Probing beyond the Standard Model at Low Energy

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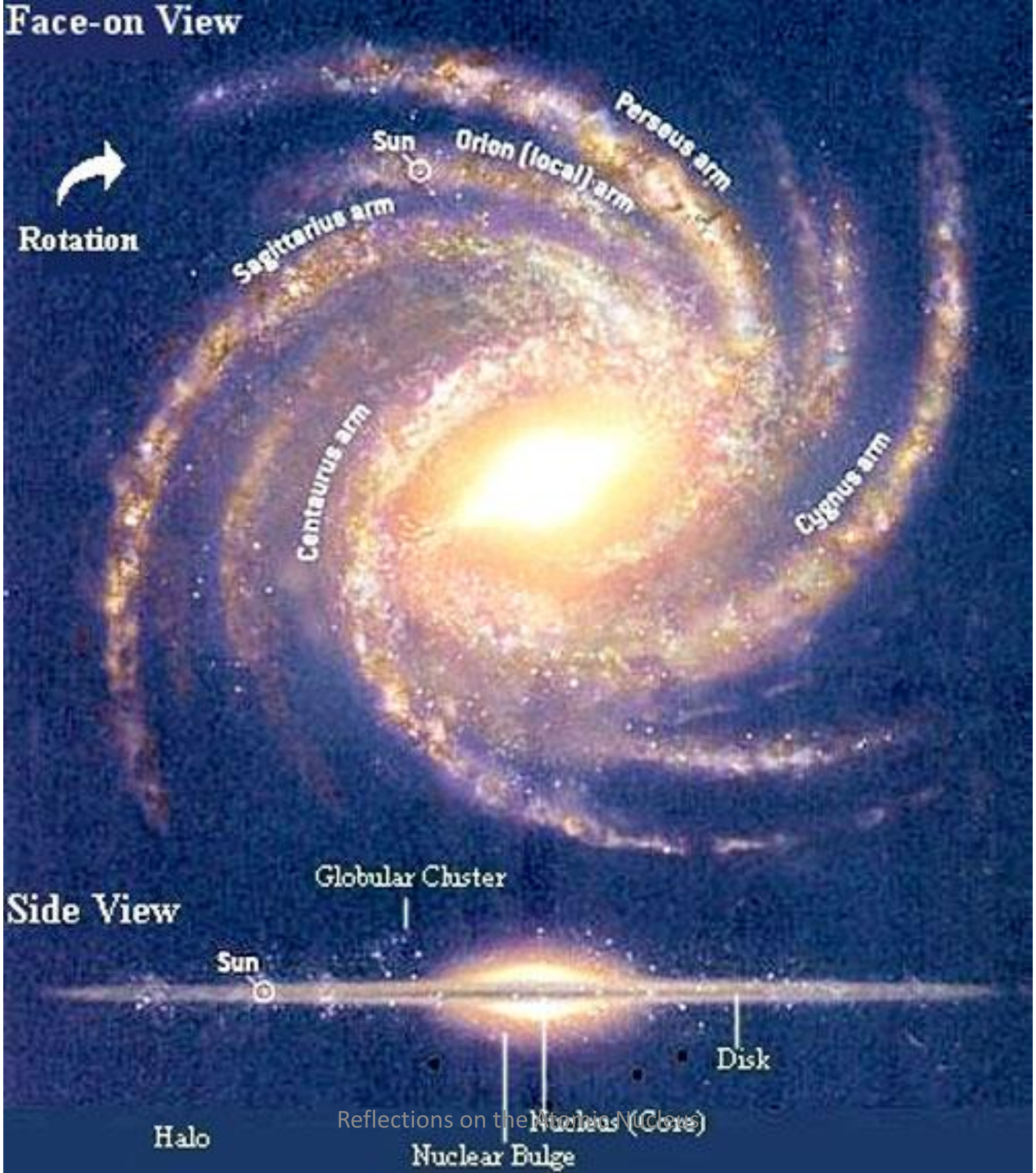
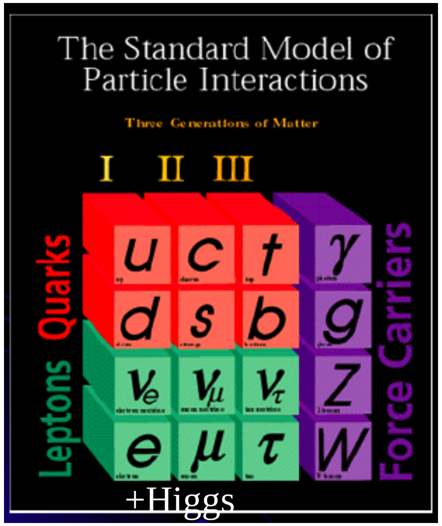

Face-on View
Rotation
Sun
Orion (local) arm
Perseus arm
Sagittarius arm
Centaurus arm
Cygnus arm
Globular Cluster
Side View
Sun
Disk
Halo
Nucleus (Core)
Nuclear Bulge

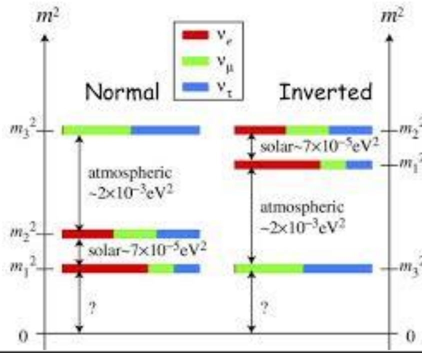
What we know

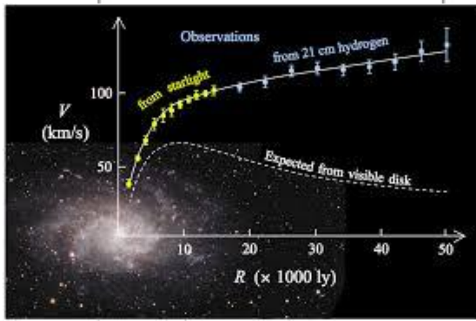
- The Standard Model of particles and forces
  - QFT with radiative corrections
  - Massive neutrinos
- Gravity weak and strong (GR) => dynamics
  (we can send a satellite to Pluto!)
  - Dark matter/Dark energy
- The universe is MATTER dominant



What we don't know

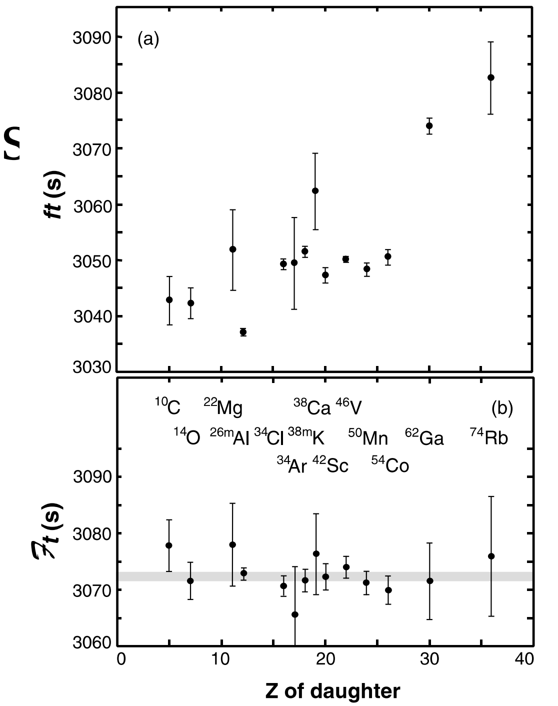
- How neutrinos acquire mass
  - Dirac/Higgs($m_\nu < 10^{-6}\, m_e$; $m_u \sim m_d \sim 10^{-6}\, m_t$)
- What is *THE* dark matter/what is dark energy
- What made the universe MATTER dominant
  - Baryogenesis

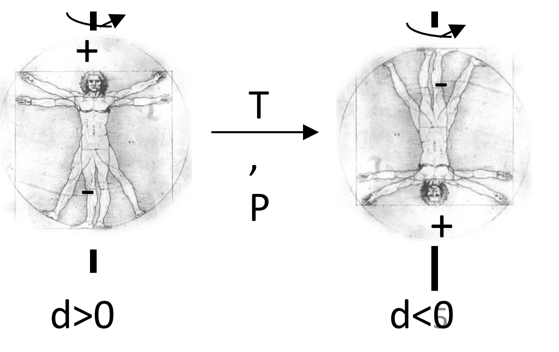




Where to look

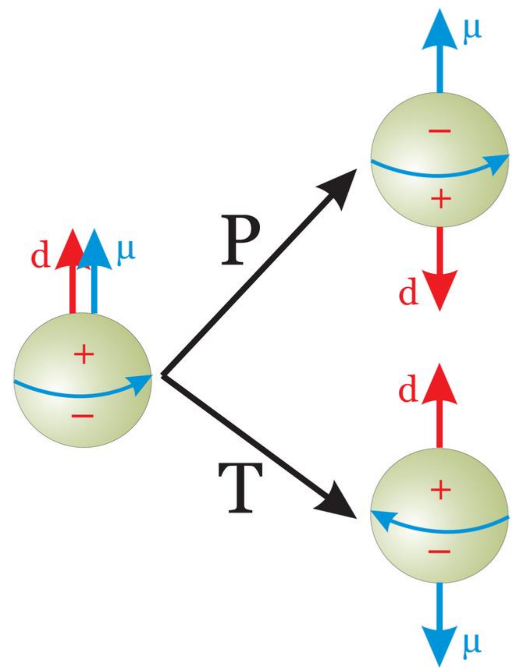
- High energy, rare decays, exotic processes (astro)
- Muon g-2
  - Precise SM predictions (with uncertainties
  - 3.7σ difference of experiment and theory
- Beta-decay: neutron, nuclei
  - Probe BSM through T violation
  - Measure CKM element V_{ud}
- Permanent electric dipole moments
  - SM predicts EDMs<<current sensitivity
    - Note θ_{QCD} contribution (inexplicably small)





EDMs

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



Put this in *E* and *B* fields

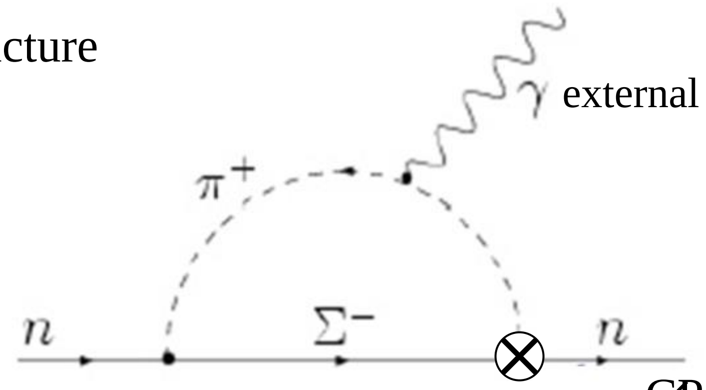
$$H = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E} = -\mu\underbrace{\vec{J}\cdot\vec{B}}_{P_e T_e} - d\underbrace{\vec{J}\cdot\vec{E}}_{P_o T_o \,\to\, \not{CP}}$$

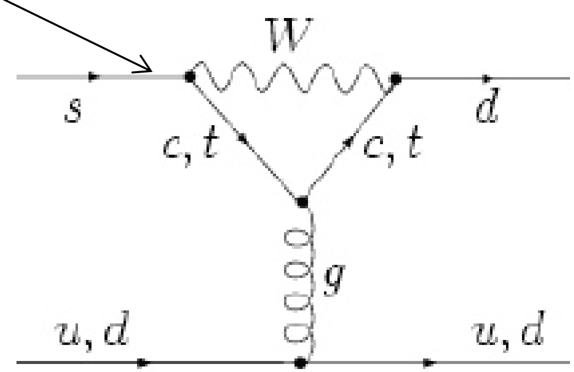
Standard-model EDMs are small

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

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

Pion-nucleon picture



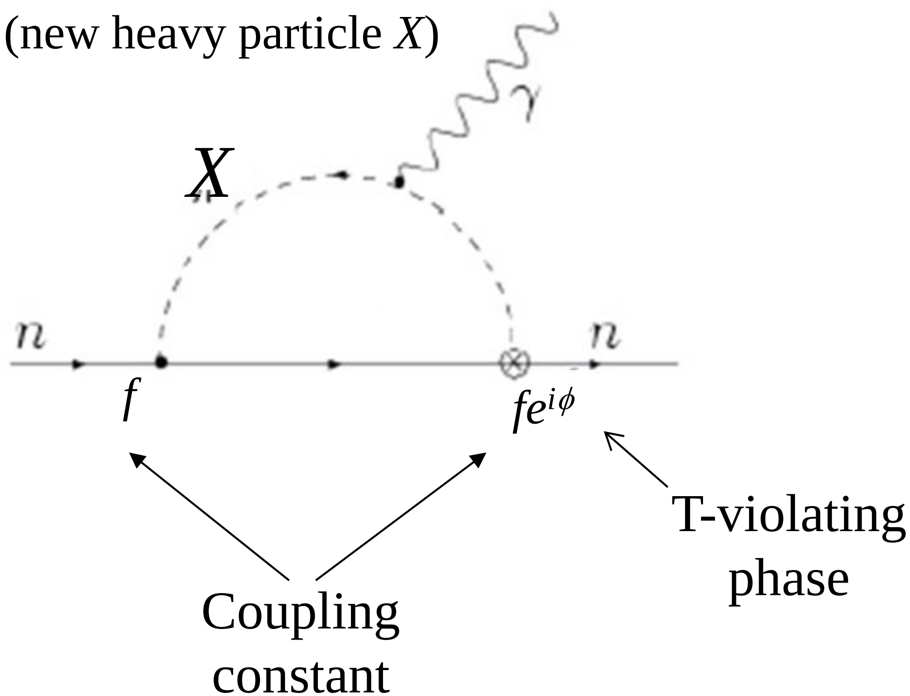


$$d_n^{SM} \approx 10^{-32} \text{ e cm}$$

$$d_e^{SM} \approx 10^{-37} \text{ e cm}$$

$$d_\mu^{SM} \approx 10^{-34} \text{ e cm}$$

EDMs probe TeV-scale "new" physics



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

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

$\approx 10^{-14}$ $\approx \alpha$ ≈ 1

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

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

loops

$m_x \sim$ 1 TeV - LHC scale
or ϕ is small

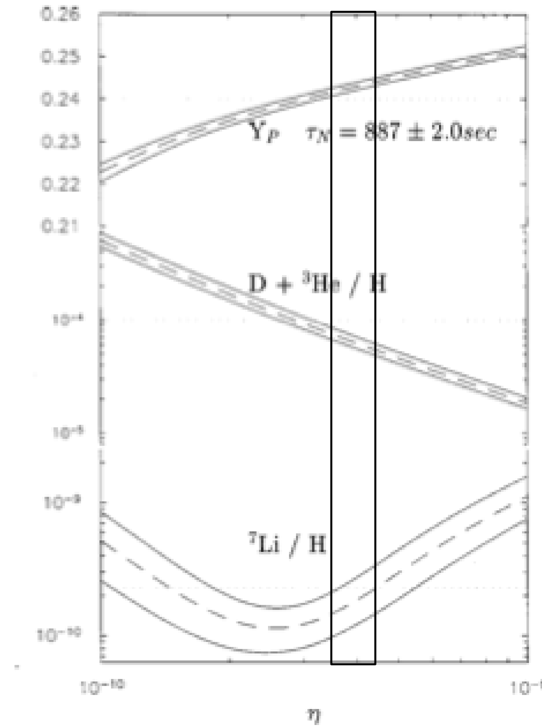
Baryon Asymmetry

$\not{C}\not{P} \longrightarrow$ 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

B) Evolution from η=0

1) Baryon number violation

2) CP Violation

3) Rapid expansion (non-equilibrium)

A. Shakarov
Nobel Peace Prize 1975

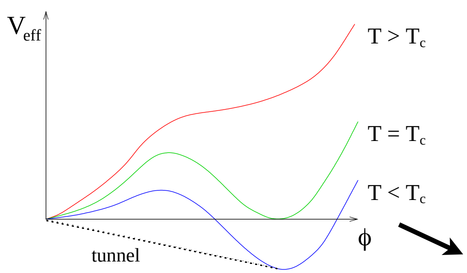
Another possibility: CP violation in neutrinos + "seesaw"

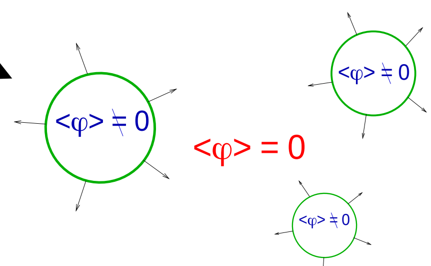
Electroweak Baryongenesis

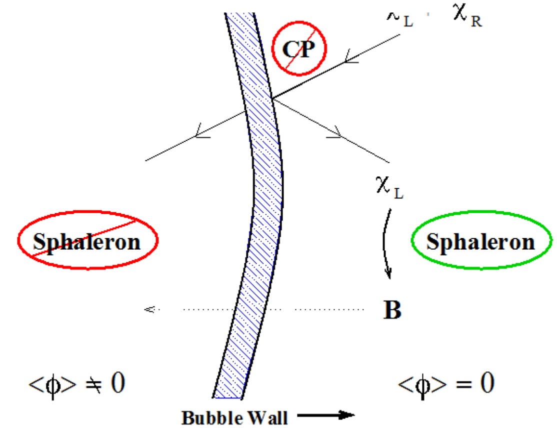
Kuzmin, Rubakov, Shaposhnikov 87; Cohen, Kaplan, Nelson 90&95

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 a baryons

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







DOESN'T WORK:

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

   Kajantie, Laine, Rummukainen, Shaposhnikov 98

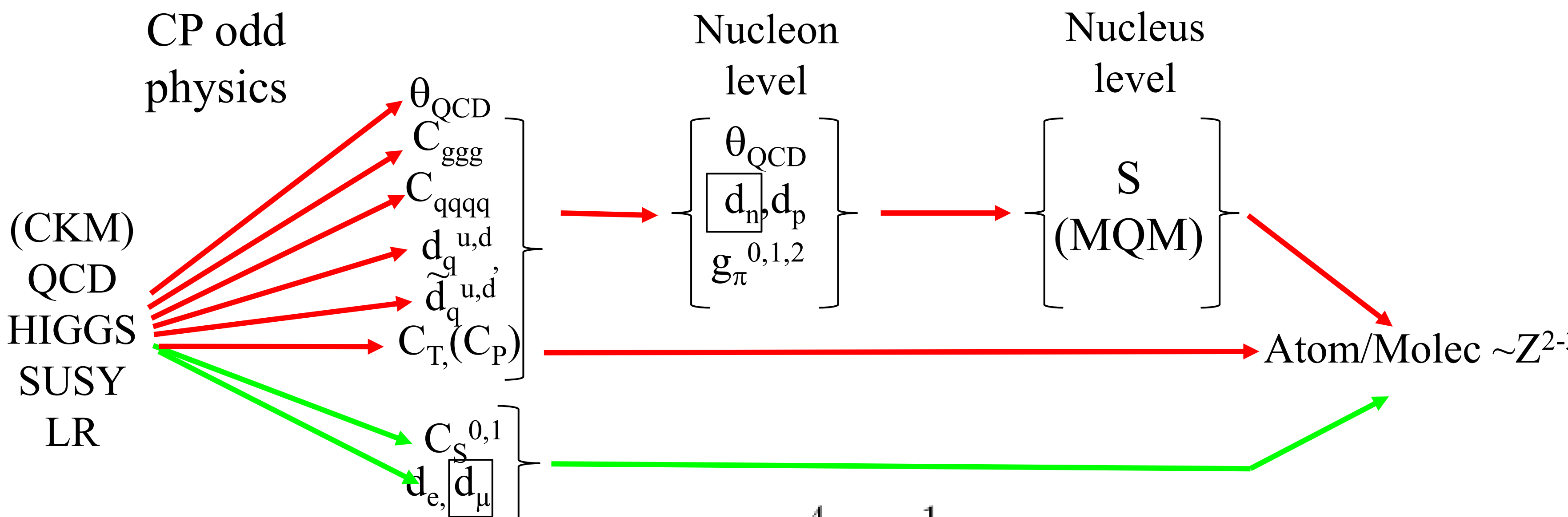
2. Not enough effective CP violation.

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

From D. Morrissey

EDM's

TC, MJ Ramsey Musolf Phys. Rev. C **91** 035502 (2015)
Upcoming Review: TC, Fierlinger, Ramsey-Musolf, Singh



$$d_n = 3.6 \times 10^{-16}\theta_{QCD}\ e\text{−cm} + (\frac{4}{3}d_d - \frac{1}{3}d_u) + (1.1\bar{d}_d + 0.55\bar{d}_u)$$

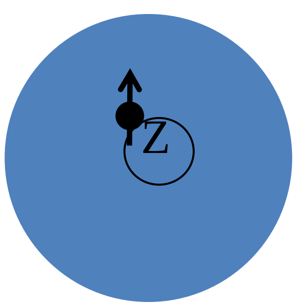
$$d_A = \kappa_S S(\theta_{QCD}, g_\pi) + (k_T C_T + k_S C_S) + \eta_e d_e + \text{h.o.} \quad \text{(MQM)}$$

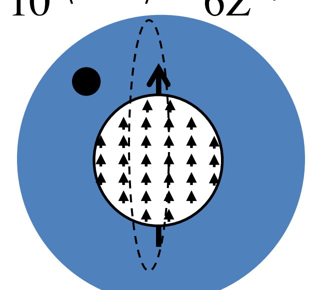
Paramagnetic atoms ($\vec{L}\times\vec{S}$ coupling)
Cs, Tl, YbF, ThO

Diamagnetic atoms: Schiff moment
Xe, Hg, TlF

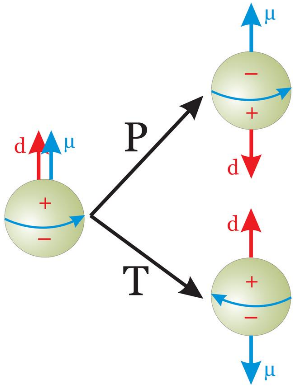
$$\vec{S} = \frac{1}{10}\langle r^2 \vec{r}_p\rangle - \frac{1}{6Z}\langle r^2\rangle\langle \vec{r}_p\rangle$$

$\vec{E}(\vec{r}_e)$ ¹ 0

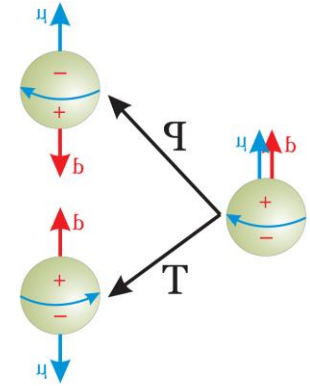




$\vec{E}$ u $\vec{J}$



Pioneers - experiment



Normal Ramsey & Ed Purcel (neutron)

→ Norval Fortson, Blayne Heckel (^{129}Xe, ^{199}**Hg**)

→ TC (^{129}Xe, Rn)

Adelberger/Heckel

Pat (P.G.H.) Sandars (Cs, Xe^{m}, TlF)

→ Ed Hinds (TlF, YbF)

Gene Commins (Tl)

→ Larry Hunter (Cs)

→ deMille, Doyle, Gabrielse (ThO)

→ Zheng-Tian Lu (^{225}Ra)

Stuart Freedman

System	Year/ref	Result	
Paramagnetic systems			
Cs	1989 [33]	$d_A = (-1.8 \pm 6.9) \times 10^{-24}$	e-cm
		$d_e = (-1.5 \pm 5.6) \times 10^{-26}$	e-cm
Tl	2002 [9]	$d_A = (-4.0 \pm 4.3) \times 10^{-25}$	e-cm
		$d_e = (\ \ 6.9 \pm 7.4) \times 10^{-28}$	e-cm
YbF	2011 [8]	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$	e-cm
ThO	2014 [7]	$\omega^{\mathcal{N}E} = 2.6 \pm 5.8$	mrad/s
		$d_e = (-2.1 \pm 4.5) \times 10^{-29}$	e-cm
		$C_S = (-1.3 \pm 3.0) \times 10^{-9}$	
Diamagnetic systems			
^{199}Hg	2006 [5]	$d_A = (0.49 \pm 1.5) \times 10^{-29}$	e-cm
^{129}Xe	2001 [34]	$d_A = (0.7 \pm 3) \times 10^{-27}$	e-cm
TlF	2000 [35]	$d\ = (-1.7 \pm 2.9) \times 10^{-23}$	e-cm
neutron	2006 [4]	$d_n = (0.2 \pm 1.7) \times 10^{-26}$	e-cm

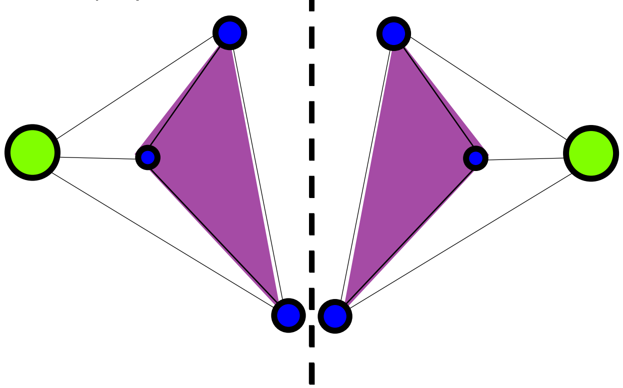
Octupole Enhancements

Intrinsic (body-frame) moment

Polarizabitliy

NH$_3$ (see Feynman vol 3.)

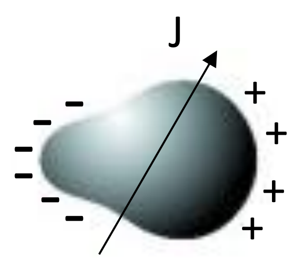
$|a\rangle$ $|b\rangle$

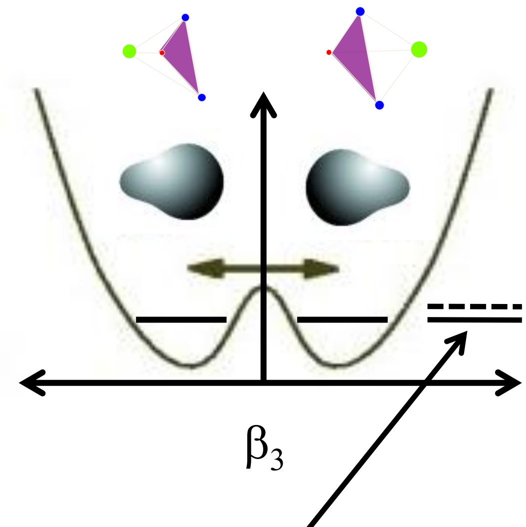


Reflection Symmetry

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

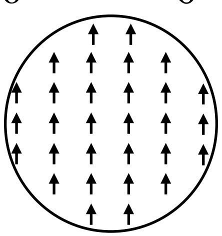
$$|\psi_-\rangle = \frac{1}{\sqrt{2}}\left(|a\rangle - |b\rangle\right)$$





Small splitting (tunnel frequency)
Large electric polarizability

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



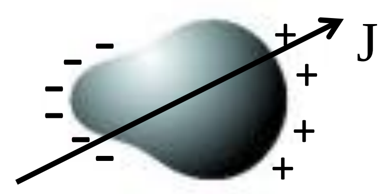
$\vec{E} \propto \vec{J}$

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

Nuclei with Octupole Deformation/Vibration

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

$$S \,\mu\, \frac{\langle + | h r^2 \cos q | - \rangle}{E_+ - E_-} \;» \;\frac{h b_2 b_3^2 A^{2/3} r_0^3}{E_+ - E_-}$$



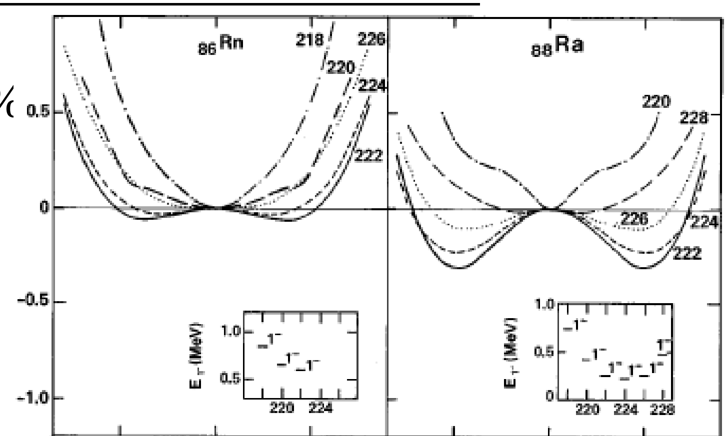
	^{223}Rn	^{223}Ra	^{225}Ra	^{223}Fr	^{129}Xe	^{199}Hg
$t_{1/2}$	23.2 m	11.4 d	14.9 d	22 m		
I	7/2	3/2	1/2	3/2	1/2	1/2
ΔE th (keV)	37*	170	47	75		
ΔE exp (keV)	-	50.2	55.2	160.5		
$10^{11} S$ (e-fm^3)	375	150	115	185	0.6	-0.75
$10^{28} d_A$ (e-cm)	1250	1250	940	1050	0.3	2.1

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

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

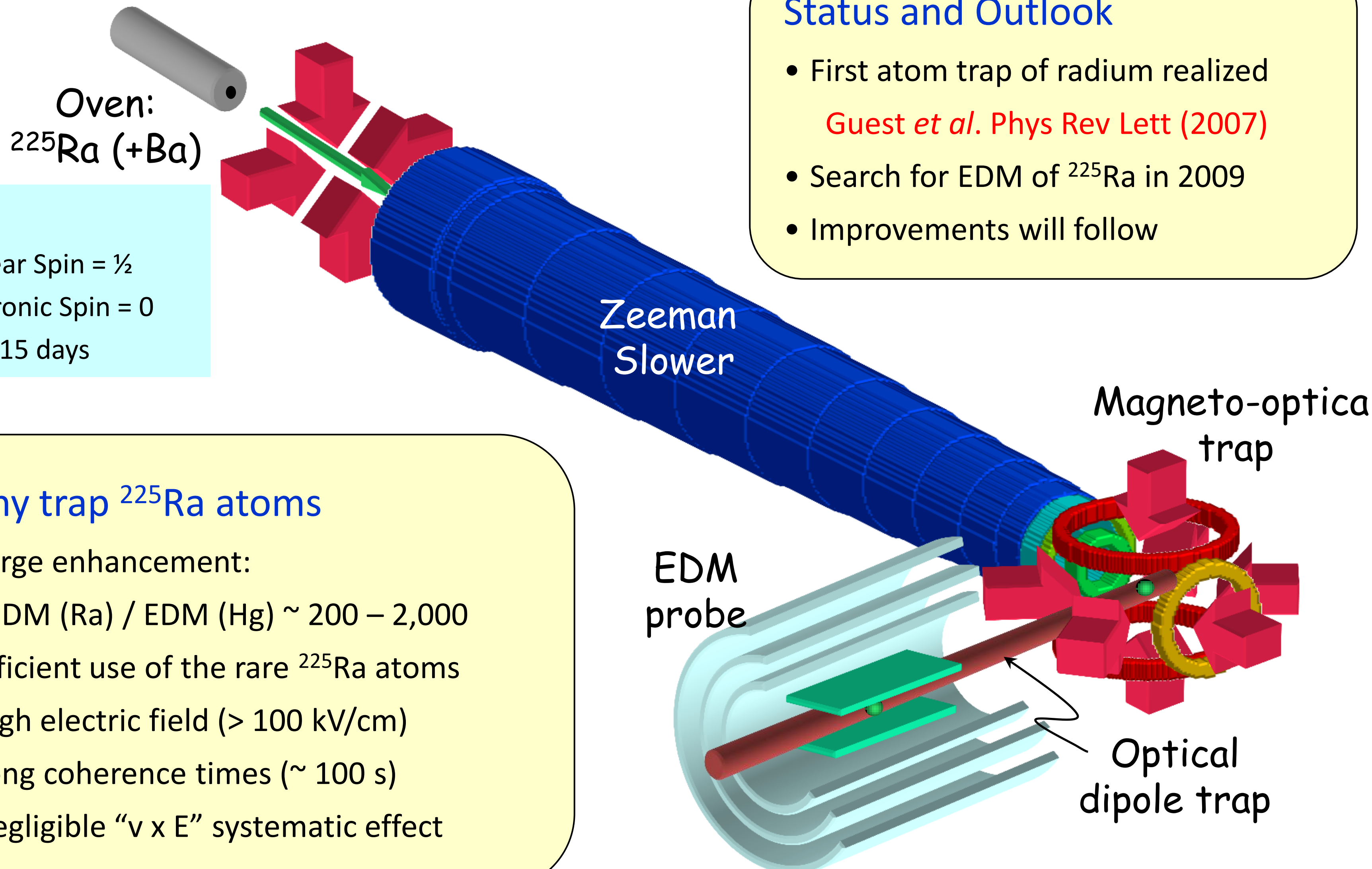
*Based on Woods-Saxon Potential

† 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



^{225}Ra
Nuclear Spin = ½
Electronic Spin = 0
$t_{1/2}$ = 15 days

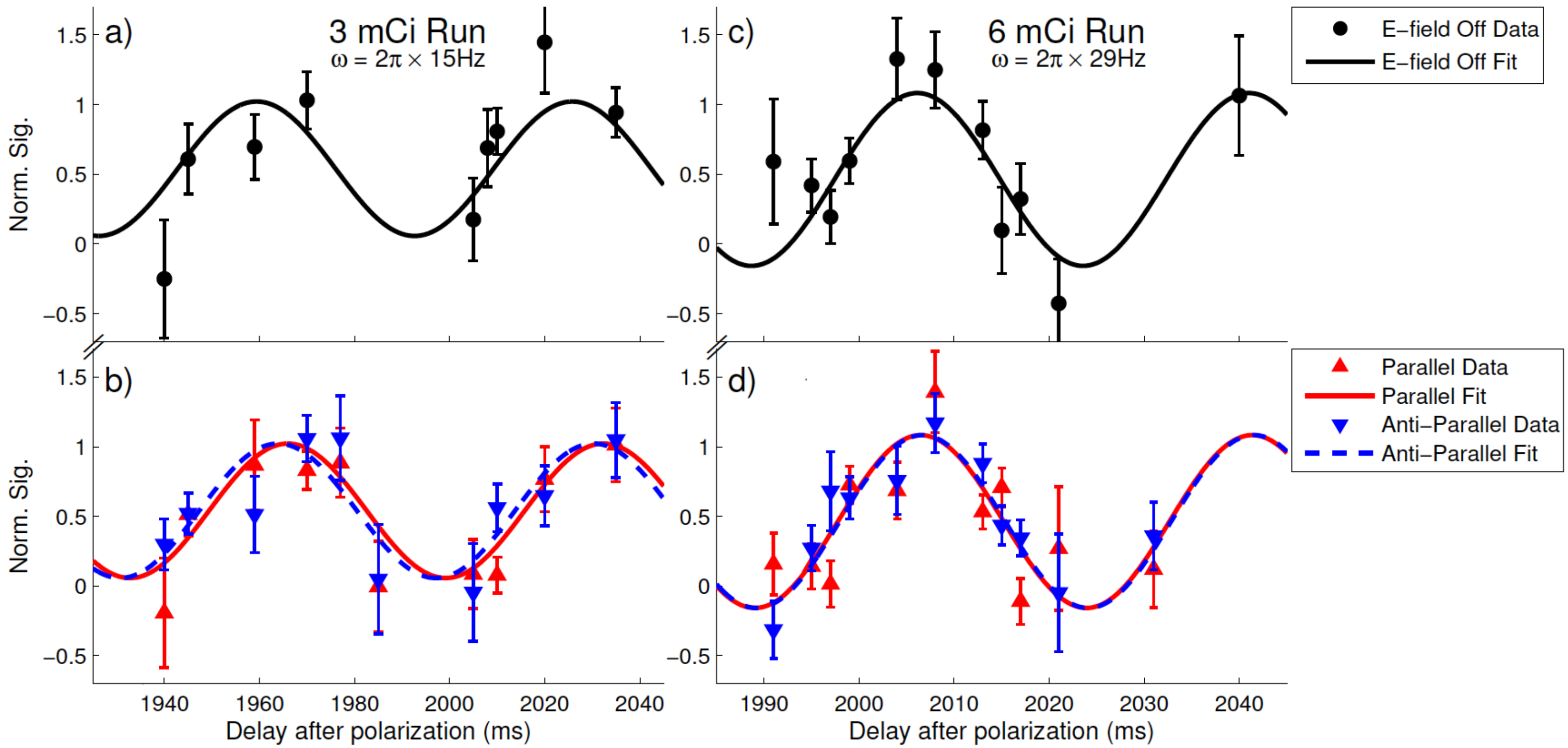
Status and Outlook

- First atom trap of radium realized
  Guest *et al*. Phys Rev Lett (2007)
- Search for EDM of ^{225}Ra in 2009
- Improvements will follow

Why trap ^{225}Ra atoms

- Large enhancement:
  EDM (Ra) / EDM (Hg) ~ 200 – 2,000
- Efficient use of the rare ^{225}Ra atoms
- High electric field (> 100 kV/cm)
- Long coherence times (~ 100 s)
- Negligible "v x E" systematic effect

First Ra-225 EDM Measurement

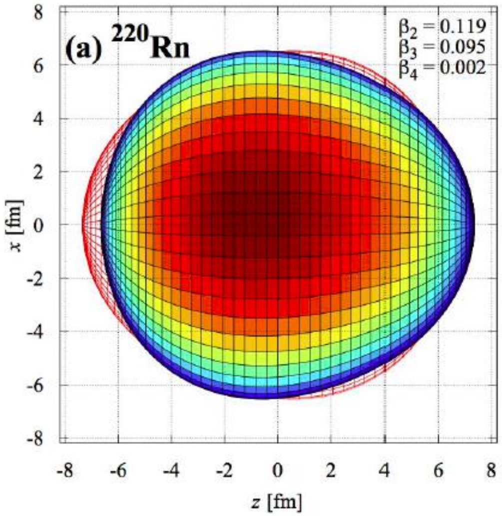


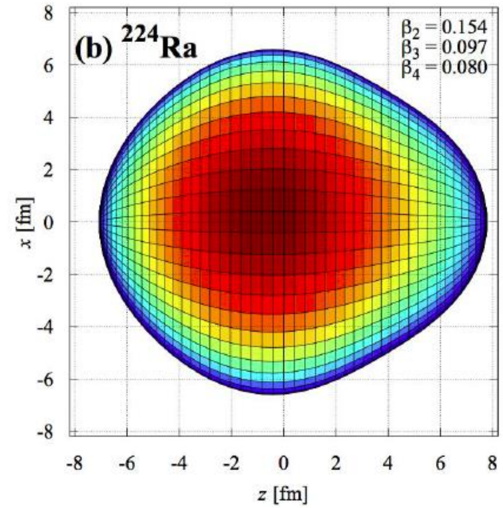
Phys. Rev. Lett. 114, 233002: $|d(\text{Ra-225})| < 5\times10^{-22}\ e$ cm (95%)

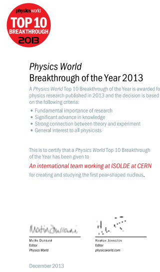
- all systematic effects estimated to be $<10^{-25}\ e$ cm (goal)
- first EDM measurement made in a laser trap
- first EDM measurement of an octupole-deformed species

Thanks to Jaideep Singh

^{221}Rn Enhancement







L. Gaffney
P. Butler
M. Scheck
et al.

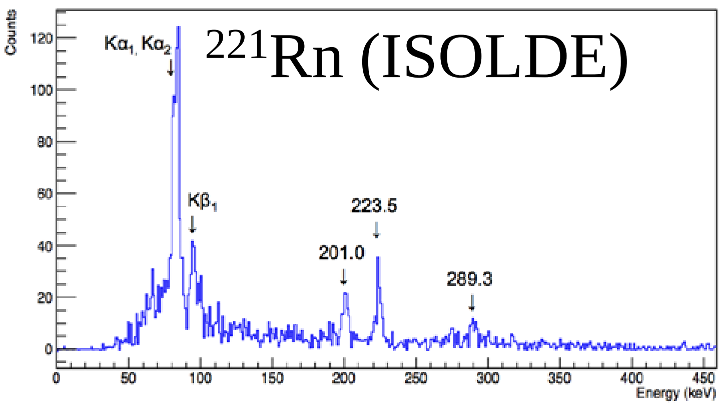
$$S \propto \frac{\eta \beta_2 \beta_3^2 A^{2/3} r_0^3}{E_+ - E_-}$$

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

50 keV

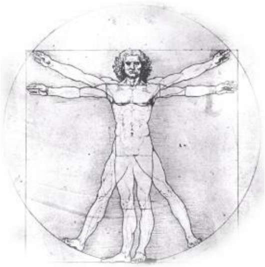
400 keV

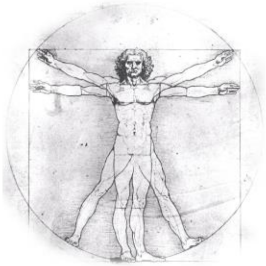
500-1000
(J. Engel et al.)



^{223}Rn: TBD

Radon-EDM Experiment





TRIUMF E929

Spokesmen: Timothy Chupp & Carl Svensson

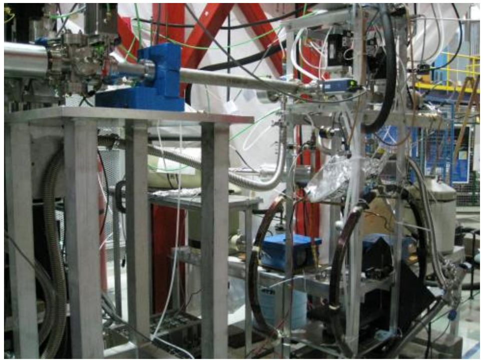
E-929 Collaboration (Guelph, Michigan, SFU, TRIUMF)

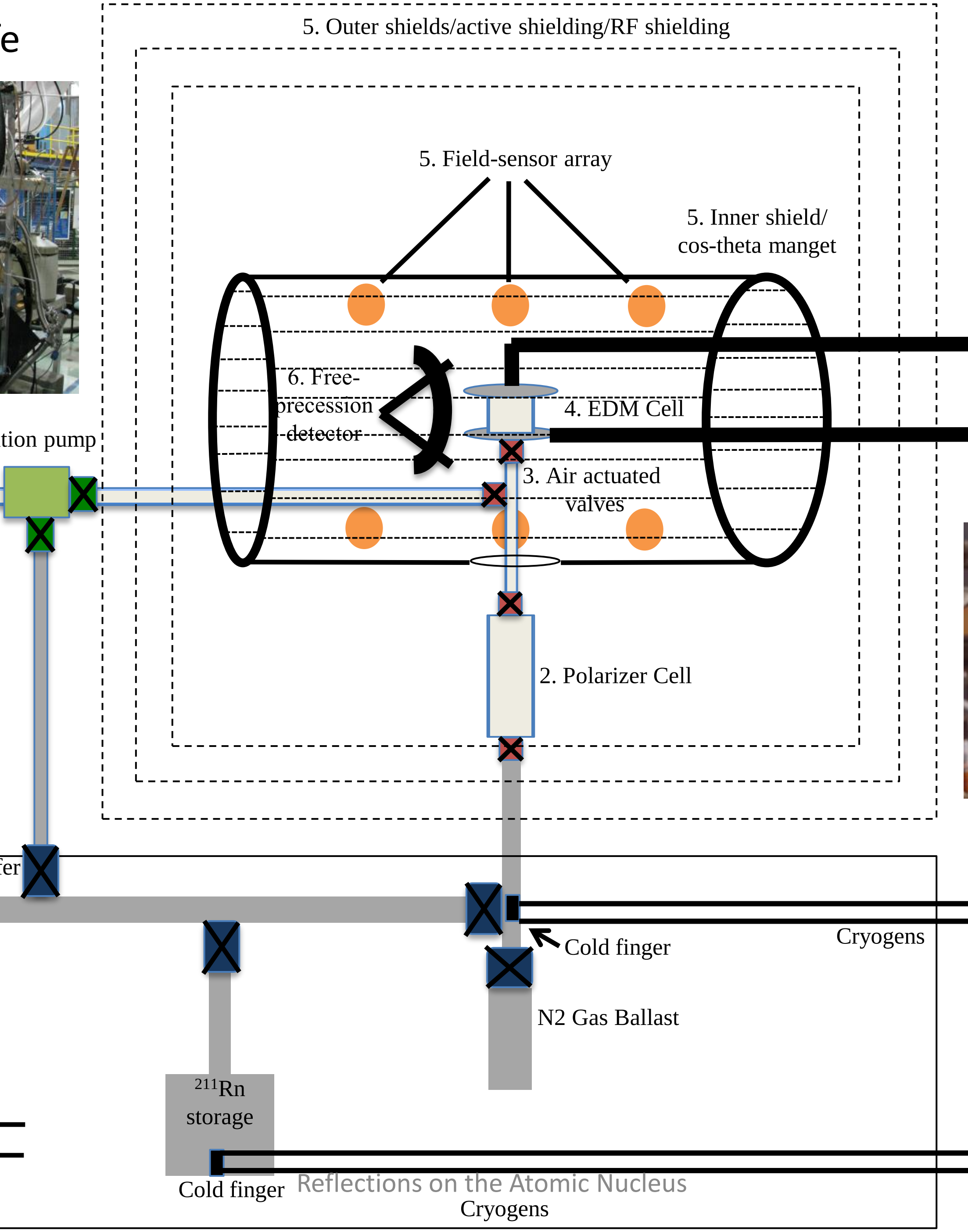
TRIUMF

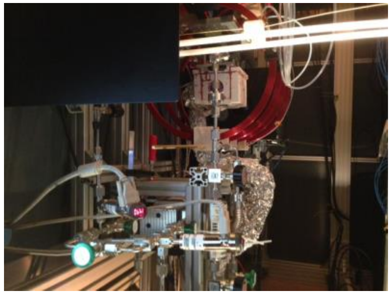
Canada's National Laboratory for Particle and Nuclear Physics

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

20-30 min half-life

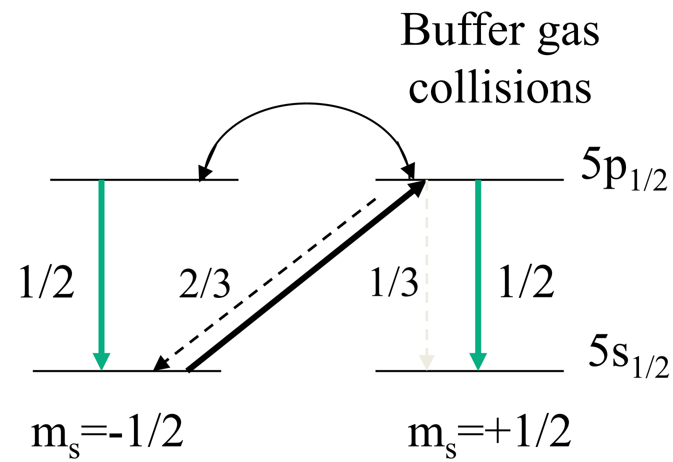


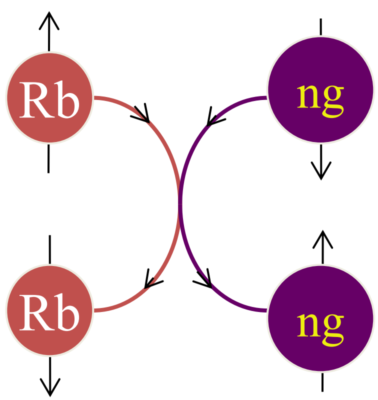




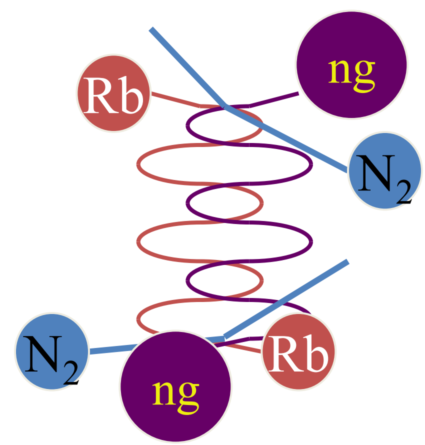
Spin-Exchange Optical Pumping

- Optically pump the Rb with circularly polarized laser light.
- Spin-exchange collisions transfer the polarization to the ^3He, ^{129}Xe, radon nuclei.





Binary Collision:
$\tau \sim 10^{-12}$ sec.



van Der Waals Molecule

VOLUME 60, NUMBER 21 PHYSICAL REVIEW LETTERS 23 MAY 1988

Nuclear Orientation of Radon Isotopes by Spin-Exchange Optical Pumping

M. 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	$(\frac{3}{2}^-)$-$\frac{9}{2}^-$	1.009(7)	$+0.9\pm0.7$
689	$\frac{5}{2},\frac{7}{2}^-$-$\frac{5}{2}^-$	1.079(22)	$+7.9\pm2.2$
745	$(\frac{7}{2}^-)$-$\frac{9}{2}^-$	1.129(14)	$+12.9\pm1.4$

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]

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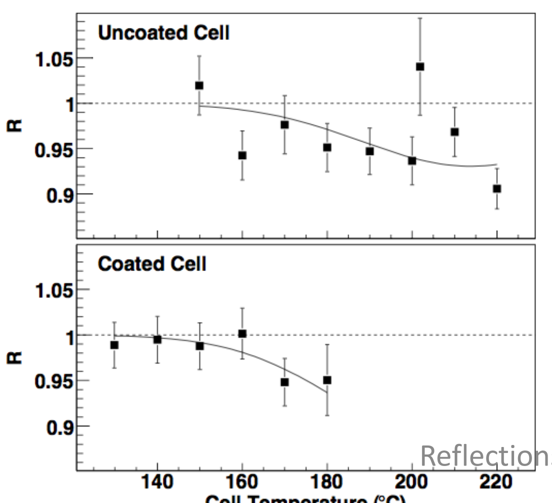
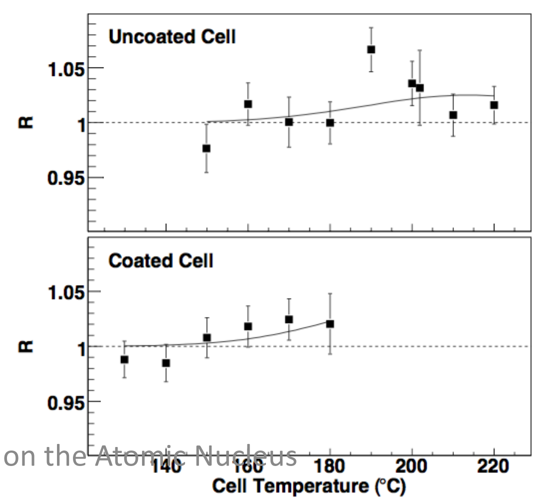
[3] *TRIUMF, 4004 Westbrook Mall, Vancouver V6T 2A3, Canada*
[4] *SUNY Stony Brook Department of Physics and Astronomy, Stony Brook 11794-3800, USA*

(Dated: December 6, 2006)

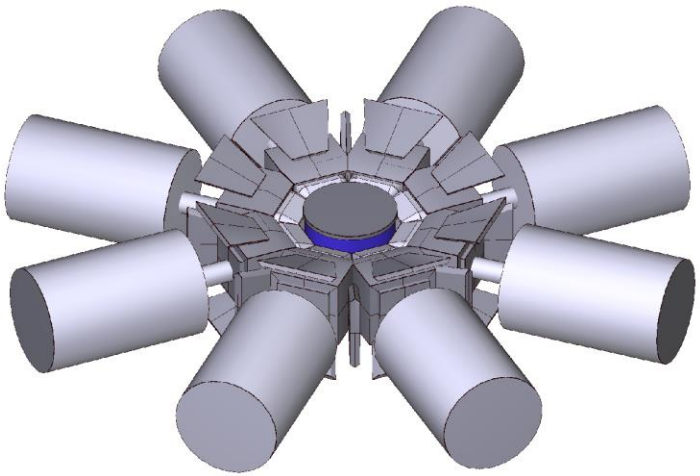


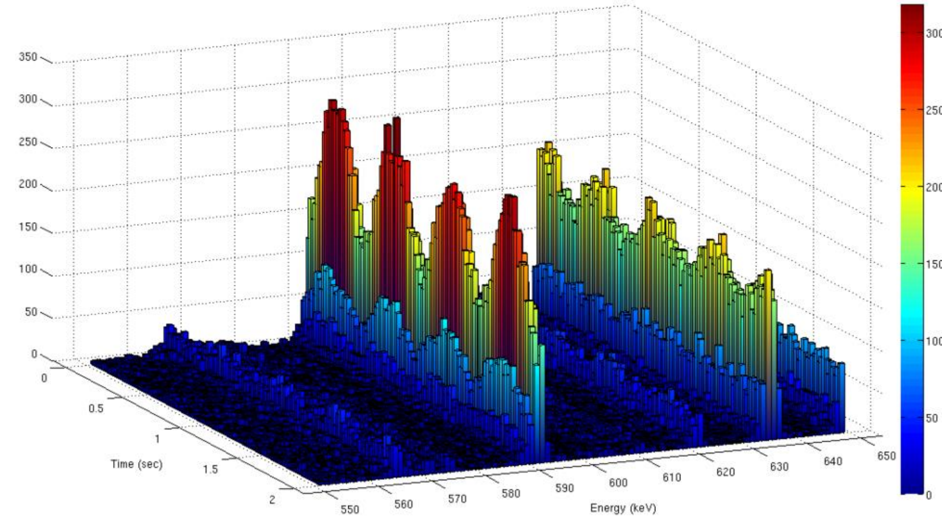


Fit for Γ_2 (T_a=300°K):
0.05 Hz (uncoated);
0.03 Hz (coated)s
Use $2.5\text{x}10^{-21}$ cm^2

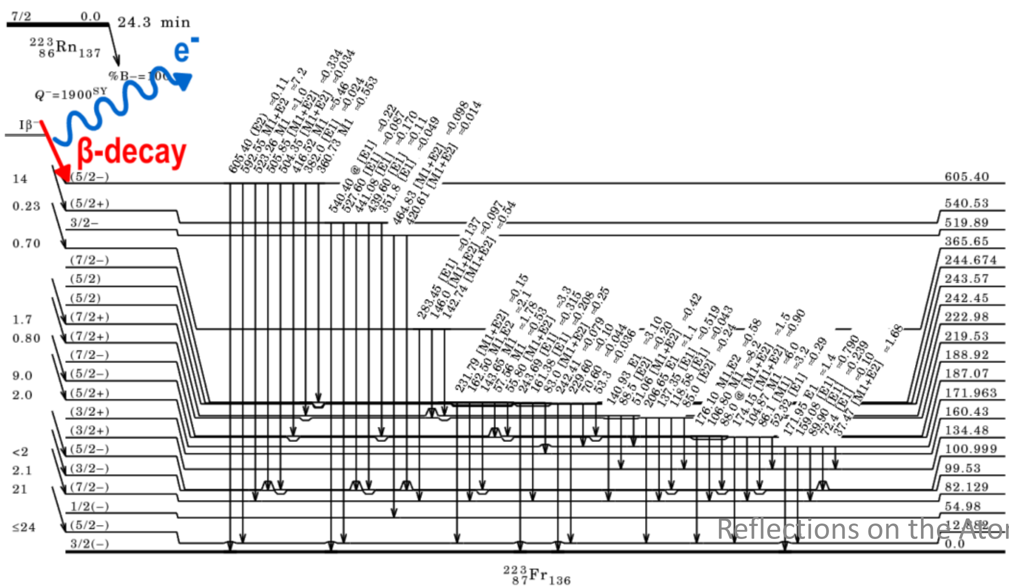
Genat-4 simulations by Evan Rand

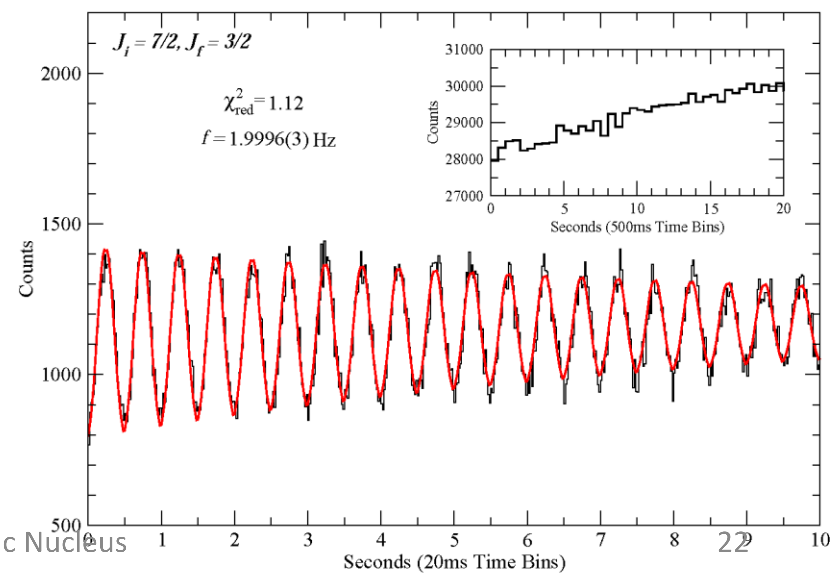
γ-ray energy-time matrix from the β decay of 1.2 billion ^{223}Rn nuclei from an initial 8×10^{10} nuclei located in the EDM cell surrounded by a ring of eight GRIFFIN detectors in the forward position.





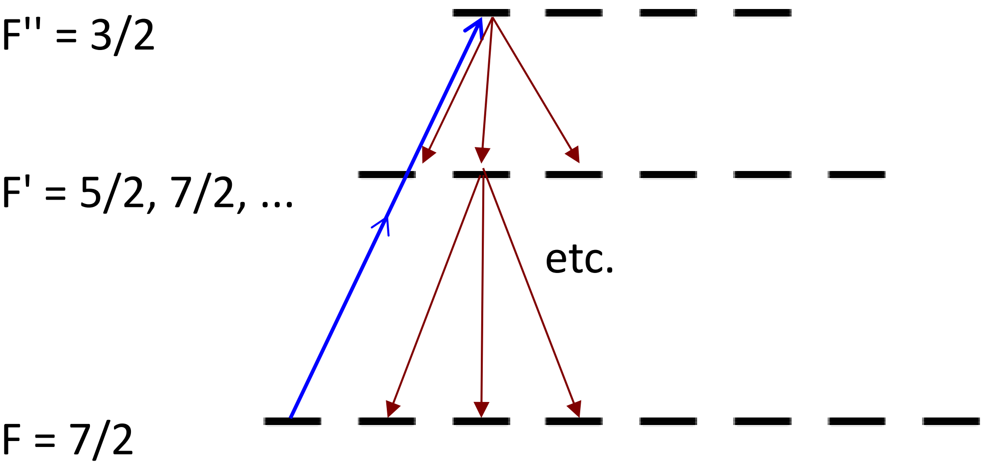
Known Level Structure of ^{223}Fr - *Nuclear Data Sheets (2001)*

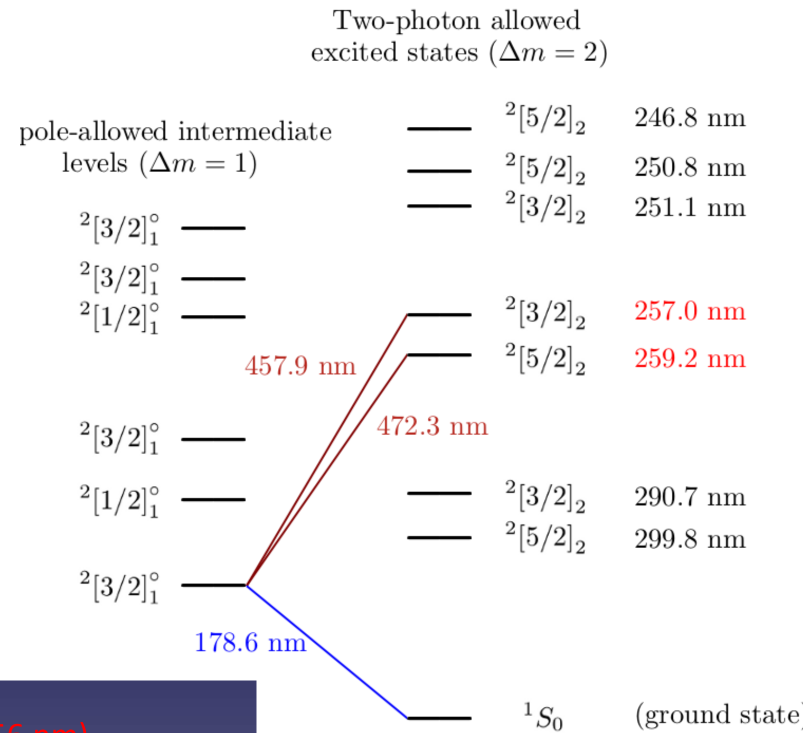


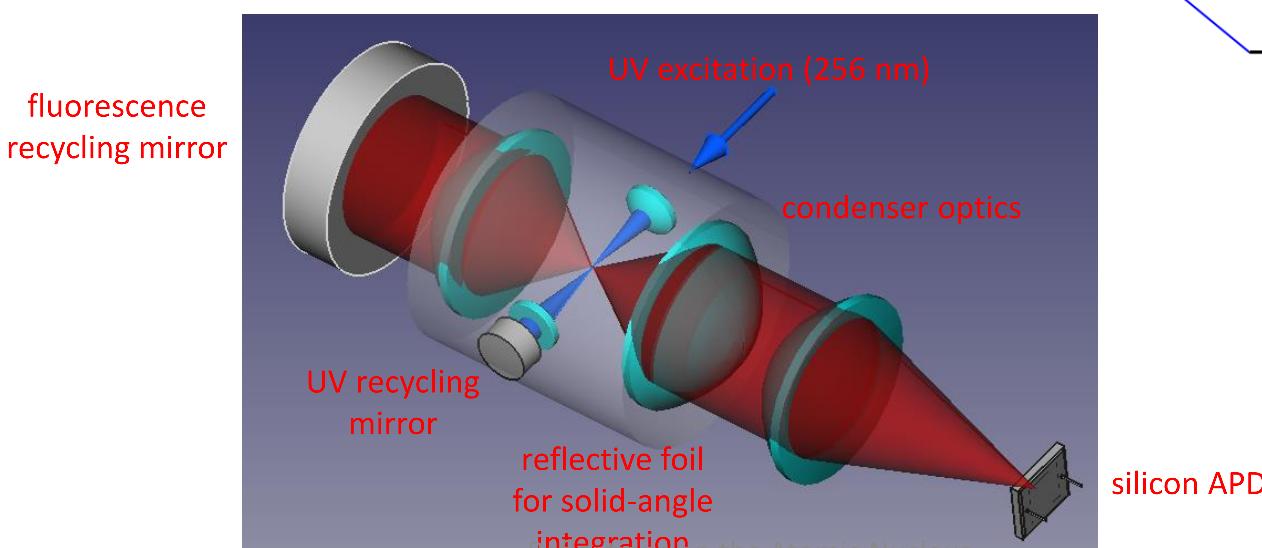


Two-photon magnetometry with $^{221/223}$Rn (J=7/2)

S. Degenkolb







Radon-EDM Prospects

Global analysis: TC, Ramsey Musolf PRC **91** 035502 (2015)

Goal ~10^{-26} e-cm

Facility	TRIUMF-ISAC	FRIB(^{223}Th)
Rate	$2.5x10^{7}$ s^{-1}	$1x10^{9}$ s^{-1}
# atoms	$3.5x10^{10}$	$1.4x10^{12}$
σ_{EDM} (100 d)	$2x10^{-27}$ e-cm	$3x10^{-28}$ e-cm
^{199}Hg equivalent	$4x10^{-28/29}$ e-cm	$6x10^{-29/30}$ e-cm

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

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

Summary

EDMs probe TeV-scale “new” physics

$\not{CP} \longrightarrow$ Baryon Asymmetry $\longrightarrow$ NEW PHYSICS (BSMP)

Measurements in NEW SYSTEMS are essential

Octupole collectivity enhances Schiff moments:
^{225}Ra and $^{221/223}$Rn underway …. $10^{-25/26}$ e-cm

THANK YOU!
and
Happy *transition(s)* PETER!