Survey of EDM Experiments and prospects (*sans* nEDM)

"The Once and Future EDM"

Tim Chupp

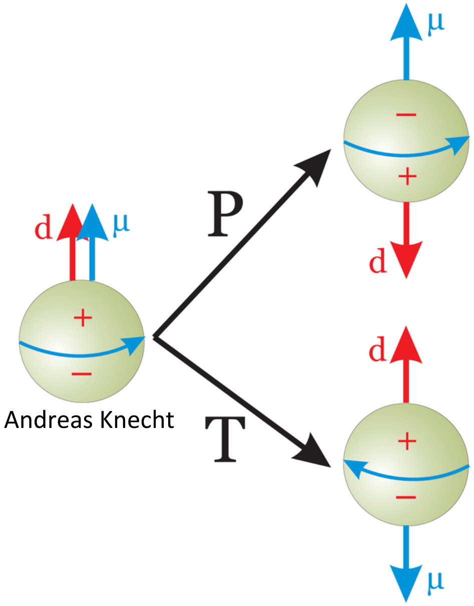
University of Michigan

1. Definitions, etc.
2. Electron-spin dependent (d_e/C_S)
   - Molecules ThO/HfF+
   - Other eEDM
3. Nuclear spin dependent
   - Hg, Xe (HeXe), TlF
   - Octupole deformed Ra/Rn

4. Storage Ring EDMs

EDMs

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



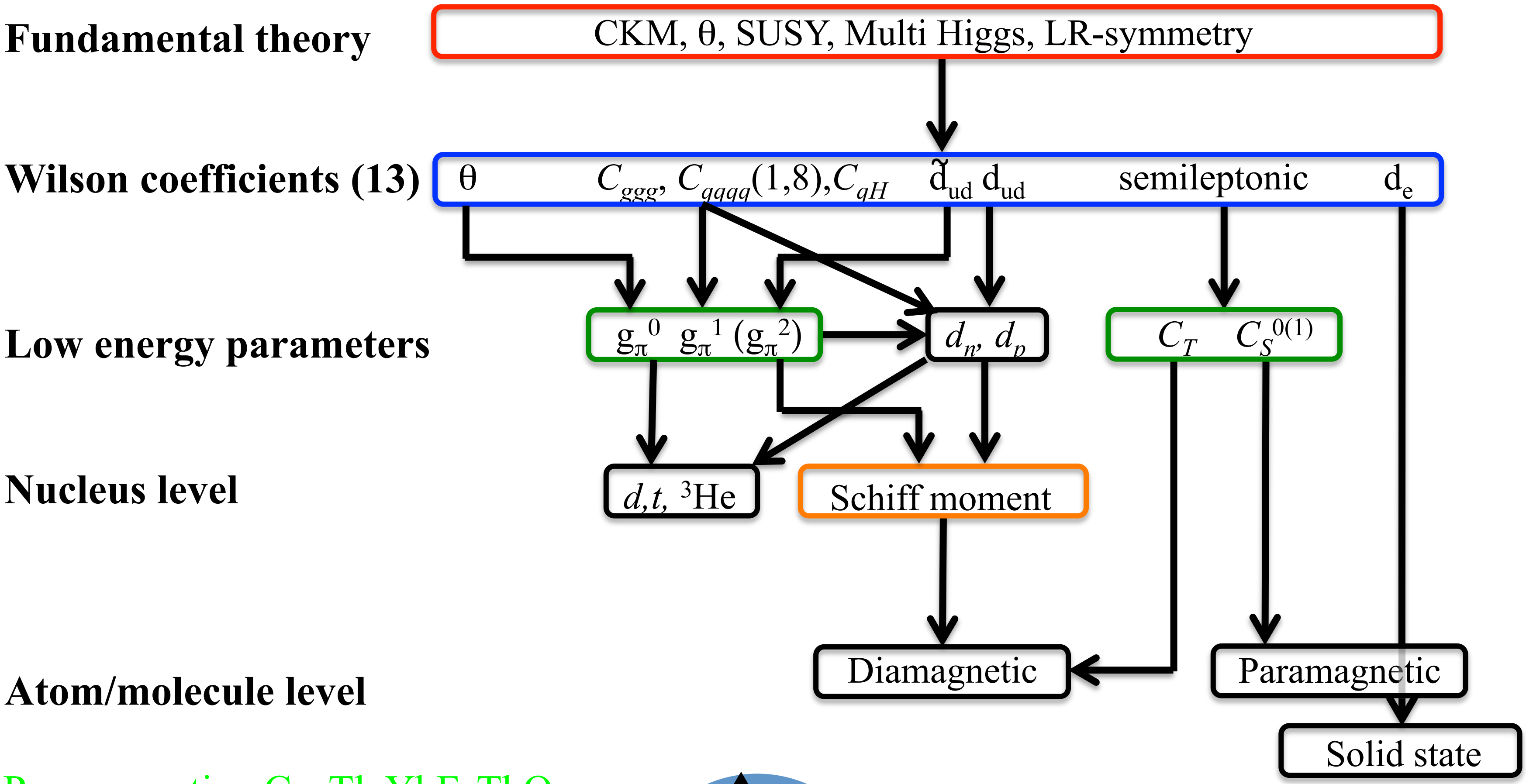
Andreas Knecht

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)

Atomic/Molecular EDMs arise from many sources



Fundamental theory

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

Wilson coefficients (13)

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

Low energy parameters

$g_\pi^{\ 0}$ $g_\pi^{\ 1}$ $(g_\pi^{\ 2})$

d_n, d_p

C_T $C_S^{0(1)}$

Nucleus level

d,t, ^{3}He

Schiff moment

Atom/molecule level

Diamagnetic

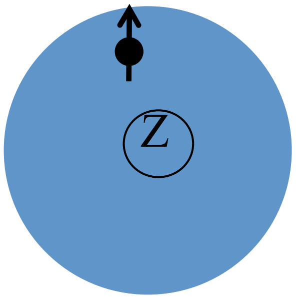
Paramagnetic

Solid state

Paramagnetic : Cs, Tl, YbF, ThO

($\vec{L}\cdot\vec{S}$ coupling)

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



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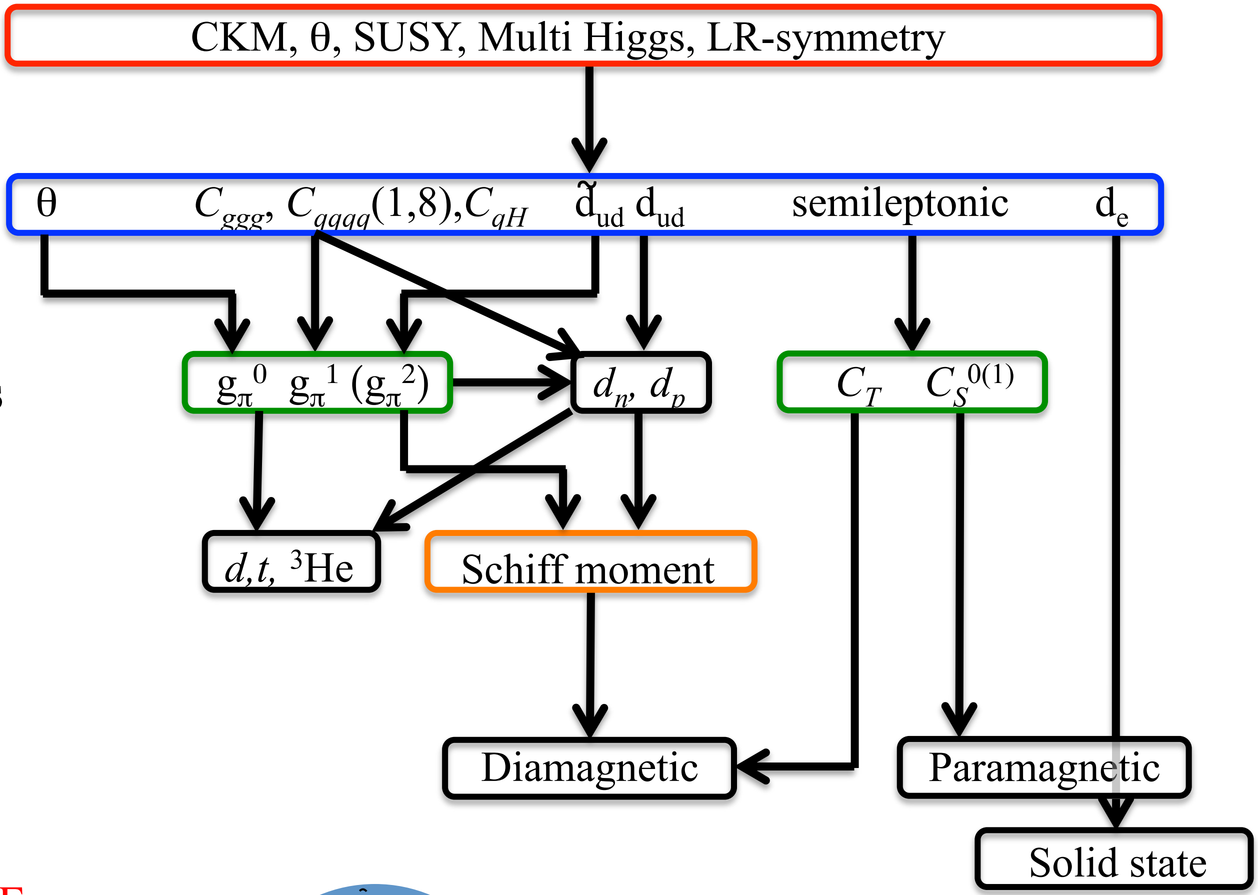

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Wilson coefficients (13) θ C_{ggg}, $C_{qqqq}(1,8)$, C_{qH} $\tilde{d}_{ud}$ d_{ud} semileptonic d_e

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

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

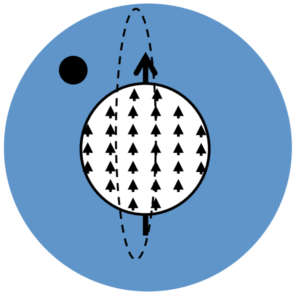
Atom/molecule level Diamagnetic Paramagnetic Solid state

Diamagnetic: Xe, Hg, TlF

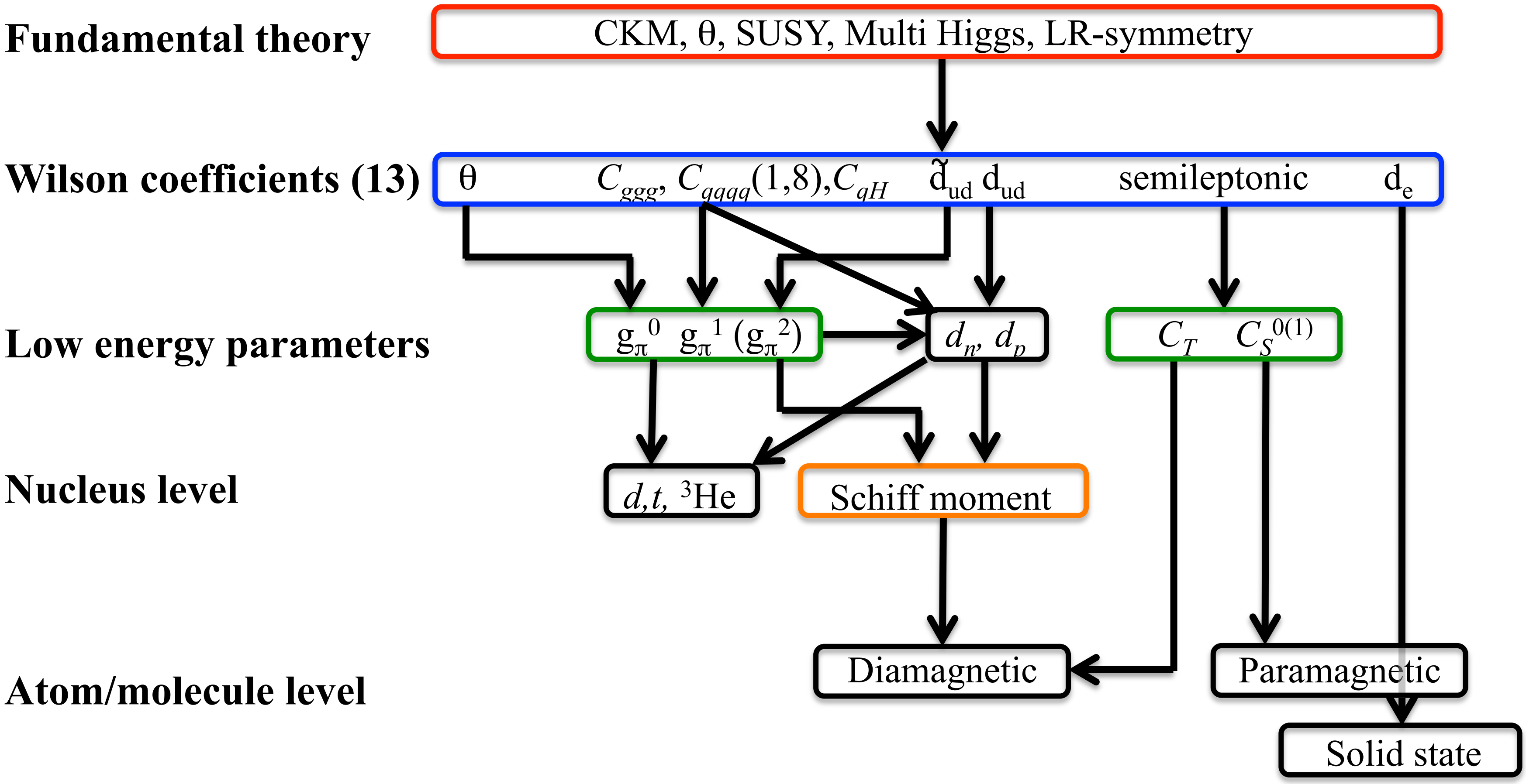
Schiff moment

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

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



Atomic/Molecular EDMs arise from many sources



Fundamental theory

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Low energy parameters

g_π^0 g_π^1 (g_π^2)

d_n, d_p

C_T $C_S^{0(1)}$

Nucleus level

d,*t*, ^{3}He

Schiff moment

Atom/molecule level

Diamagnetic

Paramagnetic

Solid state

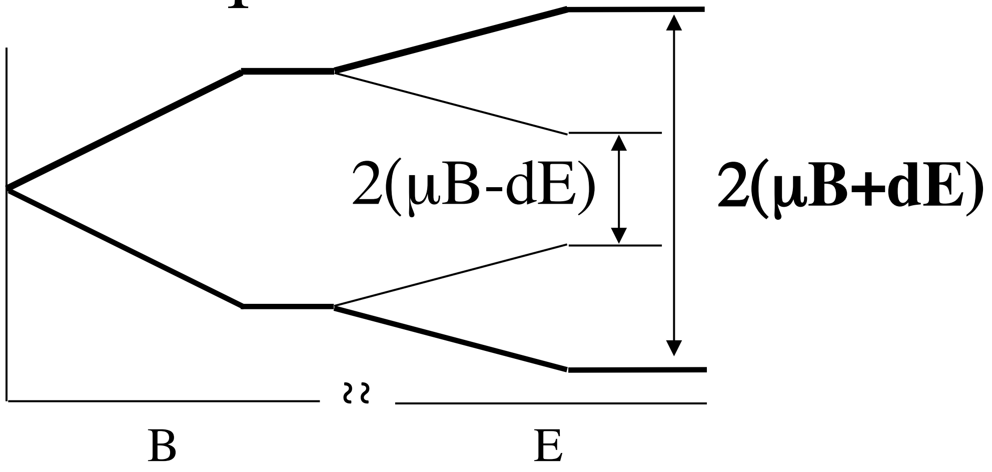
$$d_A = \eta_e d_e + \kappa_S S(\theta_{QCD}, g_\pi) + (k_T C_T + k_S C_S) + \text{h.o}$$

EDM results

	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	$d_A = (-1.8 \pm 6.9) \times 10^{-24}$ $d_e = (-1.5 \pm 5.7) \times 10^{-26}$ $C_S = (2.5 \pm 9.8) \times 10^{-6}$	1.4×10^{-23} e cm 1.2×10^{-25} e cm 2×10^{-5}	b
Tl	$d_A = (-4.0 \pm 4.3) \times 10^{-25}$ $d_e = (\ \ 6.9 \pm 7.4) \times 10^{-28}$	1.1×10^{-24} e cm 1.9×10^{-27} e cm	c
YbF	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$	1.2×10^{-27} e cm	d
ThO	$d_e = (4.3 \pm 4.0) \times 10^{-30}$ $C_S = (2.8 \pm 2.6) \times 10^{-10}$	1.2×10^{-29} e cm 8.0×10^{-10}	e
HfF^+	$d_e = (0.9 \pm 7.9) \times 10^{-29}$	1.6×10^{-28} e cm	f
Diamagnetic systems			
^{199}Hg	$d_A = (2.2 \pm 3.1) \times 10^{-30}$	7.4×10^{-30} e cm	g
^{129}Xe	$d_A = (0.7 \pm 3.3) \times 10^{-27}$	6.6×10^{-27} e cm	h
^{225}Ra	$d_A = (4 \pm 6) \times 10^{-24}$	1.4×10^{-23} e cm	i
TlF	$d\ \ = (-1.7 \pm 2.9) \times 10^{-23}$	6.5×10^{-23} e cm	j
n	$d_n = (-0.21 \pm 1.82) \times 10^{-26}$	3.6×10^{-26} e cm	k
μ	$d_\mu = (0.0 \pm 0.9) \times 10^{-19}$	1.8×10^{-19} e cm	l
τ	$Re(d_\tau) = (1.15 \pm 1.70) \times 10^{-17}$	3.9×10^{-17} e cm	m
Λ	$d_\Lambda = (-3.0 \pm 7.4) \times 10^{-17}$	1.6×10^{-16} e cm	n

Experiments

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



- Strong electric field (static): need neutral particles (or confined ion)
- Large signal needs POLARIZATION (usually optical pumping)

- MEASURE FREQUENCIES:

$$\sigma_d \approx \frac{1}{2E}\frac{\hbar}{T_2}\frac{1}{S/N}$$

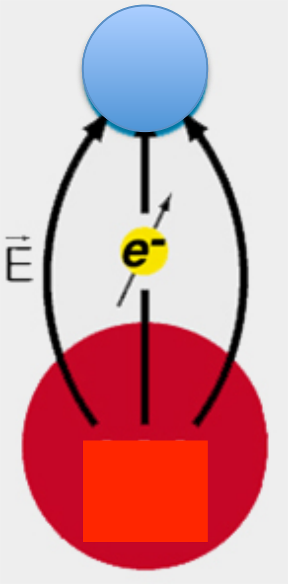
$$\frac{1}{2E}\frac{\hbar}{T_2}\frac{1}{\sqrt{\varphi_n T_2}}$$

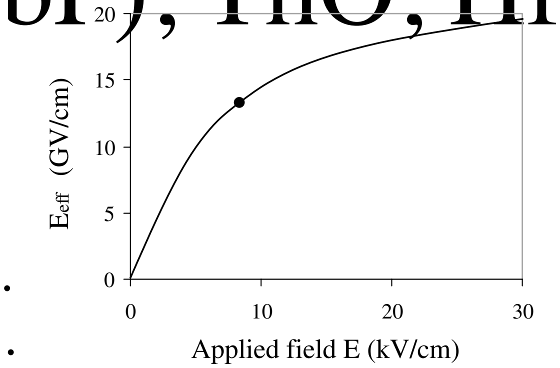
Phase-noise limit

$$\frac{1}{2E}\frac{\hbar}{T_2}\frac{1}{\sqrt{N_\gamma}}$$

Count-rate limit

Paramagnetic Molecules: (YbF), ThO, HfF$^+$





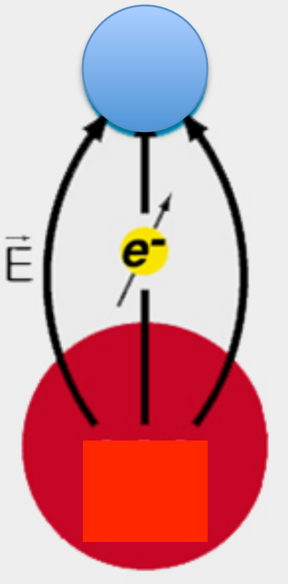
1. ***Large*** internal electric fields.
   1. $E_{eff} \sim 10^{11}$ V/cm.
   - Compared to $E_{lab} < 10^5$ V/cm.
2. ***Accessible*** internal electric fields.
   - Easy to electically polarize, need only $E_{lab} \sim 1$ V/cm.
3. Rejection of systematic errors.
   - Electron spins triple/L=1 (J=0)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

Molecules of Choice:

- Yale: TlF (diamagnetic)
- Imperial College, London: YbF
- Harvard/Yale: ThO
- Yale: PbO

- JILA: HfF

Molecules: **TlF**, YbF, HfF+



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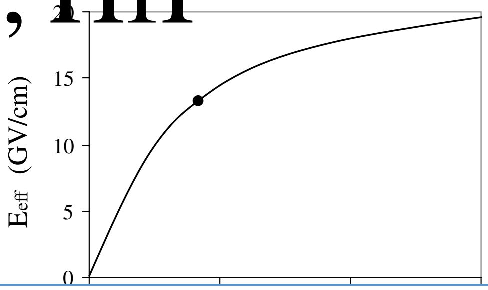
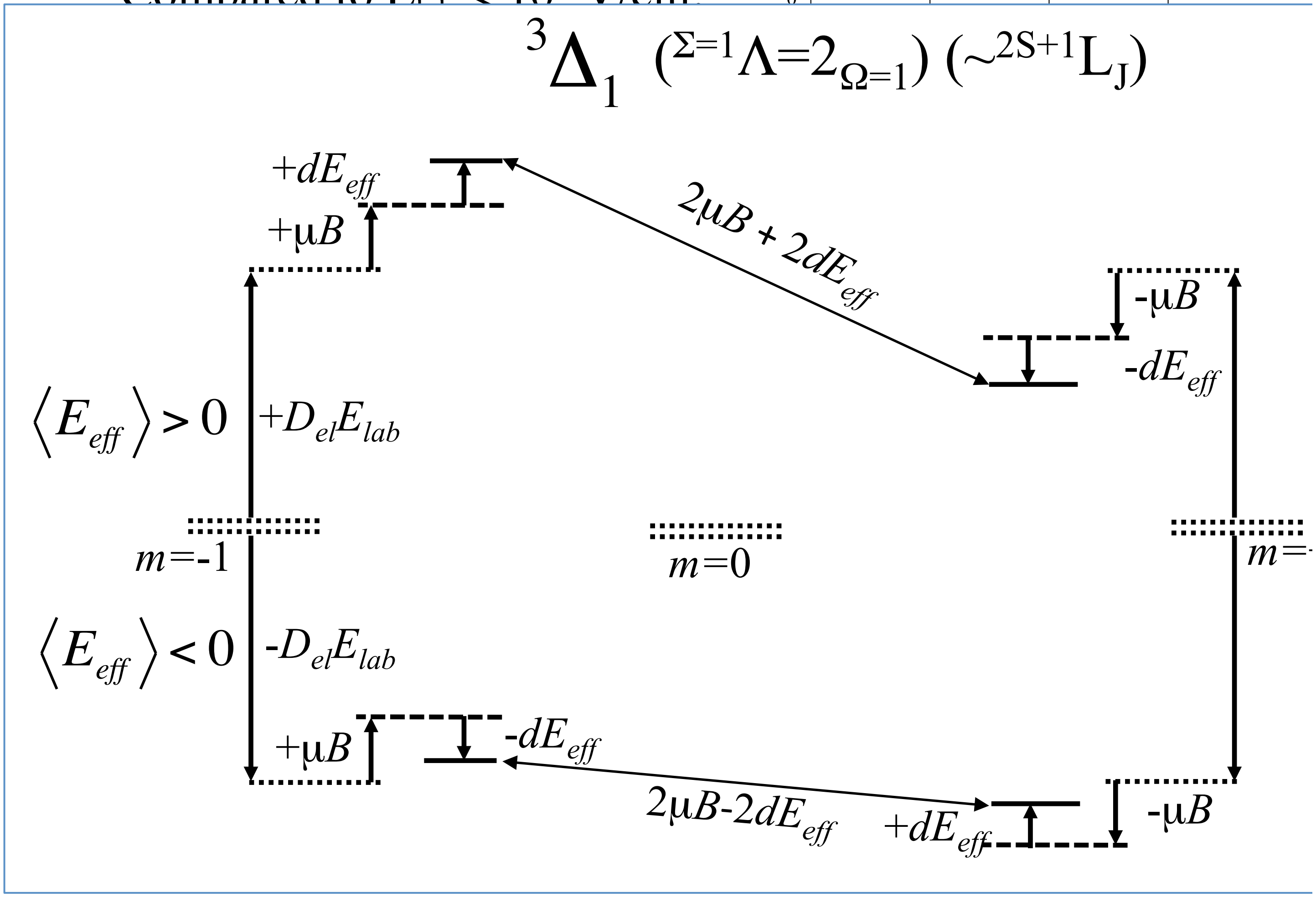
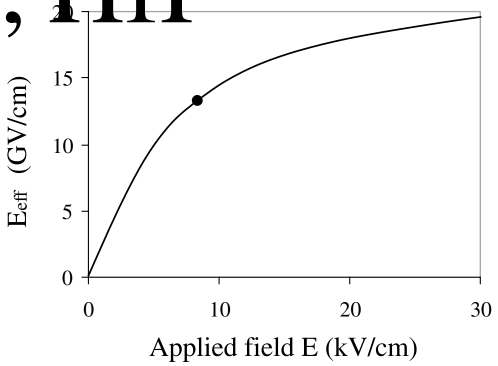
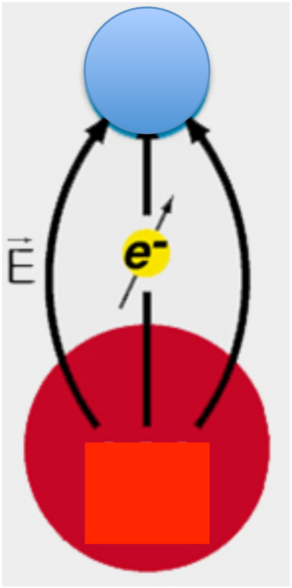



$^3\Delta_1$ $(^{\Sigma=1}\Lambda=2_{\Omega=1})$ $(\sim^{2S+1}L_J)$

Molecules: **TlF**, YbF, HfF$^+$





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.
   - **Can be laser cooled**
3. Rejection of systematic errors.
   - Electron spins triple/L=1 (J=0) μ small
   - E_{eff} ***independent*** of E_{lab}.

Molecules of Choice:

- Yale: TlF (diamagnetic)
- Imperial College, London: YbF
- **Harvard: ThO**
- Yale: PbO
- JILA: HfF+

Molecules: **TlF**, YbF, HfF$^+$

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

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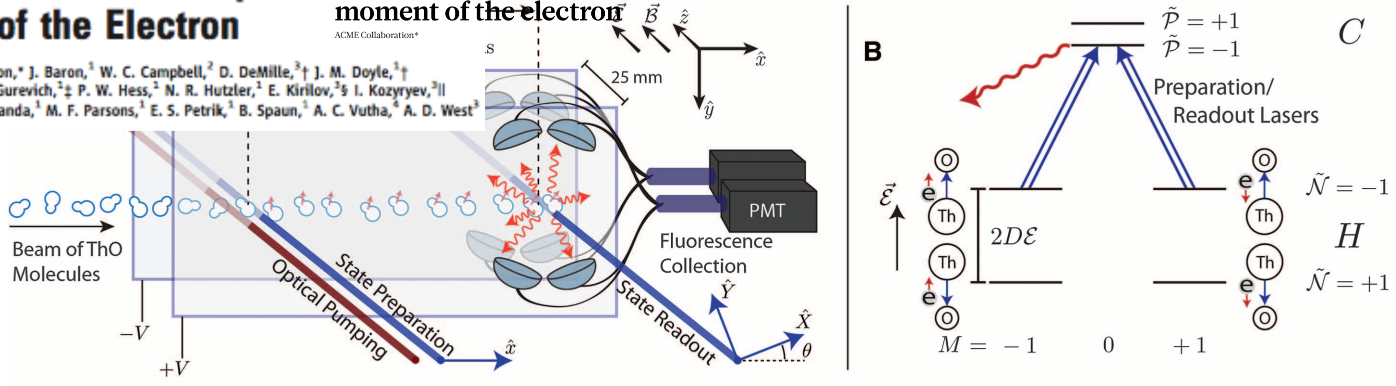
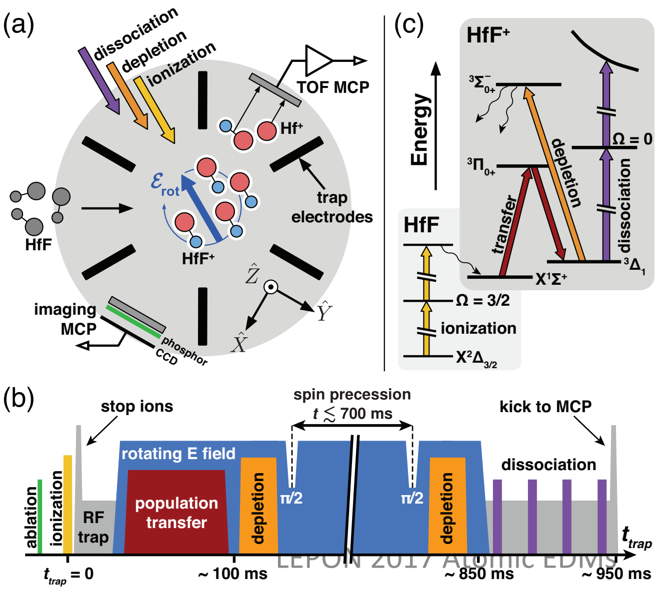
Improved limit on the electric dipole moment of the electron

ACME Collaboration*



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



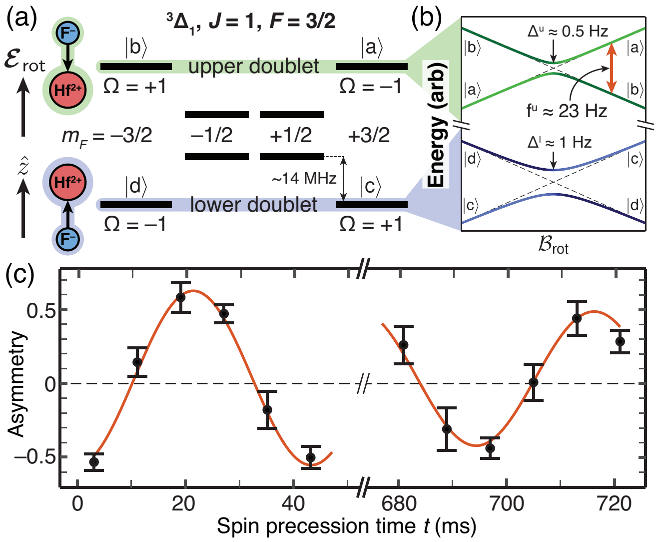
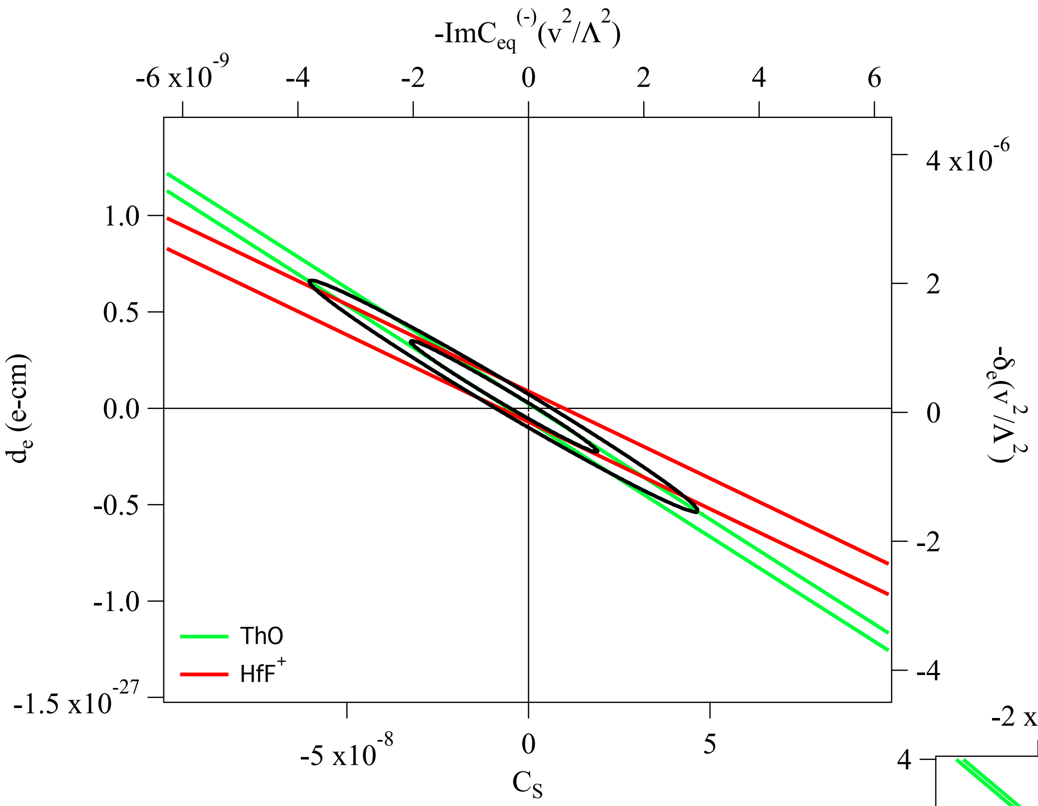
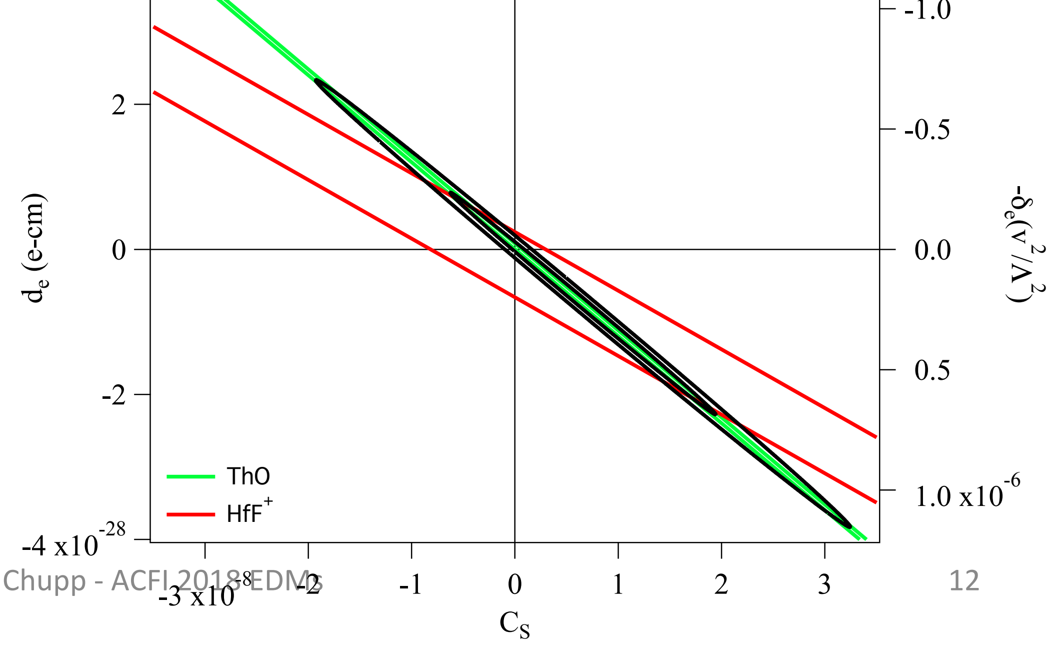


FIG. 2. Electron spin resonance spectroscopy in HfF$^+$. (a)



7ximprovement leads to
d_e/C_S improvement by about 2x



Solid State Searches for d_e

i. a high number density of unpaired electrons (10^{22} cm^{-3}), providing signal amplification; $d_{Gd^{3+}} \approx 20 d_e$

ii. confinement of the electrons, mitigating such effects as motional fields;

iii. features of solid-state samples including collective effects, *e.g.* for ferro-electric systems, a large electric field spin-polarizes the electrons resulting in a magnetization that reverses with the electric field;

iv. minimal magnetic order to mitigate spurious magnetic effects.

$Gd_3Ga_5O_{12}$

$$d_e = (-5.57 \pm 7.98_{stat} \pm 0.12_{syst}) \times 10^{-25} (\text{Kim} \;\; et \;\; al., 2015)$$

$Eu_{0.5}Ba_{0.5}TiO_3$

$$d_e = (-1.07 \pm 3.06_{stat} \pm 1.74_{syst}) \times 10^{-25} \;\; e\,\text{cm.} \;\; (\text{Eckel } et\ al.,\ 2012)$$

Nuclear-spin-dependent systems

^{129}Xe and ^{199}Hg - SM

$$S(^{129}\mathrm{Xe}) \approx \ 1.75 \times 10^{-8} \ \eta_{np} \ e \ \mathrm{fm}^3 \qquad d_A(^{129}\mathrm{Xe})^{\mathrm{CKM}(n)} \approx 6 \times 10^{-6} d_n$$

$$S(^{199}\mathrm{Hg}) \approx -1.4 \times 10^{-8} \ \eta_{np} \ e \ \mathrm{fm}^3. \qquad d_A(^{199}\mathrm{Hg})^{\mathrm{CKM}(n)} \approx 4 \times 10^{-4} d_n,$$

$$|d_A(^{129}\mathrm{Xe})^{\mathrm{CKM}}| \lesssim 5 \times 10^{-35} \ \ e \ \mathrm{cm} \qquad |d_A(^{129}\mathrm{Xe})^{\mathrm{CKM}(n)}| \lesssim 3.6 \times 10^{-37} \ \ e \ \mathrm{cm}$$

$$|d_A(^{199}\mathrm{Hg})^{\mathrm{CKM}}| \lesssim 4 \times 10^{-34} \ \ e \ \mathrm{cm} \qquad |d_A(^{199}\mathrm{Hg})^{\mathrm{CKM}(n)}| \lesssim 2.4 \times 10^{-35} \ \ e \ \mathrm{cm}.$$

Experiment ~ 10^{-27} (Xe) and 10^{-29} (Hg)

^{205}TlF

$$d_{\mathrm{TlF}}^{p-vol} = 0.46 \ d_p \quad \sim 10^{-32} \ e \ \mathrm{cm}$$

Experiment ~ 10^{-23}

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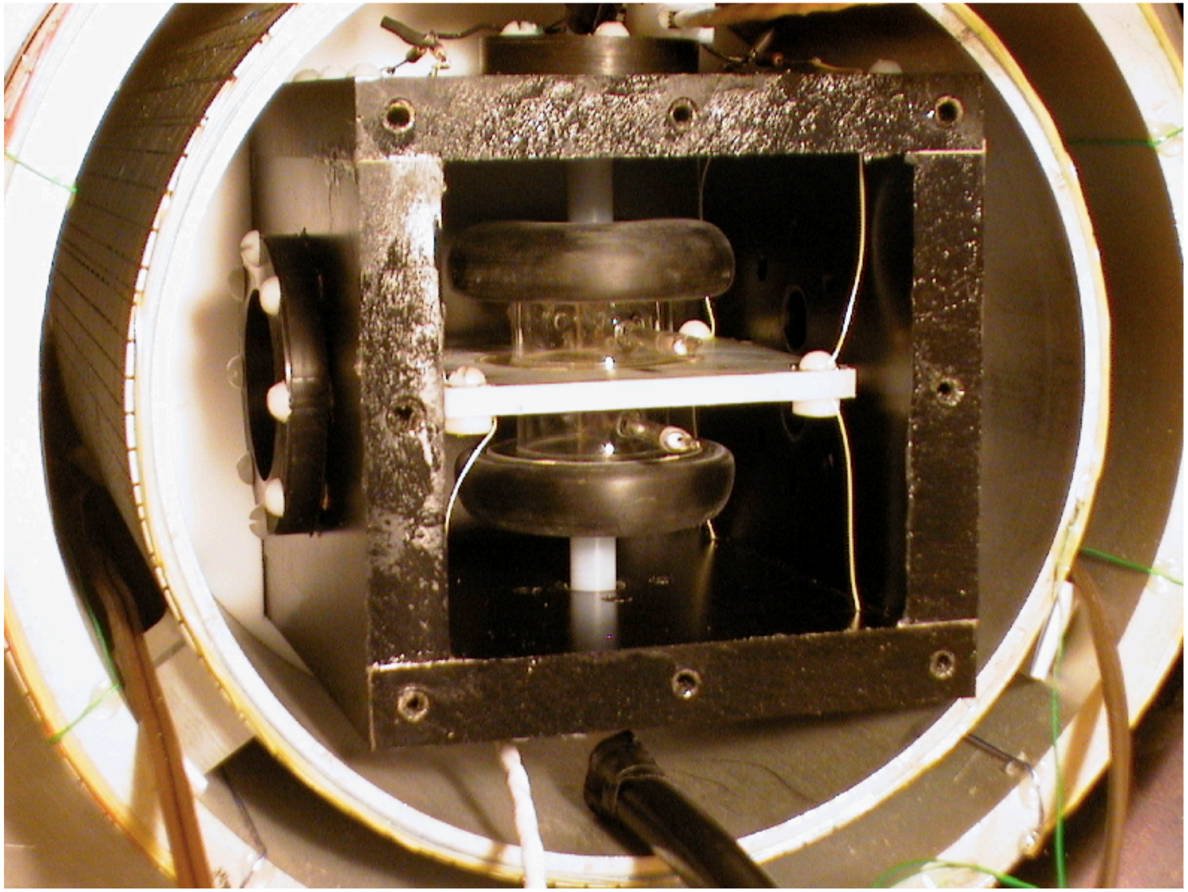
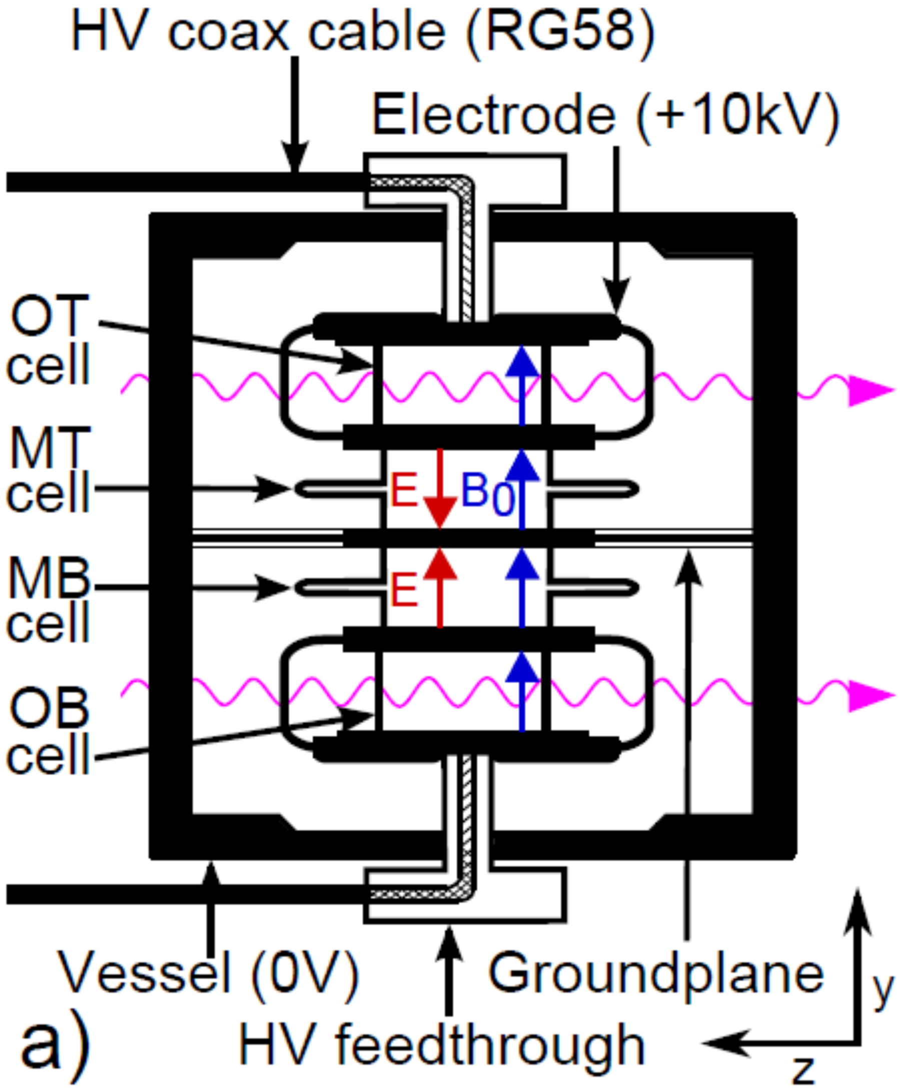
Reduced Limit on the Permanent Electric Dipole Moment of ^{199}Hg

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

Faraday Rotation Detection

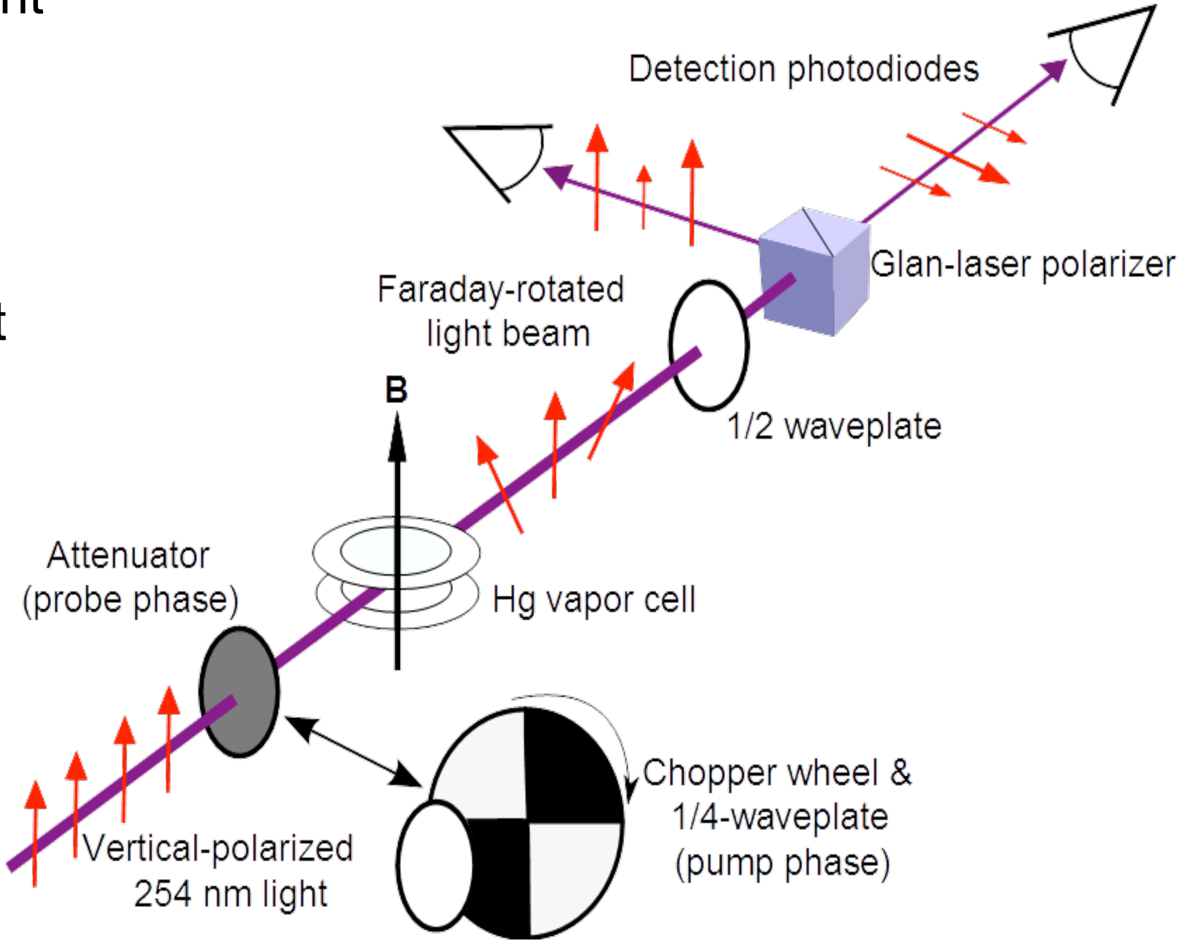
- Atomic polarization changes the index of refraction for σ_+ and σ_- light

- Incoming linearly polarized probe light is rotated

- Rotation angle oscillates at the Larmor frequency

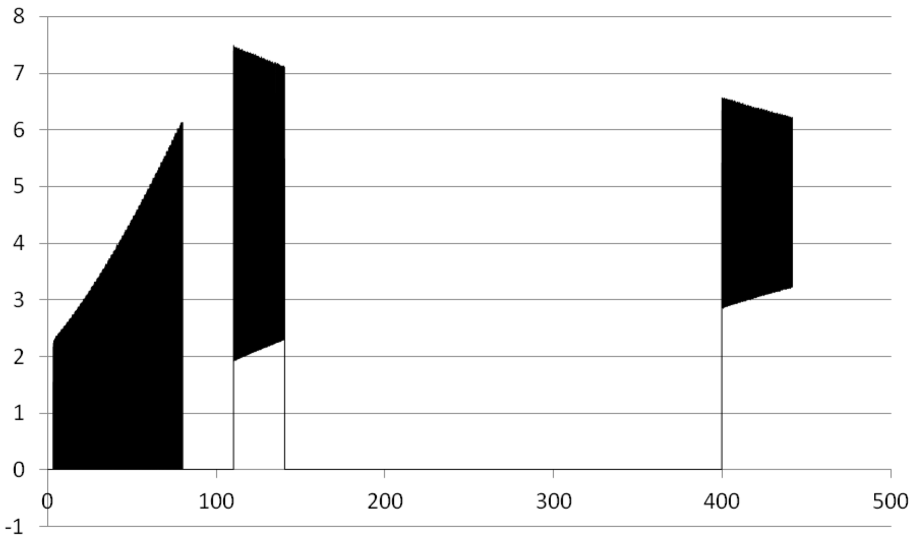
- A polarizing beam splitter separates the beam into vertical, horizontal components

- Intensity of 2 orthogonal polarization states oscillate out of phase



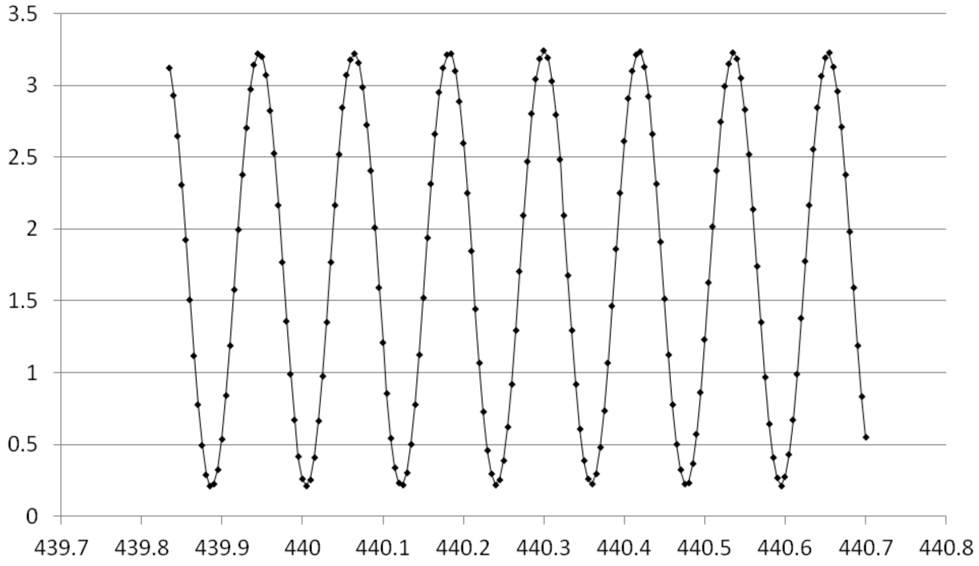
Phase Difference Analysis

^{199}Hg EDM raw data (run 16030, 5/29/2013)



Photodiode signal (V) vs. time (seconds)

^{199}Hg EDM run 16030 data excerpt (-3.0V offset)

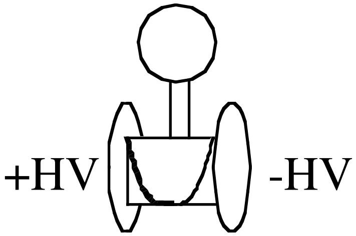


Photodiode signal (V) vs. time (seconds)

- Instead of fitting a single long sample for **ω**, we can apply the Ramsey method: fit 2 samples for Δφ with light off in between for time Δt
- Freq. difference $(\omega_{MT} - \omega_{MB}) = \Delta\, \varphi_{MT\text{-}MB}(t_f) - \Delta\varphi_{MT\text{-}MB}(t_i)$
- $\mathbf{d}_{Hg}$ signal $= \Delta_{HV}[(\omega_{MT} - \omega_{MB}) - 1/3(\omega_{OT} - \omega_{OB})]$

^{199}Hg Systematics

Source	Error (10^{-31} e cm)
Axial Cell Motion	12.6
Leakage Currents	5.02
Radial Cell Motion	3.36
E^2 effects	3.04
Parameter Correlations	2.33
v x **E B** fields	2.29
Charging Currents	1.83
Geometric Phase	0.06
Quadrature sum	**14.8**



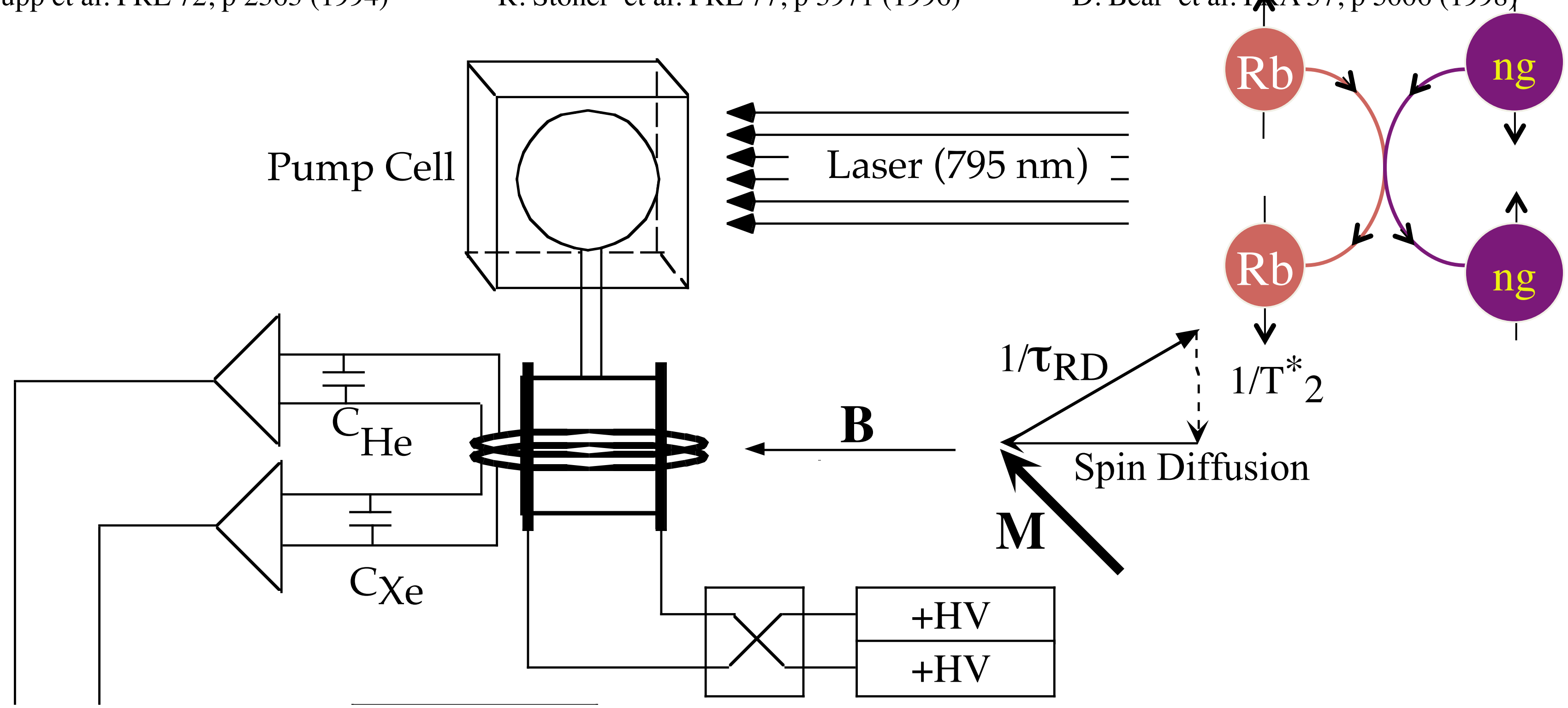
Polarizability; Noise

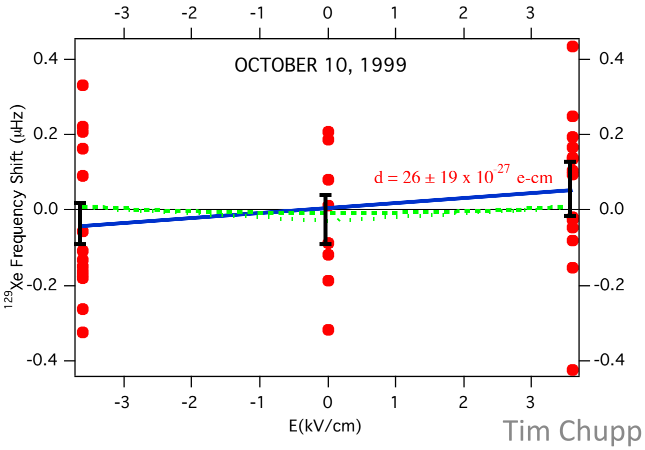
Current ^{129}Xe efforts

- TRIUMF/nEDM
- Active maser: Tokyo
- Xe-129/He-3 MIXed (Mainz/Heidelberg/Juelich)
- HeXe (TUM, PTB, MSU, Umich)

^{129}Xe EDM: Spin Exchange Pumped Zeeman Maser

T. Chupp et al. PRL 72, p 2363 (1994) R. Stoner et al. PRL 77, p 3971 (1996) D. Bear et al. PRA 57, p 5006 (1998)





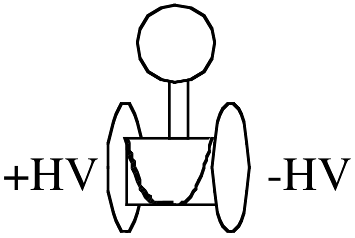
Final: $d_{Xe}=(0.7\pm3.3)\mathrm{x}10^{-27}$ e-cm

$d_{Xe}<6.6\mathrm{x}10^{-27}$ e-cm

M.Rosenberry, TC, PRL **86**, 22 (**2001**)

False EDM Signals

Cell Leakage Currents
Two Species -- BUT not quite in the same place
CHECK: (1μA loop around cell) $d<1x10^{-28}$ e-cm (20 pA)



E^2 Correlations (Polarizability; Noise)

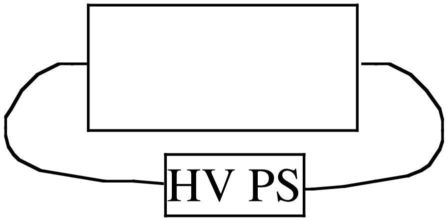
CHECK: $(d\nu/d(E^2) = (7\pm3)x10^{-9}$ Hz/kV^2/cm^2

Reference Oscillators Disturbed by E, E2

CHECK: (clock test) $d<1x10^{-28}$ e-cm

Charging Currents Magnetize Shields
PLL Control Loop Droop
Cavity Pulling Changes

CHECK: Zeros: $d<1x10^{-26}$ e-cm (stat)



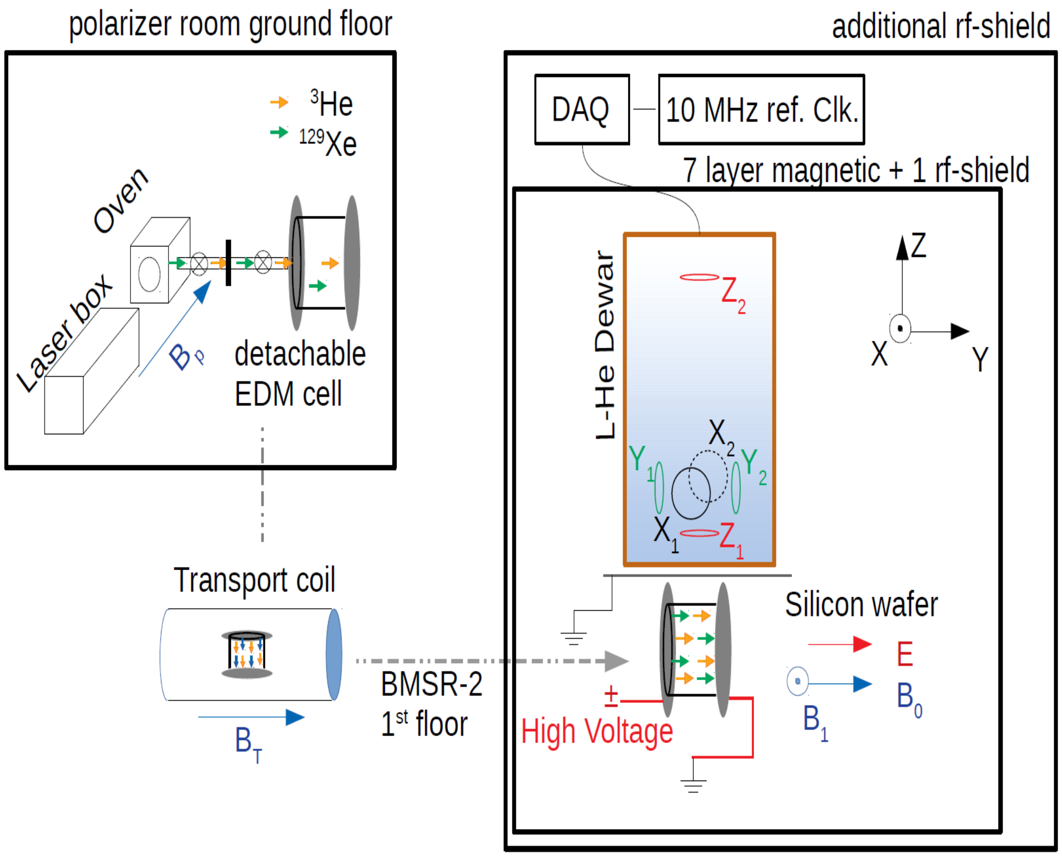
0 + - + - 0 - + - + 0 + - + - 0 - + - + ...

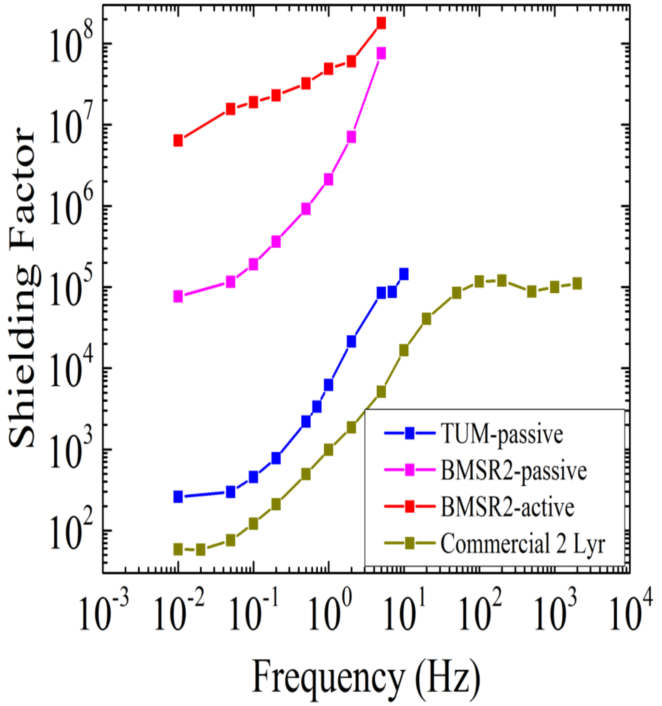
+ Memory?
- Memory?
+ Memory?

FLIP B

Much smaller than statistical error.

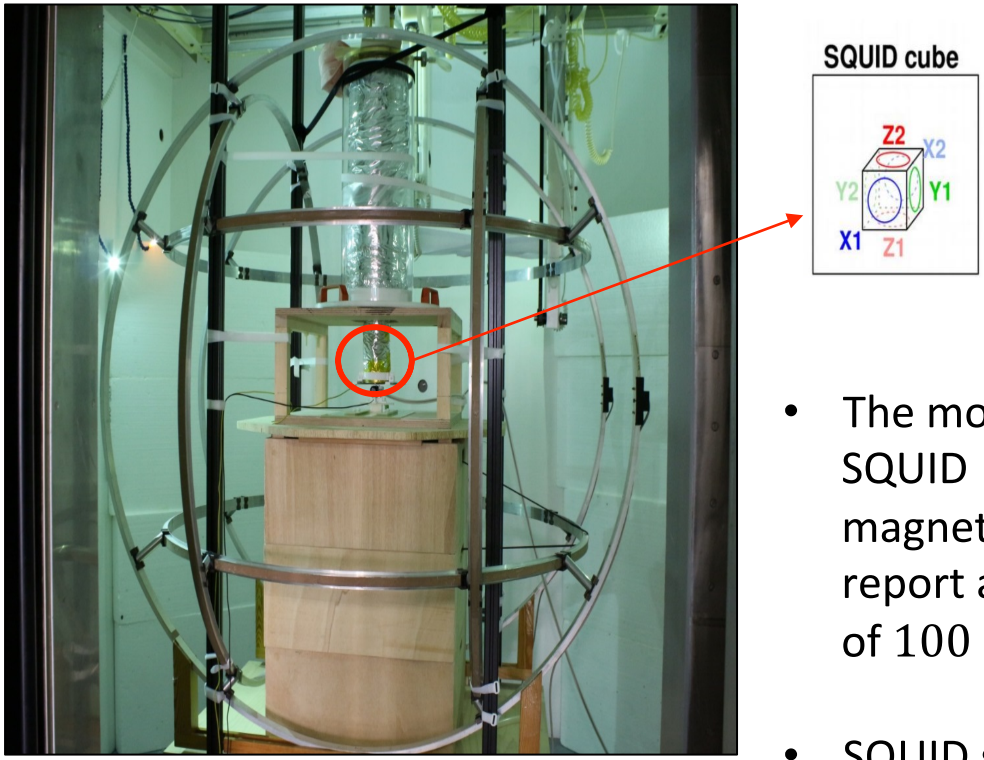
HeXeEDM experiment at BMSR-2 (PTB-Berlin)





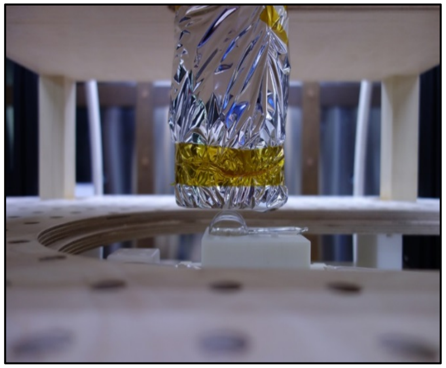
8-layer shield, significant shielding factor improvement over TUM's 2-layer outer shield

Superconducting Quantum Interference Devices (SQUIDs)



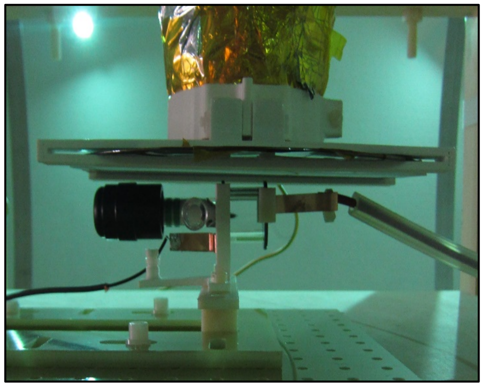
MRX SQUID system in the BMSR-2 at PTB Berlin.

- SQUIDs are very sensitive low-temperature magnetometers
- More sensitive than atomic magnetometers for the frequency range of interest (10-100 Hz)
- The most sensitive SQUID magnetometers report a sensitivity of 100 $aT/\sqrt{Hz}$
- SQUID sensitivity is limited by Johnson noise from dewar insulating and protective materials.

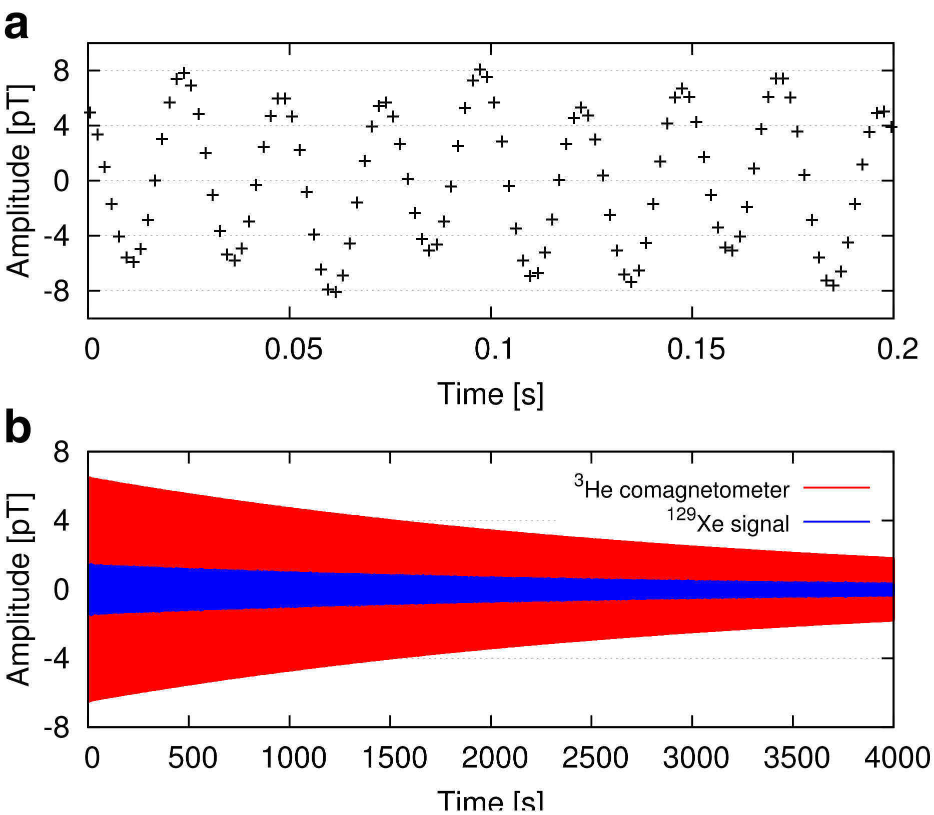


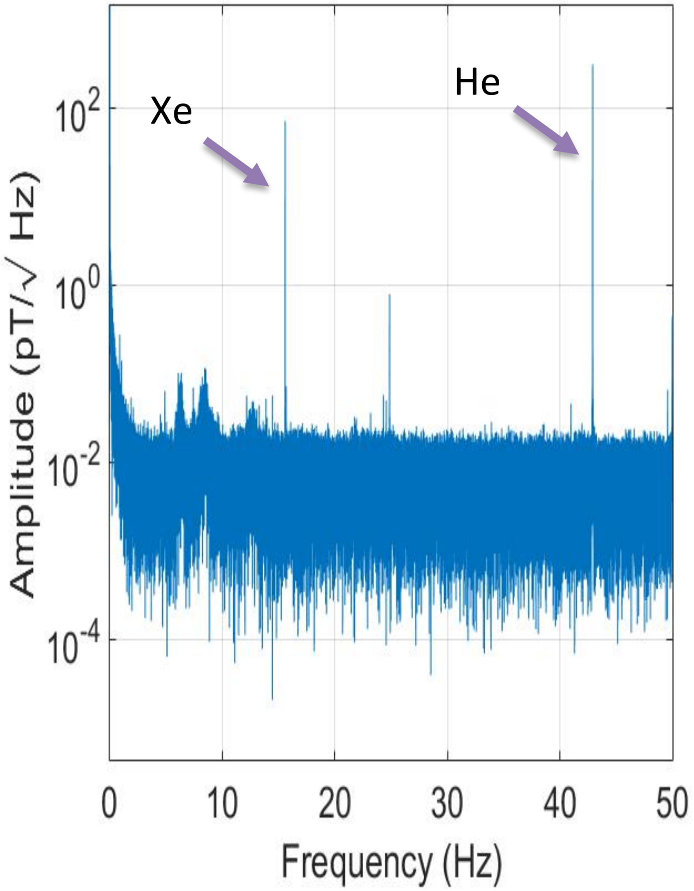
MRX SQUIDs over a sealed cell at the FRM-II MSR.

HeXeEDM experiment at BMSR-2 (PTB-Berlin)



Detection with SQUID magnetometer array





Systematic effects

$$\omega' \approx -\gamma_{\mathrm{He}}(1-\sigma_{\mathrm{He}})\Delta R B_0 + \gamma_{\mathrm{Xe}}(1-\sigma_{\mathrm{Xe}})(\Delta B_{\mathrm{Xe}} - \Delta B_{\mathrm{He}}) + \omega^{sd}_{\mathrm{Xe}} - R\omega^{sd}_{\mathrm{He}} + (1-R)\vec{\Omega}\cdot\hat{B}.$$

Source of systematic error	Description
Leakage current	HV leaking across cell to other electrode. Corkscrew pattern will generate a magnetic field
Charging currents	Current from charging electrode up to target HV. May magnetize materials on or near cell (like an o-ring) which will cause a magnetic field gradient across the cell.
E^2 effects	Any effect that scales with the magnitude of the electric field, e.g., xenon chemical shift, HV-induced phase noise.
Comagnetometer drift	Residual longitudinal magnetization causes a drift seen in the comagnetometer corrected Xe frequency.
E-field uncertainty	Uncertainty in the electric field magnitude.
E-field correlated cell motion	The applied electric field may cause the cell to shift. This will cause the magnetic field and gradients within the cell to be slightly different.
Geometric phase	Motional magnetic field (v x E) effects.

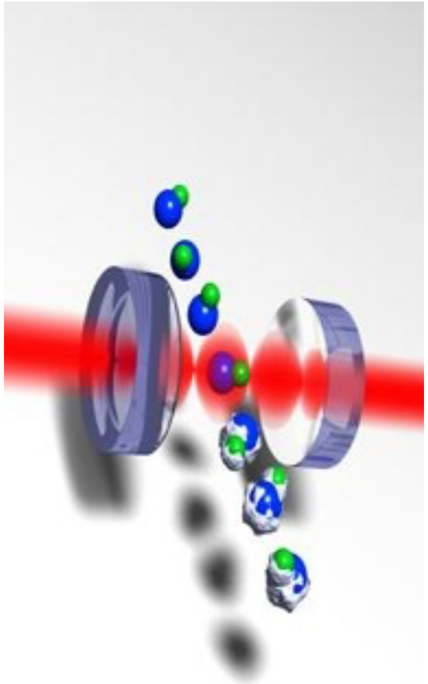
Systematic effects

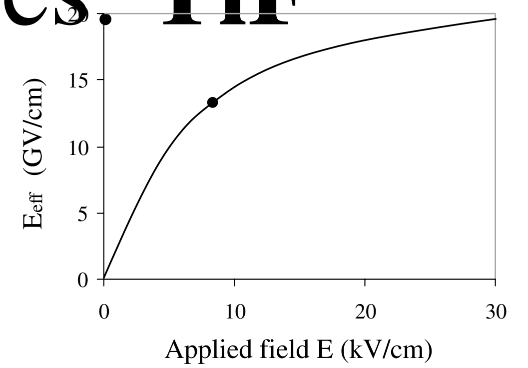
$$\omega' \approx -\gamma_{\mathrm{He}}(1-\sigma_{\mathrm{He}})\Delta R B_0 + \gamma_{\mathrm{Xe}}(1-\sigma_{\mathrm{Xe}})(\Delta B_{\mathrm{Xe}} - \Delta B_{\mathrm{He}}) + \omega^{sd}_{\mathrm{Xe}} - R\omega^{sd}_{\mathrm{He}} + (1-R)\vec{\Omega}\cdot\hat{B}.$$

Source	Sys. Error (e-cm)
Leakage Current	1.6×10^{-28}
Charging currents	1.7×10^{-29}
Comagnetometer drift	6.3×10^{-28}
E-correlated cell motion (rotation)	3.0×10^{-28}
E-correlated cell motion (translation*)	7.6×10^{-28}
Geometric phase	1×10^{-31}
$\|E\|$ uncertainty	$(0.1)\ d_A(^{129}\mathrm{Xe})$
$\|E\|^2$ effects	2×10^{-29}

Final result: [redacted] ± 2.4 (*stat*) ± [redacted]

Diamagnetic Molecules: **TlF**





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.
    - **Can be laser cooled**
3. Rejection of systematic errors.
    - Electron spins triple/L=1 (J=0) μ small
    - E_{eff} ***independent*** of E_{lab}.

CeNTREX experiment (Yale/Umass). 205Tl has an unpaired proton has an EDM, it will lead to a deformation in the shape of atomic nuclei known as a Schiff moment. CeNTREX will search for the Schiff moment of the ^{205}Tl nucleus inside a TlF (thallium fluoride) molecule. The observable signature of a Schiff moment will be a shift in the NMR frequency of ^{205}Tl nuclei when the molecules are polarized by a strong electric field. The size of the NMR shift is 3-4 orders of magnitude larger than in similar experiments that use atoms instead of molecules, for the same size of the Schiff moment.

The first generation of CeNTREX, now under construction, will use a cryogenic molecular beam of TlF (similar to that used in our ACME electron EDM search) and will perform state preparation and detection using optical cycling (similar to methods developed for our experiments to laser cool and trap SrF molecules). Later generations of CeNTREX aim to laser cool and trap the TlF molecules for increased sensitivity.

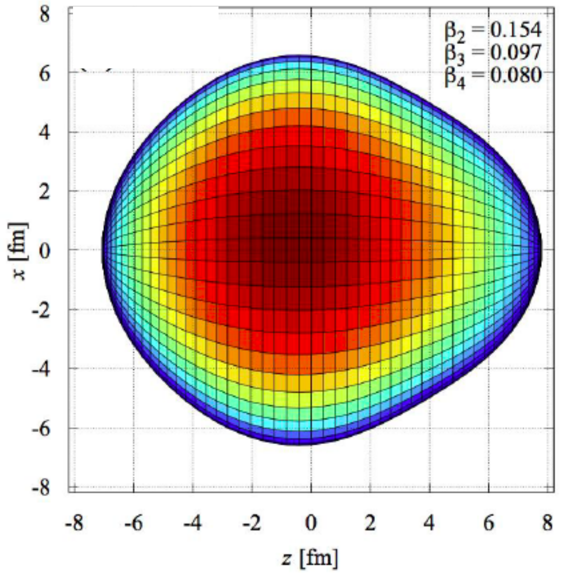
Octupole Enhancements of Schiff Moments

^{225}Ra $^{221/223}$Rn

Spherical

Quadrupole

Octupole

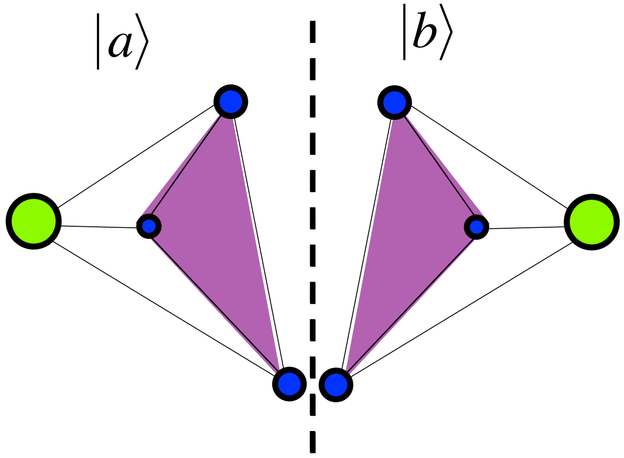


Octupole Enhancements

Intrinsic (body-frame) moment

Polarizabitliy

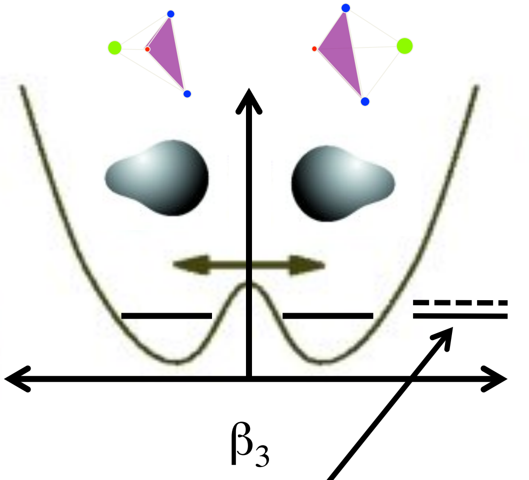
NH_3 (see Feynman vol 3.)



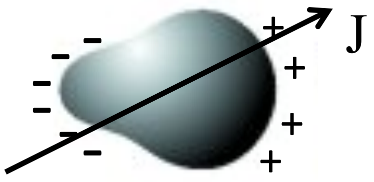
Reflection Symmetry

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

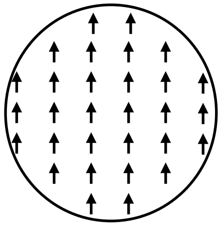
$$|\psi_-\rangle = \frac{1}{\sqrt{2}}\left(|a\rangle - |b\rangle\right)$$



Small splitting (tunnel frequency)
Large electric polarizability



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



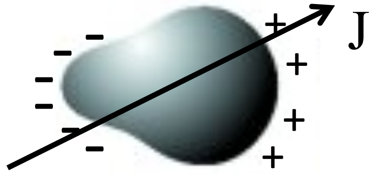
$\vec{E} \propto \vec{J}$

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

Nuclei with Octupole Deformation/Vibration

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

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



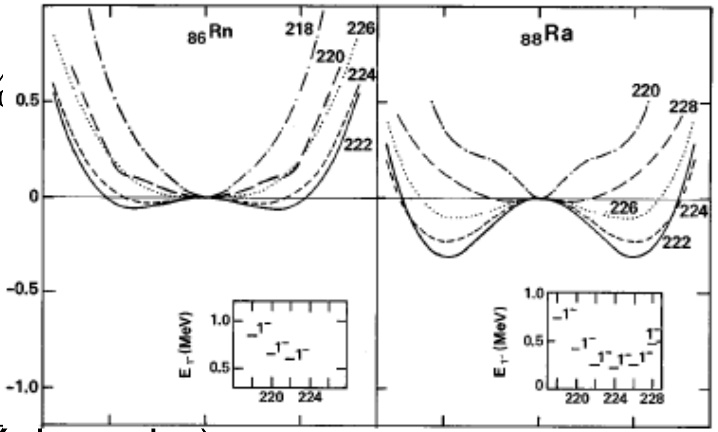
	^{223}Rn	^{223}Ra	^{225}Ra	^{223}Fr	^{129}Xe	^{199}Hg
$t_{1/2}$	23.2 m	11.4 d	14.9 d	22 m		
I	7/2	3/2	1/2	3/2	1/2	1/2
ΔE th (keV)	37*	170	47	75		
ΔE exp (keV)	-	50.2	55.2	160.5		
$10^{11} S$ (e-fm^3)	375	150	115	185	0.6	-0.75
$10^{28} d_A$ (e-cm)	1250	1250	940	1050	0.3	2.1

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

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

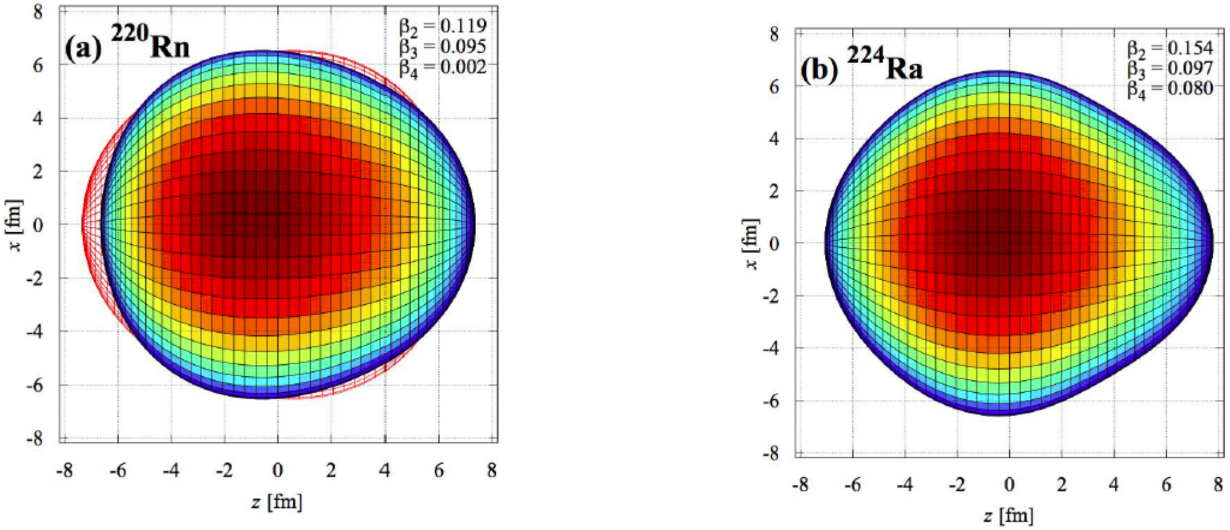
*Based on Woods-Saxon Potential

† 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)

Estimate of ^{221}Rn Enhancement



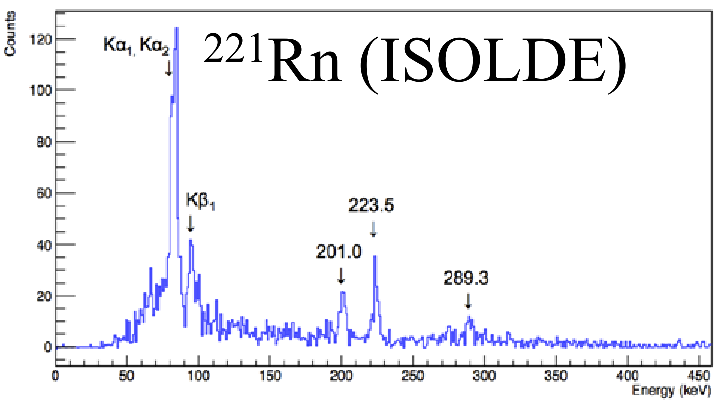
$$S \propto \frac{\eta\beta_2\beta_3^2 A^{2/3} r_0^3}{E_+ - E_-}$$

50 keV

$$\frac{S_{Rn}}{S_{Hg}} = \frac{S_{Ra}}{S_{Hg}}\frac{S_{Rn}}{S_{Ra}} \approx 1000\,\frac{\beta_2}{\beta_2}\frac{\beta_3^2}{\beta_3^2}\frac{\Delta E_{Ra}}{\Delta E_{Rn}} \approx 50 - 100$$

400 keV

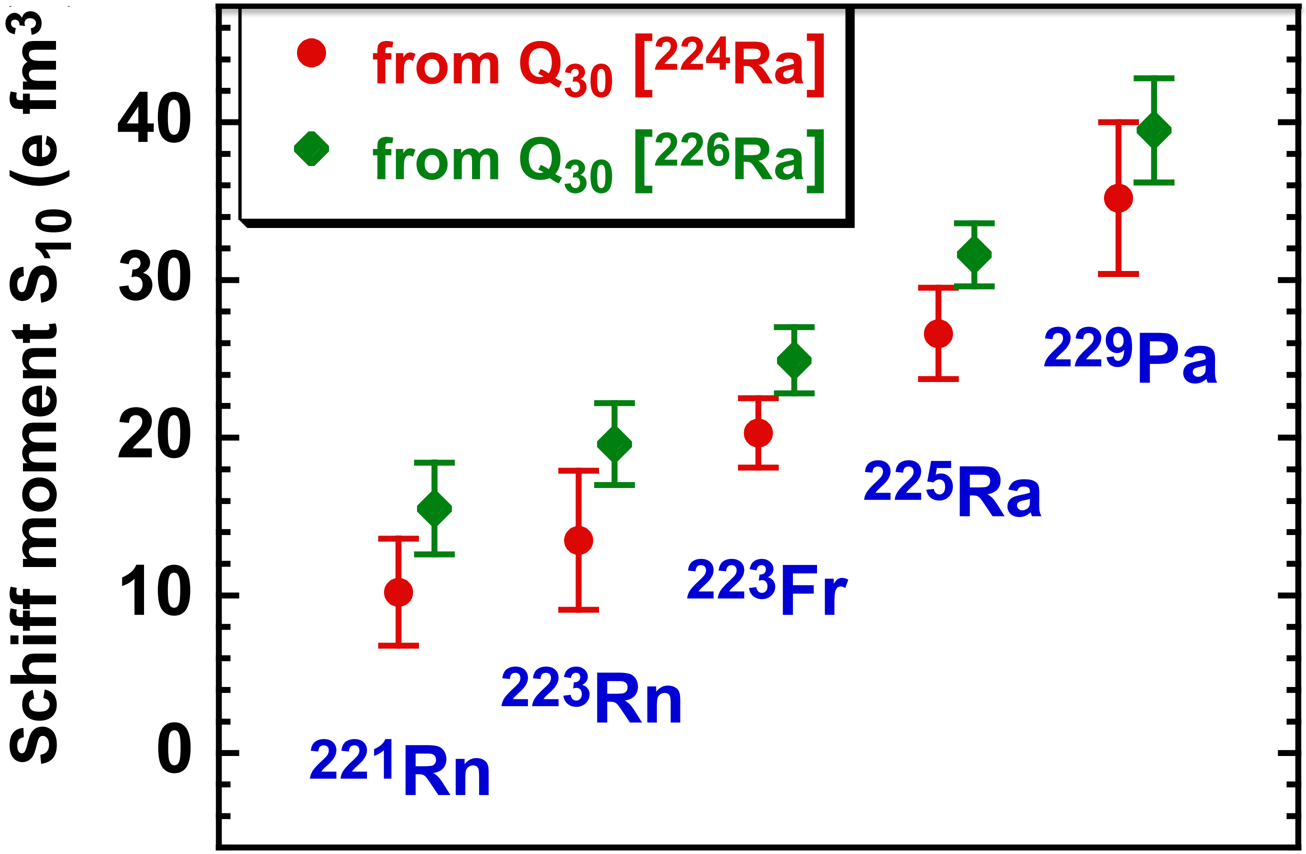
500-1000
(J. Engel et al.)



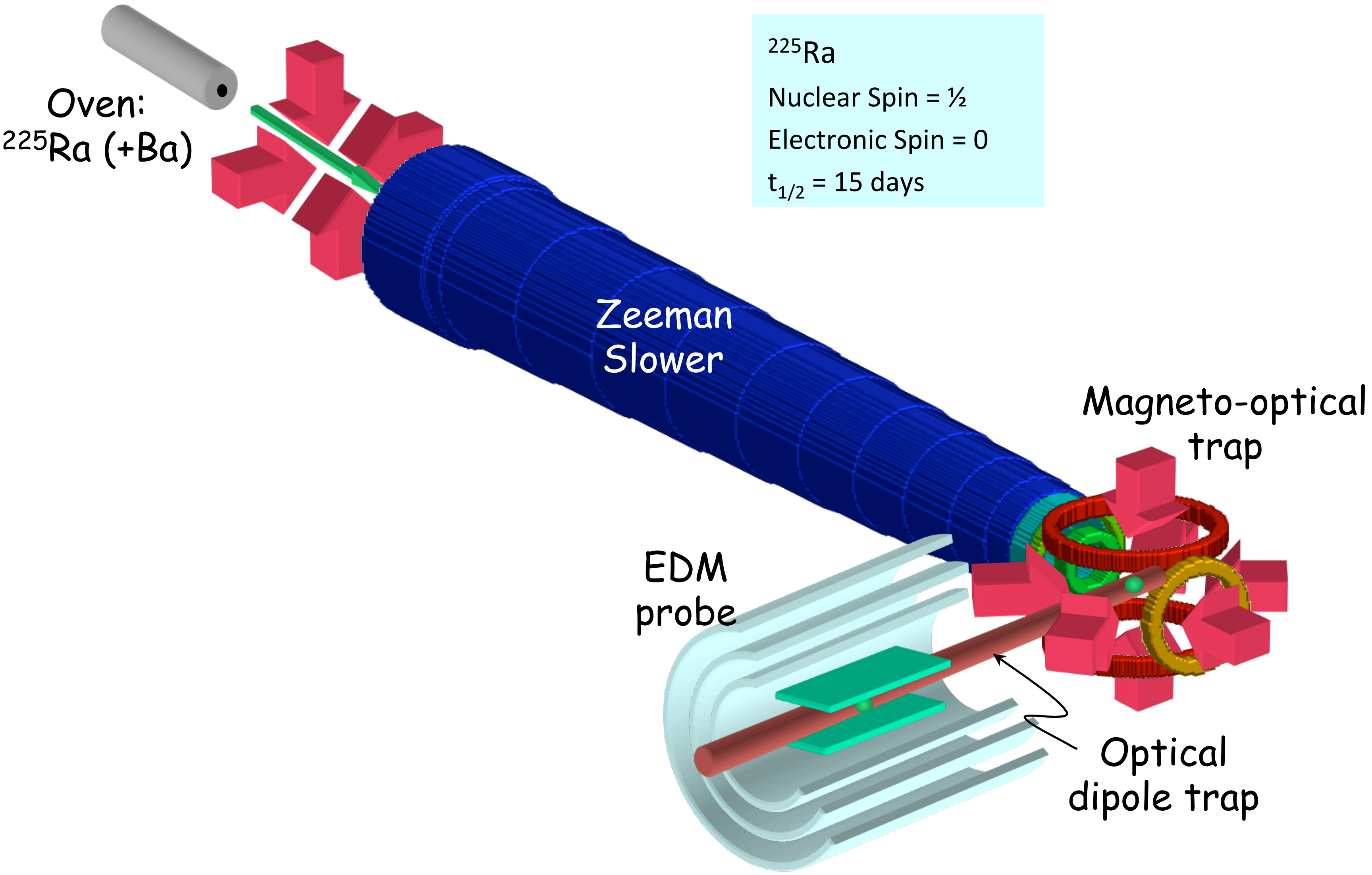
^{221}Rn (ISOLDE)

^{223}Rn: TBD

Estimate intrinsic Schiff moments from Q_3's



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



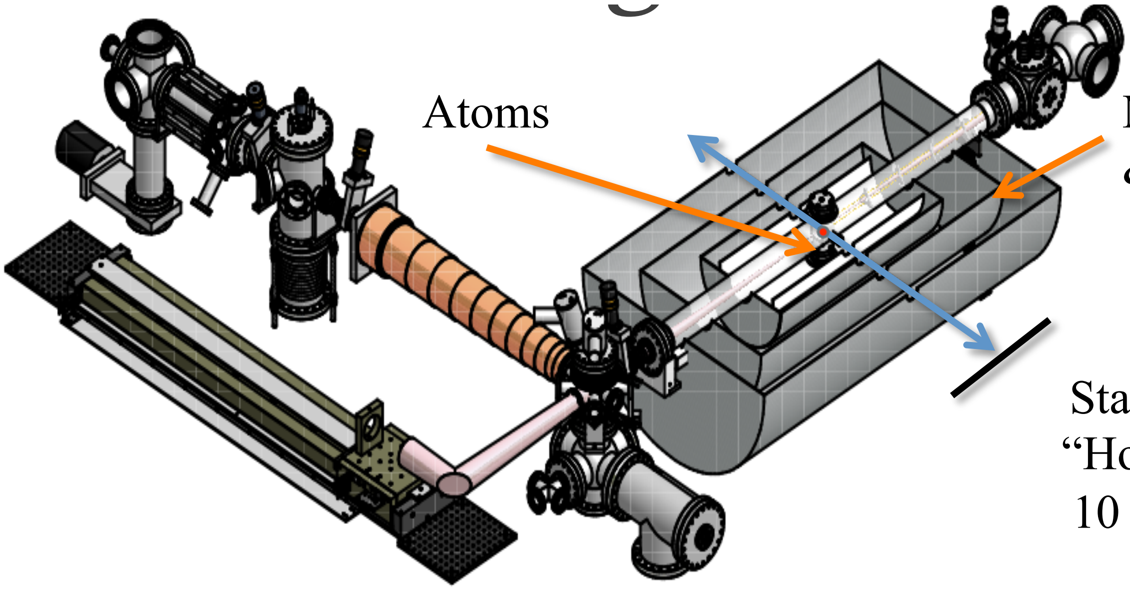
^{225}Ra

Nuclear Spin = ½

Electronic Spin = 0

$t_{1/2}$ = 15 days

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



Atoms

Magnetic Shielding
& Magnet Coils

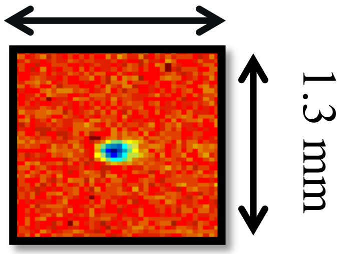
Standing Wave
“Holding” ODT
10 W 1550 nm

ODT→ODT Transfer: 70% Efficiency

R. H. Parker *et al.*, PRC **86**, 065503
(2012)

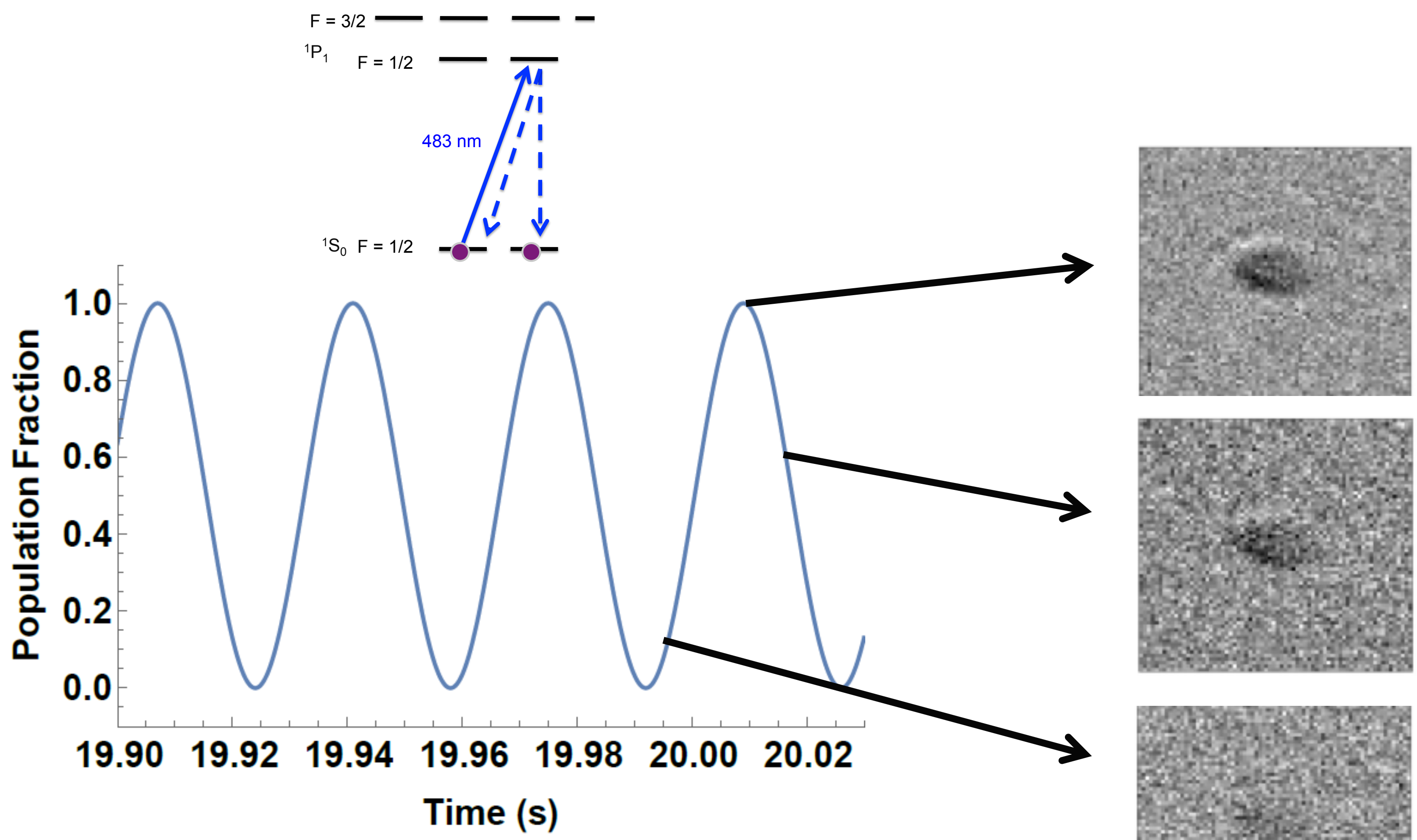
1.3 mm

700 atoms



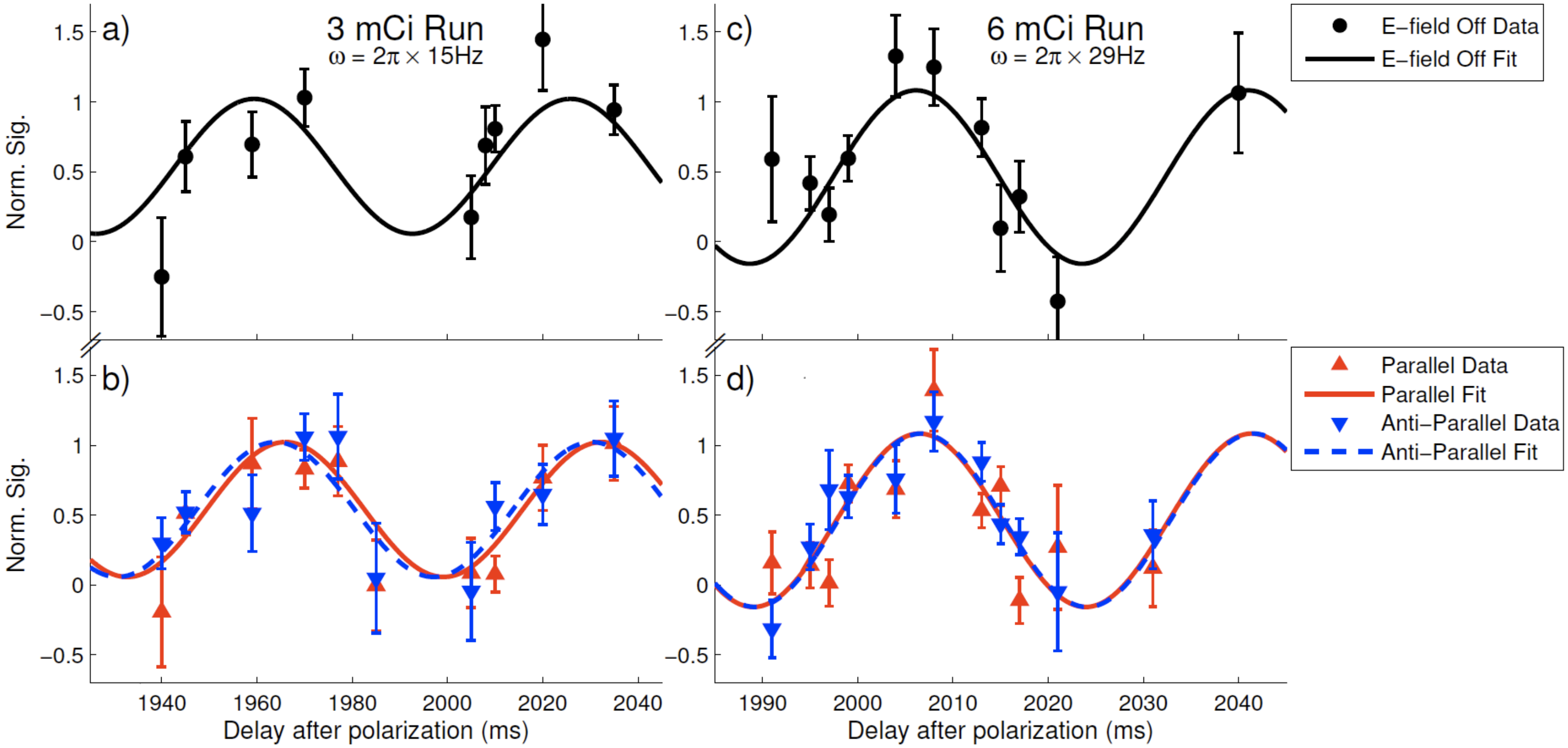
Absorption
Imaging

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



$$\sigma_d \approx \frac{1}{2E}\frac{\hbar}{T_2}\frac{1}{S/N}$$

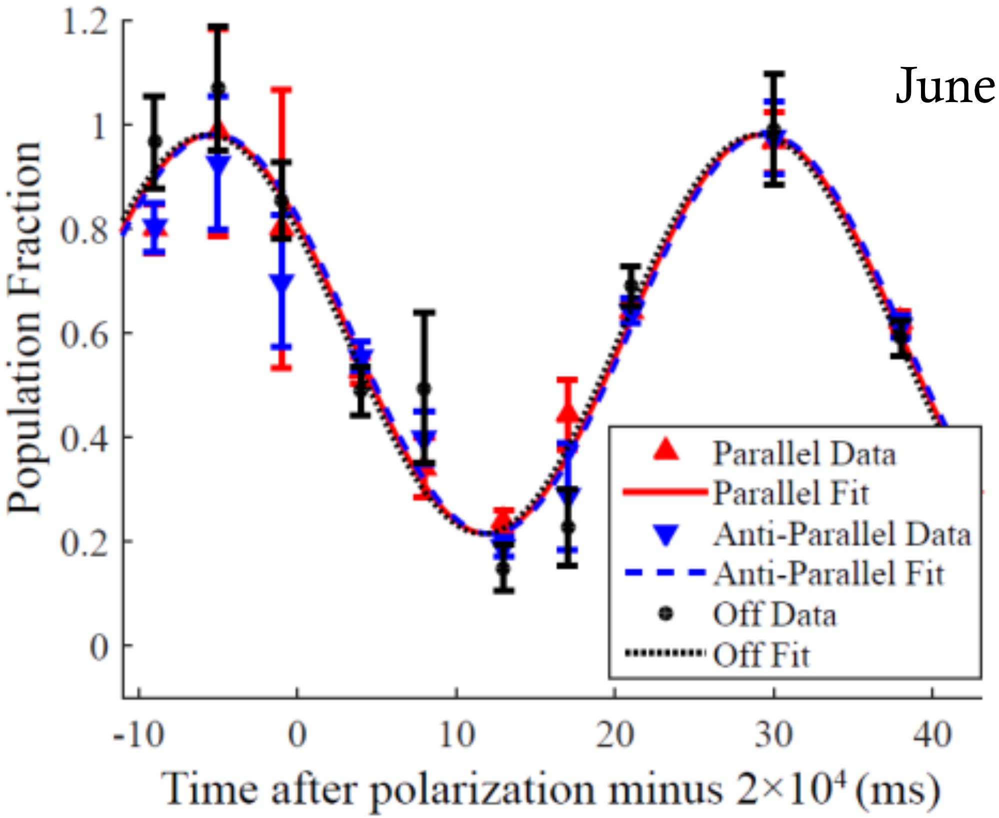
First Ra-225 EDM Measurements



$$|d(\text{Ra-225})| < 5\text{x}10^{-22}\ e\ \text{cm}\ (95\%)$$

- all systematic effects estimated to be $<10^{-25}$ *e* cm
- first EDM measurement made in a laser trap
- first EDM measurement of an octupole-deformed species

Second Ra-225 EDM Measurements



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

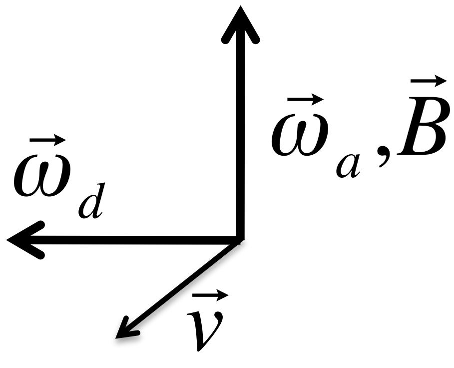
36-fold improvement in 6 months

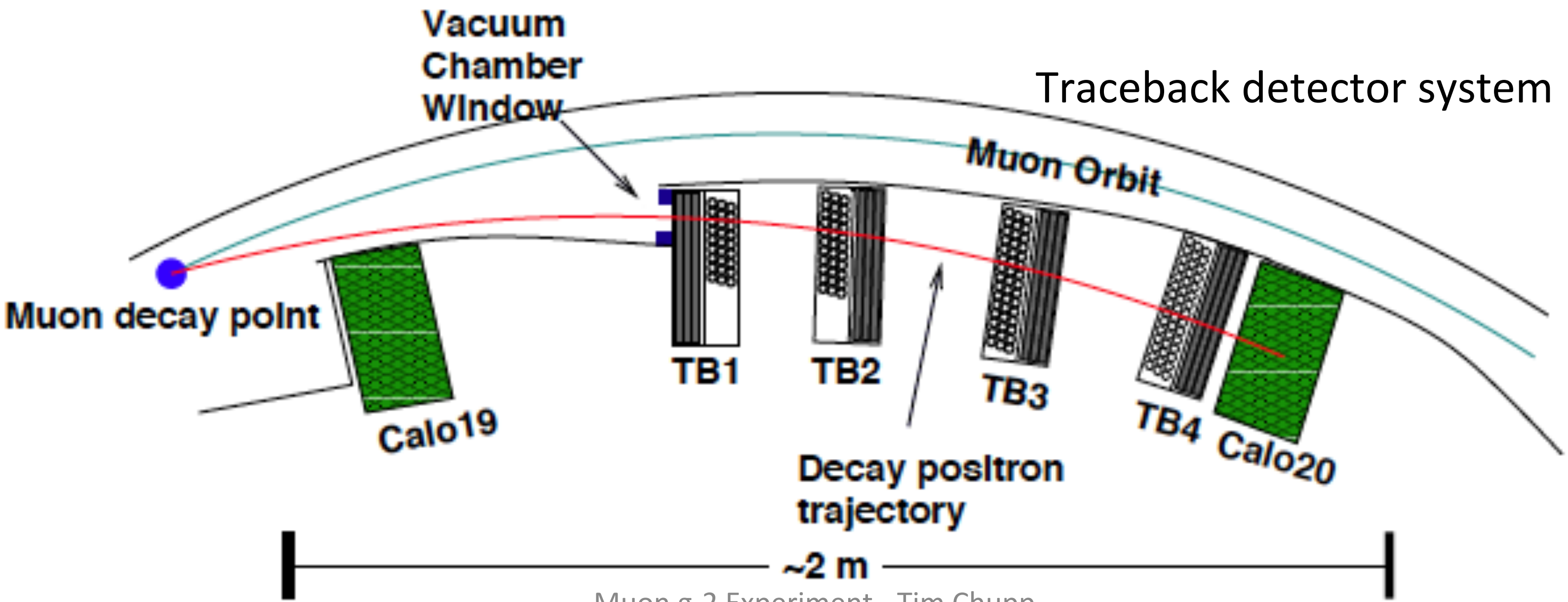
Hoping for 10^{-26} e-cm and smaller.

Storage ring EDMs $d_\mu \vec{s}_\mu$

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

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



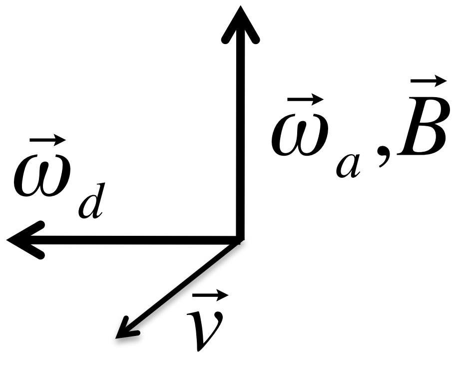


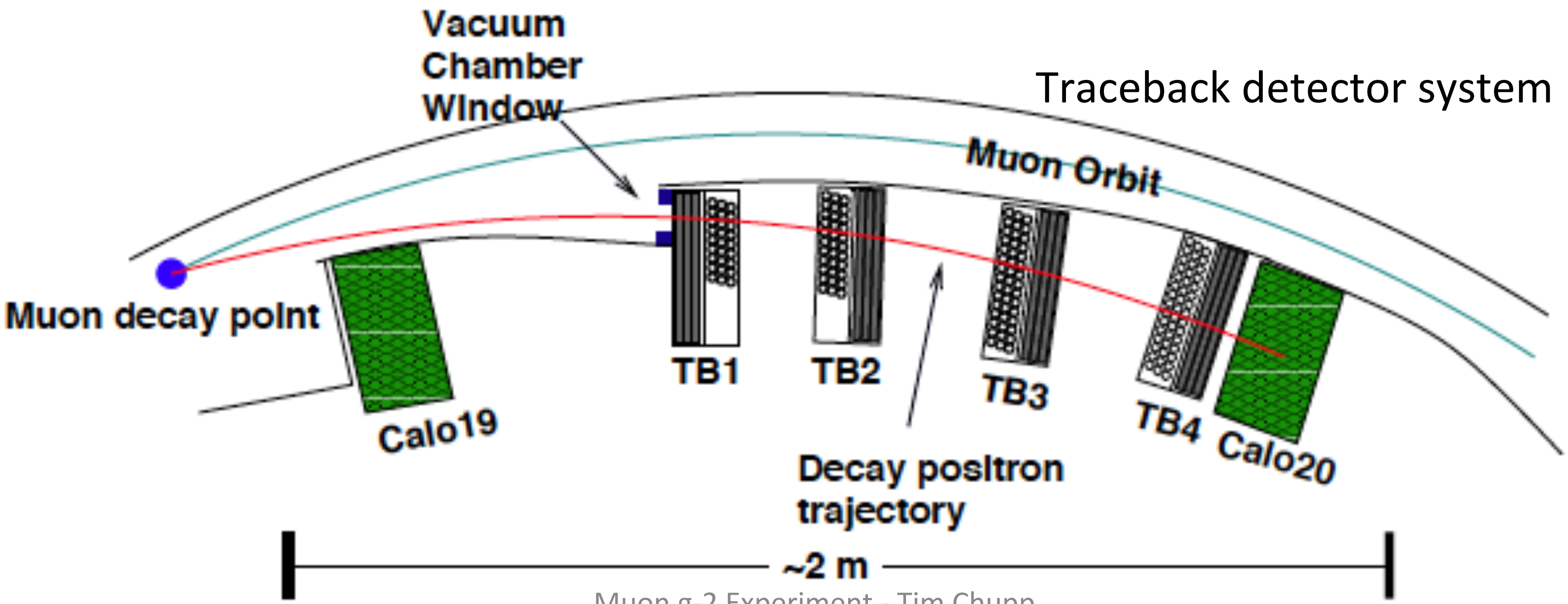
Traceback detector system

Storage ring EDMs $d_\mu \vec{s}_\mu$

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

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

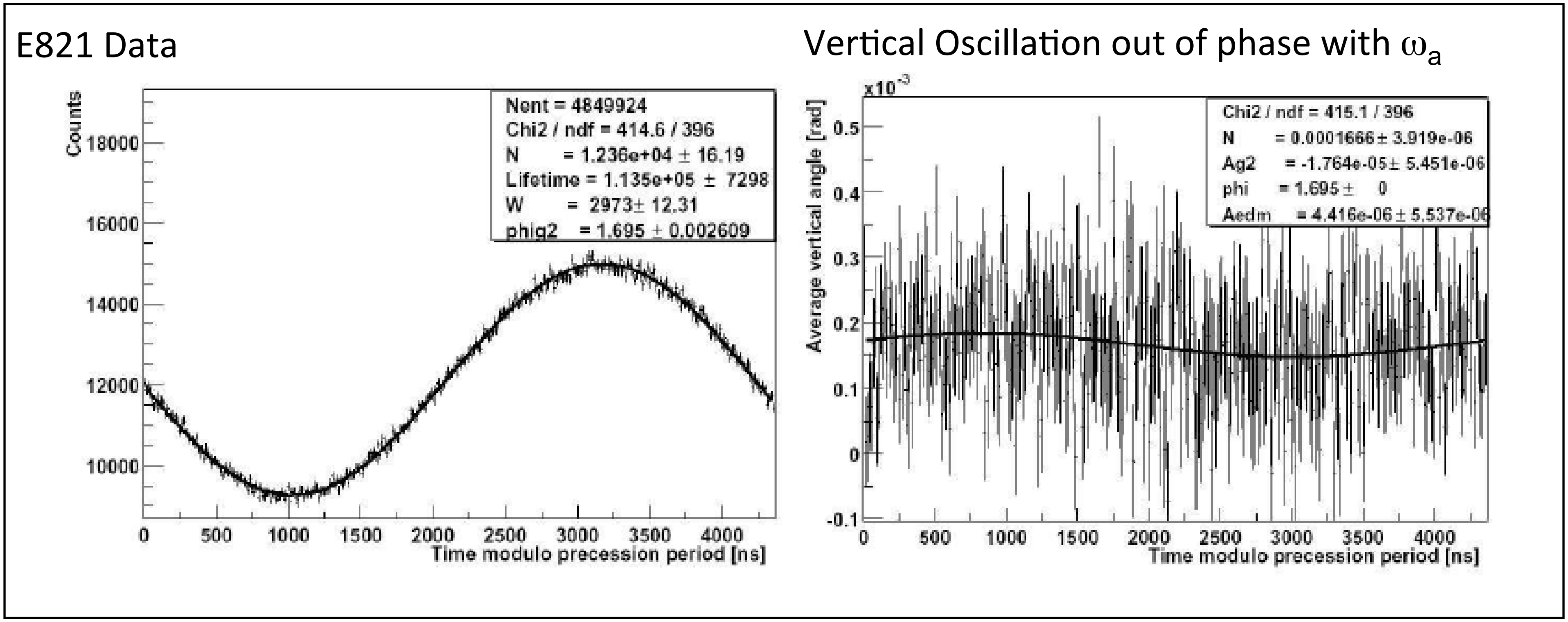




Traceback detector system

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

(g-2) EDM



E821 Data

Vertical Oscillation out of phase with ω_a

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

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

The industry of storage ring EDM efforts

particle (units)	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	+0.00117	3.094	29.3	1.45	0	4300	7.11	10^{-21}	E989
			0.3	3.0	3.0	0	8500	0.333	10^{-21}	E34
			0.5	5.0	0.25	22	760	7	10^{-24}	srEDM
			0.125	1.57	1	6.7	2300	0.42	10^{-24}	PSI
p^+	1/2	+1.79285	0.7007	1.248	0	80	80	52.3	10^{-29}	srEDM
			0.7007	1.248	0	140	140	30	10^{-29}	JEDI
d^+	1	−0.14299	1.0	1.13	0.5	120	580	8.4	10^{-29}	srEDM
			1.000	1.13	0.135	33	160	30	10^{-29}	JEDI
$^3\mathrm{He}^{++}$	1/2	−4.18415	1.211	1.09	0.042	140	89	30	10^{-29}	JEDI

Summary

New Results

- ThO – But 7x improvement improves 2-parameter limits by 2x
  - Need other experiments (HfF+) to "keep pace"

- ^{225}Ra – Octupole deformed
  - 100-1000x more sensitive to N-N CPV than Hg
  - 10^{6}x less sensitive experiment (for now)

- ^{129}Xe – HeXe WILL get 10x in coming ~year

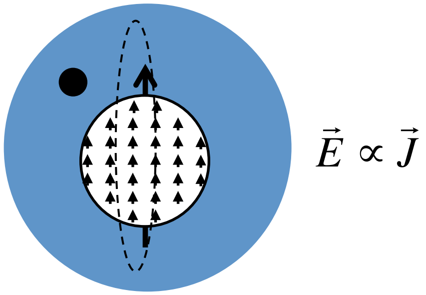
- ^{199}Hg will incrementally improve

Any experiment has discovery potential!

Backup Slides

Hadronic Systems

Currently: data from 5 experiments:



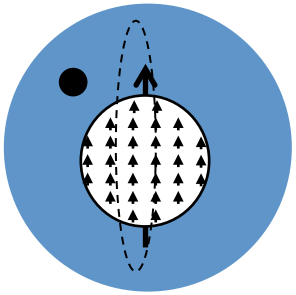
		d_0^{sr}	d_1^{sr}	C_T	g_π^0	g_π^1	
Current	neutron	1	-1				
	Xe, Hg, TlF, Ra			x	x	x	**Talk 0003** **1WDA.3**
Future	proton	1	+1				
	d, ^{3}H, ^{3}He				x	x	
	TlF, ^{173}YbOH						**Talk 0002/7**

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

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

Hadronic Systems

Currently: data from 5 experiments:



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

Results

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

Talk 00003

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

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

System	$\kappa_S = \frac{d}{S}$ (cm/fm^3)	$a_0 = \frac{S}{13.5\bar{g}_\pi^{(0)}}$ (e-fm^3)	$a_1 = \frac{S}{13.5\bar{g}_\pi^{(1)}}$ (e-fm^3)	$a_2 = \frac{S}{13.5\bar{g}_\pi(2)}$ (e-fm^3)	s_N (fm^2)
^{129}Xe	0.27×10^{-17} (0.27-0.38)	$-0.008(-0.005\text{-}(-0.05))$	$-0.006(-0.003\text{-}(-0.05))$	[illegible]	0.63
^{199}Hg	$-2.8 \times 10^{-17}(-4.0\text{-}(-2.8))$	0.01 (0.005-0.05)	± 0.02 $(-0.03\text{-}0.09)$		1.895 ± 0.035
^{225}Ra	-8.5×10^{-17} $(-8.5\text{-}(-6.8))$	-1.5 $(-6\text{-}(-1))$	+6.0 (4-24)	-4.0 $(-15\text{-}(-3))$	
TlF	-7.4×10^{-14}	-0.0124	0.1612	-0.0248	0.62

Talk 00004

Octupole enhanced Schiff moments: Talk IWDA:00001/2

Global Analysis

Find χ^2 contours for 4-parameters

$$d = \alpha_{d_e} d_e + \alpha_{C_S} C_S + \alpha_{C_T} C_T + \alpha_{\bar{d}_n^{\rm sr}} \bar{d}_n^{\rm sr} + \alpha_{\bar{d}_p^{\rm sr}} \bar{d}_p^{\rm sr} + \alpha_{g_\pi^0} \bar{g}_\pi^0 + \alpha_{g_\pi^1} \bar{g}_\pi^1$$

$$d_i = \sum_i \alpha_{ij} C_j$$

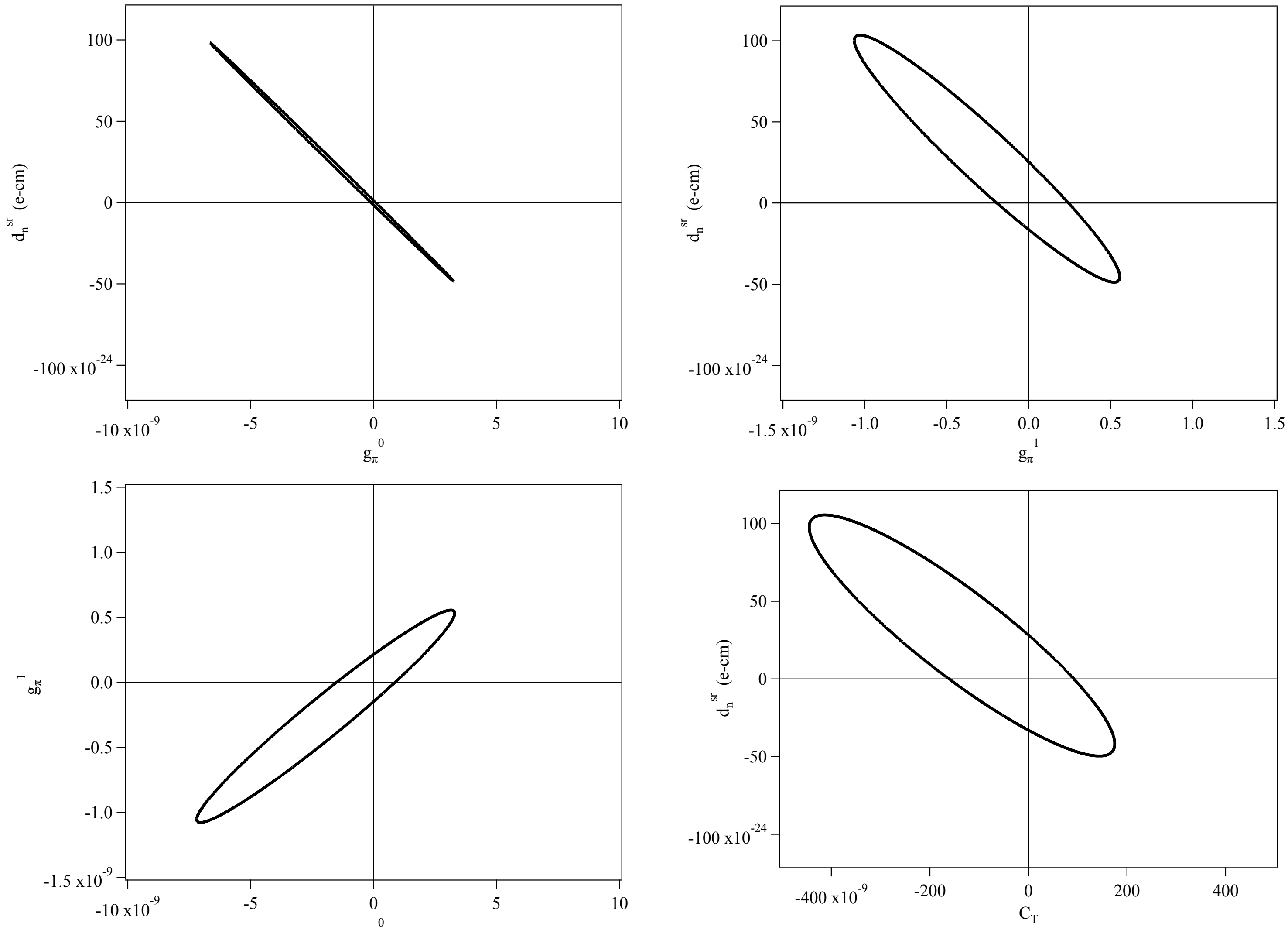
System	$\partial d^{exp}/\partial d_e$	$\partial d^{exp}/\partial C_S$	$\partial d^{exp}/\partial C_T^{(0)}$	$\partial d^{exp}/\partial g_\pi^0$	$\partial d^{exp}/\partial g_\pi^1$	$\partial d^{exp}/\partial \bar{d}_n^{sr}$
neutron	0	0	0	1.5×10^{-14}	1.4×10^{-16}	1
^{129}Xe	-0.0008	-4.4×10^{-23} -4.4-(-5.6)	-6.1×10^{-21} -6.1-(-9.1)	-0.4×10^{-19} -23.4-(1.8)	-2.2×10^{-19} -19-(-1.1)	1.7×10^{-5} 1.7-2.4
^{199}Hg	-0.014 -0.014-0.012	-5.9×10^{-22}	3.0×10^{-20} 3.0-9.0	-11.8×10^{-18} -38-(-9.9)	0 $(-4.9$-$1.6) \times 10^{-17}$	-5.3×10^{-4} -7.7-(-5.2)
^{225}Ra			5.3×10^{-20}	1.7×10^{-15} 6.9-0.9	-6.9×10^{-15} -27.5-(-3.8)	$(-1.6$-$0) \times 10^{-3}$
TlF	81	2.9×10^{-18}	2.7×10^{-16}	1.9×10^{-14} 0.5-2	-1.6×10^{-13}	0.46 -0.5-0.5

$$\chi^2(\mathbf{C_j}) = \sum_i \frac{(d_i^{\rm exp} - d_i)^2}{\sigma^2_{d_i^{\rm exp}}}$$

TC, Fierlinger, Ramsey-Musolf, Singh

Global Analysis

$$\chi^2(\mathbf{C_j}) = \sum_i \frac{(d_i^{\exp} - d_i)^2}{\sigma^2_{d_i^{\exp}}}$$



TC, Fierlinger, Ramsey-Musolf, Singh

Global Analysis

$$\chi^2(\mathbf{C_j}) = \sum_i \frac{(d_i^{\mathrm{exp}} - d_i)^2}{\sigma^2_{d_i^{\mathrm{exp}}}}$$

	$\bar{d}_n^{\mathrm{sr}}$ (e cm)	$\bar{g}_\pi^{(0)}$	$\bar{g}_\pi^{(1)}$	$C_T^{(0)}$
Range from best values with $\alpha_{g_\pi^1}(\mathrm{Hg}) = +1.6 \times 10^{-17}$	$(-4.8\text{-}9.8) \times 10^{-23}$	$(-6.6\text{-}3.2) \times 10^{-9}$	$(-1.0\text{-}0.5) \times 10^{-9}$	$(-3.5\text{-}1.6) \times 10^{-7}$
Range from best values with $\alpha_{g_\pi^1}(\mathrm{Hg}) = 0$	$(-4.3\text{-}3.4) \times 10^{-23}$	$(-2.3\text{-}2.9) \times 10^{-9}$	$(-0.6\text{-}1.3) \times 10^{-9}$	$(-3.2\text{-}4.0) \times 10^{-7}$
Range from best values with $\alpha_{g_\pi^1}(\mathrm{Hg}) = -4.9 \times 10^{-17}$	$(-9.3\text{-}2.6) \times 10^{-23}$	$(-1.8\text{-}6.3) \times 10^{-9}$	$(-1.2\text{-}0.4) \times 10^{-9}$	$(-11\text{-}3.8) \times 10^{-7}$
Range from full variation of α_{ij}	$(-12\text{-}12) \times 10^{-23}$	$(-7.9\text{-}7.8) \times 10^{-9}$	$(-1.3\text{-}1.1) \times 10^{-9}$	$(-6.6\text{-}4.6) \times 10^{-7}$
Upper limits (95% c.l.)	2.4×10^{-22}	1.5×10^{-8}	2.4×10^{-9}	1.1×10^{-6}

Deciding which experiment to work on

$$d_i = \sum_i \alpha_{ij} C_j$$

$$\begin{bmatrix} d_n \\ d_{Xe} \\ d_{Hg} \\ d_{Ra} \end{bmatrix} = \begin{bmatrix} 1.00\mathrm{E} & 1.50\times10^{-14} & 1.40\times10^{-16} & 0 \\ 1.70\times10^{-5} & -5.50\times10^{-19} & -2.20\times10^{-19} & 4.00\times10^{-21} \\ -5.30\times10^{-4} & -1.20\times10^{-17} & 1.60\times10^{-17} & -2.00\times10^{-20} \\ -1.00\times10^{-3} & 1.70\times10^{-15} & -6.90\times10^{-15} & 5.30\times10^{-6} \end{bmatrix} \times \begin{bmatrix} C_T \\ \tilde{g}_\pi^0 \\ \tilde{g}_\pi^1 \\ d_n^{sr} \end{bmatrix}$$

$$\begin{bmatrix} C_T \\ \tilde{g}_\pi^0 \\ \tilde{g}_\pi^1 \\ d_n^{sr} \end{bmatrix} = \begin{bmatrix} 2.55 & 1.73\times10^{4} & 3.47\times10^{3} & 7.55 \\ -1.03\times10^{14} & -1.15\times10^{18} & -2.31\times10^{17} & -5.01\times10^{14} \\ -2.60\times10^{13} & -2.85\times10^{17} & -5.78\times10^{16} & -2.70\times10^{14} \\ -2.65\times10^{16} & 3.16\times10^{18} & -4.97\times10^{19} & -1.16\times10^{17} \end{bmatrix} \times \begin{bmatrix} d_{Hg} \\ d_{Xe} \\ d_{TlF} \\ d_n \end{bmatrix}$$

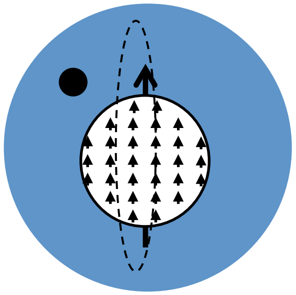
$$\bar{d}_n^{sr} = 5.2 d_n + 4.7 \times 10^4 d_{\mathrm{Xe}} + 9.5 \times 10^3 d_{\mathrm{Hg}} \boxed{+ 21 d_{\mathrm{Ra}}}$$

TC, Fierlinger, Ramsey-Musolf, Singh

Hadronic Systems

Currently: data from 5 experiments:

Upcoming experiments

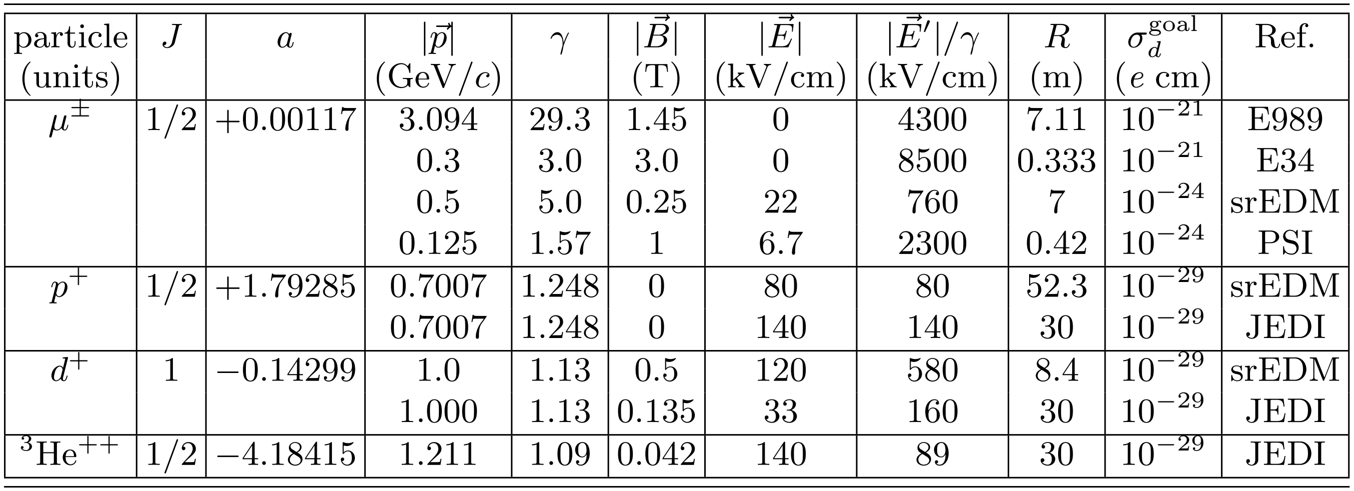


$\vec{E} \propto \vec{J}$

	d_0^{sr}	d_1^{sr}	C_T	g_π^0	g_π^1
proton	1	+1			
d, ^3H, ^3He				x	x
TlF, $^{173}YbOH$					

Talk 00002

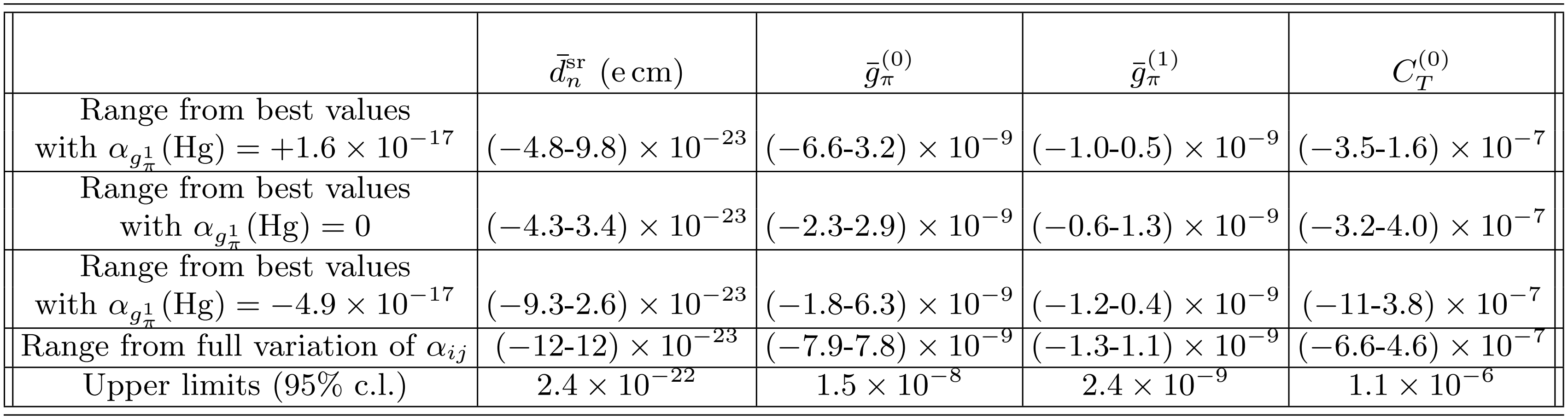
Talk 00007



particle (units)	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	+0.00117	3.094	29.3	1.45	0	4300	7.11	10^{-21}	E989
			0.3	3.0	3.0	0	8500	0.333	10^{-21}	E34
			0.5	5.0	0.25	22	760	7	10^{-24}	srEDM
			0.125	1.57	1	6.7	2300	0.42	10^{-24}	PSI
p^+	1/2	+1.79285	0.7007	1.248	0	80	80	52.3	10^{-29}	srEDM
			0.7007	1.248	0	140	140	30	10^{-29}	JEDI
d^+	1	−0.14299	1.0	1.13	0.5	120	580	8.4	10^{-29}	srEDM
			1.000	1.13	0.135	33	160	30	10^{-29}	JEDI
$^3He^{++}$	1/2	−4.18415	1.211	1.09	0.042	140	89	30	10^{-29}	JEDI

Global Analysis

$$\chi^2(\mathbf{C_j}) = \sum_i \frac{(d_i^{\mathrm{exp}} - d_i)^2}{\sigma^2_{d_i^{\mathrm{exp}}}}$$



	$\bar{d}_n^{\mathrm{sr}}$ (e cm)	$\bar{g}_\pi^{(0)}$	$\bar{g}_\pi^{(1)}$	$C_T^{(0)}$
Range from best values with $\alpha_{g_\pi^1}(\mathrm{Hg}) = +1.6 \times 10^{-17}$	$(-4.8\text{-}9.8) \times 10^{-23}$	$(-6.6\text{-}3.2) \times 10^{-9}$	$(-1.0\text{-}0.5) \times 10^{-9}$	$(-3.5\text{-}1.6) \times 10^{-7}$
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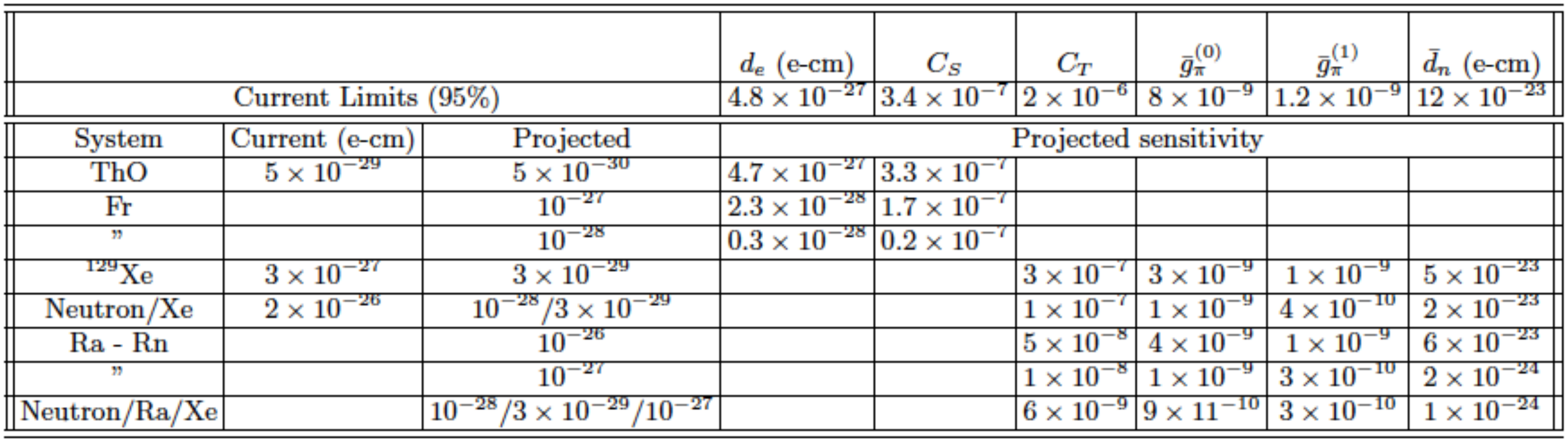
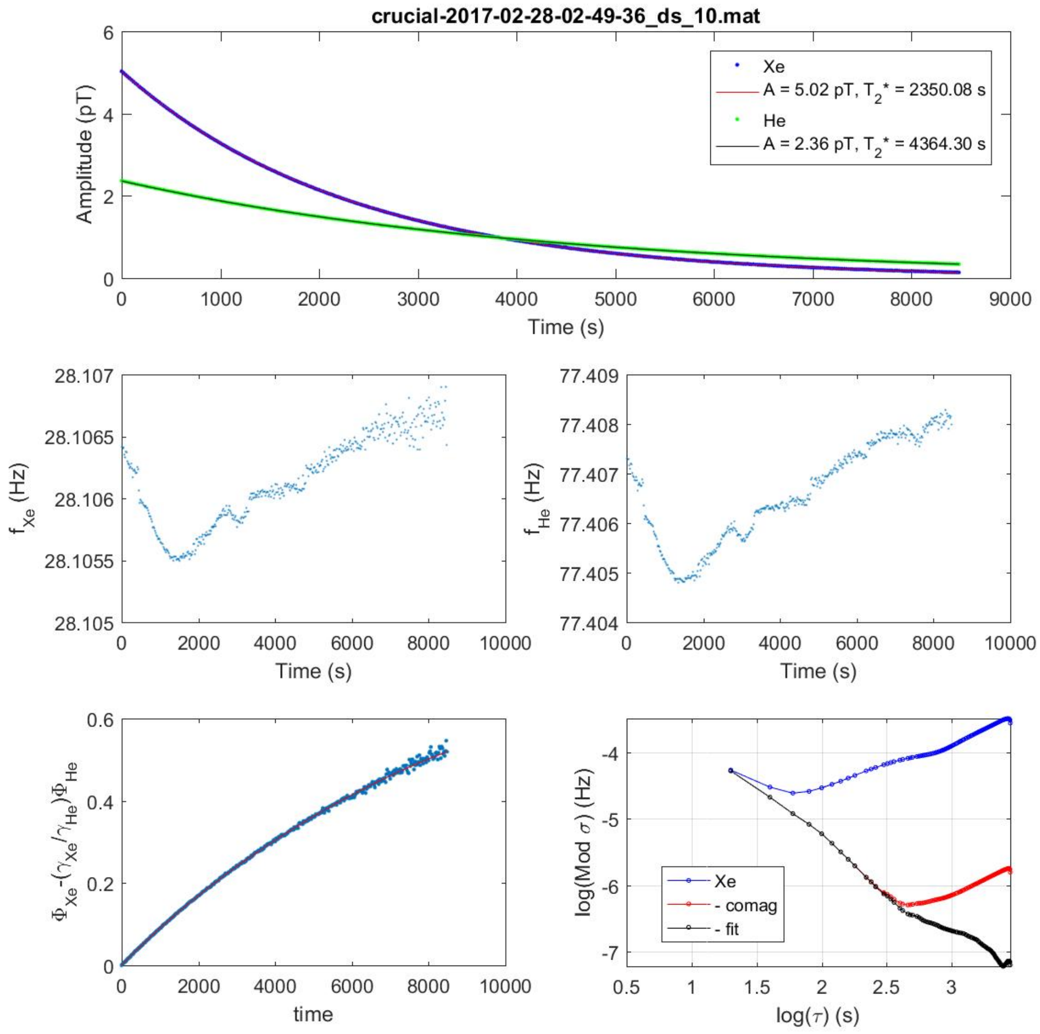
Upper limits (95% c.l.)	2.4×10^{-22}	1.5×10^{-8}	2.4×10^{-9}	1.1×10^{-6}

Prospects

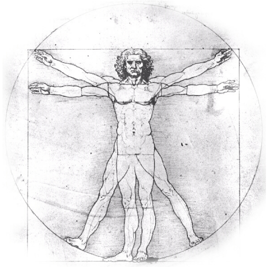


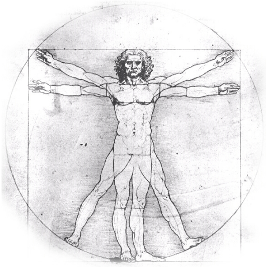
			d_e (e-cm)	C_S	C_T	$\bar{g}_\pi^{(0)}$	$\bar{g}_\pi^{(1)}$	$\bar{d}_n$ (e-cm)
Current Limits (95%)			4.8×10^{-27}	3.4×10^{-7}	2×10^{-6}	8×10^{-9}	1.2×10^{-9}	12×10^{-23}
System	Current (e-cm)	Projected	Projected sensitivity					
ThO	5×10^{-29}	5×10^{-30}	4.7×10^{-27}	3.3×10^{-7}				
Fr		10^{-27}	2.3×10^{-28}	1.7×10^{-7}				
”		10^{-28}	0.3×10^{-28}	0.2×10^{-7}				
^{129}Xe	3×10^{-27}	3×10^{-29}			3×10^{-7}	3×10^{-9}	1×10^{-9}	5×10^{-23}
Neutron/Xe	2×10^{-26}	$10^{-28}/3 \times 10^{-29}$			1×10^{-7}	1×10^{-9}	4×10^{-10}	2×10^{-23}
Ra - Rn		10^{-26}			5×10^{-8}	4×10^{-9}	1×10^{-9}	6×10^{-23}
”		10^{-27}			1×10^{-8}	1×10^{-9}	3×10^{-10}	2×10^{-24}
Neutron/Ra/Xe		$10^{-28}/3 \times 10^{-29}/10^{-27}$			6×10^{-9}	9×11^{-10}	3×10^{-10}	1×10^{-24}

HeXeEDM


crucial-2017-02-28-02-49-36_ds_10.mat
Amplitude (pT)
Time (s)
Xe
A = 5.02 pT, T_2^* = 2350.08 s
He
A = 2.36 pT, T_2^* = 4364.30 s
0
2
4
6
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
f_{Xe} (Hz)
28.107
28.1065
28.106
28.1055
28.105
Time (s)
f_{He} (Hz)
77.409
77.408
77.407
77.406
77.405
77.404
Time (s)
0
2000
4000
6000
8000
10000
$\Phi_{Xe}-(\gamma_{Xe}/\gamma_{He})\Phi_{He}$
0.6
0.4
0.2
0
time
log(Mod σ) (Hz)
-4
-5
-6
-7
log(τ) (s)
0.5
1
1.5
2
2.5
3
Xe
- comag
- fit

Radon-EDM Experiment





TRIUMF E929

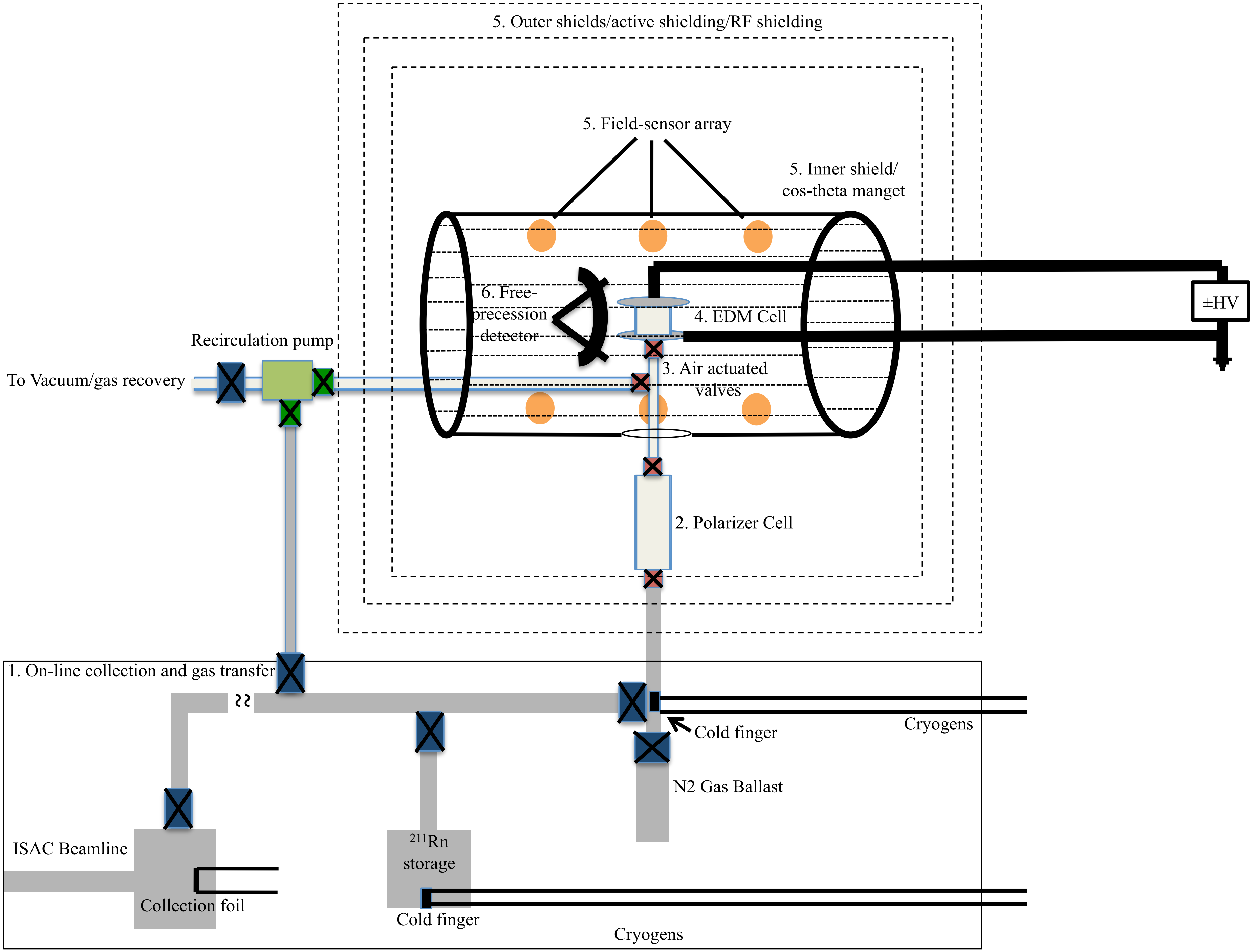
Spokesmen: Timothy Chupp & Carl Svensson

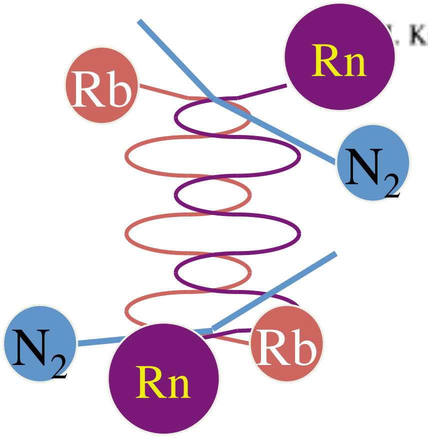
E-929 Collaboration (Guelph, Michigan, SFU, TRIUMF)

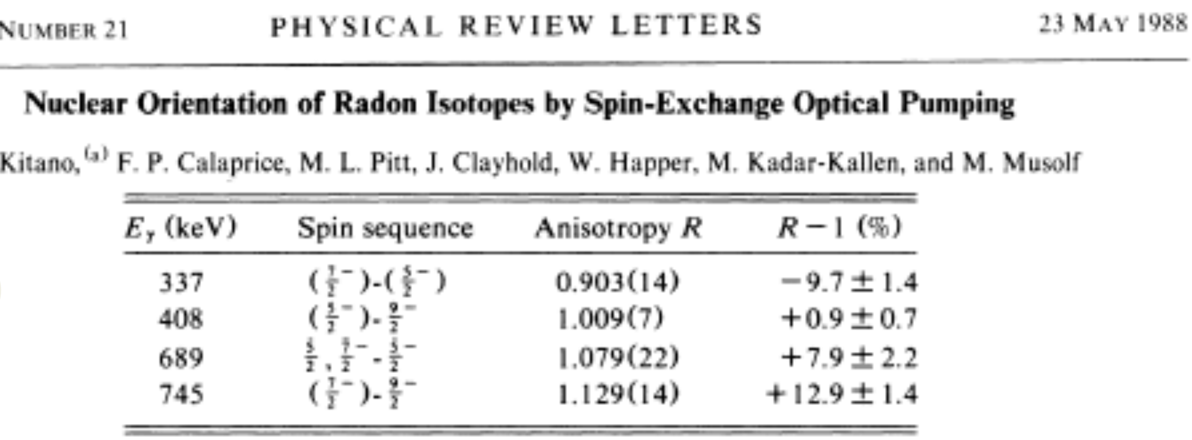
TRIUMF

Canada's National Laboratory for Particle and Nuclear Physics

Funding: NSF-Focus Center, DOE, NRC (TRIUMF), NSERC


5. Outer shields/active shielding/RF shielding
5. Field-sensor array
5. Inner shield/
cos-theta manget
6. Free-
precession
detector
4. EDM Cell
±HV
Recirculation pump
To Vacuum/gas recovery
3. Air actuated
valves
2. Polarizer Cell
1. On-line collection and gas transfer
Cold finger
Cryogens
N2 Gas Ballast
ISAC Beamline
Collection foil
^{211}Rn
storage
Cold finger
Cryogens

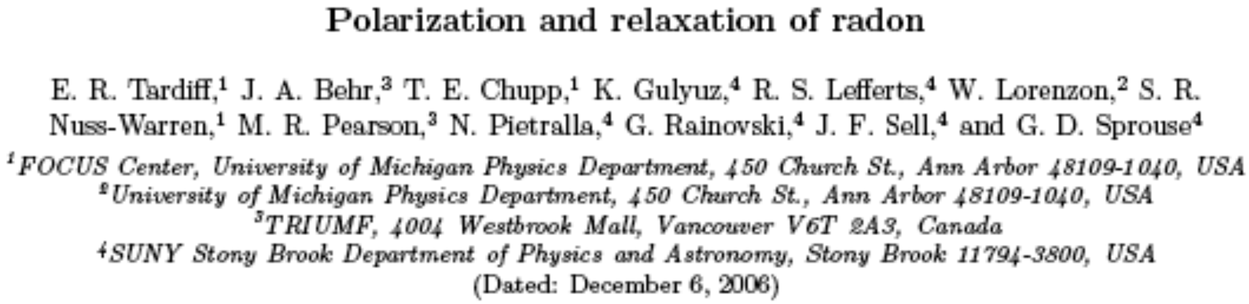



VOLUME 60, NUMBER 21 PHYSICAL REVIEW LETTERS 23 MAY 1988

Nuclear Orientation of Radon Isotopes by Spin-Exchange Optical Pumping

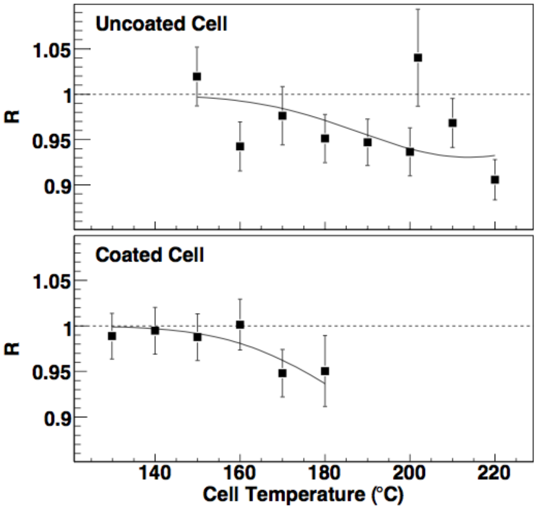
Kitano,(a) F. P. Calaprice, M. L. Pitt, J. Clayhold, W. Happer, M. Kadar-Kallen, and M. Musolf

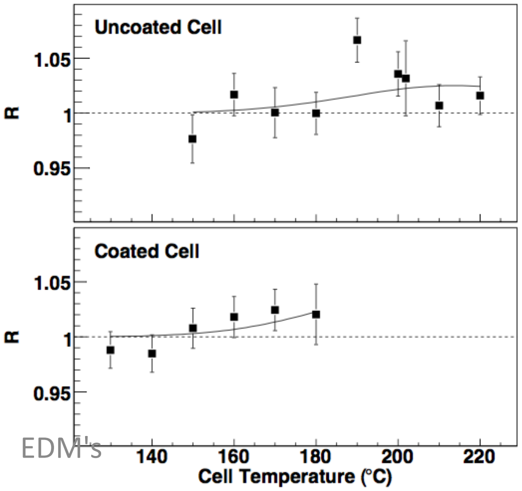
E_γ (keV)	Spin sequence	Anisotropy R	$R-1$ (%)
337	$(\frac{7}{2}^-)$-$(\frac{5}{2}^-)$	0.903(14)	-9.7 ± 1.4
408	$(\frac{5}{2}^-)$-$\frac{9}{2}^-$	1.009(7)	$+0.9 \pm 0.7$
689	$\frac{5}{2}, \frac{7}{2}^-$-$\frac{5}{2}^-$	1.079(22)	$+7.9 \pm 2.2$
745	$(\frac{7}{2}^-)$-$\frac{9}{2}^-$	1.129(14)	$+12.9 \pm 1.4$


Polarization and relaxation of radon

E. R. Tardiff,[1] J. A. Behr,[3] T. E. Chupp,[1] K. Gulyuz,[4] R. S. Lefferts,[4] W. Lorenzon,[2] S. R. Nuss-Warren,[1] M. R. Pearson,[3] N. Pietralla,[4] G. Rainovski,[4] J. F. Sell,[4] and G. D. Sprouse[4]

[1] *FOCUS Center, University of Michigan Physics Department, 450 Church St., Ann Arbor 48109-1040, USA*
[2] *University of Michigan Physics Department, 450 Church St., Ann Arbor 48109-1040, USA*
[3] *TRIUMF, 4004 Westbrook Mall, Vancouver V6T 2A3, Canada*
[4] *SUNY Stony Brook Department of Physics and Astronomy, Stony Brook 11794-3800, USA*
(Dated: December 6, 2006)

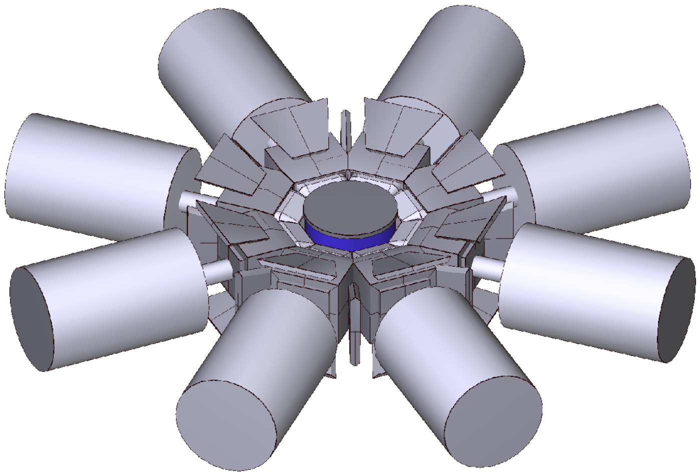


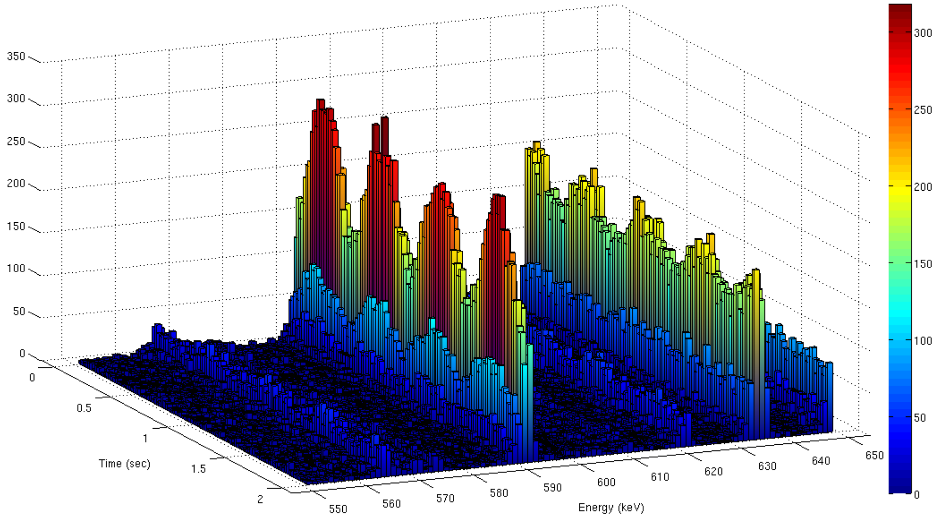


Fit for Γ_2 (T_a=300°K):
0.05 Hz (uncoated);
0.03 Hz (coated)s
Use $2.5\text{x}10^{-21}$ cm^2

Genat-4 simulations by Evan Rand

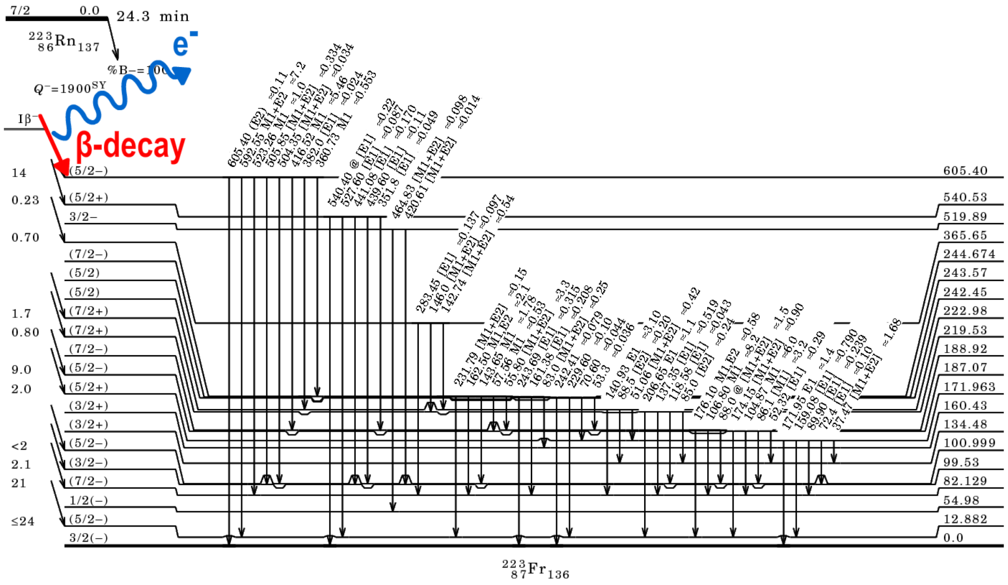
γ-ray energy-time matrix from the β decay of 1.2 billion ^{223}Rn nuclei from an initial 8×10^{10} nuclei located in the EDM cell surrounded by a ring of eight GRIFFIN detectors in the forward position.

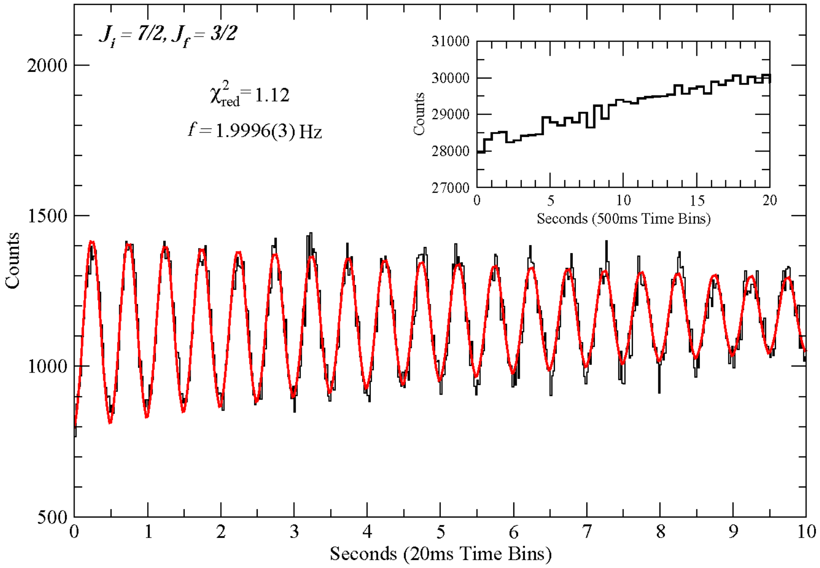




Known Level Structure of ^{223}Fr

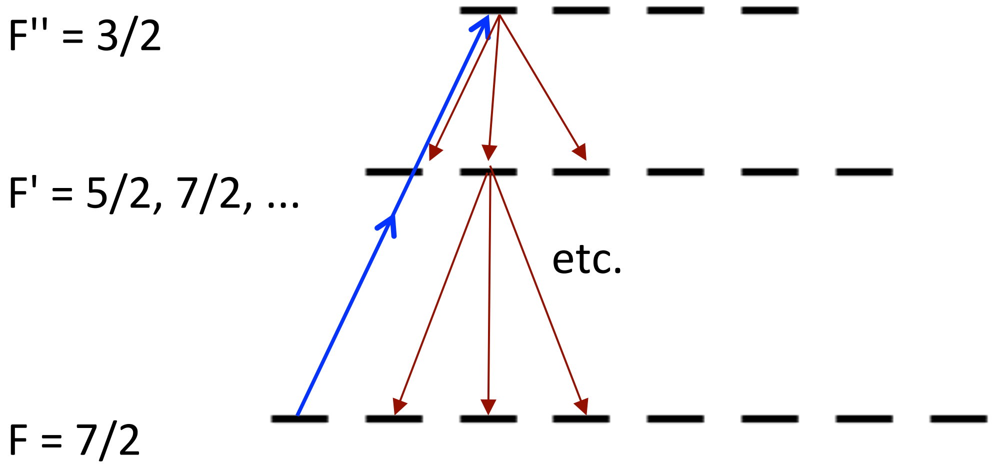
- *Nuclear Data Sheets (2001)*

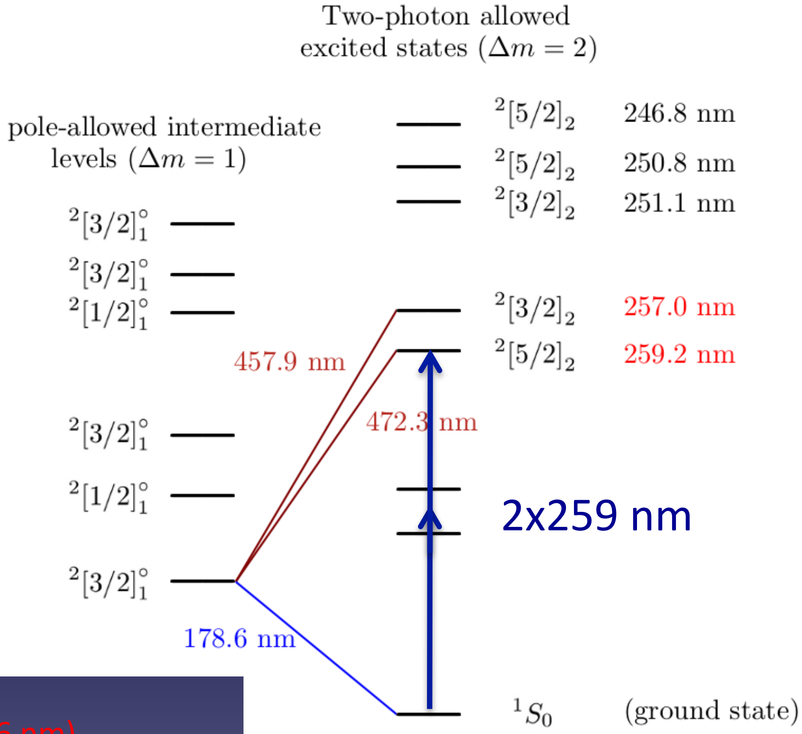


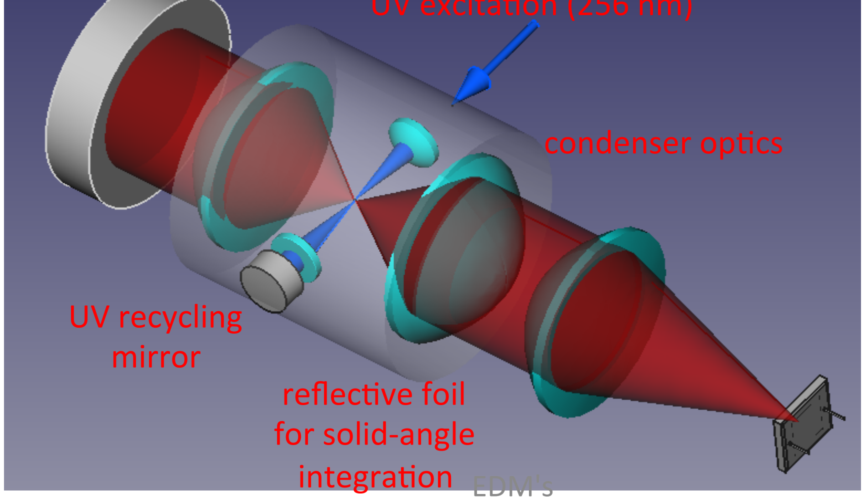


Two-photon magnetometry with $^{221/223}$Rn (J=7/2)

S. Degenkolb







Radon-EDM Prospects

Compare to ^{199}Hg: $d<3\times10^{-29}$ e-cm (90%)

Facility	**TRIUMF-ISAC**	**FRIB(^{223}Th)**
Rate	$2.5\text{x}10^{7}$ s^{-1}	$1\text{x}10^{9}$ s^{-1}
# atoms	$3.5\text{x}10^{10}$	$1.4\text{x}10^{12}$
σ_{EDM} (100 d)	$2\text{x}10^{-27}$ e-cm	$3\text{x}10^{-28}$ e-cm
^{199}Hg equivalent	$4\text{x}10^{-28/29}$ e-cm	$6\text{x}10^{-29/30}$ e-cm

Assumptions: E=10 kV/cm, T_2=15 s, A=0.2, 25% duty factor

$$\sigma_d \approx \frac{1}{2E}\frac{\hbar}{AT_2}\frac{1}{\sqrt{N_\gamma}}$$