Electric Dipole Moment Prospects: Experiments and Interpretation

Tim Chupp

University of Michigan

Los Alamos Nat. Lab (Rosen Scholar)

1. EDMs in a Global Context
2. Brief history
3. Recent and current efforts
4. Interpretation
5. The horizon

NSF

U.S. DEPARTMENT OF ENERGY
Office of Science

APS physics

GORDON AND BETTY MOORE FOUNDATION

MICHIGAN

Thursday:

09:00

Introduction *Adam RITZ*

https://ca01web.zoom.us/j/69998354433 (password: 972986)

EDMs and molecules: state of the art and prospects for rapid improvements in hadronic and leptonic CP violation *Prof. Dave DEMILLE*

https://ca01web.zoom.us/j/69998354433 (password: 972986)

Assembling and disassembling molecules for quantum science and precision measurement *Dr. Will CAIRNCROSS*

10:00

Probing Physics Beyond the Standard Model with the JILA eEDM Experiment *Kia Boon NG*

Discussion

https://ca01web.zoom.us/j/69998354433 (password: 972986)

Health break

11:00

https://ca01web.zoom.us/j/69998354433 (password: 972986)

Extending the reach of fundamental symmetries research with beta decay and measurements with polarized ultracold neutrons *Prof. Albert YOUNG*

https://ca01web.zoom.us/j/69998354433 (password: 972986)

12:00

Probing for BSM physics through Precision Measurements of the Neutron Lifetime and the Neutron Electric Dipole Moment *Prof. Chen-Yu LIU*

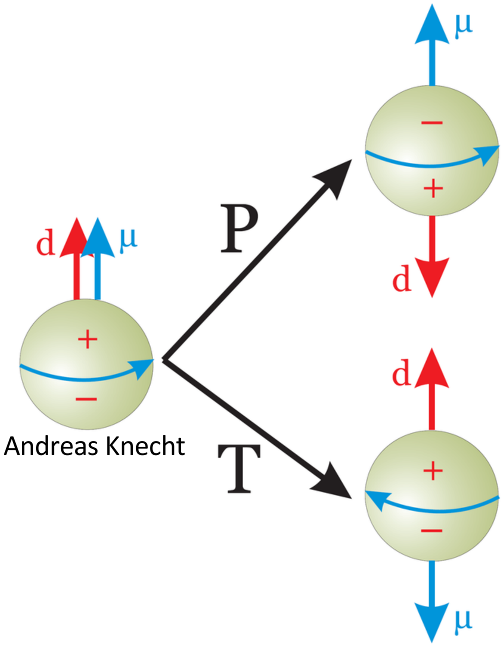
https://ca01web.zoom.us/j/69998354433 (password: 972986)

Discussion

https://ca01web.zoom.us/j/69998354433 (password: 972986)

Electric Dipole Moment

$$\vec{d} = \int \vec{r}(\rho_Q(\vec{r}) - \rho_m(\vec{r}))dV = d\vec{J}$$



Andreas Knecht

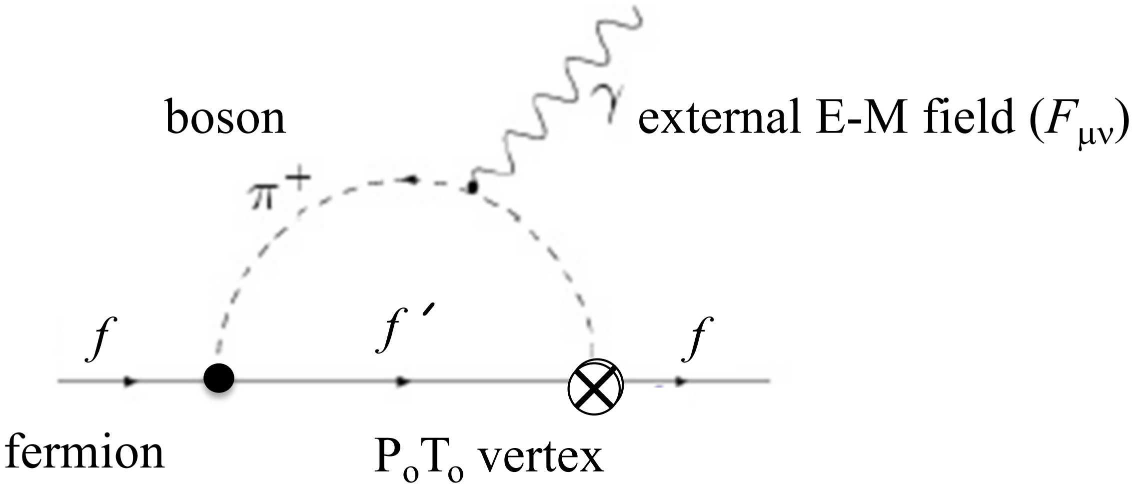
Put this in *E* and *B* fields

$$H = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E} = -\mu\underbrace{\vec{J}\cdot\vec{B}}_{P_e T_e} - d\underbrace{\vec{J}\cdot\vec{E}}_{P_o T_o \,\llcorner\, \cancel{CP}}$$

$\cancel{CP}$ ⟷ Baryon Asymmetry ⟷ NEW PHYSICS (BSMP)

Electric Dipole Moment

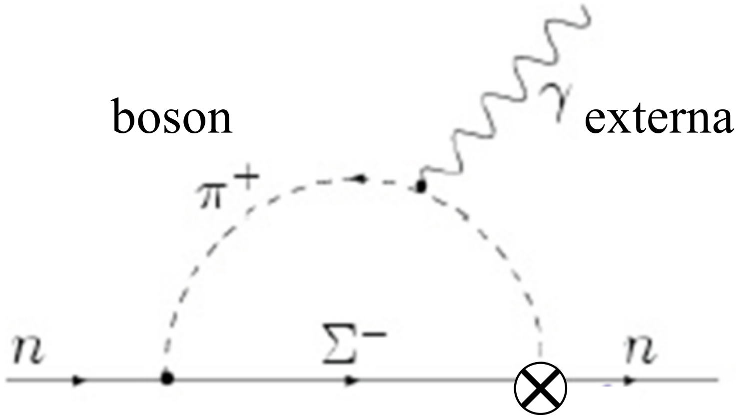
$$\mathcal{L}_{EM} = -\frac{\mu}{2}\bar{\Psi}\sigma^{\mu\nu}F_{\mu\nu}\Psi - \frac{d}{2}\bar{\Psi}\sigma^{\mu\nu}i\gamma^{5}F_{\mu\nu}\Psi$$



$$H = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E} = -\mu\underbrace{\vec{J}\cdot\vec{B}}_{P_eT_e} - d\underbrace{\vec{J}\cdot\vec{E}}_{P_oT_o}$$

Electric Dipole Moment

$$\mathcal{L}_{EM} = -\frac{\mu}{2}\bar{\Psi}\sigma^{\mu\nu}F_{\mu\nu}\Psi - \frac{d}{2}\bar{\Psi}\sigma^{\mu\nu}i\gamma^5 F_{\mu\nu}\Psi$$



boson

external E-M field ($F_{\mu\nu}$)

fermion

P_oT_o vertex

$$H = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E} = -\mu\underbrace{\vec{J}\cdot\vec{B}}_{P_eT_e} - d\underbrace{\vec{J}\cdot\vec{E}}_{P_oT_o}$$

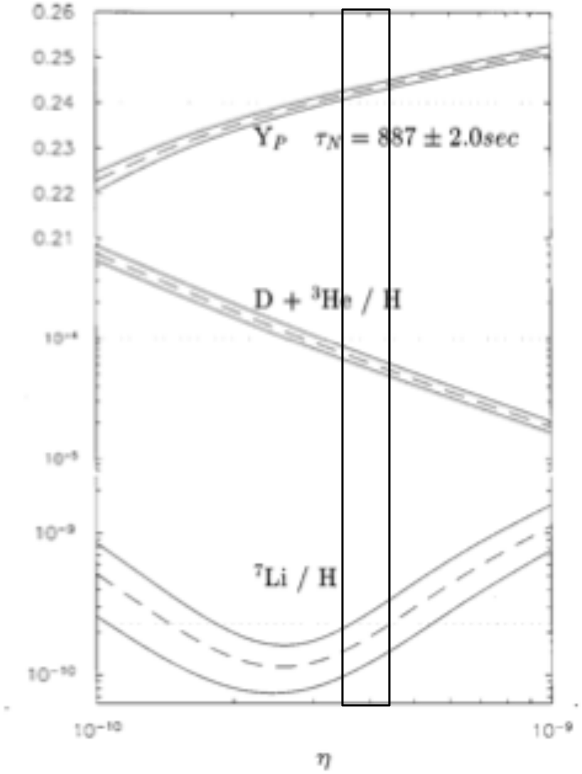
Baryon Asymmetry requires BSMP

$\cancel{C}P \longrightarrow$ Baryon Asymmetry $\longrightarrow$ NEW PHYSICS (BSMP)

Fact: There is more matter than antimatter

$$n_p \neq n_{\bar{p}} \quad \eta = \frac{n_p - n_{\bar{p}}}{n_p + n_{\bar{p}}} \approx few \times 10^{-10}$$

(WMAP/PLANCK, [^{4}He]$_{,,\ldots}$)



How? A) Initial condition – NO (inflation)

B) Evolution from η=0

1) Baryon number violation

2) **CP Violation make and EDM**

3) Rapid expansion (non-equilibrium)

A. Shakarov
Nobel Peace Prize 1975

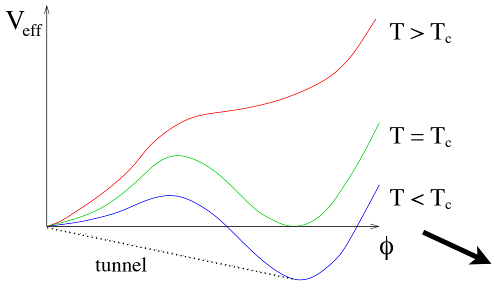
Another possibility: CP violation in neutrinos + “seesaw”

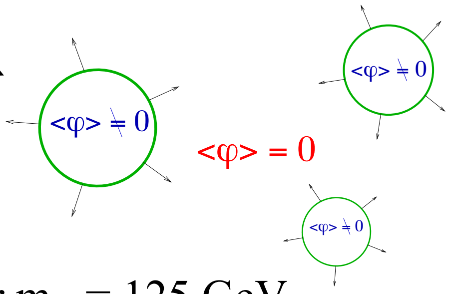
Electroweak Baryongenesis

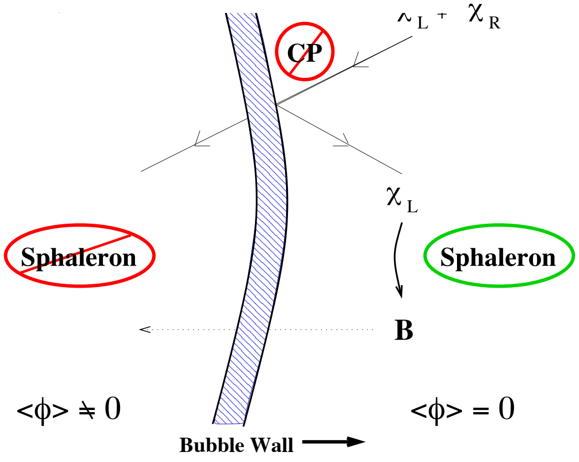
Kuzmin, Rubakov, Shaposhnikov 87; Cohen, Kaplan, Nelson 90&95

1. First-order EW PT produces expanding bubbles.
2. C and CP violation near the bubble wall induce asymmetries.
3. Electroweak physics (sphalerons) convert this to baryons

$$V(H,T) \simeq -\frac{1}{2}(\mu^2-\zeta T^2)H^2-\gamma T H^3+\frac{\lambda}{4}H^4$$







DOESN'T WORK:

1. The EW PT is not first order for m_h = 125 GeV.

   Kajantie, Laine, Rummukainen, Shaposhnikov 98

2. Not enough effective CP violation.

   Gavela, Hernandez, Orloff, Pene'94; Huet + Sather '95

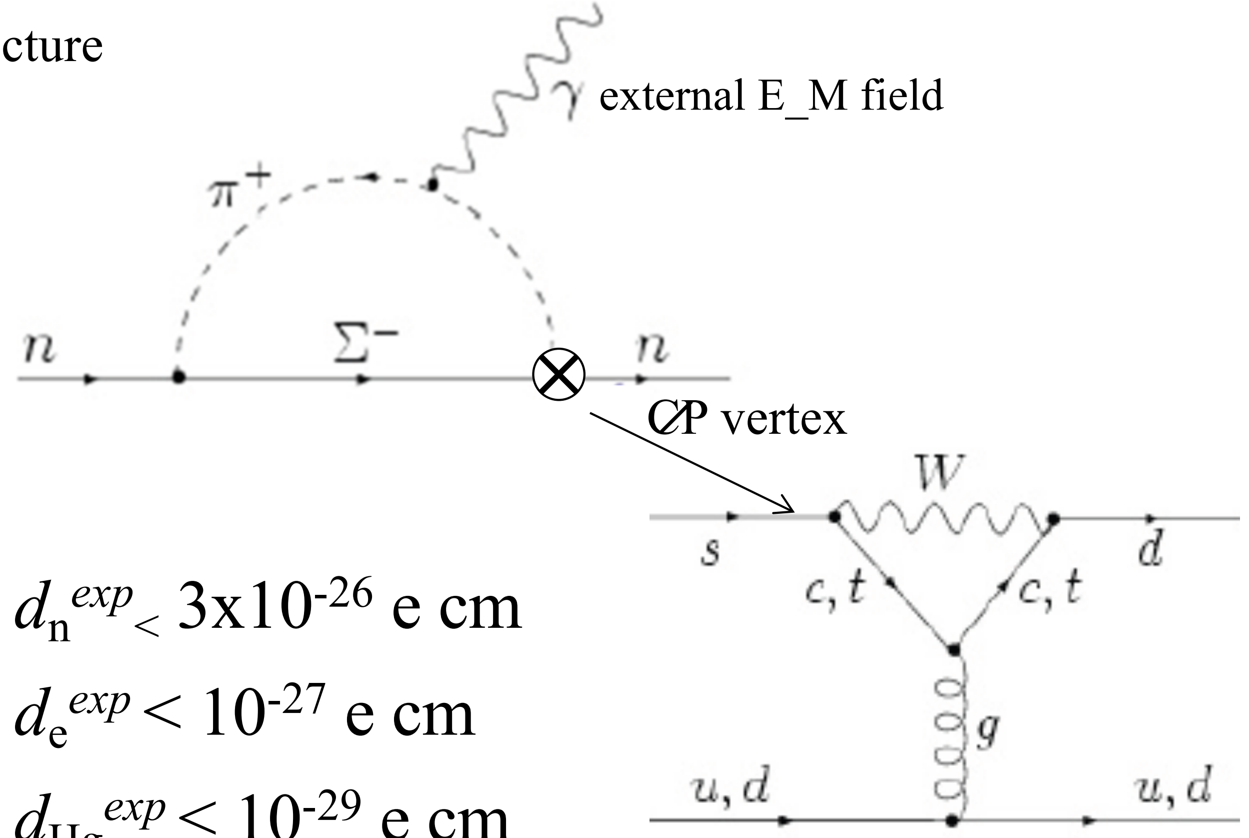
From D. Morrissey

Standard-model/CKM EDMs small

Vanish at 2-loops for quarks and 3-loops for leptons

Khriplovich, Zhitnitsky (1982), McKellar et al., (1987)

Pion-nucleon picture



$d_n^{SM} \approx 10^{-32}$ e cm; $d_n^{exp} < 3x10^{-26}$ e cm

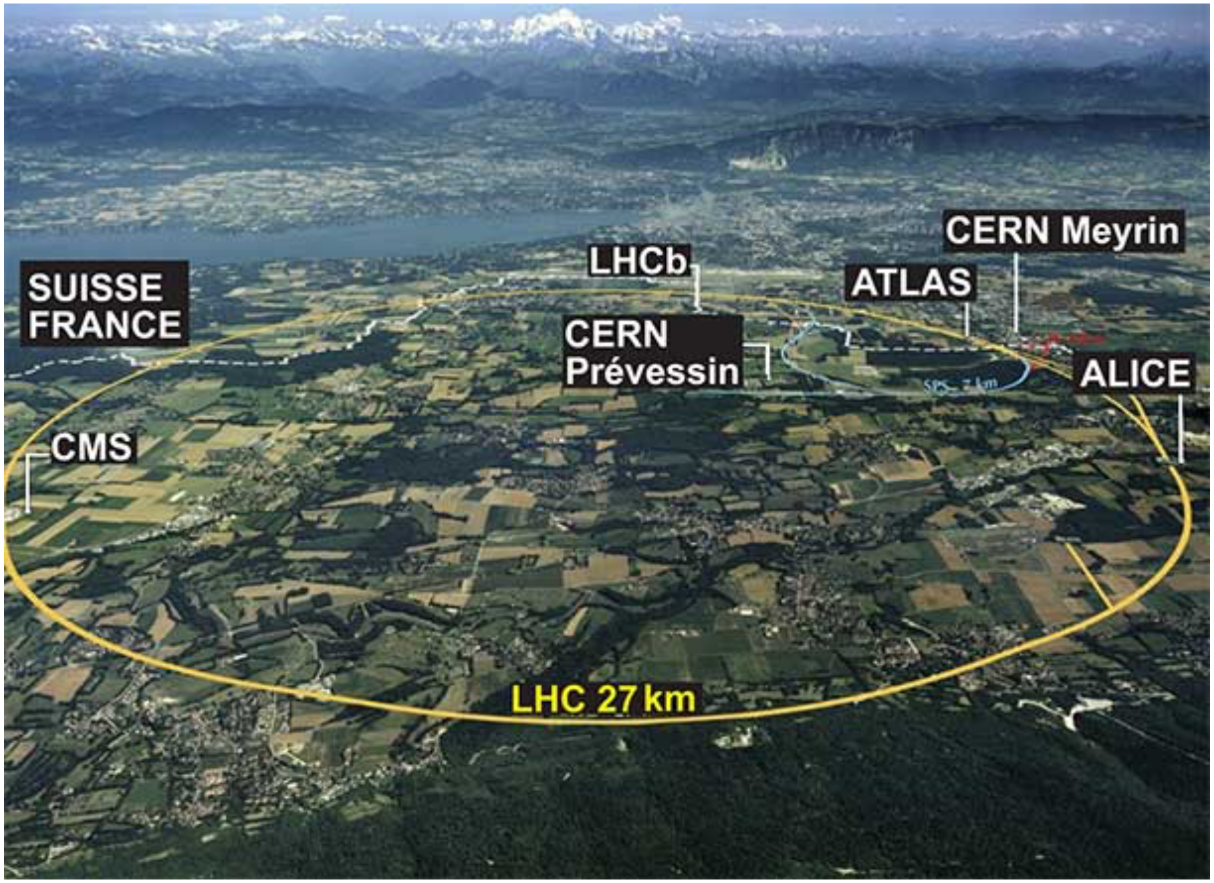
$d_e^{SM} \approx 10^{-37}$ e cm; $d_e^{exp} < 10^{-27}$ e cm

$d_{Hg}^{SM} \approx 5x10^{-34}$ e cm; $d_{Hg}^{exp} < 10^{-29}$ e cm

$d_{Xe}^{SM} \approx 4x10^{-35}$ e cm; $d_{He}^{exp} < 5x\ 10^{-27}$ e cm

DISCOVERY POTENTIAL!

EDMs probe TeV-scale "new" physics



$$\mu \approx \frac{e\hbar}{2m} \qquad \left(\alpha = \frac{e^2}{\hbar c}\right)$$

$$\frac{d}{\mu} \approx f^{2N}\left(\frac{m_q}{m_X}\right)^2 \sin\phi$$

≈ 1

$\approx \alpha$

$\approx 10^{-14}$ $d_n \sim 10^{-26}$ e-cm

$$m_X \approx m_q\sqrt{10^{14}\,\alpha^N}$$

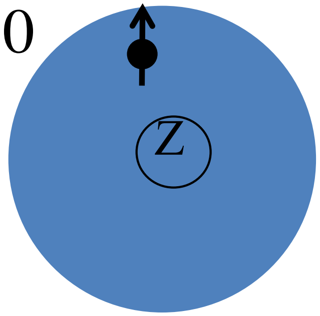
loops

$m_x \sim$ 1 TeV - LHC scale

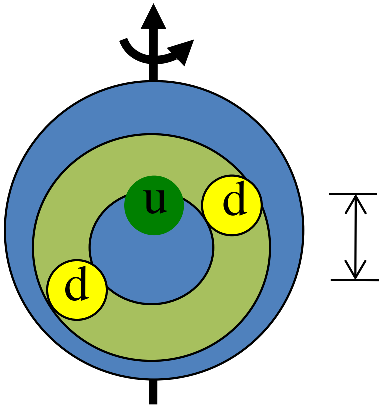
or ϕ is small

Particle Interactions Polarize Particles, Atoms, Molecules

$\vec{E}(\vec{r}_e) \neq 0$

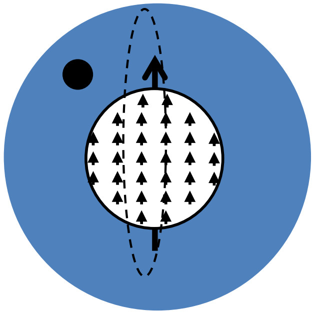


Paramagnetic ($\vec{L} \cdot \vec{S}$ coupling) $\propto Z^{\approx 3}$



$\langle \vec{r}_Q \rangle$: *EDM*

Nucleon



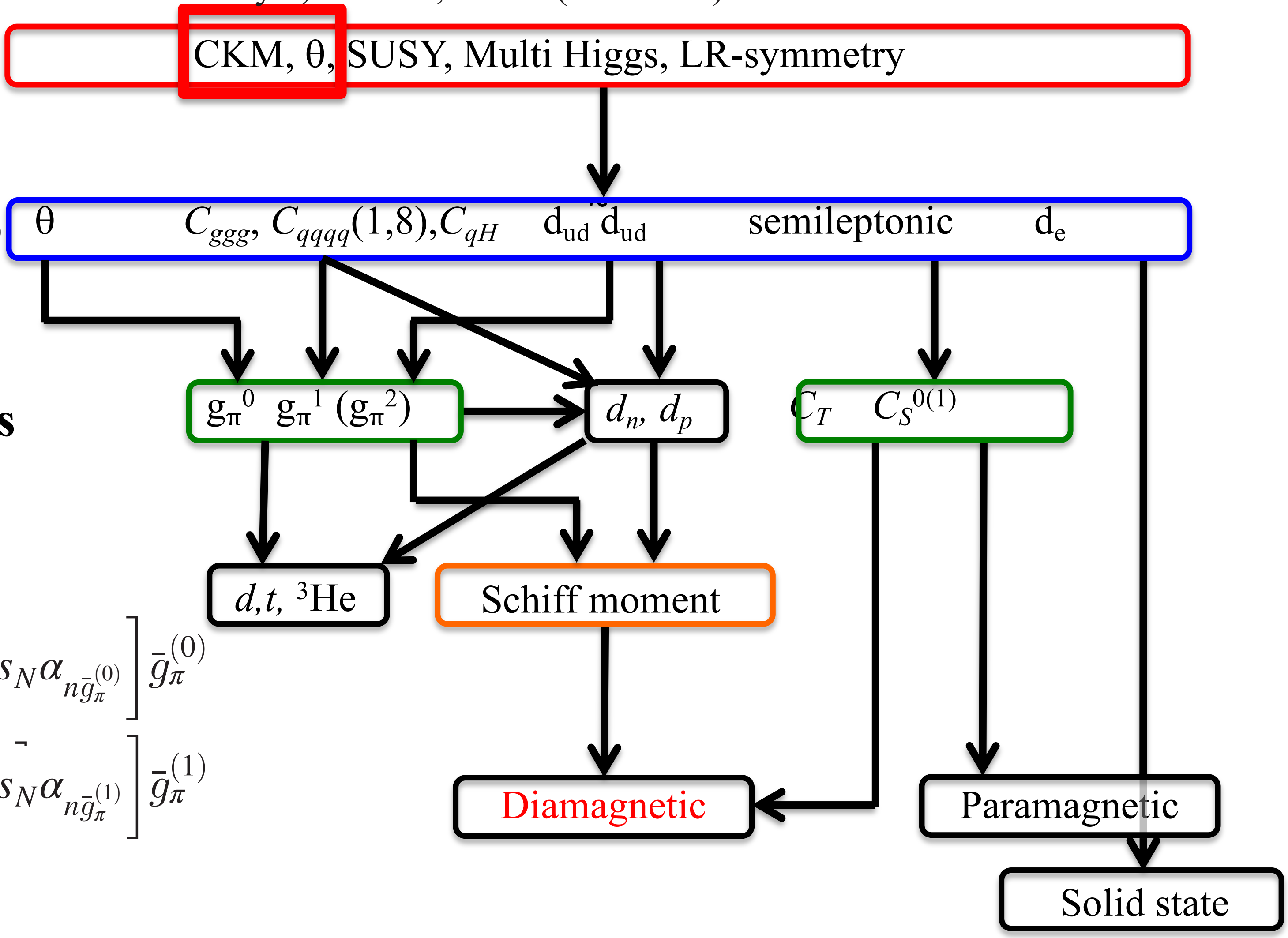
$\vec{E} \propto \vec{J}$

Diamagnetic: Schiff moment, MQM $\propto Z^2$

$$\vec{S} = S\vec{J} = \frac{1}{10}\langle r^2 \vec{r}_p \rangle - \frac{1}{6} Z \langle r^2 \rangle \langle \vec{r}_p \rangle$$

EDMs arise from many sources

Rev. Mod. Phys., Vol. 91, No. 1 (Jan 2019)



Fundamental theory CKM, θ, SUSY, Multi Higgs, LR-symmetry

Wilson coefficients (13) θ C_{ggg}, $C_{qqqq}(1,8)$, C_{qH} d_{ud} $\tilde{d}_{ud}$ semileptonic d_e

$$\mathcal{L}_{\rm CPV}^{\rm eff} = \sum_{k,d} \alpha_k^{(d)} \left(\frac{1}{\Lambda}\right)^{d-4} \mathcal{O}_k^{(d)}$$

Low energy parameters g_π^0 g_π^1 (g_π^2) d_n, d_p C_T $C_S^{0(1)}$

$$\bar{g}_{CP}^0 \approx 0.027\ \theta_{QCD}$$

Nucleus level $d,t,{}^3\text{He}$ Schiff moment

$$S = s_N \bar{d}_N^{sr} + \left[\frac{m_N g_A}{F_\pi} a_0 + s_N \alpha_{n\bar{g}_\pi^{(0)}}\right] \bar{g}_\pi^{(0)} + \left[\frac{m_N g_A}{F_\pi} a_1 + s_N \alpha_{n\bar{g}_\pi^{(1)}}\right] \bar{g}_\pi^{(1)}$$

Diamagnetic Paramagnetic Solid state

Atom/molecule level

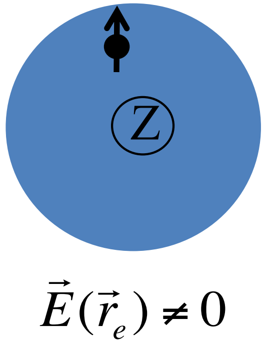
$$d_A = \eta_e d_e + \kappa_S S(\theta_{QCD}, g_\pi) + (k_T C_T + k_S C_S) + \boldsymbol{h.o.}$$

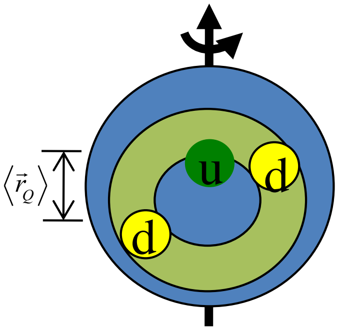
$\sim Z^3$ $\sim Z^3$

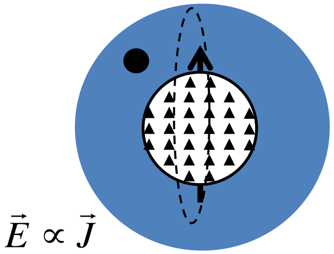
Rev. Mod. Phys. v. 91 015001 (2019)

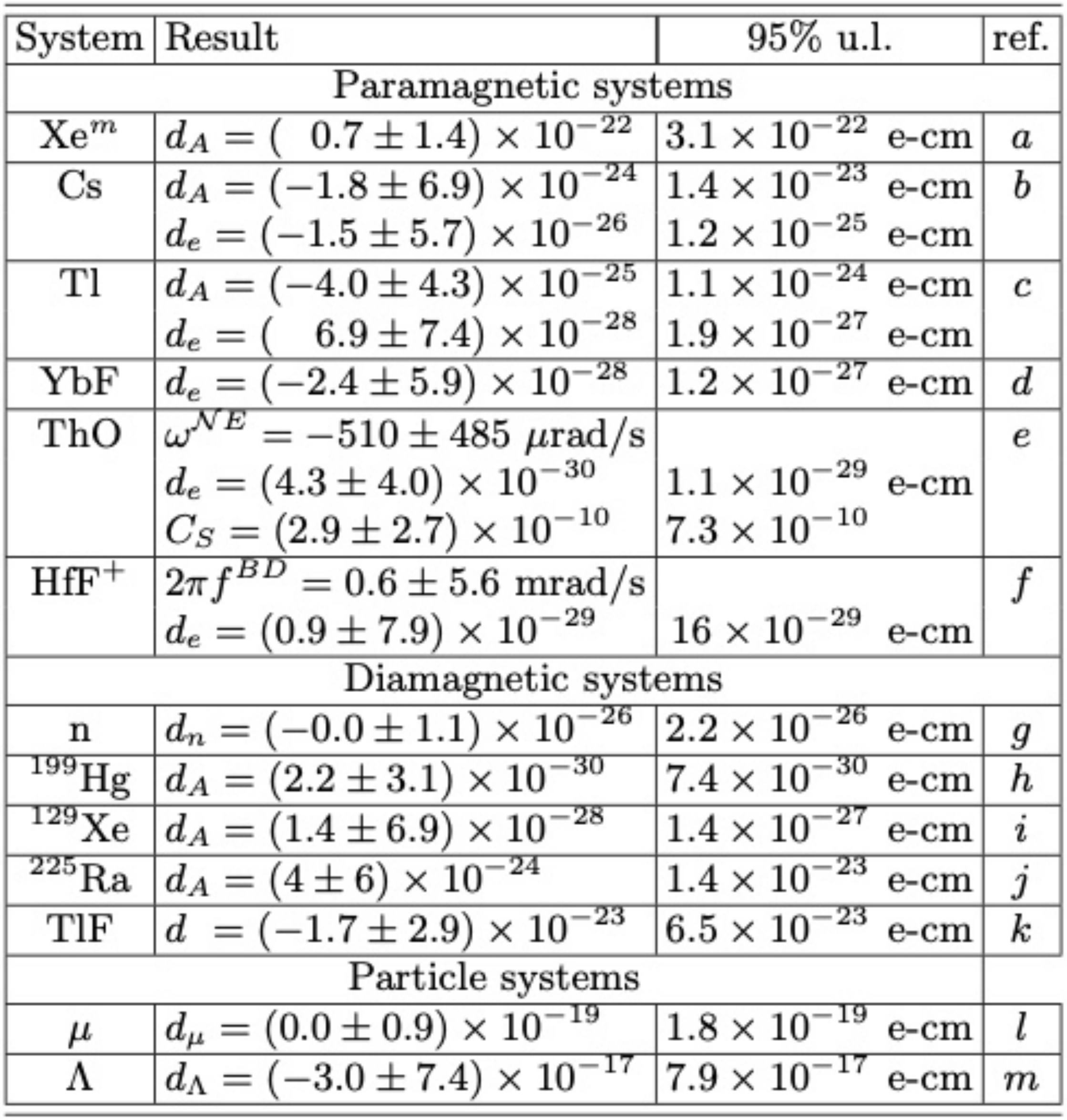
EDM results

Rev. Mod. Phys., Vol. 91, No. 1 (Jan 2019)









System	Result	95% u.l.	ref.
Paramagnetic systems			
Xe^m	$d_A = (\ \ 0.7 \pm 1.4) \times 10^{-22}$	3.1×10^{-22} e-cm	a
Cs	$d_A = (-1.8 \pm 6.9) \times 10^{-24}$	1.4×10^{-23} e-cm	b
	$d_e = (-1.5 \pm 5.7) \times 10^{-26}$	1.2×10^{-25} e-cm	
Tl	$d_A = (-4.0 \pm 4.3) \times 10^{-25}$	1.1×10^{-24} e-cm	c
	$d_e = (\ \ 6.9 \pm 7.4) \times 10^{-28}$	1.9×10^{-27} e-cm	
YbF	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$	1.2×10^{-27} e-cm	d
ThO	$\omega^{NE} = -510 \pm 485\ \mu\mathrm{rad/s}$		e
	$d_e = (4.3 \pm 4.0) \times 10^{-30}$	1.1×10^{-29} e-cm	
	$C_S = (2.9 \pm 2.7) \times 10^{-10}$	7.3×10^{-10}	
HfF^+	$2\pi f^{BD} = 0.6 \pm 5.6$ mrad/s		f
	$d_e = (0.9 \pm 7.9) \times 10^{-29}$	16×10^{-29} e-cm	
Diamagnetic systems			
n	$d_n = (-0.0 \pm 1.1) \times 10^{-26}$	2.2×10^{-26} e-cm	g
$^{199}\mathrm{Hg}$	$d_A = (2.2 \pm 3.1) \times 10^{-30}$	7.4×10^{-30} e-cm	h
$^{129}\mathrm{Xe}$	$d_A = (1.4 \pm 6.9) \times 10^{-28}$	1.4×10^{-27} e-cm	i
$^{225}\mathrm{Ra}$	$d_A = (4 \pm 6) \times 10^{-24}$	1.4×10^{-23} e-cm	j
TlF	$d\ \ = (-1.7 \pm 2.9) \times 10^{-23}$	6.5×10^{-23} e-cm	k
Particle systems			
μ	$d_\mu = (0.0 \pm 0.9) \times 10^{-19}$	1.8×10^{-19} e-cm	l
Λ	$d_\Lambda = (-3.0 \pm 7.4) \times 10^{-17}$	7.9×10^{-17} e-cm	m

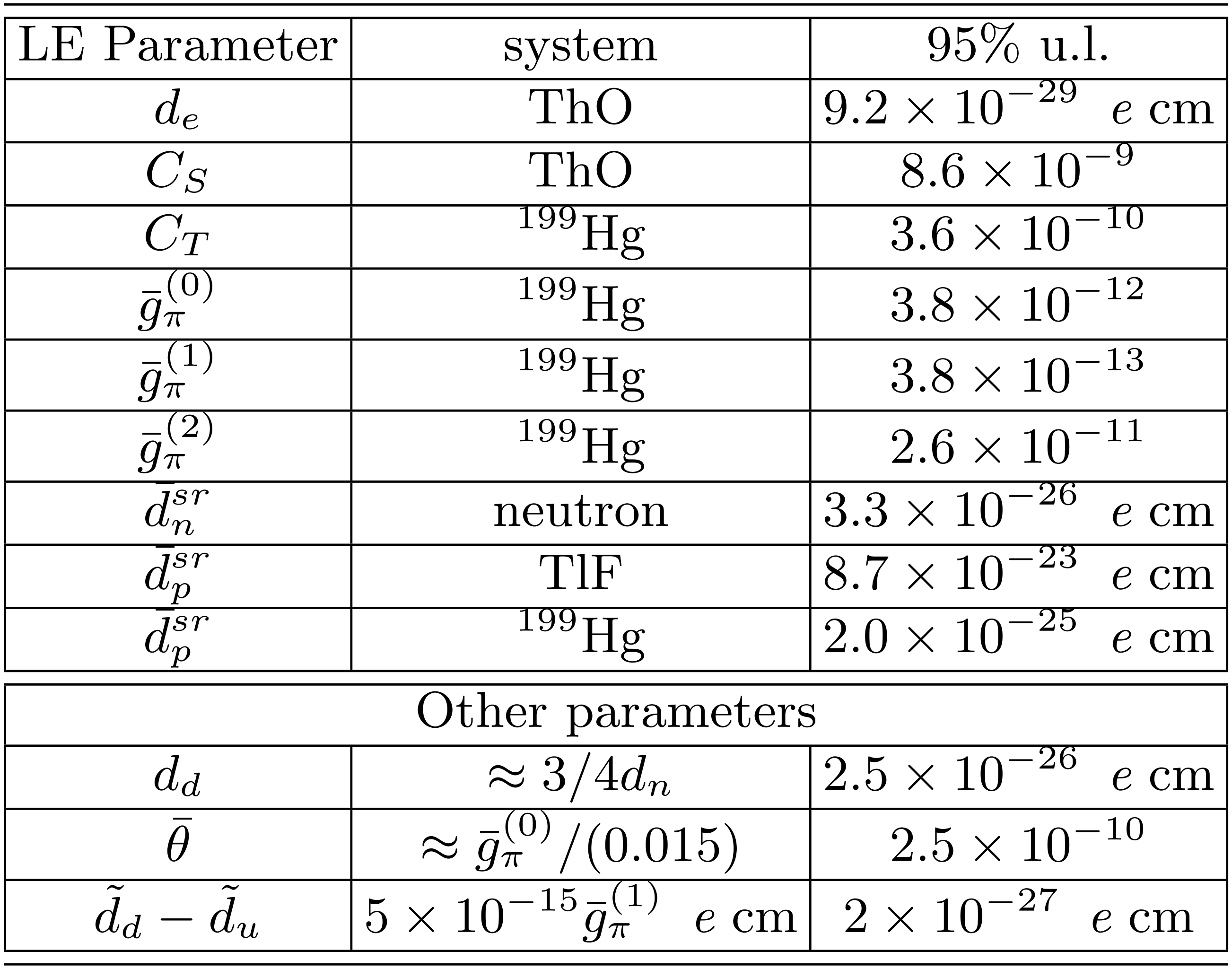
2017

2018 (8x)

2020 (1.6x)
2017 (4x)
2019 (5x)
2016

Sole-source analysis

$$d_j = \alpha_{ij} P_j$$



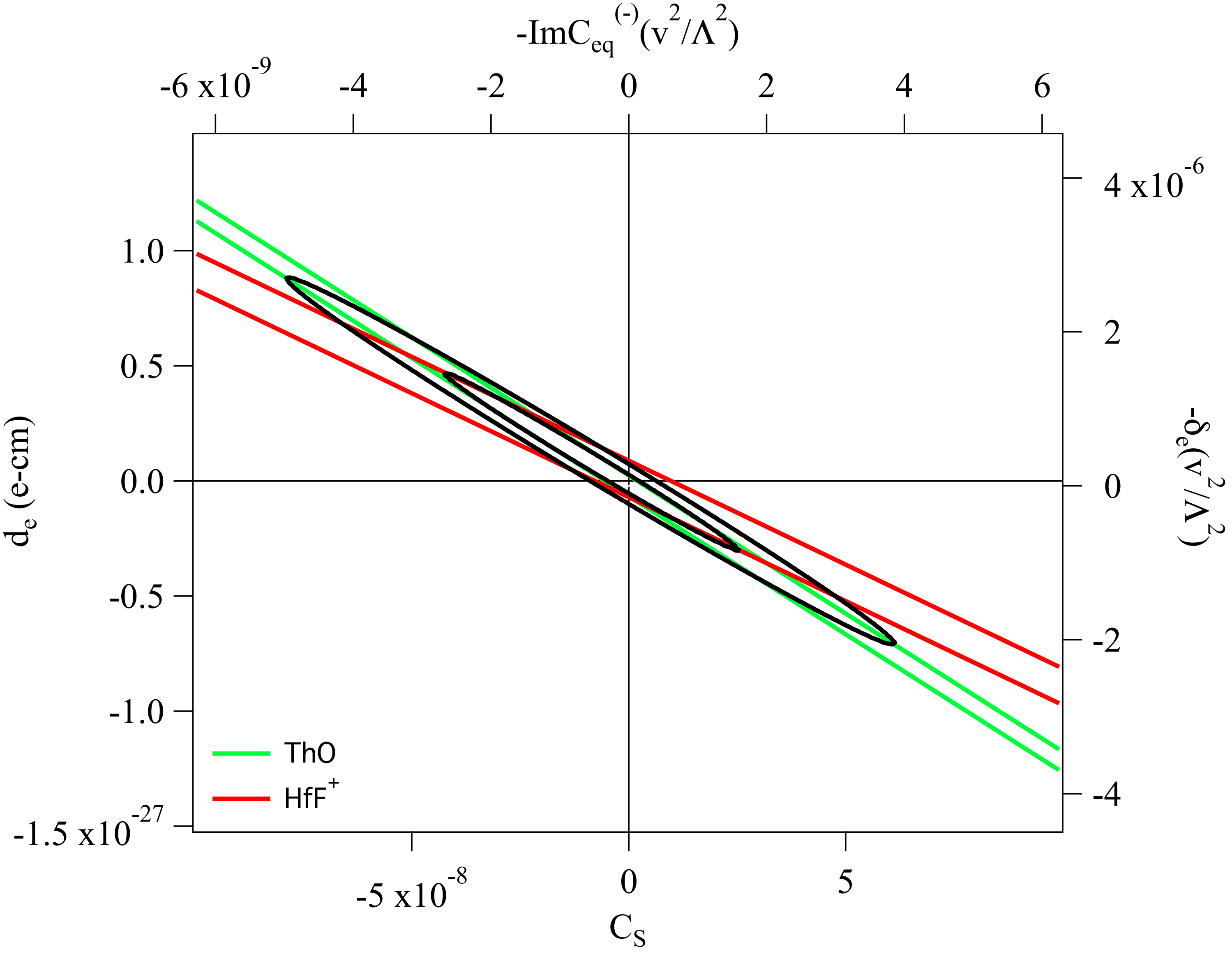
LE Parameter	system	95% u.l.
d_e	ThO	9.2×10^{-29} e cm
C_S	ThO	8.6×10^{-9}
C_T	^{199}Hg	3.6×10^{-10}
$\bar{g}_\pi^{(0)}$	^{199}Hg	3.8×10^{-12}
$\bar{g}_\pi^{(1)}$	^{199}Hg	3.8×10^{-13}
$\bar{g}_\pi^{(2)}$	^{199}Hg	2.6×10^{-11}
$\bar{d}_n^{sr}$	neutron	3.3×10^{-26} e cm
$\bar{d}_p^{sr}$	TlF	8.7×10^{-23} e cm
$\bar{d}_p^{sr}$	^{199}Hg	2.0×10^{-25} e cm

Other parameters		
d_d	$\approx 3/4 d_n$	2.5×10^{-26} e cm
$\bar{\theta}$	$\approx \bar{g}_\pi^{(0)}/(0.015)$	2.5×10^{-10}
$\tilde{d}_d - \tilde{d}_u$	$5 \times 10^{-15} \bar{g}_\pi^{(1)}$ e cm	2×10^{-27} e cm

Global Analysis: d_e and C_S

T.C. & M. Ramsey-Musolf – Phys. Rev. C **91** 035502 (2015)

Also: Fleig and Jung *J. High Energy Phys.* **2018,** 12 (2018)



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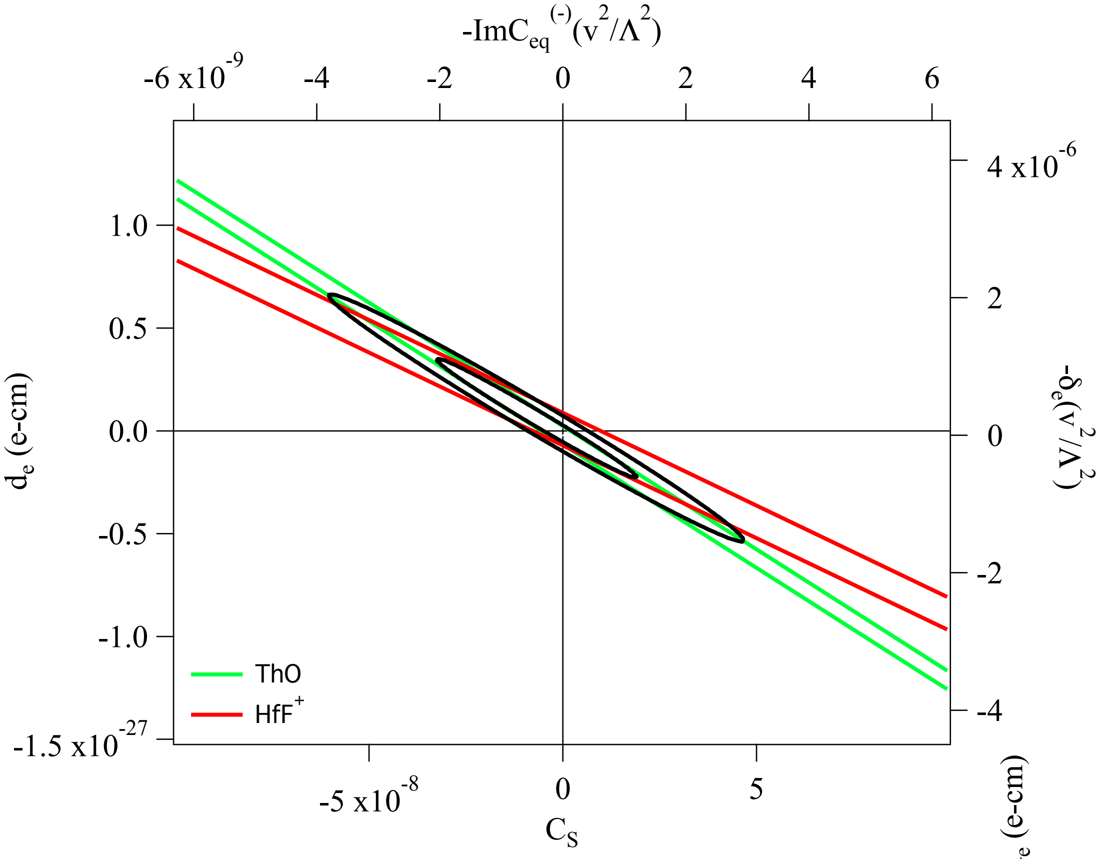
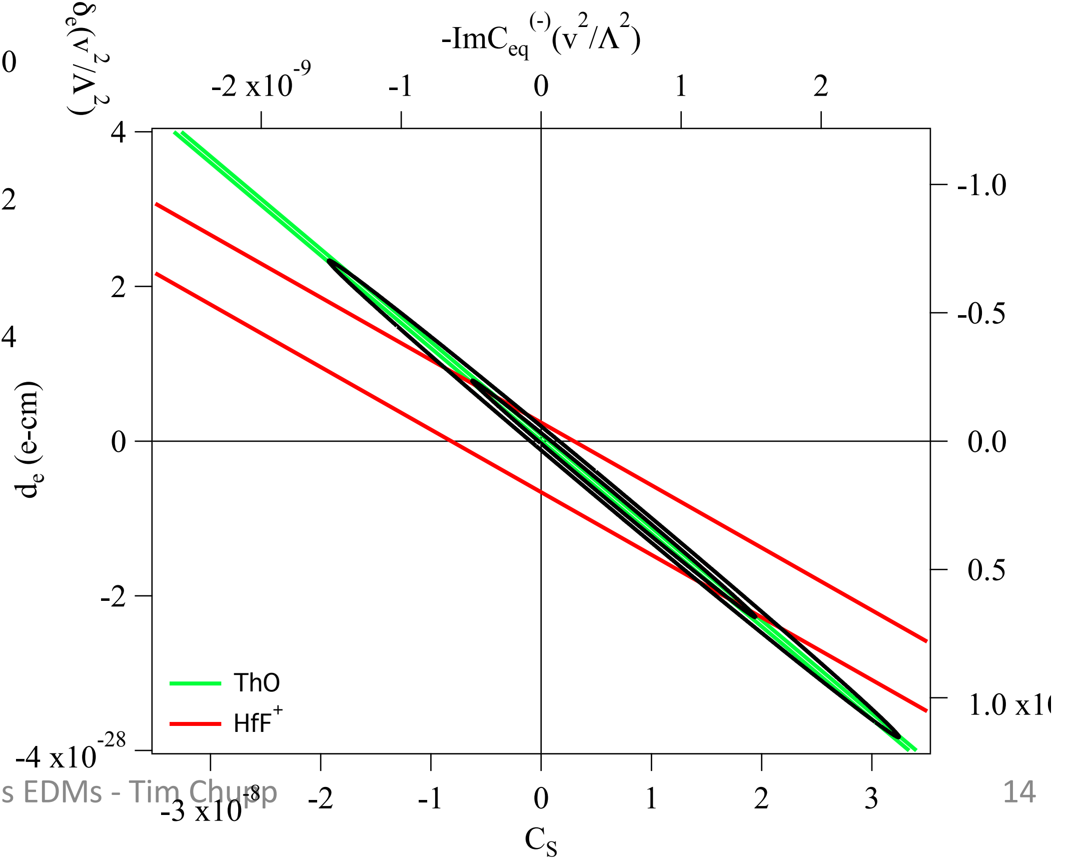


Also consider francium

8x ThO improvement leads to d_e/C_S improvement by about 2x



Diagmagetic atoms and nucleons

T.C. & M. Ramsey-Musolf – Phys. Rev. C **91** 035502 (2015)

	d_n^0	d_n^1	C_T	g_π^0	g_π^1
neutron	1	-1		x	x
Xe, Hg, TlF			x	x	x
Ra			x	x	x
proton	1	+1		x	x
d, ^{3}H, ^{3}He				x	x

Schiff Moment

$$d_n = \bar{d}_n^{\rm sr} - \frac{e g_A \bar{g}_\pi^{(0)}}{8\pi^2 F_\pi}\left\{\ln\frac{m_\pi^2}{m_N^2} - \frac{\pi m_\pi}{2m_N} + \frac{\bar{g}_\pi^{(1)}}{4\bar{g}_\pi^{(0)}}(\kappa_1-\kappa_0)\frac{m_\pi^2}{m_N^2}\ln\frac{m_\pi^2}{m_N^2}\right\}$$

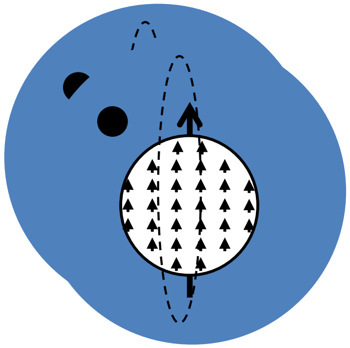
$$\approx \bar{d}_n^{sr} - (1.44\times10^{-14} g_\pi^{(0)} - 8.3\times10^{-16} g_\pi^{(1)})\ e-cm$$

$$S = g_{\pi NN}(a_0\bar{g}_{CP}^0 + a_1\bar{g}_{CP}^1 + a_2\bar{g}_{CP}^2)$$

$$\bar{g}_{CP}^0 \approx 0.027\ \theta_{QCD}$$

A global analysis

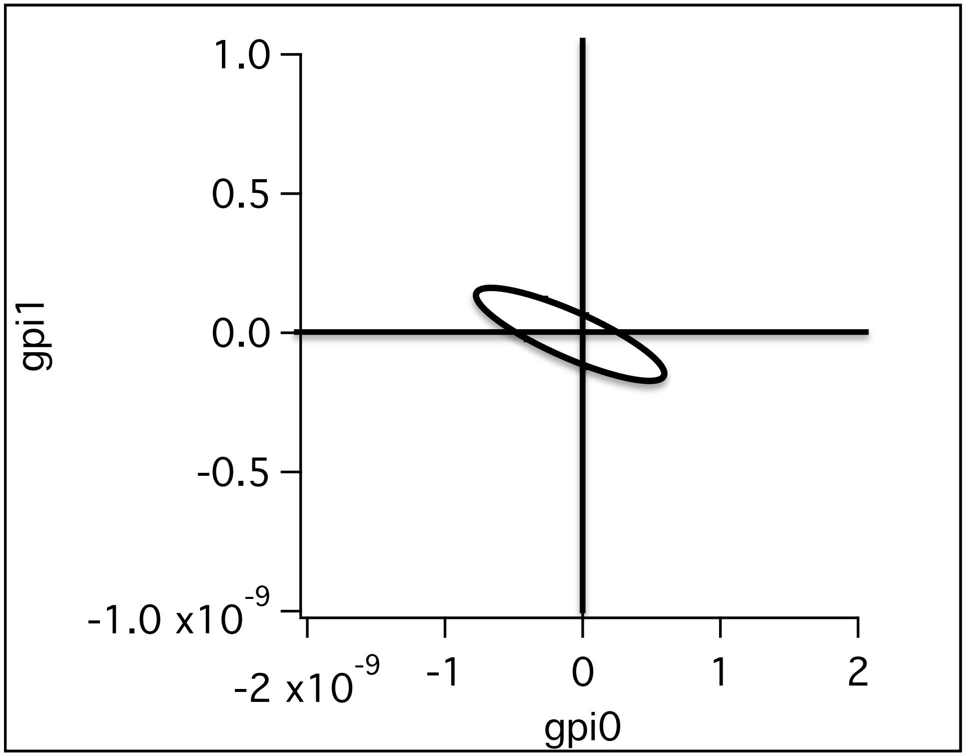
TC&MJ Ramsey-Musolf: PHYSICAL REVIEW C **91**, 035502 (2015)

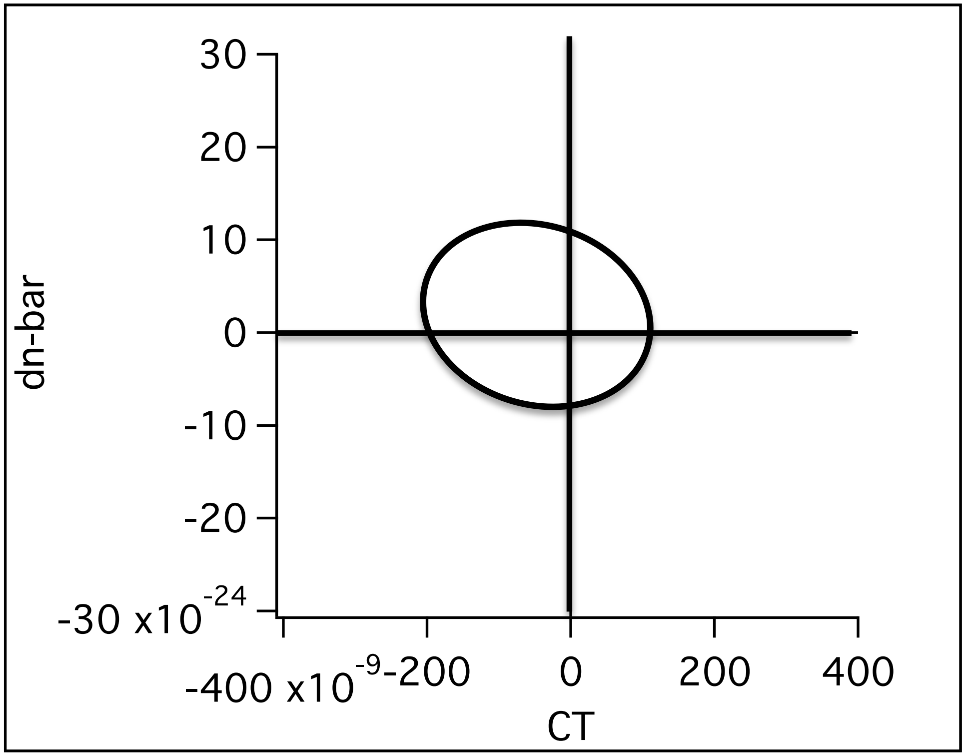


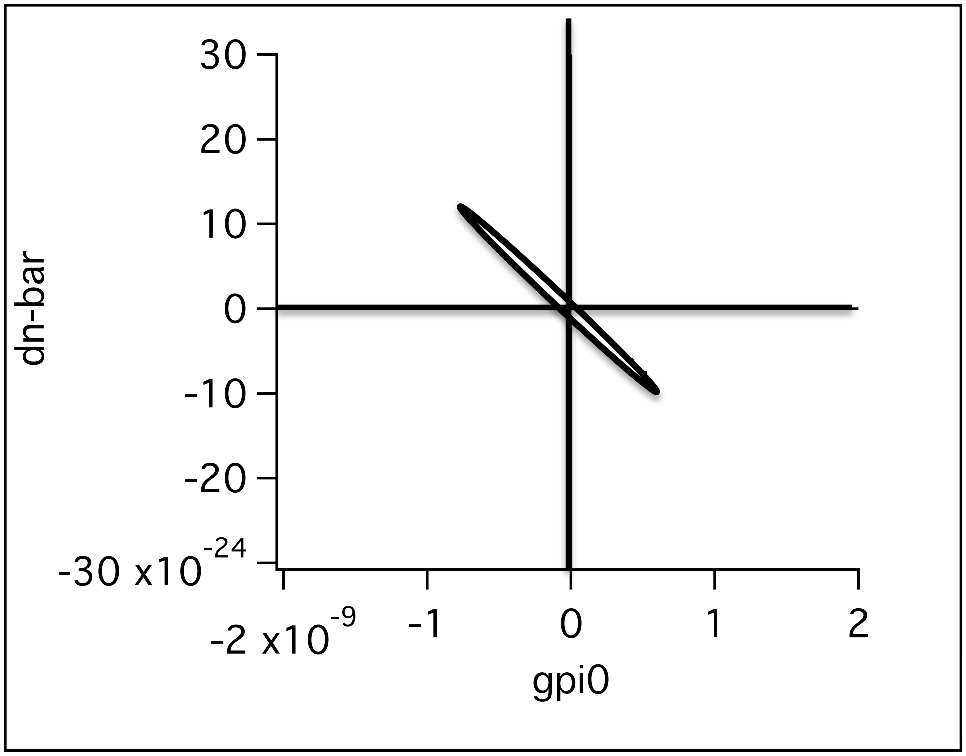
	d_0^{sr}	d_1^{sr}	C_T	g_π^0	g_π^1
neutron	1	-1			
Xe, Hg, TlF, Ra			x	x	x

$$d_A = \alpha_{C_T} C_T + \kappa_S (a_0 \bar{g}_\pi^0 + a_1 \bar{g}_\pi^1 + \xcancel{a_2 \bar{g}_\pi^2})$$

$$d_n = \bar{d}_n^{\rm sr} - \frac{e g_A \bar{g}_\pi^{(0)}}{8\pi^2 F_\pi} \left\{ \ln \frac{m_\pi^2}{m_N^2} - \frac{\pi m_\pi}{2 m_N} + \frac{\bar{g}_\pi^{(1)}}{4 \bar{g}_\pi^{(0)}} (\kappa_1 - \kappa_0) \frac{m_\pi^2}{m_N^2} \ln \frac{m_\pi^2}{m_N^2} \right\}$$


1.0
0.5
0.0
-0.5
-1.0 x10^-9
gpi1
-2 x10^-9
-1
0
1
2
gpi0


30
20
10
0
-10
-20
-30 x10^-24
dn-bar
-400 x10^-9
-200
0
200
400
CT


30
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-30 x10^-24
dn-bar
-2 x10^-9
-1
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1
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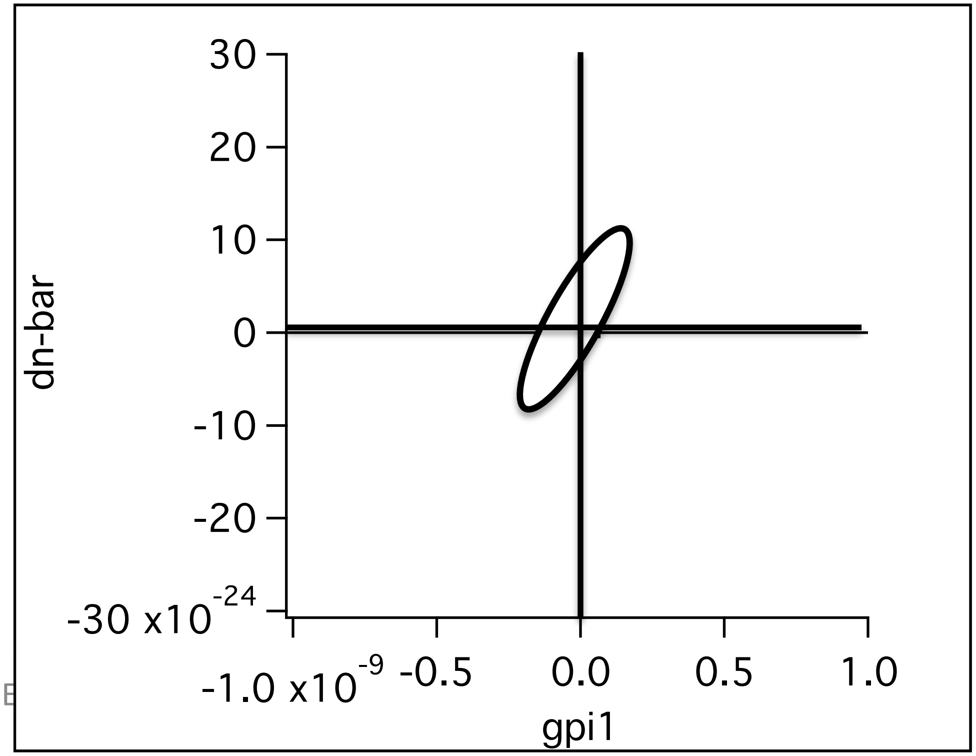
gpi0


30
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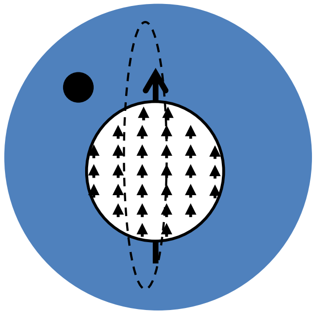
-10
-20
-30 x10^-24
dn-bar
-1.0 x10^-9
-0.5
0.0
0.5
1.0
gpi1

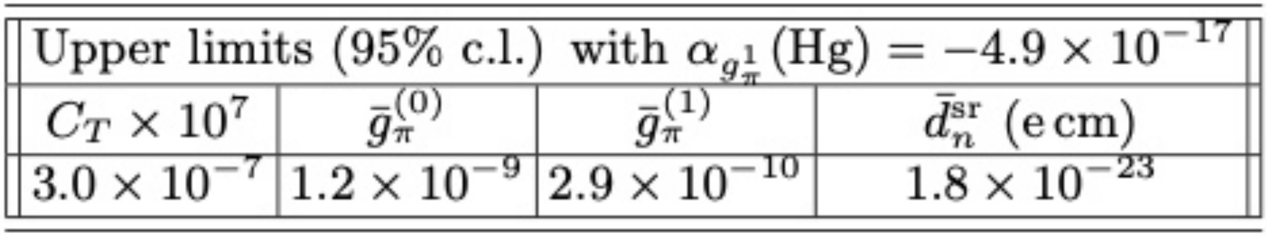
A global analysis

TC&MJR Musolf: PHYSICAL REVIEW C **91**, 035502 (2015)



Results

	d_0^{sr}	d_1^{sr}	$\mathbf{C_T}$	g_π^0	g_π^1
neutron	1	-1			
Xe, Hg, TlF, Ra			x	x	x



Upper limits (95% c.l.) with $\alpha_{g_\pi^1}$(Hg) $= -4.9 \times 10^{-17}$			
$C_T \times 10^7$	$\bar{g}_\pi^{(0)}$	$\bar{g}_\pi^{(1)}$	$\bar{d}_n^{\rm sr}$ (e cm)
3.0×10^{-7}	1.2×10^{-9}	2.9×10^{-10}	1.8×10^{-23}

Experiments

$$H = \boxed{-\vec{\mu}\cdot \vec{B}} - \vec{d}\cdot \vec{E}$$

- Strong electric field

- Large signal needs POLARIZATION (usually optical pumping)

- MEASURE FREQUENCIES $\propto \frac{1}{\tau^{3/2}}$ Per HV dwell

- **AND MAGNETIC FIELDS - (Co)magnetometry**

$$\sigma_d \approx \frac{1}{2E}\frac{\hbar}{\tau}\frac{1}{S/N} \nearrow \frac{1}{2E}\frac{\hbar}{\tau}\frac{1}{\sqrt{\varphi_n \tau}}$$

Phase-noise limit

$$\searrow \frac{1}{2E}\frac{\hbar}{\tau}\frac{1}{\sqrt{N}}$$

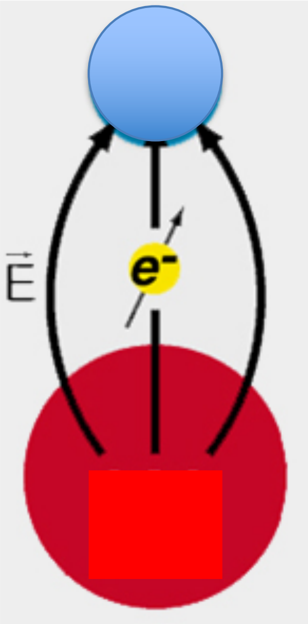
Count-rate limit
(P=A=1)

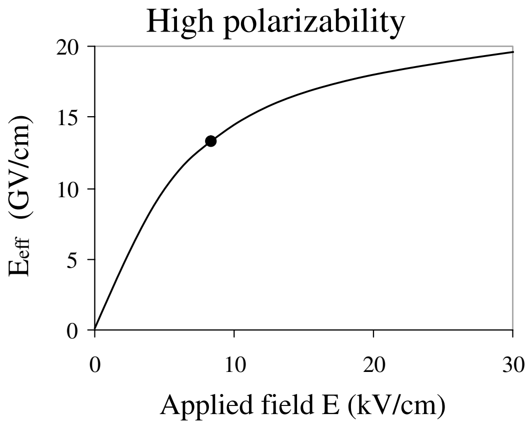
Measurement time
(HV dwell)

$$\sigma_d \approx \frac{1}{2E}\frac{\hbar}{\tau}\frac{1}{S/N}$$

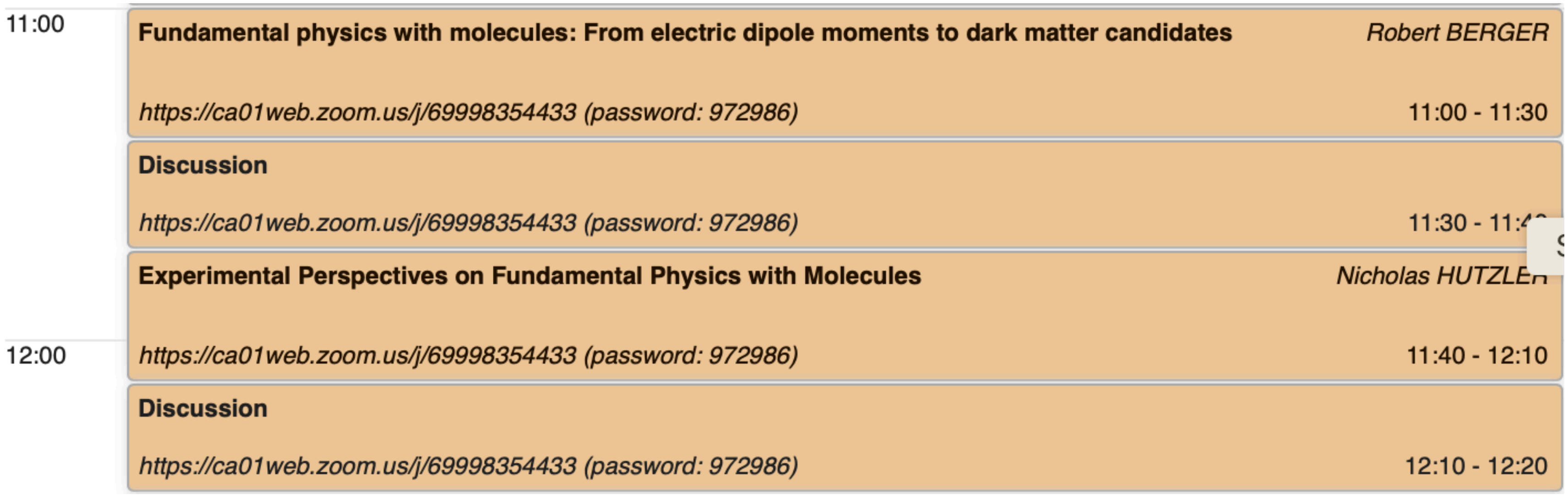
Paramagnetic Molecules

Large E, small τ





1. ***Large*** internal electric fields.
    1. $E_{eff} \sim 10^{11}$ V/cm.
    - Compared to $E_{lab} < 10^5$ V/cm.
2. ***Accessible*** internal electric fields.
    - Easy to electically polarize, need only $E_{lab} \sim 1$ V/cm.
3. Rejection of systematic errors.
    - Electron spins triple/L=1 (J=0) μ small
    - E_{eff} ***independent*** of E_{lab}.



11:00

Fundamental physics with molecules: From electric dipole moments to dark matter candidates *Robert BERGER*

https://ca01web.zoom.us/j/69998354433 (password: 972986) 11:00 - 11:30

Discussion

https://ca01web.zoom.us/j/69998354433 (password: 972986) 11:30 - 11:4

Experimental Perspectives on Fundamental Physics with Molecules *Nicholas HUTZLE*

12:00

https://ca01web.zoom.us/j/69998354433 (password: 972986) 11:40 - 12:10

Discussion

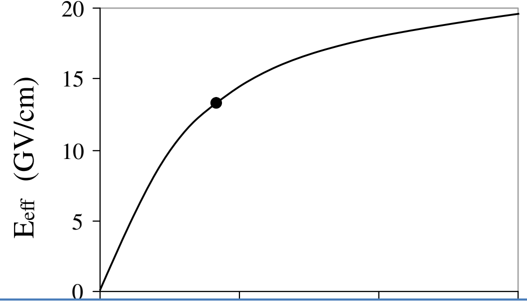
https://ca01web.zoom.us/j/69998354433 (password: 972986) 12:10 - 12:20

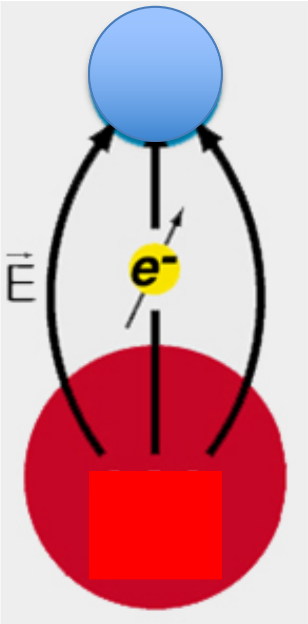
$$\sigma_d \approx \frac{1}{2E}\frac{\hbar}{\tau}\frac{1}{S/N}$$

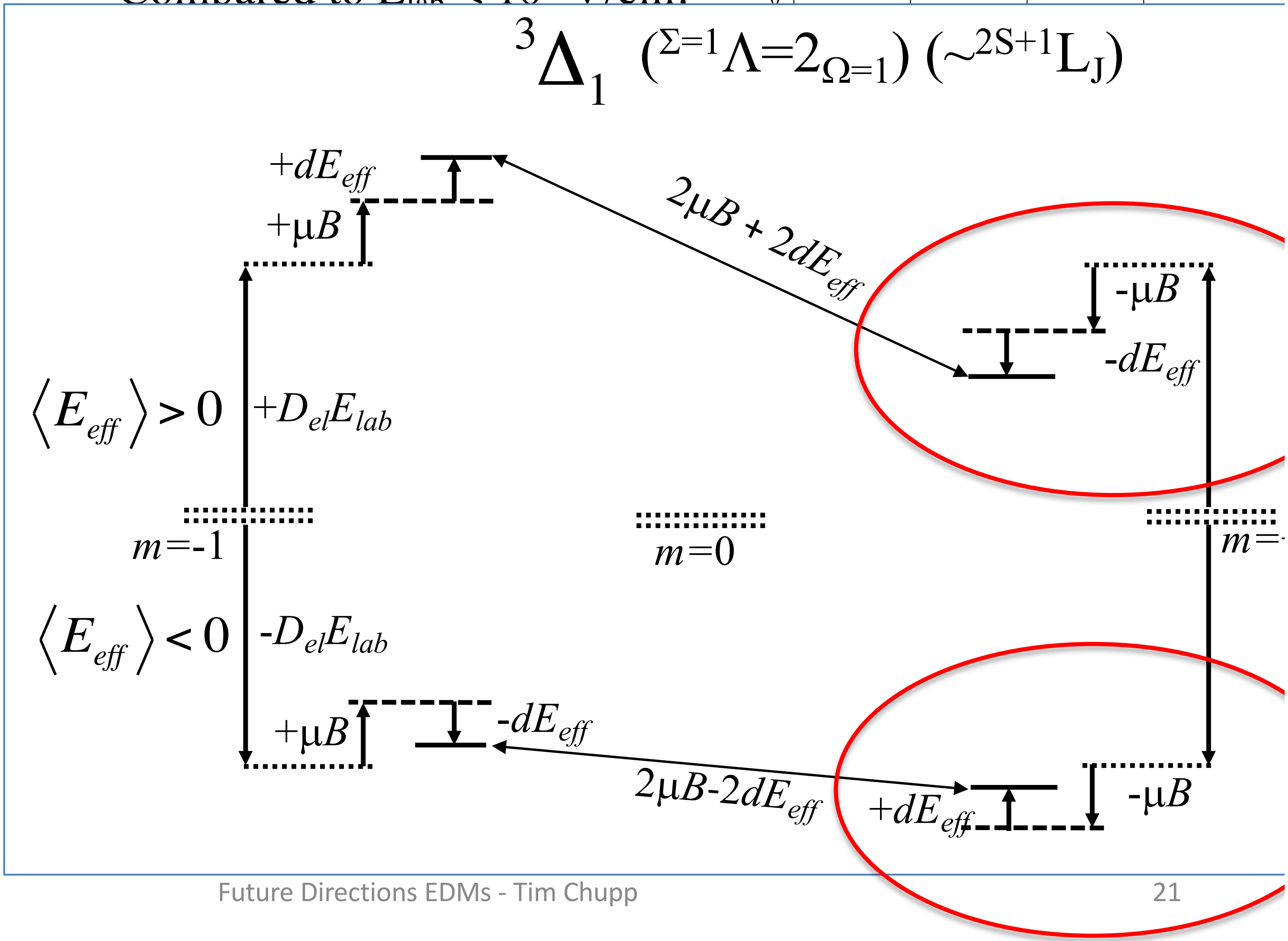
Paramagnetic Molecules

Large E, small τ

1. ***Large*** internal electric fields.
   1. $E_{eff} \sim 10^{11}$ V/cm.
   - Compared to $E_{lab} < 10^5$ V/cm.







$$\sigma_d \approx \frac{1}{2E}\frac{\hbar}{T_c}\frac{1}{S/N}$$

Order of Magnitude Smaller Limit on the Electric Dipole Moment of the Electron

The ACME Collaboration,* J. Baron,[1] W. C. Campbell,[2] D. DeMille,[3]† J. M. Doyle,[1]† G. Gabrielse,[1]† Y. V. Gurevich,[1]‡ P. W. Hess,[1] N. R. Hutzler,[1] E. Kirilov,[3]§ I. Kozyryev,[3]|| B. R. O'Leary,[3] C. D. Panda,[1] M. F. Parsons,[1] E. S. Petrik,[1] B. Spaun,[1] A. C. Vutha,[4] A. D. West[3]

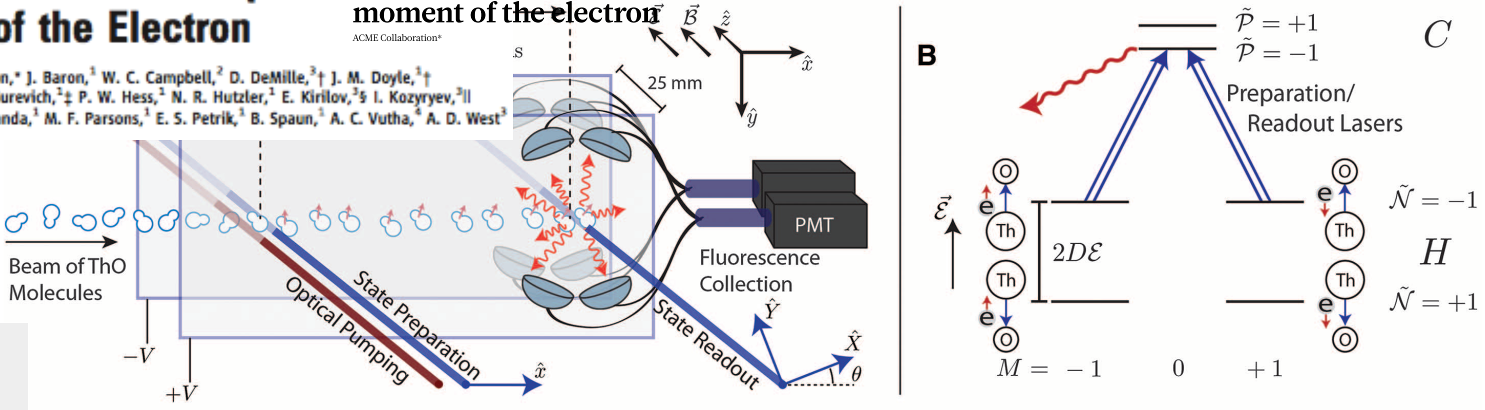
ARTICLE

https://doi.org/10.1038/s41586-018-0599-8

Improved limit on the electric dipole moment of the electron

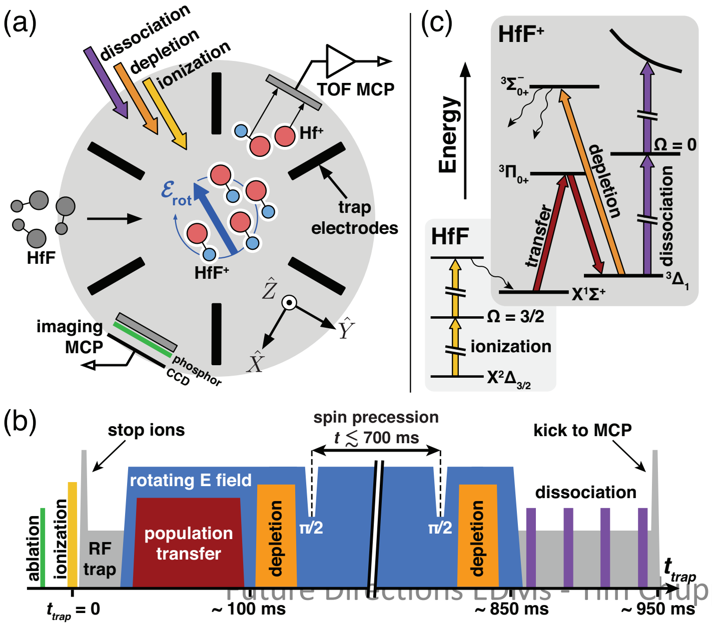
ACME Collaboration*

Atomic clocks for fundamental physics *Dr. Jun YE*



A precision measurement of the electron's electric dipole moment using trapped molecular ions

William B. Cairncross,* Daniel N. Gresh, Matt Grau,† Kevin C. Cossel,‡
Tanya S. Roussy, Yiqi Ni,§ Yan Zhou, Jun Ye, and Eric A. Cornell



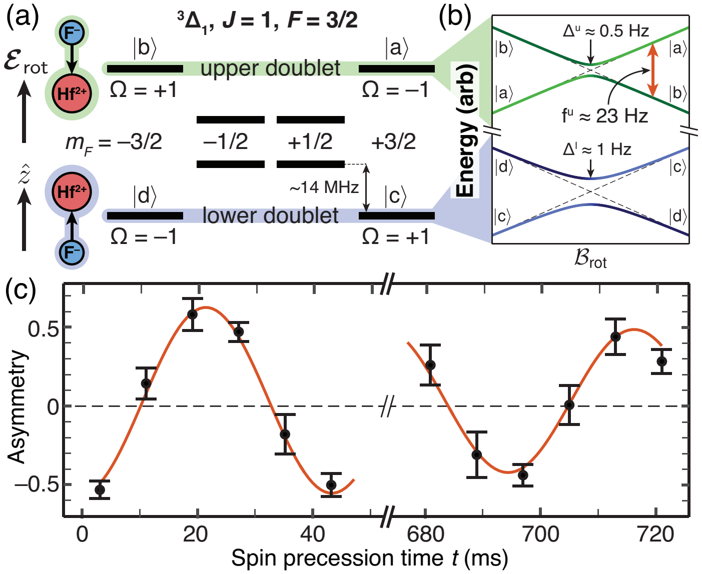


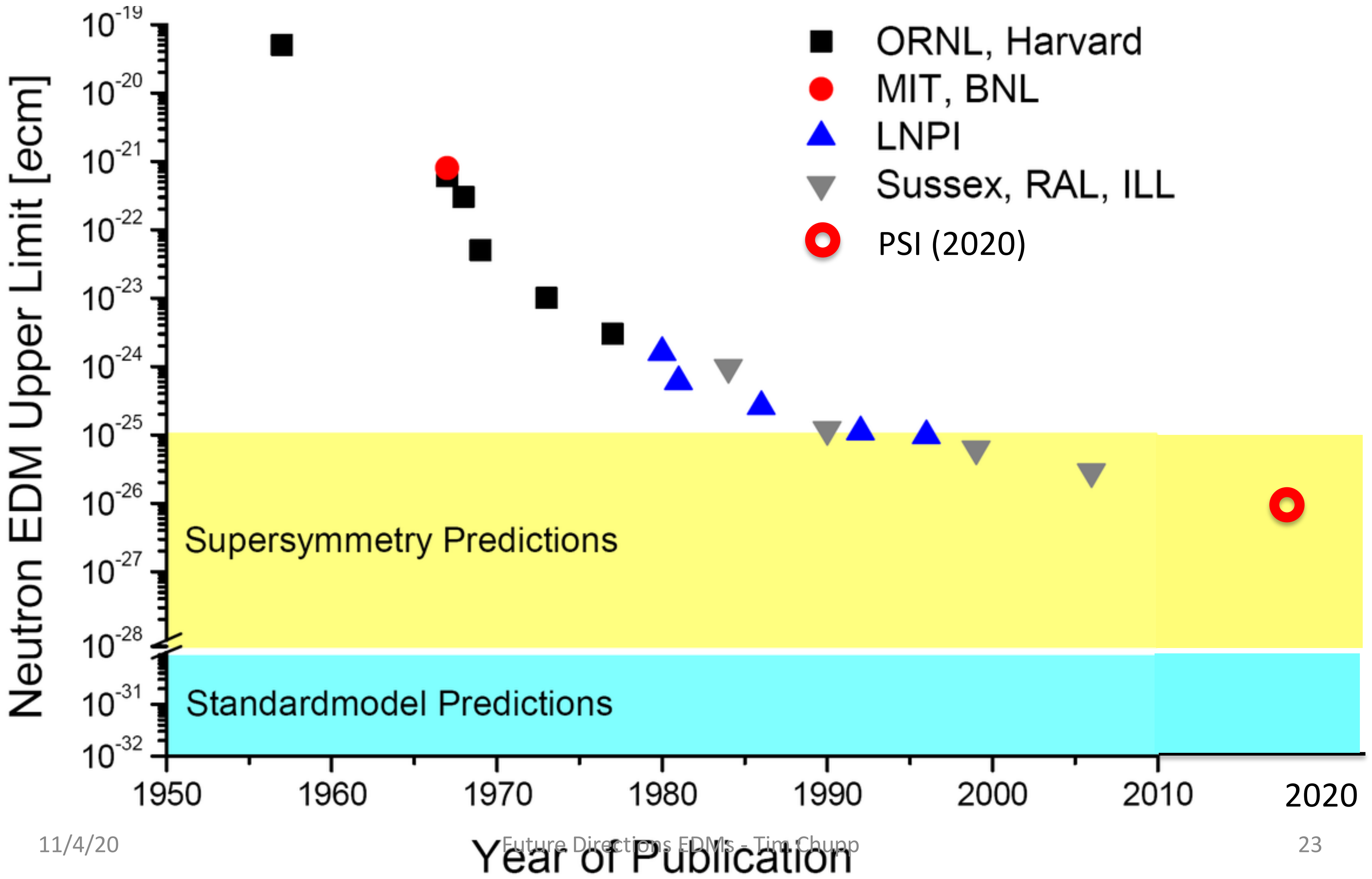
FIG. 2. Electron spin resonance spectroscopy in HfF⁺. (a)

Neutron electric dipole moment

From Wikipedia, the free encyclopedia

"NEDM" redirects here. For the Sussex experiment, see Sussex/RAL/ILL neutron EDM experiment.

The **neutron electric dipole moment (nEDM)** is a measure for the distribution of positive and negative charge inside the neutron. A finite electric dipole moment can only exist if the centers of the negative and positive charge distribution inside the particle do not coincide. So far, no neutron EDM has been found. The current best upper limit amounts to $|d_n| < 2.9 \times 10^{-26} e{\cdot}\text{cm}$.[1]



$$\sigma_d \approx \frac{1}{2E}\frac{\hbar}{\tau}\frac{1}{S/N}$$

Ultra-Cold Neutrons (UCN)

SLOW (<8 m/s), “long” wavelength (50 nm) Ns with OPTICAL PROPERTIES

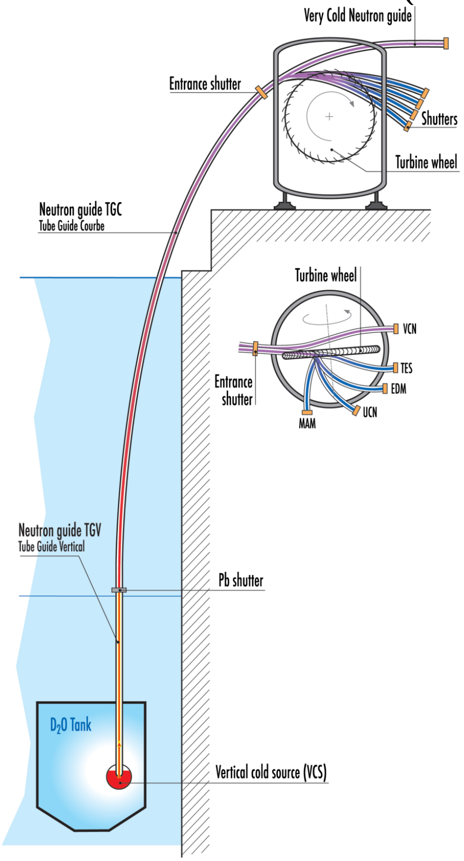
Neutrons properties:

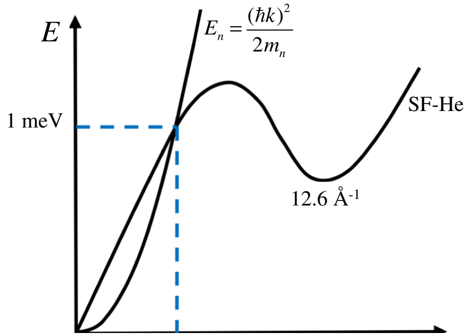
Charge: 0

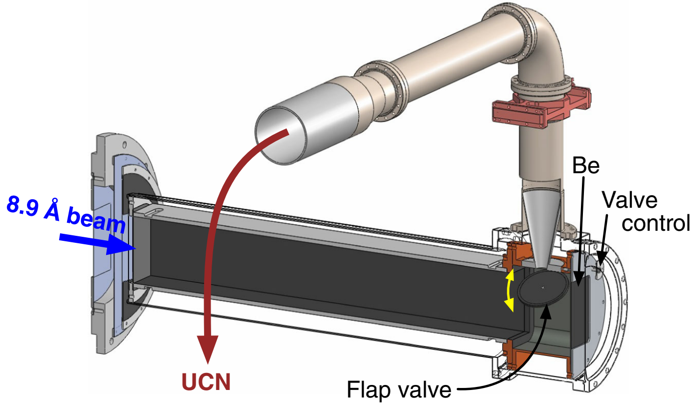
Weight (m=1.67x10^{-27} kg): g=(3.1 m/s)^2/m

Magnetic moment: μ= (3.4 m/s)^2/T

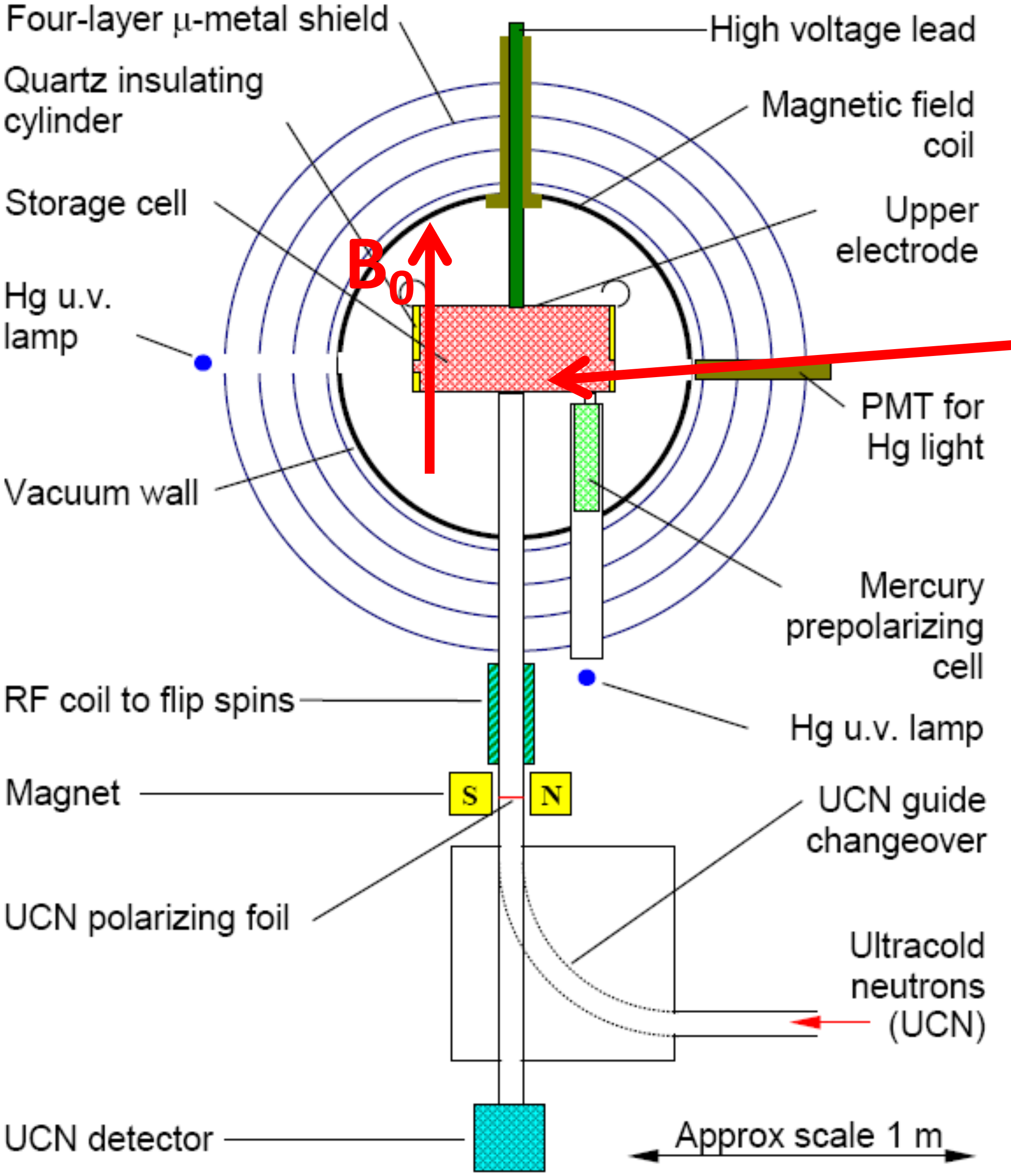
Interactions: Weak (decay) Strong (reflecton/absorption/depolarization)

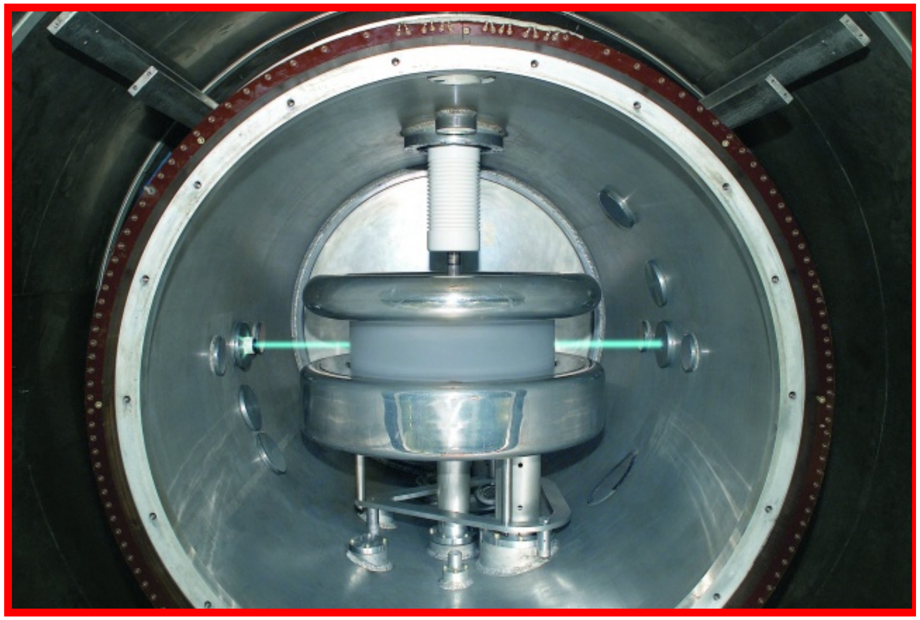




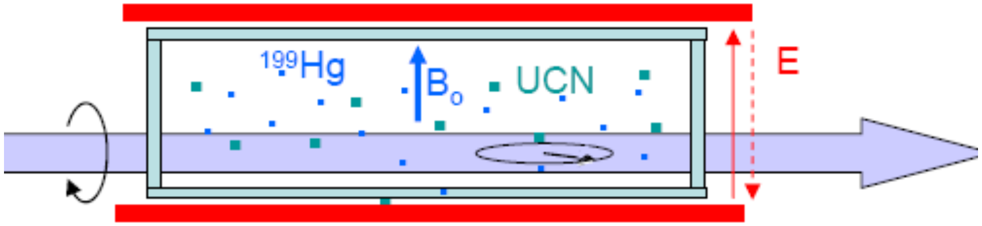


RAL-Sussex-ILL n-EDM



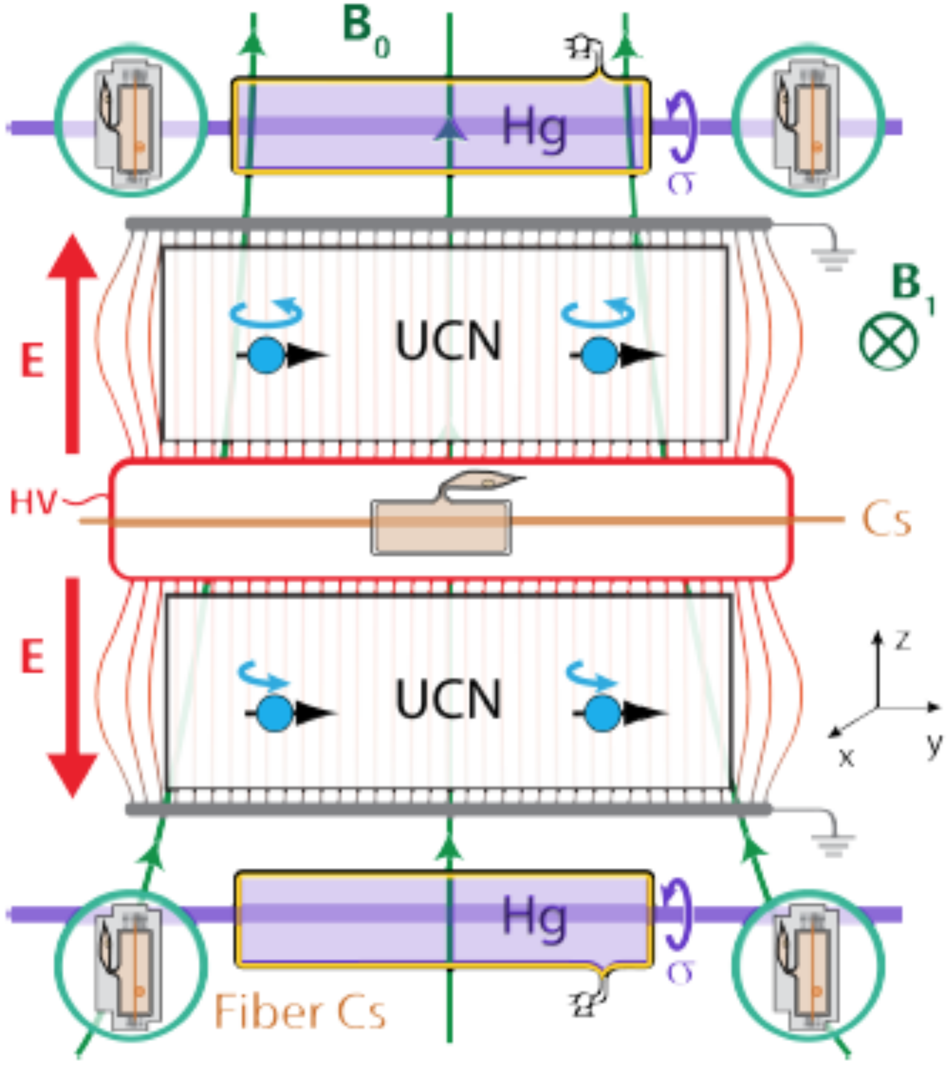


^{199}Hg comagnetometer



$d_n < 2.2 \times 10^{-26}$ e cm

Putting it all together: panEDM



Next Generation nEDM Experiments

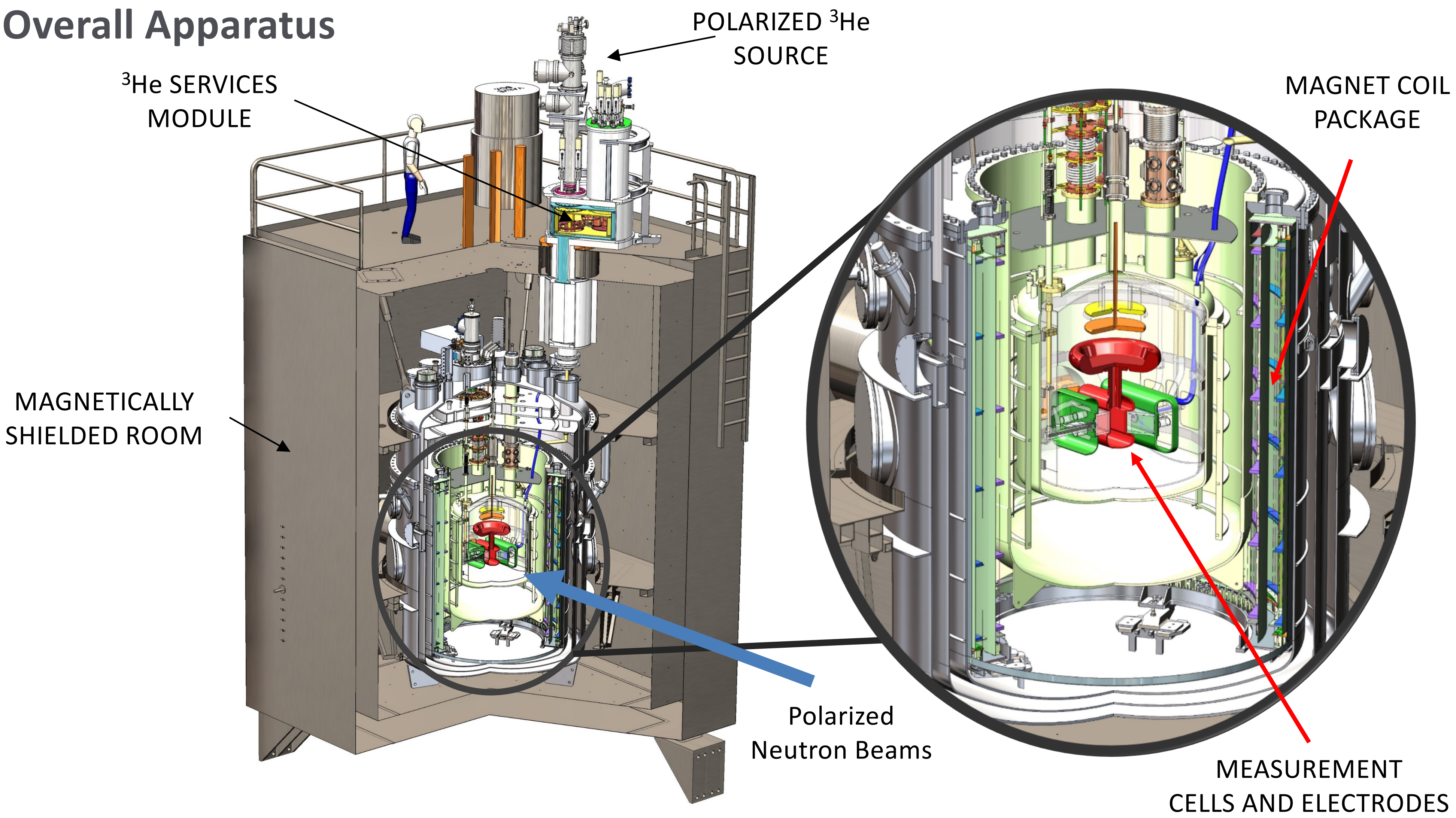
$$\sigma_d \approx \frac{1}{2E}\frac{\hbar}{\tau}\frac{1}{S/N}$$

Cryogenic UCN source, room temperature storage cells

- PSI
- ILL – panEDM (Munich/ILL)
- PNPI Petersburg
- TRIUMF TUCAN
- US SNS
- **LANL nEDM**

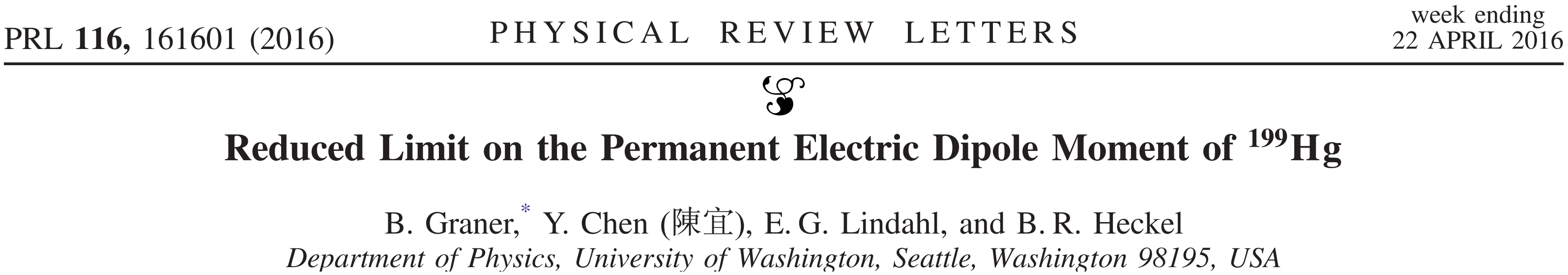
Projected: 10-100x improvement (10^{-28} e-cm)

Stolen from Brad Filippone



$$\sigma_d \approx \frac{1}{2E}\frac{\hbar}{\tau}\frac{1}{S/N}$$

^{199}Hg and ^{129}Xe

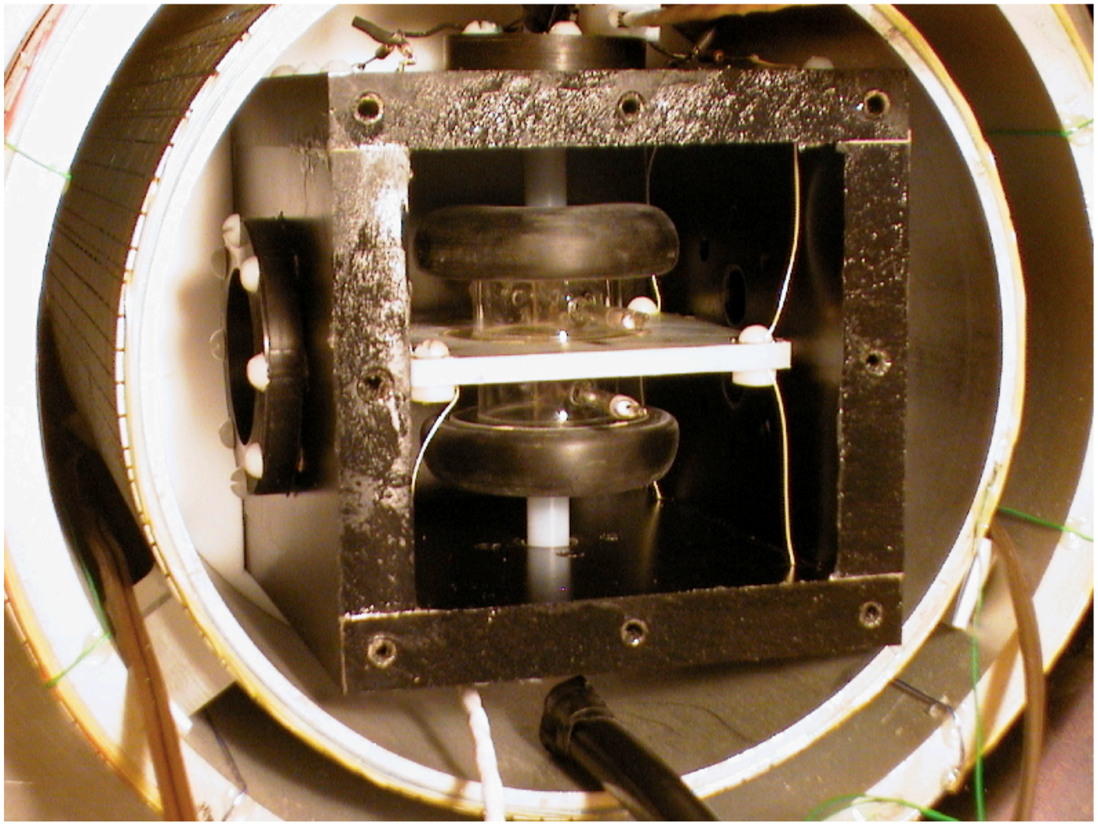


PRL **116,** 161601 (2016) PHYSICAL REVIEW LETTERS week ending 22 APRIL 2016

Reduced Limit on the Permanent Electric Dipole Moment of ^{199}Hg

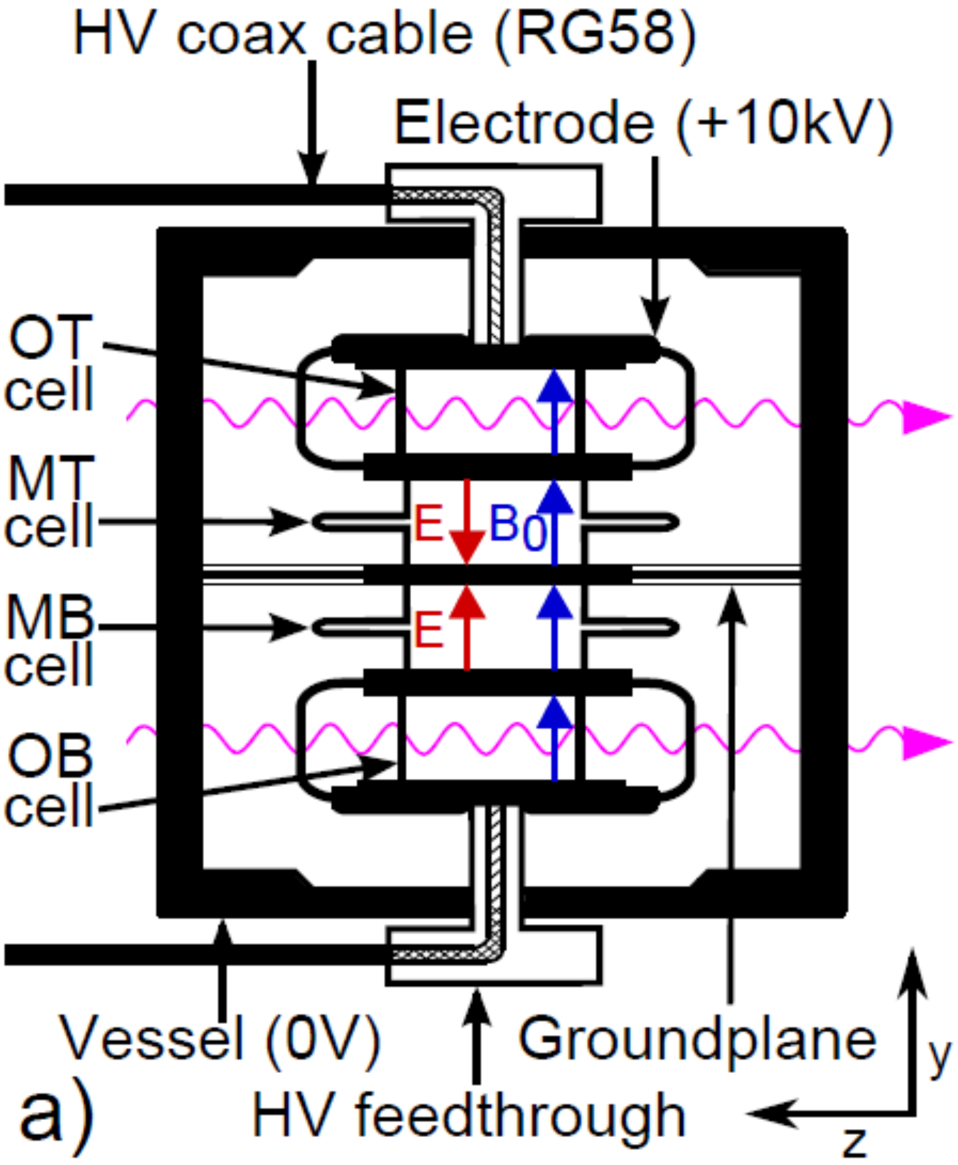
B. Graner,* Y. Chen (陳宜), E. G. Lindahl, and B. R. Heckel

Department of Physics, University of Washington, Seattle, Washington 98195, USA



$$d_{\mathrm{Hg}} = (-2.20 \pm 2.75_{\mathrm{stat}} \pm 1.48_{\mathrm{syst}}) \times 10^{-30}\, e\ \mathrm{cm}.$$

Measurement Technique



- •Atoms are contained in a stack of 4 vapor cells in a common B field
- •2 conducting plastic electrodes at the same potential hold the 2 outer cells
- •Opposite E field causes an EDM to shift the relative frequency of the 2 inner cells
- .^{199}Hg is pumped to align spins with laser beams
- .Precession is observed by detecting Faraday rotation of weak, linear polarized light

^{129}Xe EDM with ^{3}He <u>Comagnetometry</u>

HeXe

PHYSICAL REVIEW LETTERS **123,** 143003 (2019)

N. Sachdeva,[1,*] I. Fan,[2] E. Babcock,[3] M. Burghoff,[2] T. E. Chupp,[1] S. Degenkolb,[1,4] P. Fierlinger,[5] E. Kraegeloh,[5,1] W. Kilian,[2] S. Knappe-Grüneberg,[2] F. Kuchler,[5,6] T. Liu,[2] M. Marino,[5] J. Meinel,[5] Z. Salhi,[3] A. Schnabel,[2] J. T. Singh,[7] S. Stuiber,[5] W. A. Terrano,[5] L. Trahms,[2] and J. Voigt[2]

[1] *Department of Physics, University of Michigan, Ann Arbor, Michigan 48109, USA*
[2] *Physikalisch-Technische Bundesanstalt (PTB) Berlin, 10587 Berlin, Germany*
[3] *Jülich Center for Neutron Science, 85748 Garching, Germany*
[4] *Institut Laue-Langevin, 38042 Grenoble, France*
[5] *Excellence Cluster Universe and Technische Universität München, 85748 Garching, Germany*
[6] *TRIUMF, Vancouver, British Columbia V6T 2A3, Canada*
[7] *National Superconducting Cyclotron Laboratory and Department of Physics & Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*

$$d_A(^{129}\mathrm{Xe}) = (1.4 \pm 6.6_{\mathrm{stat}} \pm 2.0_{\mathrm{syst}}) \times 10^{-28}\ e\,\mathrm{cm}$$

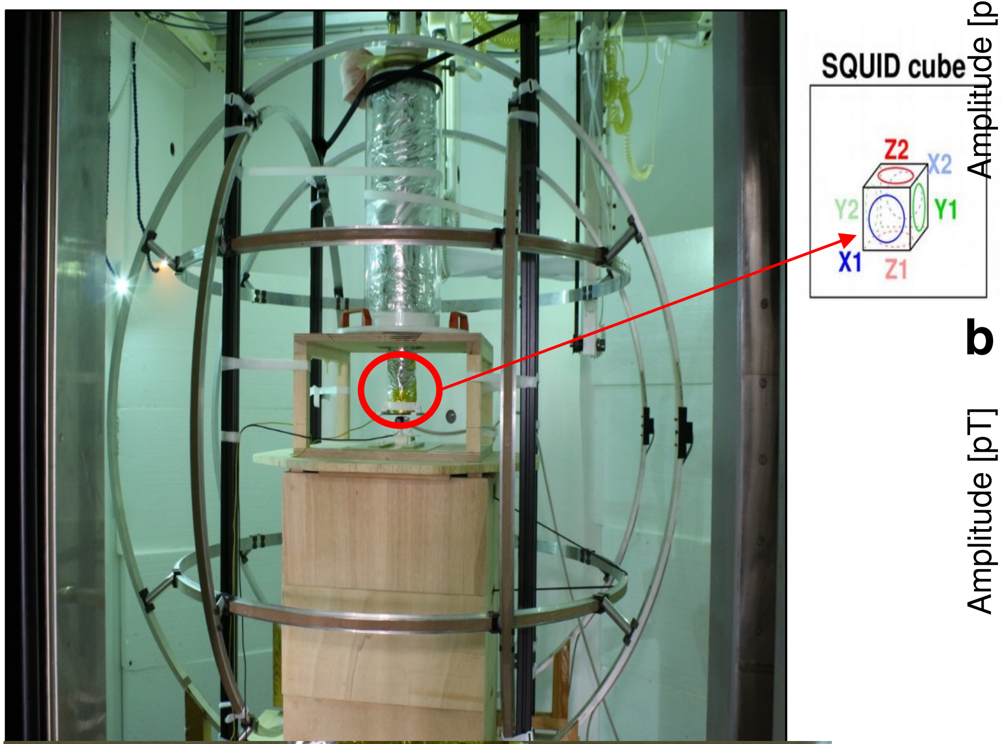
$$|d_A(^{129}\mathrm{Xe})| < 1.4 \times 10^{-27}\ e\,\mathrm{cm}\ (95\%\ \mathrm{C.L.}),$$

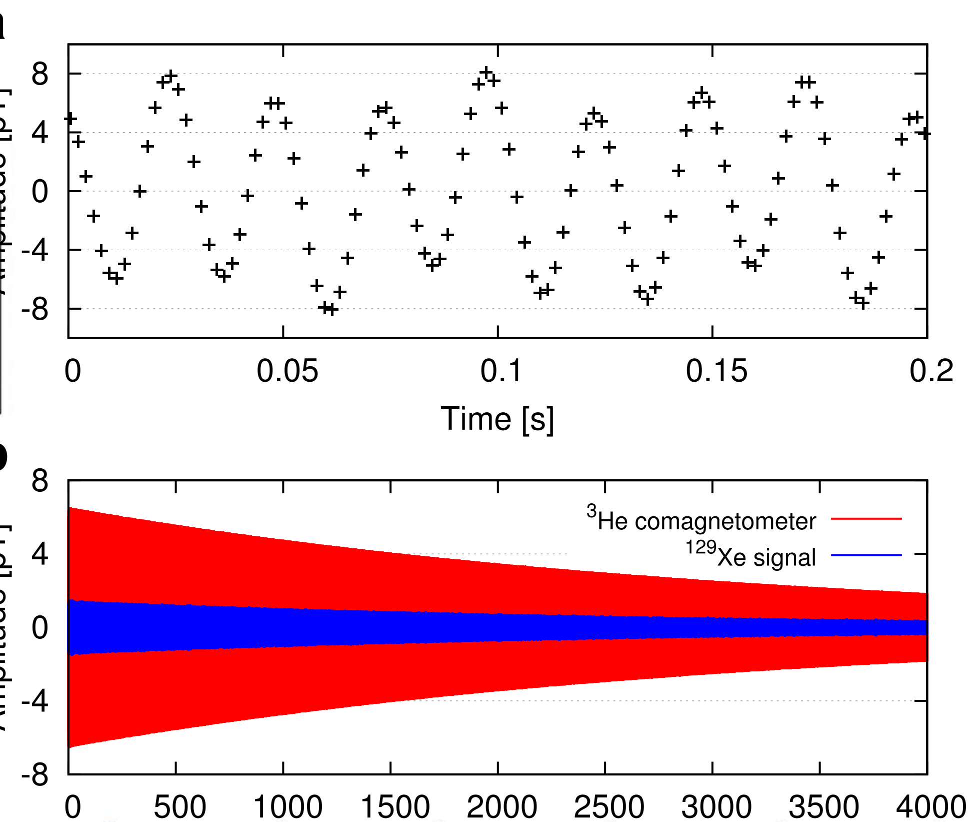
Other recent work

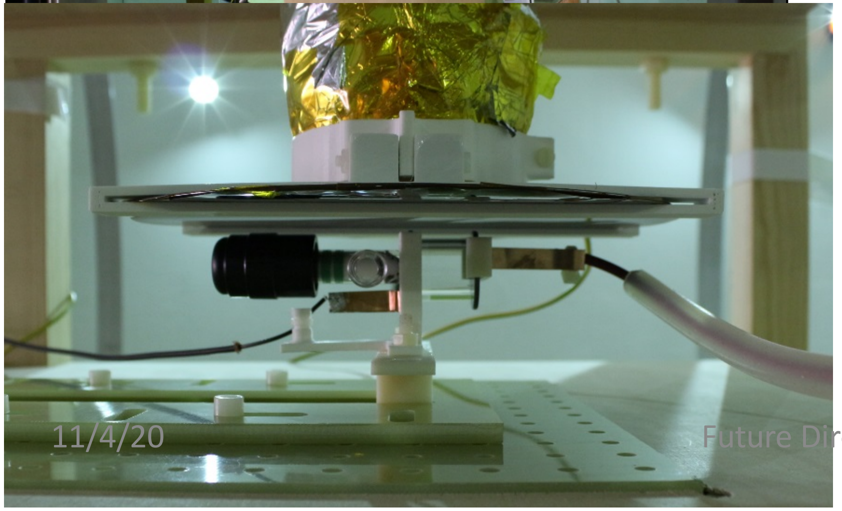
PRA **100**, 022505 (2019) - MIXed

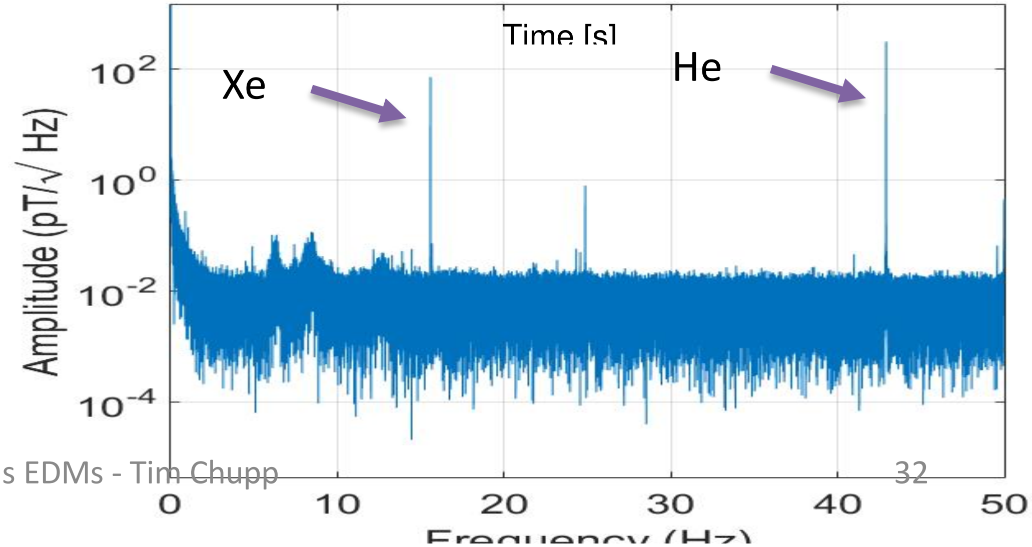
arXiv 2008.07975

SQUID Detection







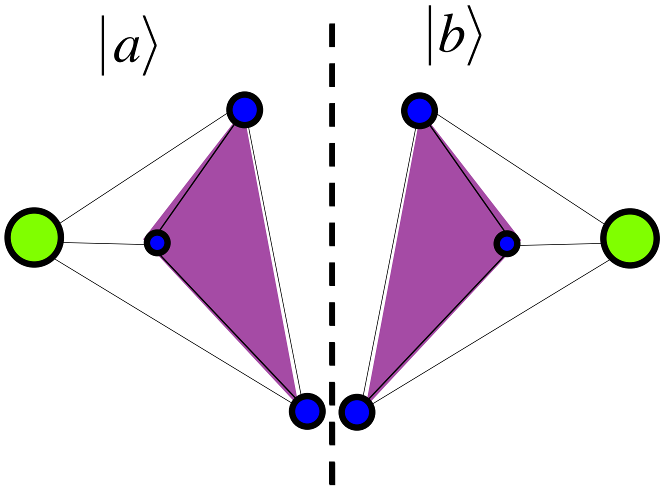


Octupole Enhancemed Schiff Moment

Intrinsic (body-frame) moment

Polarizabitliy

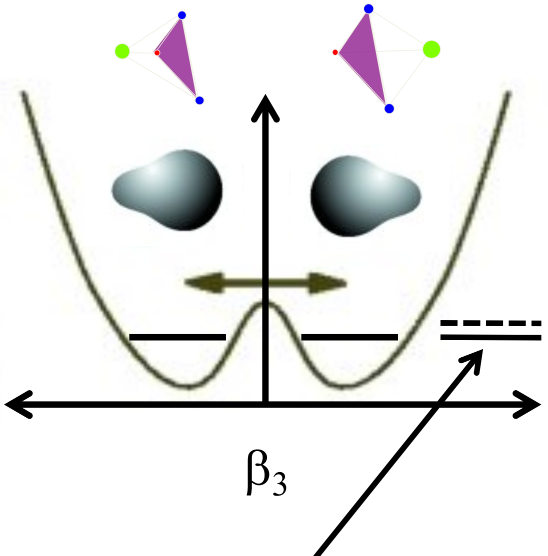
NH$_3$ (see Feynman vol 3.)



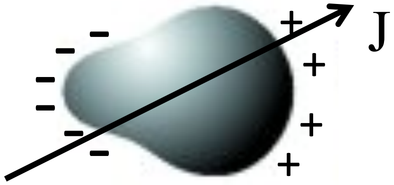
Reflection Symmetry

$$|\psi_+\rangle = \frac{1}{\sqrt{2}}\left(|a\rangle + |b\rangle\right)$$

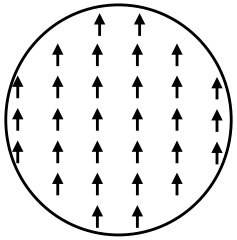
$$|\psi_-\rangle = \frac{1}{\sqrt{2}}\left(|a\rangle - |b\rangle\right)$$



Small splitting (tunnel frequency)
Large electric polarizability



$$\vec{S} = \frac{1}{10}\left\langle r^2 \vec{r}_p \right\rangle - \frac{1}{6} Z \left\langle r^2 \right\rangle \left\langle \vec{r}_p \right\rangle$$



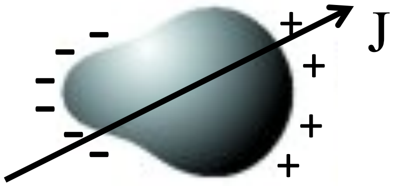
$\vec{E} \propto \vec{J}$

$$S \propto \frac{\left\langle + \middle| \eta r^2 \cos\theta \middle| - \right\rangle}{E_+ - E_-} \approx \frac{\eta \beta_2 \beta_3^2 A^{2/3} r_0^3}{E_+ - E_-}$$

Nuclei with Octupole Deformation/Vibration

(Haxton & Henley; Auerbach, Flambaum, Spevak; Engel et al., Hayes & Friar, etc.)

$$S \propto \frac{\langle + | \eta r^2 \cos\theta | - \rangle}{E_+ - E_-} \approx \frac{\eta \beta_2 \beta_3^2 A^{2/3} r_0^3}{E_+ - E_-}$$



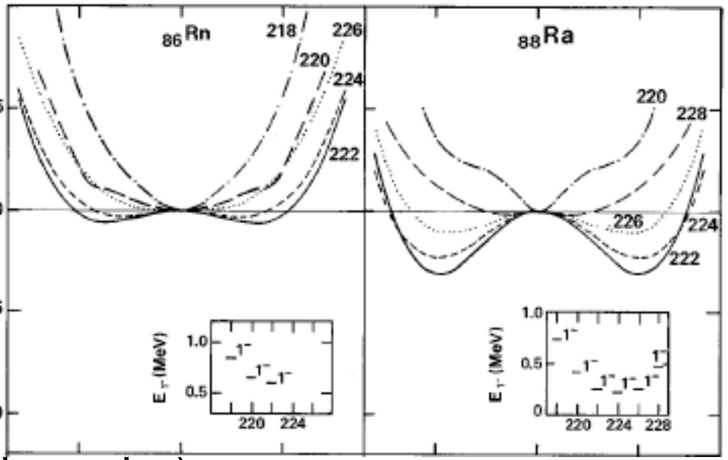
	^{223}Rn	^{223}Ra	^{225}Ra	^{223}Fr	^{129}Xe	^{199}Hg
$t_{1/2}$	23.2 m	11.4 d	14.9 d	22 m		
I	7/2	3/2	1/2	3/2	1/2	1/2
ΔE th (keV)	37*	170	47	75		
ΔE exp (keV)	-	50.2	55.2	160.5		
$10^{11} S$ (e-fm^3)	375	150	115	185	0.6	-0.75
$10^{28} d_A$ (e-cm)	1250	1250	940	1050	0.3	2.1

$\eta_{qq} = 3.75 \times 10^{-4}$

Ref: Dzuba PRA66, 012111 (2002) - Uncertainties of 50%

*Based on Woods-Saxon Potential

† Nilsson Potential Prediction is 137 keV



NOTES:
Ocutpole Enhancements
Engel et al. agree with Flambaum et al.
Even octupole vibrations enhance S (Engel, Flambaum& Zelevinsky)

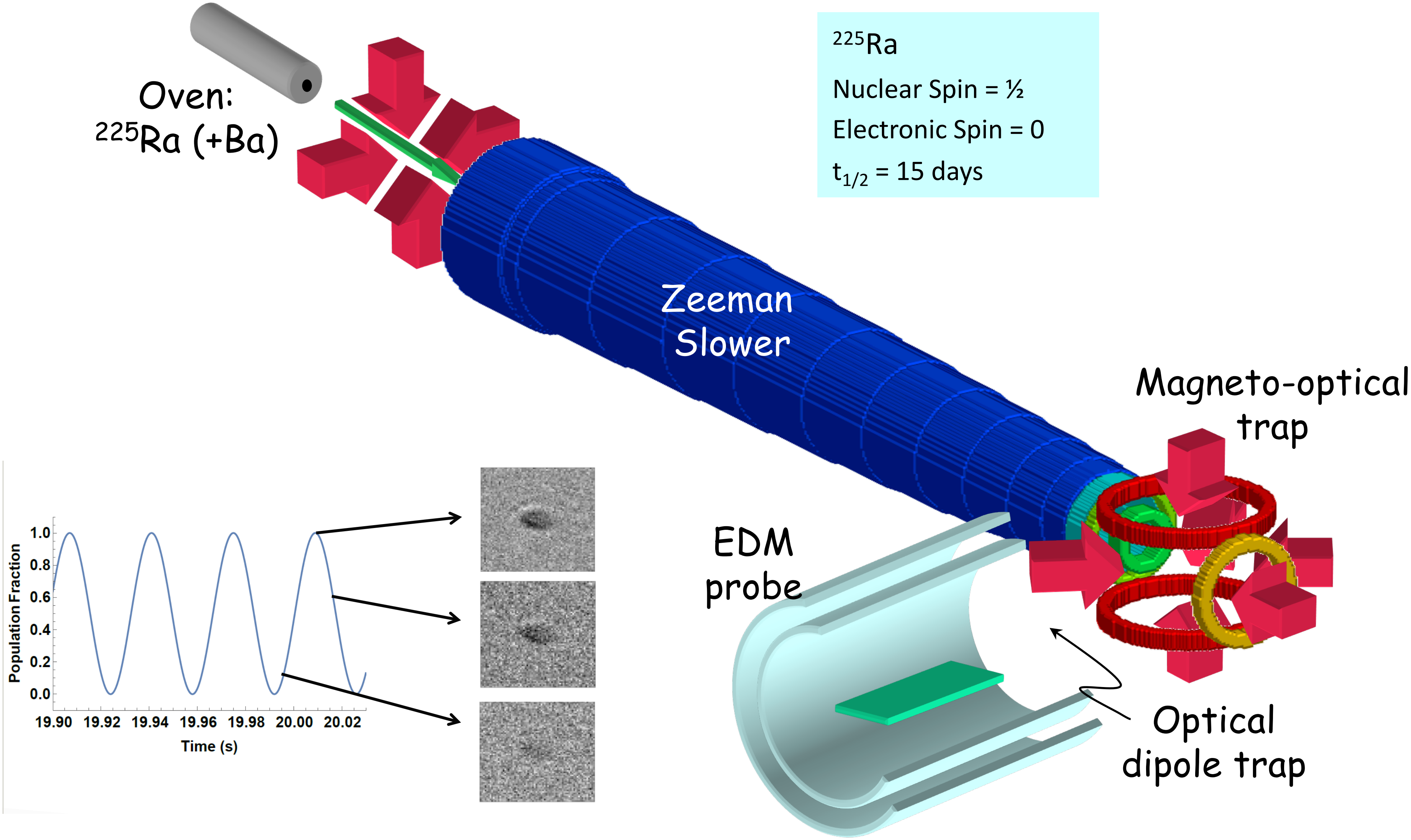
Search for EDM of ^{225}Ra at Argonne
(Thanks Matt Dietrich)

^{225}Ra

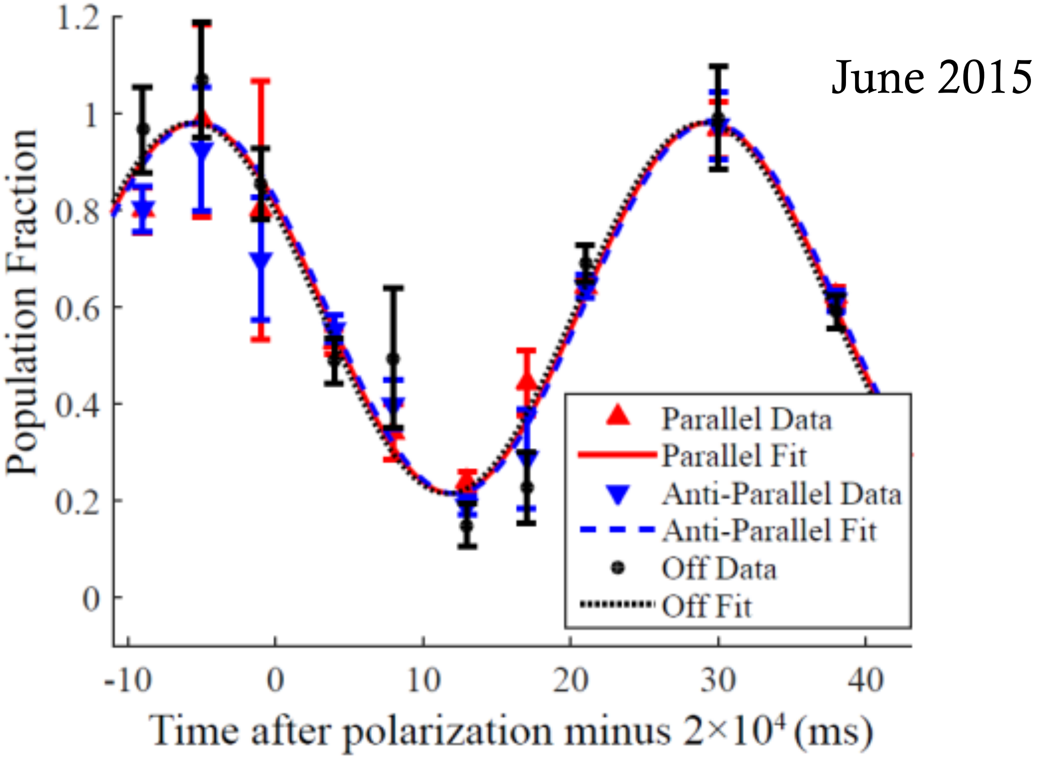
Nuclear Spin = ½

Electronic Spin = 0

$t_{1/2}$ = 15 days



Second Ra-225 EDM Measurements



$d_{Ra\text{-}225} < 1.4 \times 10^{-23}$ e-cm 95% C.L.

36-fold improvement in 6 months

Hoping for 10^{-26} e-cm and smaller.

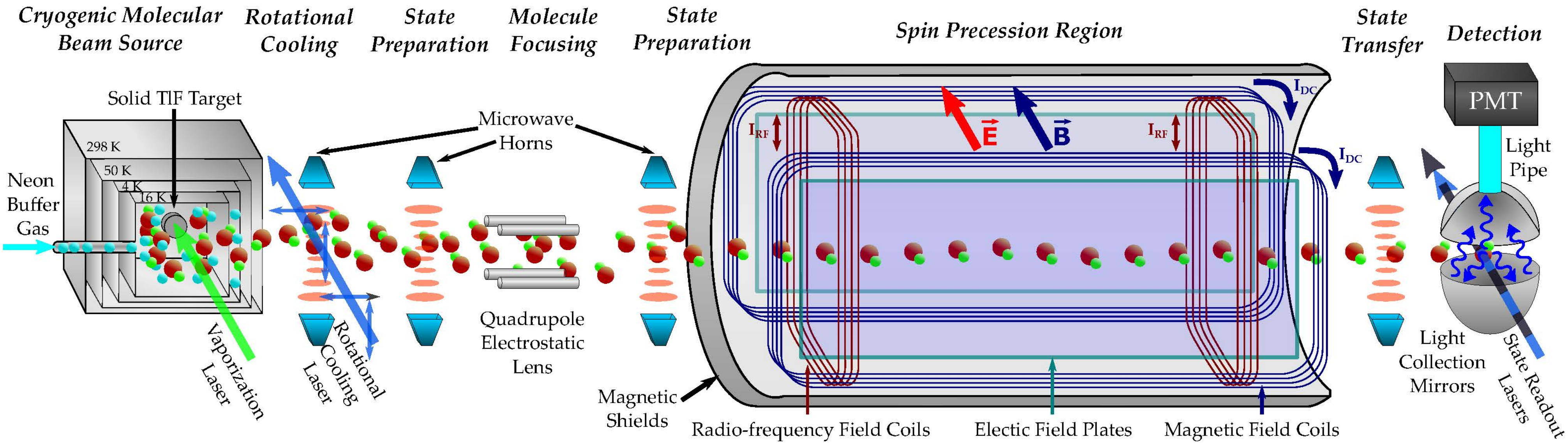
225Ra production may use FRIB etc. (harvesting)

*Cold molecule **Nuclear** Time-Reversal Experiment (CeNTREX)*

(D. DeMille[Chicago+Argonne], T. Zelevinsky [Columbia], D. Kawall [UMass], S. Lamoreaux [Yale])

Incorporates many methods from ACME + new techniques

(slow molecular beam, rotational cooling + cycling fluorescence for detection, etc.)



1st generation design & construction well underway

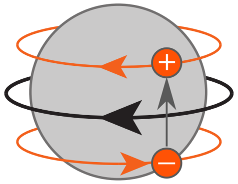
Future generations of CeNTREX could incorporate

--transverse laser cooling for increased flux

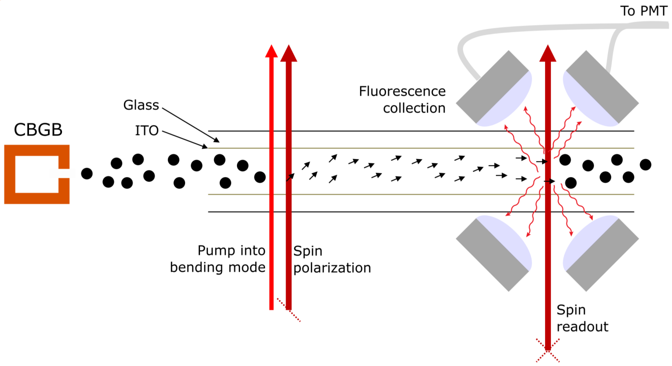
--laser slowing and/or trapping for increased interaction time?

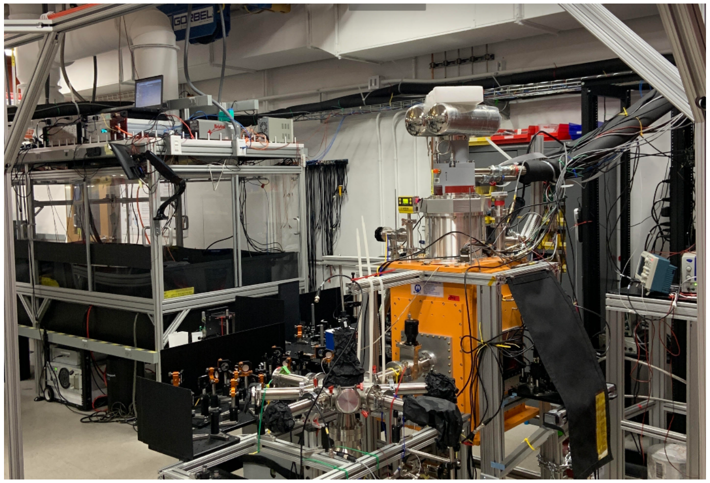
Project 20x improvement on proton EDM (10^{-27} e-cm), 10-100 on θ_{QCD}

^{173}YbOH NMQM Experiment @ Caltech



- Building a NMQM search in ^{173}YbOH at Caltech
  - ^{173}Yb (I=5/2), large quadrupole deformation ($\beta_2 \approx 0.3$)
  - Cryogenic buffer gas beam experiment
  - Laser cooling, trapping in future generations?



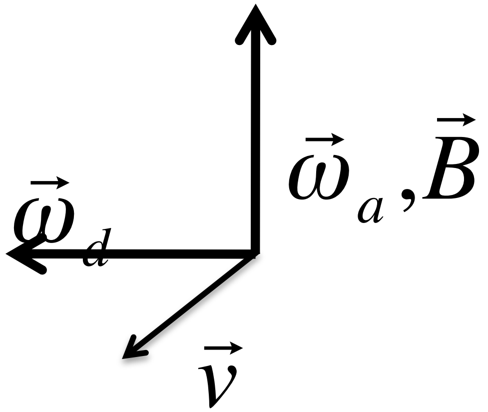


V. V. Flambaum, D. DeMille, and M. G. Kozlov, PRL 113, 103003 (2014)
I. Kozyryev and NRH, PRL 119, 133002 (2017)
D. E. Maison, L. V. Skripnikov, and V. V. Flambaum, PRA 100, 032514 (2019)
M. Denis, Y. Hao, E. Eliav, NRH, M. K. Nayak, R. G. E. Timmermans, A. Borschesvky, J. Chem. Phys. 152, 084303 (2020)

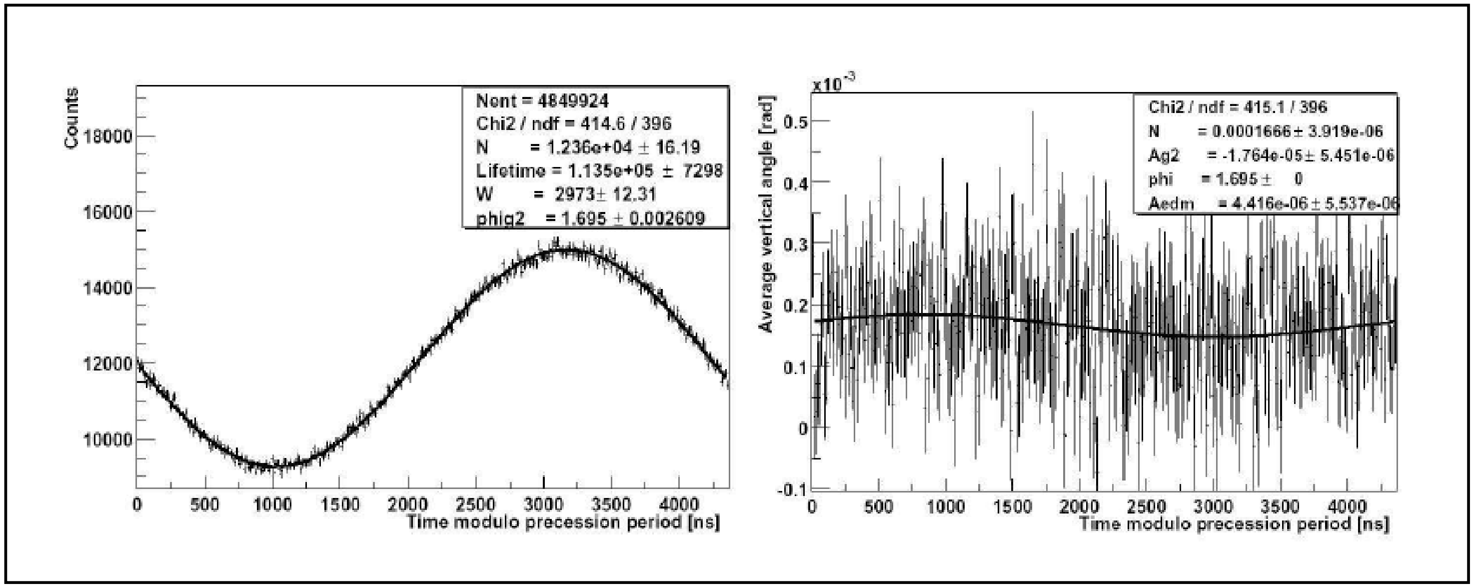
Storage-ring EDMs (e.g. muon)

g-2: $$\vec{\omega}_a = -\frac{q}{m} a_\mu \vec{B}$$

$$\vec{\omega}_d = -\frac{q}{2m} d_\mu \left(\frac{\vec{v}}{c} \times \vec{B} + \vec{E} \right)$$

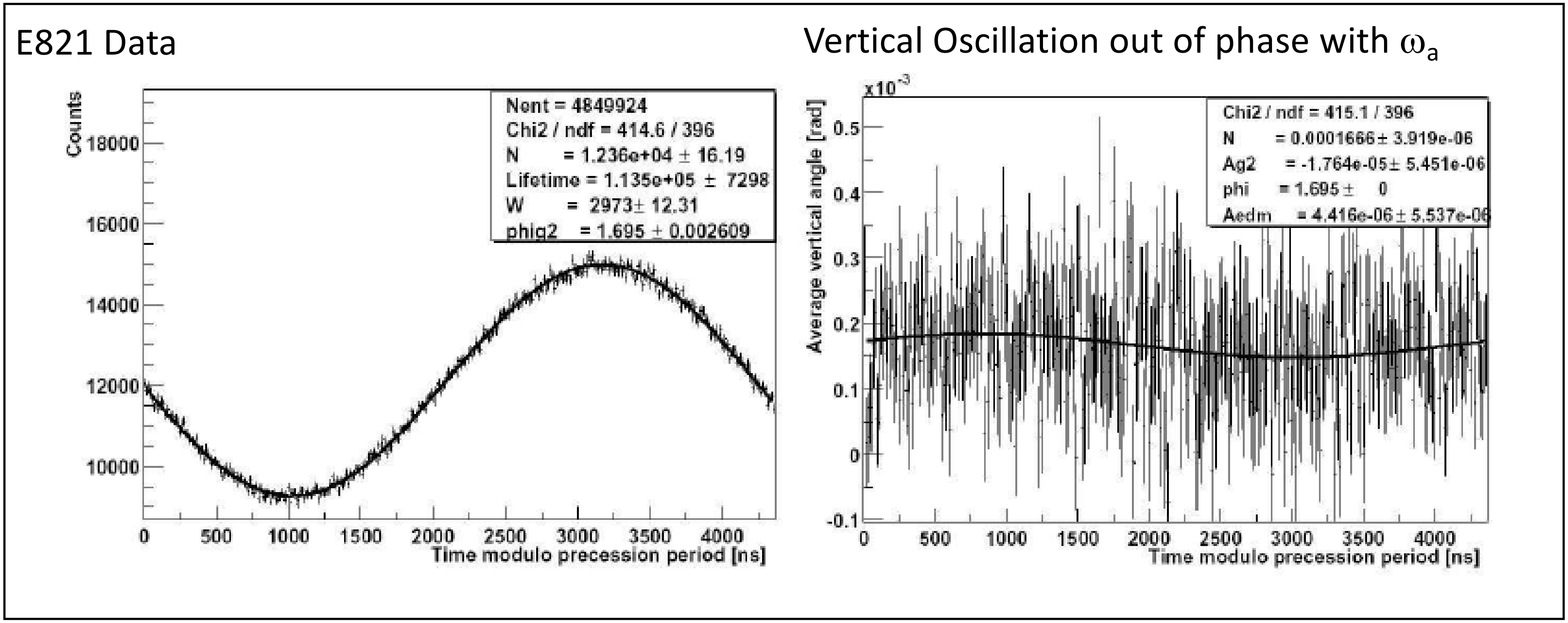


EDM Signal: out-of-plane oscillation out of phase with ω_a



EDM Signal: out-of-plane oscillation out of phase with ω_a

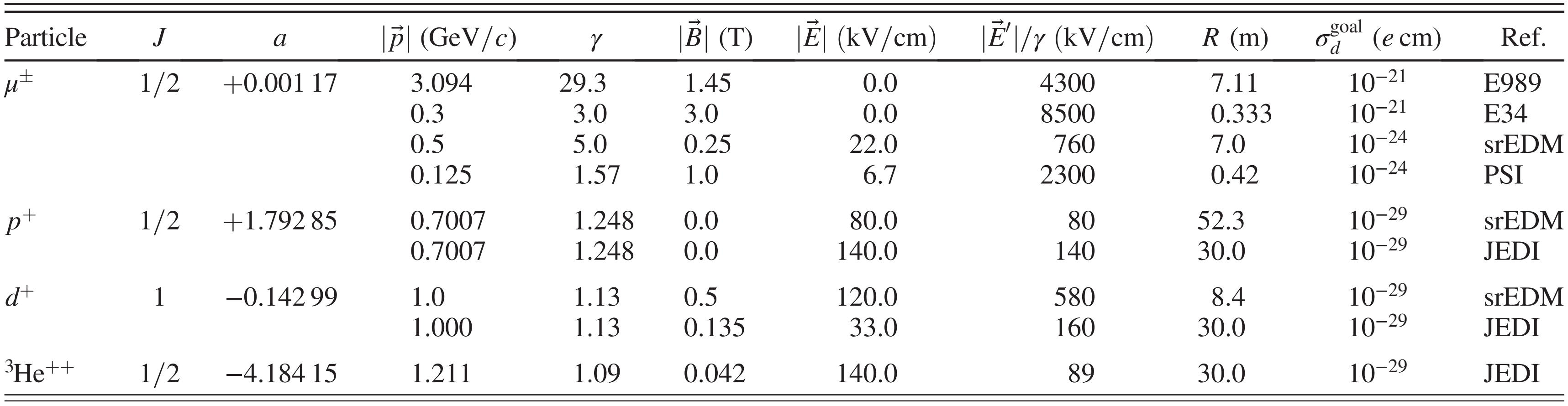
(g-2) EDM



$$E821: d_\mu = (0.9 \pm 1.9) \times 10^{-19} \text{ e-cm}$$

Improve by 100x (potential large effort for p,d,^{3}He - Cosy, BNL, FNAL)

Storage ring EDMs
Fermilab, Jparc, BNL, COSY



Particle	J	a	$\lvert\vec{p}\rvert$ (GeV/c)	γ	$\lvert\vec{B}\rvert$ (T)	$\lvert\vec{E}\rvert$ (kV/cm)	$\lvert\vec{E}'\rvert/\gamma$ (kV/cm)	R (m)	σ_d^{goal} (e cm)	Ref.
$\mu^{\pm}$	1/2	+0.001 17	3.094	29.3	1.45	0.0	4300	7.11	10^{-21}	E989
			0.3	3.0	3.0	0.0	8500	0.333	10^{-21}	E34
			0.5	5.0	0.25	22.0	760	7.0	10^{-24}	srEDM
			0.125	1.57	1.0	6.7	2300	0.42	10^{-24}	PSI
p^{+}	1/2	+1.792 85	0.7007	1.248	0.0	80.0	80	52.3	10^{-29}	srEDM
			0.7007	1.248	0.0	140.0	140	30.0	10^{-29}	JEDI
d^{+}	1	−0.142 99	1.0	1.13	0.5	120.0	580	8.4	10^{-29}	srEDM
			1.000	1.13	0.135	33.0	160	30.0	10^{-29}	JEDI
$^3\mathrm{He}^{++}$	1/2	−4.184 15	1.211	1.09	0.042	140.0	89	30.0	10^{-29}	JEDI

EDM results

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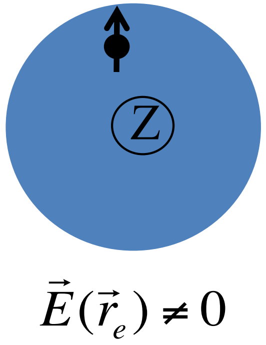
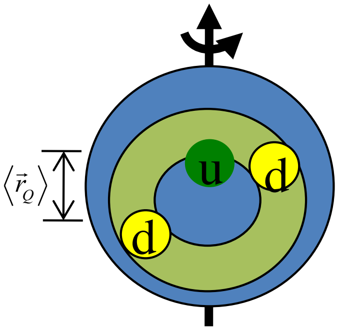
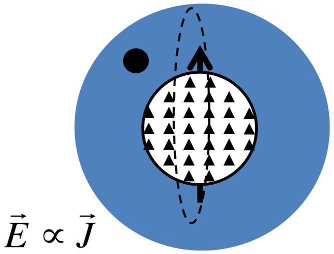
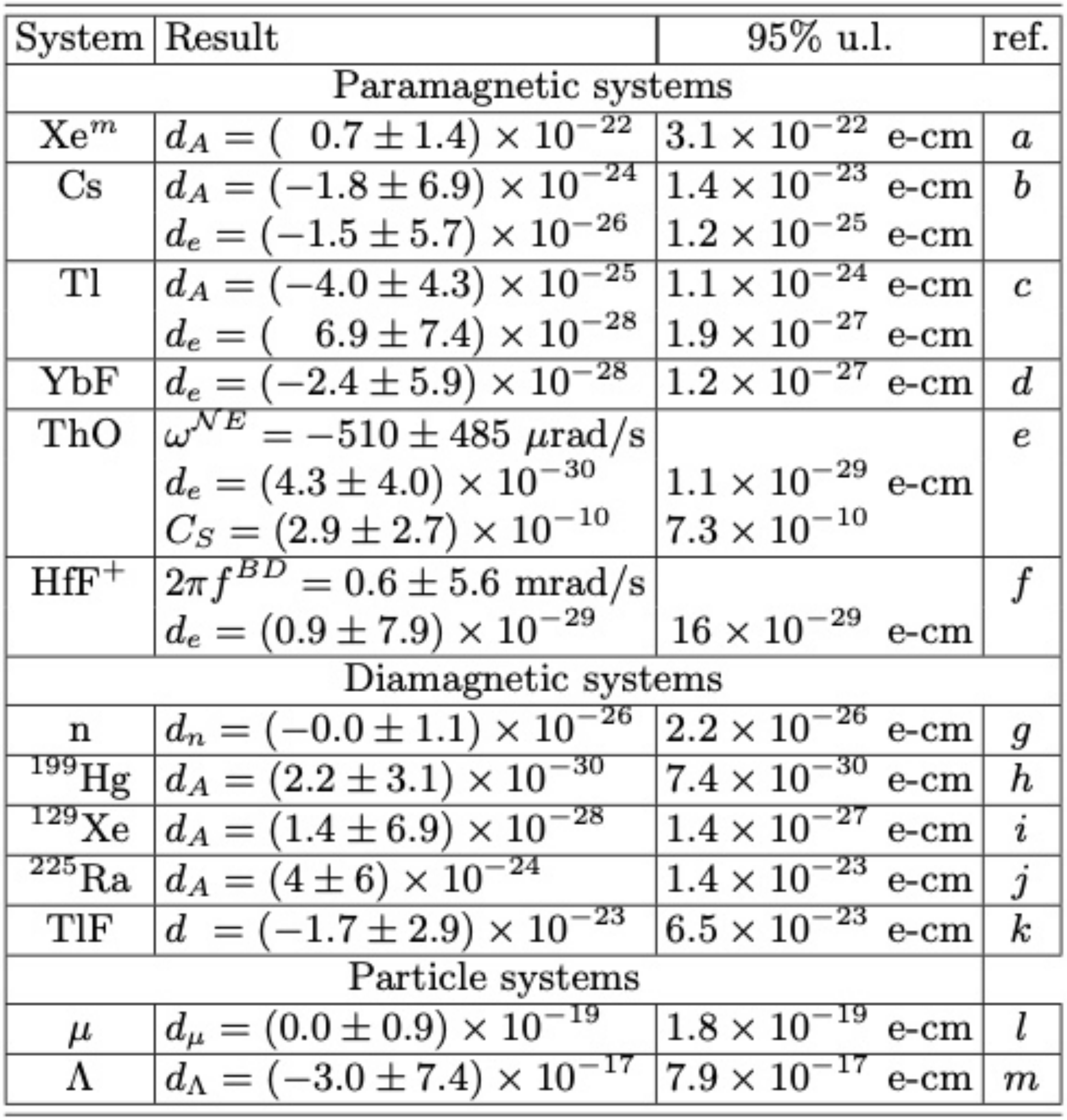


$\vec{E}(\vec{r}_e) \neq 0$





$\vec{E} \propto \vec{J}$



System	Result	95% u.l.	ref.
	Paramagnetic systems		
Xe^m	$d_A = (\ \ 0.7 \pm 1.4) \times 10^{-22}$	3.1×10^{-22} e-cm	a
Cs	$d_A = (-1.8 \pm 6.9) \times 10^{-24}$	1.4×10^{-23} e-cm	b
	$d_e = (-1.5 \pm 5.7) \times 10^{-26}$	1.2×10^{-25} e-cm	
Tl	$d_A = (-4.0 \pm 4.3) \times 10^{-25}$	1.1×10^{-24} e-cm	c
	$d_e = (\ \ 6.9 \pm 7.4) \times 10^{-28}$	1.9×10^{-27} e-cm	
YbF	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$	1.2×10^{-27} e-cm	d
ThO	$\omega^{NE} = -510 \pm 485\ \mu\text{rad/s}$		e
	$d_e = (4.3 \pm 4.0) \times 10^{-30}$	1.1×10^{-29} e-cm	
	$C_S = (2.9 \pm 2.7) \times 10^{-10}$	7.3×10^{-10}	
HfF^+	$2\pi f^{BD} = 0.6 \pm 5.6$ mrad/s		f
	$d_e = (0.9 \pm 7.9) \times 10^{-29}$	16×10^{-29} e-cm	
	Diamagnetic systems		
n	$d_n = (-0.0 \pm 1.1) \times 10^{-26}$	2.2×10^{-26} e-cm	g
^{199}Hg	$d_A = (2.2 \pm 3.1) \times 10^{-30}$	7.4×10^{-30} e-cm	h
^{129}Xe	$d_A = (1.4 \pm 6.9) \times 10^{-28}$	1.4×10^{-27} e-cm	i
^{225}Ra	$d_A = (4 \pm 6) \times 10^{-24}$	1.4×10^{-23} e-cm	j
TlF	$d\ \ = (-1.7 \pm 2.9) \times 10^{-23}$	6.5×10^{-23} e-cm	k
	Particle systems		
μ	$d_\mu = (0.0 \pm 0.9) \times 10^{-19}$	1.8×10^{-19} e-cm	l
Λ	$d_\Lambda = (-3.0 \pm 7.4) \times 10^{-17}$	7.9×10^{-17} e-cm	m

2017

2018 (8x)

2020 (1.6x)

2017 (4x)

2019 (5x)

2016

The decadal horizon

1. Molecules (cold) will rule
   - Next generation ACME (CFP-Northwestern)
   - Diamagnetic TlF (CeTREX)
   - MQMs etc. (N. Hutzler)
   - Ra(F) – octupole enhancement (Argonne/Dietrich)

2. UCNs sources will peak: 10x-100x (SNS nEDM)
   - Magnetometry challenges!
3. Storage rings will emerge

$$\sigma_d \approx \frac{1}{2E}\frac{\hbar}{\tau}\frac{1}{S/N}$$

A TRIUMF perspective

1. TUCAN (nEDM) go-go-go!
   We are all learning from eachother

2. Francium: competes with paramagnetic molecules

3. Ocutpole enhancements: (molecules)

Thanks to everyone