Weinberg operator contribution to the nucleon EDM in the quark model

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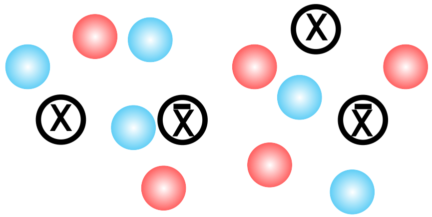
第5回クラスター階層領域研究会

How is generated the matter (baryon number) excess?

Asymmetric decays generates excess of matters in the early Universe

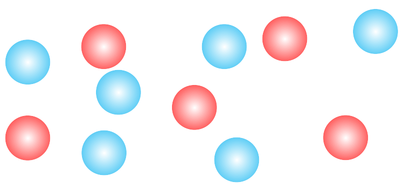
T > m_X (X, matter and anti-matter in equilibrium)



- : Matter (q,l)
- : Anti-matter ($\bar{q}$,$\bar{l}$)
- : Heavy particles
- : Photon

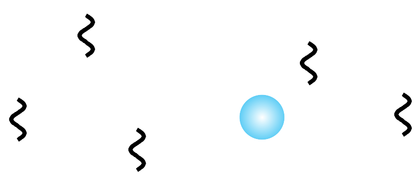
T < m_X (X decouple from equilibrium)

Decay of heavy particles



T < m_{matter} (now)

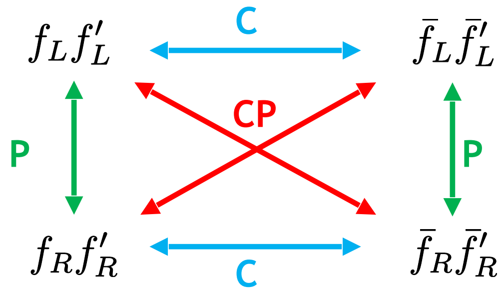
Pair annihilation of matter-anti-matter



➡ **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 …

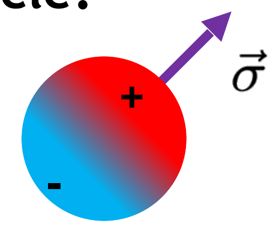
	ratio photon : matter
Prediction of Standard model:	10^{20} : 1
Real observed data:	10^{10} : 1

➡ **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.



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

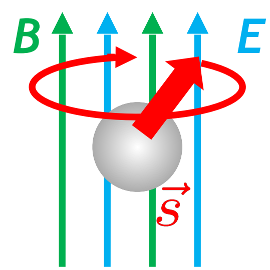
⇒ This is what will be evaluated!

- 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 !

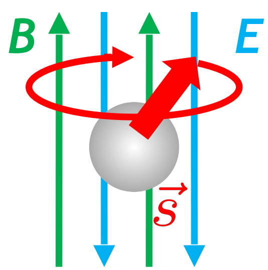
Experimental principle of EDM measurement (neutral sys.)

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:

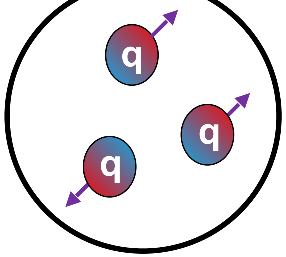
$$d = \frac{\hbar}{4E}(\omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow})$$

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

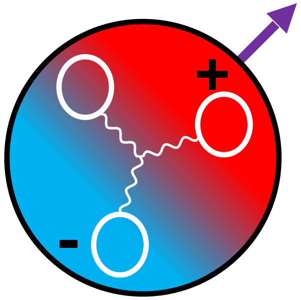
EDM of composite systems

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

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

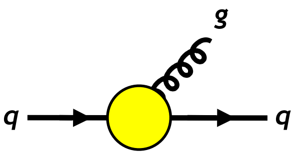


EDM of constituents

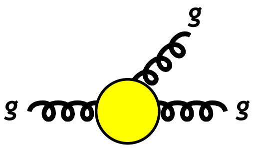


CP-odd many-body interaction

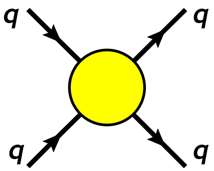
Example of QCD level many-body interactions inducing neutron EDM:



quark chromo-EDM



Weinberg operator



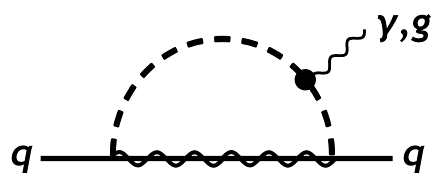
P, CP-odd 4-quark interaction

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

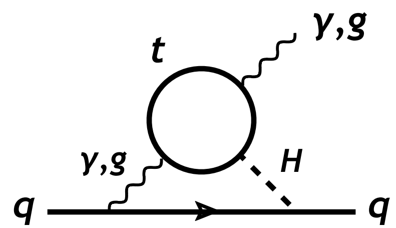
Dimension-6 QCD level interactions and their origin

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

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



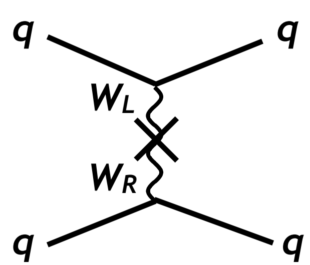
SUSY: 1-loop

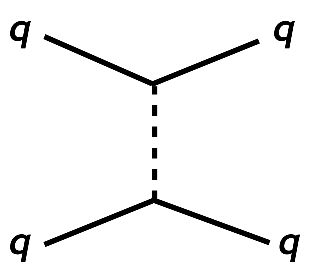


2-Higgs doublet: 2-loop

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

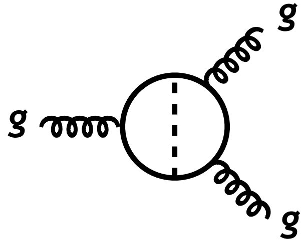
Tree level:
* Left-right sym.
* Scalar exchange





- **Weinberg operator:**

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

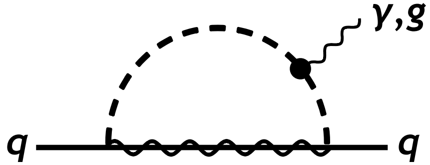


Probe BSM sectors
without mixing
with light quarks

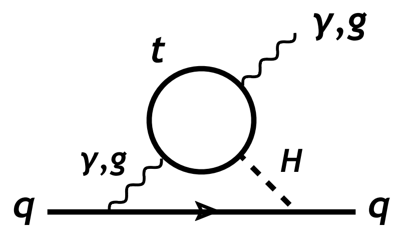
Dimension-6 QCD level interactions and their origin

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

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



SUSY: 1-loop



2-Higgs doublet: 2-loop

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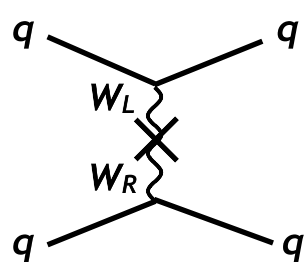
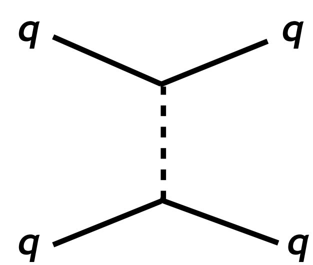
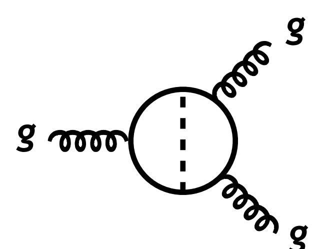




- **Weinberg operator:**

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

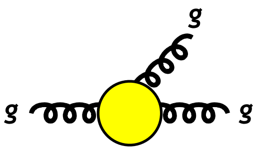


Probe BSM sectors
without mixing
with light quarks

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**

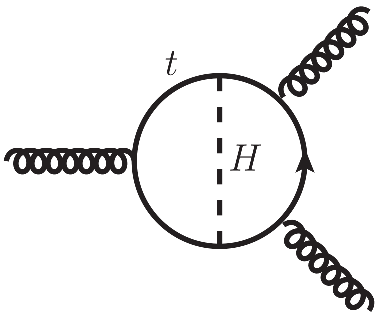
  S. Weinberg, Phys. Rev. Lett. **63**, 2333 (1989).

- **Minimal supersymmetric standard model**

  J. Dai *et al.*, Phys. Lett. B **237**, 216 (1990).

- **Vectorlike quark model**

  K. Choi *et al.*, Phys. Lett. B **760**, 666 (2016).



Typical 2-loop diagram

The Weinberg operator contributes to the neutron EDM, measured in experiment ($d_n < 1.8 \times 10^{-26}$ e cm)

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

Let us quantify the Weinberg operator contribution

Hadronic calculation of Weinberg operator

List of previous works:

- **Naive dimensional analysis**

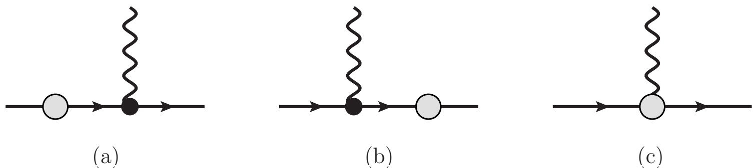
$$d_N \approx e\frac{\Lambda}{4\pi}w \approx w \times 90\, e\, \mathrm{MeV}$$

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

- **Lattice QCD : not yet**

J. Dragos *et al.*, EPJ Web Conf. **175**, 06018 (2018);
M. D. Rizik *et al.*, arXiv:2005.04199 [hep-lat].

- **Hadron effective theory analysis (Bigi et al.)**



Assumed to be dominant

⇒ γ_5-rotation of g-2!

$$d_N \approx \mu_N \times \frac{m_{\rm odd}}{m_N}$$

$m_{\rm odd}$: CP-odd nucleon mass

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

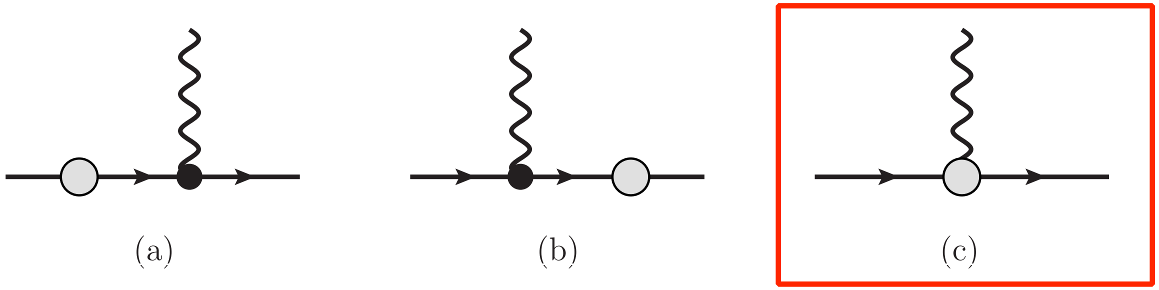
- **QCD sum rules calculation of CP-odd nucleon mass**

$$d_N(w) \approx \begin{cases} w \times 50\, e\, \mathrm{MeV} & (N=n) \\ -w \times 10\, e\, \mathrm{MeV} & (N=p) \end{cases}$$

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

Object of study

What about the direct contribution to the nucleon EDM? Really small?



γ_5-rotation of CP-odd mass (a,b) is a relativistic effect

We expect this relativistic effect to damp in nonrelativisitic frameworks, such as the quark model

Object:

Evaluate the Weinberg operator contribution to the nucleon EDM in the nonrelativistic quark model.

Setup of quark model interactions

We assume nonrelativisitic three-body model with confining force (quark model) and CP-odd interquark interaction calculated with massive quark-gluon.

- Quark model interaction (CP-even sector):

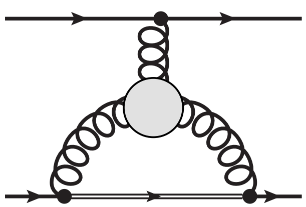
We calculate with three parameter sets (Bhaduri, AP1, AL1)

C. Semay *et al.*, Z. Phys. C **61**, 271 (1994).

⇒ We estimate the systematic error with the variation between them

- CP-odd interquark interaction:

Three-body force suppressed by velocity : we only consider two-body force



Two-body force:

$$\mathcal{H}_{CPV} = -\frac{N_c g_s \alpha_s m_g}{2} w(\vec{\sigma}_1 - \vec{\sigma}_2) \cdot \vec{\nabla} \frac{e^{-m_g r}}{4\pi r} (t_a)_1 \otimes (t_a)_2$$

We assumed heavy quark and massive gluon

Gluon mass given from lattice Landau gauge QCD : m_g = 350 MeV

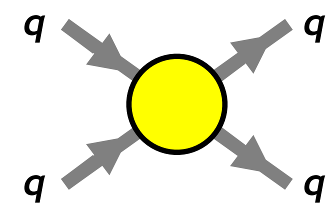
A. F. Falcao *et al.*, arXiv:2008.02614 [hep-lat].

Nucleon EDM (polarization) from CP-odd interquark force

Electric dipole operator requires CP mixing to have finite expectation value

Total hamiltonian:

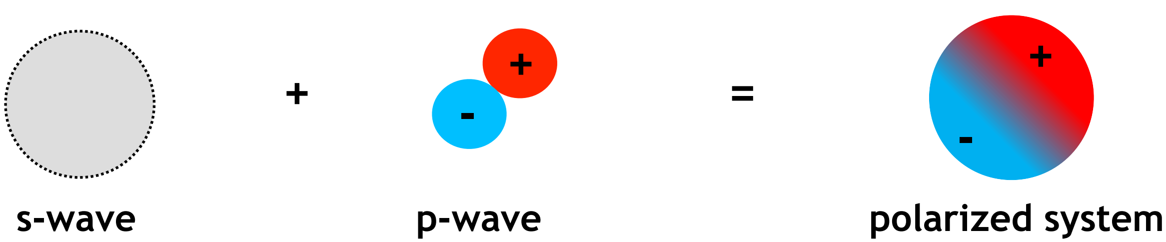
$$H = \begin{pmatrix} H_{\text{realistic}} & H_{\not P \not T} \\ H_{\not P \not T} & H_{\text{realistic}} \end{pmatrix}$$



P, CP-odd
interquark force

P, CP-even
realistic interquark force
(quark model)

CP-odd interquark force mixes opposite parity states



Parity mixing ⇒ Polarized ground state!

Infinitesimally shifted Gaussian expansion method

How to solve few-body Schroedinger equation?

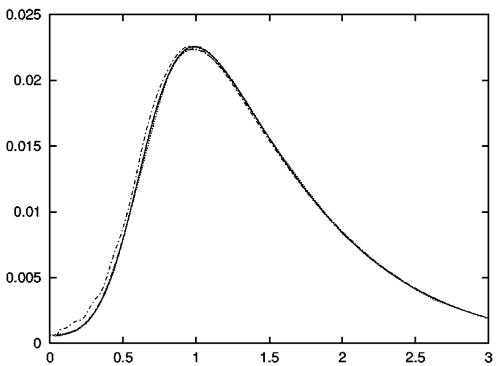
We use the **Gaussian expansion method.**

A sophisticated method to calculate few-body system

E. Hiyama *et al.*, Prog. Part. Nucl. Phys. **51**, 223 (2003).

- Basis function: $\phi_{lm}(\mathbf{r}) = \sum_n N_{nl} \sum_k C_{lm,k} e^{-\nu_n (\mathbf{r}-\mathbf{D}_{lm,k})^2}$
- Variational method
- Successful in the benchmark calculation of ^{4}He binding energy

  H. Kamada et al., Phys. Rev. C **64**, 044001 (2001).



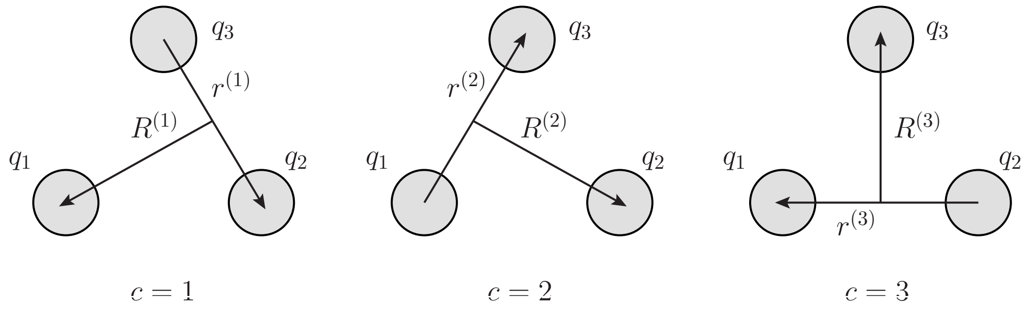
^{4}He Density distribution

- It is applied in many subjects:
  Nuclei, Hypernuclei, atoms, hadrons, astrophysics, …

We expect accurate calculation of nucleon EDM!

Three-body calculation

Jacobi coordinates:



We add three types of Jacobi coordinates to antisymmetrize the wave function.

Angular momentum channels:

We took all channels with orbital angular momenta of the two Jacobi coordinates up to l,L < 3 (2500 channels in total, 1100 are parity even).

Computational cost:

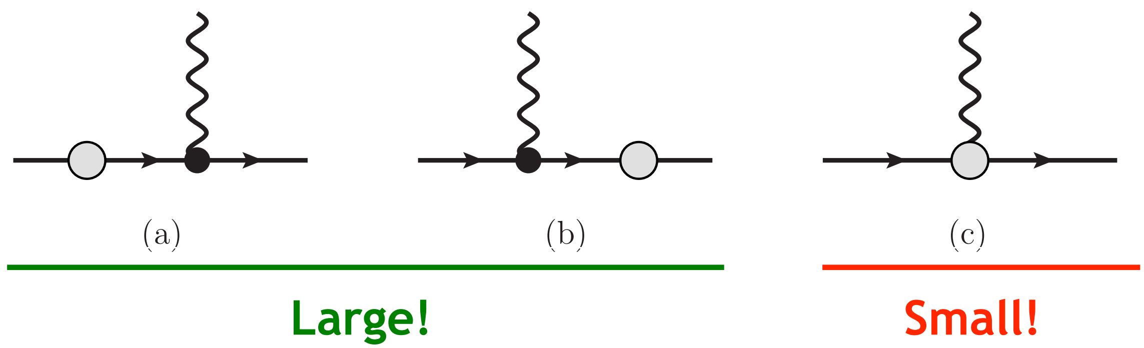
Less than 10 minutes with a workstation with 48 cores.

Result

$$d_N \approx \begin{cases} w \times (4-5)\, e\, \mathrm{MeV} & (N = n) \\ -w \times (4-5)\, e\, \mathrm{MeV} & (N = p) \end{cases}$$

- Smaller than the γ_5-rotation contribution (QCD sum rules)

  Bigi's analysis was correct!



- This analysis may also be applied to the CP-odd N-N force

Summary

- EDM is an important probe of BSM CP violation.
- The Weinberg operator (gluon chromo-EDM) is generated in many BSM candidates.
- We evaluated the Weinberg operator contribution to the nucleon EDM in the nonrelativisitic quark model.
- The CP-odd interquark force was calculated with massive quark-gluon at one-loop level.
- We found that the γ_5-rotation contribution is dominant (Bigi was correct).

Future studies:

- We can evaluate the CP-odd N-N interaction in a similar way.
- We are waiting for experiments!

End

Advertisement

- For details of nuclear EDM calculation, see

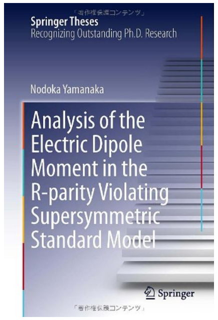
  N. Yamanaka,
  Review of the electric dipole moment of light nuclei,
  International Journal of Modern Physics E 26, 1730002 (2017)
  arXiv:1609.04759 [nucl-th].

- 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 !!