Search for the Nuclear Schiff Moment of Radium-225

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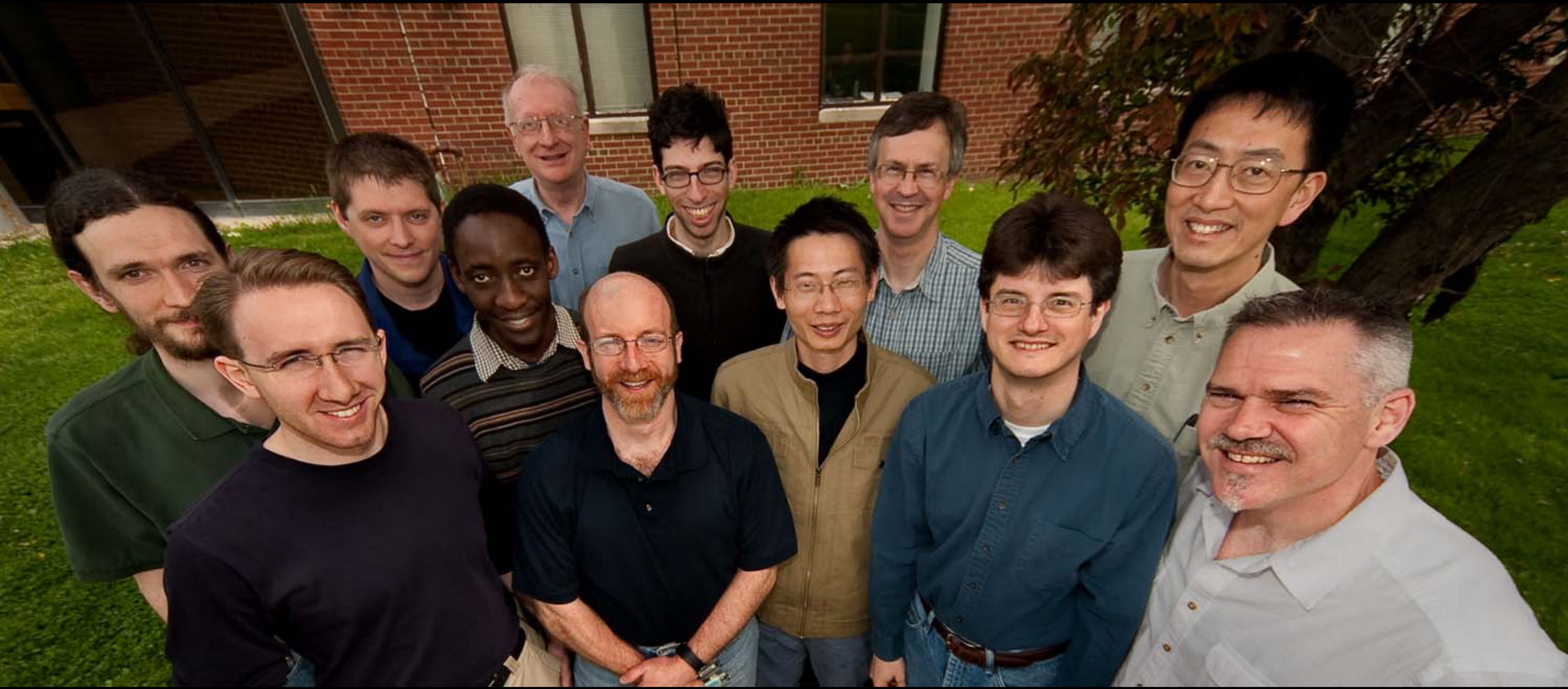
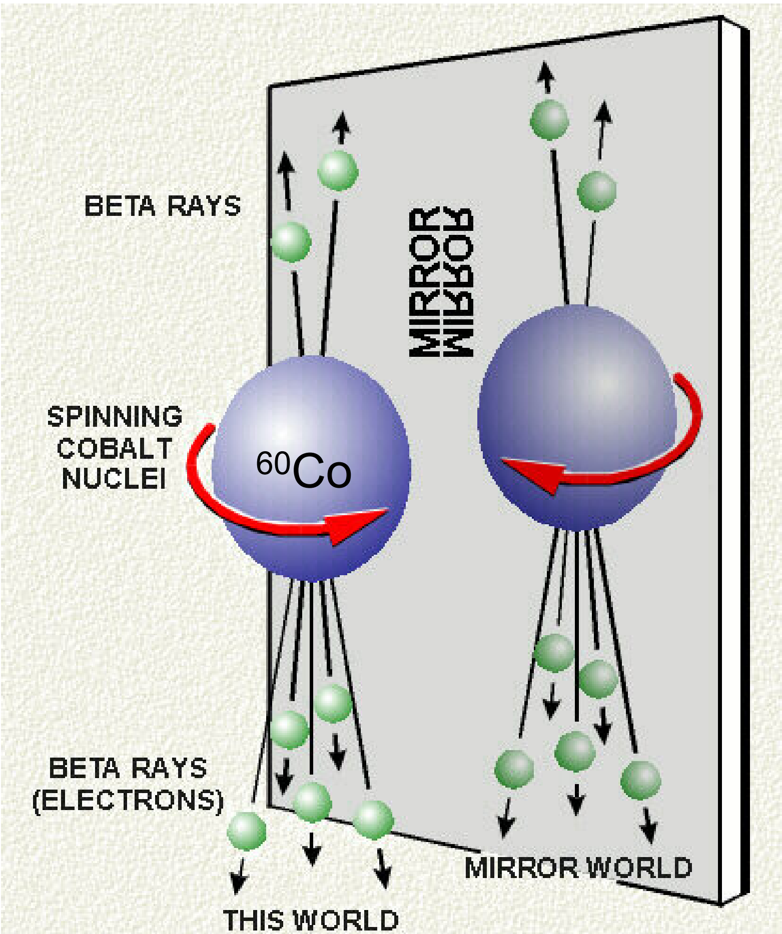


Discrete Fundamental Symmetries

Parity violation – First observation



C. S. Wu *et al*. (1957)

- P — Parity
- C — Charge conjugation
- CP — CP symmetry
- T — Time reversal
- CPT — CPT – Exact symmetry in quantum field theory with Lorentz invariance

More CP-Violation Mechanisms?

Supersymmetry

More particles → More CP-violating phases

Matter-antimatter asymmetry

Require additional CP-violation mechanism(s)

Strong CP problem

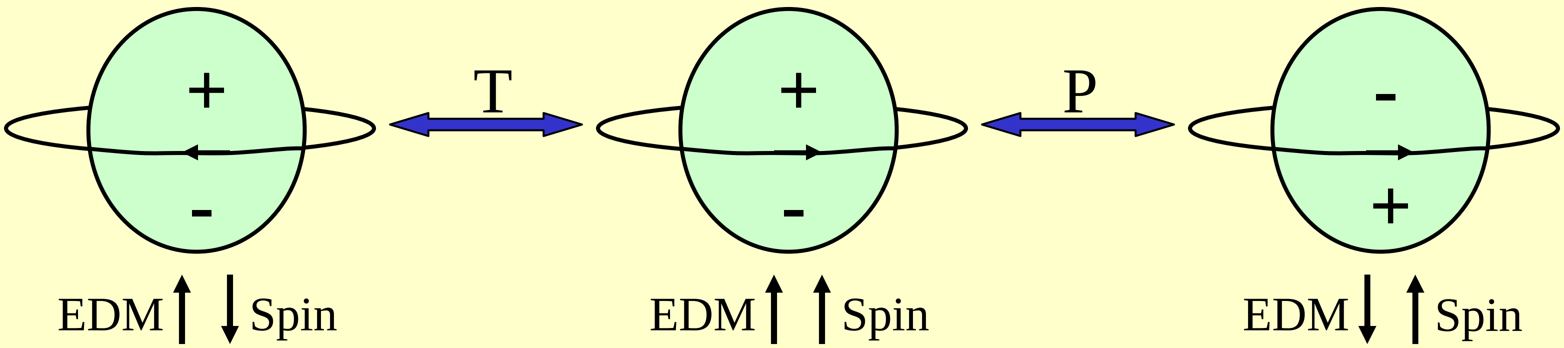
CP-violating phase in Quantum Chromodynamics

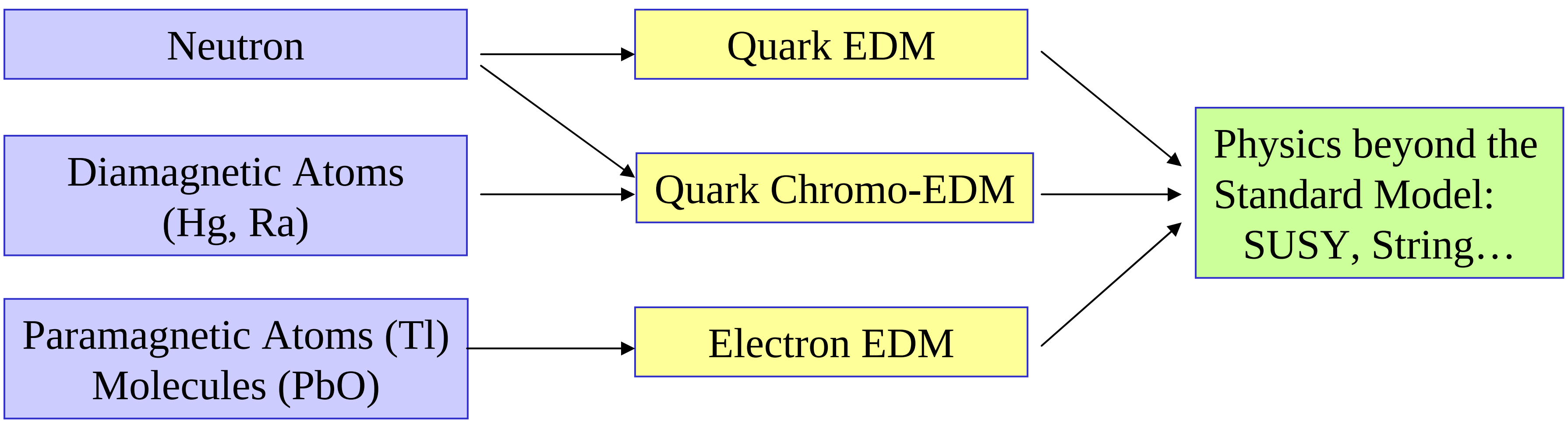
$$\mathcal{L}_{\mathrm{mass}} \to -m(\bar{\psi}_{\mathrm{L}}\psi_{\mathrm{R}} + \bar{\psi}_{\mathrm{R}}\psi_{\mathrm{L}}) + \frac{\theta g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$$

Fortson, Sandars, Barr, Physics Today (June 2003)

Electric Dipole Moment (EDM) Violates Both P and T

A permanent EDM violates both time-reversal symmetry and parity





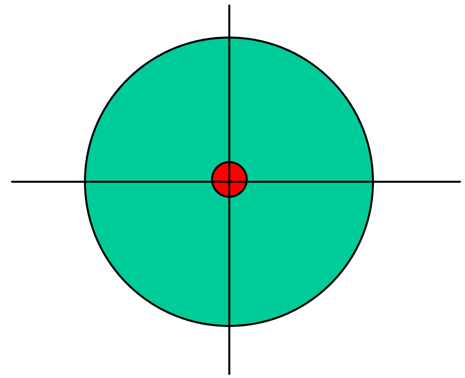
Measurability of Nuclear EDM

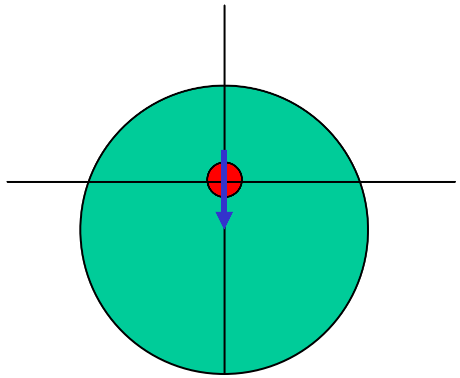
L.I. Schiff, Phys. Rev. (1963)

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.

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

Schiff moment (toy model)

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

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

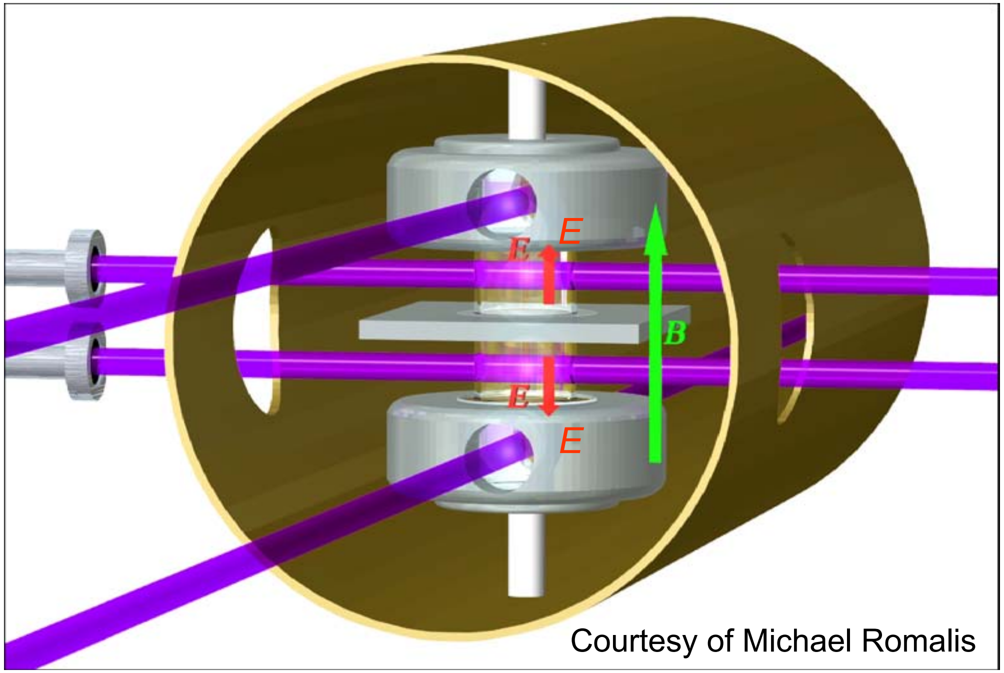
$$d_{atom} \sim S \cdot r_{atom}^{-1} \cdot r_c^{-1}$$

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

a 'radially-weighted dipole moment'

The Seattle EDM Measurement

^{199}Hg stable, high Z, J = 0, I = ½, high vapor pressure



Courtesy of Michael Romalis

$$f_+ = \frac{2\mu B + 2dE}{h} \approx 15 \text{ Hz}$$

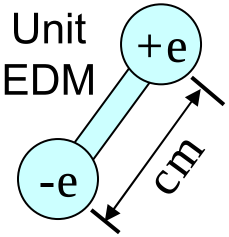
$$f_- = \frac{2\mu B - 2dE}{h} \approx 15 \text{ Hz}$$

$$|f_+ - f_-| < 0.6 \text{ nHz}$$

The best limit on atomic EDM

EDM (^{199}Hg) < 3 x 10^{-29} e-cm

Griffith *et al.*, Phys Rev Lett (2009)



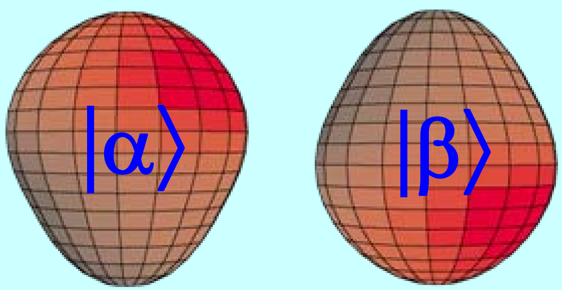
EDM of ^{225}Ra enhanced

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)

Parity doublet



$$\Psi^{-} = (|\alpha\rangle - |\beta\rangle)/\sqrt{2}$$

55 keV

$$\Psi^{+} = (|\alpha\rangle + |\beta\rangle)/\sqrt{2}$$

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)

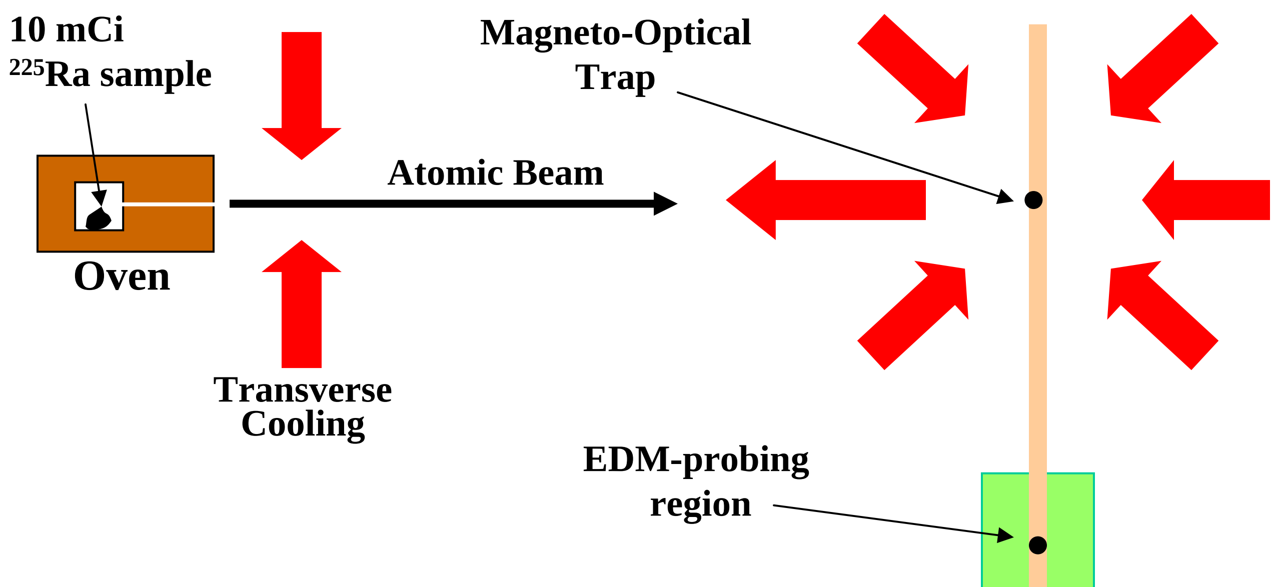
Search for Electric Dipole Moment of ^{225}Ra

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) | < 3 x 10^{-29} e-cm (95% C.L.) *Griffith et al., PRL (2009)*
- Ra / Hg Enhancement factor ~ 10^2 -10^3

Optical Dipole Trap

^{225}Ra Source

^{229}Th 7300 yr $\xrightarrow{\alpha}$ ^{225}Ra 15 days $\xrightarrow{\beta}$ ^{225}Ac 10 days $\xrightarrow{\alpha}$ Fr, At, Rn… ~ 4 hours $\xrightarrow{\alpha,\beta}$ ^{209}Bi stable

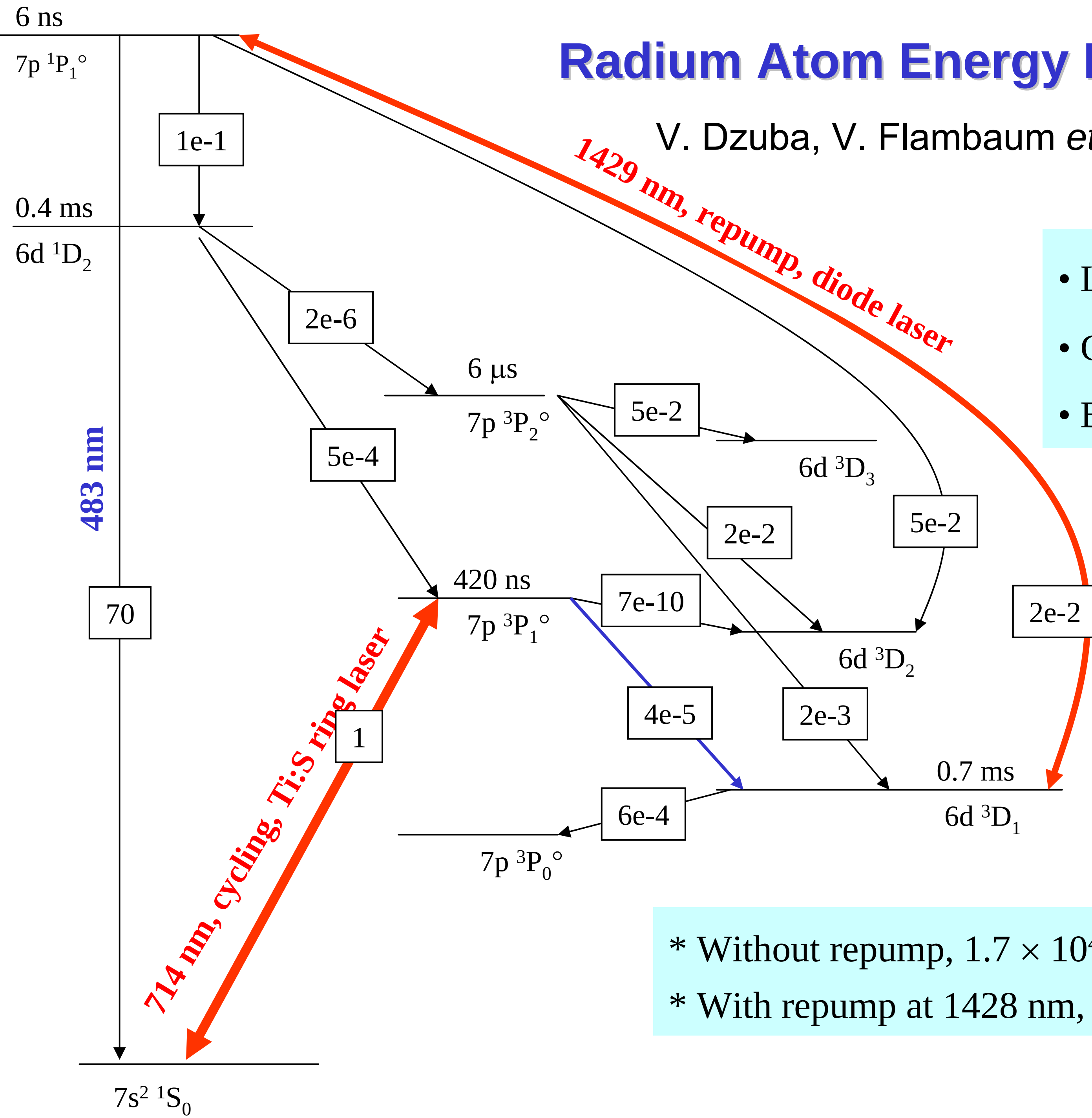
- 2 mCi (or 60 ng) ^{225}Ra sources available from Oak Ridge National Lab
- Test source: 300 nCi ^{226}Ra (1600 yr) -- invaluable for testing
- $Ra(NO_3)_2$ reduced by Ba metal and Al in 700 C oven

Rare Isotope Facility

Yield for ^{225}Ra ~ 10^{10} s^{-1} - 10^{12} s^{-1} ?

Radium Atom Energy Level Diagram

V. Dzuba, V. Flambaum *et al.*, PRA 61 (2000)



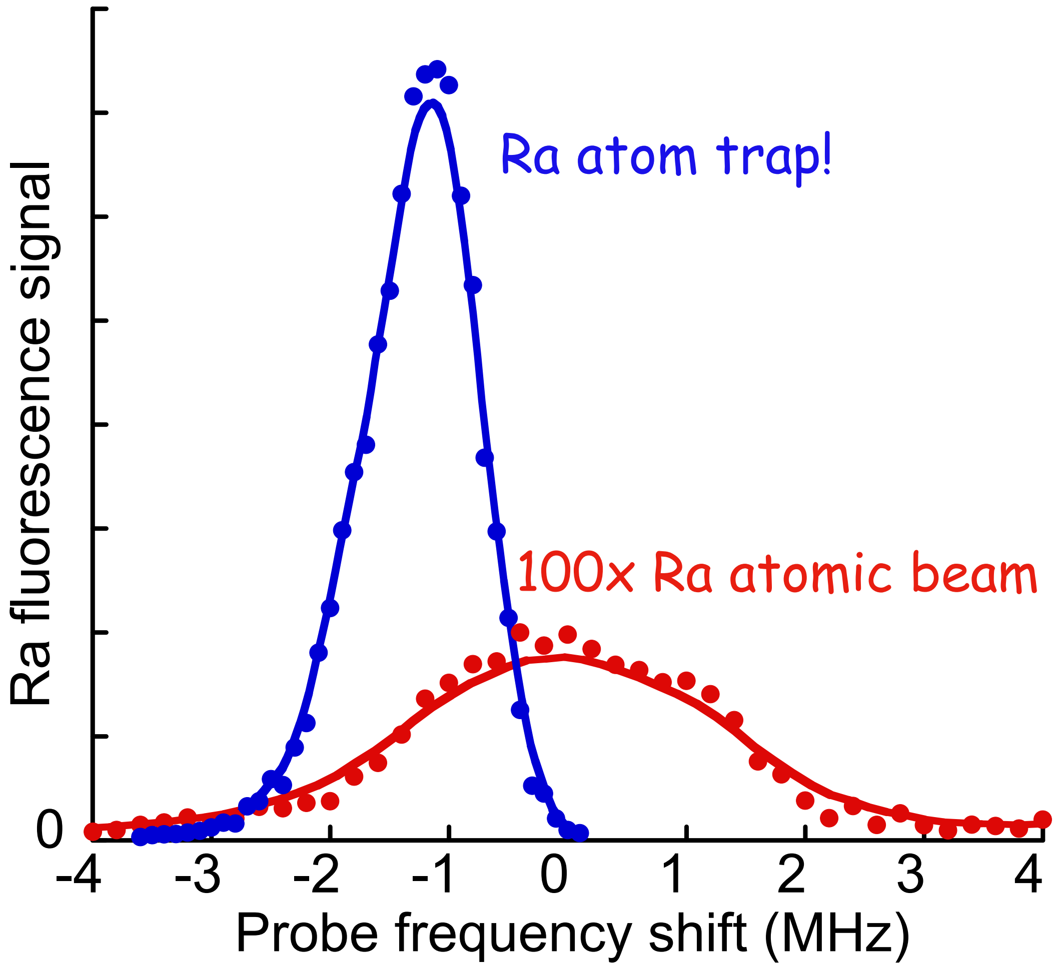
- Linewidth ~ 400 kHz
- Cooling 7 μK, 14 mm/s
- B gradient ~ 1 G / cm

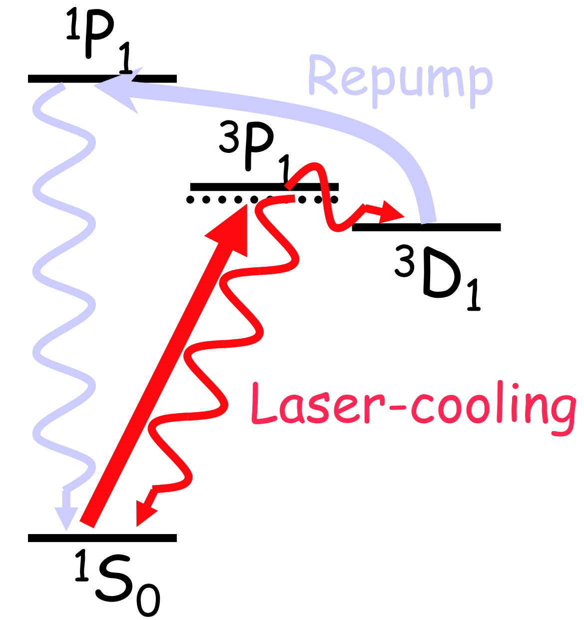
* Without repump, 1.7×10^4 cycles.

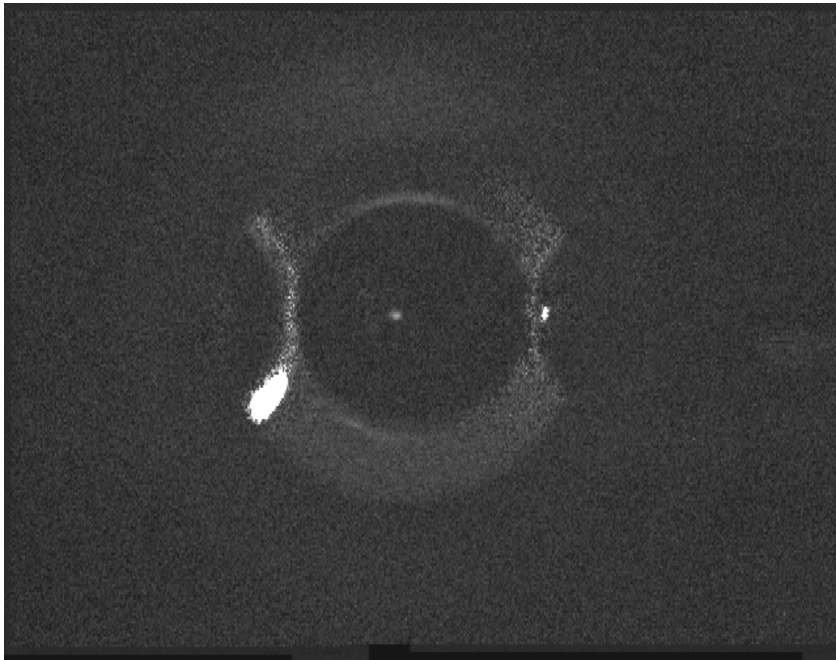
* With repump at 1428 nm, 1.7×10^7 cycles.

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

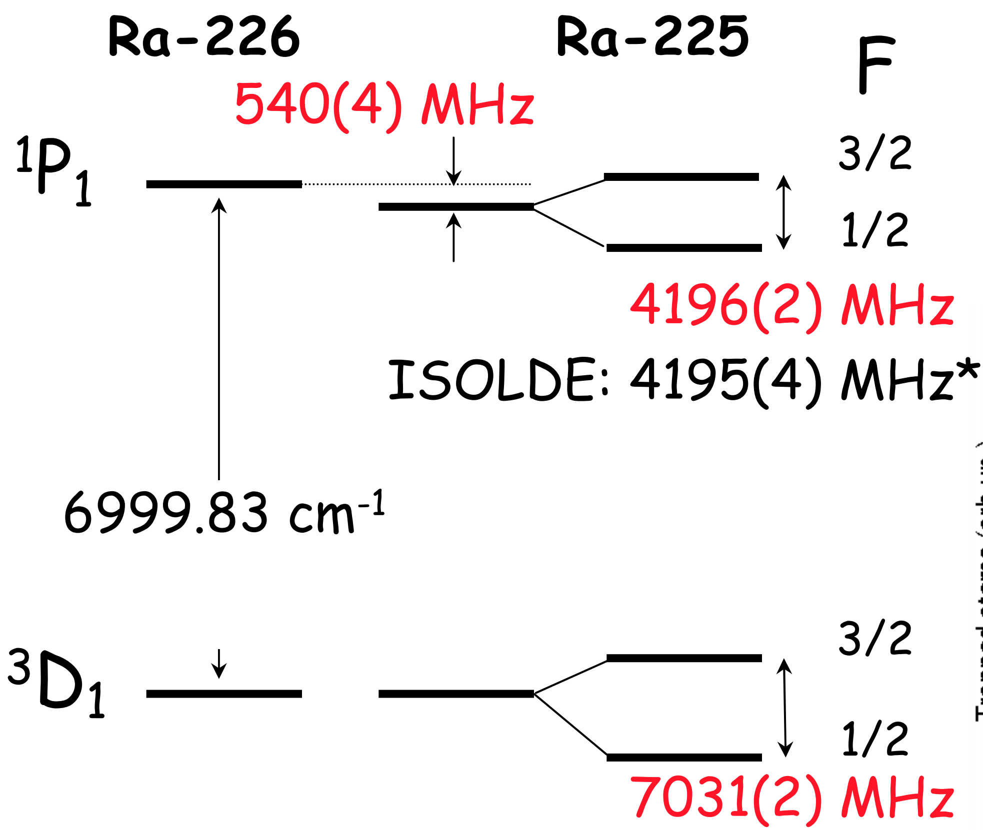
- **Key ^{225}Ra frequencies, lifetimes measured**
  Scielzo et al. PRA (2006)
- **^{225}Ra laser cooled and trapped!**
  Guest et al. PRL (2007)

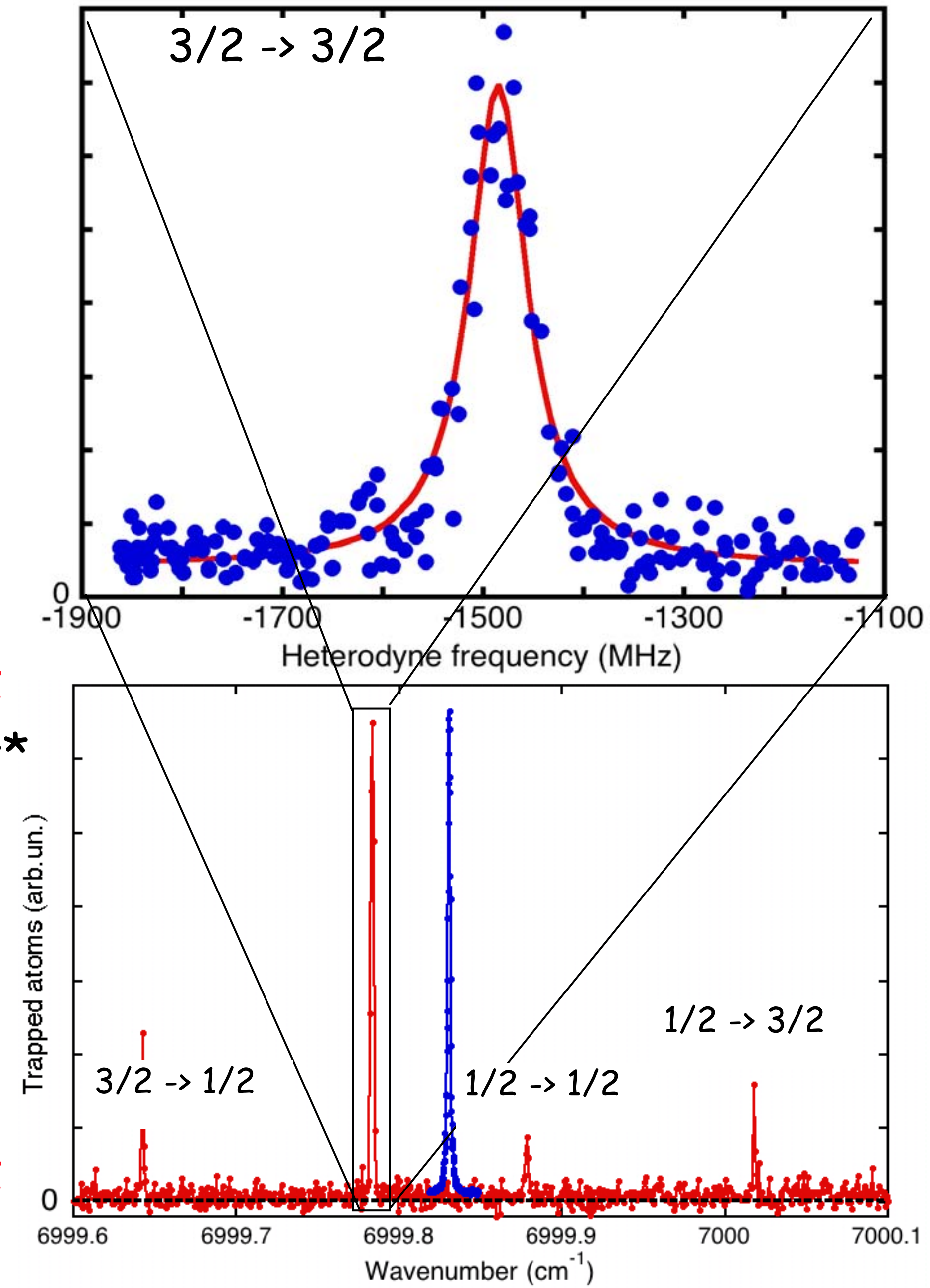






^{226}Ra and ^{225}Ra Hyperfine constants and isotope shift on $^{3}D_{1}$ - $^{1}P_{1}$

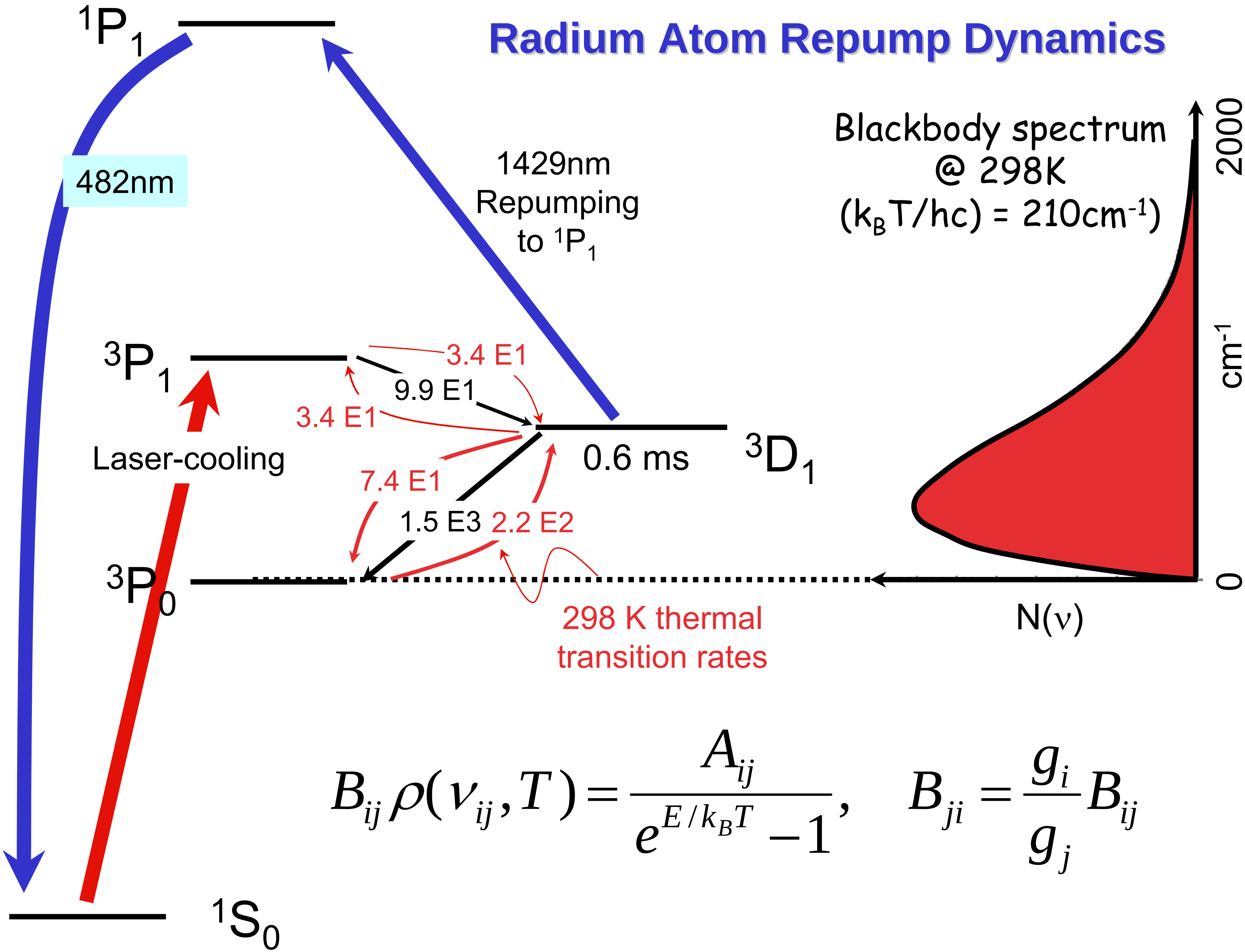




*Ahmad *et al.*, *Phys. Lett.* ***133B****, 47 (1983)*

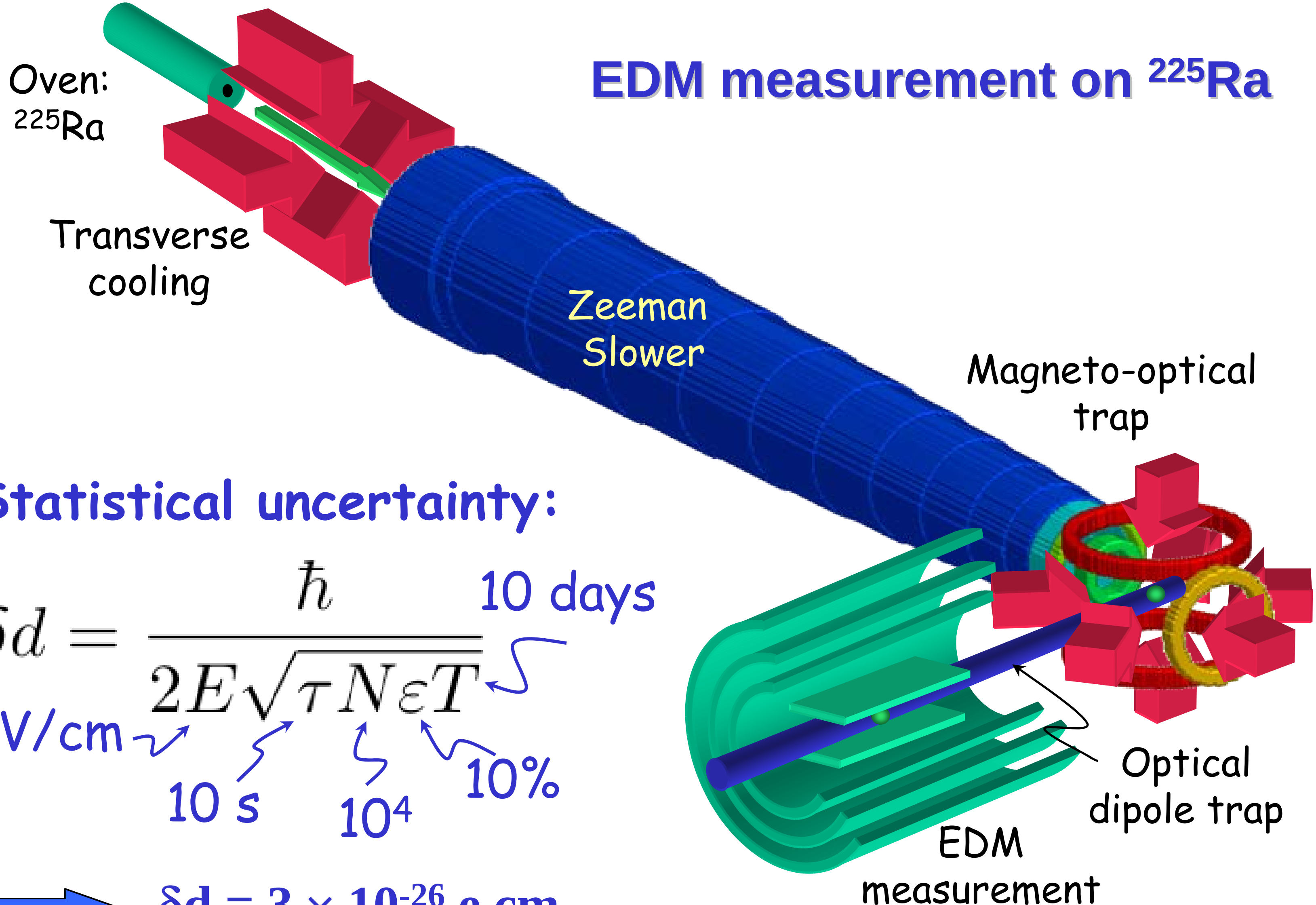
Guest *et al*. PRL (2007)

Radium Atom Repump Dynamics



$$B_{ij}\,\rho(\nu_{ij},T)=\frac{A_{ij}}{e^{E/k_BT}-1},\qquad B_{ji}=\frac{g_i}{g_j}B_{ij}$$

EDM measurement on ^{225}Ra



Statistical uncertainty:

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

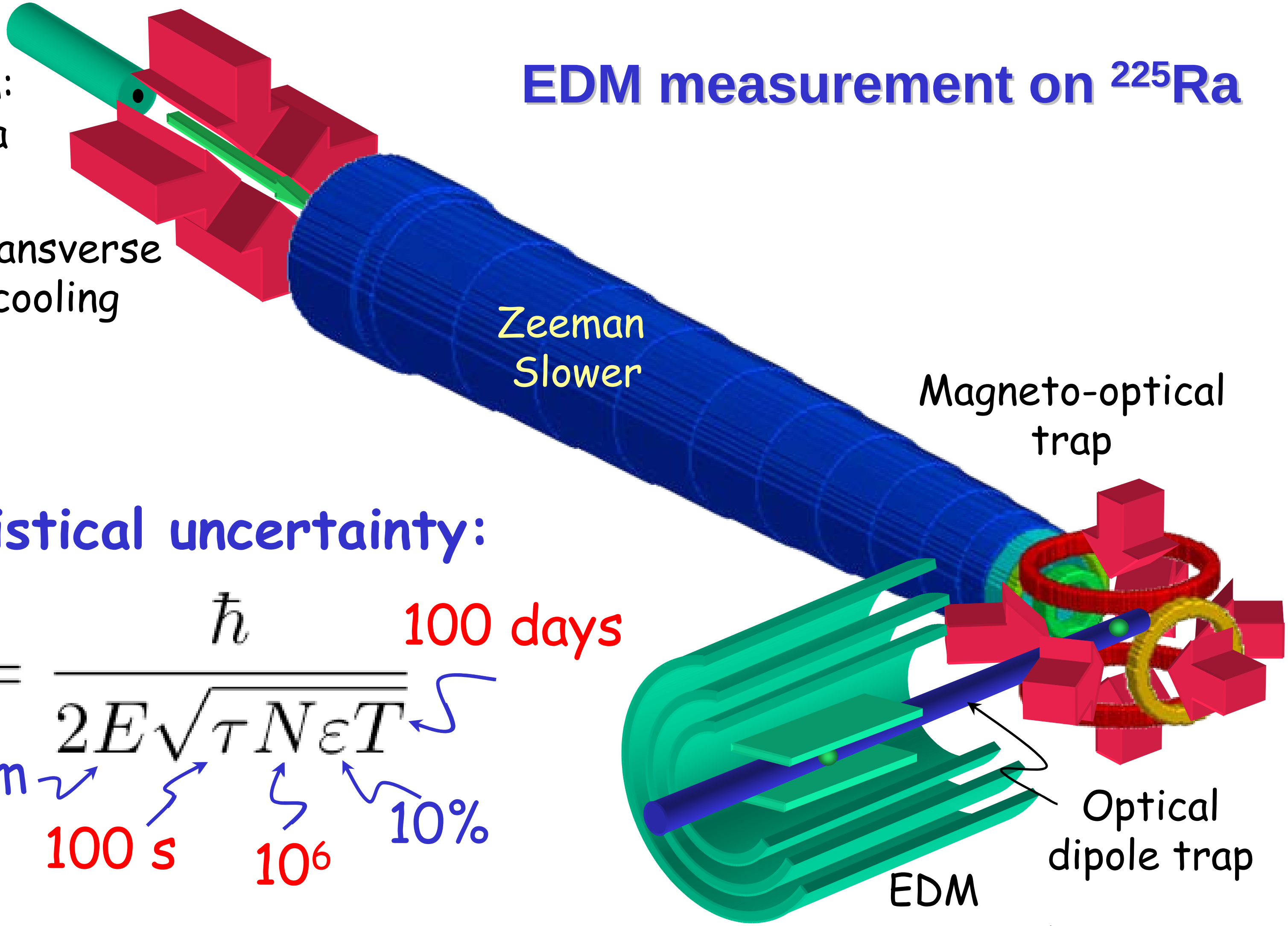
100 kV/cm (E), 10 s (τ), 10^4 (N), 10% (ε), 10 days (T)

→ **$\delta d = 3 \times 10^{-26}$ e cm**

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

Best experimental limit: d(^{199}Hg) < 3×10^{-29} e cm

EDM measurement on ^{225}Ra



Statistical uncertainty:

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

E: 100 kV/cm

τ: 100 s

N: 10^6

ε: 10%

T: 100 days

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

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

Best experimental limit: d(^{199}Hg) < 3×10^{-29} e cm

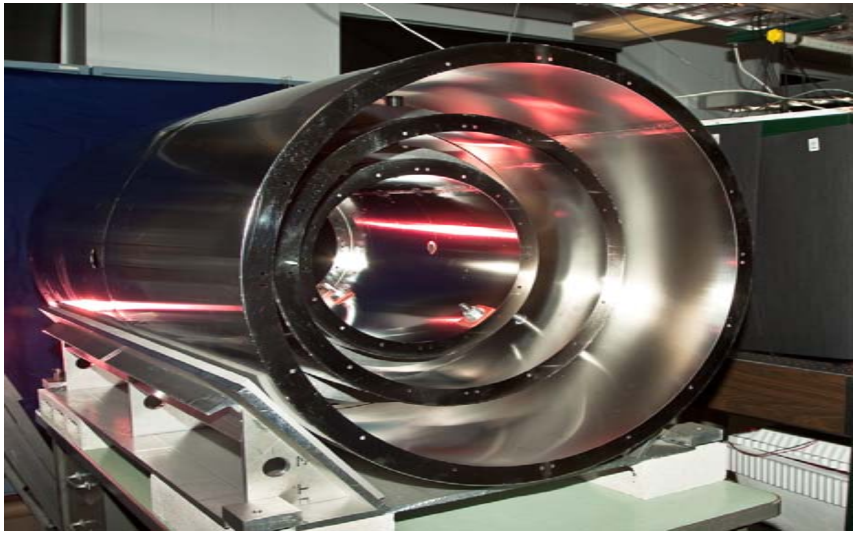
B-Field: Shields, Coils, Magnetometers

Design Goal

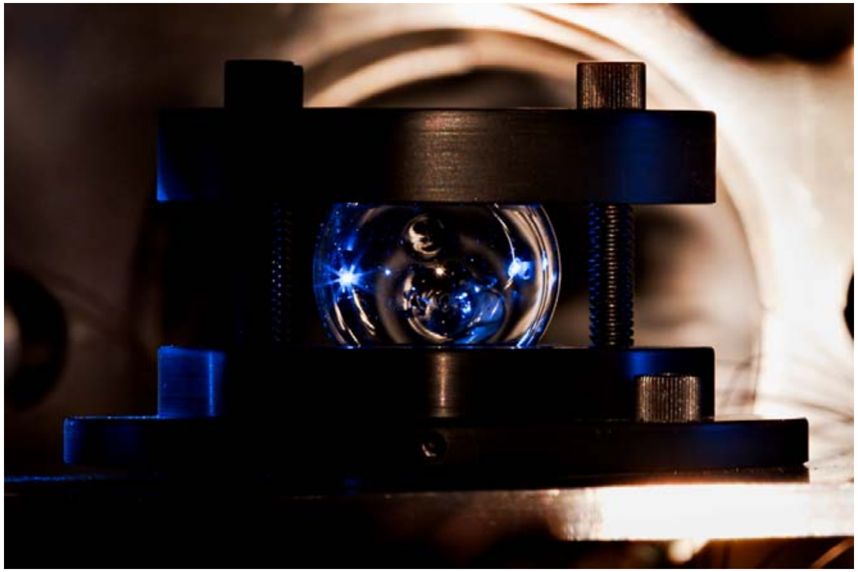
B = 10 mG

Stability: < 1 ppm in 100 sec

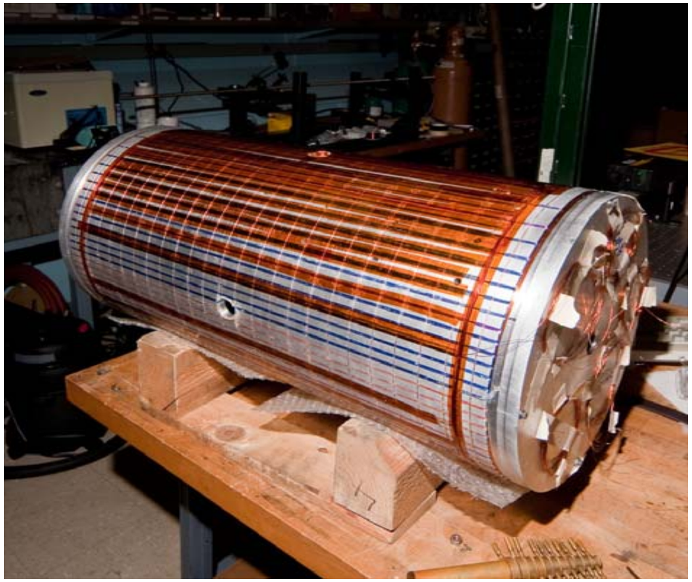
Uniformity: < 1% / cm



μ-shields: Shielding factor = 2×10^4



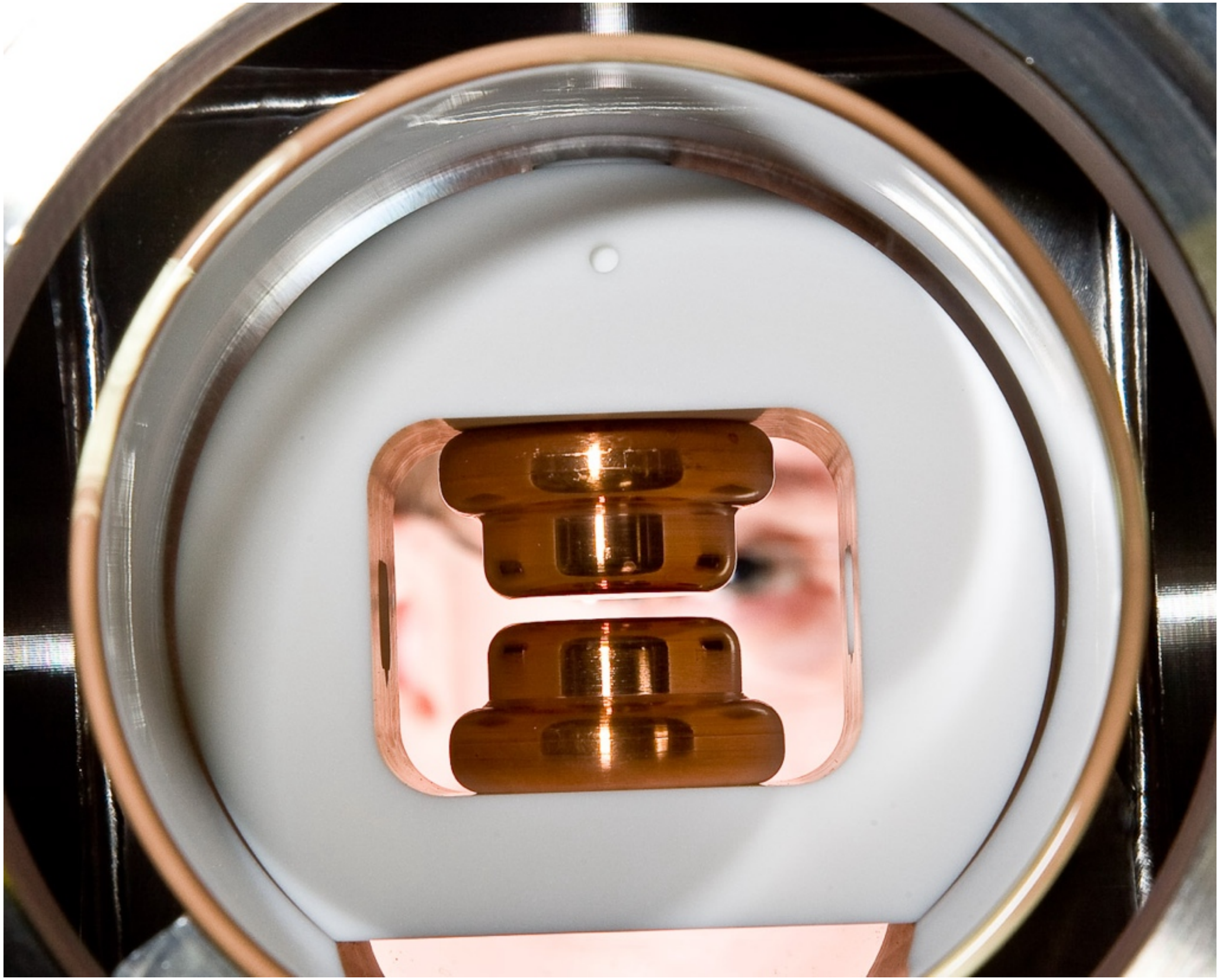
Rb cell magnetometer: Budker design



B gradient < 10 μG/cm

E-Field: 100 kV / cm -- Done.

- 20 kV over 2mm vacuum gap
- < 50 pA leakage currents observed



Optical Dipole Trap

$$H = -\tilde{d}E = -\frac{1}{4}\alpha E_0^2$$

Polarizabilities at 1550 nm

-- calculated by V. Dzuba

$^1S_0$: α_s = 270 a.u. (+/- 5%)

$^3P_1$: α_s = 271 a.u. (+/- 5%)

α_t = 28 a.u.

- Fiber laser:

  λ = 1.55 μm, Power = 8 W

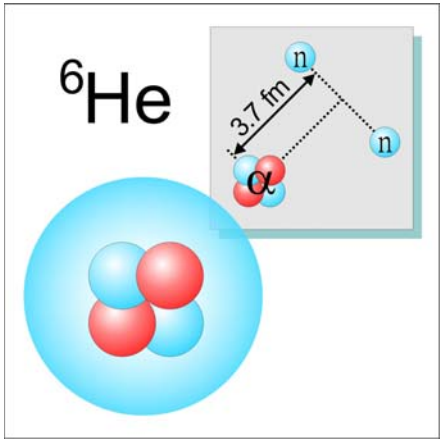
- Focused to 100 μm diameter

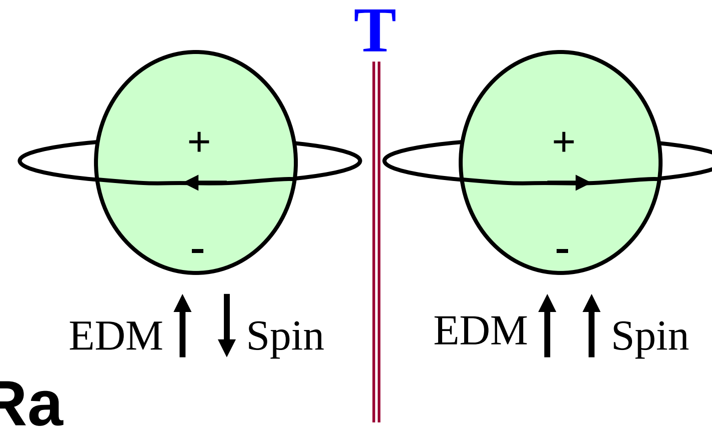
  → 120 μK trap depth

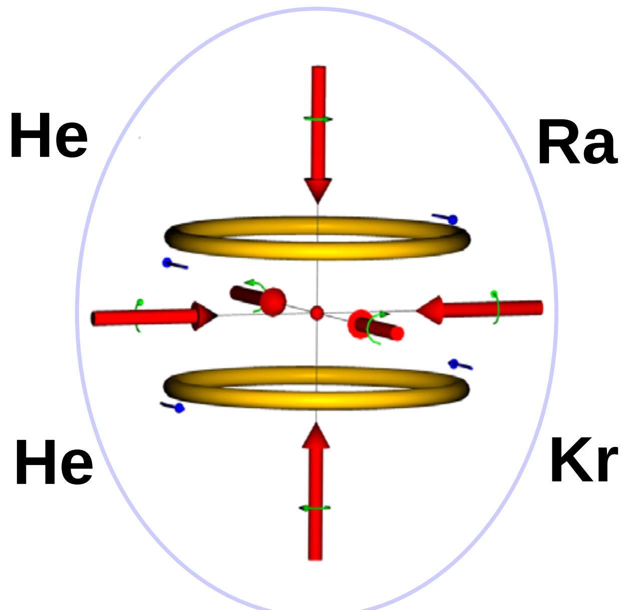
- Raman excitation rate ~ 10^{-5} s^{-1}

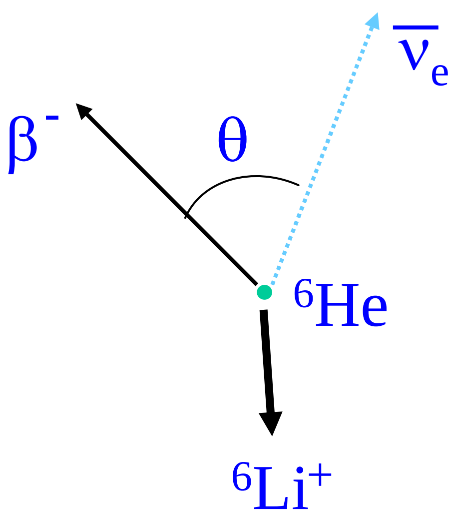
Nuclear EDM Searches

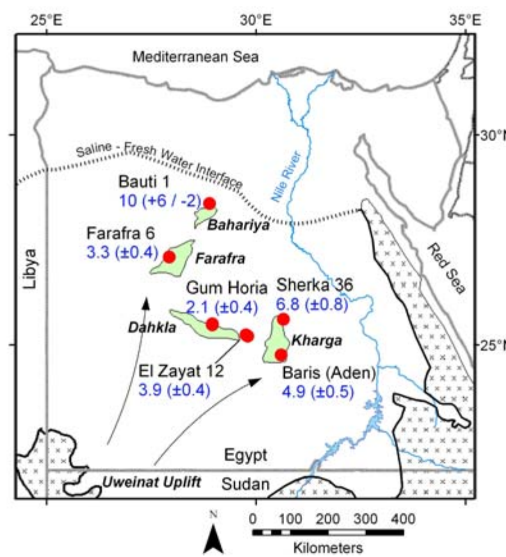
Isotope	Current Limit (e cm)	Institution	Technique
Neutron	< 2.9E-26 Grenoble	SNS Grenoble	Superfluid He
^{199}Hg	< 3E-29 Washington	Washington	4 cells
^{129}Xe	(0.7 ± 3.3)E-27 Michigan	Princeton	Liquid cell
^{225}Ra	N/A	Argonne KVI	Trap
^{223}Rn	N/A	Michigan & TRIUMF	Cell
^{2}H	N/A	Brookhaven	Storage ring











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