Electric dipole moments: a theory overview

Emanuele Mereghetti

May 29th, 2018

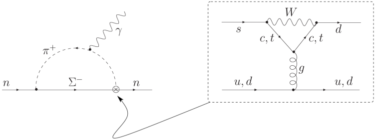
CIPANP 2018, Palm Springs

Introduction

A permanent Electric Dipole Moment (EDM)

- signal of *T* and *P* violation (*CP*)
- insensitive to *CP* violation in the SM
- BSM *CP* violation needed for baryogenesis

neutron

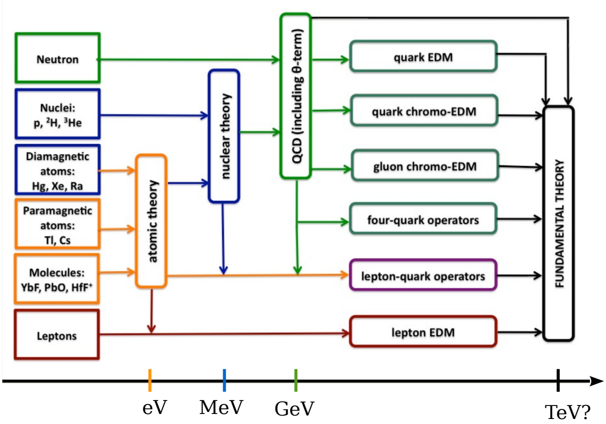


current bound
$|d_n| < 3.0 \cdot 10^{-13}\, e$ fm
J. M. Pendlebury *et al.*, ‘15

SM
$d_n \sim 10^{-19}\, e$ fm
M. Pospelov and A. Ritz, ‘05

- large window & strong motivations for new physics!

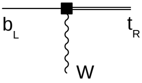
Introduction



(stolen from Jordy de Vries)

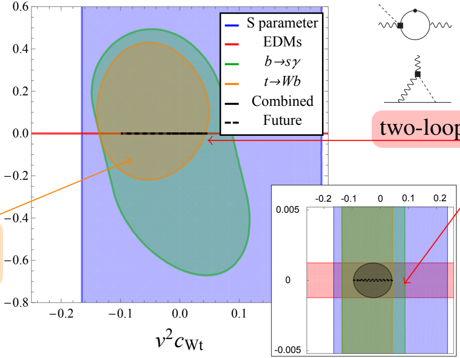
what do we learn from EDM measurements?
multiscale problem, involving atomic, nuclear & hadronic physics

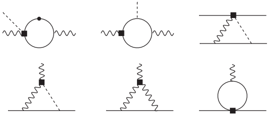
The reach of EDM experiments



$\frac{m_t}{\Lambda^2}\bar{b}_L\sigma^{\mu\nu}t_R W_{\mu\nu}$

tree level top prod.
& decay





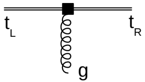
two-loop running to eEDM

Non standard top couplings: top weak-EDM

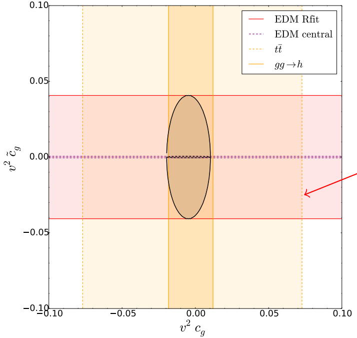
- electron EDM much more constraining than LHC

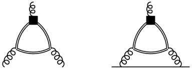
$\Lambda > 7$ TeV

…and the issue of theory uncertainties



$$\frac{m_t}{\Lambda^2}\bar{t}_L\sigma^{\mu\nu}t_R G_{\mu\nu}$$





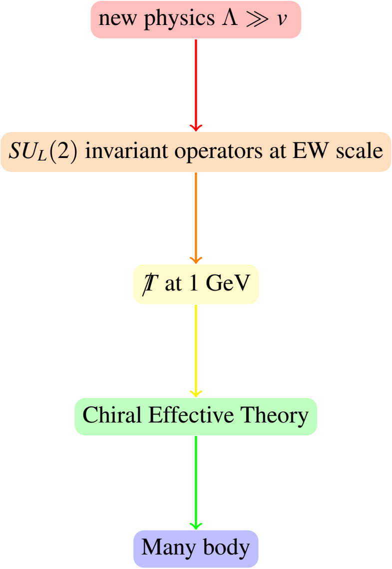
one/two-loop running to gCEDM, qCEDM

Non standard top couplings: top chromo-EDM

- runs onto gluon-CEDM and light-quark CEDM $\Longrightarrow$ nEDM
- nucleon ME have $\sim 100\%$ uncertainties

  bounds weakers by factor of 10, commensurable with LHC

Effective Field Theories



new physics $\Lambda \gg v$

$SU_L(2)$ invariant operators at EW scale

$\not{T}$ at 1 GeV

Chiral Effective Theory

Many body

- model independent link
  to collider phenomenology

- minimal set of low-energy $\not{T}$ operators
- connection with flavor/low energy probes

- from quarks to hadrons
  non-perturbative matching (LQCD)

- EDMs of nucleons & light nuclei

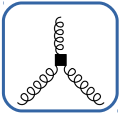
EFT for T violations

- one dim-4 operator: QCD $\bar\theta$ term

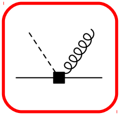
$$\mathcal{L}_{\not{T}\,4} = m_* \bar\theta \bar q i \gamma_5 q$$

in principle $\bar\theta = \mathcal{O}(1)$
... strong CP problem

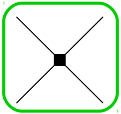
- 9 (+ 10 w. strangeness) dim-6 hadronic operators:



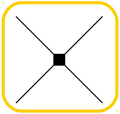
gluon CEDM
$C_{\tilde G}$



quark (C)EDM
$c_{g,\gamma}^{(u,d,s)}$



LL RR 4-quark
$\Xi^{(1,8)}_{ud,us,ds}$



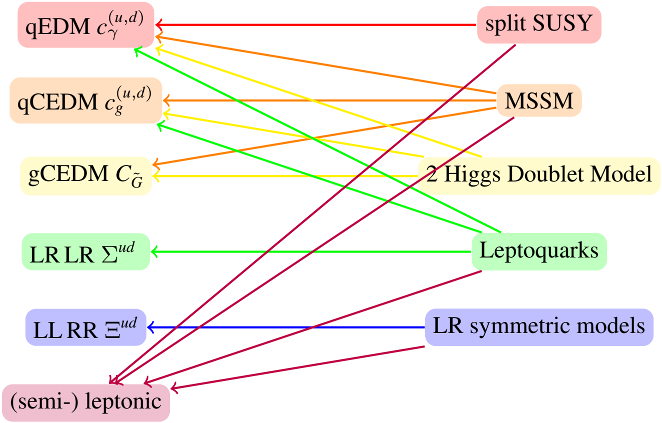
LR LR 4-quark
$\Sigma^{(1,8)}_{ud,us}$, $\Sigma^{(1,8)}_{us,S}$

- electron, muon EDMs
  + 3 (+1) scalar and tensor semileptonic operators

$$\mathcal{L}_{qe} = C_{LedQ}\, \bar e_L e_R \bar d_R d_L + C^{(1)}_{LeQu}\, \bar e_L e_R\, \bar u_L u_R + C^{(3)}_{LeQu}\, \bar e_L \sigma^{\mu\nu} e_R\, \bar u_L \sigma_{\mu\nu} u_R$$

Connection to models

- new physics models induce one, a subset or all these operators



qEDM $c_\gamma^{(u,d)}$

qCEDM $c_g^{(u,d)}$

gCEDM $C_{\tilde{G}}$

LR LR Σ^{ud}

LL RR Ξ^{ud}

(semi-) leptonic

split SUSY

MSSM

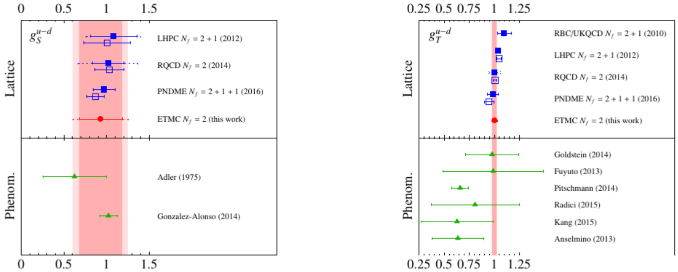
2 Higgs Doublet Model

Leptoquarks

LR symmetric models

M. Pospelov and A. Ritz, ‘05; W. Dekens *et al*, ‘14;
J. Engel, M. Ramsey-Musolf and U. van Kolck, ‘13;
T. E. Chupp, P. Fierlinger, M. Ramsey-Musolf and J. T. Singh, ‘17;

From quarks to nucleons: quark bilinears.



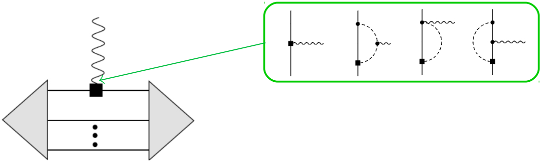
C. Alexandrou *et al*, ‘17

- single nucleon charges well determined by LQCD
- and so are qEDM contribs. to d_n
- and C_{LedQ}, $C_{LeQu}^{(1,3)}$ to molecules, paramagnetic/diamagnetic atoms

I. Khriplovich and S. Lamoreaux, ‘97; K. Yanase *et al*, ‘18

little theory uncertainty on (semi-) leptonic operators

From quarks to nucleons. Hadronic operators.



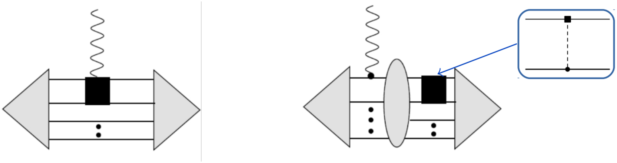
$$\mathcal{L}_{\not T} \quad = \quad -2\bar{N}\left(\bar{d}_0 + \bar{d}_1\tau_3\right) S^{\mu} v^{\nu} N F_{\mu\nu} - \frac{\bar{g}_0}{F_\pi}\bar{N}\boldsymbol{\pi}\cdot\boldsymbol{\tau}N - \frac{\bar{g}_1}{F_\pi}\pi_3\bar{N}N$$

- operators in $\mathcal{L}_{\not T}$ & scaling of couplings dictated by chiral symmetry

$\bar{d}_0, \bar{d}_1$	neutron & proton EDM, one-body contribs. to A $\geq$ 2 nuclei
$\bar{g}_0, \bar{g}_1$	pion loop to nucleon & proton EDMs leading $\not T$ OPE potential

relative size of the coupling
depends on chiral/isospin properties of $\not T$ source

From quarks to nucleons. Hadronic operators.



$$\mathcal{L}_{\not{T}} = -2\bar{N}\left(\bar{d}_0 + \bar{d}_1\tau_3\right) S^\mu v^\nu N F_{\mu\nu} - \frac{\bar{g}_0}{F_\pi}\bar{N}\boldsymbol{\pi}\cdot\boldsymbol{\tau}N - \frac{\bar{g}_1}{F_\pi}\pi_3\bar{N}N$$

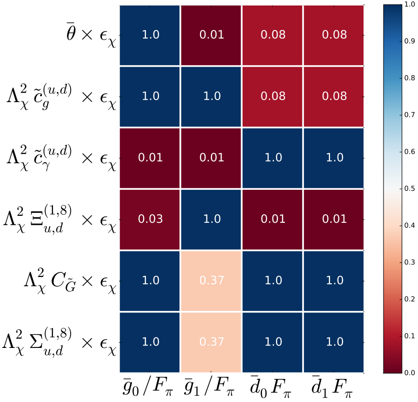
- operators in $\mathcal{L}_{\not{T}}$ & scaling of couplings dictated by chiral symmetry

$\bar{d}_0, \bar{d}_1$ neutron & proton EDM,
one-body contribs. to A $\geq$ 2 nuclei

$\bar{g}_0, \bar{g}_1$ pion loop to nucleon & proton EDMs
leading $\not{T}$ OPE potential

relative size of the coupling
depends on chiral/isospin properties of $\not{T}$ source

From quarks to nucleons. Hadronic operators



	$\bar{g}_0\,/F_\pi$	$\bar{g}_1\,/F_\pi$	$\bar{d}_0\,F_\pi$	$\bar{d}_1\,F_\pi$
$\bar{\theta} \times \epsilon_\chi$	1.0	0.01	0.08	0.08
$\Lambda_\chi^2\,\tilde{c}_g^{(u,d)} \times \epsilon_\chi$	1.0	1.0	0.08	0.08
$\Lambda_\chi^2\,\tilde{c}_\gamma^{(u,d)} \times \epsilon_\chi$	0.01	0.01	1.0	1.0
$\Lambda_\chi^2\,\Xi_{u,d}^{(1,8)} \times \epsilon_\chi$	0.03	1.0	0.01	0.01
$\Lambda_\chi^2\,C_{\tilde{G}} \times \epsilon_\chi$	1.0	0.37	1.0	1.0
$\Lambda_\chi^2\,\Sigma_{u,d}^{(1,8)} \times \epsilon_\chi$	1.0	0.37	1.0	1.0

$$\Lambda_\chi \sim 1\ \mathrm{GeV}$$

$$\epsilon_\chi \sim \frac{m_\pi}{\Lambda_\chi} \sim 0.15$$

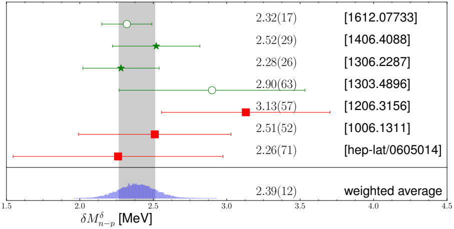
WARNING
naive dim. analysis!

- chiral breaking operators generate large $\bar{g}_0$
- chiral & isospin breaking large $\bar{g}_1$

enhanced nuclear EDMs

- can we be more precise?

Pion-nucleon couplings. $\bar{\theta}$ term.



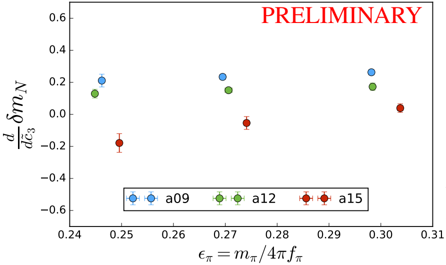
- χ-symmetry relates π-N couplings to spectral properties
- LQCD calculations of $m_n - m_p$ determines $\bar{g}_0$

$$\frac{\bar{g}_0}{F_\pi}(\bar{\theta}) = \frac{(m_n - m_p)|_{\rm str}}{F_\pi}\frac{1-\varepsilon^2}{2\varepsilon}\bar{\theta} = (15.5 \pm 2.0 \pm 1.6)\cdot 10^{-3}\bar{\theta}$$

LQCD N^{2}LO χPT

- precise prediction of chiral log in $d_n(\bar{\theta})$

Pion-nucleon couplings. qCEDM



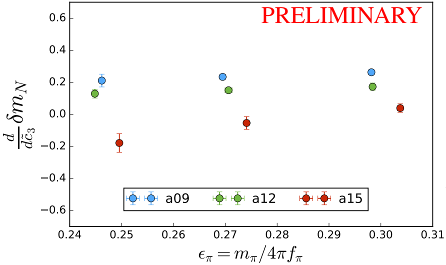
thanks to D. Brantley, CalLat coll.

- π-N couplings poorly determined

$$\begin{aligned}\frac{\bar{g}_0}{F_\pi} &= (5 \pm 10)(m_u \tilde{c}_g^{(u)} + m_d \tilde{c}_g^{(d)})\,\mathrm{fm}^{-1}\\ \frac{\bar{g}_1}{F_\pi} &= (20^{+40}_{-10})(m_u \tilde{c}_g^{(u)} - m_d \tilde{c}_g^{(d)})\,\mathrm{fm}^{-1}.\end{aligned}$$

QCD sum rules, M. Pospelov and A. Ritz, ‘05

Pion-nucleon couplings. qCEDM



thanks to D. Brantley, CalLat coll.

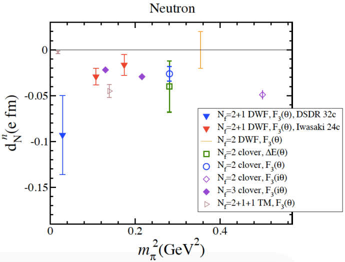
- can use similar relations to spectrum

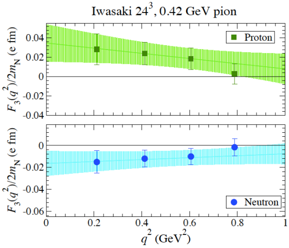
$$\begin{aligned}\bar{g}_0 &= (m_u\tilde{c}_g^{(u)} + m_d\tilde{c}_g^{(d)})\left(\frac{d}{d\tilde{c}_3} - r\frac{d}{d\bar{m}\varepsilon}\right)(m_n - m_p)\\ \bar{g}_1 &= (m_u\tilde{c}_g^{(u)} - m_d\tilde{c}_g^{(d)})\left(\frac{d}{d\tilde{c}_0} + r\frac{d}{d\bar{m}}\right)(m_n + m_p)\end{aligned}$$

$\tilde{c}_{0,3}$: iso-scalar (-vector) chromo-magnetic operators

- results coming soon!

Nucleon EDM





E. Shintani, *et al*, ‘15

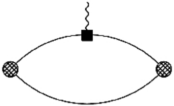
- LQCD effort to determine nucleon EDM from $\bar{\theta}$, $\tilde{c}_g^{(u,d)}$, $C_{\tilde{G}}$

  BLN-RIKEN, LANL, Michigan State, Cyprus, Bonn-Julich,. . .

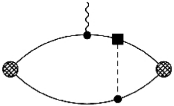
- chiral symmetry predicts m_π dependence
  & $\mathbf{q}^2$ dependence of the EDFF F_3

see Sergey Syritsyn’s talk

From nucleons to nuclei. Light nuclei



one-body $\propto d_n, d_p$



corrections to wavefunction

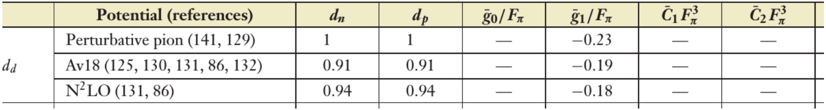
- in storage ring experiments, constituent EDMs are not screened
- correction to the wavefunction dominate for χ-breaking operators

unless forbidden by isospin selection rules

- one- and two-body contribs. comparable for χ-inv operators
- nuclear theory is well under control

C. P. Liu and R. Timmermans, ‘05; J. de Vries *et al*, ‘11;
J. Bsaisou *et al*, ‘13, J. Bsaisou *et al*, ‘15;
N. Yamanaka and E. Hiyama, ‘15

From nucleons to nuclei. Light nuclei



	Potential (references)	d_n	d_p	$\bar{g}_0/F_\pi$	$\bar{g}_1/F_\pi$	$\bar{C}_1 F_\pi^3$	$\bar{C}_2 F_\pi^3$
d_d	Perturbative pion (141, 129)	1	1	—	−0.23	—	—
	Av18 (125, 130, 131, 86, 132)	0.91	0.91	—	−0.19	—	—
	N^2LO (131, 86)	0.94	0.94	—	−0.18	—	—

from EM and U.van Kolck, '15

- in storage ring experiments, constituent EDMs are not screened
- correction to the wavefunction dominate for χ-breaking operators

unless forbidden by isospin selection rules

- one- and two-body contribs. comparable for χ-inv operators
- nuclear theory is well under control

C. P. Liu and R. Timmermans, '05; J. de Vries *et al*, '11;
J. Bsaisou *et al*, '13, J. Bsaisou *et al*, '15;
N. Yamanaka and E. Hiyama, '15

From nucleons to nuclei. Diamagnetic atoms

Nucl.	Best value			Range		
	a_0	a_1	a_2	a_0	a_1	a_2
^{199}Hg	0.01	± 0.02	0.02	0.005 – 0.05	-0.03 – +0.09	0.01 – 0.06
^{129}Xe	-0.008	-0.006	-0.009	-0.005 – -0.05	-0.003 – -0.05	-0.005 – -0.1
^{225}Ra	-1.5	6.0	-4.0	-1 – -6	4 — 24	-3 – -15

from M. Ramsey-Musolf, J. Engel, U. van Kolck, ‘13

- constituent EDM are screened
- EDM depends on screening factor *A* and the Schiff moment

$$S = -\frac{m_N g_A}{F_\pi}\left(a_0\frac{\bar{g}_0}{F_\pi} + a_1\frac{\bar{g}_1}{F_\pi} + a_2\frac{\bar{g}_2}{F_\pi}\right) e\,\mathrm{fm}^3 + (\alpha_n d_n + \alpha_p d_p)\,\mathrm{fm}^2$$

- π-N contribs. affected by large theory uncertainties

hard calculations!

- single nucleon contrib. better determined

$$\alpha_n = 1.9 \pm 0.1, \quad \alpha_p = 0.20 \pm 0.06$$

V. F. Dmitriev and R. A. Senkov, ‘03

Disentangling $\not{T}$ sources

	$v^2\tilde{c}_g^{(u)}$	$v^2\tilde{c}_g^{(d)}$	$v^2\Xi^{ud}$	$\bar{\theta}$	$v^2 C_{\tilde{G}}$
$(d_d - d_n - d_p)/d_n$	$\{2, 50\}$	$\{1, 22\}$	$\{30, 300\}$	$\{-1.4, -0.02\}$	$\lesssim 1$

neutron, proton & deuteron EDM

$$d_d = d_n + d_p - 0.2\frac{\bar{g}_1}{F_\pi}$$

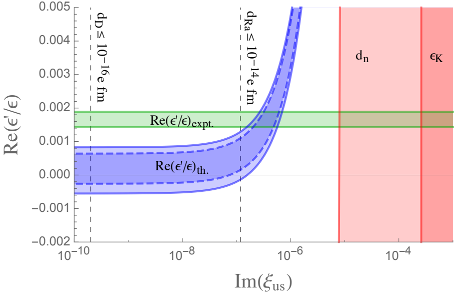
- sensitive to $\bar{g}_1$, not sensitive to $\bar{g}_0$

$\Longrightarrow$ isospin breaking operators $\tilde{c}_g^{(u)} - \tilde{c}_g^{(d)}$, Ξ_{ud}

- qCEDM & LL RR: strong enhancement of d_d
- $\bar{\theta}$ term : ratio at most $\mathcal{O}(1)$
- gCEDM & LR LR : ratio $\lesssim 1$
- qEDM: $d_d = d_n + d_p$

need experiment & better LECs!

Disentangling $\not{T}$ sources



$$(\epsilon'/\epsilon)_{\rm expt} = (16.6 \pm 2.3) \cdot 10^{-4}$$

$$(\epsilon'/\epsilon)_{\rm LQCD} = (1.4 \pm 6.9) \cdot 10^{-4}$$

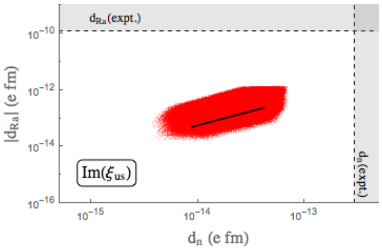
- LQCD/experiment discrepancy in ϵ'/ϵ could be explained with tiny right-handed currents

$$\mathcal{L} = \frac{g}{\sqrt{2}} \left(\xi_{ud}\, \bar{u}_R \gamma^\mu d_R + \xi_{us}\, \bar{u}_R \gamma^\mu s_R\right) W_\mu + \text{h.c.}$$

- in this scenario: d_n, d_d and $d_{\rm Ra}$ in the next generation of experiments
- and correlated!

falsify with better hadronic and nuclear input

Disentangling $\not{T}$ sources



- LQCD/experiment discrepancy in ϵ'/ϵ could be explained with tiny right-handed currents

$$\mathcal{L} = \frac{g}{\sqrt{2}} \left(\xi_{ud}\, \bar{u}_R \gamma^\mu d_R + \xi_{us}\, \bar{u}_R \gamma^\mu s_R \right) W_\mu + \text{h.c.}$$

- in this scenario: d_n, d_d and d_{Ra} in the next generation of experiments
- and correlated!

falsify with better hadronic and nuclear input

Conclusion

Exciting times for EDMs

- several experiments running or coming online
- increase sensitivity to CP violation by one-two orders of magnitude

To take full advantage of EDM experiments:

1. first principle calculations of d_n, d_p

   ongoing LQCD effort

2. robust estimates of π-N coupings $\bar{g}_0$, $\bar{g}_1$

   LQCD + χEFT

3. progress in many-body nuclear theory

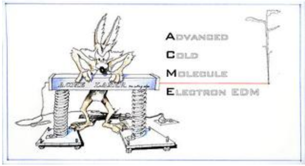
- …not there yet …stay tuned!

Introduction

- electron EDM
  (via ThO energy levels)

$$|d_e| \leq 8.7 \cdot 10^{-16}\, e\,\mathrm{fm}$$

ACME collaboration, ‘14.



- neutron EDM

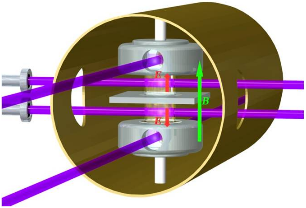
$$|d_n| \leq 3.0 \cdot 10^{-13}\, e\,\mathrm{fm}$$

J. M. Pendlebury *et al*, ‘15

- Hg EDM

$$|d_{^{199}\mathrm{Hg}}| \leq 6.2 \cdot 10^{-17}\, e\,\mathrm{fm}$$

B. Graner *et al*, ‘16.

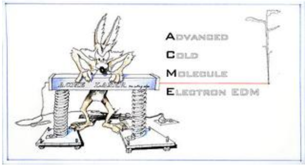


Introduction

- electron EDM
  (via ThO energy levels)

$$|d_e| \leq 8.7 \cdot 10^{-16}\, e\,\mathrm{fm}$$

ACME collaboration, ‘14.



- neutron EDM

$$|d_n| \leq 3.0 \cdot 10^{-13}\, e\,\mathrm{fm}$$

J. M. Pendlebury *et al*, ‘15

- Hg EDM

$$|d_{^{199}\mathrm{Hg}}| \leq 6.2 \cdot 10^{-17}\, e\,\mathrm{fm}$$

B. Graner *et al*, ‘16.