An experimentalist's take on:

Estimation of CP violating EDMs from known mechanisms in the SM

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Overview

CPV in SM

① Sub-atomic particles

②

Atoms

③

④ Molecules

Summary

⑤

① T/CP Violation?

CPT: CP Violation ↔ T Violation

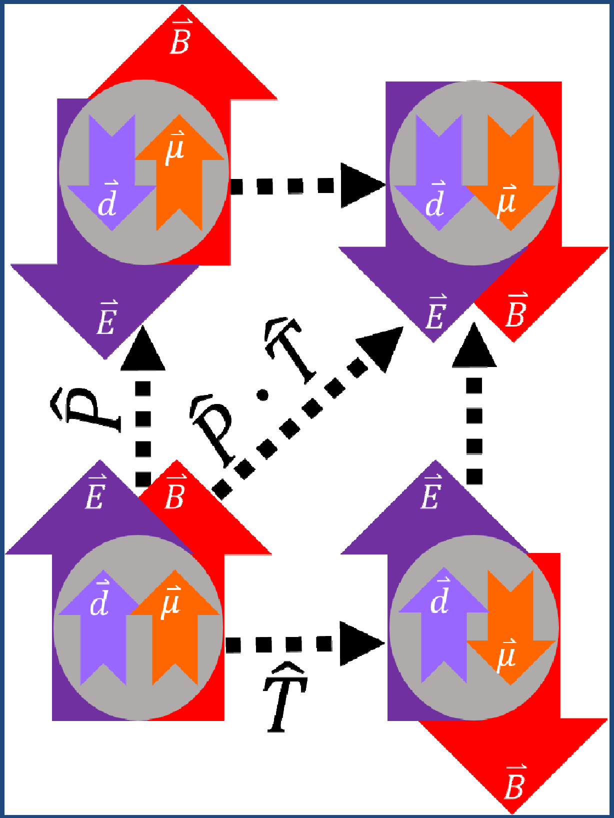
Non zero EDM of sub-atomic particles:

- Leptons
- Baryons

violate P, CP, and T symmetries.

Even atomic EDM violate P/CP/T.

Example: in e, n →



G Lüders, Ann. Phys. 2.1 (July 1957), pp. 1–15

① Sources of CPV in SM

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

(i) 'δ': CKM Matrix

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

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

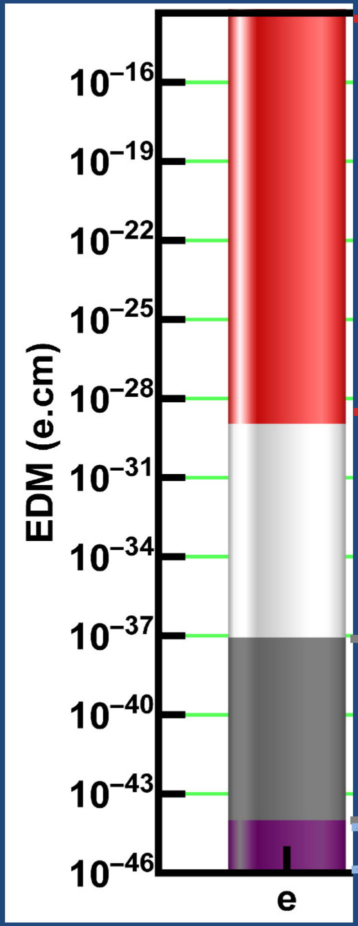
(ii) '$\bar{\boldsymbol{\theta}}$': QCD, $\bar{\theta} < 10^{-10}$

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

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

② Charged Leptons

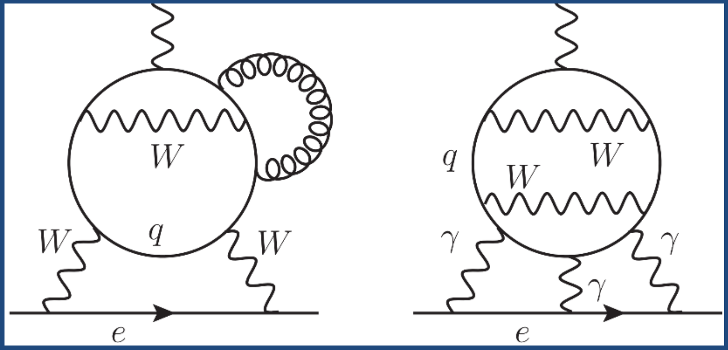
(i) EDM from SM-CKM (4-loop); (ii) EDM from SM-θ_{QCD}



\>\>\>EDM estimates from single origin<<<

ACME Collaboration, Nature 562.7727 (Oct. 2018), pp. 355–360

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



Electron SM-**θ**-EDM, from Ghosh & Sato.

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

Electron SM-CKM-EDM from Pospelov & Ritz

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

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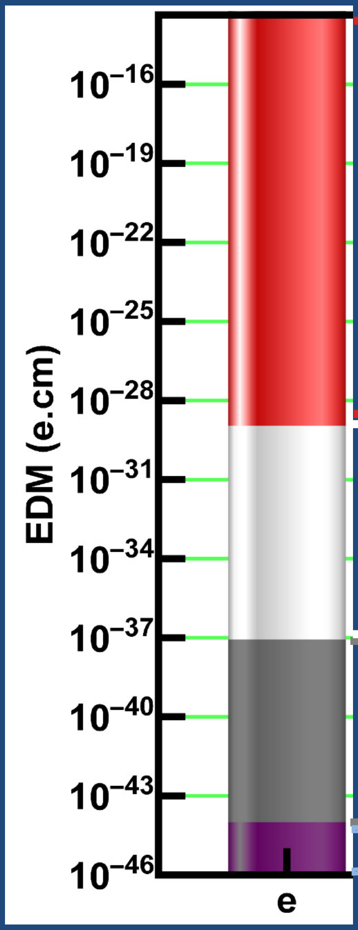

>>>EDM estimates from single origin<<<

ACME Collaboration, Nature 562.7727 (Oct. 2018), pp. 355–360

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

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

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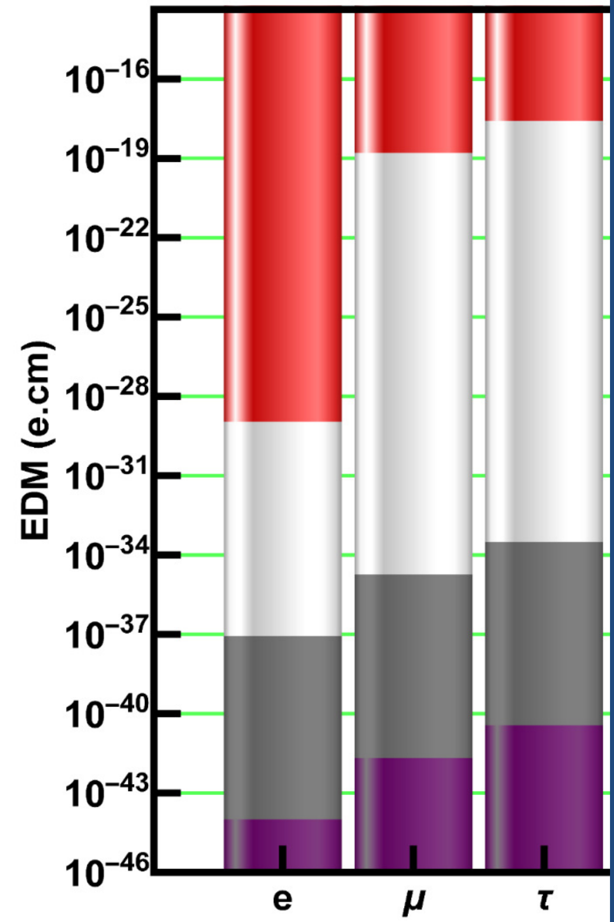


$$d_l \propto {}^{1}/_{m_l}$$

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

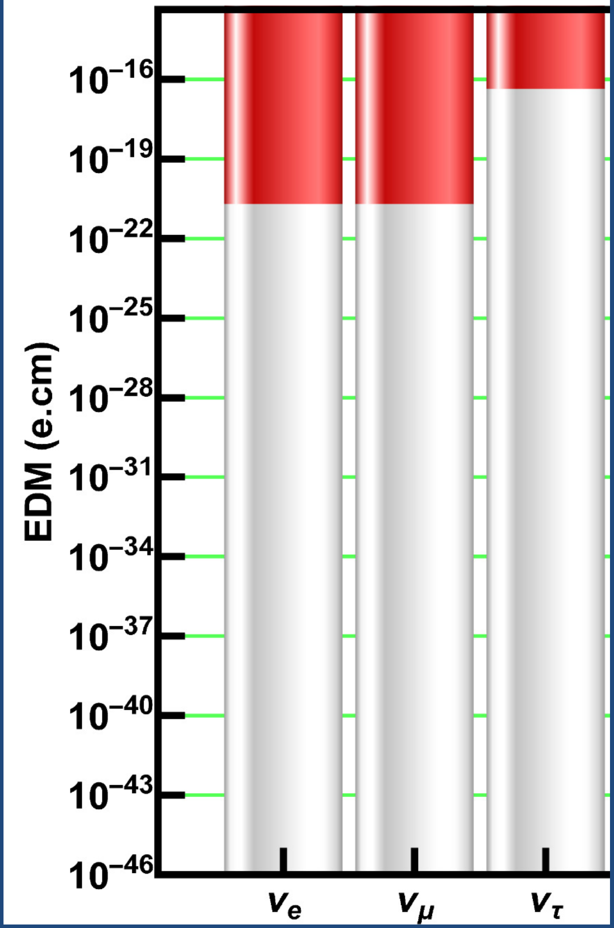
D Ghosh and R Sato, Phys. Lett. B 777 (Feb. 2018), pp. 335–339.

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).

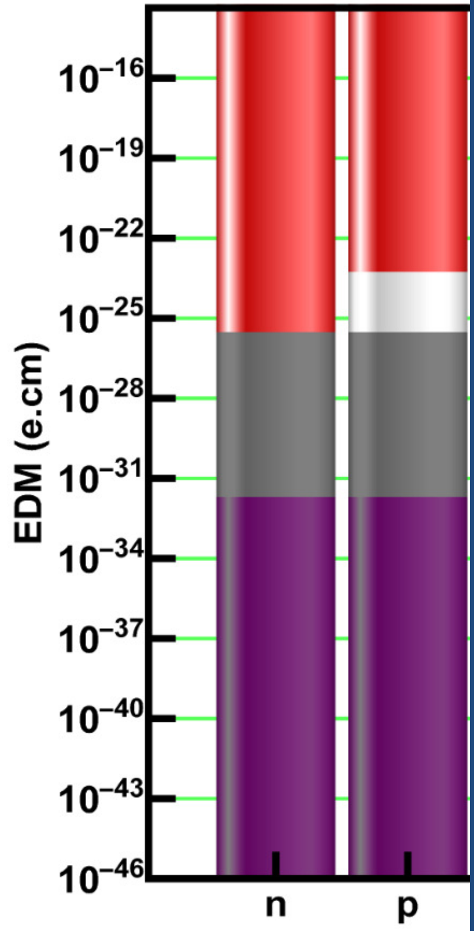
Tau-Neutrino

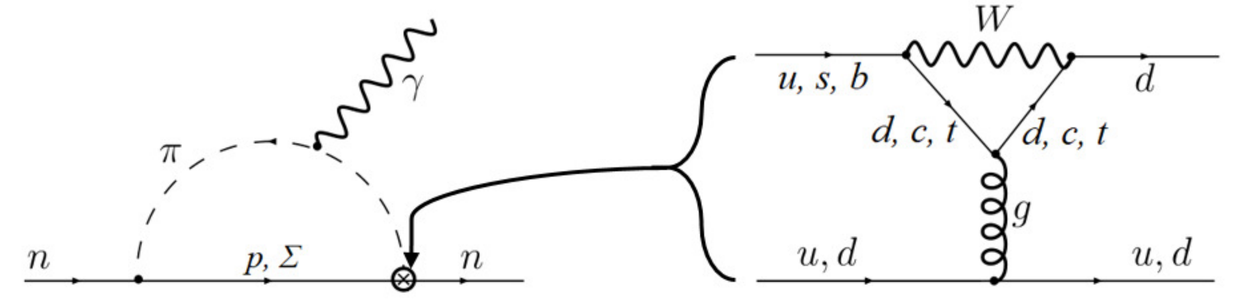
90 % C.L. upper limit from indiect $e\bar{e}$: collisions

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.

② Light Baryons

(i) SM-CKM-EDM (1-loop); (ii) SM-$\bar{\theta}$ directily from nEDM





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.

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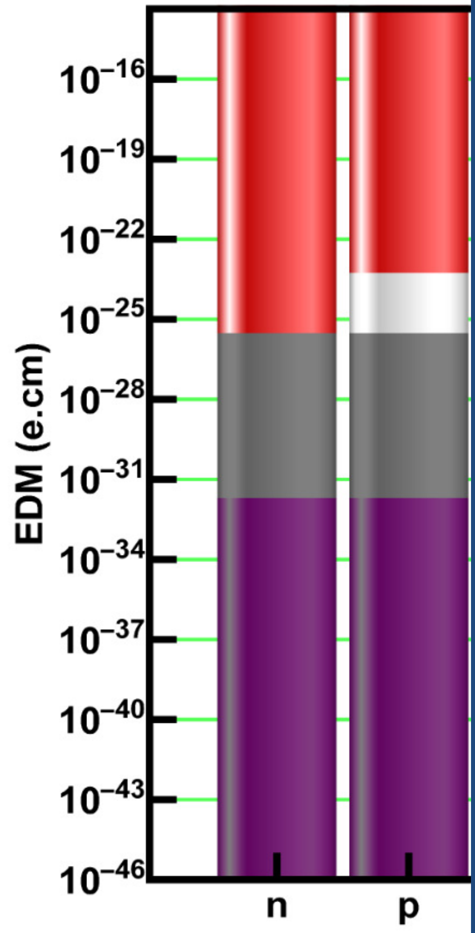
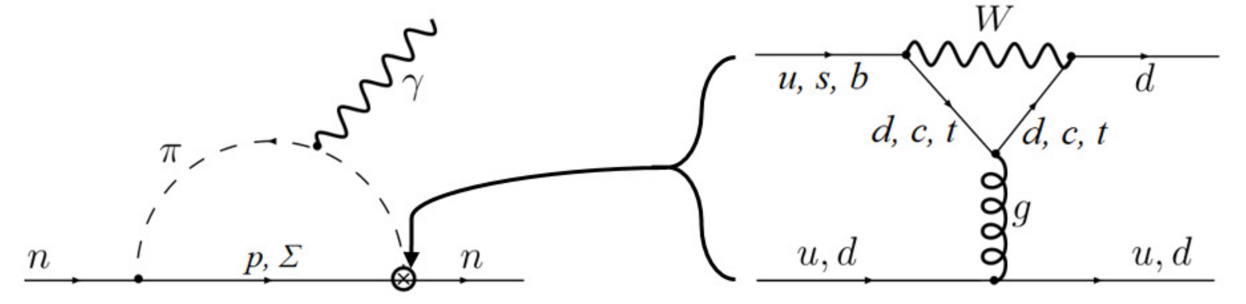




Neutrons ~ Proton

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

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

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

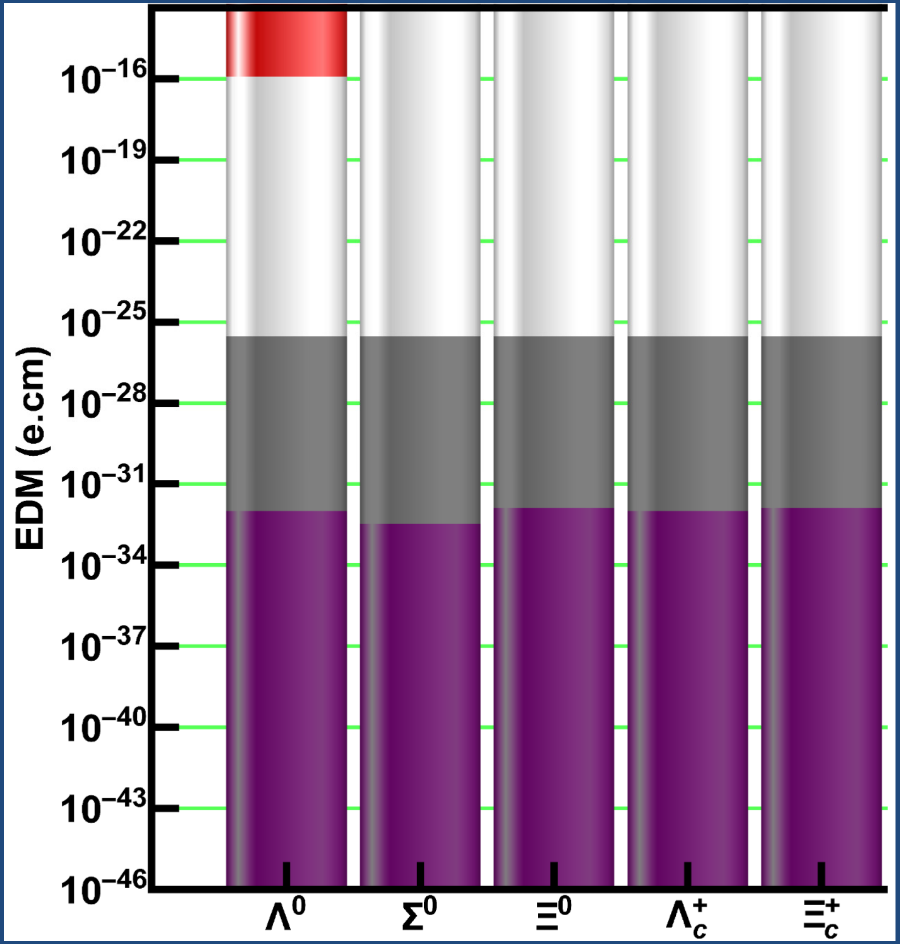
M Pospelov and A Ritz. Ann. Phys. 318.1 (July 2005), pp. 119–169

n,p SM-CKM-EDM from diagrams above

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

② Strange and Charmed Baryons

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

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

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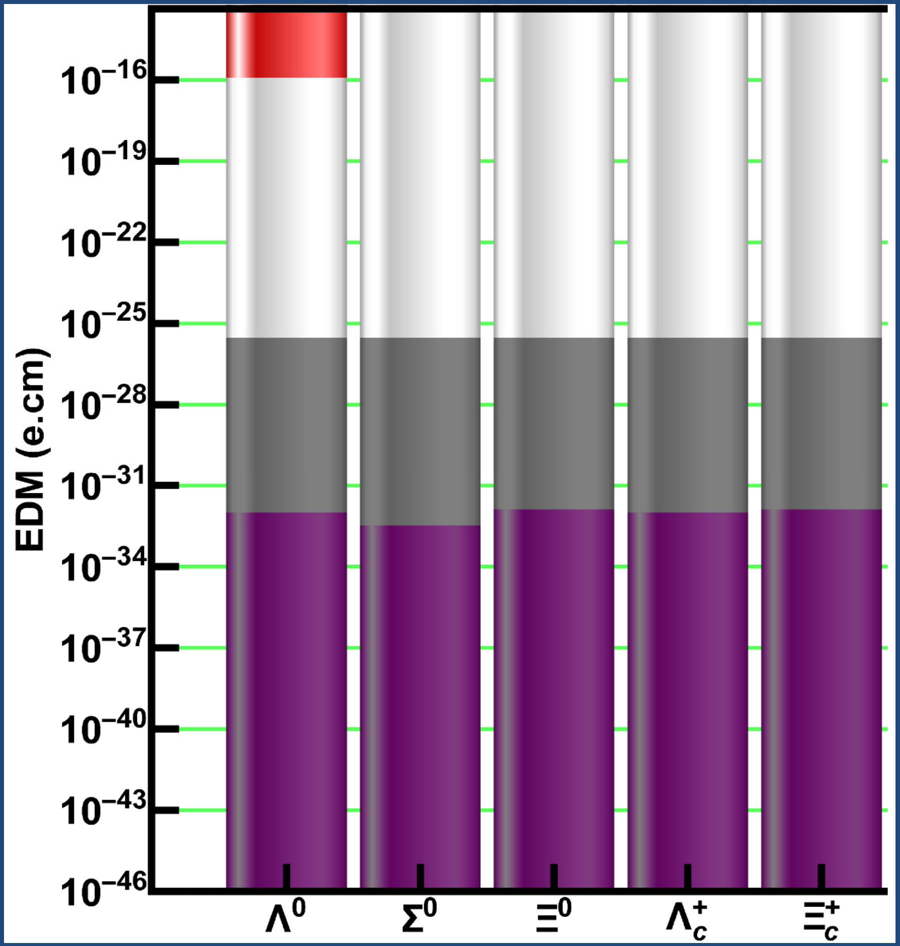

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A. Pich & E. de Rafael, Nucl. Phys. B 367.2 (Dec. 1991), pp. 313–33

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

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

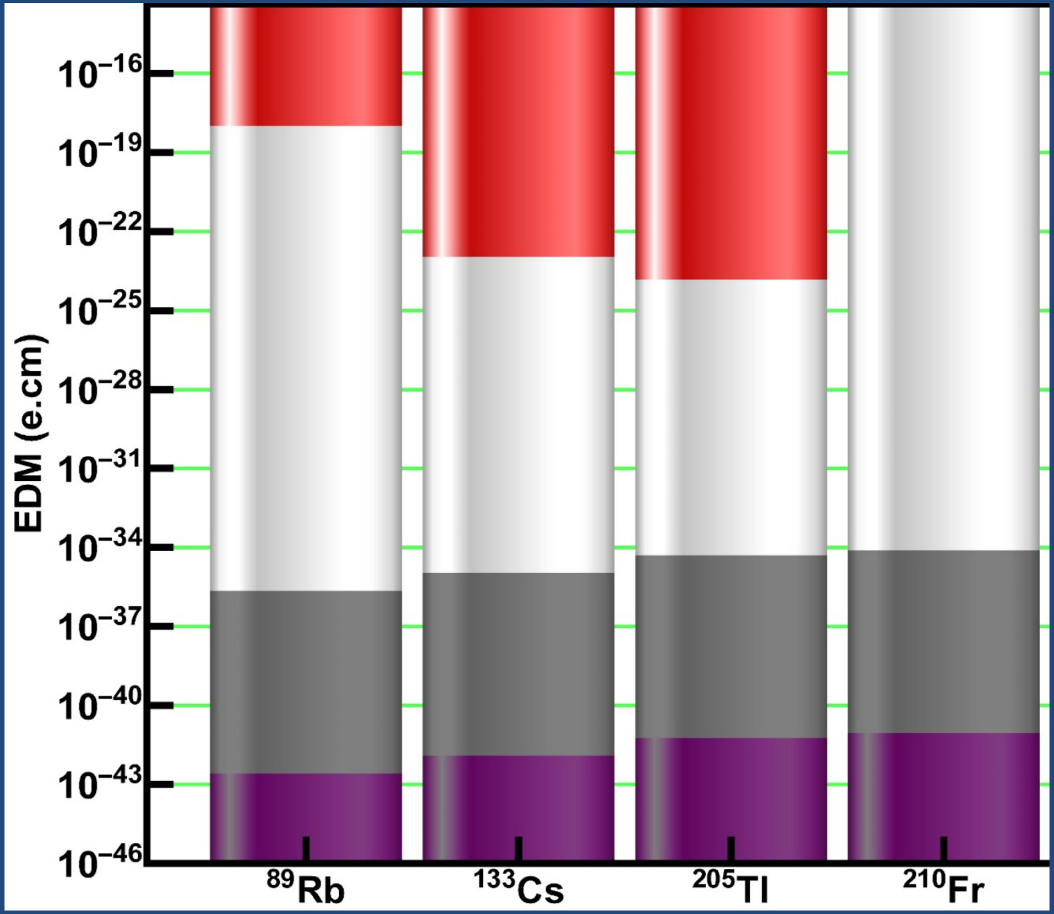
Λ_c^+, Ξ_c^+

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

③ Atoms: Paramagnetic

>>Single Source: Neglecting eN scalar and tensor terms<<

Underestimates paramagnetic atoms, their CKM-EDM could be as high as 10^{-27} (e.cm)



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]
^{210}Fr	In progress	

[1] ES Ensberg, Phys. Rev. 153.1 (Jan. 1967), pp. 36–43.
[2] SA Murthy et al., Phys. Rev. Lett. 63.9 (Aug. 1989), pp. 965–968.
[3] ED Commins et al, Phys. Rev. A 50.4 (Oct. 1994), pp. 2960–2977.

$\text{SM-}\bar{\theta}\text{-EDM} \propto (*)\ \text{e-SM-}\bar{\theta}\text{-EDM}$

$\text{SM–CKM–EDM} \propto (*)\ \text{e–SM–CKM–EDM}$

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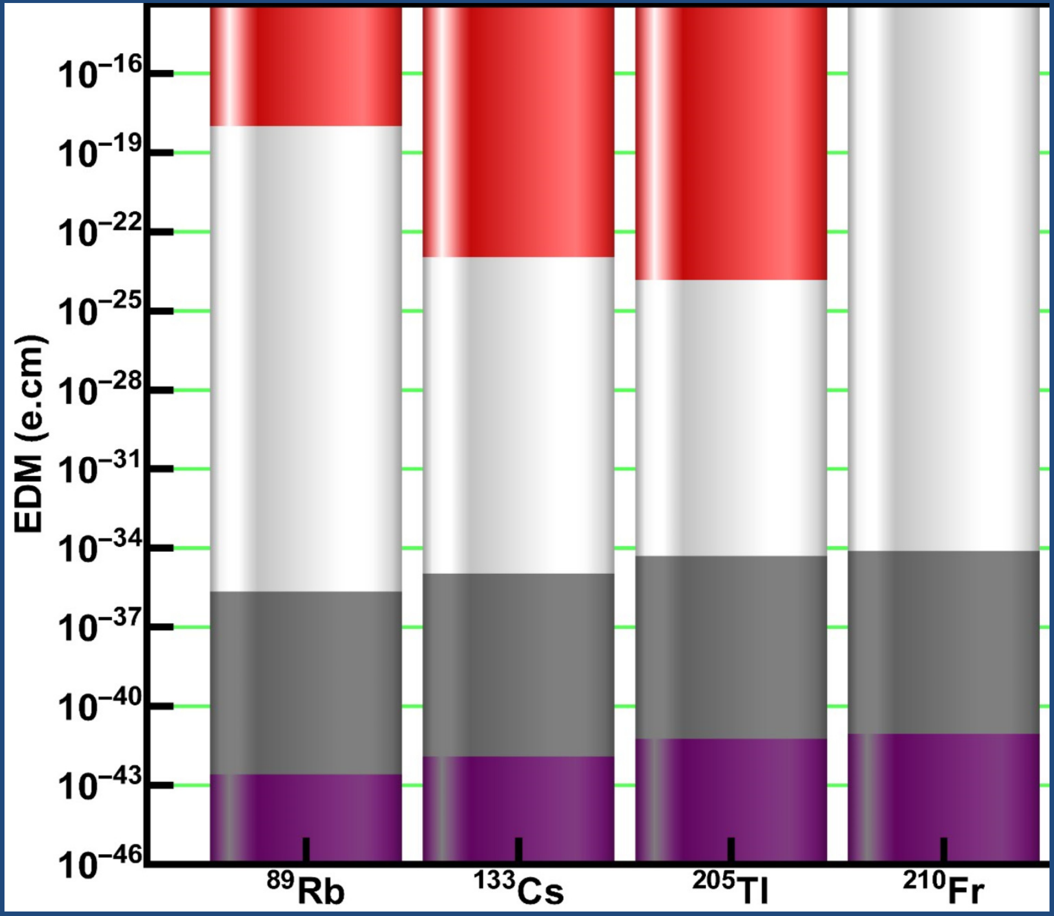


SM-$\bar{\theta}$-EDM ∝ (∗) e-SM-$\bar{\theta}$-EDM

SM–CKM–EDM ∝ (∗) e–SM–CKM–EDM

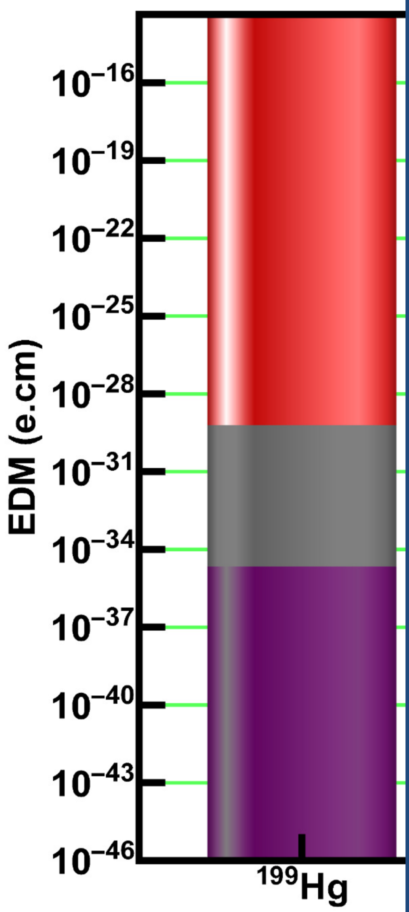
Atom	(∗)	Ref.
^{89}Rb	25.7	[1]
^{133}Cs	123	[1]
^{205}Tl	573	[2]
^{210}Fr	903	[3]

[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 Atoms: Diamagnetic

>>Single Source: Electron contribution is small, dominated by CPV Schiff moment<<

Underestimates again, but better estimates than for paramagnetic atoms. <u>Nuclear CPV EDMs are suppressed due to Schiff screening.</u>



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

e-EDM

n,p-EDM

Schiff mo.

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

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

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

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.

Plug in: {n, p}-SM-θ̄-EDM

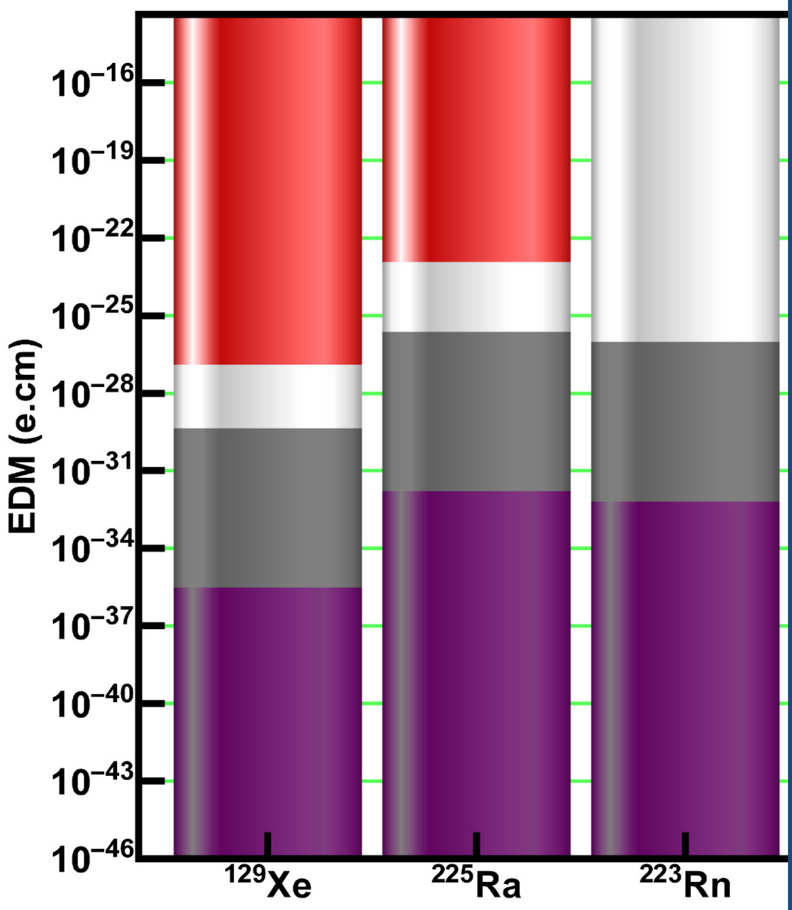
Plug in: {n, p}–SM–CKM–EDM

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

③ Other Diamagnetic Atoms

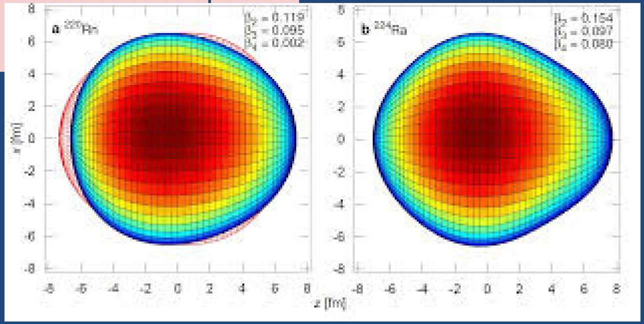
Some are nuclear octupole/quadrupole deformed which enhances atomic EDM.

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.

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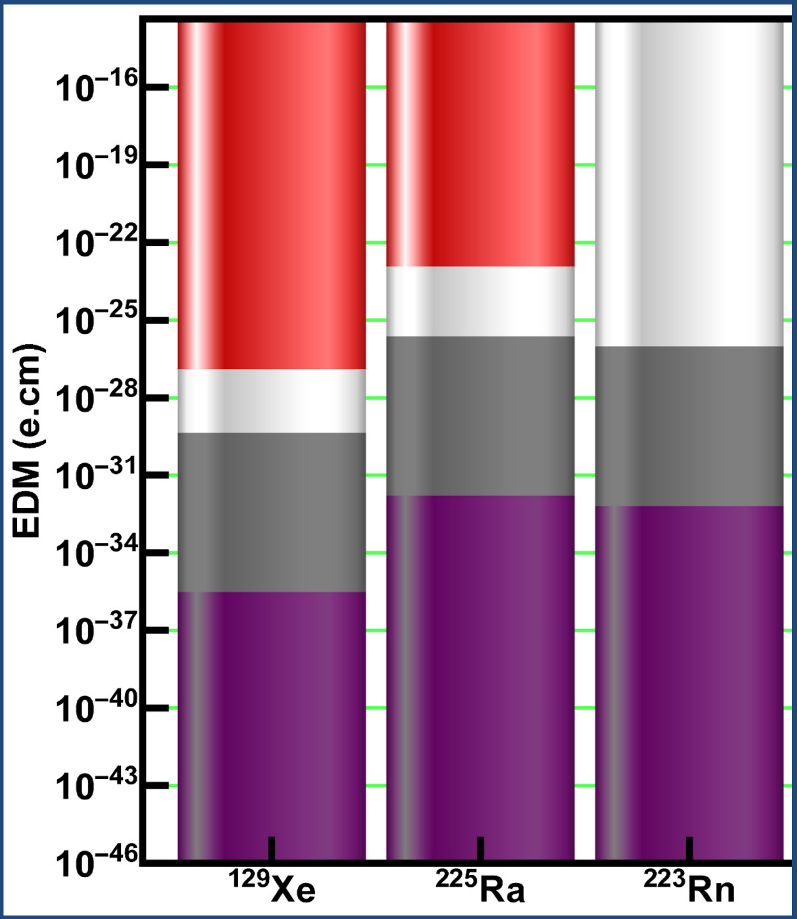


In case of $\boldsymbol{\beta_3}, \boldsymbol{\beta_2}$ deformed nuclei,
$d_{Atom}* = (\boldsymbol{\beta_3}-$enc.)

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

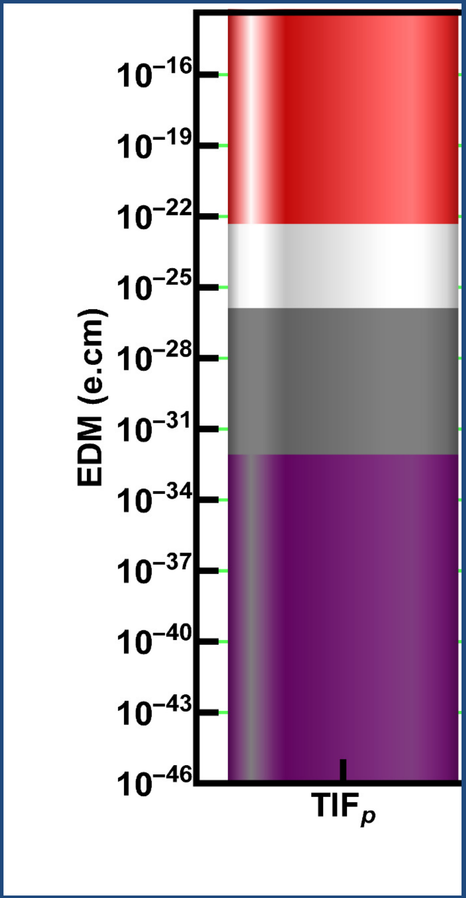
Plug in: {n, p}-SM-CKM-EDM → Multiply by the appropriate enc factors.

Atom	$\kappa_S^{(\text{Atom})}/\kappa_S^{(^{199}Hg)}$	$\boldsymbol{\beta_3}$-enc
^{129}Xe	1/7.4 [1]	-
^{225}Ra	3 [1]	240 [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 Diamagnetic Molecules

There is one diamagnetic molecule of interest: TlF. Behaves like diamagnetic atom. Underestimate SM-CKM-EDM and SM-θ-EDM: Neglecting tensor eN couplings…



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

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

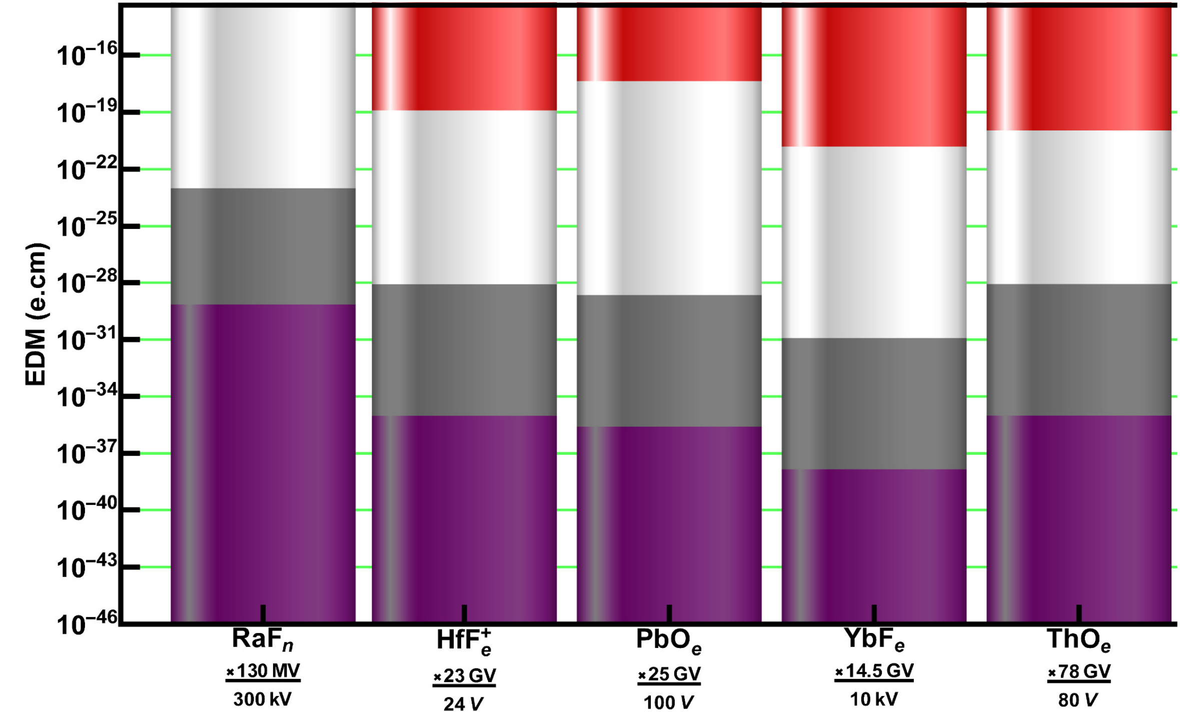
Plug in: {n, p}-SM-$\bar{\theta}$-EDM → Multiply by the appropriate enc factors.

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 Polar Molecules

**Polar molecules take advantage of LARGE intra-molecular E-field~ GV/cm.
In order to compare them, we have normalized the extracted EDMs with this field.
Save for RaF, the rest underestimate for the same reason as for paramagnetic atoms.**



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

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

SM–CKM–EDM $\propto$ (∗) e–SM–CKM–EDM

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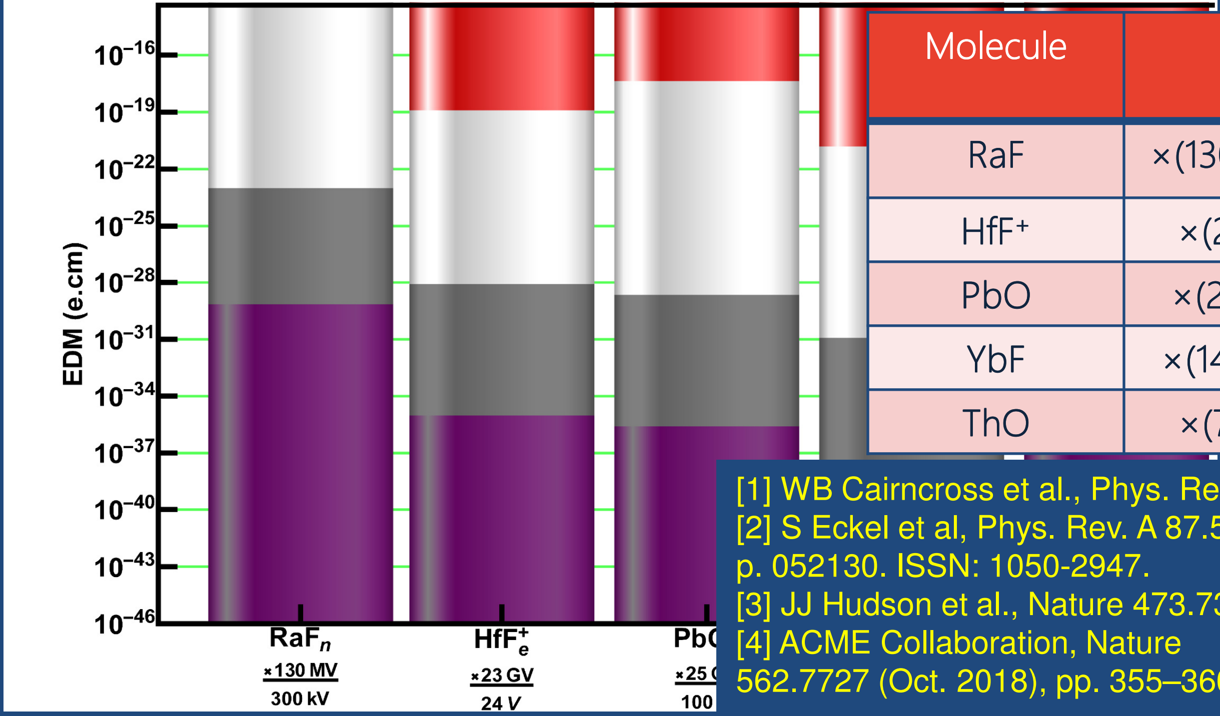

Molecule	$(*)$	$d \times (*)$ (e.cm)	Ref.
RaF	×(130 MV/300 kV)	–	
HfF⁺	×(23 GV/24 V)	1.2×10^{-19}	[1]
PbO	×(25 GV/100 V)	4.3×10^{-18}	[2]
YbF	×(14.5 GV/10 kV)	1.5×10^{-21}	[3]
ThO	×(78 GV/80 V)	1.1×10^{-20}	[4]

[1] WB Cairncross et al., Phys. Rev. Lett. 119.15 (Oct. 2017), p. 153001.
[2] S Eckel et al, Phys. Rev. A 87.5 (May 2013), p. 052130. ISSN: 1050-2947.
[3] JJ Hudson et al., Nature 473.7348 (May 2011), pp. 493–496.
[4] ACME Collaboration, Nature 562.7727 (Oct. 2018), pp. 355–360.

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

SM–CKM–EDM ∝ $(*)$ e–SM–CKM–EDM

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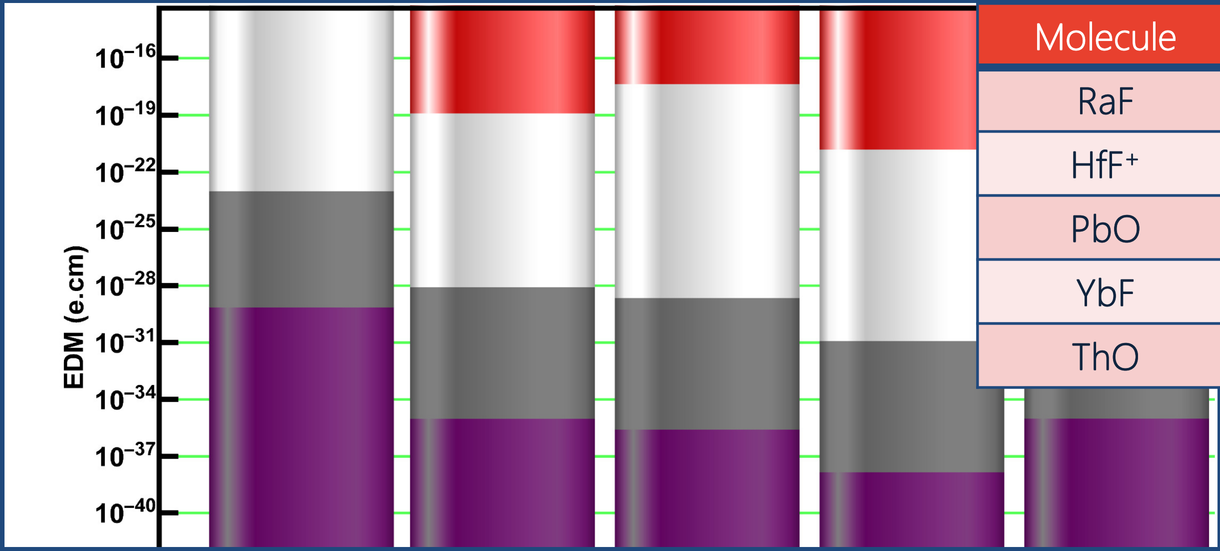


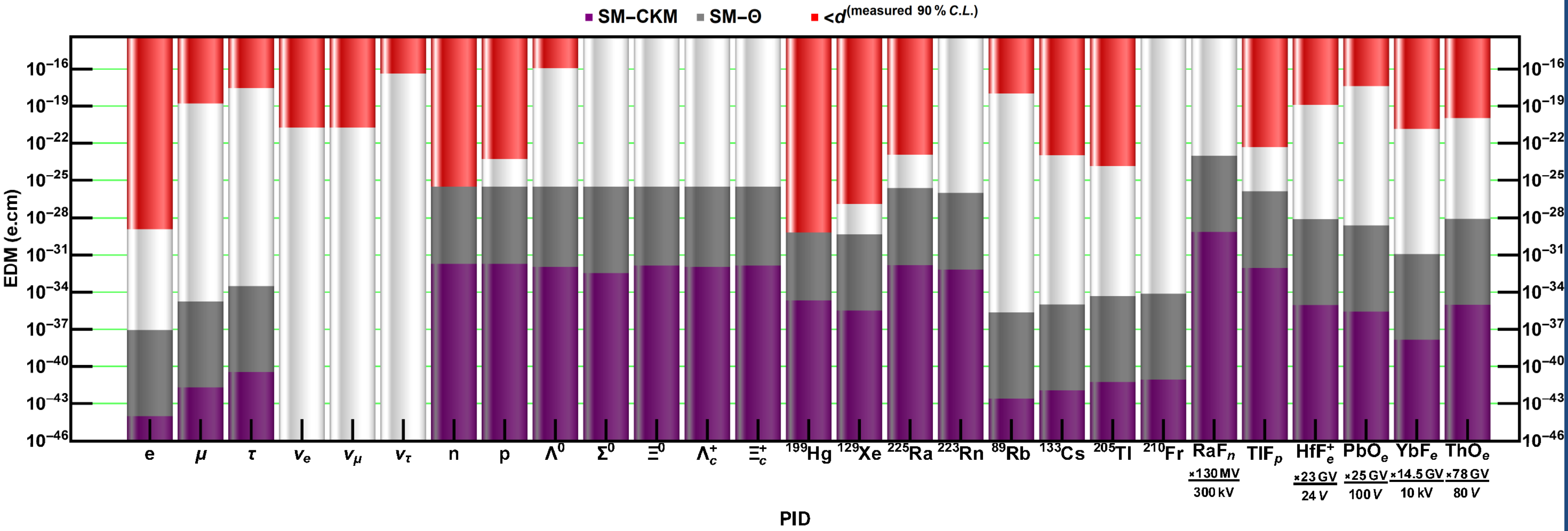
Molecule	$E_{\text{Mol.}}$ (GV/cm)	E
RaF	0.130 [1]	300 kV [A]
HfF^+	23 [2]	24 V [B]
PbO	25 [3]	100 V [C]
YbF	14.5 [4]	10 kV [D]
ThO	78 [5]	80 V [E]

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

SM–CKM–EDM $\propto$ (∗) e–SM–CKM–EDM

⑤ Summary



! The CKM and θ estimates stray away on the side of underestimation for paramagnetic atoms and polar molecules with paramagnetic atoms.

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

Thanks: K. Kirch & J. Winger
SERI-FCS: # 2015.0594, Sigma Xi: # G2017100190747806 and #G2019100190747806, DOE # DE-SC0014448.

J. Engel et. al., Prog. Part. Nucl. Phys. **71**, 21 (2013).
T. E. Chupp et. al., Rev. Mod. Phys. **91**, 015001 (2019).