Observed Electric Dipole Moment (EDM) Effect Induced by Electron-gluon Interaction

Ying-nan Mao (毛英男)

National Center for Theoretical Sciences (Hsinchu)

(Dated: July 30, 2019)

1904.10808

Talk @ HFCPV-2019 (IMU, Hohhot)

⟸ Based on my recent paper JHEP **07** (2019), 074 [arXiv: 1904.10808], in collaboration with Kingman Cheung, Wai-Yee Keung, and Chen Zhang.

I. INTRODUCTION AND BACKGROUND KNOWLEDGE

- In Oct. 2018, ACME collaboration presented their new measurement on electron electric dipole moment (EDM) using ThO molecule [ACME collaboration, Nature **562**, 355 (2018)], the result:

$$|d_e^{\mathrm{eff}}| \equiv |d_e + kC_N| < 1.1 \times 10^{-29}\ e \cdot \mathrm{cm} \quad @ \quad 90\%\ \mathrm{C.L.}$$

- This limit is 8.6 times better than that obtained five years ago $|d_{e,\mathrm{eff}}| < 9.4 \times 10^{-29}\ e \cdot \mathrm{cm}$ @ 90% C.L. [J. Baron *et al.* (ACME collaboration), Science **343**, 269 (2014); New J. Phys. **19**, 071001 (2017)].

- Here d_e is the electron EDM, $k \approx 1.6 \times 10^{-21}\ \mathrm{TeV}^{-2} \cdot e \cdot \mathrm{cm}$, and C_N is the coefficient of the CP-violated electron-nucleon interaction $\mathcal{L} \supset \mathrm{i} C_N \bar{e} \gamma^5 e \bar{N} N$, later I will show more explanations why this interaction is important: I will focus on it in this talk.

A. Why is New ACME Result So Important?

- Let's begin with the electron EDM operator: $\mathcal{L} \supset -(\mathrm{i}d_e/2)\bar{e}\sigma^{\mu\nu}\gamma^5 e F_{\mu\nu} \Rightarrow$ it violated P and CP $\Rightarrow$ pure quantum effect (different from the classical EDM), and in the non-relativistic (NR) limit $\hat{H} = -d_e \vec{E} \cdot \vec{s}/s$.

- The coefficient d_e is the electron EDM, which is predicted extremely small by the standard model (SM): $|d_e| \sim \mathcal{O}(10^{-38})\ e \cdot \mathrm{cm}$ [M. Pospelov and A. Ritz, Phys. Rev. **D89**, 056006 (2014)].

- However, in some new physics (NP) models, the typical value of electron EDM can be predicted several orders larger than that in SM, thus it must face strict constraints by the EDM measurements with better accuracy.

- It is almost a background-free observable to test NP (with CP-violation).

- Recent improvements on electron EDM measurements using molecules (90% C.L.):

Year	Molecule	d_e Limit	Reference
2011	YbF	$< 1.05 \times 10^{-27}\ e \cdot \mathrm{cm}$	J. J. Hudson *et al.*, Nature **473**, 493
2014	ThO	$< 0.94 \times 10^{-28}\ e \cdot \mathrm{cm}$	ACME Collaboration, Science **343**, 269
2017	HfF^+	$< 1.3 \times 10^{-28}\ e \cdot \mathrm{cm}$	W. B. Cairncross *et al.*, PRL **119**, 153001
2018	ThO	$< 1.1 \times 10^{-29}\ e \cdot \mathrm{cm}$	ACME Collaboration, Nature **562**, 355

- The ACME experiment obtained the strictest constraint on electron EDM, though still far above the SM prediction, it is already able to set constraints on NP models in which electron EDM can be generated at one- or two-loop level.

B. ACME Experiment: Theoretical and Experimental Details

- We first ignore the electron-nucleon interaction in this section.

- We cannot use free electron because it will fly away in electric fields, we must use the electrons bounded in materials, the detailed effects can be described as an effective electric field: $\hat{H} = -d_e \vec{E}_{\text{eff}} \cdot \vec{s}/s$.

- The ACME experiment choose ThO: for the $^3\Delta_1$ state, $|E_{\text{eff}}|$ can reach 78 GV/cm, see [L. V. Skripnikov, J. Chem. Phys. **147**, 021101 (2017)]

$$\boxed{\begin{array}{cccc} s, p, d, f & \Longleftrightarrow & S, P, D, F & \text{(Atom)} \\ \Updownarrow & & \Updownarrow & \\ \sigma, \pi, \delta, \phi & \Longleftrightarrow & \Sigma, \Pi, \Delta, \Phi & \text{(Molecule)} \\ \text{Single} & & \text{Double} & \end{array}}$$

  - Corresponding convention for single/double electron states in atoms and molecules;
  - Denote the state with $^{2S+1}|L_z|_J$, and the $^3\Delta_1$ state contains a σ and a δ electron.

- σ-electron can travel near Th-nuclear easier and dominant the effects in EDM measurements [J. Baron *et al.*, New J. Phys. **19**, 071001 (2017)].

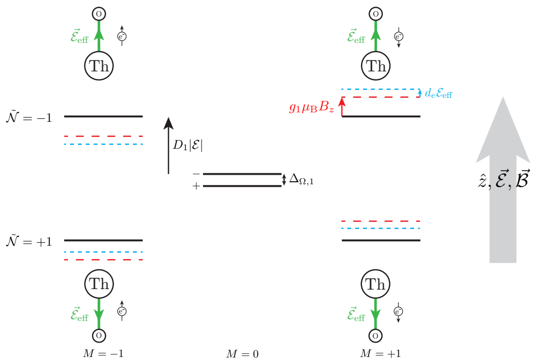
- The state is also easy to fully polarize, after which the $|E_{\rm eff}|$ is independent on the applied external electric field.

- Long enough lifetime ~ 1.8 ms, meaning the measuring time can reach $\tau_{\rm m} \sim 1$ ms, the statistic uncertainty $\delta d_e \propto (2|E_{\rm eff}|\tau_{\rm m})^{-1}$.

- Small magnetic moment $\mu = g\mu_B$ with $g = 4.4\times 10^{-3}$ and μ_B is the Bohr megneton, due to the cancelation between contributions from σ and δ electrons [A. N. Petrov *et al.*, Phys. Rev. **A89**, 062505 (2014)]; external magnetic field is used to reduce systematic uncertainty, because large magnetic moment will induce large spin precession and the contribution from EDM will be hidden.

- Put external electric field $\vec{\mathcal{E}}$ and magnetic field $\vec{\mathcal{B}}$ along $\hat{z}$-axel, $|\vec{\mathcal{E}}| \sim \mathcal{O}(10)$ V/cm is enough to fully polarize ThO molecules.

- Energy levels of ThO $^3\Delta_1$ state in external electric and magnetic fields, figure from [J. Baron *et al.*, New J. Phys. **19**, 071001 (2017)]



  - Angular momentum $J = 1$ and M is its $\hat{z}$-component;
  - D_1 is the classical EDM of ThO (polar molecule, not CPV), and fully polarized condition $D_1|\vec{\mathcal{E}}| \gg \Delta_\Omega$ [A. C. Vutha *et al.*, Phys. Rev. **A84**, 034502 (2011)].

- We use $|\pm\rangle$ to denote the state with $M = \pm 1$, since the spin of σ-electron $\vec{s}_\sigma$ is always anti-parallel with $\vec{J}$, it can also be used to denote the spin state of σ-electron; prepare initial state for which the spin is polarized in $\hat{x} - \hat{y}$ plane using a linear polarized laser beam: for example, spin polarized in $\hat{x}$-axel $|\psi_{t=0}\rangle = \frac{1}{\sqrt{2}}(|+\rangle + |-\rangle)$.

- It is not an energy eigenstate and thus its evolution follows the Schrödinger equation $\mathrm{i}\partial_t|\psi_t\rangle = \delta\hat{H}|\psi_t\rangle$, with $\delta\hat{H} \equiv -\omega\hat{\sigma}_z$, here we only consider the parts which can lead to energy splitting for different spin states.

- $\omega = g\mu_B\mathcal{B}_z + \mathcal{N}d_e|E_{\text{eff}}|$, we ignore other parts of the Hamiltonian because they just bring an overall phase which contribute nothing to spin precession.

- It is direct to have the solution $|\psi_{t=\tau}\rangle = \frac{1}{\sqrt{2}}\left(\mathrm{e}^{-\mathrm{i}\phi}|+\rangle + \mathrm{e}^{\mathrm{i}\phi}|-\rangle\right)$ where $\phi \equiv \omega\tau$.

- $|\psi_{t=\tau}\rangle$ is not the eigenstate of $\hat{\sigma}_x$, it is the eigenstate of the operator $\cos(2\phi)\hat{\sigma}_x - \sin(2\phi)\hat{\sigma}_y$, which means the spin precession angle is 2ϕ measuring the energy shift induced by spin flipping.

- The ACME experiment tried to measure this spin precession through reading out the spin polarization in final states and extract the part induced by electron EDM.

C. The Electron-Nucleon Interaction(s) with CP-violation

- In the discussions above, we considered only the effects induced by electron EDM d_e, as a short summary, the measured quantity is the spin precession induced by any energy shift after σ-electron spin flipping.

- For the four-fermion contact electron-nucleon interaction $\mathcal{L} \supset \mathrm{i} C_N \bar{e}\gamma^5 e \bar{N} N$ which also violates CP, in the NR limit, the spin is introduced through

$$\bar{\psi}\gamma^5\psi \overset{\text{NR limit}}{\propto} \vec{s}_\psi / m_\psi .$$

- Besides this, σ-electron wave function also have large overlap with Th-nuclear.

- Thus in the electron spin-space, $\hat{H}' \propto C_N \vec{s}\cdot\vec{n} \Longrightarrow$ the spin flipping will induce an energy shift and then contribute to spin precession which was measured in the experiment.

- More important, the contribution from interaction part always comes together with the d_e contribution, and any single experiment cannot divide their contributions since they are both determined by internal properties of materials, thus we must consider the combination $d_e + kC_N$ together, as was shown in the first page.

- Though usually the kC_N term contributes sub-dominantly comparing with d_e term, it is still worthy to study its contribution, since the EDM measurement itself cannot give information about a special kind of NP, thus we must consider any kind of possibility.

- Another type of CP-violated electron-nucleon interaction $\mathcal{L} \supset \mathrm{i}\tilde{C}_N \bar{e}e\bar{N}\gamma^5 N$, it is suppressed by m_N^{-1}, and more complex to treat.

- Besides this, for $^{232}\mathrm{Th}^{16}\mathrm{O}$ used in ACME experiment, there is no spin in the nuclear thus it cannot be used to test the operator $\mathrm{i}\bar{e}e\bar{N}\gamma^5 N$, thus we don't discuss it here.

II. CONSTRAINT ON ELECTRON-GLUONIC OPERATOR: $\mathrm{i}\bar{e}\gamma^5 e G_{\mu\nu}G^{\mu\nu}$

- In this section, I will show the standard procedure if we have some new physics models or operators with CP-violation, how will it contribute to the low-energy EDM observable and compare with the experiment results:
  - Operator at high energy $\xrightarrow{\text{QCD running}}$ Low-energy behavior $\xrightarrow{\text{Nucleon matrix elements}}$ Matching to electron-nucleon interaction $\xrightarrow{\text{NR limit}}$ ACME experiment.

- Since there are both quark and gluon contents in nucleons, below the hadron scale,

$$\mathrm{i}\bar{e}\gamma^5 e \left\{ \begin{array}{c} \bar{q}q \\ G_{\mu\nu}G^{\mu\nu} \end{array} \right\} \xrightarrow{\text{Nucleon level}} \mathrm{i}\bar{e}\gamma^5 e\bar{N}N, \qquad \bar{e}e \left\{ \begin{array}{c} \mathrm{i}\bar{q}\gamma^5 q \\ G_{\mu\nu}\tilde{G}^{\mu\nu} \end{array} \right\} \xrightarrow{\text{Nucleon level}} \mathrm{i}\bar{e}e\bar{N}\gamma^5 N.$$

- We only discuss the left case here.

A. The Operator

- We begin from the SU(2) × U(1) invariant form, define

$$\mathcal{O}_g = \frac{\mathrm{i}}{\Lambda^4}\bar{L}_L \Phi e_R \left(\frac{\alpha_s}{4\pi} G_{\mu\nu} G^{\mu\nu}\right) + \text{H.c.} \xrightarrow{\mathrm{U(1)-invariant}} \frac{\mathrm{i}v}{\sqrt{2}\Lambda^4}\bar{e}\gamma^5 e \left(\frac{\alpha_s}{4\pi} G_{\mu\nu} G^{\mu\nu}\right).$$

- It is a dimension-eight operator.

- Lepton-doublet $L_L \equiv (\nu_e, e)_L^T$ and Φ is the SM Higgs-doublet with $\langle \Phi \rangle = \frac{1}{\sqrt{2}}(0, v)^T$, $v = 246$ GeV; G is gluon field strength, and α_s is the strong coupling.

- Λ is some high scale [$\sim \mathcal{O}(\mathrm{TeV})$], the appearance of $\frac{\alpha_s}{4\pi}$ means we assume this high-dimension operator is generated through some loop process.

B. QCD Running Effects

- We begin from the $\mathrm{U}(1)_{\mathrm{em}}$ invariant operator basis

$$\mathcal{O}_g = \frac{\mathrm{i}v}{\sqrt{2}\Lambda^4}\bar{e}\gamma^5 e\left(\frac{\alpha_s}{4\pi}G_{\mu\nu}G^{\mu\nu}\right); \qquad \mathcal{O}_q = \frac{\mathrm{i}v}{\sqrt{2}\Lambda^4}\bar{e}\gamma^5 e\left(m_q\bar{q}q\right).$$

- $\mathcal{L} \supset C_g\mathcal{O}_g + C_q\mathcal{O}_q$, we focus on the $\mathcal{O}_g$ operator in this talk, but the two operators will always mix with each other during the QCD-running.

- We consider the scenario in which $\mathcal{O}_g$ is generated at a high scale $\mu = \Lambda$, Λ may be at several TeV, we should consider the low energy behavior, for example, the hadron scale $\mu \sim 1$ GeV, and then match to nucleon level.

- The leading order QCD running behavior under $\overline{\mathrm{MS}}$ scheme is shown as [R. J. Hill and M. P. Solon, Phys. Rev. **D91**, 043505 (2015); etc.]:

$$\frac{d}{d\ln\mu^2}\begin{pmatrix} C_g \\ C_q \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ \frac{\alpha_s^2}{\pi^2} & 0 \end{pmatrix}\begin{pmatrix} C_g \\ C_q \end{pmatrix}.$$

- The diagonal elements are zero because we choose the basis that they are proportional to the trace of energy-momentum tensor.

- Use three-loop α_s as *input*, and when crossing a heavy quark threshold $2m_q$, we should integrate it out and induce a jumping $C_g \to C_g - \frac{1}{3}C_q(2m_q)$, there are three active quarks u, d, s at hadron scale.

- Numerical solution: for $\Lambda = (1-10)$ TeV, if $C_g(\Lambda) = 1$ and $C_q(\Lambda) = 0$, we have $C_q(1\ \mathrm{GeV}) \approx -0.06$, which is independent on quark type and depends weakly on Λ.

C. Matching to Electron-nucleon Interaction

- For the electron-nucleon interaction $\mathcal{L} \supset \mathrm{i} C_N \bar{e}\gamma^5 e \bar{N} N$, we have

$$C_N = \frac{v}{\sqrt{2}\Lambda^4}\left(C_g \left\langle \frac{\alpha_s}{4\pi} G_{\mu\nu}G^{\mu\nu} \right\rangle_N + \sum_{q=u,d,s} C_q \left\langle m_q \bar{q} q \right\rangle_N \right).$$

- Here $\langle \mathcal{O} \rangle_N \equiv \langle N|\mathcal{O}|N\rangle$, and the numbers are close to each other for $N = p$ or n;

- The matrix elements satisfy the sum rule [X. Ji, Phys. Rev. Lett. **74**, 1071 (1995)]:

$$m_N = \left(1 + \frac{2\alpha_s}{\pi}\right) \sum_{q=u,d,s} \left\langle m_q \bar{q} q \right\rangle_N - \frac{9}{2} \left\langle \frac{\alpha_s}{4\pi} G_{\mu\nu}G^{\mu\nu} \right\rangle_N .$$

- The gluon content is a higher order effect in α_s, but numerically not small.

- The quark contents' contributions can all be obtained at lattice [Y.-B. Yang *et al.* (χQCD Collaboration), Phys. Rev. **D94**, 054503 (2016); etc.], and thus we can derive the gluon content's contribution, see the table below for details:

	$\langle m_u \bar{u} u \rangle_N$	$\langle m_d \bar{d} d \rangle_N$	$\langle m_s \bar{s} s \rangle_N$	$\left\langle \sum_q m_q \bar{q} q \right\rangle_N$	$\left\langle \frac{\alpha_s}{4\pi} G_{\mu\nu} G^{\mu\nu} \right\rangle_N$
$N = p$	15.5 MeV	29.4 MeV	40.2 MeV	85.1 MeV	-183 MeV
$N = n$	13.5 MeV	33.4 MeV	40.2 MeV	87.1 MeV	-183 MeV
Error	± 2.7 MeV	± 5.5 MeV	± 12.2 MeV	± 14.6 MeV	± 5 MeV

- Numerically, the gluon matrix element is large, which means the gluon content is important in nucleons, the numbers are almost the same for proton and neutron. [For this method, see also more details in R. J. Hill and M. P. Solon, Phys. Rev. **D91**, 043505 (2015); H.-Y. Cheng and C.-W. Chiang, JHEP **07** (2012), 009; etc.]

- The QCD-running correction is about $\delta C_N / C_N \approx 4\%$.

D. Comparing with ACME Result

- If $\mathcal{O}_g$ is generated at Λ where $C_q(\Lambda) = 0$, it contributes to the effective ThO EDM as $d_e^{\rm eff} = -5.3 \times 10^{-26} \frac{C_g(\Lambda)}{(\Lambda/\mathrm{TeV})^4}\ e \cdot \mathrm{cm}$.

- Assuming in the special NP scenario, the d_e itself is ignorable, then the ACME result can be used to set a very strict constraint $\Lambda > 8.2 C_g(\Lambda)^{1/4}$ TeV.

- Similar assumptions appear frequency in the analysis of effective field theory, any time we consider a single (or a small number of) operator(s) and study the behavior, but sometimes it can not lead to the final conclusion.

- Future ThO measurements will increase the sensitivities $(1-2)$ order(s) better than the recent result [C. D. Panda *et al.*, Phys. Rev. **A93**, 052110 (2016); etc.], which will lead to a $(2-3)$ times better limit on Λ.

III. SUMMARY AND DISCUSSION

- A recent update by ACME II showed an order's better limit on electron EDM.
- The measured quantity is spin precession induced by the energy shift under electron spin flipping: the electron-nucleon interaction always appear together with the electron EDM contribution, any single measurement cannot separate them.
- In this talk, we disscuss the CP-violated electron-gluonic operator since the gluon content is important in nucleons, we assume they are generated at the scale of a few TeV, and consider the constraints through EDM measurement.
- We focus on $\mathcal{O}_g \propto \mathrm{i}\bar{e}\gamma^5 e G_{\mu\nu}G^{\mu\nu}$ in this talk, because it can contribute significantly to the measured ThO effective EDM, and the constraint can be set as $\Lambda > 8.2$ TeV, assuming $\mathcal{O}_g$ contributes dominantly comparing with d_e, and $C_g(\Lambda) = 1$, $C_q(\Lambda) = 0$.


The end,
thank you!
ynmao@cts.nthu.edu.tw