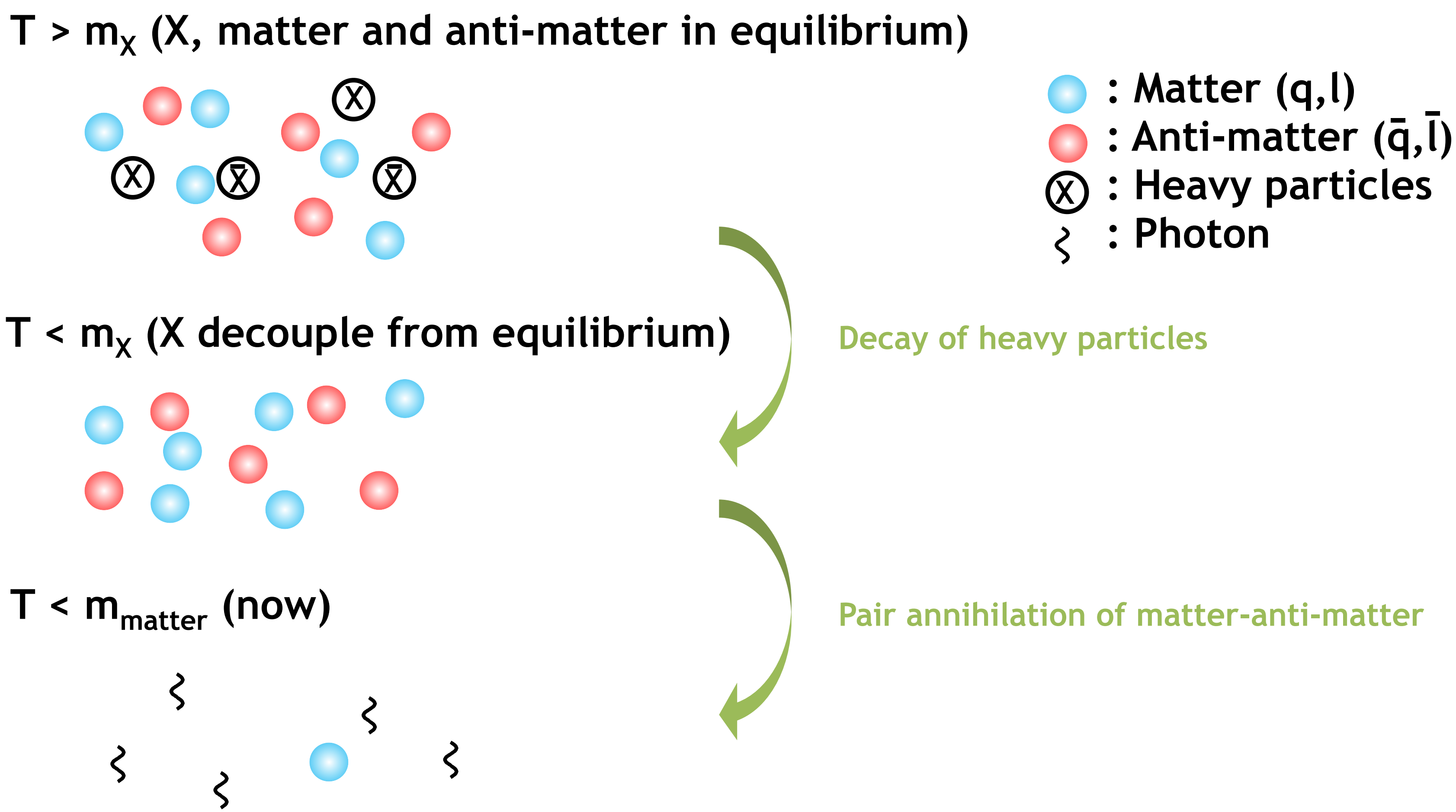
Baryon number asymmetry of the Universe

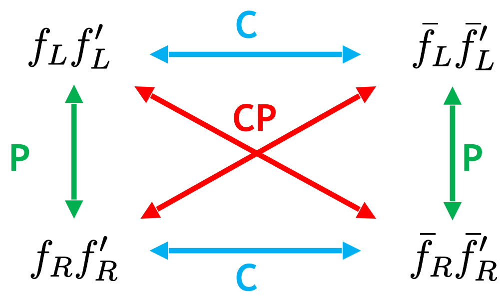
Asymmetric decays generates excess of matters in the early Universe



➡ 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!**

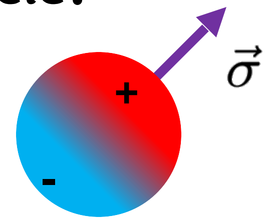
We need new source(s) of
large CP violation beyond the standard model !

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:

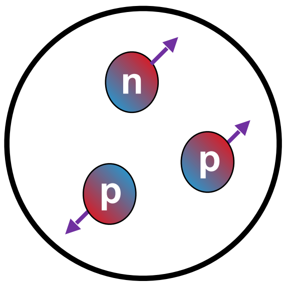
  - Under parity tr.: $\begin{cases} \vec{E} \xrightarrow{P} -\vec{E} \\ \vec{\sigma} \xrightarrow{P} \vec{\sigma} \end{cases}$ → H_{EDM} is P-odd

  - Under time reversal: $\begin{cases} \vec{E} \xrightarrow{T} \vec{E} \\ \vec{\sigma} \xrightarrow{T} -\vec{\sigma} \end{cases}$ → H_{EDM} is CP-odd !

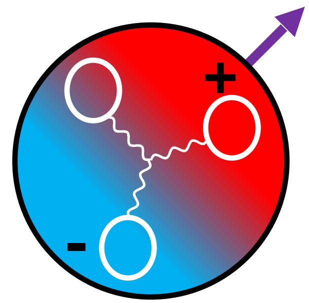
EDM of composite systems

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.

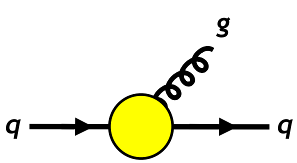


EDM of constituents

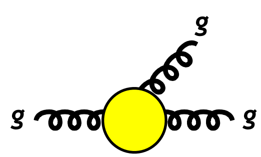


CP-odd many-body interaction

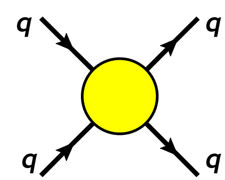
Example of QCD level many-body interactions inducing nucleon EDM:



quark chromo-EDM



Weinberg operator



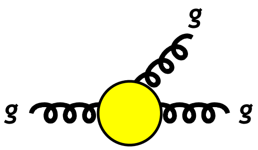
P, CP-odd 4-quark interaction

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

Weinberg operator

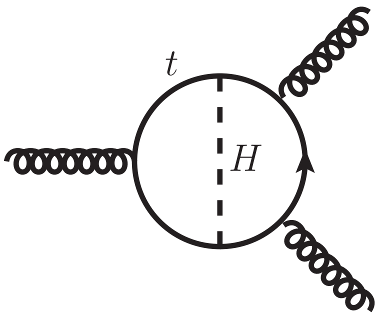
$$\mathcal{L}_w = \frac{1}{3!} w f^{abc} \epsilon^{\alpha\beta\gamma\delta} G^a_{\mu\alpha} G^b_{\beta\gamma} G^{\mu,c}_{\delta}$$

(= gluon chromo-EDM)



Induced in many candidates of BSM physics

- **2-Higgs doublet model**
  S. Weinberg, Phys. Rev. Lett. **63**, 2333 (1989).
- **Minimal supersymmetric standard model**
  J. Dai *et al*., Phys. Lett. B **237**, 216 (1990).
- **Left-right symmetric model**
  D. Chang *et al*., Phys. Rev. D **42**, 867 (1990).
- **Vectorlike quark model**
  K. Choi *et al*., Phys. Lett. B **760**, 666 (2016).



Typical 2-loop diagram

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).

Let us quantify the Weinberg operator contribution

Review of Weinberg operator contribution to nucleon EDM

List of previous works:

- **Naive dimensional analysis**

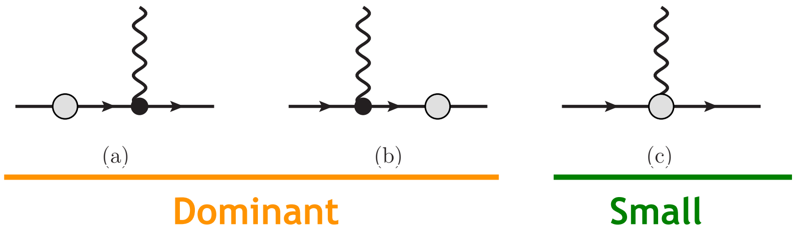
$$d_N \approx e\frac{\Lambda}{4\pi}w \approx w \times 90\,e\,\mathrm{MeV}$$

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

- **Lattice QCD : not yet available**

J. Dragos *et al.*, EPJ Web Conf. **175**, 06018 (2018);
M. D. Rizik *et al.*, Phys. Rev. D **102**, 034509 (2020).

- **Hadron effective theory analysis**



⇒ **Chiral rotation of g-2 by the CP-odd mass** $(m_{CP}\bar{\psi}i\gamma_5\psi)$ **is important!**

I. I. Bigi *et al.*, Nucl. Phys. B **353**, 321 (1991).

Dominant part from QCD sum rules

D. Demir et al., Phys. Rev. D **67**, 015007 (2003);
U. Haisch *et al.*, JHEP **1911** (2019) 154.

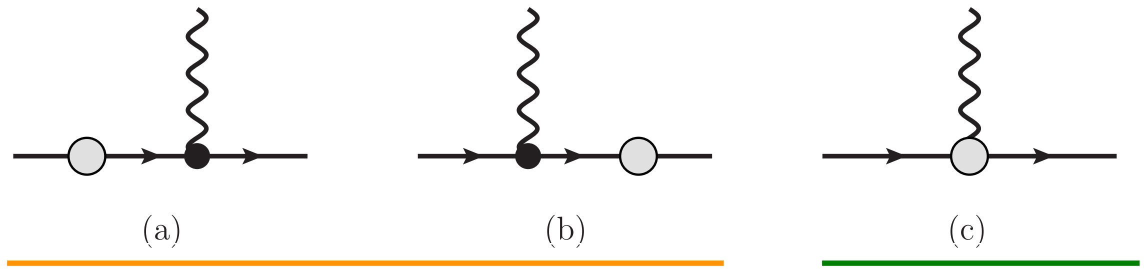
Subdominant part from quark model

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

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

Object of study

We found that the chiral rotation of anomalous magnetic moment by CP-odd mass (Figs. a,b) gives the leading contribution to the nucleon EDM



Large! **Small!**

What about the contribution to the nuclear CP-odd moments?
(= contribution to atomic and nuclear EDMs)

Object:

Estimate the Weinberg operator contribution to the nuclear EDM and atomic EDM (Schiff moment).

CP-odd baryon mass and chiral rotation

CP-odd fermion mass converts to complex phase difference between left- and right-handed components of fermions

$$m_{\rm even}\bar\psi\psi + \underline{m_{\rm odd}\bar\psi i\gamma_5\psi}$$

$$\equiv m\left[\cos(\alpha)\bar\psi\psi + \sin(\alpha)\bar\psi i\gamma_5\psi\right] = m\left[\frac{1}{2}e^{i\alpha}\bar\psi(1+\gamma_5)\psi + \frac{1}{2}e^{-i\alpha}\bar\psi(1-\gamma_5)\psi\right]$$

$$= me^{i\alpha}\bar\psi_L\psi_R + me^{-i\alpha}\bar\psi_R\psi_L$$

Complex phase may be absorbed with field redefinition, e.g.

$$\begin{cases}\psi_L \to e^{\frac{i\alpha}{2}}\psi'_L \\ \psi_R \to e^{-\frac{i\alpha}{2}}\psi'_R\end{cases}$$

The mass term is then converted as

$$m_{\rm even}\bar\psi\psi + m_{\rm odd}\bar\psi i\gamma_5\psi \to m\bar\psi'\psi' \qquad m = \sqrt{m_{\rm even}^2 + m_{\rm odd}^2} \approx m_{\rm even}$$

The mass term has no complex phases in the physical basis

➡ **After this redefinition, we will have to rotate chiral-odd operators, like fermion g-2, operators with scalar density, etc.**

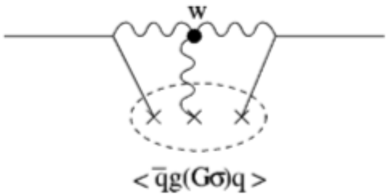
CP-odd baryon mass in QCD sum rules

CP-odd baryon mass is given by $\langle N|\tilde{G}GG|N\rangle$

Calculate with QCD sum rules

⇒ Insert quark propagator with the Weinberg operator

$$iS(p) = \frac{i\not{p}}{p^2} + \frac{ig_s w}{8p^4}\gamma_5\langle\bar{q}g_s(G\sigma)q\rangle$$



to the nucleon correlator:

$$\int d^4x e^{ip\cdot x}\langle\eta(0)\bar{\eta}(x)\rangle = \frac{1}{16\pi^2}p^2\ln(-\Lambda_{\rm UV}^2/p^2)\langle\bar{q}q\rangle\left[1 + i\gamma_5\underline{\frac{3g_s w}{32\pi^2}m_0^2\ln(-p^2/\mu_{IR}^2)}\right] + \cdots$$

CP-odd part

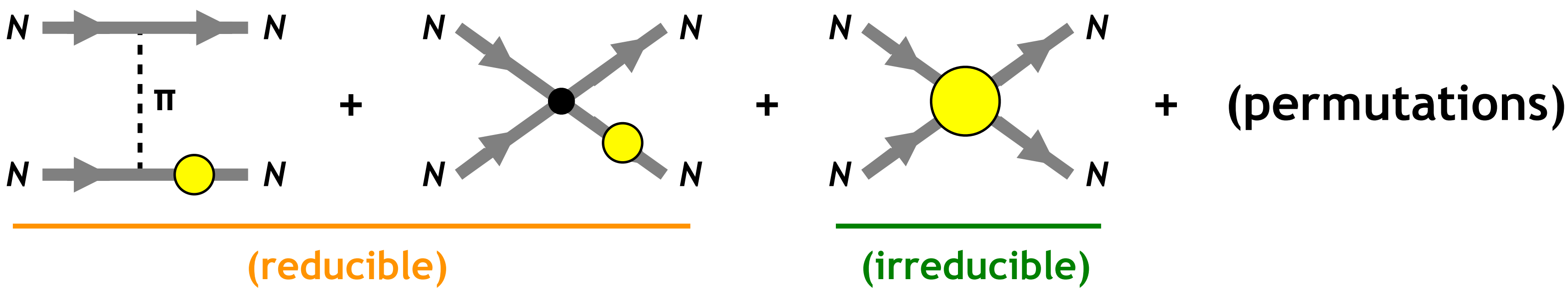
$$\langle N|\tilde{G}GG|N\rangle = m_N\frac{3g_s m_0^2}{32\pi^2}w\ln(M^2/\mu_{IR}^2)$$

D. Demir et al., Phys. Rev. D **67**, 015007 (2003);
U. Haisch *et al.*, JHEP **1911** (2019) 154.

Contribution from the CP-odd mass (chiral rotation)

CP-odd nuclear moments are generated by the CP-odd nuclear force.

We may decompose the CP-odd nuclear force into three leading pieces



Reducible part may be obtained with the chiral rotation due to the CP-odd mass calculated using QCD sum rules.

D. Demir et al., Phys. Rev. D **67**, 015007 (2003);
U. Haisch *et al.*, JHEP **1911** (2019) 154.

Irreducible part is unknown, but expected to be small, in analogy with the quark model calculation of the nucleon EDM.

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

➡ We expect the reducible part to be leading!

Result of the estimation of CP-odd nuclear moments

Pion exchange CP-odd nuclear force:

$$\mathcal{H}_{CPV} = \frac{\bar{G}_\pi^{(0)}}{2m_N}(\tau_1 \cdot \tau_2)(\vec{\sigma}_1 - \vec{\sigma}_2) \cdot \vec{\nabla} \frac{e^{-|\vec{r}_1 - \vec{r}_2| m_\pi}}{4\pi |\vec{r}_1 - \vec{r}_2|}$$

Obtained by chiral rotating the (CP-even) one-pion exchange nuclear force

(Leading contribution)

Contact CP-odd nuclear force:

$$C_1 \bar{N} N \, \bar{N} i\gamma_5 N$$

Obtained by chiral rotating the contact term of EFT or vector meson exchange

(EFT coupling from LO chPT, Epelbaum, 0811.1338; Bernard, hep-ph/9501384)

^{199}Hg (atom) EDM:

$|d_{Hg}|$ = 0.3 w e MeV

(Even with Schiff screening!)

^{3}He (nuclear) EDM:

$|d_{He}|$ = 120 w e MeV

Compare with nucleon EDM

$|d_N|$ = 20 w e MeV

Suggest that nuclei are more sensitive to the Weinberg operator than single nucleons!

Summary

- The Weinberg operator is generated in many BSM candidates.
- The Weinberg operator contributes to the nuclear/ atomic EDM.
- We evaluated the Weinberg operator contribution to the nuclear CP-odd nuclear moments using chiral rotation: atoms and nuclei are more sensitive than single nucleons?
- Theoretical uncertainty due to the unknown irreducible contact CP-odd nuclear force.

Future prospects:

- Evaluate the irreducible contact CP-odd N-N interaction in the quark model to determine the theoretical error.
- The most promising experiment is the nuclear EDM measurement using storage ring.

End

Backup slides

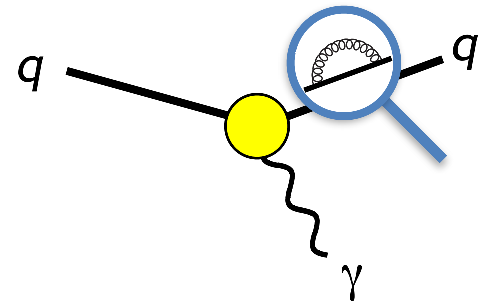
Renormalization group evolution

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

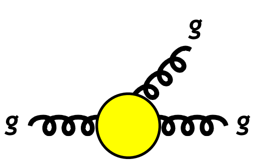
Note:
this analysis is perturbative, large uncertainty due to nonperturbative effect near μ = 1 GeV

1) Example 1: quark EDM

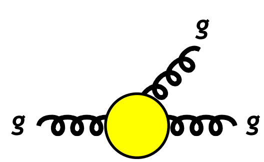
d_q → $0.8\ d_q$

μ = 1 TeV μ = 1 GeV

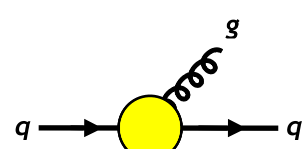
2) Example 2: Weinberg operator



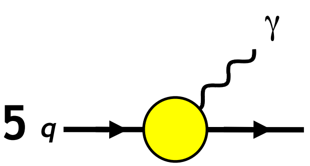
→ 0.17



\+ 0.30



\- 0.15



μ = 1 TeV μ = 1 GeV

Results

EDM	isoscalar (a_0)	isovector (a_1)	isotensor (a_2)
^{129}Xe atom K. Yanase et al., arXiv:2006.15142 [nucl-th] 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
^{199}Hg atom K. Yanase et al., arXiv:2006.15142 [nucl-th] 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
^{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)	0.015 *e* fm	0.0108 *e* fm	0.026 *e* fm
^{6}Li nucleus NY et al., PRC **91**, 054005 (2015)	–	0.022 *e* fm	–
^{7}Li nucleus NY et al., PRC **100**, 055501 (2019)	– 0.015 *e* fm	0.016 *e* fm	– 0.026 *e* fm
^{9}Be nucleus NY et al., PRC **91**, 054005 (2015)	0.01 *e* fm	0.014 *e* fm	0.01 *e* fm
^{11}B nucleus NY et al., PRC **100**, 055501 (2019)	– 0.01 *e* fm	0.016 *e* fm	– 0.02 *e* fm
^{13}C nucleus NY et al., PRC 95,065503 (2017)	– 0.003 *e* fm	–0.0020 *e* fm	– 0.003 *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
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

atoms (^{129}Xe, ^{199}Hg, ^{225}Ra); nuclei (Deuteron through Simple shell model)

Advertisement

- For details of nuclear EDM calculation, see

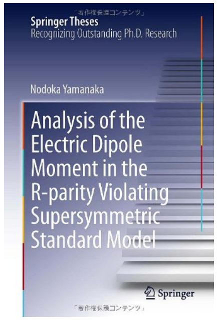
  N. Yamanaka,
  Review of the electric dipole moment of light nuclei,
  International Journal of Modern Physics E 26, 1730002 (2017)
  arXiv:1609.04759 [nucl-th].

- 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 !!