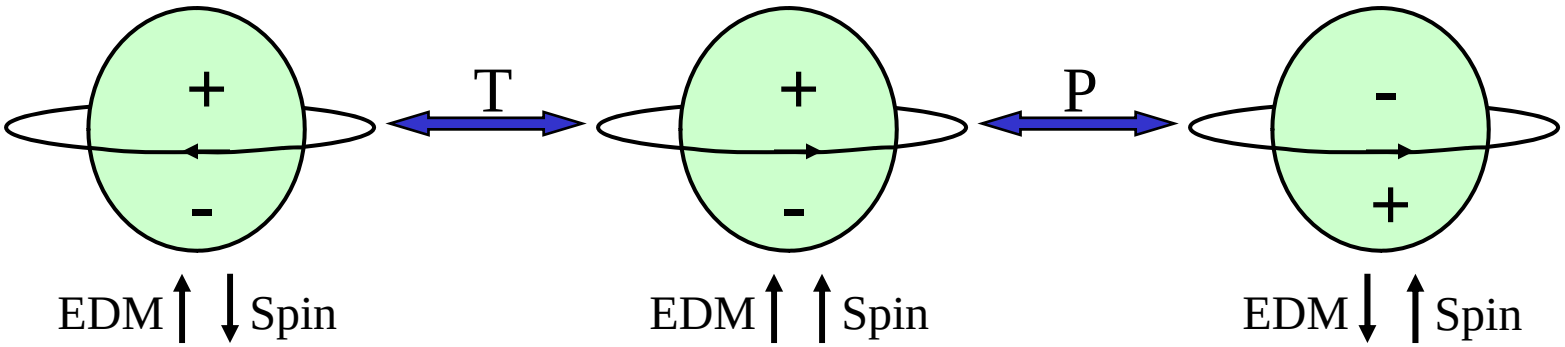
Search for a Permanent Electric Dipole Moment in Ra-225



Pseudo-scalar

$$\vec{s} \cdot \vec{d}$$

C. S. Wu
1912-1997

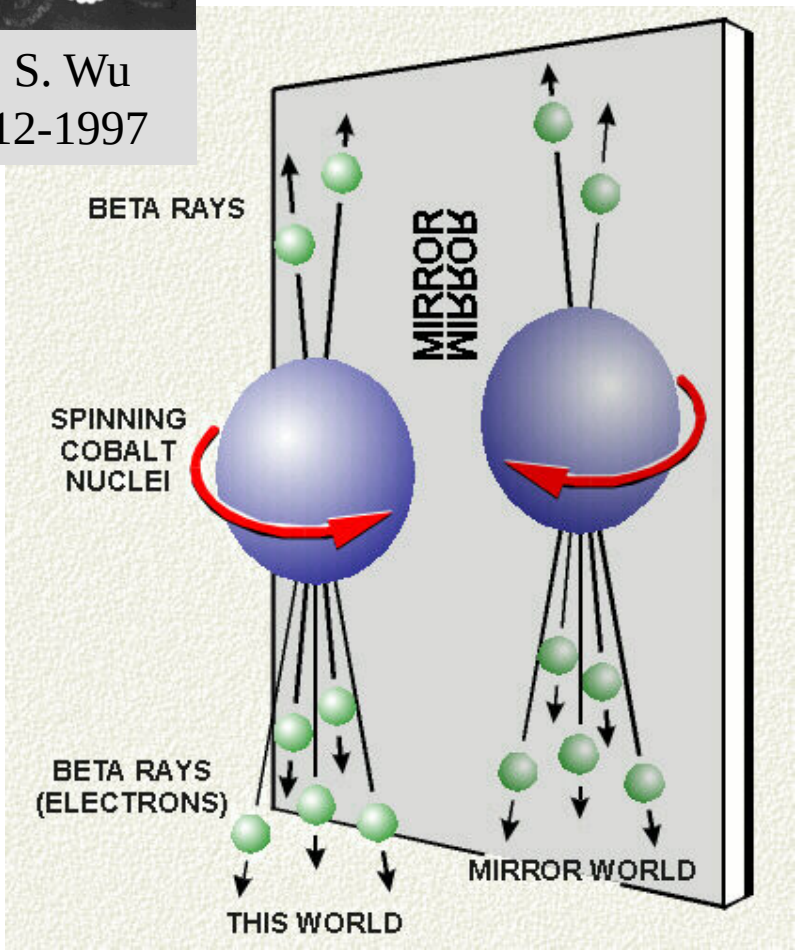
Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

AND

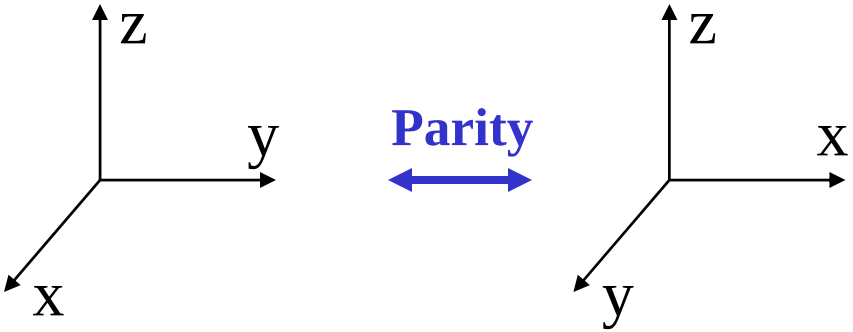
E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson,
National Bureau of Standards, Washington, D. C.

(Received January 15, 1957)



Parity (space reversal)

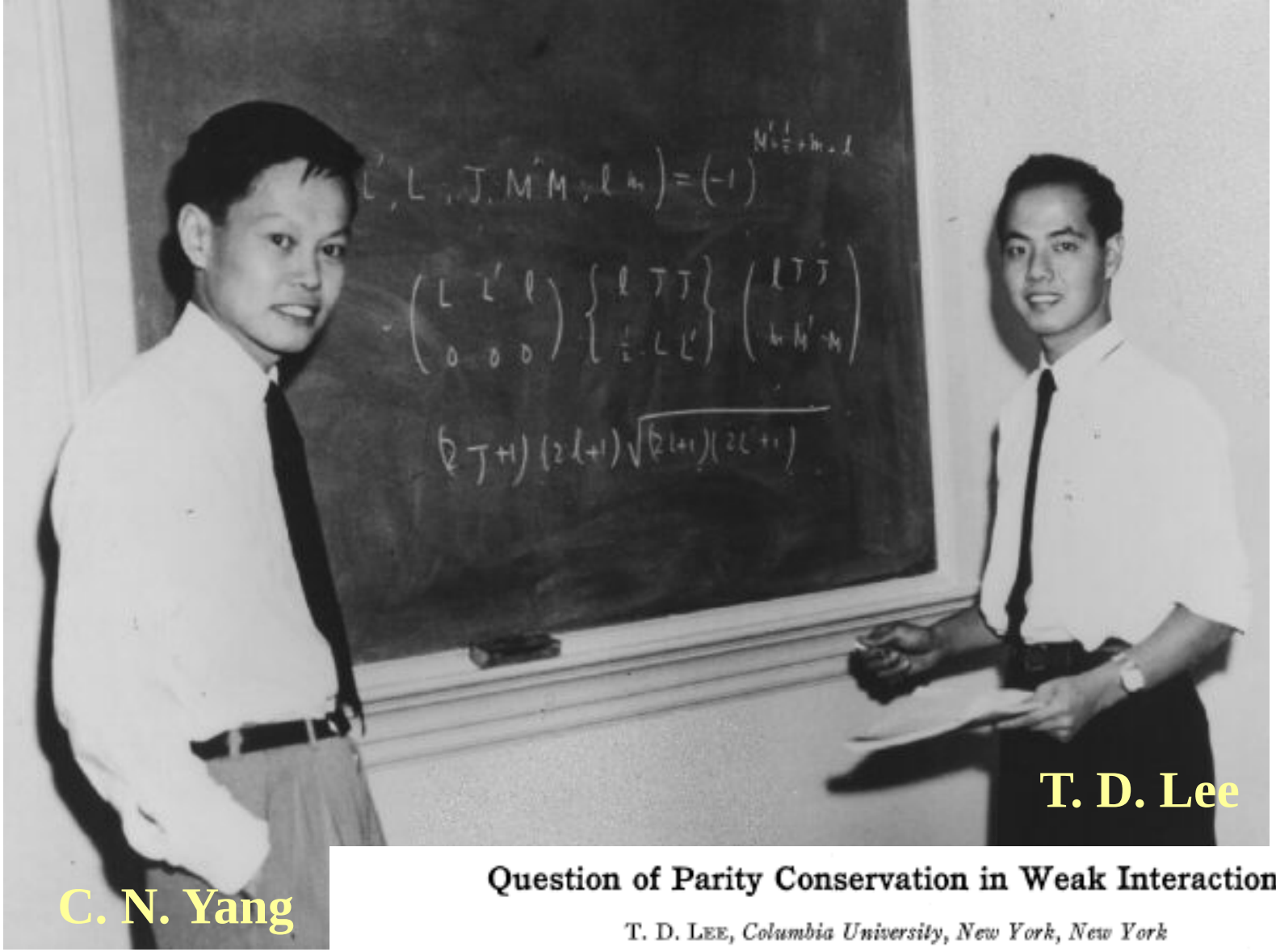
x, y, z → -x, -y, -z



Pseudo-scalar

$$(\vec{x} \times \vec{y}) \cdot \vec{z}$$

$$\vec{s} \cdot \vec{p}$$



Question of Parity Conservation in Weak Interactions*

T. D. Lee, *Columbia University, New York, New York*

AND

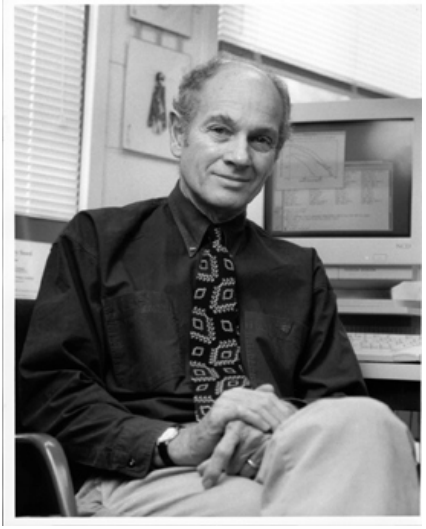
C. N. Yang,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

Discrete Fundamental Symmetries

~~P~~	Parity, or Spatial Inversion
~~C~~	Charge conjugation, or particle – antiparticle symmetry
T	Time reversal
CP	
CPT	Exact symmetry in quantum field theory with Lorentz invariance



James W. Cronin

4 PHYSICAL REVIEW LETTERS

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

This Letter reports the results of experimental studies designed to search for the 2π decay of the K_2^0 meson. Several previous experiments have served[1,2] to set an upper limit of 1/300 for the fraction of K_2^0's which decay into two charged pions. The present experiment, using spark chamber techniques, proposed to extend this limit.

Neutral K mesons $K^0 = \bar{s}d \qquad \overline{K}^0 = \bar{d}s$

Particles of definite CP $K_{even} = \dfrac{K^0 + \overline{K}^0}{\sqrt{2}} \qquad K_{odd} = \dfrac{K^0 - \overline{K}^0}{\sqrt{2}}$

Allowed decay mode $K_{even} \rightarrow \pi\pi \qquad K_{odd} \rightarrow \pi\pi\pi$

$K_{odd} \rightarrow \pi\pi$ at the level of 0.2% !!!

P violation and CP violation in the Standard Model

Parity Violation

Weak interaction coupling via (Vector – Axial Vector)

CP Violation

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

Cabbibo-Kobayashi-Maskawa Matrix

$$= \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

More CP-Violation Mechanisms?

Strong CP problem

CP-violating phase in Quantum Chromodynamics

$$\mathcal{L}_{\rm mass} \to -m(\bar{\psi}_{\rm L}\psi_{\rm R} + \bar{\psi}_{\rm R}\psi_{\rm L}) + \frac{\theta g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$$

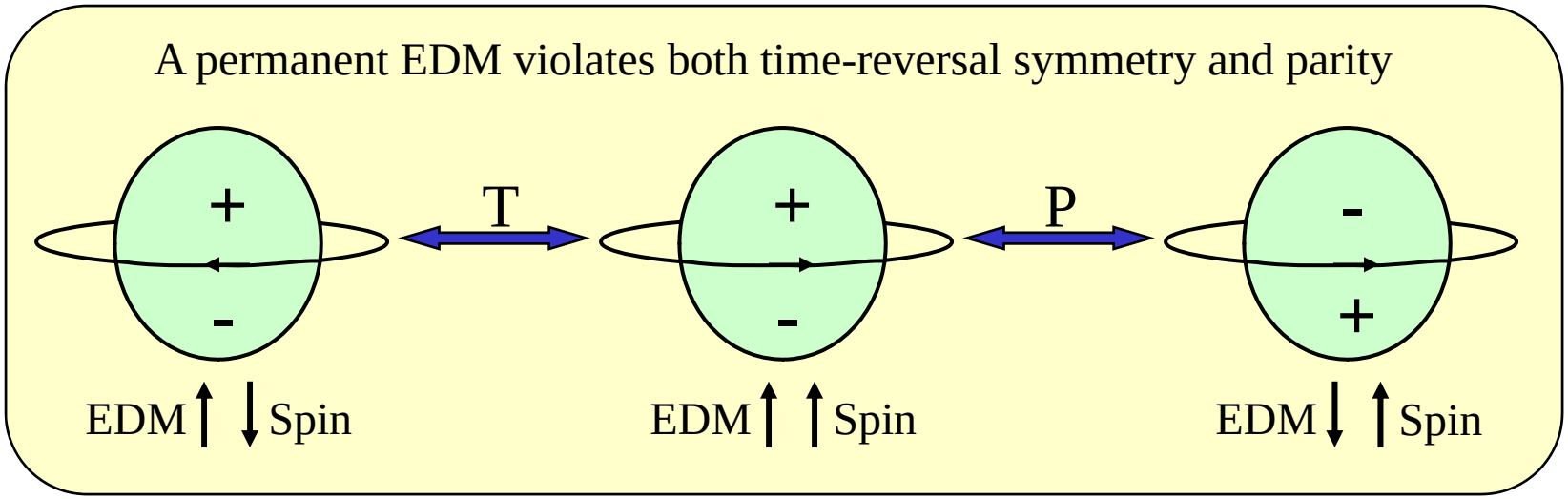
Supersymmetry

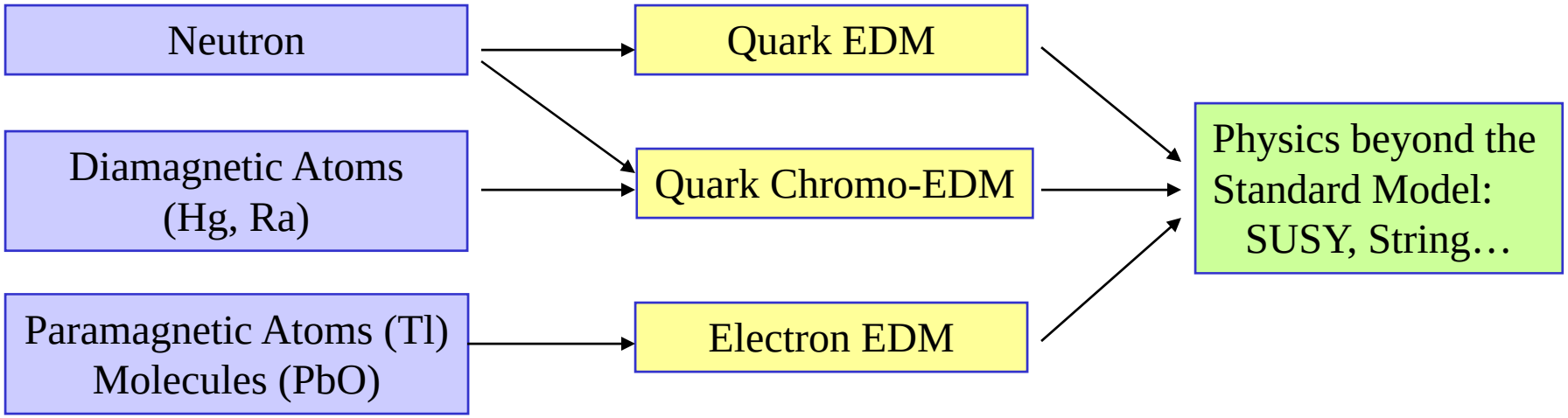
More particles → More CP-violating phases

Matter-antimatter asymmetry

Require additional CP-violation mechanism(s)

EDM Violates Both P and T





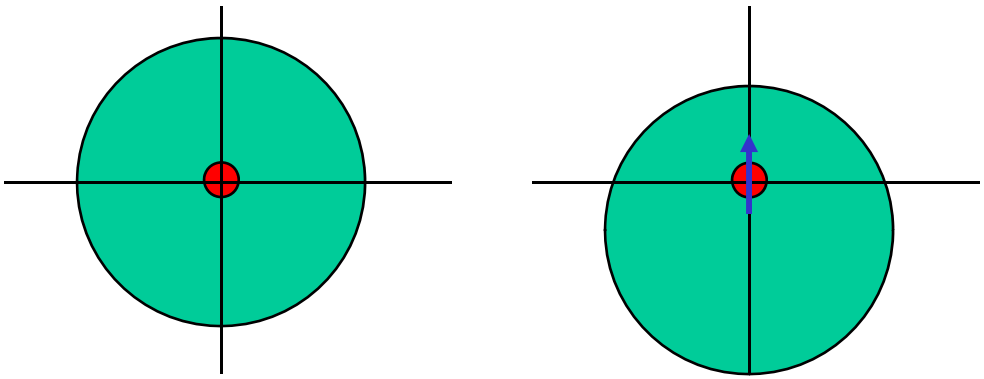
Measurability of Nuclear EDM

L.I. Schiff, Phys. Rev. (1963)

Schiff shielding

$$\tilde{d}_{atom} = -d_{nucleus}$$

$$d_{atom} = \tilde{d}_{atom} + d_{nucleus} = 0$$



Incomplete cancellation

$$d_{atom} = \tilde{d}_{atom} + d_{nucleus} \neq 0$$

1) nucleus has finite size;
2) charge distribution ≠ EDM distribution.

Schiff moment (toy model)

$$d_{atom} \sim d_{nucleus} \cdot \frac{|r_c - r_d|}{r_{atom}} \sim 10^{-5} d_{nucleus}$$

$$S \sim d_{nucleus} \cdot \left(r_d^2 - r_c^2\right)$$

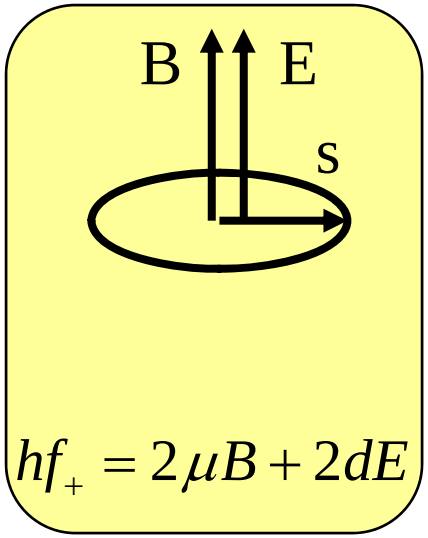
$$d_{atom} \sim S \cdot r_{atom}^{-1} \cdot r_c^{-1}$$

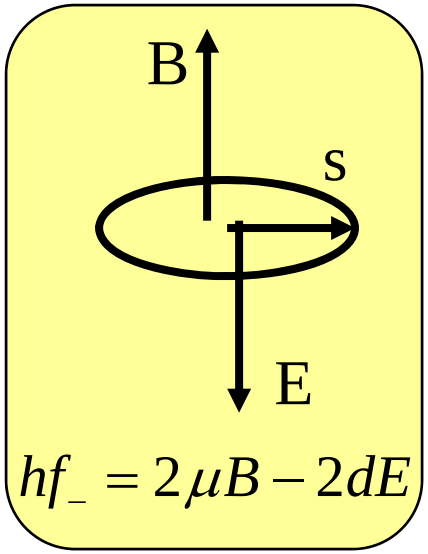
Nuclear Schiff moment is lowest order, P,T-odd, measurable electric moment.

$$\langle \vec{S} \rangle = \left\langle \frac{e}{10} \sum_p \left(r_p^2 - \tfrac{5}{3} \overline{r_{ch}^2} \right) \vec{r}_p \right\rangle$$

a 'radially-weighted dipole moment'

EDM Measurement





Parameters

$B = 10\ mGauss$

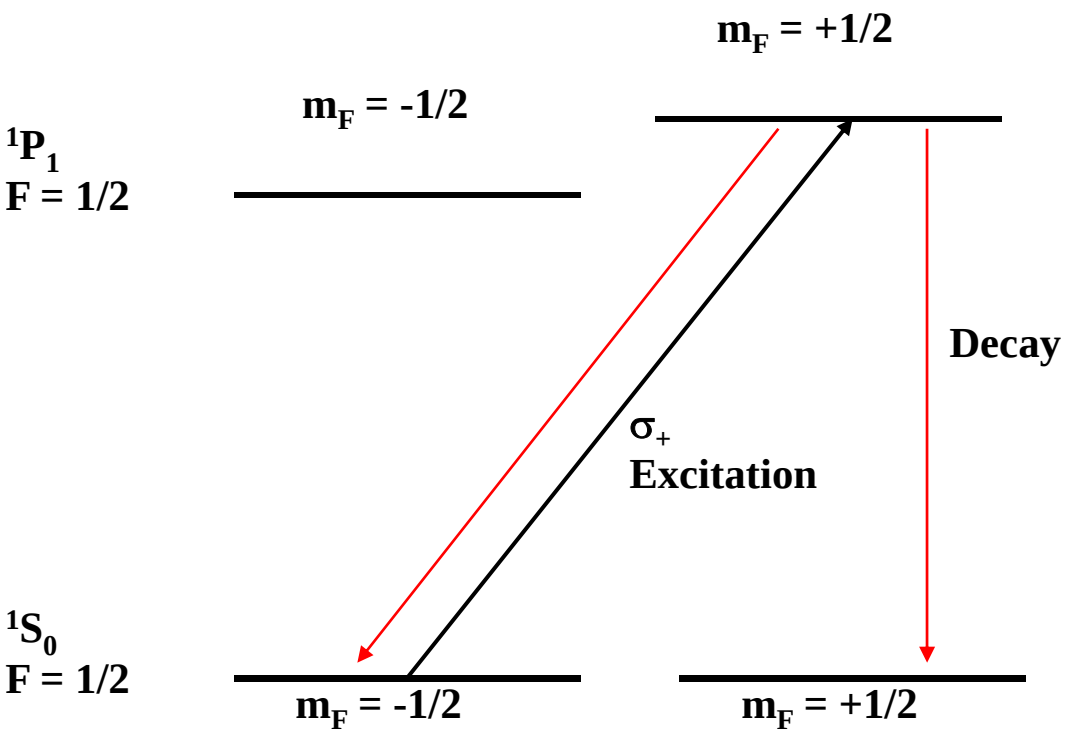
$f = 11\ Hz$

$E = 100\ kV/cm$

$f_+ - f_- = 10\ nHz$

$d = 1 \times 10^{-28}\ e\ cm$

Optical Pumping



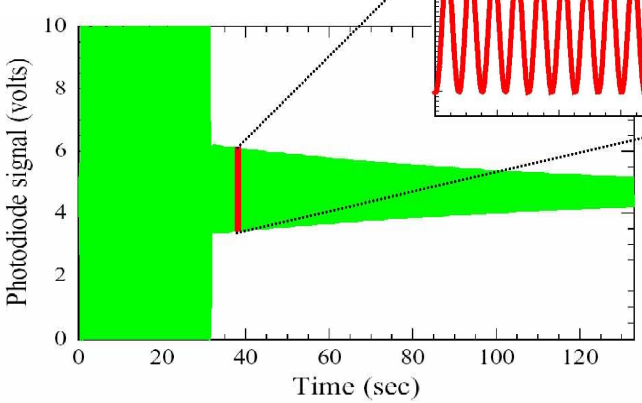
2001 Hg EDM search

Result:
$[-10.6 \pm 4.9_{stat.} \pm 4.0_{syst.}] \times 10^{-29}\ e$ cm
$d(^{199}Hg) < 2.1 \times 10^{-28}\ e$ cm
Romalis, Griffith, Jacobs, Fortson

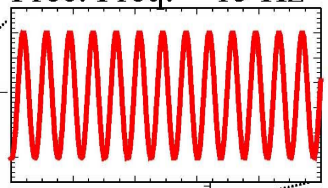
Frequency uncertainty = 1 nHz

~ 80 days data

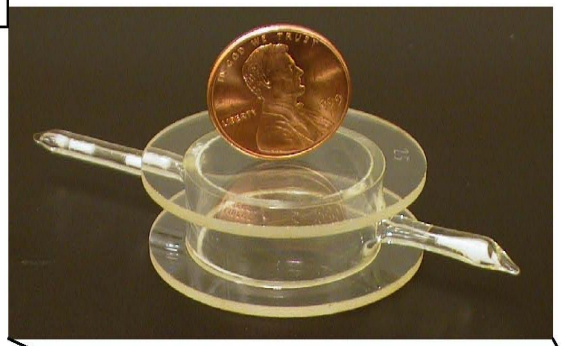
Spin precession signal:



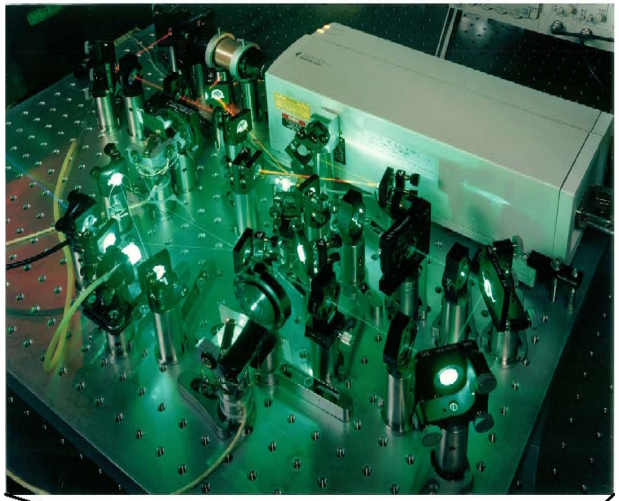
Prec. Freq. = 15 Hz

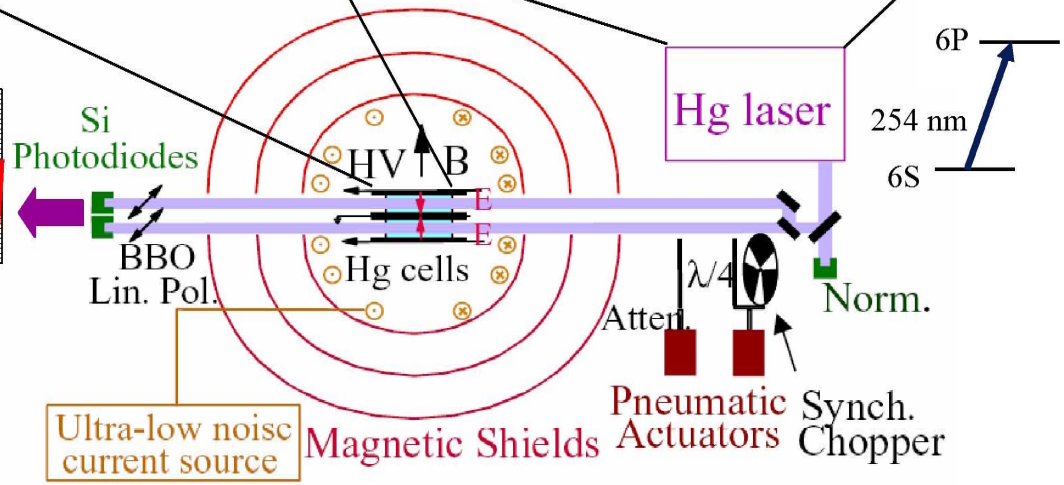


Vapor cells:
10^{14} Hg atoms
Coherence time 200 sec
Wall resistance > $10^{16}\ \Omega$



6mW, 254 nm laser from quadrupled 1016 diode:





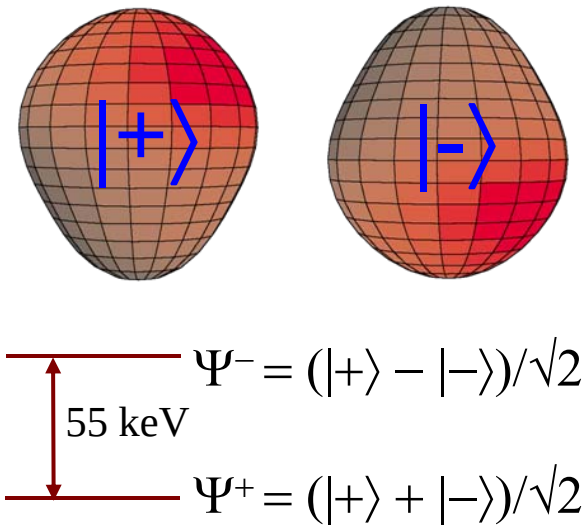
Courtesy of Mike Romalis

EDM of ^{225}Ra enhanced

EDM of ^{225}Ra enhanced:

- Large intrinsic Schiff moment due to octupole deformation;
- Closely spaced parity doublet;
- Relativistic atomic structure.

Haxton & Henley (1983)
Auerbach, Flambaum & Spevak (1996)
Engel, Friar & Hayes (2000)



Enhancement Factor: EDM (^{225}Ra) / EDM (^{199}Hg)

Skyrme Model	Isoscalar	Isovector	Isotensor
SkM*	1500	900	1500
SkO’	450	240	600

Schiff moment of ^{199}Hg, de Jesus & Engel, PRC72 (2005)
Schiff moment of ^{225}Ra, Dobaczewski & Engel, PRL94 (2005)

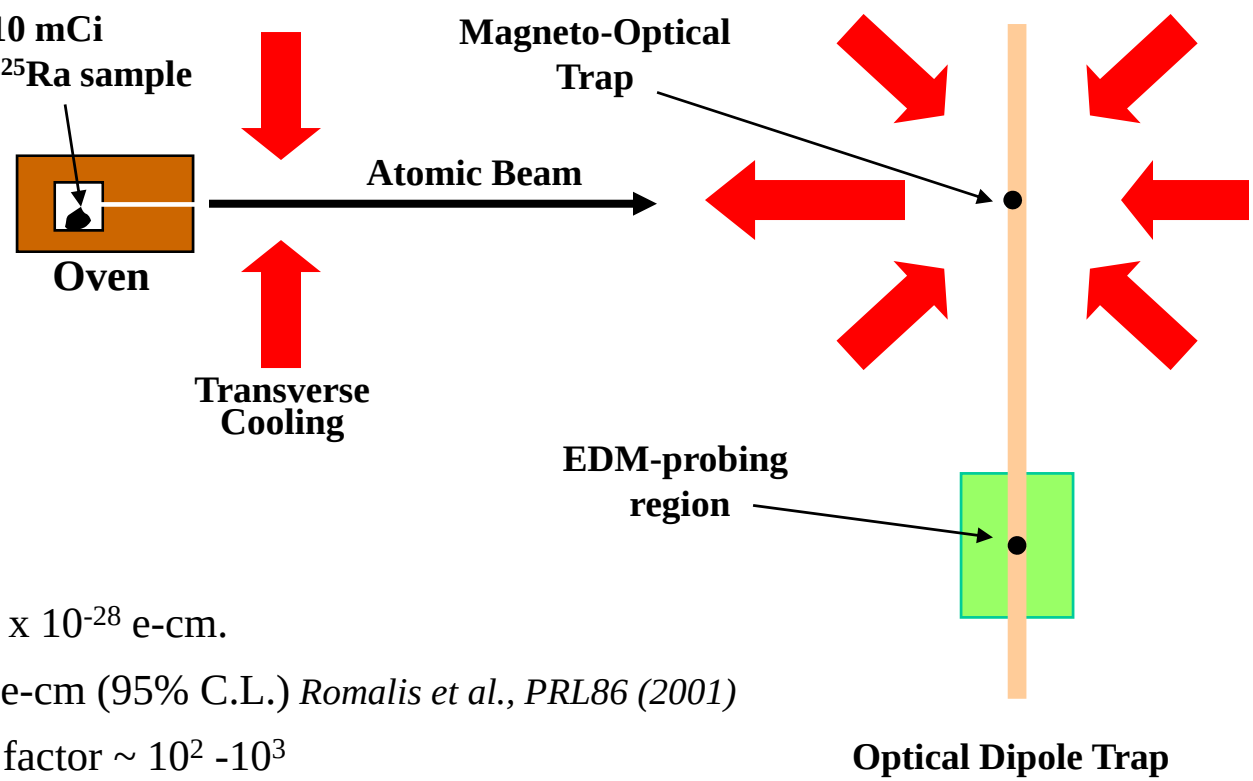
Search for Electric Dipole Moment of ^{225}Ra

Advantages of an EDM measurement on ^{225}Ra atoms in a trap

- EDM enhanced by ~ 10^2-10^3 due to nuclear octupole deformation.
- Trap allows the efficient use of the rare and radioactive ^{225}Ra atoms.
- Long coherence time (~ 100 s), negligible "v x E" systematics, high electric field (100 kV/cm).

Proposed setup

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



- Our sensitivity goal: 1 x 10^{-28} e-cm.
- | d(^{199}Hg) | < 2 x 10^{-28} e-cm (95% C.L.) *Romalis et al., PRL86 (2001)*
- Ra / Hg Enhancement factor ~ 10^2 -10^3

^{225}Ra Source

229Th	α	225Ra	β	225Ac	α	Fr, At, Rn…	α,β	209Bi
7300 yr	→	15 days	→	10 days	→	~ 4 hours	→	stable

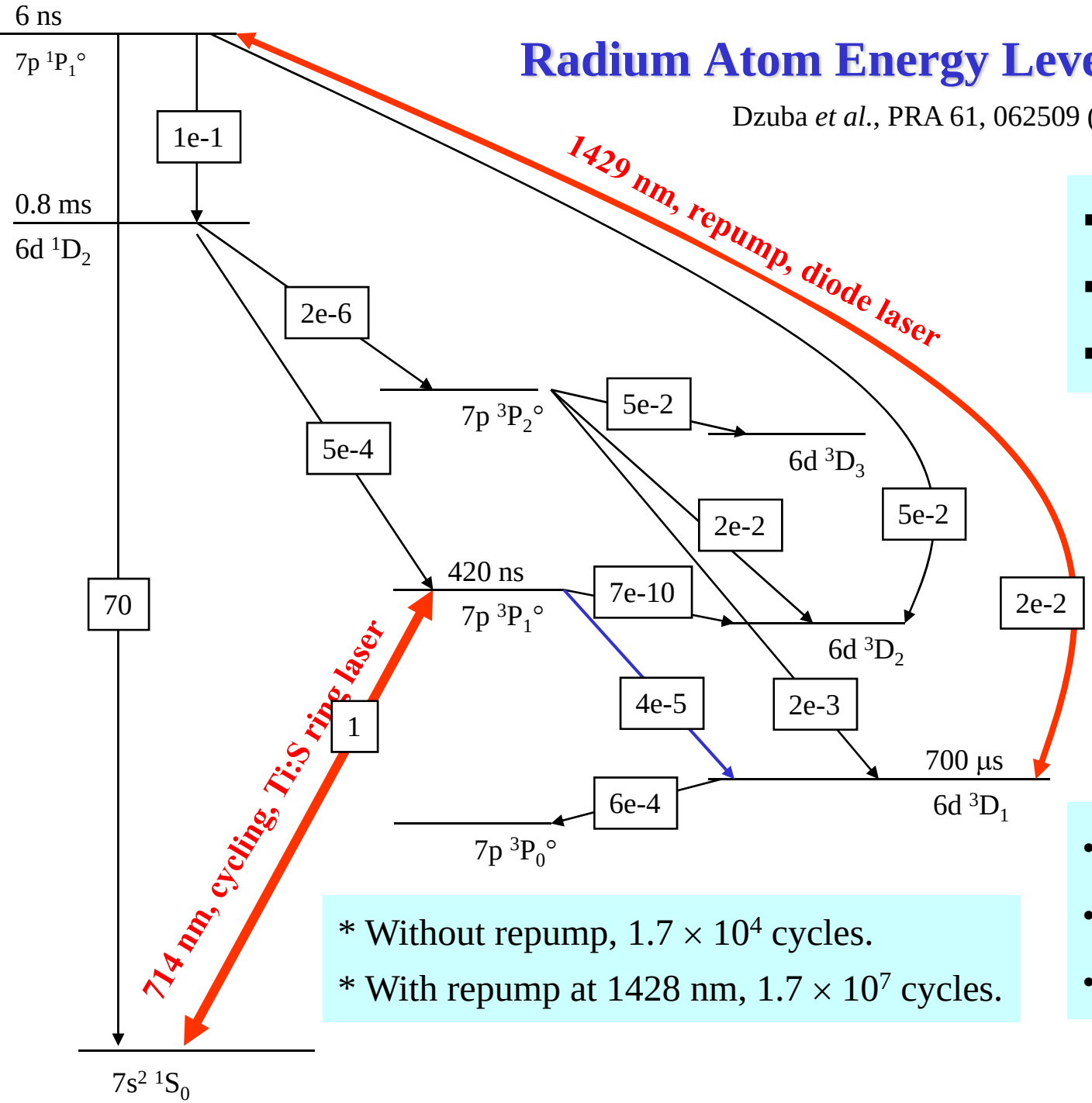
- 1 mCi ^{229}Th source produces 4×10^{7} s^{-1} ^{225}Ra
- Chemical extraction of Ra from Th
- Reduction of $Ra(NO_3)_2$ with Ba, Al, Ti…

RIA ~ 1 Ci ^{229}Th

Expected yield for ^{225}Ra: 2.6×10^{10} s^{-1}

Radium Atom Energy Level Diagram

Dzuba *et al.*, PRA 61, 062509 (2000)



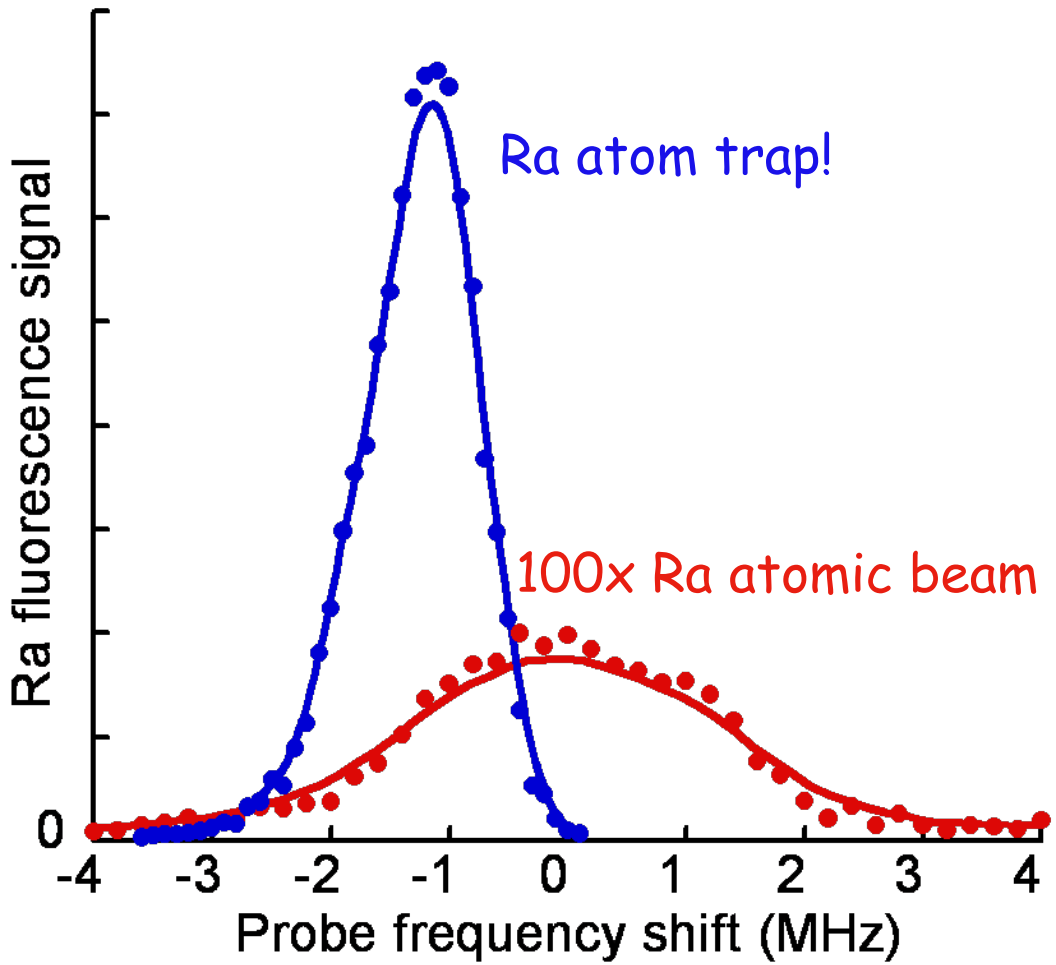
- $\delta v / \gamma = 2.5$ mm/s
- Cycling rate ~ 1 MHz
- MOT lifetime ~ 20 s

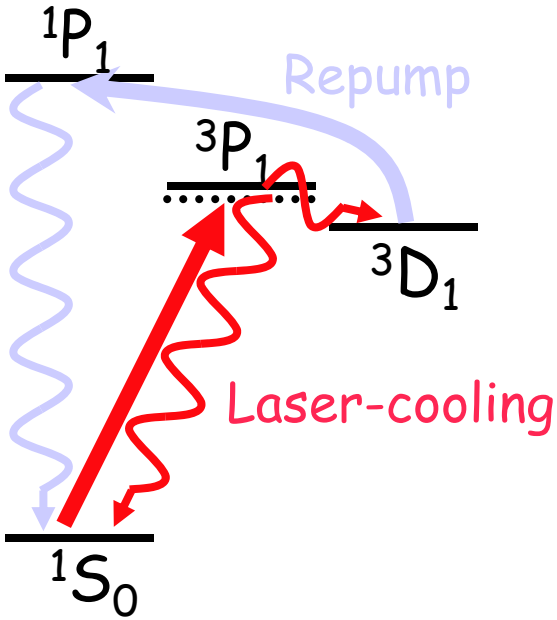
* Without repump, 1.7×10^4 cycles.
* With repump at 1428 nm, 1.7×10^7 cycles.

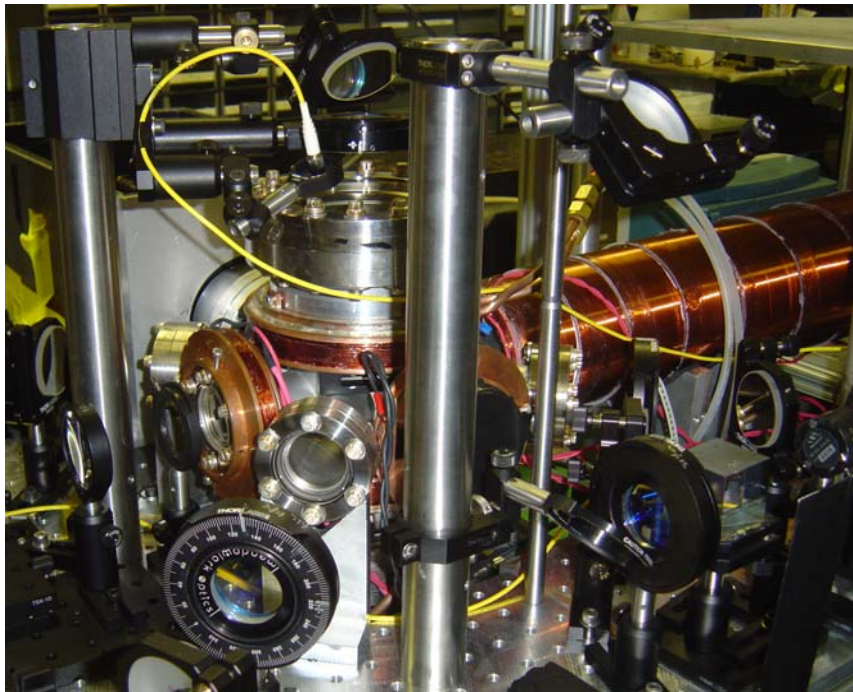
- Linewidth ~ 400 kHz
- Cooling 7 μK, 14 mm/s
- B gradient ~ 1 G / cm

Laser-Trapping of ^{225}Ra and ^{226}Ra Atoms

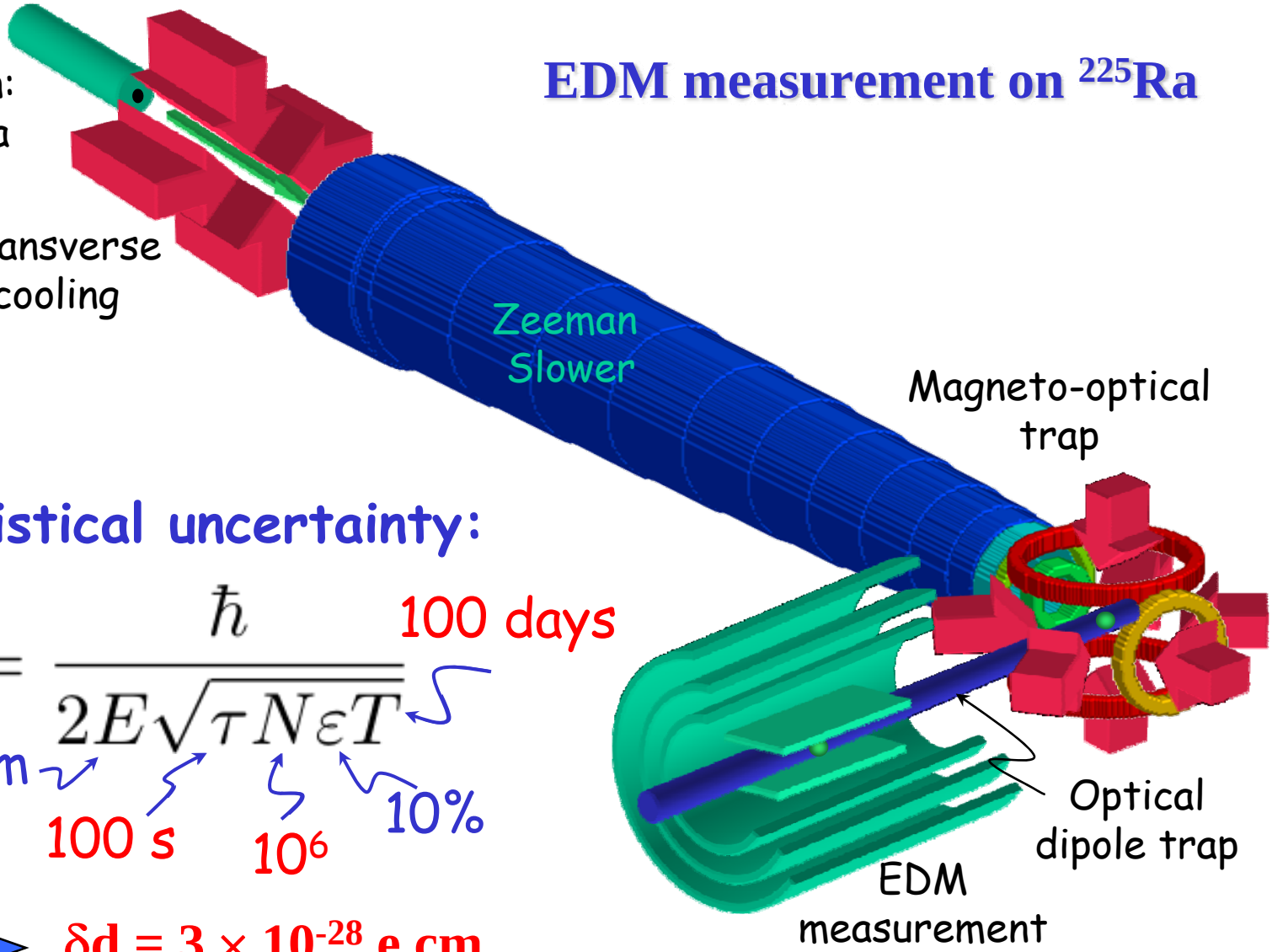
- **Key ^{225}Ra frequencies, lifetimes measured**
  Scielzo et al. PRA (2006)
- **^{225}Ra laser cooled and trapped!**
  Guest et al. PRL (2007)







EDM measurement on ^{225}Ra



Statistical uncertainty:

$$\delta d = \frac{\hbar}{2E\sqrt{\tau N \varepsilon T}}$$

100 kV/cm

100 s

10^6

10%

100 days

$\delta d = 3 \times 10^{-28}$ e cm

Ra / Hg Enhancement factor ~ 10^2 -10^3

Best experimental limit: d(^{199}Hg) < 2×10^{-28} e cm

Nuclear EDM Searches

Isotope	Current Limit (e cm)	Institution	Technique
Neutron	< 2.9E-26 Grenoble	SNS Grenoble	Superfluid He
^{199}Hg	< 2.1E-28 Washington	Washington	4 cells
^{129}Xe	(0.7 ± 3.3)E-27 Michigan	Princeton	Liquid cell
^{225}Ra	N/A	Argonne KVI	Trap
^{223}Rn	N/A	Michigan & TRIUMF	Cell
^{2}H	N/A	Brookhaven	Storage ring

Radium EDM Collaboration

Irshad Ahmad	Kevin Bailey	Michael Bishof
Jeff Guest	John Greene	Harvey Gould
Roy Holt	Zheng-Tian Lu	Peter Mueller
Tom O'Connor	Ibrahim Sulai	Will Trimble