An experimentalist's take on…

An update to
Estimation of CP violating EDMs from known mechanisms in the SM

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Mississippi State University

Overview: Very much an update!

LNS

CPV in SM | Atoms | Summary

1 2 3 4 5

Sub-atomic particles | Molecules

① T/CP Violation?

LNS

Naively, equal amounts of matter and antimatter; but, most of this is matter…

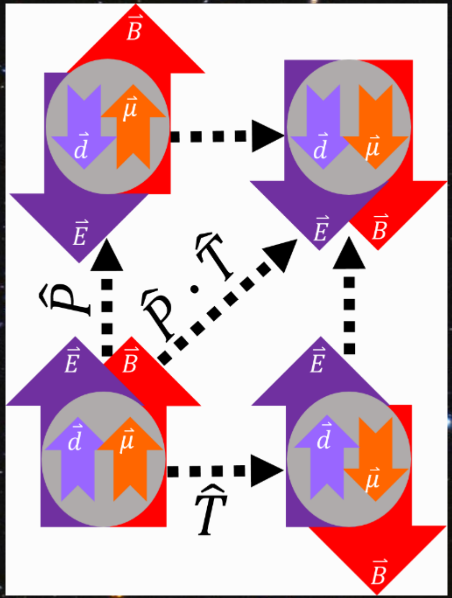
Asymmetry given by, $\boldsymbol{\eta_B = (n_B - n_{\bar{B}})/n_\gamma = (6.135 \pm 0.027) \times 10^{-10}}$

<u>Sakharov Conditions</u>

- ❑ Baryon # violation
- ❑ C & CP violation → $\eta_B^{(SM)} \sim 10^{-18}$
- ❑ Out of thermodynamic equilibrium

CKM (QCD-$\bar{\theta}$)

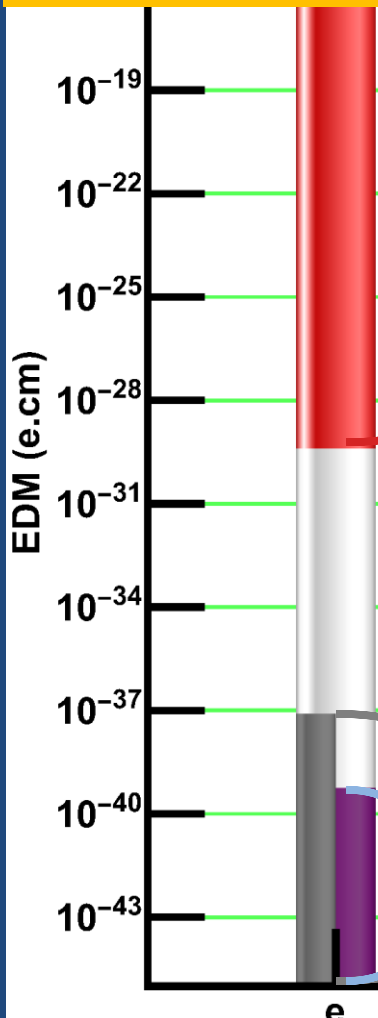
An EDM is a signature of P, T, CP, CT violation



Plank Collaboration, arXiv: 1807.06209

② Charged Leptons: e

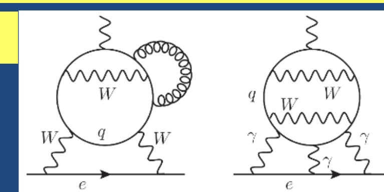
(i) EDM from SM-CKM (4-loop); (ii) EDM from SM-θ_{QCD}



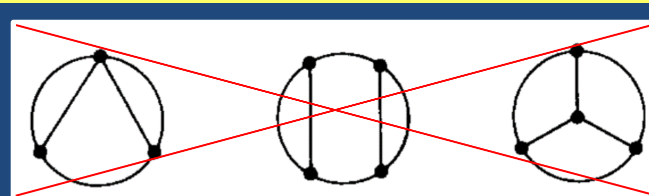
90 % C.L. upper limit from YbF⁺ e-EDM experiment

T. S. Roussy et al., Science **381**, 46 (2023)

M. Pospelov and A. Ritz, Phys. Rev. D **89**, 056006 (2014)



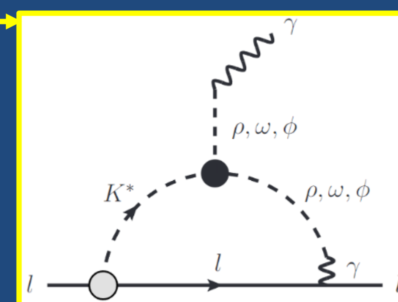
4-loop



F. Hoogeveen, Nucl. Phys. B **341**, 322 (1990)

3-loop

4-loop
Dressed with mesons



D. Ghosh & R. Sato, Phys. Lett. B **777**, 335 (2018)

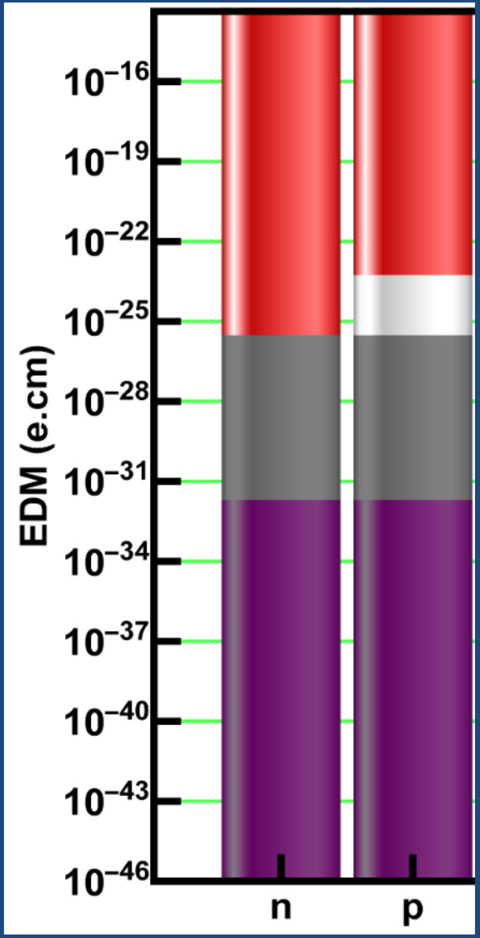
Electron SM-θ-EDM

Electron SM-CKM-EDM

Y. Yamaguchi and N. Yamanaka, Phys. Rev. Lett. **125**, 241802 (2020)

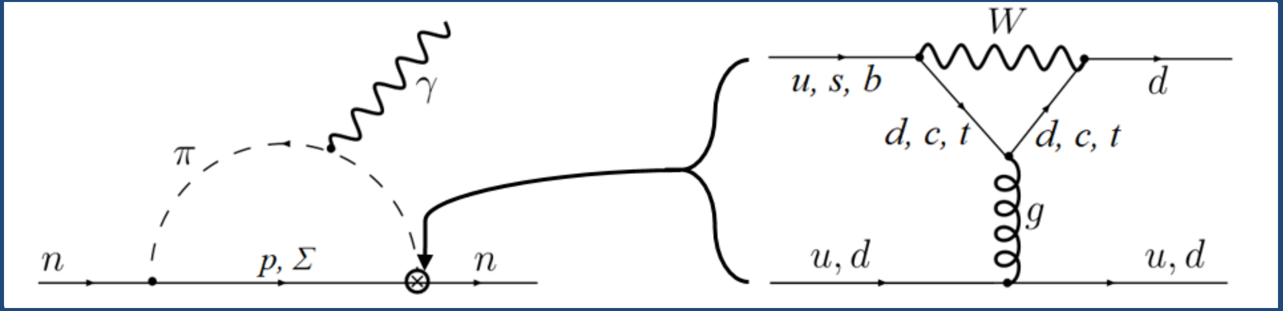
② Reminder: Light Baryons

(i) SM-CKM-EDM (1-loop); (ii) SM-θ̄ directily from nEDM



$d_n < (1.8 \times 10^{-26})$ e.cm (UCN)

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



Neutrons ~ Proton

$(n \to p\pi^-)$ $(p \to n\pi^+)$

$d_n \sim \bar{\theta}(6 \times 10^{-17})$ e.cm $\to \bar{\theta} < 3 \times 10^{-10}$

n,p SM-θ-EDM, nEDM directly from QCD-$\bar{\theta}$

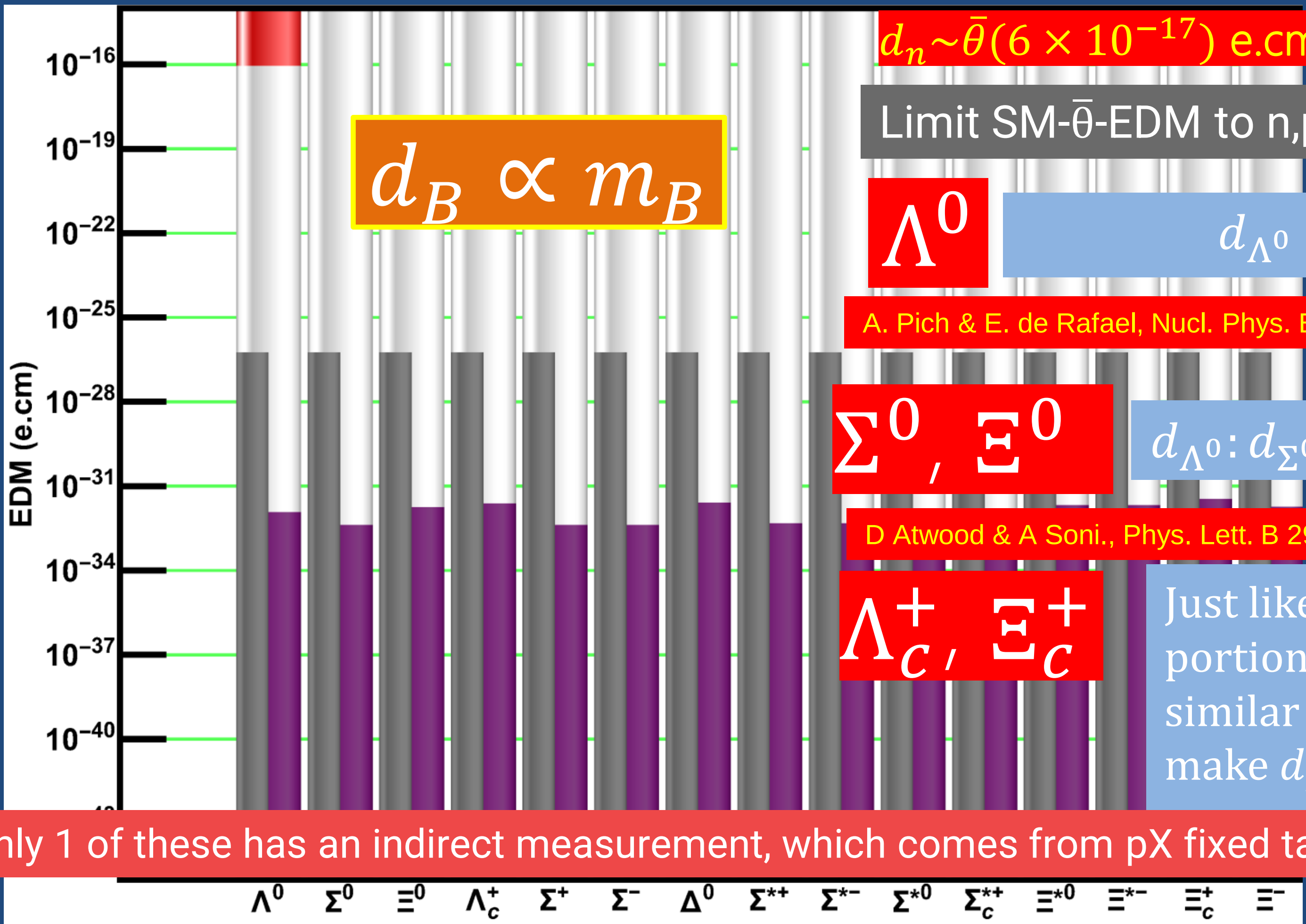
M Pospelov and A Ritz. Ann. Phys. 318.1 (July 2005), pp. 119–169

n,p SM-CKM-EDM from diagrams above

IB Khriplovich and AR Zhitnitsky, Phys. Lett. B 109.6 (Mar. 1982), pp. 490–492.

② HEP Community: Do this!

(i) SM-CKM-EDM (1-loop); (ii) SM-$\bar{\theta}$ similar to n,p EDM



$d_B \propto m_B$

$d_n \sim \bar{\theta}(6 \times 10^{-17})$ e.cm $\rightarrow \bar{\theta} < 3 \times 10^{-10}$

Limit SM-$\bar{\theta}$-EDM to n,p-SM-$\bar{\theta}$-EDM

Λ^0 $\quad d_{\Lambda^0} \sim d_n/2$

A. Pich & E. de Rafael, Nucl. Phys. B 367.2 (Dec. 1991), pp. 313–33

Σ^0, Ξ^0 $\quad d_{\Lambda^0} : d_{\Sigma^0} : d_{\Xi^0} = 3 : \text{-}1 : 4$

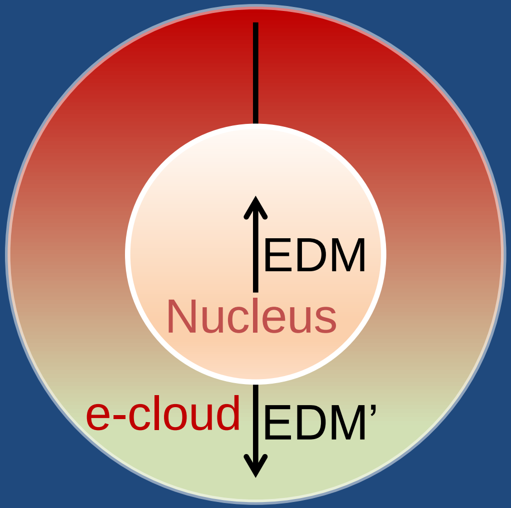
D Atwood & A Soni., Phys. Lett. B 291.3 (Sept. 1992), pp. 293–296.

Λ_c^+, Ξ_c^+ $\quad$ Just like n~p, for CKM portion of the EDM, similar quark exchanges make $d_{\Lambda^0} \sim d_{\Lambda_c^+}, d_{\Xi^0} \sim d_{\Xi_c^+}$

Only 1 of these has an indirect measurement, which comes from pX fixed target experiments.

③ Atoms

In an atom…



Net ~ 0

Exceptions:

- Relativistic electrons in high-z atoms (Eg.: ^{210}Fr)
- Deformed nuclei (Eg.: ^{225}Ra)
- CPV interaction between nucleus & electrons

③ Atoms: LE parameters

$$d_{Atom} = \rho_A^e d_e$$ Electron

$$+ \sum_{N=\{p,n\}} \rho_Z^N d_N$$ Neutrons & Protons

$$+ \alpha_{C_s} C_s$$ Scalar eN coupling

$$+ \alpha_{C_T} C_T$$ Tensor eN couping

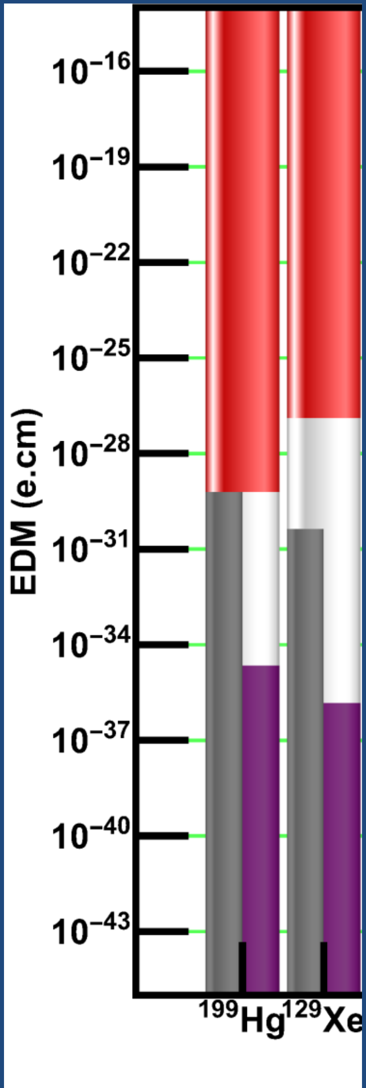
$$+ \underbrace{\alpha_{\bar{g}_\pi^0} \bar{g}_\pi^0 + \alpha_{\bar{g}_\pi^1} \bar{g}_\pi^1}_{\kappa_S S}$$ πNN interactions; Schiff moment

Para-M: $C_s \approx 7 \times 10^{-16}$

Dia-M: $C_T \approx (\alpha/\pi) C_s \approx 1.6 \times 10^{-18}$

T. Chupp and M. Ramsey-Musolf, Phys. Rev. C **91**, 035502 (2015)
Y. Ema, T. Gao, and M. Pospelov, Phys. Rev. Lett. **129**, 231801 (2022)

③ Atoms



>>Single Source: Electron, eN contributions are small<<

Dominated by CPV Schiff moment

Nuclear CPV EDMs are suppressed due to Schiff screening.

$$d_{Atom} = \rho_A^e d_e + \sum_{N=\{p,n\}} \rho_Z^N d_N + \kappa_s S + \alpha_{C_s} C_s + \alpha_{C_T} C_T$$

e-EDM

n,p-EDM

Schiff mo.

$$S_{^{199}Hg} = (0.200\ \text{fm}^2)\, d_p + (1.895\ \text{fm}^2)\, d_n$$

$$\rho_p = (-0.56 \times 10^{-4}),\ \rho_n = (-5.3 \times 10^{-4}),\ \kappa_s = (-2.4 \times 10^{-4})\ \text{fm}^{-2}$$

$$\alpha_{C_s} = (-5.9 \times 10^{-20}),\ \alpha_{C_T} = (3.0 \times 10^{-22})$$

$$C_s = 0.03\theta$$

$$C_T \approx (\alpha/\pi) C_s$$

$$\bar{\theta} < 9.5 \times 10^{-11}$$

B Graner et al, Phys. Rev. Lett. 116.16 (Apr. 2016), p. 161601.
J Engel et al., Prog. Part. Nucl. Phys. 71 (July 2013), pp. 21–74.

③ Atoms: Paramagnetic

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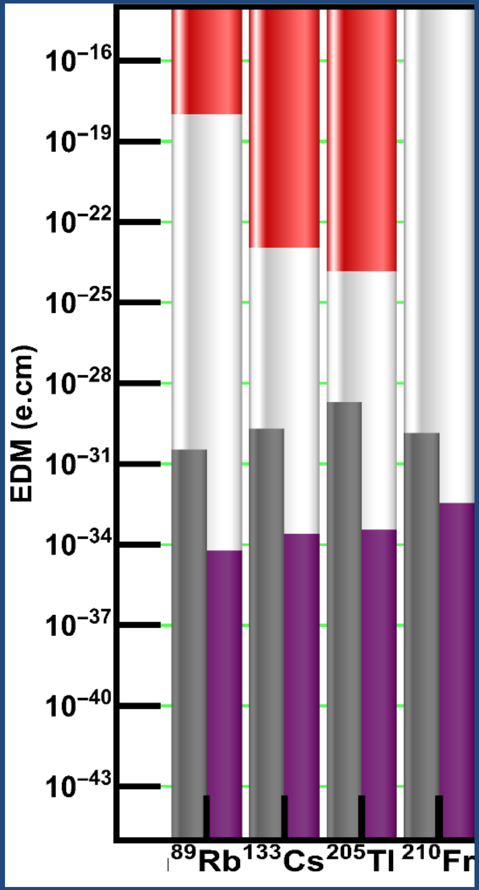
>>Single Source: Electron contribution is small, dominated by CPV eN interactions<<

Underestimates: Lack of nuclear contributions, but comparable to ^{199}Hg



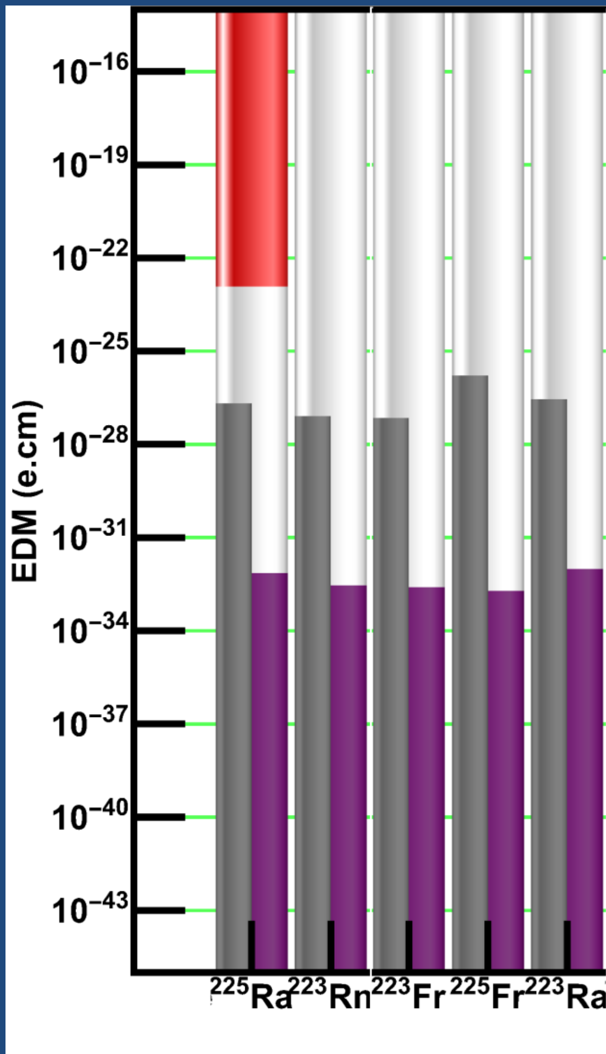
Atom	ρ_A^e	α_{C_s} (10^{-19})	Ref.
^{89}Rb	25.7	1.2	[1]
^{133}Cs	123	7.1	[1]
^{205}Tl	573	70	[2]
^{210}Fr	903	5.0	[3]

$$d_{Atom} = \rho_A^e d_e + \boldsymbol{\alpha_{C_s} C_s}$$

$$C_s \approx 0.03\theta$$

[1] HS Nataraj et al., Phys. Rev. Lett. 101.3 (July 2008), p. 033002.
[2] ZW Liu and HP Kelly, Phys. Rev. A 45.7 (Apr. 1992), pp. 4210–4213.
[3] TMR Byrnes et al., Phys. Rev. A 59.4 (Apr. 1999), pp. 3082–3083.

③ Deformed Atoms

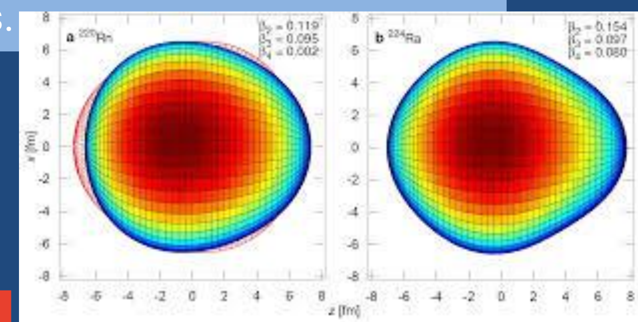


Nuclear Octupole+Quadrupole deformation enhances atomic EDM

Rest of the diamagnetic systems are represented as a ratio w.r.t. ^{199}Hg

$$d_{Atom} \approx \kappa_\beta \kappa_s S + \alpha_{C_{S/T}} C_{S/T}$$

Plug in: {n, p}-SM-CKM/ $\bar{\theta}$ -EDM → Multiply by the appropriate enc. factors.



Atom	$\kappa_s^{(\mathrm{Atom})}/\kappa_s^{(199_{Hg})}$	κ_β
^{223}Ra	3 [1]	326 [2]
^{225}Ra	3 [1]	240 [2]
^{223}Fr	3 [1]	84 [2]
^{225}Fr	3 [1]	67 [2]
^{223}Rn	1.2 [1]	240 [3]

[1] VA Dzuba et al., Phys. Rev. A 66.1 (July 2002), p. 012111
[2] JHd Jesus and J Engel, Phys. Rev. C Nucl. Phys. 72.4 (Oct. 2005), p. 045503
[3] V Spevak, et al., Phys. Rev. C Nucl. Phys. 56.3 (Sept. 1997), pp. 1357–1369

④ Mols: LE parameters

When nuclei with MQM, NSM is put in an mol. → Large (x10^5) CPV EDM

$$H = W_d d_e \mathbf{S}\cdot\mathbf{n} + W_Q \frac{Q}{I}\mathbf{I}\cdot\mathbf{n} - \frac{W_M M}{2I(2I-1)}\mathbf{S}\hat{\mathbf{T}}\mathbf{n}$$

- e-EDM
- e-spin
- Mol.'s symmetry axis
- Nuclear Schiff Moment
- Nuclear MQM
- Nuclear-spin

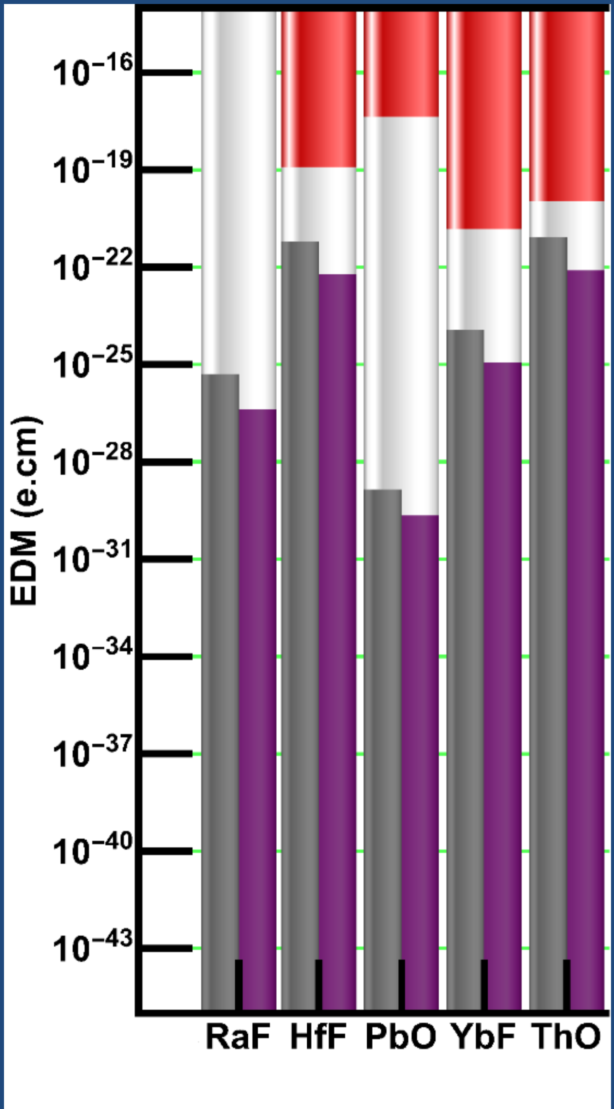
$$M_p(\bar\theta) = 1.9\times10^{-29}\,\bar\theta\mathrm{e.cm}^2$$
$$M_n(\bar\theta) = 2.5\times10^{-29}\,\bar\theta\mathrm{e.cm}^2$$

$$M_N \approx 4.5\times10^{-44}\mathrm{e.cm}^2$$

Nucleus	J^π	MQM
^{173}Yb	5/2-	$14M_p + 26M_n$
$^{177(179)}$Hf	7/2- (9/2+)	$17(20)M_p + 42(50)M_n$
^{181}Ta	7/2+	$19M_p + 45M_n$
^{229}Th	5/2+	$13M_p + 27M_n$

B. G. C. Lackenby and V. V. Flambaum, Phys. Rev. D **98**, 115019 (2018)

④ Polar Molecules



- **Polar molecules have LARGE intra-molecular E-field ~ GV/cm.**
- **Comparing EDMs requires normalizing with this field.**

$$\sigma_d \propto {}^{1}/_{E}$$

$$d \sim \alpha_e d_e + \alpha_p d_p + \alpha_{C_S} C_S + W_M M_N + \alpha_{\text{ud}} (\widetilde{d_u} - \widetilde{d_d})$$

Molecule	α_e/E	$W_{S,M}$ (μHz/efm²)	α_{ud} (10^{27}μHz/cm)	α_{C_S} (10^{-21})	$d \times \alpha_e$ (e.cm)
RaF	×(130 MV/300 kV)	1.2	22	29.6	-
HfF^+	**×(23 GV/24 V)**	**0.49**	**37**	**8.9**	**3.9×10^{-21} [1]**
PbO	×(25 GV/100 V)	0.28	~18*	4.2	4.3×10^{-18} [2]
YbF	×(14.5 GV/10 kV)	2.1	53	8.6	1.5×10^{-21} [3]
ThO	×(78 GV/80 V)	1.1	56	13	1.1×10^{-20} [4]

Best e-EDM: $d_e^{(\text{HfF}^+)} < 4.1 \times 10^{-30}$ e.cm (90% CL)

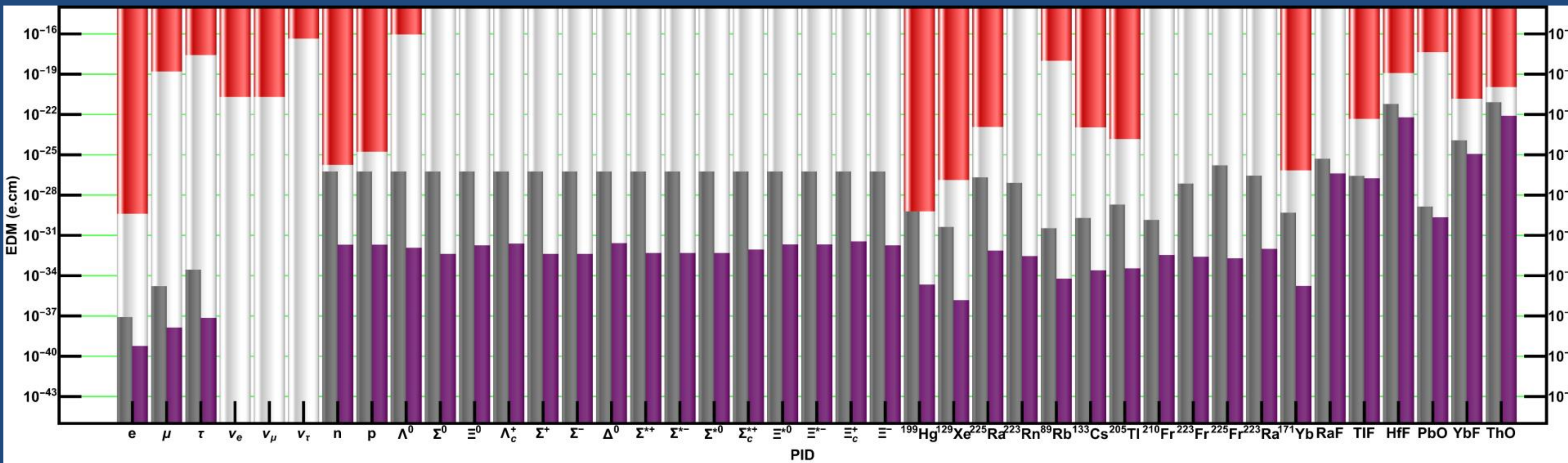
Missing: FrAg, RaAg

SM−CKM,$\bar{\theta}$−EDM ∝ (∗) e−SM−CKM,$\bar{\theta}$−EDM

[1] T. S. Roussy et al., Science 381, 46 (2023). [2] S Eckel et al, Phys. Rev. A 87.5 (May 2013), p. 052130. [3] JJ Hudson et al., Nature 473.7348 (May 2011), pp. 493-496. [4] ACME Collaboration, Nature 562.7727 (Oct. 2018), pp. 355-360.

⑤ Summary

C_S, C_T → $\bar{\theta} < 9.5 \times 10^{-11}$ ← S, M_N



! HEP Community, impose limits (10^{-17} e.cm) on: $\Sigma^{+,*+,0,-,*-}, \Xi^{-,*-,0}, \Delta^0, \Lambda_c^+, \Sigma_c^{*+}, \Xi_c^+$

✔ Systems where SM "background free": eg.-{e,μ,τ}. Systems where SM can explain any EDM discovered (without improvement in sensitivity): eg.-{n, ^{199}Hg}.

ASK ME ABOUT: ^{3}**He, p, n, Ra**

Thanks: K. Kirch
DOE # DE-SC0014448/19768

Backup

① Motivation

Absence of CPV in Strong Sector

Strong CP Problem

① Motivation

?

Baryon Asymmetry of the Universe

$$\eta = \frac{\eta_B - \eta_{\bar{B}}}{\eta_\gamma} = (6.135 \pm 0.027) \times 10^{-10}$$

Planck Collaboration et al. arXiv: 1807.06209 [astro-ph.CO]

① Sakharov Conditions

Lopsided baryon generation requires:

- Baryon number violation (like $p \rightarrow \bar{e}\pi^0$)
- C & CP Violation: CPV (n,e) EDM
- Interactions out of thermal equilibrium

AD Sakharov, JETP Lett. 5.1 (1967), pp. 24–27.

① Sources of CPV in SM

$$\mathfrak{L}_{CPV} = \mathfrak{L}_{CKM} + \mathfrak{L}_{\bar{\theta}} + \mathfrak{L}_{BSM}$$

(i) 'δ': CKM Matrix

$\delta = (1.20 \pm 0.08)$ rad

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

(ii) '$\bar{\boldsymbol{\theta}}$': QCD, $\bar{\theta} \lesssim 10^{-10}$

$$\mathscr{L}_{QCD} = \overline{\psi}_i \left(\mathbb{i}(\gamma^\mu D_\mu)_{ij} - m\delta_{ij} \right) \psi_j - \frac{1}{4} G^\alpha_{\mu\nu} G^{\mu\nu}_\alpha - \frac{g_s^2}{16\pi^2} \theta_s G^\alpha_{\mu\nu} \tilde{G}^{\mu\nu}_\alpha$$

G 't Hooft, Phys. Rev. Lett. 37.1 (July 1976)

① Sources of CPV in SM

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$\eta_{CKM} \sim 10^{-18}$

$\eta_{BAU} \sim 10^{-10}$

A. Riotto and M. Trodden, Annu. Rev. Nucl. Part. Sci. **49**, 35 (1999).

① Sources of CPV in SM

$$\mathfrak{L}_{CPV} = \mathfrak{L}_{CKM} + \mathfrak{L}_{\bar{\theta}} + \mathfrak{L}_{BSM}$$

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What can we expect from $\mathfrak{L}_{\bar{\theta}}$

Too Little… Need other sources.

A. Riotto and M. Trodden, Annu. Rev. Nucl. Part. Sci. **49**, 35 (1999).

① Strong CP Problem

LNS

Traditional Answer:
CP Violating Term – θ

Parity violation in weak sector? ✓

$$L_\theta = \frac{\alpha_s \theta}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

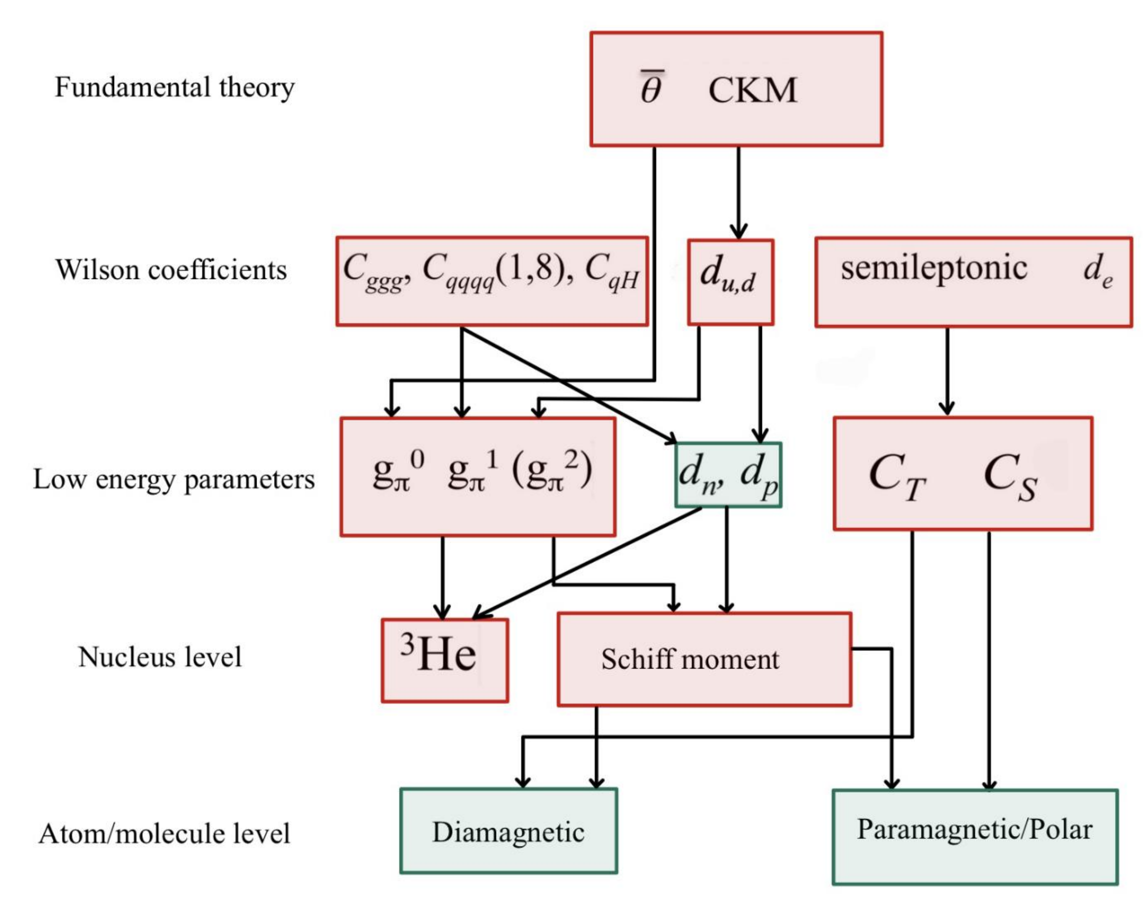
$d_n < 2.9 \times 10^{-26}$ e.cm (90%C.L.)
$\theta < 10^{-10}$

Strong CP Problem

?

Solution in strong sector:
Promote the "Theta" term to a QCD field. This field undergoes symmetry breaking to give rise to **QCD Axions**.

① Low energy parameters



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$$C_T \approx (\alpha/\pi) C_S \approx 1.6 \times 10^{-18}$$

T. Chupp and M. Ramsey-Musolf, Phys. Rev. C **91**, 035502 (2015)
Y. Ema, T. Gao, and M. Pospelov, Phys. Rev. Lett. **129**, 231801 (2022)
A. Chauhan, BS Thesis, Wellesley College (2024)

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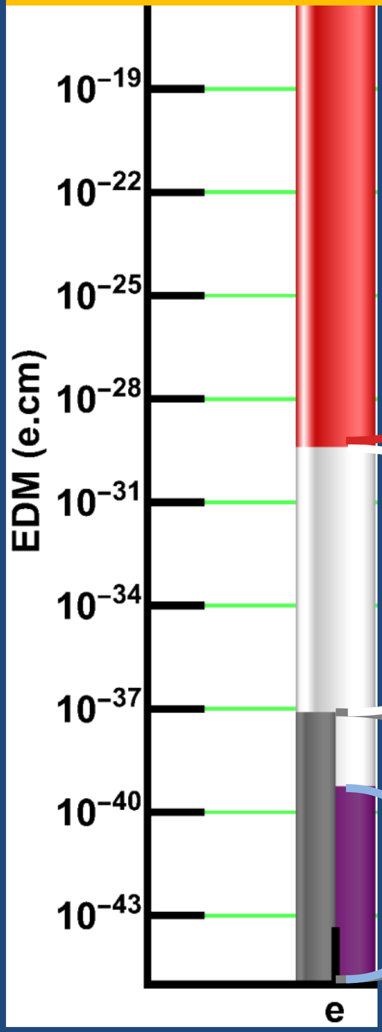

90 % C.L. upper limit from YbF⁺ e-EDM experiment

T. S. Roussy et al., Science **381**, 46 (2023)

$$\mathcal{L}_{CPV} = \mathcal{L}_{CKM} + \mathcal{L}_{\bar{\theta}} + \not{\mathcal{L}}_{\not{?}}$$

EDM if measured in this portion has a chance of having BSM origins.

Electron SM-**θ**-EDM

Electron SM-CKM-EDM

Y. Yamaguchi and N. Yamanaka, Phys. Rev. Lett. **125**, 241802 (2020)

② Charged Leptons: μ,τ

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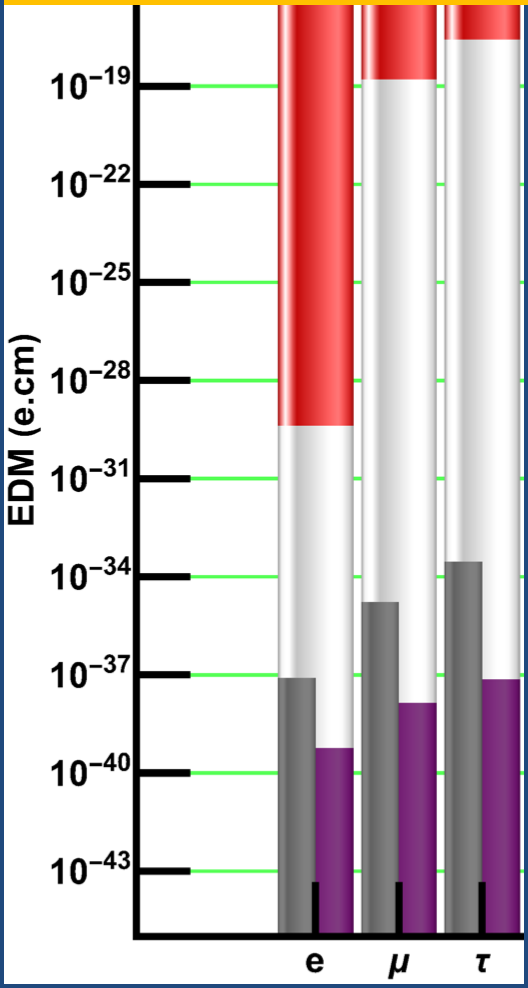


$$d_l \propto m_l$$

Muon

90 % C.L. upper limit from Muon g-2 experiment

Muon (g-2) Collaboration, Phys. Rev. D 80.5 (Sept. 2009), p. 052008.

Tau-Lepton

90 % C.L. upper limit from $e\bar{e}$: Belle Collaboration

K Inami et al. Phys. Lett. B 551.1 (Jan. 2003), pp. 16–26.
Updated by: K. Kirch and P. Schmidt-Wellenburg, arXiv: 2003.00717 (2020).

τ, μ SM-**θ**-EDM, scaled by mass from electron

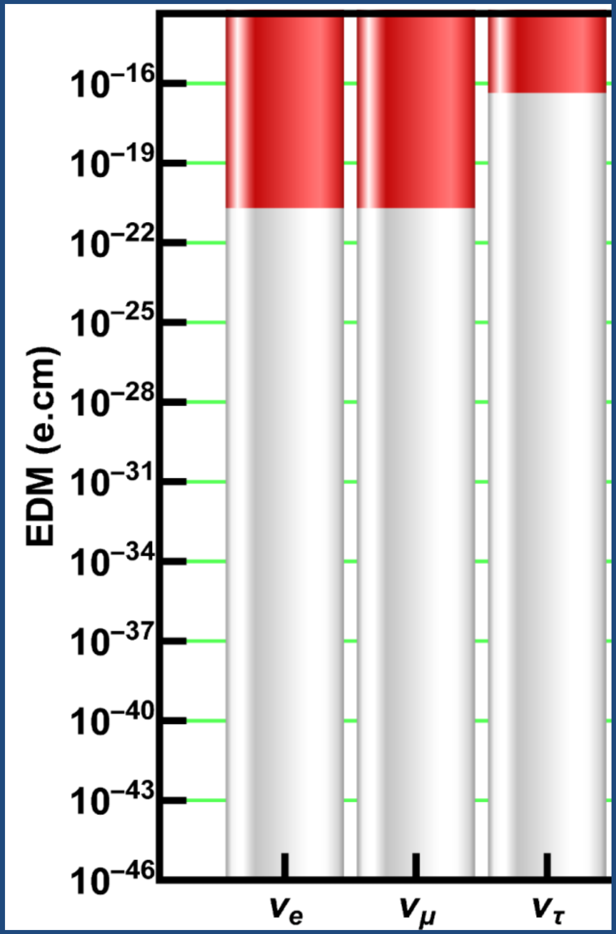
D Ghosh and R Sato, Phys. Lett. B 777 (Feb. 2018), pp. 335–339.

τ, μ SM-CKM-EDM, scaled by mass from electron

M Pospelov and A Ritz, Phys. Rev. D 89.5 (Mar. 2014), p. 056006.

② Neutrinos

(i) Not known! ; (ii) Not known! (iii) Only experimental constraints



Electron & Muon-Neutrino

90 % C.L. upper limit from indiect $e\bar{e}$: collisions

F del Aguila and M Sher, Phys. Lett. B 252.1 (Dec. 1990), pp. 116–118.
LB Okun, Sov. J. Nucl. Phys. ITEP–14 (1986).

Tau-Neutrino

90 % C.L. upper limit from indiect $e\bar{e}$: collisions

A Gutiérrez-Rodríguez et. al., Phys. Rev. D 69.7 (Apr. 2004), p. 073008.
R Escribano and E Massó, Phys. Lett. B 395.3 (Mar. 1997), pp. 369–372.

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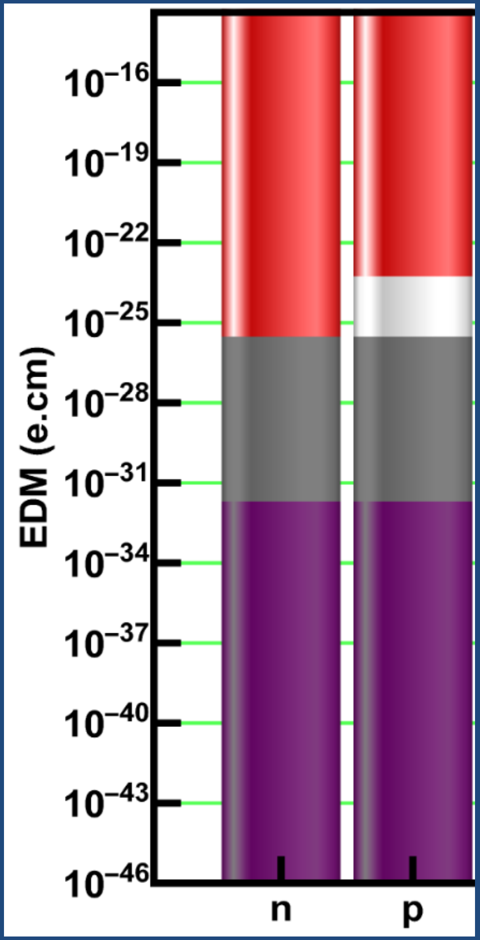
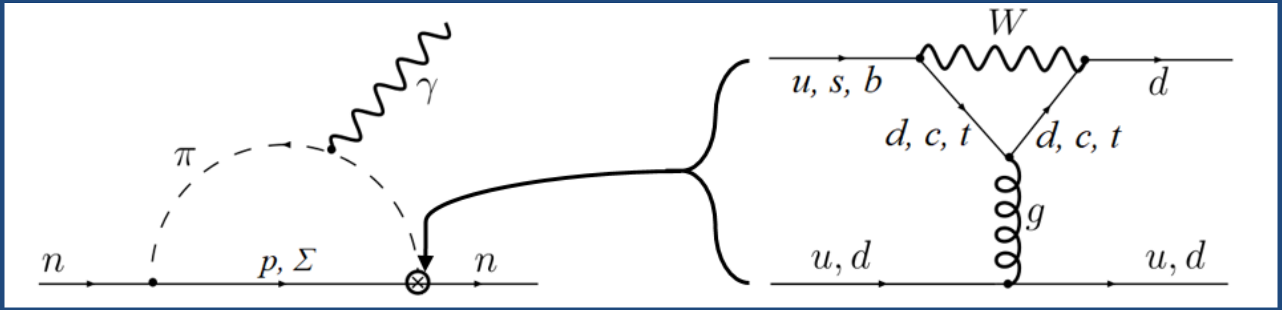




Neutrons ~ Proton

$(n \to p\pi^-)$ $(p \to n\pi^+)$

$d_n < (1.8 \times 10^{-26})$ e.cm (UCN)

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

- Direct nEDM upper limit ($<1.8\times10^{-26}$ e.cm) from UCN experiments
- Better limit ($<1.3\times10^{-26}$ e.cm) from ^{199}Hg, but a dirtier extraction

$d_n < (1.3 \times 10^{-26})$ e.cm [^{199}**Hg**] $d_p < (1.7 \times 10^{-25})$ e.cm

B. Graner et al, Phys. Rev. Lett. 116.16 (Apr. 2016), p. 161601.

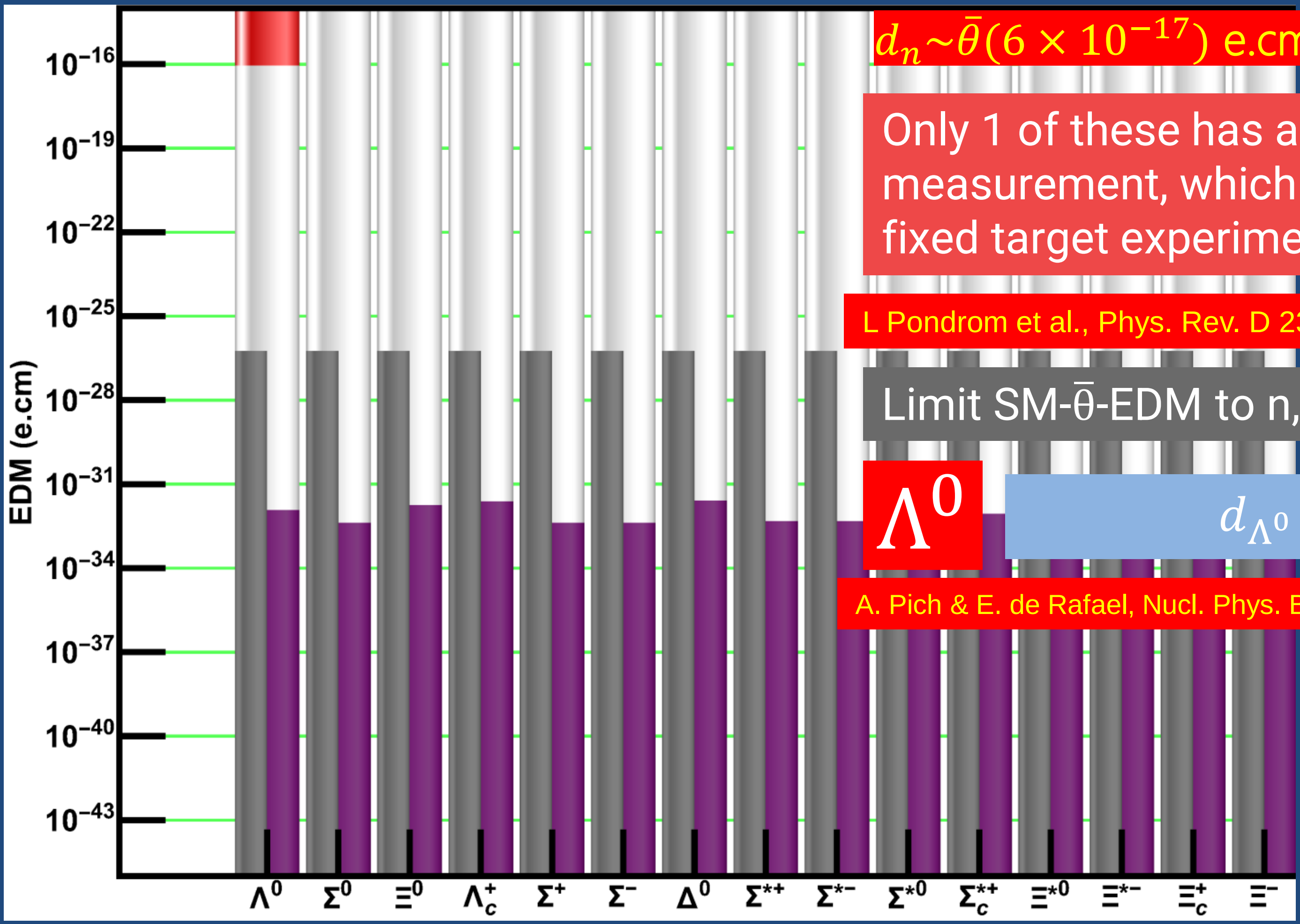
M Pospelov and A Ritz. Ann. Phys. 318.1 (July 2005), pp. 119–169

IB Khriplovich and AR Zhitnitsky, Phys. Lett. B 109.6 (Mar. 1982), pp. 490–492

② Strange and Charmed Baryons

LNS

(i) SM-CKM-EDM (1-loop); (ii) SM-$\bar{\theta}$ similar to n,p EDM



$d_n \sim \bar{\theta}(6 \times 10^{-17})$ e.cm $\rightarrow \bar{\theta} < 3 \times 10^{-10}$

Only 1 of these has an indirect measurement, which comes from pX fixed target experiments.

L Pondrom et al., Phys. Rev. D 23.3 (Feb. 1981), pp. 814–816.

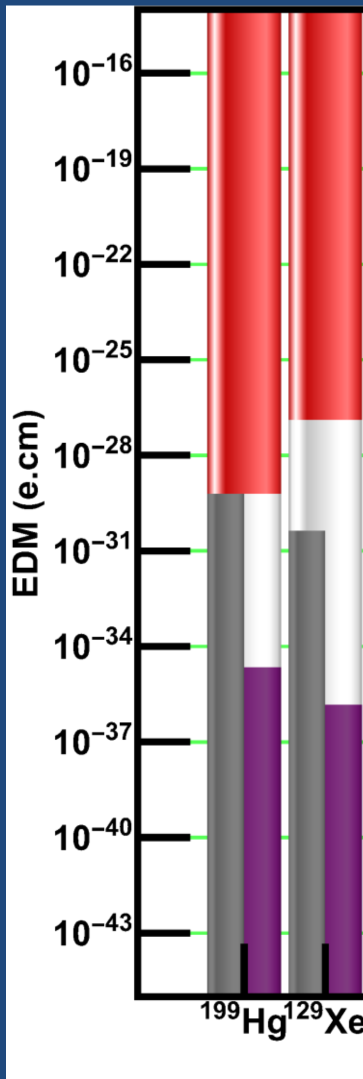
Limit SM-$\bar{\theta}$-EDM to n,p-SM-$\bar{\theta}$-EDM

Λ^0

$d_{\Lambda^0} \sim d_n/2$

A. Pich & E. de Rafael, Nucl. Phys. B 367.2 (Dec. 1991), pp. 313-33

③ Atoms: Diamagnetic



!!Single Source: Electron, eN contributions are small!!

>>dominated by CPV Schiff moment<<

Nuclear CPV EDMs are suppressed due to Schiff screening.

$$d_{Atom} = \rho_A^e d_e + \sum_{N=\{p,n\}} \rho_Z^N d_N + \kappa_s S$$

$$+\alpha_{C_s} C_s + \alpha_{C_T} C_T$$

e-EDM | n,p-EDM | Schiff mo.

$$d_{^{199}Hg} = \rho_p\, d_p + \rho_n\, d_n + \kappa_s S$$

$$S_{^{199}Hg} = (0.200\ \mathrm{fm}^2)\, d_p + (1.895\ \mathrm{fm}^2)\, d_n$$

$$\rho_p = (-0.56 \times 10^{-4}), \rho_n = (-5.3 \times 10^{-4}), \kappa_s = (-2.4 \times 10^{-4})\ \mathrm{fm}^{-2}$$

$$\alpha_{C_s} = (-5.9 \times 10^{-20}), \alpha_{C_T} = (3.0 \times 10^{-22})$$

Plug in: {n, p}-SM-$\bar{\theta}$-EDM

Plug in: {n, p}−SM−CKM−EDM

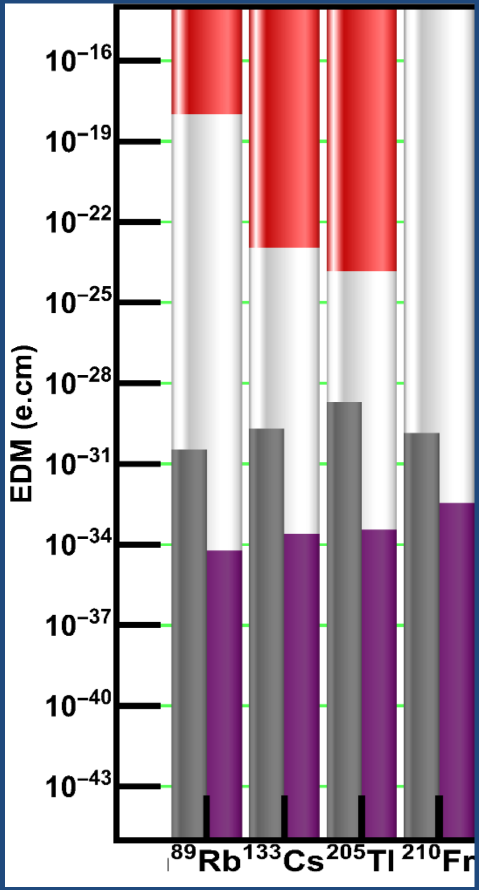
$$d_{^{199}Hg} < 6.2 \times 10^{-30}\mathrm{e.cm}$$

B Graner et al, Phys. Rev. Lett. 116.16 (Apr. 2016), p. 161601.
J Engel et al., Prog. Part. Nucl. Phys. 71 (July 2013), pp. 21–74.

③ Atoms: Paramagnetic

>>Single Source: Electron contribution is small, dominated by CPV eN interactions<<

Underestimates: Lack of nuclear contributions, but comparable to ^{199}Hg



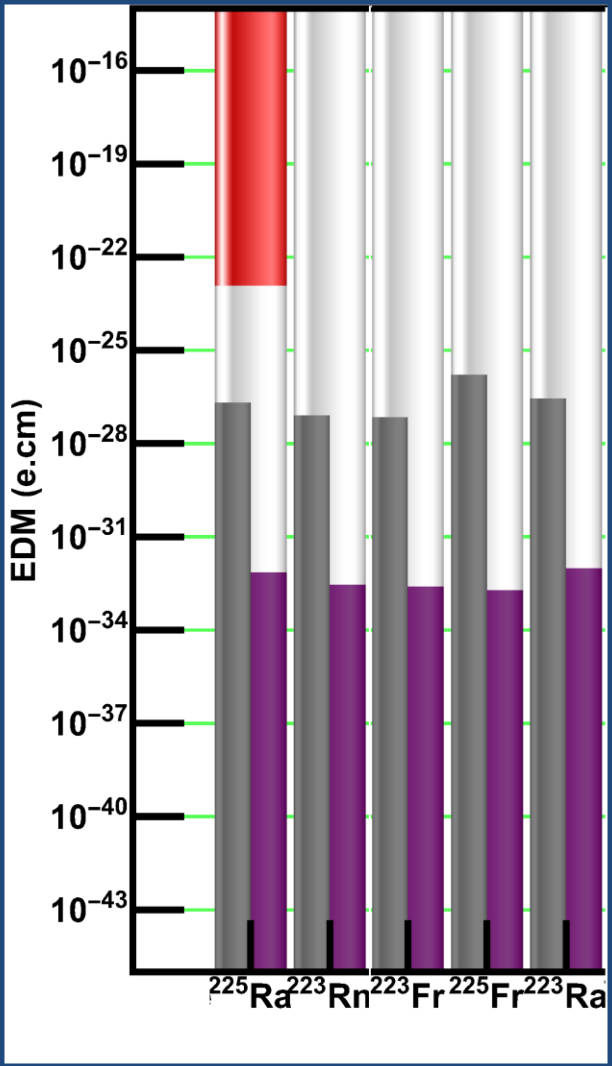
Atom	d (e.cm)	Ref.
^{89}Rb	1×10^{-18}	[1]
^{133}Cs	1.1×10^{-23}	[2]
^{205}Tl	1.5×10^{-24}	[3]
^{171}Yb*	1.5×10^{-26}	[4]
^{210}Fr	In progress	

$$d_{Atom} = \rho_A^e d_e + \alpha_{C_s} C_s$$

$$C_s \approx 0.03\theta$$

[1] ES Ensberg, Phys. Rev. 153.1 (1967), 36–43. [2] SA Murthy et al., Phys. Rev. Lett. 63.9 (1989), 965–968. [3] ED Commins et al, Phys. Rev. A 50.4 (1994), 2960–2977. [4] T. A. Zheng et. al, Phys. Rev. Lett. **129**, 083001 (2022).

③ Deformed Diamagnetic Atom

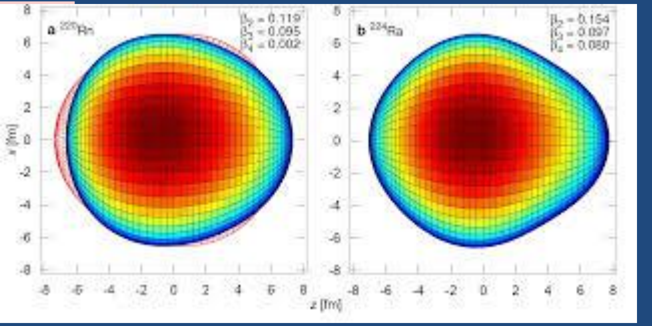


Nuclear Octupole+Quadrupole deformation enhances atomic EDM

Rest of the diamagnetic systems are represented as a ratio w.r.t. ^{199}Hg

There are experimental limits for both symmetric and deformed nuclear atoms.

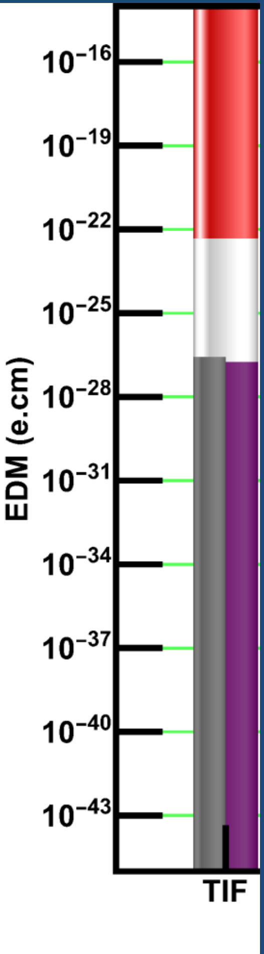
Atom	*d* (e.cm)	Ref.
^{129}Xe	1.3×10^{-27}	[1]
^{225}Ra	1.2×10^{-23}	[2]
^{223}Rn	-	



[1] Allmendinger et al., arXiv: 1904.12295
[2] M Bishof et al., Phys. Rev. C Nucl. Phys. 94.2 (Aug. 2016), p. 025501.

④ Diamagnetic Molecules

There is one diamagnetic molecule of interest: TlF. Behaves like diamagnetic atom.



$d_{TlF} < 4.3 \times 10^{-23}$e.cm

$$d_{TlF} \sim 573 d_e + d_p/2$$

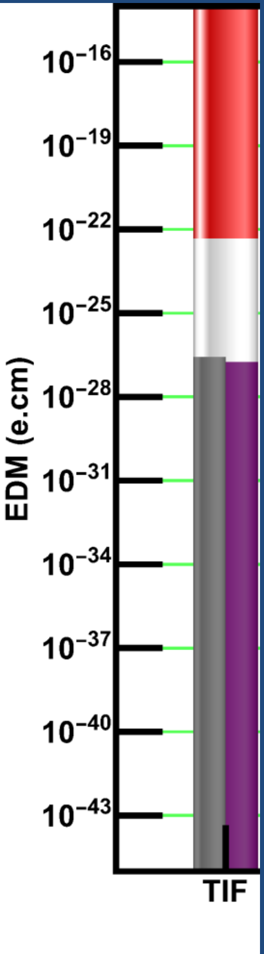
Plug in: {n, p}-SM-$\bar{\theta}$-EDM → Multiply by the appropriate enc factors.

Plug in: {n, p}-SM-CKM-EDM → Multiply by the appropriate enc factors.

Cho, K Sangster, and EA Hinds, Phys. Rev. A 44.5 (Sept. 1991), pp. 2783–2799.

④ Diamagnetic Molecules

There is one diamagnetic molecule of interest: TlF. Behaves like diamagnetic atom.



$$d_{TlF} < 4.3 \times 10^{-23} \text{e.cm}$$

$$d_{TlF} \sim 573 d_e + \alpha_{C_T} C_T + \alpha_{C_S} C_S + d_p/2 + W_S S$$

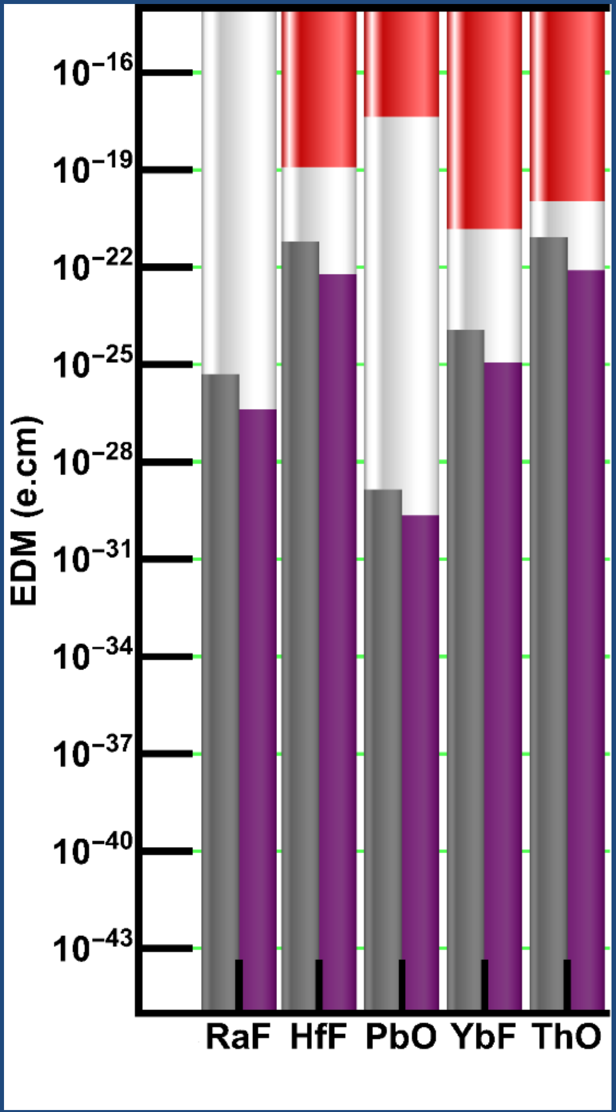
- $573 d_e$: Constituent electron contribution
- $\alpha_{C_T} C_T + \alpha_{C_S} C_S$: CPV eN Interaction
- $d_p/2 + W_S S$: Nuclear contribution

$$S_{\text{TlF}} = [d_p/4 + \text{e}(\widetilde{d_u} - \widetilde{d_d})]\ \text{fm}^2,\ W_S = 28{,}571\ \text{Hz/e fm}^3$$
$$\alpha_{C_S} = (2.9 \times 10^{-18}),\ \alpha_{C_T} = (2.7 \times 10^{-16})$$

Plug in: {n, p}-SM-CKM, $\bar{\theta}$ -EDM → Multiply by the appropriate enc. factors.

EA Hinds et al., Phys. Rev. A 44.5 (Sept. 1991), pp. 2783–2799.
P. Mohanmurthy and J. A. Winger, PoS 390, 265 (ICHEP2020) (2020)

④ Polar Molecules



- **Polar molecules have LARGE intra-molecular E-field ~ GV/cm.**
- **Comparing EDMs requires normalizing with this field.**

$$\sigma_d \propto {}^{1}/_{E}$$

Molecule	$E_{Mol.}$ (GV/cm)	E
RaF	0.130 [1]	300 kV [A]
HfF^+	23 [2]	24 V [B]
PbO	25 [3]	100 V [C]
YbF	14.5 [4]	10 kV [D]
ThO	78 [5]	80 V [E]

[1] AD Kudashov et al., Phys. Rev. A 90.5 (Nov. 2014), p. 052513. [A] M Bastani Nejad et al., Phys. Rev. ST Accel. Beams 15.8 (Aug. 2012), p. 97. [2] T Fleig and MK Nayak, Phys. Rev. A 88.3 (Sept. 2013), p. 032514. [B] WBCairncross et al., Phys. Rev. Lett. 119.15 (Oct. 2017), p. 153001. [3] MG Kozlov and D DeMille, Phys. Rev. Lett. 89.13 (Sept. 2002), p. 133001. [C] S Eckel et al., Phys. Rev. A 87.5 (May 2013), p. 052130. [4] DM Kara et al., New J. Phys. 14.10 (Oct. 2012), p. 103051. [D] JJ Hudson et al., Nature 473.7348 (May 2011), pp. 493–496.
[5] M Denis and T Fleig, J. Chem. Phys. 145.21 (Dec. 2016), p. 214307. [E] ACME Collaboration, Nature 562.7727 (Oct. 2018), pp. 355–360.

SM−CKM−EDM ∝ (∗) e−SM−CKM−EDM

SM-$\bar{\theta}$-EDM ∝ (∗) e-SM-$\bar{\theta}$-EDM