Atomic and nuclear electric dipole moments in the standard model

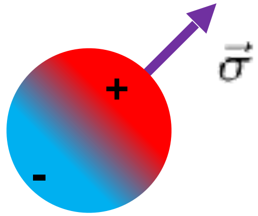
NY and E. Hiyama, JHEP **02** (2016) 067;
NY, Nucl. Phys. A **963**, 33 (2017).

N. Yamanaka
(IPN Orsay/RIKEN iTHES)

2017/10/31
Flavor Physics Workshop
Yokohama

The electric dipole moment (EDM) is a powerful tool to search CP violation beyond standard model

EDM: $$\langle \vec{d} \rangle = \langle \psi | \, e\vec{r} \, | \psi \rangle$$



EDM is CP-odd !

$$\begin{cases} \vec{E} \xrightarrow{\mathrm{T}} \vec{E} \\ \vec{\sigma} \xrightarrow{\mathrm{T}} -\vec{\sigma} \end{cases}$$

Recent development of EDM experiments is impressive:

- Atomic and molecular systems (record : $d_{Hg} < 7.4 \times 10^{-30}$ e cm!).
- EDM of light nuclei in preparation (prospect : $O(10^{-29}$ e cm)!)

We are expecting to unveil BSM CP violation

But we do not have to forget that standard model also contributes to the EDM

What about the standard model contribution?

The SM contributes to the EDM through the CP phase of CKM matrix

It is often said that the SM contribution is small for the EDM.

For the nuclear EDM and the nuclear Schiff moment,
the SM contribution was not calculated in detail so far.

The calculation of the SM contribution is important because

- The SM contribution is an important background in EDM exp.
- If the SM contribution is large, good probe of CKM unitarity.

Object of Study:

➡ **Quantify the SM (CKM) contribution to the nuclear and atomic EDMs.**

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

Questions to be answered

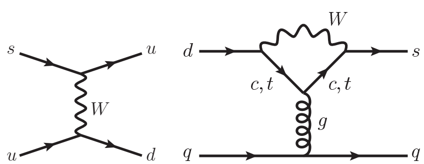
Naive estimation of SM contribution to the nuclear/atomic EDM?

⇒ Scales as $\alpha_s G_F^2 J$ ⇒ $d_A \sim O(10^{-33})$e cm

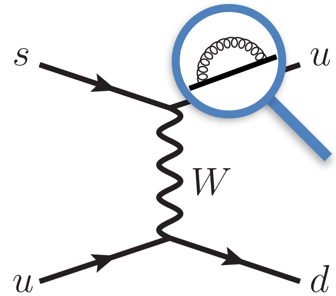
But we have to quantify it due to the progress of accuracy in experiments:

- What is the leading effect? Nucleon EDM vs. CP-odd nuclear force
- $|\Delta S|=1$ long distance contributions at hadron level with meson exchanges
- Enhancement or suppression by nuclear many-body effect?
- The error bar : what the most important one?

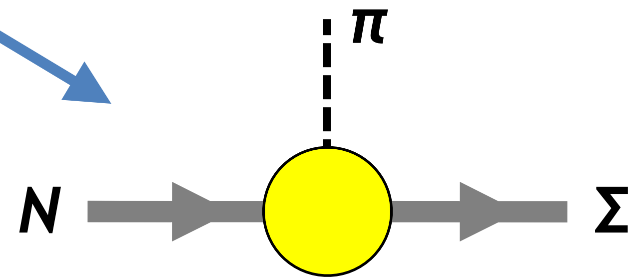
Flow of calculation of the SM contributions



Elementary level processes

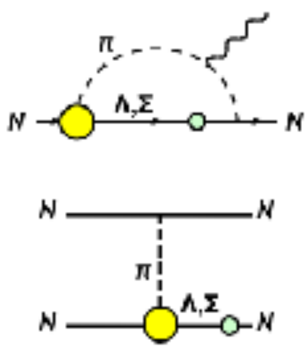


Renormalization down to hadronic scale

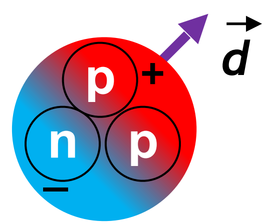


$< \pi\Sigma \mid O_{CP} \mid N >$

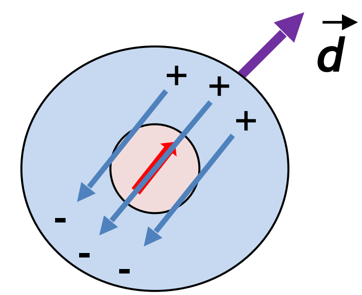
hadron matrix elements from factorization



Nucleon level CPV



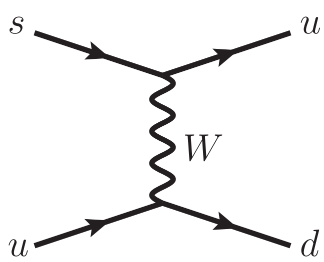
Nuclear EDM
Nuclear Schiff moment



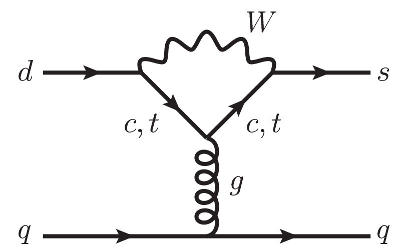
Atomic EDM

Initial conditions : physics at $\mu = m_W$

CP violation of nucleon systems arises via the combination of tree and penguin



Tree level



"Penguin diagram"

⇒ **Form Jarlskog combination (top and charm in penguin loop)**

⇒ **Both contributions are needed for CKM CP violation**

$$
\begin{cases}
Q_1 = (\bar{s}_\alpha u_\beta)_{V-A}(\bar{u}_\beta d_\alpha)_{V-A} \\
Q_2 = (\bar{s}u)_{V-A}(\bar{u}d)_{V-A} \\
Q_3 = (\bar{s}d)_{V-A} \sum_q (\bar{q}q)_{V-A} \\
Q_4 = (\bar{s}_\alpha d_\beta)_{V-A} \sum_q (\bar{u}_\beta d_\alpha)_{V-A} \\
Q_5 = (\bar{s}d)_{V-A} \sum_q (\bar{q}q)_{V+A} \\
Q_6 = (\bar{s}_\alpha d_\beta)_{V-A} \sum_q (\bar{u}_\beta d_\alpha)_{V+A}
\end{cases}
$$

Initial Wilson coefficients:

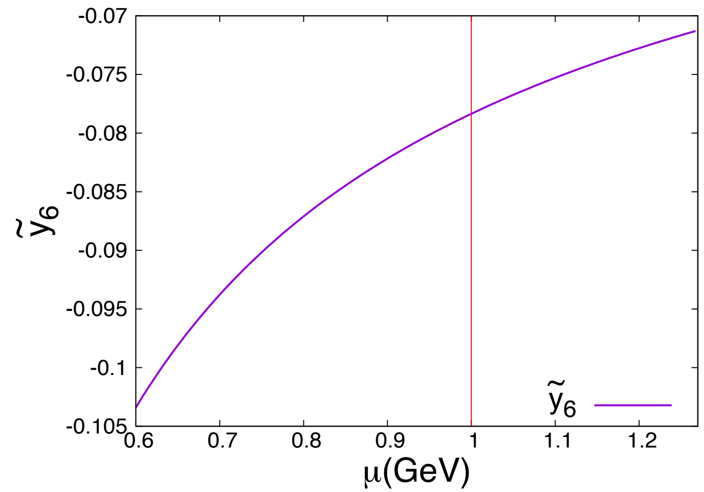
$$
C_{tree}(\mu = m_W) = \frac{G_F}{\sqrt{2}} V_{us} V_{ud} \begin{pmatrix} \frac{\alpha(M_W)}{4\pi} B_1^{NDR} \\ 1 + \frac{\alpha(M_W)}{4\pi} B_2^{NDR} \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}
$$

$$
C_{peng}(\mu = m_W) = \frac{G_F}{\sqrt{2}} V_{ts} V_{td} \begin{pmatrix} 0 \\ 0 \\ -\frac{\alpha}{24\pi}\tilde{E}(x_t) \\ \frac{\alpha}{8\pi}\tilde{E}(x_t) \\ -\frac{\alpha}{24\pi}\tilde{E}(x_t) \\ \frac{\alpha}{8\pi}\tilde{E}(x_t) \end{pmatrix}
$$

Renormalization of |ΔS|=1 operator

The Penguin and tree operators run from the scale $\mu = m_W$ (where Feynman diagrams were calculated) to the hadronic scale (where the hadron matrix elements are calculated).

$$
\begin{cases}
Q_1 = (\bar{s}_\alpha u_\beta)_{V-A}(\bar{u}_\beta d_\alpha)_{V-A} \\
Q_2 = (\bar{s}u)_{V-A}(\bar{u}d)_{V-A} \\
Q_3 = (\bar{s}d)_{V-A} \sum_q (\bar{q}q)_{V-A} \\
Q_4 = (\bar{s}_\alpha d_\beta)_{V-A} \sum_q (\bar{u}_\beta d_\alpha)_{V-A} \\
Q_5 = (\bar{s}d)_{V-A} \sum_q (\bar{q}q)_{V+A} \\
Q_6 = (\bar{s}_\alpha d_\beta)_{V-A} \sum_q (\bar{u}_\beta d_\alpha)_{V+A}
\end{cases}
$$



Running of the Wilson coefficient of Q_6 near μ = 1 GeV

A. J. Buras et al., Nucl. Phys. B **370**, 69 (1992).

⇒ The penguin operator (Q_6) is enhanced

by 40 times from μ = 80 GeV to μ = 1 GeV!

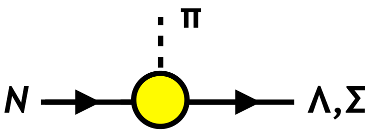
(Due to the large contribution from NLLA contribution)

Factorization approximation

Factorization : factorize the soft external hadron state and the hard intermediate (perturbative) amplitude

Factorization is needed to calculate the CP-odd hadron matrix elements

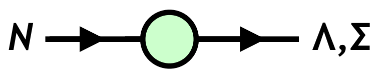
Meson-baryon vertex:



$\langle \pi \Sigma | \bar{s}u\, \bar{u}\gamma_5 d | N \rangle = \langle \pi | \bar{u}\gamma_5 d | 0 \rangle\langle \Sigma | \bar{s}u | N \rangle$ (vacuum saturation approximation)

Those matrix elements can be calculated using chiral techniques

Hyperon-nucleon transition:



$\langle \Sigma | \bar{s}d\, \bar{d}d | N \rangle = \langle 0 | \bar{d}d | 0 \rangle\langle \Sigma | \bar{s}d | N \rangle$ (vacuum saturation approximation)

Those matrix elements can be calculated using chiral techniques

We use quark model fit for the hyperon-nucleon transition which reproduces hadron spectrum

E. Hiyama et al., Prog. Theor. Phys. **112**, 99 (2004).

From $1/N_c$ expansion, factorization should work with the accuracy of $O(2/N_c)$

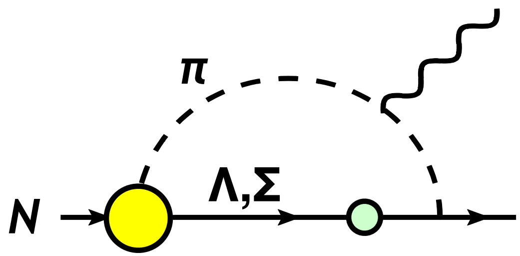
(Generically, meson-baryon vertex has O(1) error, but strange quark can be distinguished)

Nucleon level CP violation

Evaluated in the leading order of chiral EFT with |ΔS|=1 interactions

Nucleon EDM:

Pion-loop

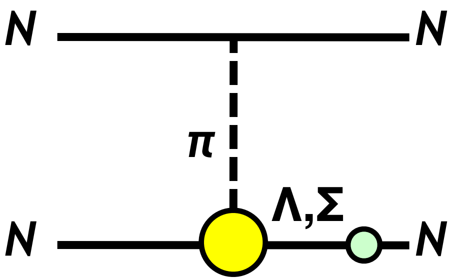


$d_N = O(10^{-32})$e cm

C.-Y. Seng, Phys. Rev. C **91**, 025502 (2015).

CP-odd nuclear force:

One-pion exchange



$$\mathcal{H}^{\pi}_{\not P \not T} = -\frac{1}{8\pi m_N}\left\{ \bar{G}^{(0)}_{\pi}(\tau_1 \cdot \tau_2)\sigma_- + \frac{1}{2}\bar{G}^{(1)}_{\pi}[\tau^z_+\sigma_- + \tau^z_-\sigma_+] \right\} \cdot \nabla \frac{e^{-m_\pi r}}{r}$$

CP-odd nuclear coupling:

$\bar{G}^{(0)}_{\pi} = -g_{\pi NN}\bar{g}^{(0)}_{\pi NN} = 1.6 \times 10^{-16}$

$\bar{G}^{(1)}_{\pi} = -g_{\pi NN}\bar{g}^{(1)}_{\pi NN} = 1.8 \times 10^{-16}$

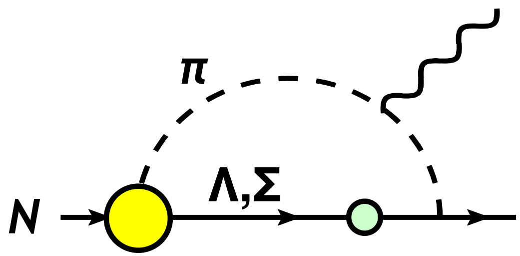
NY and E. Hiyama, JHEP **02** (2016) 067.

Nucleon level CP violation

Evaluated in the leading order of chiral EFT with |ΔS|=1 interactions

Nucleon EDM:

Pion-loop

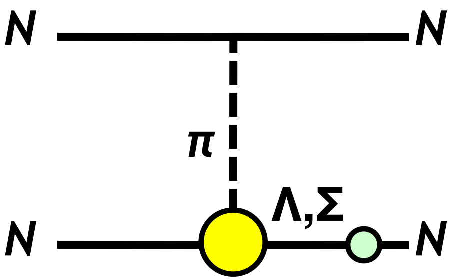


$d_N = O(10^{-32})$e cm

C.-Y. Seng, Phys. Rev. C **91**, 025502 (2015).

CP-odd nuclear force:

One-pion exchange



$$\mathcal{H}^{\pi}_{\not P \not T} = -\frac{1}{8\pi m_N}\left\{ \bar{G}^{(0)}_{\pi}(\tau_1 \cdot \tau_2)\sigma_- + \frac{1}{2}\bar{G}^{(1)}_{\pi}[\tau^z_+ \sigma_- + \tau^z_- \sigma_+] \right\} \cdot \nabla \frac{e^{-m_\pi r}}{r}$$

CP-odd nuclear coupling:

$\bar{G}^{(0)}_{\pi} = -g_{\pi NN}\bar{g}^{(0)}_{\pi NN} = 1.6 \times 10^{-16}$

$\bar{G}^{(1)}_{\pi} = -g_{\pi NN}\bar{g}^{(1)}_{\pi NN} = 1.8 \times 10^{-16}$

NY and E. Hiyama, JHEP **02** (2016) 067.

Leading contribution!

Nuclear EDM (polarization) from CP-odd nuclear force

Polarization contribution to nuclear EDM:

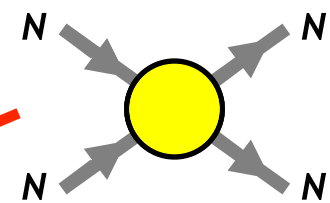
$$D^{(\mathrm{pol})} = \langle 0|\hat{D}_z|\tilde{0}\rangle + \mathrm{c.c.}, \qquad \hat{D}_z = \frac{e}{2}\sum_{i=1}^{A}(1+\tau_i^z)z_i$$

Electric dipole operator requires CP mixing to have finite expectation value

⇒ CP-odd nuclear wave function is needed

Total hamiltonian:

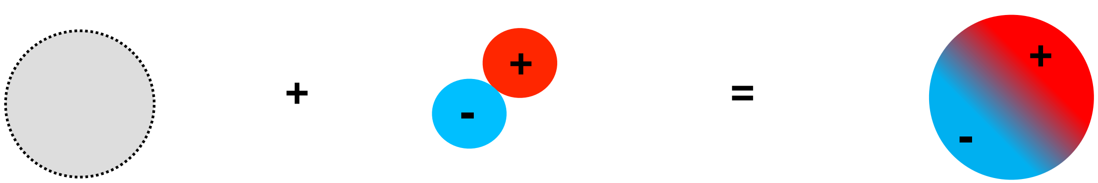
$$H = \begin{pmatrix} H_{\mathrm{realistic}} & H_{\not P \not T} \\ H_{\not P \not T} & H_{\mathrm{realistic}} \end{pmatrix}$$



P, CP-odd nuclear force

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

CP-odd N-N interactions mix opposite parity states

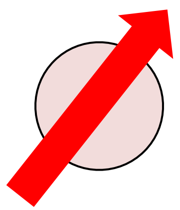


s-wave p-wave polarized system

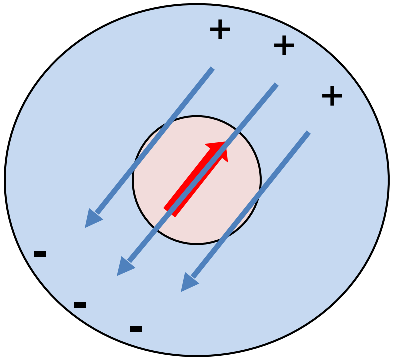
Parity mixing ⇒ Polarized ground state!

Nuclear CP violation to atomic EDM : nuclear Schiff moment

Schiff's screening:



Nuclear EDM



Nuclear EDM screened by atomic electron

Electrically neutral bound system rearranges itself to suppress EDM of components

Nuclear Schiff moment:

Residual nuclear EDM contribution to atomic EDM

$$S \equiv \langle \Psi | \frac{e}{10} \sum_{p=1}^{Z} \left(r_p^2 - \frac{5}{3} \langle r^2 \rangle_{\rm ch} \right) r_p | \Psi \rangle$$

⇒ Need nuclear level calculation!

In the SM, the nuclear Schiff moment gives the leading contribution.

(electron EDM, CP-odd electron-nucleon interaction are very small)

Nuclear and atomic EDM from nucleon level CP violation

Dependence of nuclear EDM/Schiff moment on nucleon level CPV must be written as a linear equation:

CP violating nuclear couplings from CKM CP phase

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

Given by nuclear and atomic structure calculations

EDM	isoscalar (a_0)	isovector (a_1)
^{129}Xe atom E. Teruya et al., PRC 96, 015501 (2017) Y. Singh et al., PRA **89**, 030502 (2014)	1.1×10^{-7} e fm	4.0×10^{-8} 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
^{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
Deuteron Liu et al., PRC **70**, 055501 (2004) NY and EH, PRC **91**, 054005 (2015)	—	0.0145 e fm
^{3}He nucleus Bsaisou et al., JHEP **1503** (2015) 104 NY and EH, PRC **91**, 054005 (2015)	0.0060 *e* fm	0.0108 *e* fm

High Sensitivity!

Summary of the results

	EDM in Standard model	Experimental limit
^{129}Xe atom N. Yoshinaga et al., private communication Dzuba et al., PRA 80, 032120 (2009)	d_{Xe} = 2 x 10^{-36}e cm	d_{Xe} < 4.1 x 10^{-27}e cm
^{199}Hg atom Ban et al., PRC 82, , 015501 (2010) Dzuba et al., PRA 80, 032120 (2009)	d_{Hg} = -4 x 10^{-35}e cm	d_{Hg} < 7.4 x 10^{-30}e cm
^{225}Ra atom Dobaczewski et al., PRL 94, 232502 (2005) Dzuba et al., PRA 80, 032120 (2009)	d_{Ra} = -7 x 10^{-32}e cm	d_{Ra} < 5.0 x 10^{-22}e cm
Neutron Seng, PRC 91, 025502 (2015)	d_n = 1~6 x 10^{-32}e cm	d_n < 2.9 x 10^{-26}e cm
Deuteron Liu et al., PRC **70**, 055501 (2004) NY and EH, PRC **91**, 054005 (2015)	d_D = 3 x 10^{-31}e cm	None
^{3}He nucleus Bsaisou et al., JHEP **1503** (2015) 104 NY and EH, PRC **91**, 054005 (2015)	d_{He} = 3 x 10^{-31}e cm	None

CKM contribution to atomic EDM is well below the experimental sensitivity.

NY and E. Hiyama, JHEP **02** (2016) 067.

Summary of the results

	EDM in Standard model	Experimental limit
^{129}Xe atom N. Yoshinaga et al., private communication Dzuba et al., PRA 80, 032120 (2009)	$d_{Xe} = 2 \times 10^{-36} e$ cm	$d_{Xe} < 4.1 \times 10^{-27} e$ cm
^{199}Hg atom Ban et al., PRC 82, , 015501 (2010) Dzuba et al., PRA 80, 032120 (2009)	$d_{Hg} = -4 \times 10^{-35} e$ cm	$d_{Hg} < 7.4 \times 10^{-30} e$ cm
^{225}Ra atom Dobaczewski et al., PRL 94, 232502 (2005) Dzuba et al., PRA 80, 032120 (2009)	$d_{Ra} = -7 \times 10^{-32} e$ cm	$d_{Ra} < 5.0 \times 10^{-22} e$ cm
Neutron Seng, PRC 91, 025502 (2015)	$d_n = 1\sim 6 \times 10^{-32} e$ cm	$d_n < 2.9 \times 10^{-26} e$ cm
Deuteron Liu et al., PRC **70**, 055501 (2004) NY and EH, PRC **91**, 054005 (2015)	$d_D = 3 \times 10^{-31} e$ cm	
^{3}He nucleus Bsaisou et al., JHEP **1503** (2015) 104 NY and EH, PRC **91**, 054005 (2015)	$d_{He} = 3 \times 10^{-31} e$ cm	

Prospective experimental sensitivity:

$d_A \sim O(10^{-29})$ e cm

… Not so far ??

CKM contribution to atomic EDM is well below the experimental sensitivity.

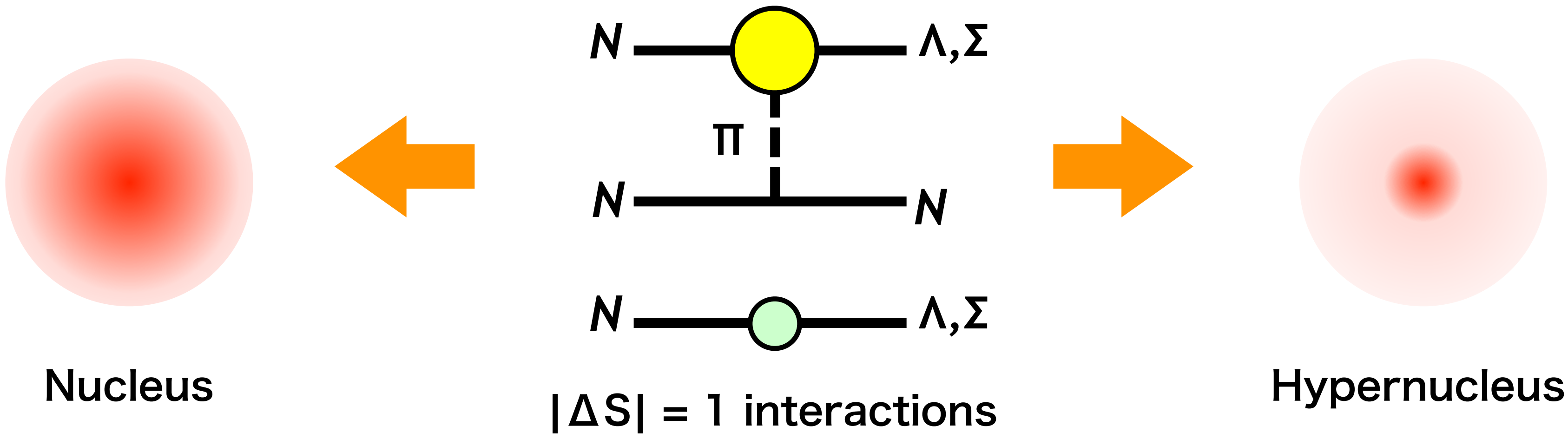
NY and E. Hiyama, JHEP **02** (2016) 067.

$|\Delta S|$ = 1 effect in heavier nuclei

So far, we did not consider nonperturbative effect for S = -1 intermediate state

(= hypernucleus)

Due to the change of structure (hyperons does not suffer Pauli exclusion),
hypernuclei and ordinary nuclei have significantly different structures.



From our study of the EDM of ^{13}C, the difference of structure
in the parity violating transition significantly suppresses the EDM.

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

⇒ $|\Delta S|$ = 1 effect may significantly suppress

the EDM in SM for heavy nuclei due to bad overlap?

Summary of error bars

- At μ = 100 GeV and RG evolution down to μ = 1 GeV:

  Electroweak corrections < 5%
  Renormalization (NLLA) : O(10%)

- Hadronic contribution:

  Factorization (large N_c) : O(60%)
  Nucleon EDM : O(10%)
  Hadronic EFT : O(30%)

- Nuclear level uncertainty:

  Light nuclei : less than 30%
  Heavy nuclei (mean field) : O(100%)
  Heavy nuclei (shell model) : 30%
  Nucleus-hypernucleus mixing : O(100%)

- Atomic level uncertainty:

  Consistency between all calculations:
  ⇒ Error < 10%

Summary:

- We studied the Standard model contribution to the nuclear and atomic EDMs.
- Nuclear EDM in SM is below the prospective experimental sensitivity (10^{-29} e cm), but not so far from it.
- Atomic EDM is well below the current experimental sensitivity: OK for new physics search.
- Our analysis involves a large theoretical uncertainty, but not impossible to reduce them in the future.

Future subjects:

- Study the mixing of nuclei and hypernuclei within $|\Delta S|=1$ interactions.
- We are waiting for experiments!

Backup slides

Results : nuclear EDM

EDM	isoscalar (a_0)	isovector (a_1)	isotensor (a_2)
Neutron Crewther et al. , PLB 88,123 (1979) Mereghetti et al., PLB 696, 97 (2011)	0.01 e fm	–	– 0.01 e fm
Deuteron Liu et al., PRC **70**, 055501 (2004) NY et al., PRC **91**, 054005 (2015)	–	0.0145 e fm	–
^{3}He nucleus Bsaisou et al., JHEP **1503** (2015) 104 NY et al., PRC **91**, 054005 (2015)	0.0060 *e* fm	0.0108 *e* fm	0.0168 *e* fm
^{6}Li nucleus NY et al., PRC **91**, 054005 (2015)	–	0.022 *e* fm	–
^{9}Be nucleus NY et al., PRC **91**, 054005 (2015)	–	0.014 *e* fm	–
^{7}Li nucleus	-0.0060 *e* fm	0.016 *e* fm Preliminary	-0.017 *e* fm
^{13}C nucleus NY et al., PRC 95,065503 (2017)	–	–0.0020 *e* fm	–
^{19}F nucleus	-0.0060 *e* fm	0.10 *e* fm Preliminary	-0.017 *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

Results : nuclear Schiff moment

Schiff moment	isoscalar (a_0)	isovector (a_1)	isotensor (a_2)
^{129}Xe atom E. Teruya et al., PRC 96, 015501 (2017)	0.0032 e fm^3	0.0012 e fm^3	0.0042 e fm^3
^{199}Hg atom Ban et al., PRC **82**, , 015501 (2010)	0.02 e fm^3	-0.007 e fm^3	0.03 e fm^3
^{225}Ra atom Dobaczewski et al., PRL **94**, 232502 (2005)	-1.5 e fm^3	6.0 e fm^3	-4.0 e fm^3
^{19}F nucleus	–	-0.5 e fm^3 Preliminary	–

➡ **^{19}F Schiff moment is larger than those of ^{129}Xe and ^{199}Hg**

Maybe important in the analysis of molecule beam exp.
(ex. : YbF beam)