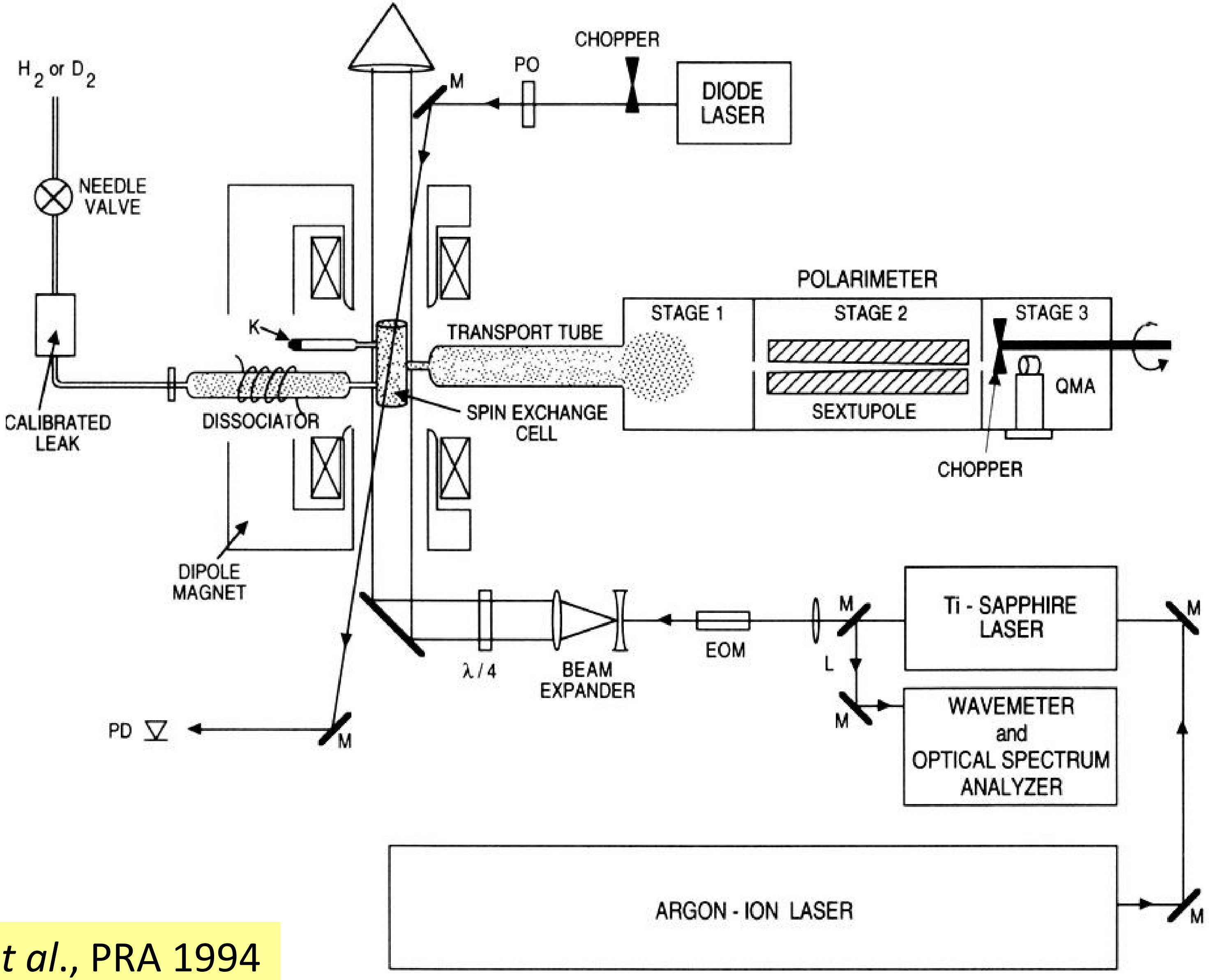
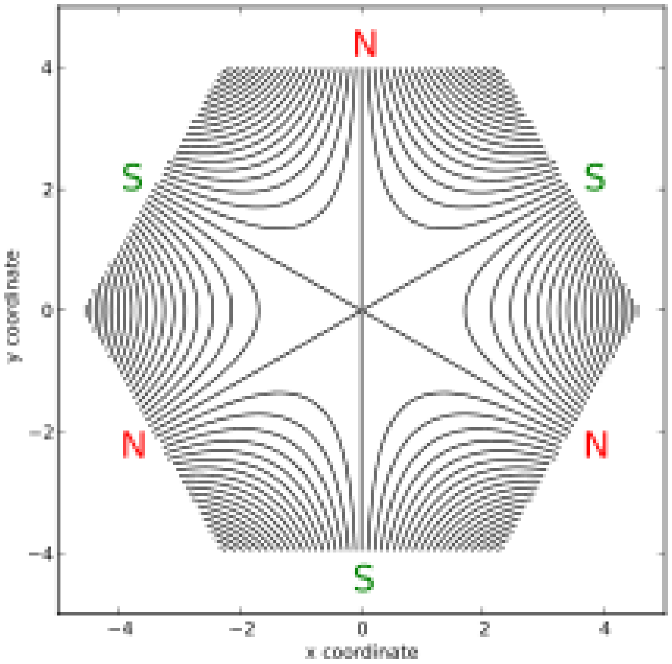
Laser Driven Source of Spin-Polarized Atomic ^{1,2}H



Poelker *et al.*, PRA 1994

What I learned from Roy, circa 1989

Adiabatic Following



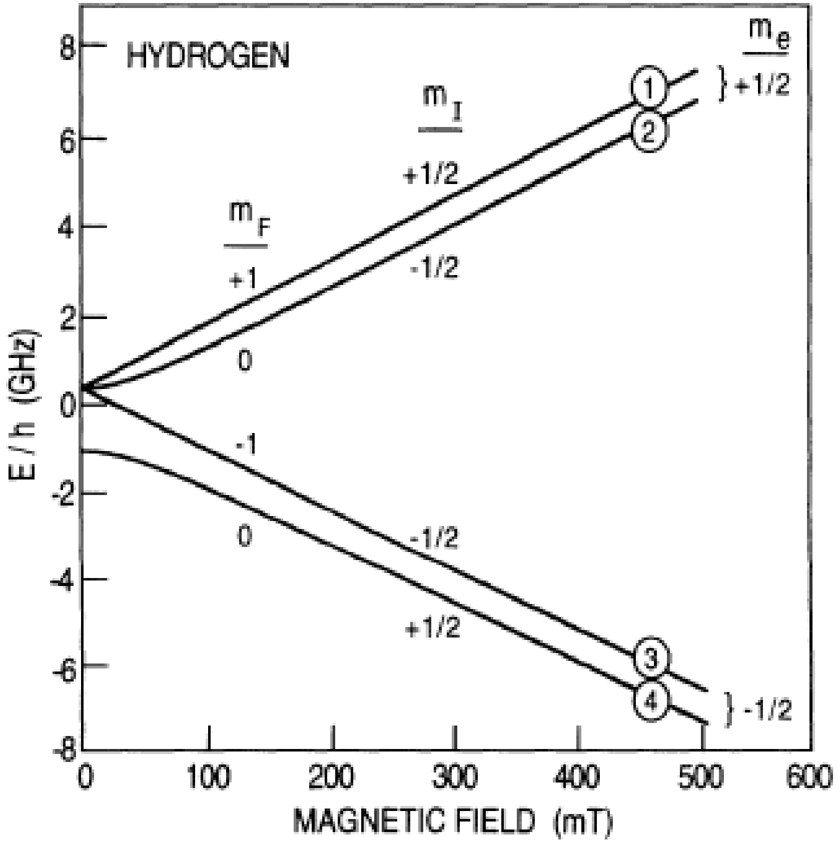
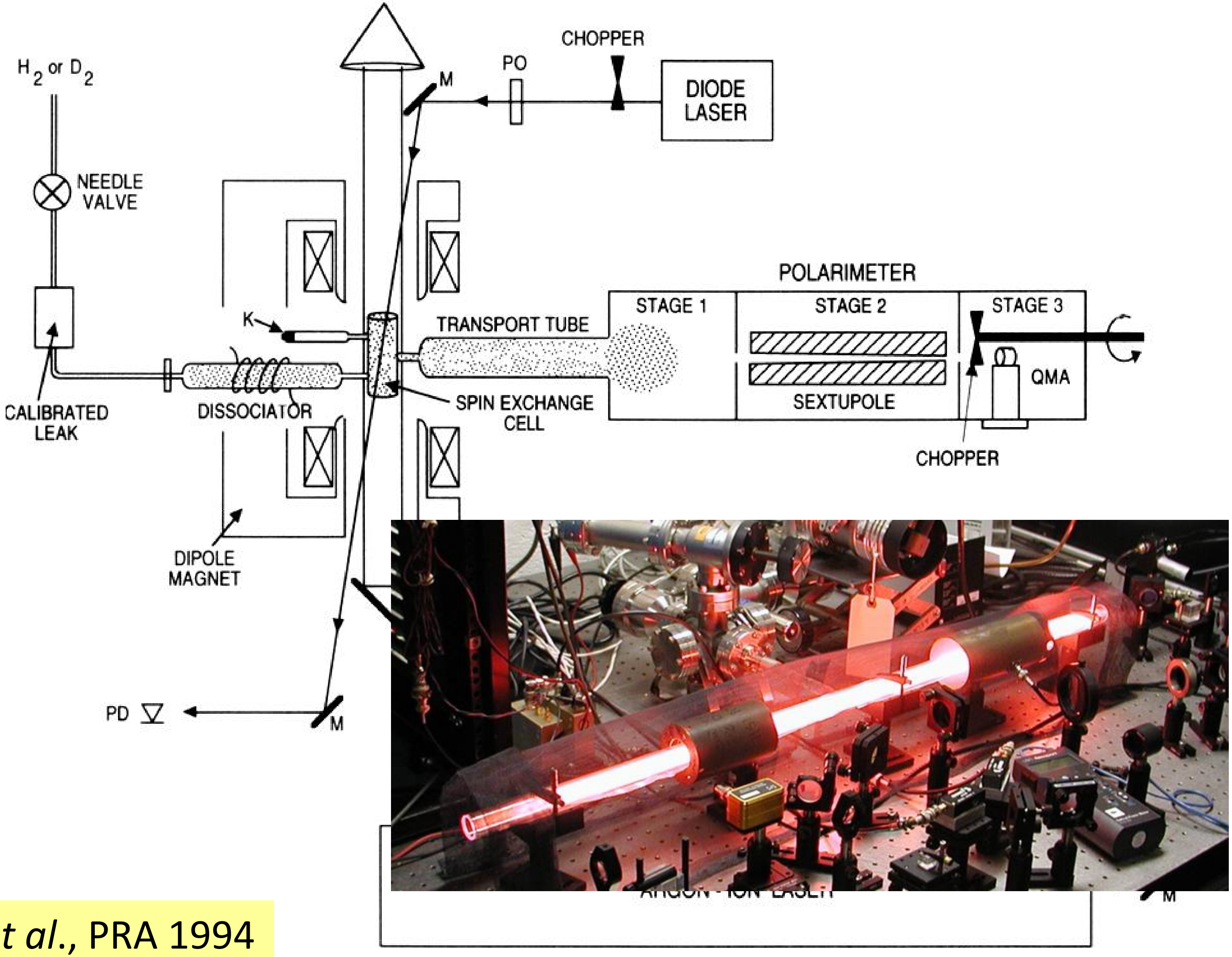


FIG. 2. Rabi diagram for H atoms in a magnetic field.

Poelker *et al.*, PRA 1994

Laser Driven Source of Spin-Polarized Atomic ^{1,2}H

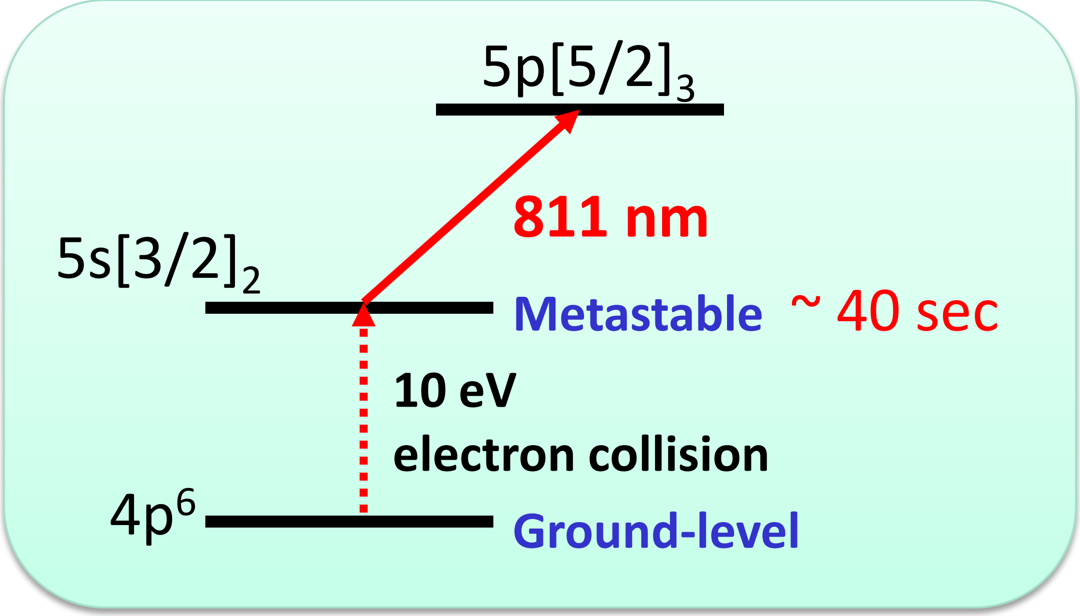


Poelker *et al.*, PRA 1994

Atom Trap Trace Analysis (ATTA)

RF-Driven Sources

- Low pressure → small-size samples
- Fast throughput → short-lived isotopes



$5p[5/2]_3$

811 nm

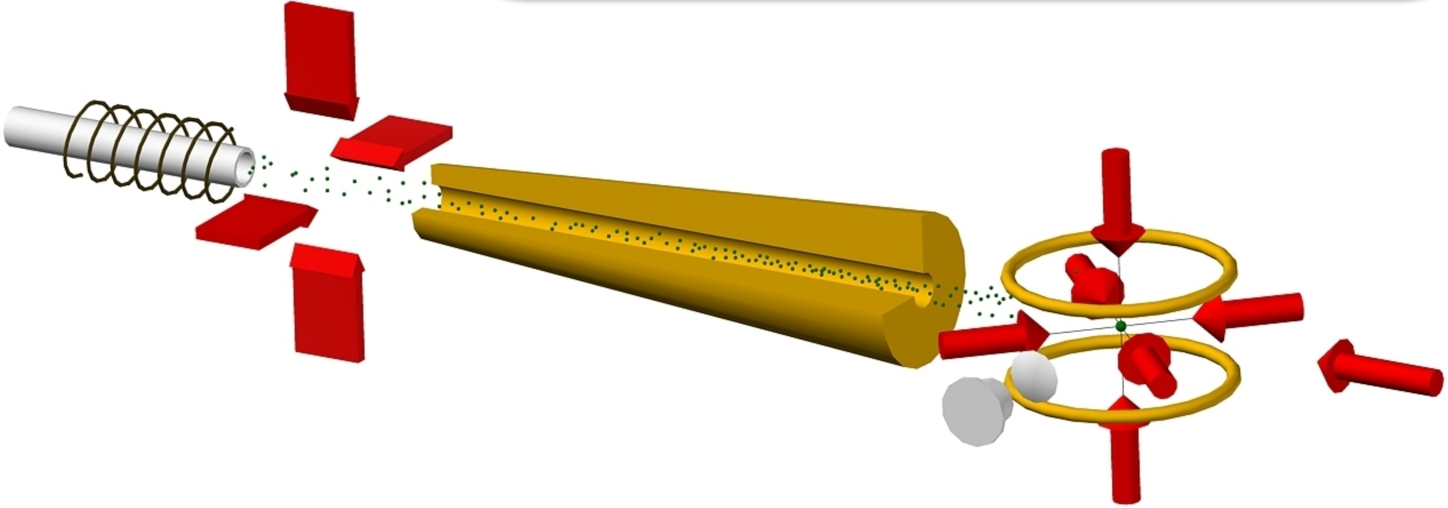
$5s[3/2]_2$

Metastable ~ 40 sec

10 eV
electron collision

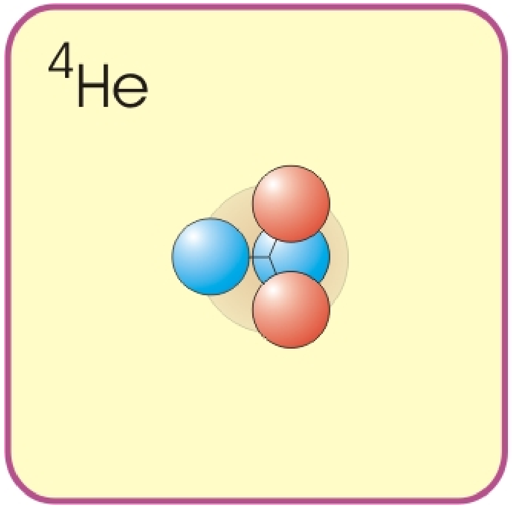
$4p^6$

Ground-level

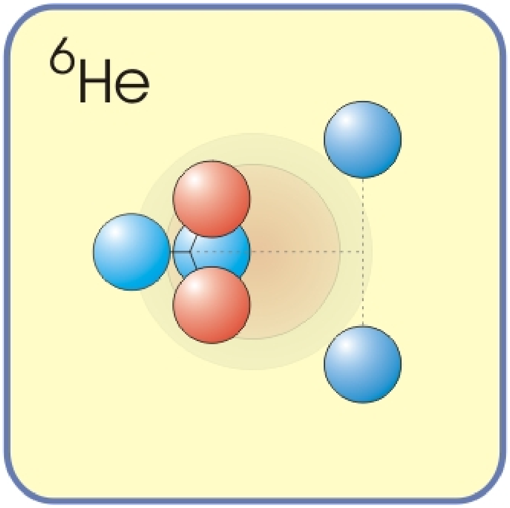


C.-Y. Chen et al., Science (1999); Z.-T. Lu et al., Ear. Sci. Rev. (2014)

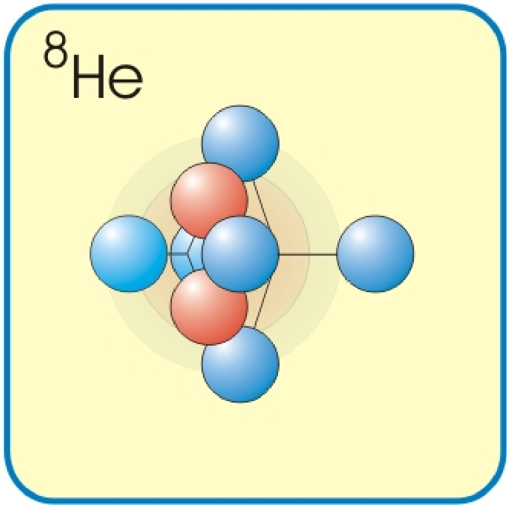
Charge Radii of Exotic Helium Nuclei



1.681(4) fm



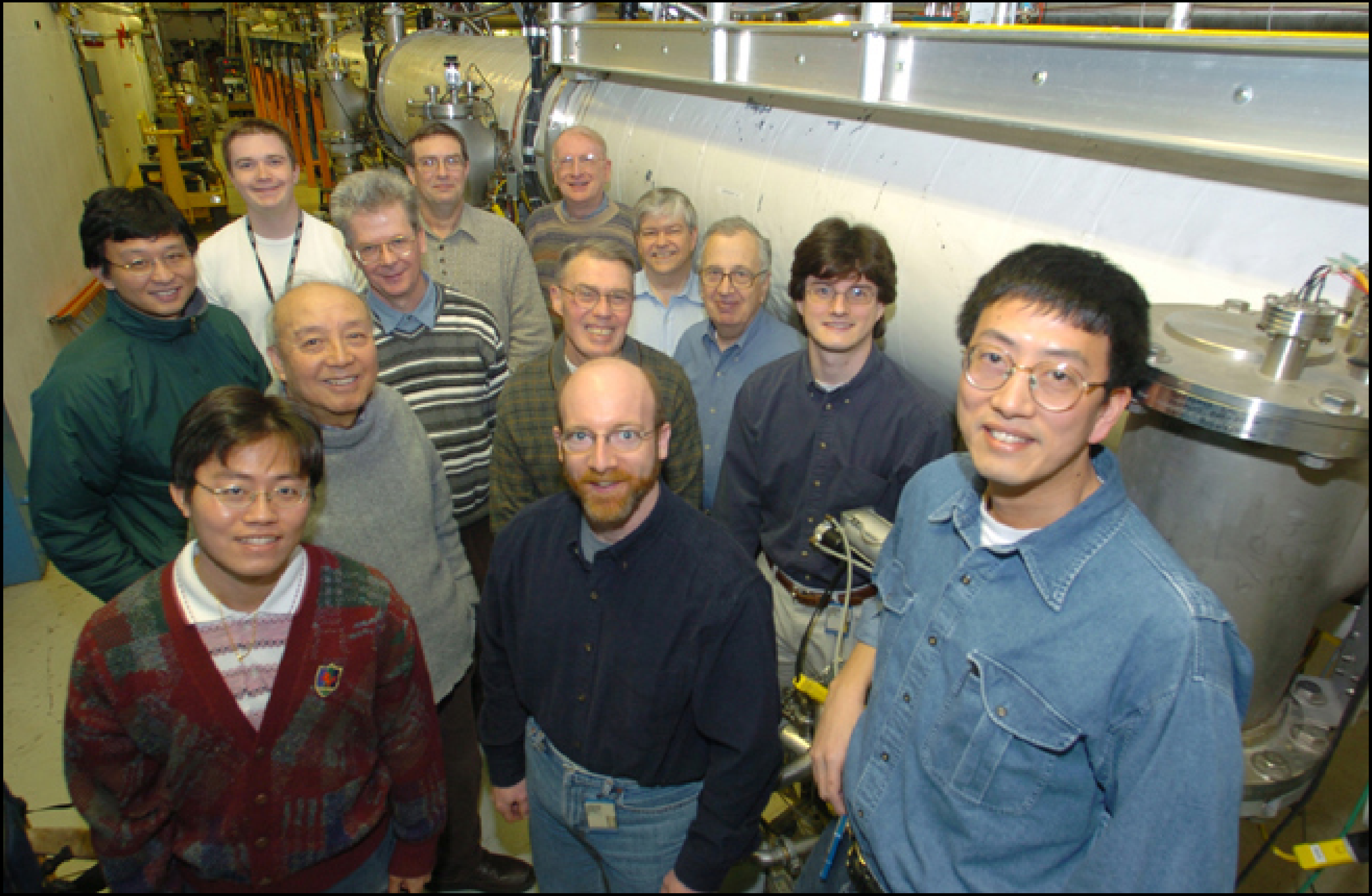
2.059(8) fm



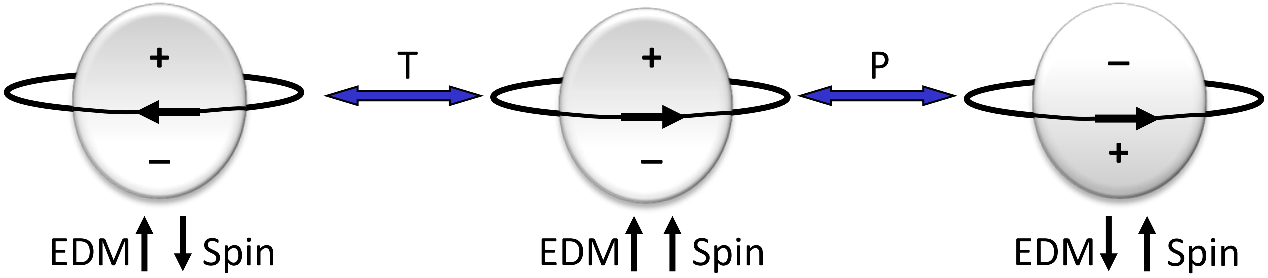
1.958(16) fm

He-6: Wang *et al*., PRL (2004)
He-8: Mueller *et al*., PRL (2007)
Review: Lu *et al*., RMP (2013)

^{6}He Collaboration, 2005, ATLAS Tunnel



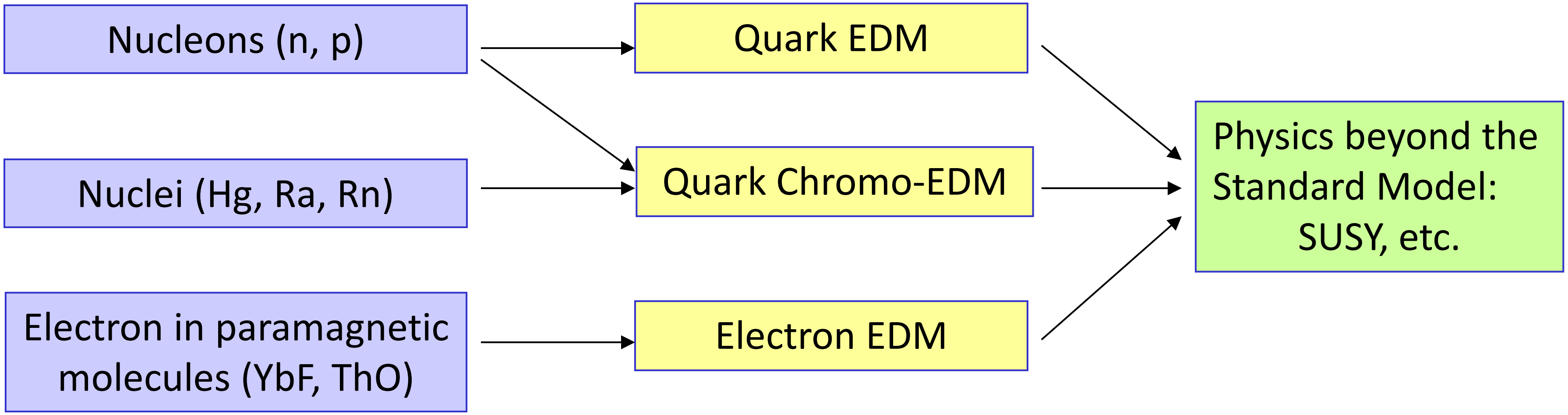
Li-Bang Wang, UIUC
2006 DNP thesis prize



Search for the EDM of Radium-225 (with Roy)

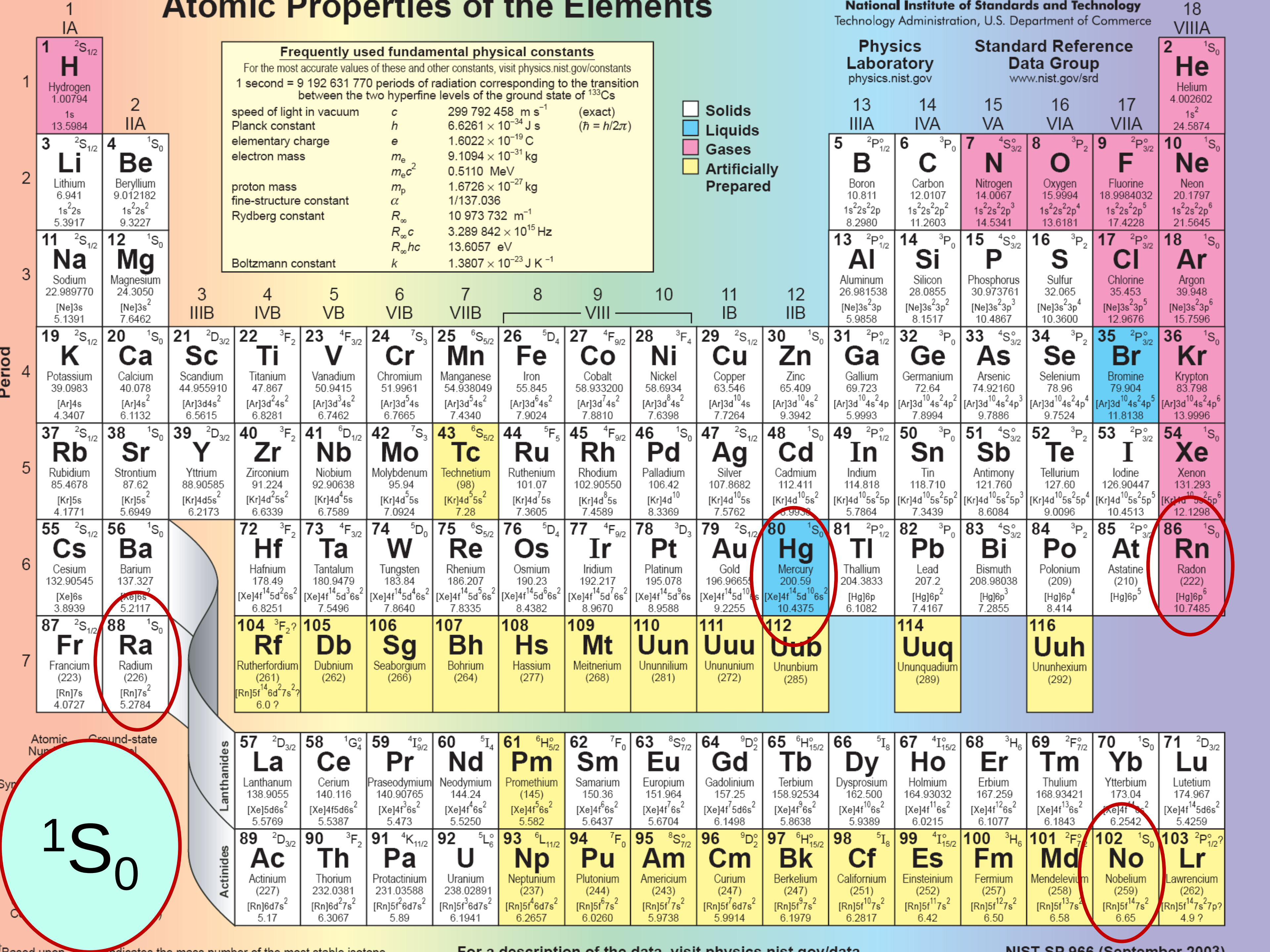
Zheng-Tian Lu
Physics Division, Argonne National Laboratory
Department of Physics, University of Chicago

EDM Searches in Three Sectors



Sector	Exp Limit (e-cm)	Method	Standard Model
Electron	9×10^{-29}	ThO in a beam	10^{-38}
Neutron	3×10^{-26}	UCN in a bottle	10^{-31}
^{199}Hg	3×10^{-29}	Hg atoms in a cell	10^{-33}

M. Ramsey-Musolf (2009)



Atomic Properties of the Elements

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Physics Laboratory
physics.nist.gov

Standard Reference Data Group
www.nist.gov/srd

Frequently used fundamental physical constants

For the most accurate values of these and other constants, visit physics.nist.gov/constants

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs

speed of light in vacuum	c	299 792 458 m s^{-1}	(exact)
Planck constant	h	6.6261×10^{-34} J s	($\hbar = h/2\pi$)
elementary charge	e	1.6022×10^{-19} C	
electron mass	m_e	9.1094×10^{-31} kg	
	$m_e c^2$	0.5110 MeV	
proton mass	m_p	1.6726×10^{-27} kg	
fine-structure constant	α	1/137.036	
Rydberg constant	R_∞	10 973 732 m^{-1}	
	$R_\infty c$	$3.289\,842 \times 10^{15}$ Hz	
	$R_\infty hc$	13.6057 eV	
Boltzmann constant	k	1.3807×10^{-23} J K^{-1}	

- ☐ Solids
- 🟦 Liquids
- 🟪 Gases
- 🟨 Artificially Prepared

Period	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIII	9 VIII	10 VIII	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 $^2S_{1/2}$ **H** Hydrogen 1.00794 $1s$ 13.5984																	2 $^1S_0$ **He** Helium 4.002602 $1s^2$ 24.5874
2	3 $^2S_{1/2}$ **Li** Lithium 6.941 $1s^2 2s$ 5.3917	4 $^1S_0$ **Be** Beryllium 9.012182 $1s^2 2s^2$ 9.3227											5 $^2P^\circ_{1/2}$ **B** Boron 10.811 $1s^2 2s^2 2p$ 8.2980	6 $^3P_0$ **C** Carbon 12.0107 $1s^2 2s^2 2p^2$ 11.2603	7 $^4S^\circ_{3/2}$ **N** Nitrogen 14.0067 $1s^2 2s^2 2p^3$ 14.5341	8 $^3P_2$ **O** Oxygen 15.9994 $1s^2 2s^2 2p^4$ 13.6181	9 $^2P^\circ_{3/2}$ **F** Fluorine 18.9984032 $1s^2 2s^2 2p^5$ 17.4228	10 $^1S_0$ **Ne** Neon 20.1797 $1s^2 2s^2 2p^6$ 21.5645
3	11 $^2S_{1/2}$ **Na** Sodium 22.989770 $[Ne]3s$ 5.1391	12 $^1S_0$ **Mg** Magnesium 24.3050 $[Ne]3s^2$ 7.6462											13 $^2P^\circ_{1/2}$ **Al** Aluminum 26.981538 $[Ne]3s^2 3p$ 5.9858	14 $^3P_0$ **Si** Silicon 28.0855 $[Ne]3s^2 3p^2$ 8.1517	15 $^4S^\circ_{3/2}$ **P** Phosphorus 30.973761 $[Ne]3s^2 3p^3$ 10.4867	16 $^3P_2$ **S** Sulfur 32.065 $[Ne]3s^2 3p^4$ 10.3600	17 $^2P^\circ_{3/2}$ **Cl** Chlorine 35.453 $[Ne]3s^2 3p^5$ 12.9676	18 $^1S_0$ **Ar** Argon 39.948 $[Ne]3s^2 3p^6$ 15.7596
4	19 $^2S_{1/2}$ **K** Potassium 39.0983 $[Ar]4s$ 4.3407	20 $^1S_0$ **Ca** Calcium 40.078 $[Ar]4s^2$ 6.1132	21 $^2D_{3/2}$ **Sc** Scandium 44.955910 $[Ar]3d4s^2$ 6.5615	22 $^3F_2$ **Ti** Titanium 47.867 $[Ar]3d^2 4s^2$ 6.8281	23 $^4F_{3/2}$ **V** Vanadium 50.9415 $[Ar]3d^3 4s^2$ 6.7462	24 $^7S_3$ **Cr** Chromium 51.9961 $[Ar]3d^5 4s$ 6.7665	25 $^6S_{5/2}$ **Mn** Manganese 54.938049 $[Ar]3d^5 4s^2$ 7.4340	26 $^5D_4$ **Fe** Iron 55.845 $[Ar]3d^6 4s^2$ 7.9024	27 $^4F_{9/2}$ **Co** Cobalt 58.933200 $[Ar]3d^7 4s^2$ 7.8810	28 $^3F_4$ **Ni** Nickel 58.6934 $[Ar]3d^8 4s^2$ 7.6398	29 $^2S_{1/2}$ **Cu** Copper 63.546 $[Ar]3d^{10}4s$ 7.7264	30 $^1S_0$ **Zn** Zinc 65.409 $[Ar]3d^{10}4s^2$ 9.3942	31 $^2P^\circ_{1/2}$ **Ga** Gallium 69.723 $[Ar]3d^{10}4s^2 4p$ 5.9993	32 $^3P_0$ **Ge** Germanium 72.64 $[Ar]3d^{10}4s^2 4p^2$ 7.8994	33 $^4S^\circ_{3/2}$ **As** Arsenic 74.92160 $[Ar]3d^{10}4s^2 4p^3$ 9.7886	34 $^3P_2$ **Se** Selenium 78.96 $[Ar]3d^{10}4s^2 4p^4$ 9.7524	35 $^2P^\circ_{3/2}$ **Br** Bromine 79.904 $[Ar]3d^{10}4s^2 4p^5$ 11.8138	36 $^1S_0$ **Kr** Krypton 83.798 $[Ar]3d^{10}4s^2 4p^6$ 13.9996
5	37 $^2S_{1/2}$ **Rb** Rubidium 85.4678 $[Kr]5s$ 4.1771	38 $^1S_0$ **Sr** Strontium 87.62 $[Kr]5s^2$ 5.6949	39 $^2D_{3/2}$ **Y** Yttrium 88.90585 $[Kr]4d5s^2$ 6.2173	40 $^3F_2$ **Zr** Zirconium 91.224 $[Kr]4d^2 5s^2$ 6.6339	41 $^6D_{1/2}$ **Nb** Niobium 92.90638 $[Kr]4d^4 5s$ 6.7589	42 $^7S_3$ **Mo** Molybdenum 95.94 $[Kr]4d^5 5s$ 7.0924	43 $^6S_{5/2}$ **Tc** Technetium (98) $[Kr]4d^5 5s^2$ 7.28	44 $^5F_5$ **Ru** Ruthenium 101.07 $[Kr]4d^7 5s$ 7.3605	45 $^4F_{9/2}$ **Rh** Rhodium 102.90550 $[Kr]4d^8 5s$ 7.4589	46 $^1S_0$ **Pd** Palladium 106.42 $[Kr]4d^{10}$ 8.3369	47 $^2S_{1/2}$ **Ag** Silver 107.8682 $[Kr]4d^{10}5s$ 7.5762	48 $^1S_0$ **Cd** Cadmium 112.411 $[Kr]4d^{10}5s^2$ 8.9938	49 $^2P^\circ_{1/2}$ **In** Indium 114.818 $[Kr]4d^{10}5s^2 5p$ 5.7864	50 $^3P_0$ **Sn** Tin 118.710 $[Kr]4d^{10}5s^2 5p^2$ 7.3439	51 $^4S^\circ_{3/2}$ **Sb** Antimony 121.760 $[Kr]4d^{10}5s^2 5p^3$ 8.6084	52 $^3P_2$ **Te** Tellurium 127.60 $[Kr]4d^{10}5s^2 5p^4$ 9.0096	53 $^2P^\circ_{3/2}$ **I** Iodine 126.90447 $[Kr]4d^{10}5s^2 5p^5$ 10.4513	54 $^1S_0$ **Xe** Xenon 131.293 $[Kr]4d^{10}5s^2 5p^6$ 12.1298
6	55 $^2S_{1/2}$ **Cs** Cesium 132.90545 $[Xe]6s$ 3.8939	56 $^1S_0$ **Ba** Barium 137.327 $[Xe]6s^2$ 5.2117		72 $^3F_2$ **Hf** Hafnium 178.49 $[Xe]4f^{14}5d^2 6s^2$ 6.8251	73 $^4F_{3/2}$ **Ta** Tantalum 180.9479 $[Xe]4f^{14}5d^3 6s^2$ 7.5496	74 $^5D_0$ **W** Tungsten 183.84 $[Xe]4f^{14}5d^4 6s^2$ 7.8640	75 $^6S_{5/2}$ **Re** Rhenium 186.207 $[Xe]4f^{14}5d^5 6s^2$ 7.8335	76 $^5D_4$ **Os** Osmium 190.23 $[Xe]4f^{14}5d^6 6s^2$ 8.4382	77 $^4F_{9/2}$ **Ir** Iridium 192.217 $[Xe]4f^{14}5d^7 6s^2$ 8.9670	78 $^3D_3$ **Pt** Platinum 195.078 $[Xe]4f^{14}5d^9 6s$ 8.9588	79 $^2S_{1/2}$ **Au** Gold 196.96655 $[Xe]4f^{14}5d^{10}6s$ 9.2255	80 $^1S_0$ **Hg** Mercury 200.59 $[Xe]4f^{14}5d^{10}6s^2$ 10.4375	81 $^2P^\circ_{1/2}$ **Tl** Thallium 204.3833 $[Hg]6p$ 6.1082	82 $^3P_0$ **Pb** Lead 207.2 $[Hg]6p^2$ 7.4167	83 $^4S^\circ_{3/2}$ **Bi** Bismuth 208.98038 $[Hg]6p^3$ 7.2855	84 $^3P_2$ **Po** Polonium (209) $[Hg]6p^4$ 8.414	85 $^2P^\circ_{3/2}$ **At** Astatine (210) $[Hg]6p^5$	86 $^1S_0$ **Rn** Radon (222) $[Hg]6p^6$ 10.7485
7	87 $^2S_{1/2}$ **Fr** Francium (223) $[Rn]7s$ 4.0727	88 $^1S_0$ **Ra** Radium (226) $[Rn]7s^2$ 5.2784		104 $^3F_2$? **Rf** Rutherfordium (261) $[Rn]5f^{14}6d^2 7s^2$? 6.0 ?	105 **Db** Dubnium (262)	106 **Sg** Seaborgium (266)	107 **Bh** Bohrium (264)	108 **Hs** Hassium (277)	109 **Mt** Meitnerium (268)	110 **Uun** Ununnilium (281)	111 **Uuu** Unununium (272)	112 **Uub** Ununbium (285)		114 **Uuq** Ununquadium (289)		116 **Uuh** Ununhexium (292)		

Lanthanides

57 $^2D_{3/2}$ **La** Lanthanum 138.9055 $[Xe]5d6s^2$ 5.5769	58 $^1G^\circ_4$ **Ce** Cerium 140.116 $[Xe]4f5d6s^2$ 5.5387	59 $^4I^\circ_{9/2}$ **Pr** Praseodymium 140.90765 $[Xe]4f^3 6s^2$ 5.473	60 $^5I_4$ **Nd** Neodymium 144.24 $[Xe]4f^4 6s^2$ 5.5250	61 $^6H^\circ_{5/2}$ **Pm** Promethium (145) $[Xe]4f^5 6s^2$ 5.582	62 $^7F_0$ **Sm** Samarium 150.36 $[Xe]4f^6 6s^2$ 5.6437	63 $^8S^\circ_{7/2}$ **Eu** Europium 151.964 $[Xe]4f^7 6s^2$ 5.6704	64 $^9D^\circ_2$ **Gd** Gadolinium 157.25 $[Xe]4f^7 5d6s^2$ 6.1498	65 $^6H^\circ_{15/2}$ **Tb** Terbium 158.92534 $[Xe]4f^9 6s^2$ 5.8638	66 $^5I_8$ **Dy** Dysprosium 162.500 $[Xe]4f^{10}6s^2$ 5.9389	67 $^4I^\circ_{15/2}$ **Ho** Holmium 164.93032 $[Xe]4f^{11}6s^2$ 6.0215	68 $^3H_6$ **Er** Erbium 167.259 $[Xe]4f^{12}6s^2$ 6.1077	69 $^2F^\circ_{7/2}$ **Tm** Thulium 168.93421 $[Xe]4f^{13}6s^2$ 6.1843	70 $^1S_0$ **Yb** Ytterbium 173.04 $[Xe]4f^{14}6s^2$ 6.2542	71 $^2D_{3/2}$ **Lu** Lutetium 174.967 $[Xe]4f^{14}5d6s^2$ 5.4259

Actinides

89 $^2D_{3/2}$ **Ac** Actinium (227) $[Rn]6d7s^2$ 5.17	90 $^3F_2$ **Th** Thorium 232.0381 $[Rn]6d^2 7s^2$ 6.3067	91 $^4K_{11/2}$ **Pa** Protactinium 231.03588 $[Rn]5f^2 6d7s^2$ 5.89	92 $^5L^\circ_6$ **U** Uranium 238.02891 $[Rn]5f^3 6d7s^2$ 6.1941	93 $^6L_{11/2}$ **Np** Neptunium (237) $[Rn]5f^4 6d7s^2$ 6.2657	94 $^7F_0$ **Pu** Plutonium (244) $[Rn]5f^6 7s^2$ 6.0260	95 $^8S^\circ_{7/2}$ **Am** Americium (243) $[Rn]5f^7 7s^2$ 5.9738	96 $^9D^\circ_2$ **Cm** Curium (247) $[Rn]5f^7 6d7s^2$ 5.9914	97 $^6H^\circ_{15/2}$ **Bk** Berkelium (247) $[Rn]5f^9 7s^2$ 6.1979	98 $^5I_8$ **Cf** Californium (251) $[Rn]5f^{10}7s^2$ 6.2817	99 $^4I^\circ_{15/2}$ **Es** Einsteinium (252) $[Rn]5f^{11}7s^2$ 6.42	100 $^3H_6$ **Fm** Fermium (257) $[Rn]5f^{12}7s^2$ 6.50	101 $^2F^\circ_{7/2}$ **Md** Mendelevium (258) $[Rn]5f^{13}7s^2$ 6.58	102 $^1S_0$ **No** Nobelium (259) $[Rn]5f^{14}7s^2$ 6.65	103 $^2P^\circ_{1/2}$? **Lr** Lawrencium (262) $[Rn]5f^{14}7s^2 7p$? 4.9 ?

Atomic Num
Ground-state
Sym

$^1S_0$

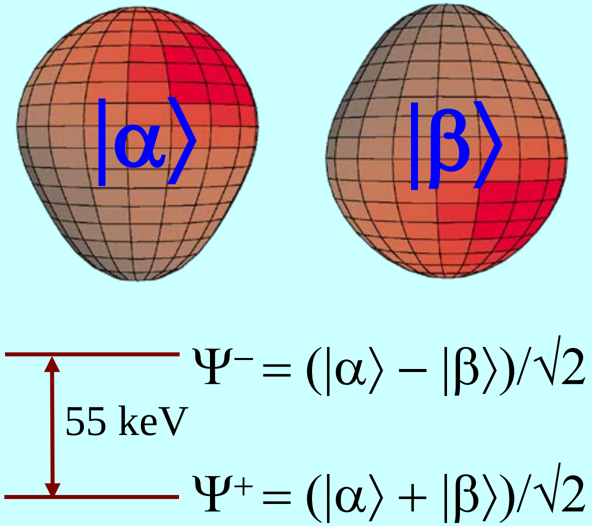
For a description of the data, visit physics.nist.gov/data

NIST SP 966 (September 2003)

EDM of ^{225}Ra enhanced and more reliably calculated

- Closely spaced parity doublet – Haxton & Henley, PRL (1983)
- Large Schiff moment due to octupole deformation – Auerbach, Flambaum & Spevak, PRL (1996)
- Relativistic atomic structure (^{225}Ra / ^{199}Hg ~ 3) – Dzuba, Flambaum, Ginges, Kozlov, PRA (2002)

Parity doublet



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

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

$$Schiff\_moment = \sum_{i \neq 0} \frac{\langle \psi_0 | \hat{S}_z | \psi_i \rangle \langle \psi_i | \hat{H}_{PT} | \psi_0 \rangle}{E_0 - E_i} + c.c.$$

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

	Isoscalar	Isovector
Skyrme SIII	300	4000
Skyrme SkM*	300	2000
Skyrme SLy4	700	8000

Schiff moment of ^{225}Ra, Dobaczewski, Engel, PRL (2005)
Schiff moment of ^{199}Hg, Dobaczewski, Engel *et al*., PRC (2010)

"[Nuclear structure] calculations in Ra are almost certainly more reliable than those in Hg."
– Engel, Ramsey-Musolf, van Kolck, Prog. Part. Nucl. Phys. (2013)

^{225}Ra:

I = ½

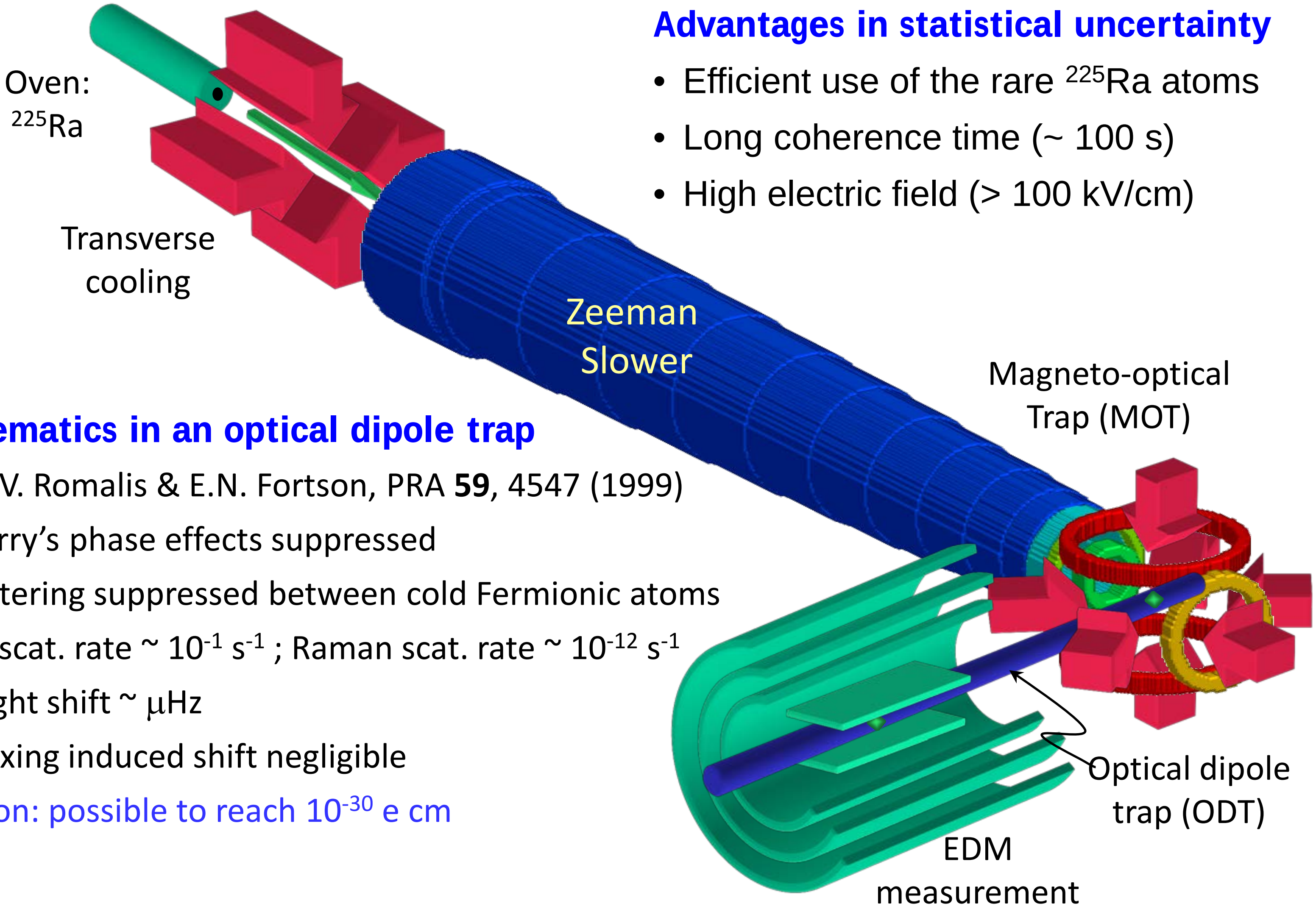
$t_{1/2}$ = 15 d

EDM measurement on ^{225}Ra in a trap

Collaboration of Argonne, U Kentucky, Michigan State U

Advantages in statistical uncertainty

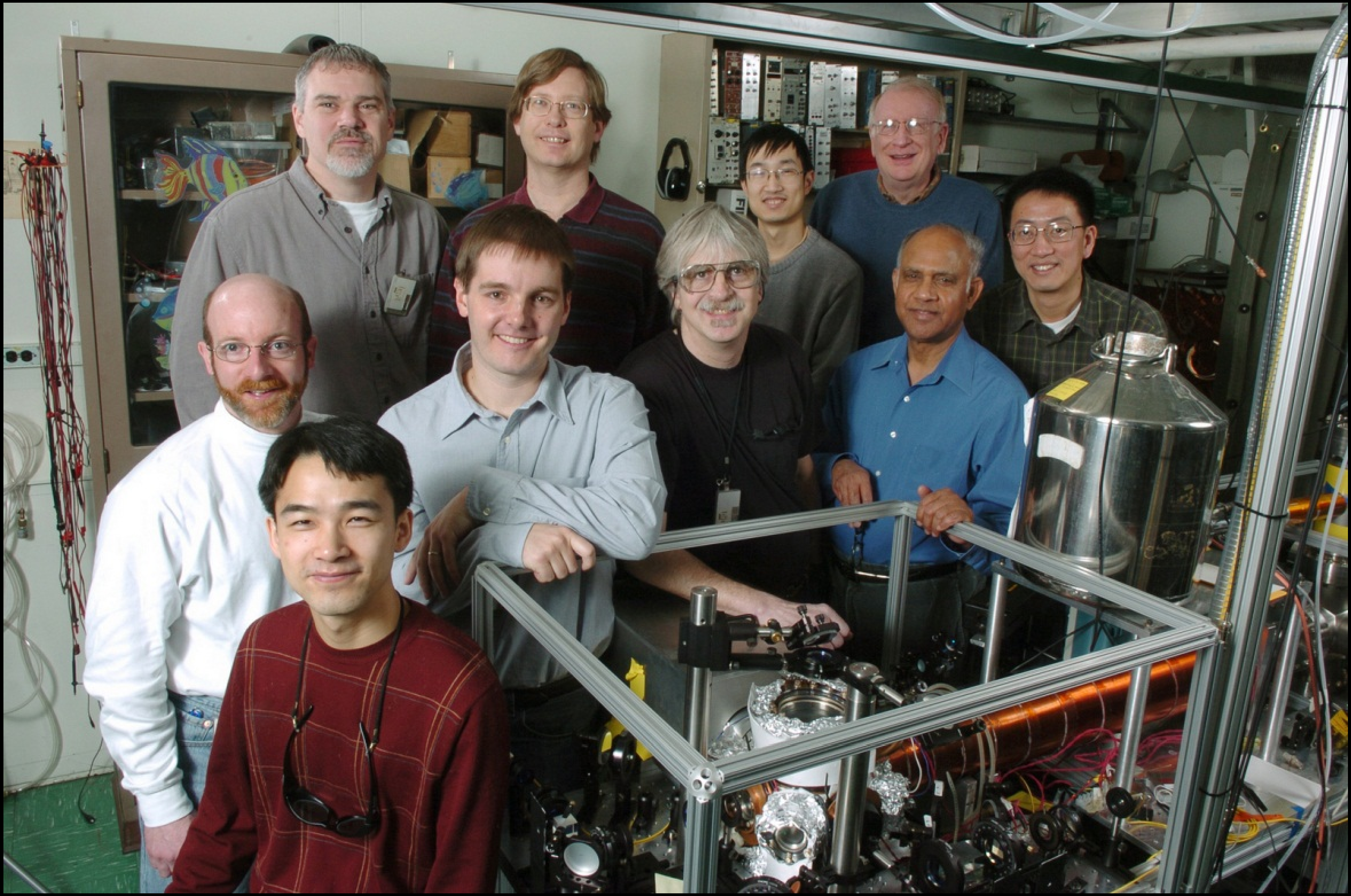
- Efficient use of the rare ^{225}Ra atoms
- Long coherence time (~ 100 s)
- High electric field (> 100 kV/cm)



EDM systematics in an optical dipole trap

– M.V. Romalis & E.N. Fortson, PRA **59**, 4547 (1999)

- v x E , Berry's phase effects suppressed
- Cold scattering suppressed between cold Fermionic atoms
- Rayleigh scat. rate ~ 10^{-1} s^{-1} ; Raman scat. rate ~ 10^{-12} s^{-1}
- Vector light shift ~ μHz
- Parity mixing induced shift negligible
- Conclusion: possible to reach 10^{-30} e cm



Radium atoms trapped!   2007

Preparation of Cold Radium Atoms for EDM

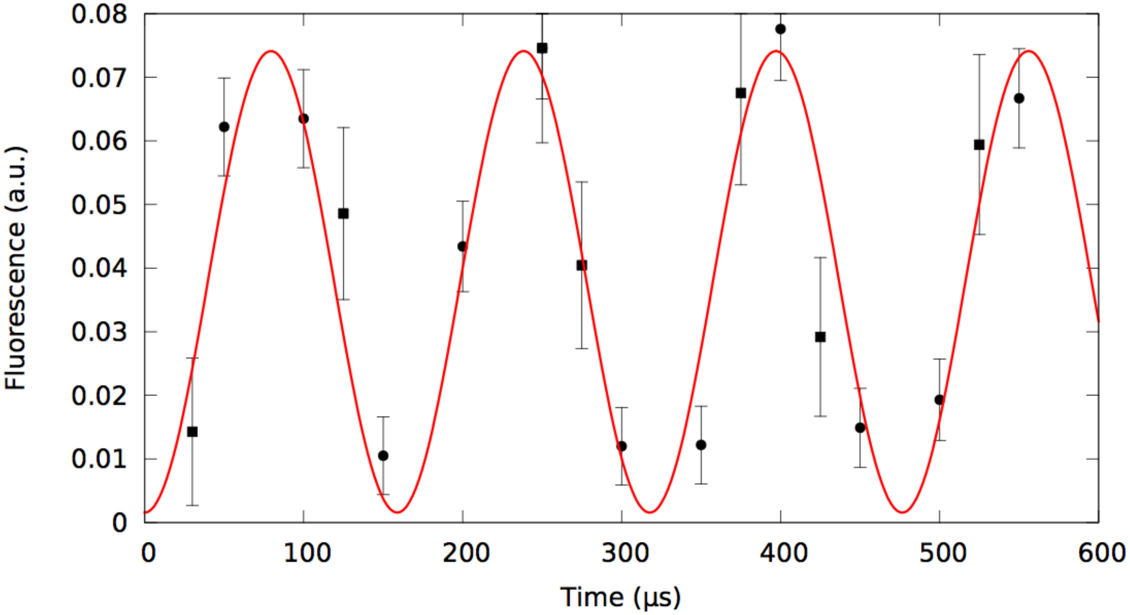
- 2006 – Atomic transitions identified and studied;
- 2007 – Magneto-optical trap (MOT) of radium realized;
- 2010 – Optical dipole trap (ODT) of radium realized;
- 2011 – Atoms transferred to the measurement trap;
- 2012 – Spin precession of Ra-225 in ODT observed;
- 2014 – Attempt to measure EDM of Ra-225.

N.D. Scielzo *et al.*, PRA Rapid **73**, 010501 (2006)

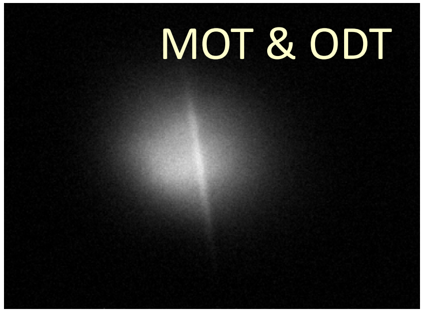
J.R. Guest *et al.*, PRL **98**, 093001 (2007)

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

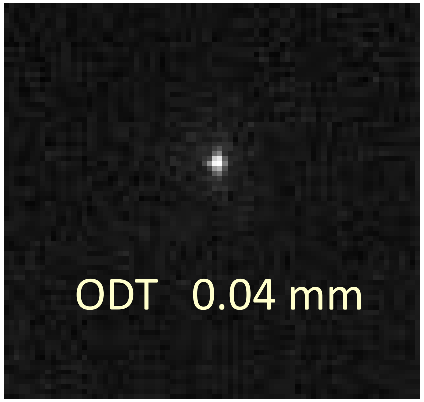
Precession frequency: $\varpi = 2\mu B$



Sideview



Head-on view

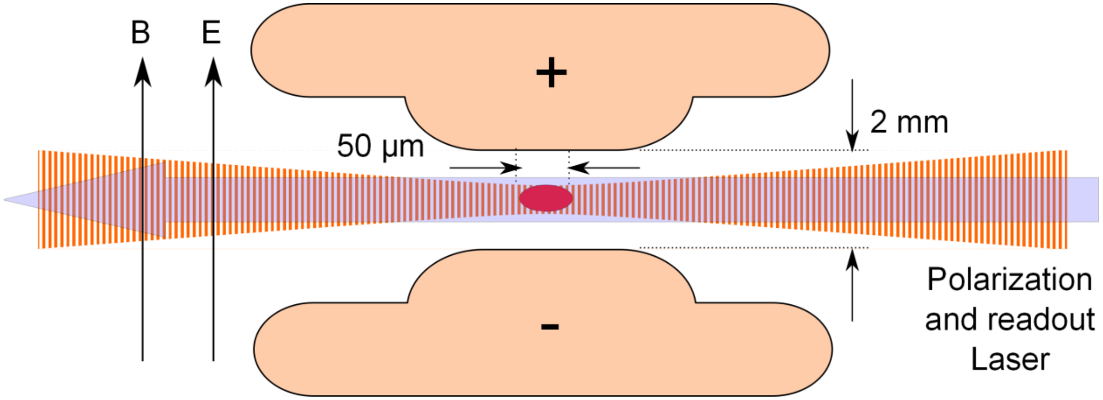


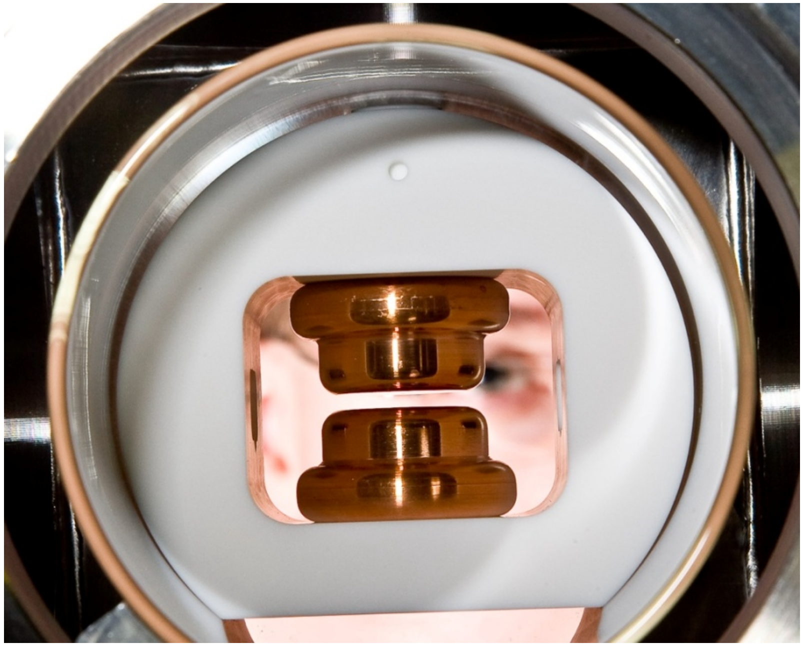
B & E Fields Installed

EDM (d) measurement:

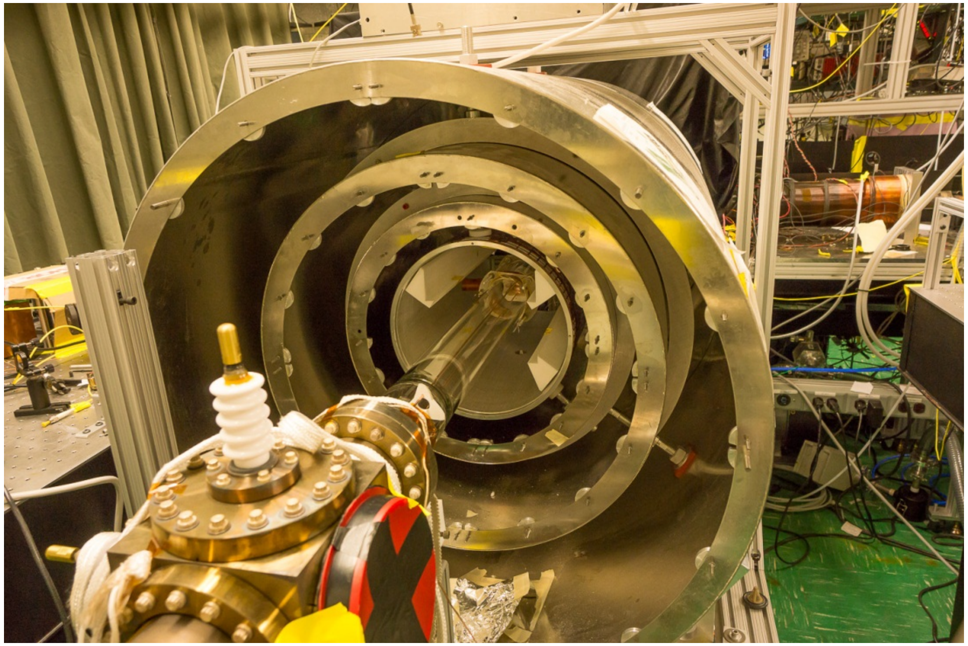
$$\varpi_+ = 2\mu B + 2dE$$

$$\varpi_- = 2\mu B - 2dE$$

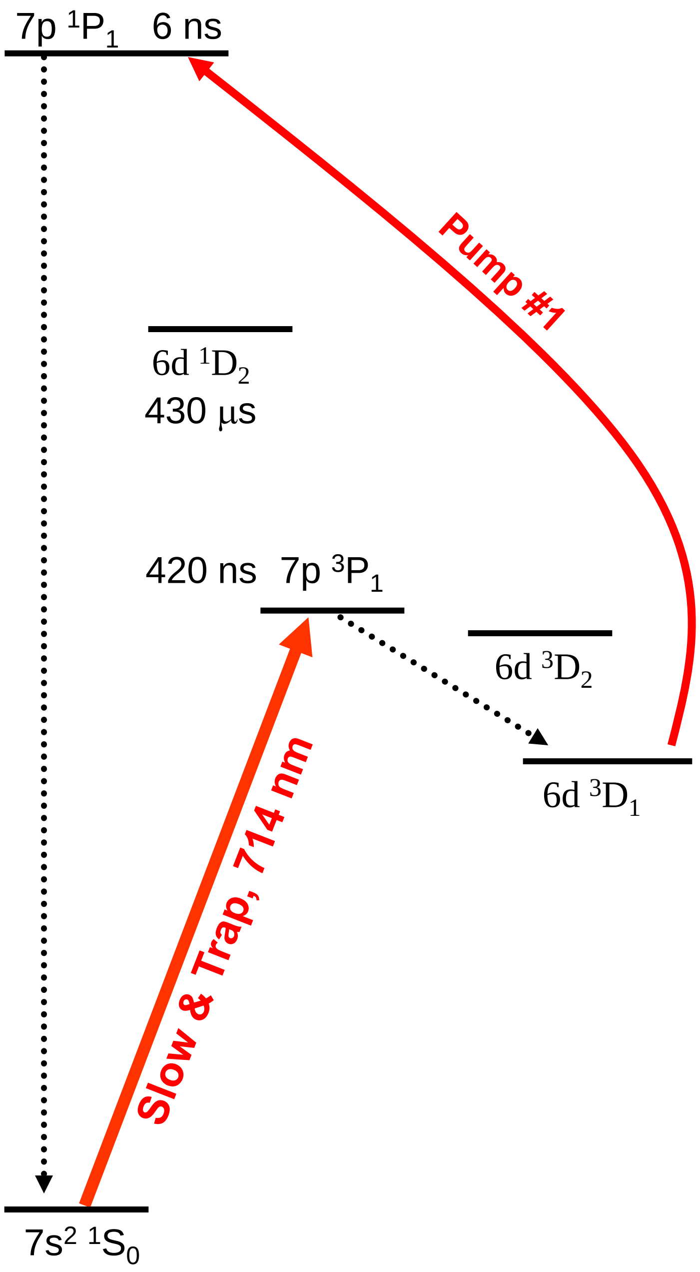




E = 100 kV/cm



B = 10 mG



Limits and Sensitivities

- Next 5 years: 10^{-26} – 10^{-27} e-cm

  (Competitive with ^{199}Hg limit at 3 x 10^{-29} e-cm)
- 2020 and beyond: 1 x 10^{-28} e-cm

Blue Upgrade

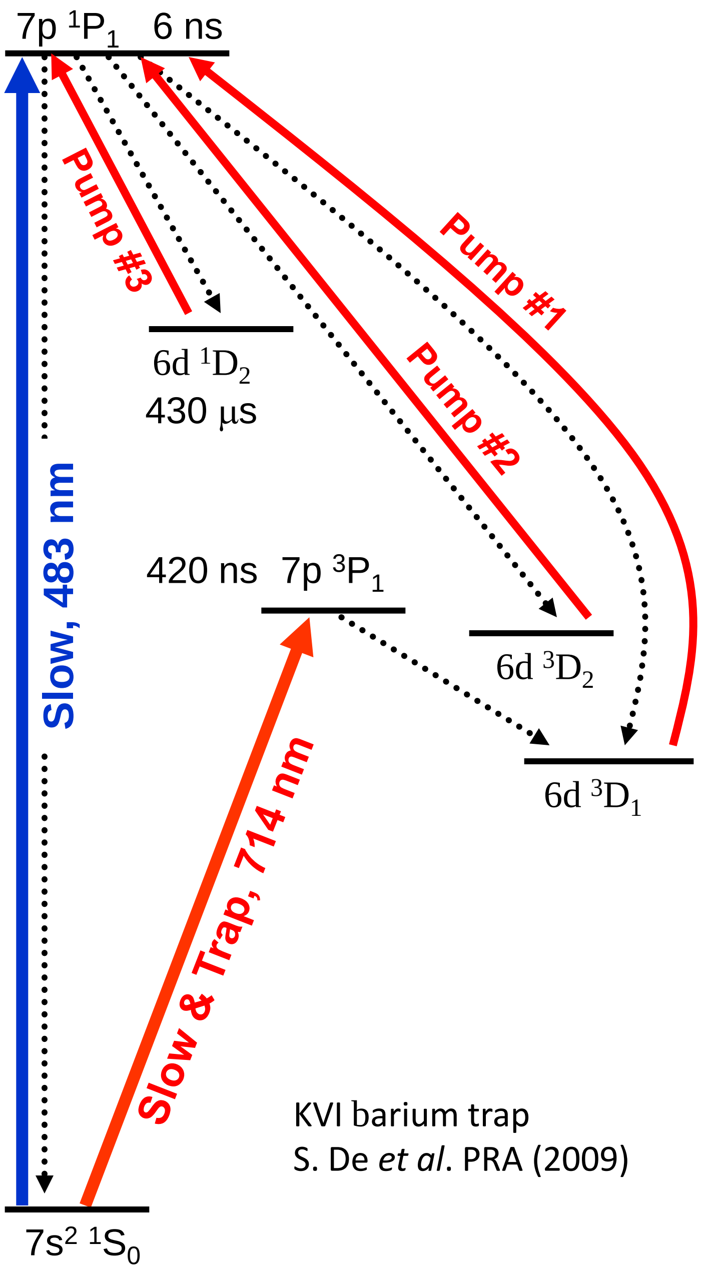
Scheme

- 1st slowing laser: 483 nm (strong)
- 2nd slowing laser: 714 nm
- 3 repumpers: 1428 nm, 1488 nm, 2.75 mm
- ^{171}Yb as co-magnetometer

  * ^{225}Ra and ^{171}Yb trapped, < 50 mm apart

Benefits

- 100 times more atoms in the trap
- Improved control on systematic uncertainties



KVI barium trap
S. De *et al*. PRA (2009)

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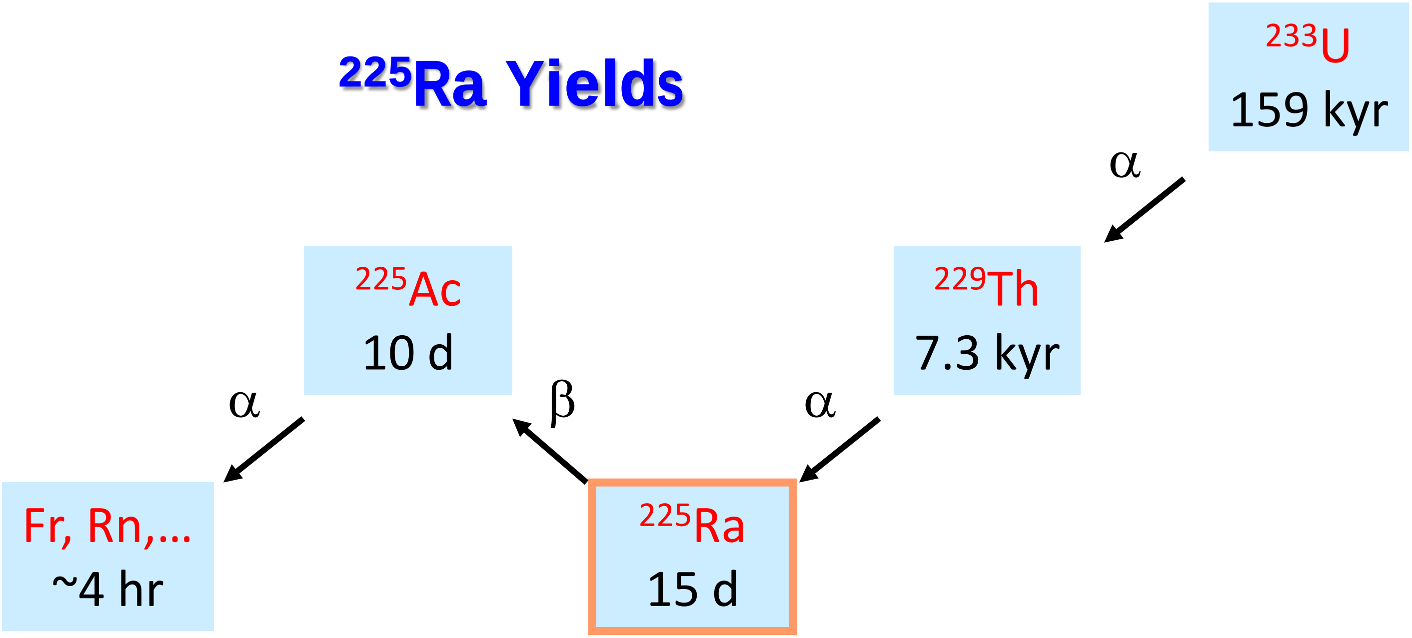
^{225}Ra Yields



Presently available

- National Isotope Development Center, ORNL
  - Decay daughters of ^{229}Th ------------------------------- ^{225}Ra: 10^{8} /s

Projected

- FRIB (B. Sherrill, MSU)
  - Beam dump recovery with a ^{238}U beam ------------- ^{225}Ra: 6 x 10^{9} /s
  - Dedicated running with a ^{232}Th beam ------------- ^{225}Ra: 5 x 10^{10} /s

- ISOL@FRIB (I.C. Gomes and J. Nolen, Argonne)
  - Protons on thorium target, 1 mA x 1 GeV = 1 MW ^{225}Ra: 10^{13} /s

"Cold" Atom Trappers

We acknowledge support by DOE, Office of Nuclear Physics