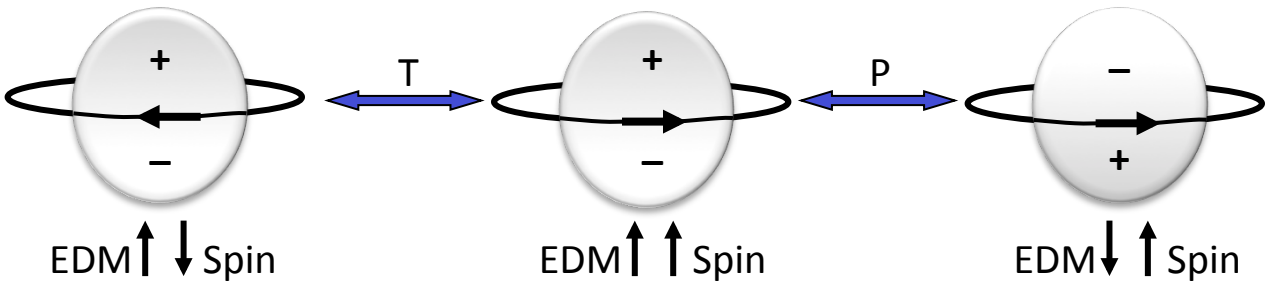


EDM Searches

Zheng-Tian Lu

Physics Division, Argonne National Laboratory

Department of Physics, University of Chicago

More CP-Violation Mechanisms?

Matter-antimatter asymmetry

Require additional CP-violation mechanism(s)

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

Intensity Frontier Workshop, Dec 2011, www.intensityfrontier.org
Convenors for nuclear physics: Haxton, Lu, Ramsey-Musolf

Priorities according to Nima Arkani-Hamed,
Institute for Advanced Study

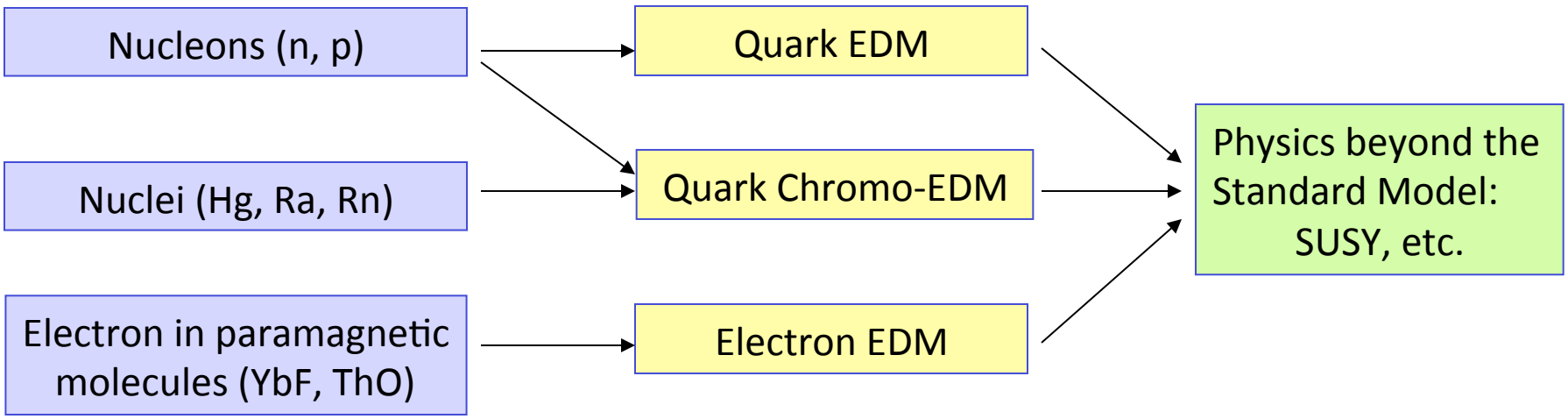
$$d_f \propto e \cdot \sin\phi_{CP} \cdot \frac{m_f}{\Lambda^2}$$

"The existence of an EDM can provide the "missing link" for explaining why the universe contains more matter than antimatter."

"A nonzero EDM would constitute a truly revolutionary discovery."
-- Nuclear Science Advisory Committee (NSAC) Long Range Plan (2007)

"The non-observation of EDMs to-date, thus provides tight restrictions to building theories beyond the Standard Model."
-- P5 report : The Particle Physics Roadmap (2006)

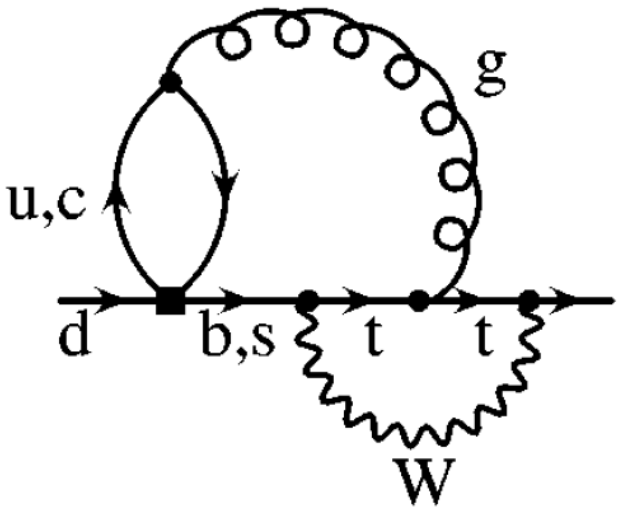
EDM Searches in Three Sectors

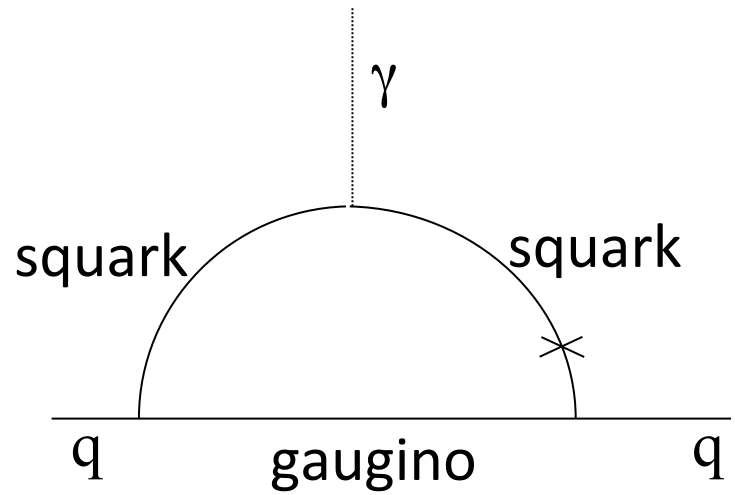


Sector	Exp Limit (e-cm)	Method	Standard Model
Electron	1×10^{-27}	YbF in a beam	10^{-38}
Neutron	3×10^{-26}	UCN in a bottle	10^{-31}
^{199}Hg	3×10^{-29}	Hg atoms in a cell	10^{-33}

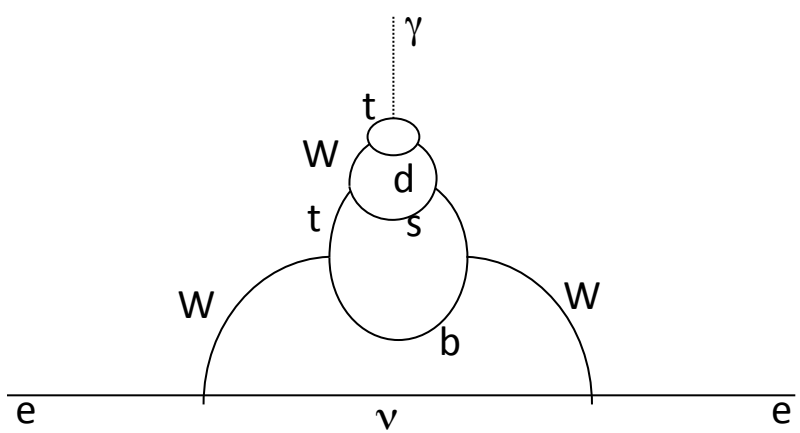
M. Ramsey-Musolf (2009)

EDM Values: SM vs. SUSY

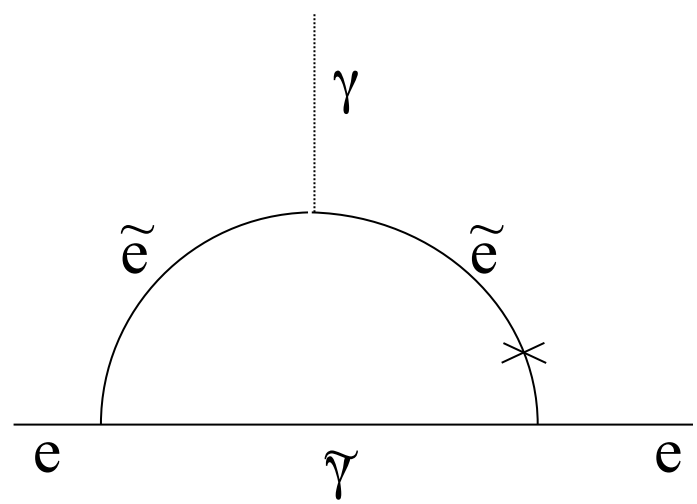




Standard Model



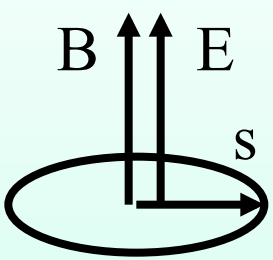
Supersymmetry



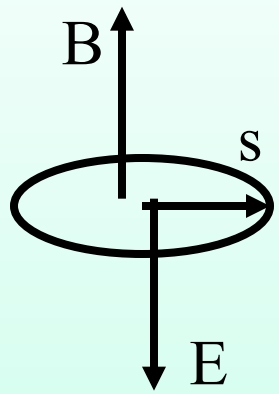
EDM Measurement

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

Statistical sensitivity



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



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

Example:

$B = 10\ mGauss$

$E = 100\ kV/cm$

$f = 11\ Hz$

$f_+ - f_- = 10\ nHz$

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

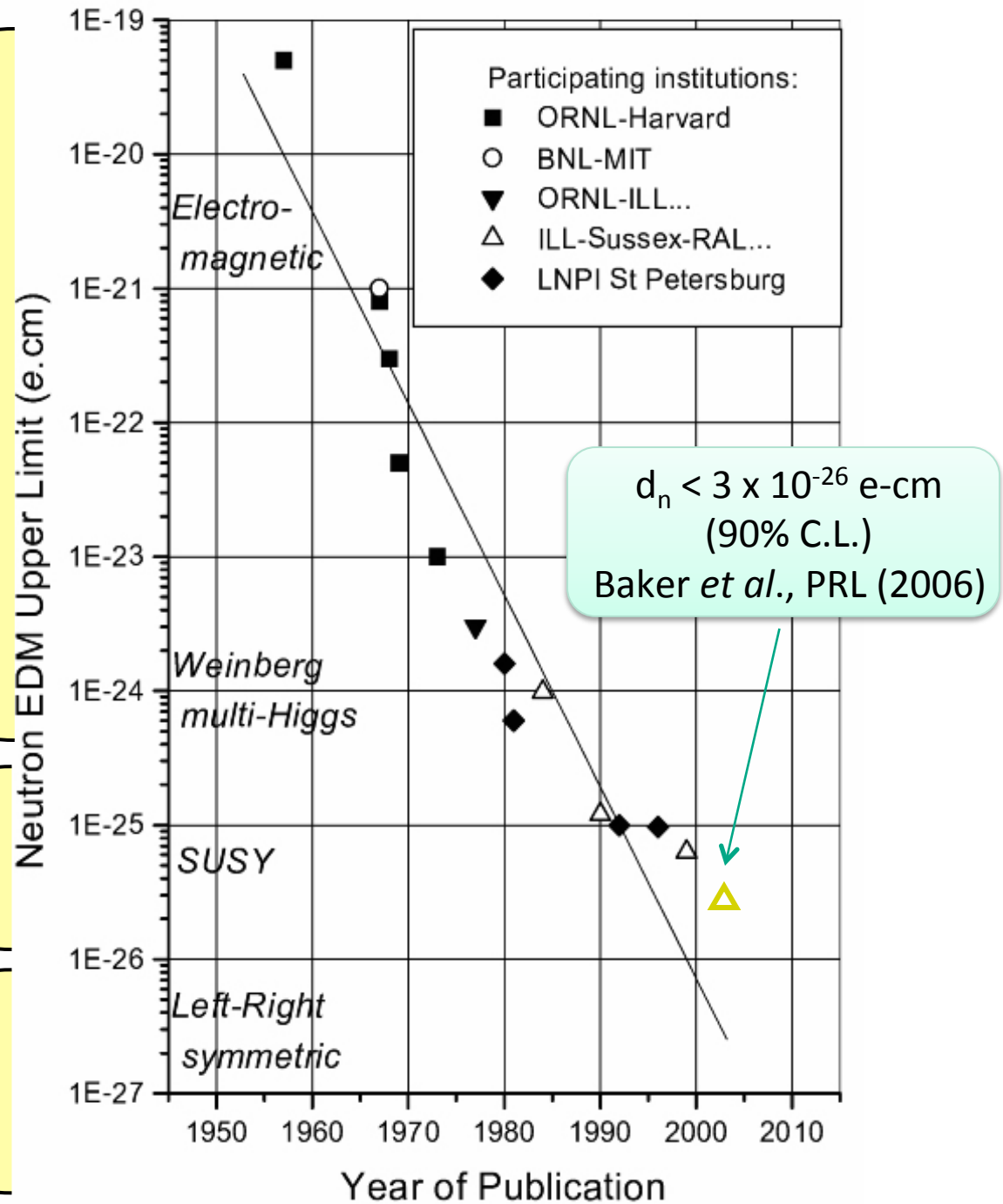
History of nEDM searches

Beam

$\Delta \mathbf{B} \approx \mathbf{v} \times \mathbf{E} / c^2$ limited

Stored UCN (ultra-cold neutrons)

Cryogenic UCN sources



Next Generation nEDM Experiments

Cryogenic UCN source, room temperature storage cells

- Intitut Laue-Langevin, PNPI/ILL
- Paul Scherrer Institute
- Munich reactor
- TRIUMF-Japan collaboration

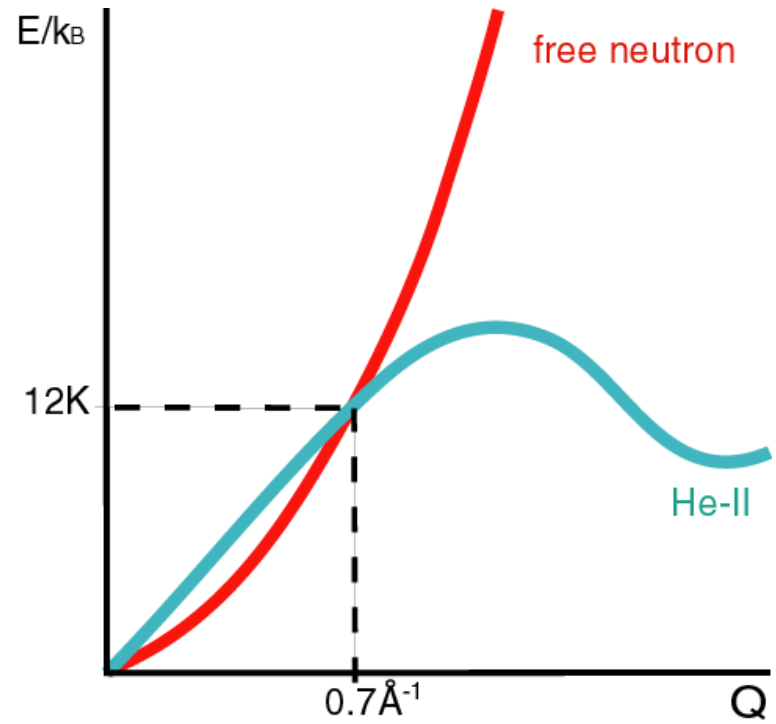
Super-fluid He source/storage cell

- Intitut Laue-Langevin, CyroEDM
- Spallation Neutron Source, nEDM

Limits and Sensitivities

- Current: 300 x 10^{-28} e-cm
- Next 5 years: 50 – 100 x 10^{-28} e-cm
- 2020 and beyond: 3 – 5 x 10^{-28} e-cm

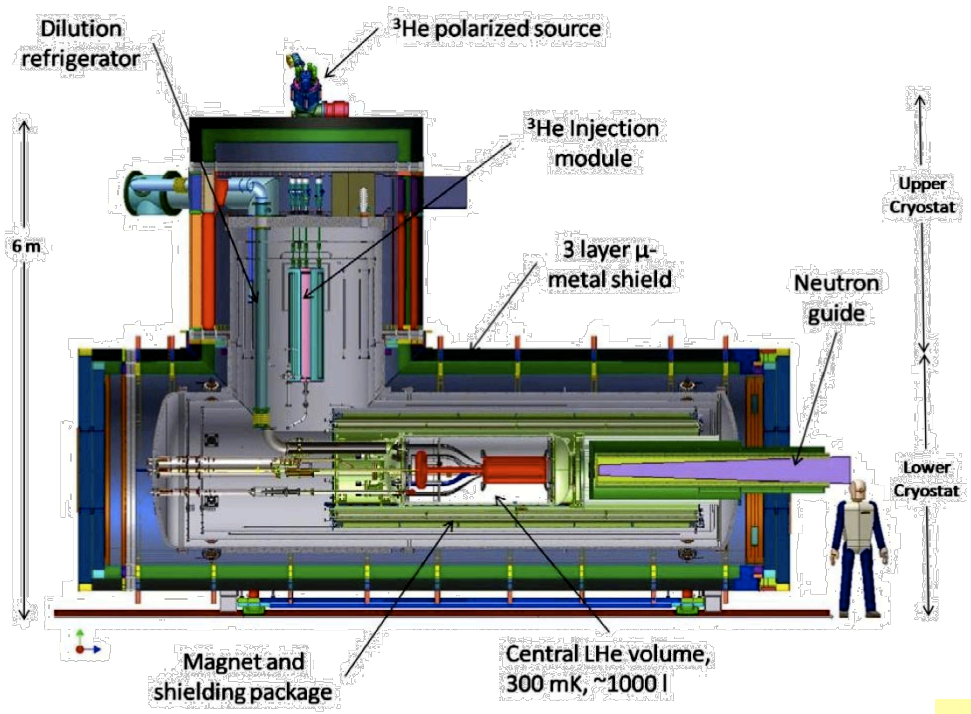
Dispersion curves for He-II and free neutrons



Golub & Pendlebury, Phys. Lett. (1977)

Neutron EDM @ SNS

1 Arizona State University
2 Brown University
3 Boston University
4 University of California, Berkeley
5 California Institute of Technology
6 Duke University
7 Harvard University
8 Indiana University
9 University of Illinois, Urbana-Champaign
10 University of Kentucky
11 Los Alamos National Laboratory
12 Massachusetts Institute of Technology
13 Mississippi State University
14 North Carolina State University
15 Oak Ridge National Laboratory
16 Simon Fraser University
17 University of Tennessee
18 Valparaiso University
19 University of Virginia



B. Filippone, Caltech

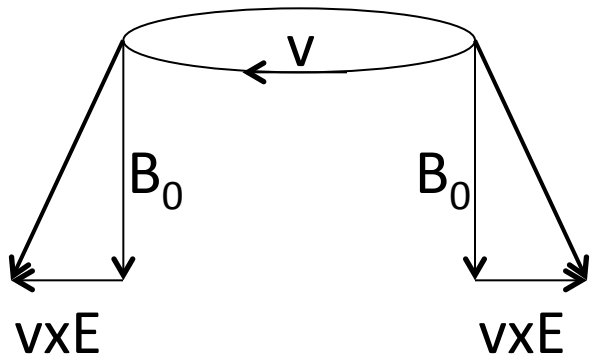
Key Features of SNS experiment

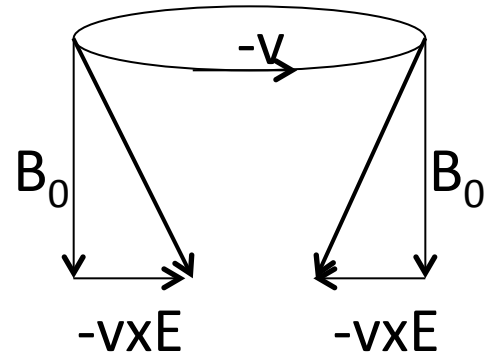
- Sensitivity: 10^{-28} e-cm, 100 times better than existing limit
- Production of UCN in superfluid helium
- Polarized ^{3}He co-magnetometer
  - Also functions as neutron spin precession monitor via spin-dependent n-^{3}He capture cross section
    - Detected via wavelength-shifted scintillation light in LHe
  - Ability to vary influence of external B-fields via "dressed spins"
    - Extra RF field allows control of n & ^{3}He relative precession frequency
  - Can study dependence on B-field, B-gradients & ^{3}He density
- Highly uniform E and B fields
- Superconducting Magnetic Shield
- Two cells with opposite E-field
- Control of central-volume temperature
  - Can vary ^{3}He diffusion which changes geometric phase effect on ^{3}He

B. Filippone, Caltech

Geometric Phase Effect

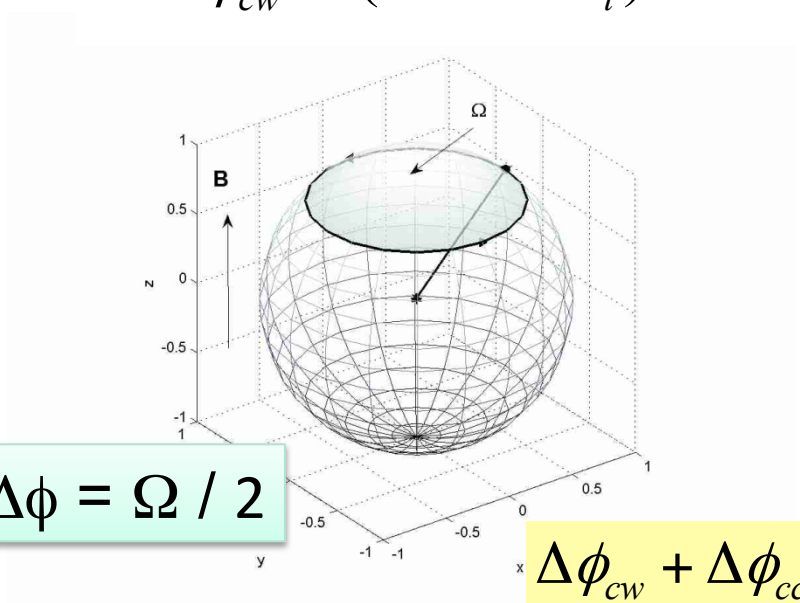
Pendlebury et al., PRA (2004)

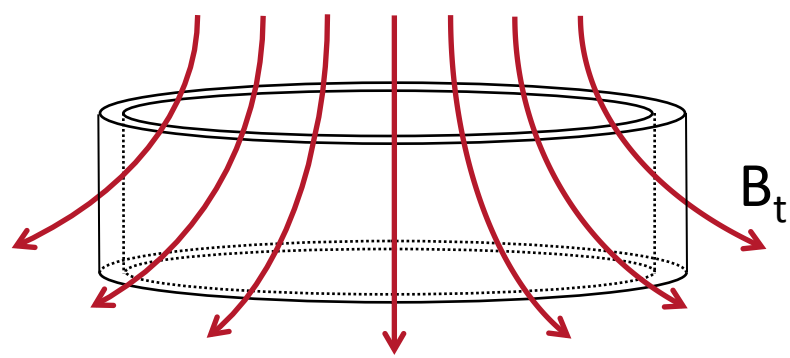




$$\Delta\phi_{cw} \propto (\mathrm{v} \times E + B_t)^2$$

$$\Delta\phi_{ccw} \propto -(-\mathrm{v} \times E + B_t)^2$$





$\Delta\phi = \Omega / 2$

$$\Delta\phi_{cw} + \Delta\phi_{ccw} \propto 2 \cdot \mathrm{v} \times E \cdot B_t$$

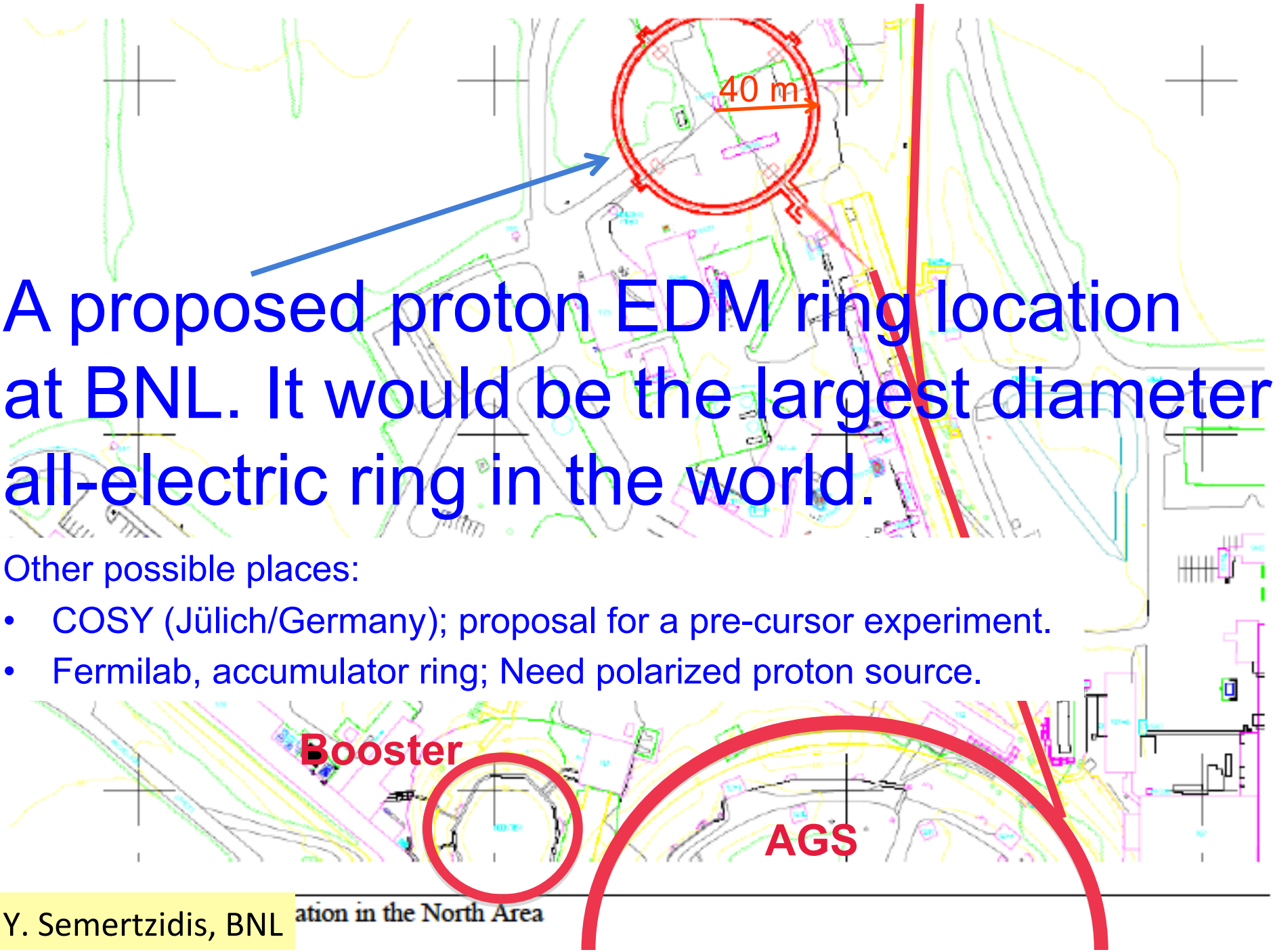
Active R&D:

- Demonstrate high E-field in superfluid LHe
- Identify novel electrode materials
- Demonstrate highly uniform B-field inside superconducting shield with reduced B-field noise
- Developing a polarized neutron & ^{3}He source for spin precession studies at NCSU research reactor
- Studies of polarized ^{3}He transport

Status and Plans:

- Complete initial R&D program: 2012-13
- Begin construction of experiment: 2013-18
- Begin operation of experiment: 2019

B. Filippone, Caltech



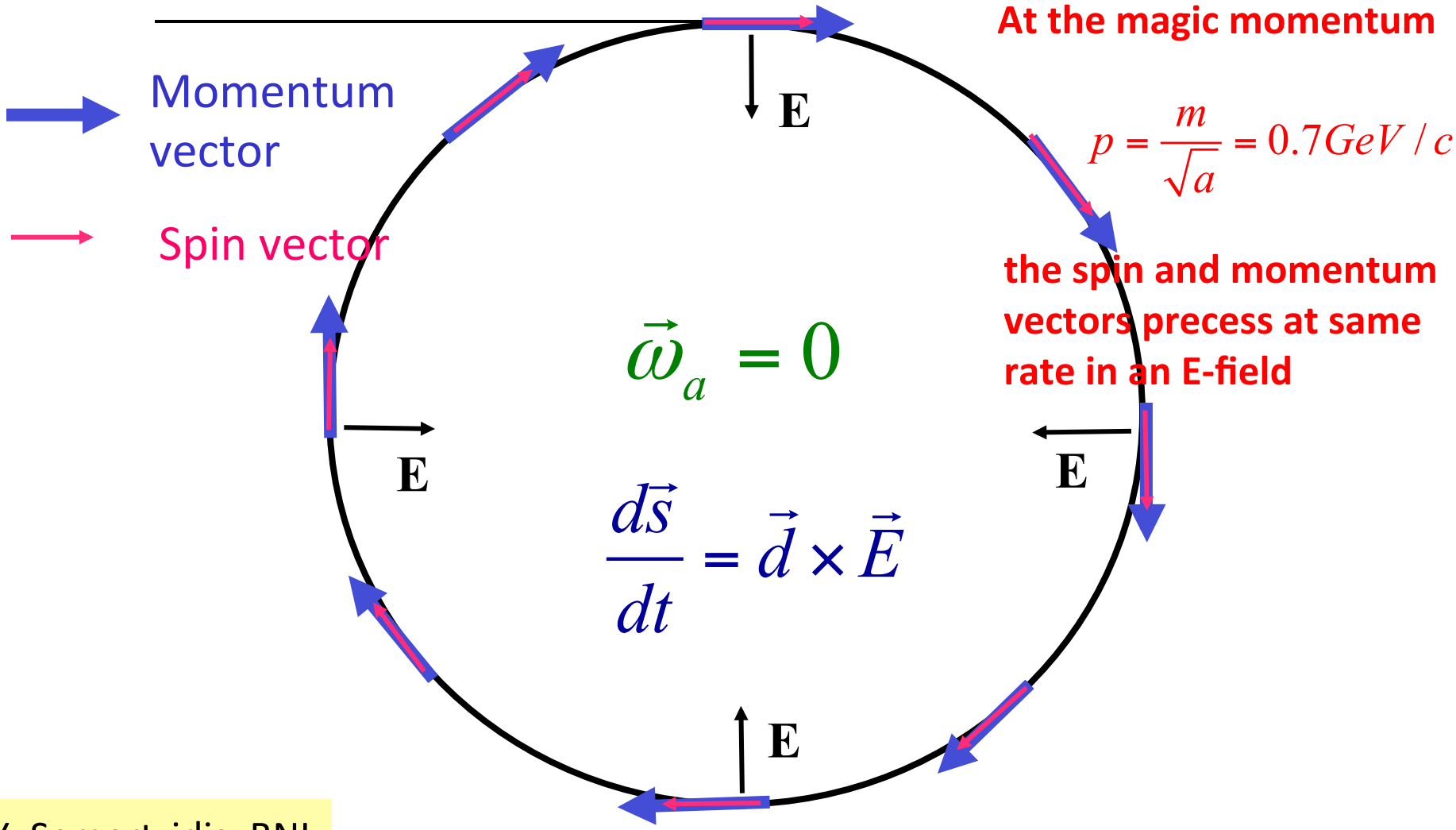
A proposed proton EDM ring location at BNL. It would be the largest diameter all-electric ring in the world.

Other possible places:

- COSY (Jülich/Germany); proposal for a pre-cursor experiment.
- Fermilab, accumulator ring; Need polarized proton source.

Y. Semertzidis, BNL

The proton EDM uses an ALL-ELECTRIC ring: spin is aligned with the momentum vector



Y. Semertzidis, BNL

The miracles that make the pEDM

1. Magic momentum (MM): **high intensity (10^{11})** pol. protons in an all-electric storage ring

2. High analyzing power: A>50% at the MM

3. Weak vertical focusing in an all-electric ring: Spin Coherence Time allows for 10^3s beneficial storage; prospects for much longer SCT with mixing

4. Co-magnetometer: Counter-rotating beams. The beam vertical splitting tells the average radial B-field; the main systematic error source

Y. Semertzidis, BNL

Common R&D with COSY

EDM at Storage Rings

JÜLICH FORSCHUNGSZENTRUM

International srEDM Network

Institutional (MoU) and Personal (Spokespersons …) Cooperation

srEDM Collaboration (BNL)	srEDM Collaboration (FZJ)

Common R & D

RHIC	EDM-at-COSY
Beam Position Monitors	Polarimetry
(…)	Spin Coherence Time
	Cooling
Spin Tracking	(…)

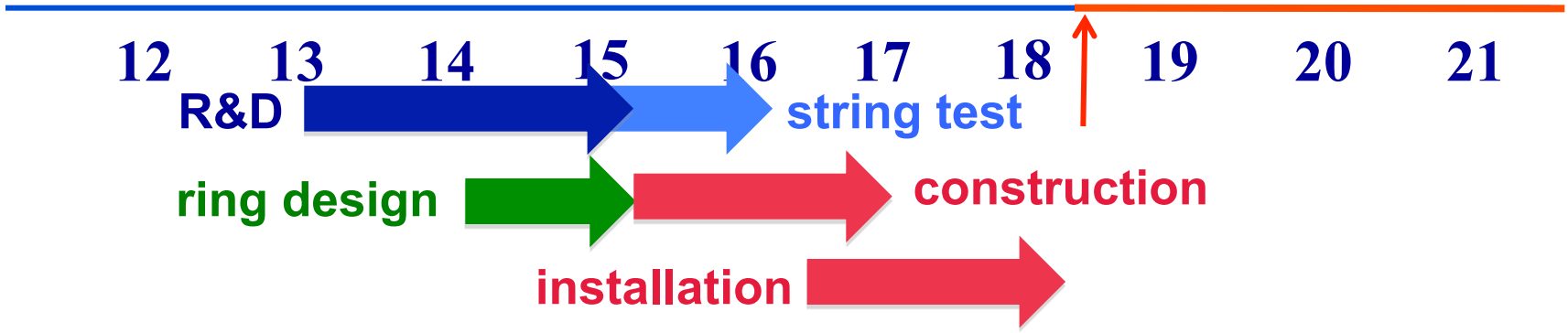
	Study Group
DOE-Proposal	Precursor; Ring Design
CD0, 1, …	HGF Application(s)

H. Stroeher, Director of IKP II

Current status

- Have developed R&D plans (need $1M/year for two years) for
  1) Beam Position Measurement magnetometers (need to test in rings)
  2) Spin Coherence Time tests at COSY (benchmark estimations)
  3) E-field development (first phase R&D done)
  4) Polarimeter prototype (first phase R&D done)
- Two successful technical reviews: Dec. 2009 and Mar. 2011.
- Sent proposal to DOE-NP for a proton EDM experiment at BNL: Nov. 2011

Technically driven pEDM timeline



Limits and Sensitivities

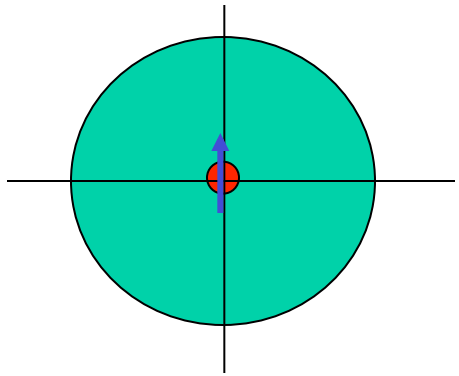
- 2020: 0.1 x 10^{-28} e-cm
- Ultimate: 0.01 x 10^{-28} e-cm

Y. Semertzidis, BNL

Measurability of Nuclear EDM

L.I. Schiff, Phys. Rev. 132, 2194 (1963)

Schiff shielding



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

However $$d_{atom} = \cancel{d}^{0}_{atom} + d_{nucleus} \neq 0$$

since nuclear charge distribution differs from EDM distribution.

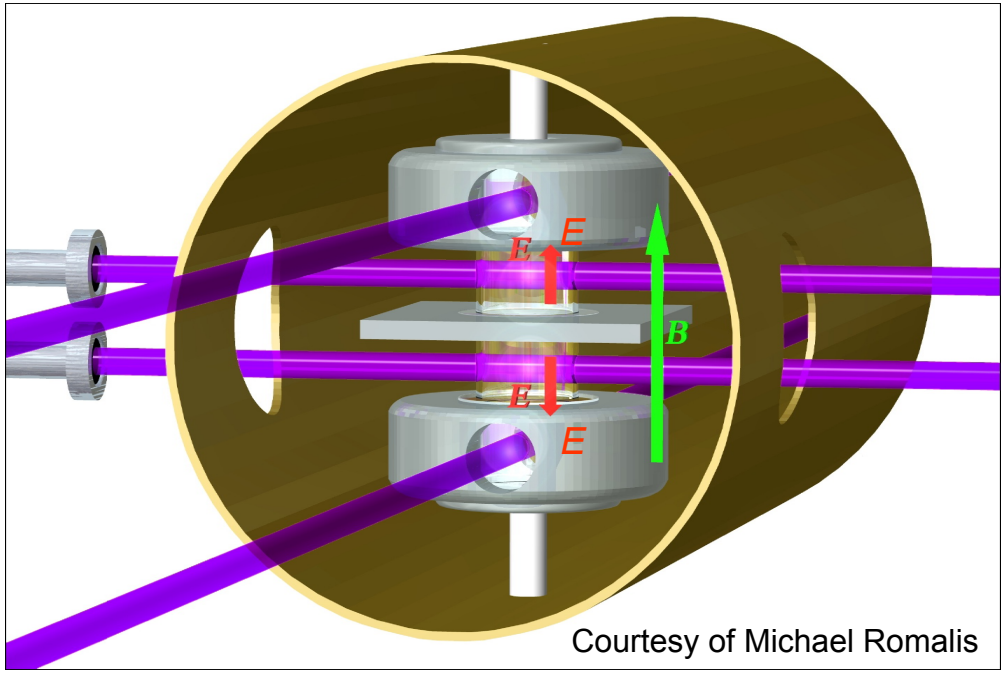
$$d\downarrow atom \propto d\downarrow nucleus \cdot (r\downarrow d\uparrow 2 - r\downarrow c\uparrow 2\ ) \cdot r\downarrow atom\uparrow -1 \cdot r\downarrow c\uparrow -$$

simplified

Schiff moment $\xrightarrow{\text{rigorous}}$ $$\vec{S} = \frac{\langle er^2\vec{r}\rangle}{10} - \frac{\langle r^2\rangle\langle e\vec{r}\rangle}{6}$$

The Seattle EDM Measurement (1980's - present)

^{199}Hg stable, high Z, groundstate $^1S_0$, I = ½, high vapor pressure



Courtesy of Michael Romalis

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

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

$$|f_+ - f_-| < 0.1 \text{ nHz}$$

Limits and Sensitivities

- Current: < 0.3 x 10^{-28} e-cm Griffith *et al.*, Phys. Rev. Lett. (2009)
- Next 5 years: 0.03 x 10^{-28} e-cm
- 2020 and beyond: 0.006 x 10^{-28} e-cm

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

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 $1s^22s$ 5.3917	4 $^1S_0$ **Be** Beryllium 9.012182 $1s^22s^2$ 9.3227											5 $^2P^o_{1/2}$ **B** Boron 10.811 $1s^22s^22p$ 8.2980	6 $^3P_0$ **C** Carbon 12.0107 $1s^22s^22p^2$ 11.2603	7 $^4S^o_{3/2}$ **N** Nitrogen 14.0067 $1s^22s^22p^3$ 14.5341	8 $^3P_2$ **O** Oxygen 15.9994 $1s^22s^22p^4$ 13.6181	9 $^2P^o_{3/2}$ **F** Fluorine 18.9984032 $1s^22s^22p^5$ 17.4228	10 $^1S_0$ **Ne** Neon 20.1797 $1s^22s^22p^6$ 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 $^2P^o_{1/2}$ **Al** Aluminum 26.981538 $[Ne]3s^23p$ 5.9858	14 $^3P_0$ **Si** Silicon 28.0855 $[Ne]3s^23p^2$ 8.1517	15 $^4S^o_{3/2}$ **P** Phosphorus 30.973761 $[Ne]3s^23p^3$ 10.4867	16 $^3P_2$ **S** Sulfur 32.065 $[Ne]3s^23p^4$ 10.3600	17 $^2P^o_{3/2}$ **Cl** Chlorine 35.453 $[Ne]3s^23p^5$ 12.9676	18 $^1S_0$ **Ar** Argon 39.948 $[Ne]3s^23p^6$ 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 $[Ar]3d^24s^2$ 6.8281	23 $^4F_{3/2}$ **V** Vanadium 50.9415 $[Ar]3d^34s^2$ 6.7462	24 $^7S_3$ **Cr** Chromium 51.9961 $[Ar]3d^54s$ 6.7665	25 $^6S_{5/2}$ **Mn** Manganese 54.938049 $[Ar]3d^54s^2$ 7.4340	26 $^5D_4$ **Fe** Iron 55.845 $[Ar]3d^64s^2$ 7.9024	27 $^4F_{9/2}$ **Co** Cobalt 58.933200 $[Ar]3d^74s^2$ 7.8810	28 $^3F_4$ **Ni** Nickel 58.6934 $[Ar]3d^84s^2$ 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 $^2P^o_{1/2}$ **Ga** Gallium 69.723 $[Ar]3d^{10}4s^24p$ 5.9993	32 $^3P_0$ **Ge** Germanium 72.64 $[Ar]3d^{10}4s^24p^2$ 7.8994	33 $^4S^o_{3/2}$ **As** Arsenic 74.92160 $[Ar]3d^{10}4s^24p^3$ 9.7886	34 $^3P_2$ **Se** Selenium 78.96 $[Ar]3d^{10}4s^24p^4$ 9.7524	35 $^2P^o_{3/2}$ **Br** Bromine 79.904 $[Ar]3d^{10}4s^24p^5$ 11.8138	36 $^1S_0$ **Kr** Krypton 83.798 $[Ar]3d^{10}4s^24p^6$ 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 $[Kr]4d^25s^2$ 6.6339	41 $^6D_{1/2}$ **Nb** Niobium 92.90638 $[Kr]4d^45s$ 6.7589	42 $^7S_3$ **Mo** Molybdenum 95.94 $[Kr]4d^55s$ 7.0924	43 $^6S_{5/2}$ **Tc** Technetium (98) $[Kr]4d^55s^2$ 7.28	44 $^5F_5$ **Ru** Ruthenium 101.07 $[Kr]4d^75s$ 7.3605	45 $^4F_{9/2}$ **Rh** Rhodium 102.90550 $[Kr]4d^85s$ 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 $^2P^o_{1/2}$ **In** Indium 114.818 $[Kr]4d^{10}5s^25p$ 5.7864	50 $^3P_0$ **Sn** Tin 118.710 $[Kr]4d^{10}5s^25p^2$ 7.3439	51 $^4S^o_{3/2}$ **Sb** Antimony 121.760 $[Kr]4d^{10}5s^25p^3$ 8.6084	52 $^3P_2$ **Te** Tellurium 127.60 $[Kr]4d^{10}5s^25p^4$ 9.0096	53 $^2P^o_{3/2}$ **I** Iodine 126.90447 $[Kr]4d^{10}5s^25p^5$ 10.4513	54 $^1S_0$ **Xe** Xenon 131.293 $[Kr]4d^{10}5s^25p^6$ 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 $[Xe]4f^{14}5d^26s^2$ 6.8251	73 $^4F_{3/2}$ **Ta** Tantalum 180.9479 $[Xe]4f^{14}5d^36s^2$ 7.5496	74 $^5D_0$ **W** Tungsten 183.84 $[Xe]4f^{14}5d^46s^2$ 7.8640	75 $^6S_{5/2}$ **Re** Rhenium 186.207 $[Xe]4f^{14}5d^56s^2$ 7.8335	76 $^5D_4$ **Os** Osmium 190.23 $[Xe]4f^{14}5d^66s^2$ 8.4382	77 $^4F_{9/2}$ **Ir** Iridium 192.217 $[Xe]4f^{14}5d^76s^2$ 8.9670	78 $^3D_3$ **Pt** Platinum 195.078 $[Xe]4f^{14}5d^96s$ 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 $^2P^o_{1/2}$ **Tl** Thallium 204.3833 [Hg]6p 6.1082	82 $^3P_0$ **Pb** Lead 207.2 $[Hg]6p^2$ 7.4167	83 $^4S^o_{3/2}$ **Bi** Bismuth 208.98038 $[Hg]6p^3$ 7.2855	84 $^3P_2$ **Po** Polonium (209) $[Hg]6p^4$ 8.414	85 $^2P^o_{3/2}$ **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) $[Rn]5f^{14}6d^27s^2$? 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 $^1G^o_4$ **Ce** Cerium 140.116 $[Xe]4f5d6s^2$ 5.5387	59 $^4I^o_{9/2}$ **Pr** Praseodymium 140.90765 $[Xe]4f^36s^2$ 5.473	60 $^5I_4$ **Nd** Neodymium 144.24 $[Xe]4f^46s^2$ 5.5250	61 $^6H^o_{5/2}$ **Pm** Promethium (145) $[Xe]4f^56s^2$ 5.582	62 $^7F_0$ **Sm** Samarium 150.36 $[Xe]4f^66s^2$ 5.6437	63 $^8S^o_{7/2}$ **Eu** Europium 151.964 $[Xe]4f^76s^2$ 5.6704	64 $^9D^o_2$ **Gd** Gadolinium 157.25 $[Xe]4f^75d6s^2$ 6.1498	65 $^6H^o_{15/2}$ **Tb** Terbium 158.92534 $[Xe]4f^96s^2$ 5.8638	66 $^5I_8$ **Dy** Dysprosium 162.500 $[Xe]4f^{10}6s^2$ 5.9389	67 $^4I^o_{15/2}$ **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 $^2F^o_{7/2}$ **Tm** Thulium 168.9342 $[Xe]4f^{13}6s$ 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 $[Rn]6d^27s^2$ 6.3067	91 $^4K_{11/2}$ **Pa** Protactinium 231.03588 $[Rn]5f^26d7s^2$ 5.89	92 $^5L^o_6$ **U** Uranium 238.02891 $[Rn]5f^36d7s^2$ 6.1941	93 $^6L_{11/2}$ **Np** Neptunium (237) $[Rn]5f^46d7s^2$ 6.2657	94 $^7F_0$ **Pu** Plutonium (244) $[Rn]5f^67s^2$ 6.0260	95 $^8S^o_{7/2}$ **Am** Americium (243) $[Rn]5f^77s^2$ 5.9738	96 $^9D^o_2$ **Cm** Curium (247) $[Rn]5f^76d7s^2$ 5.9914	97 $^6H^o_{15/2}$ **Bk** Berkelium (247) $[Rn]5f^97s^2$ 6.1979	98 $^5I_8$ **Cf** Californium (251) $[Rn]5f^{10}7s^2$ 6.2817	99 $^4I^o_{15/2}$ **Es** Einsteinium (252) $[Rn]5f^{11}7s^2$ 6.42	100 $^3H_6$ **Fm** Fermium (257) $[Rn]5f^{12}7s^2$ 6.50	101 $^2F^o_{7/2}$ **Md** Mendelevium (258) $[Rn]5f^{13}7s^2$ 6.58	102 $^1S_0$ **No** Nobelium (259) $[Rn]5f^{14}7s^2$ 6.65	103 $^2P^o_{1/2}$? **Lr** Lawrencium (262) $[Rn]5f^{14}7s^27p$? 4.9 ?

Atomic Nu… Ground-state …

Sy…

$^1S_0$

C…

Based upon … indicates the mass number of the most stable isotope

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

NIST SP 966 (September 2003)

EDM of ^{225}Ra enhanced

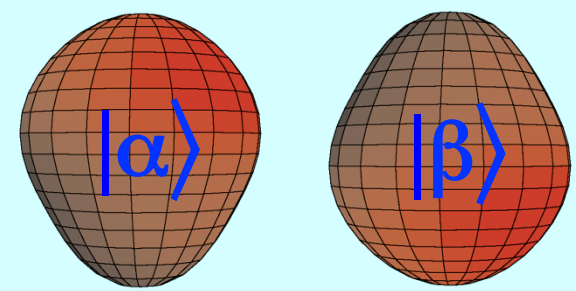
^{225}Ra:
I = ½
$t_{1/2}$ = 15 d

- Closely spaced parity doublet – *Haxton & Henley (1983)*
- Large intrinsic Schiff moment due to octupole deformation

  – *Auerbach, Flambaum & Spevak (1996)*
- Relativistic atomic structure (^{225}Ra / ^{199}Hg ~ 3)

  – *Dzuba, Flambaum, Ginges, Kozlov (2002)*

Parity doublet



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

55 keV

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

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

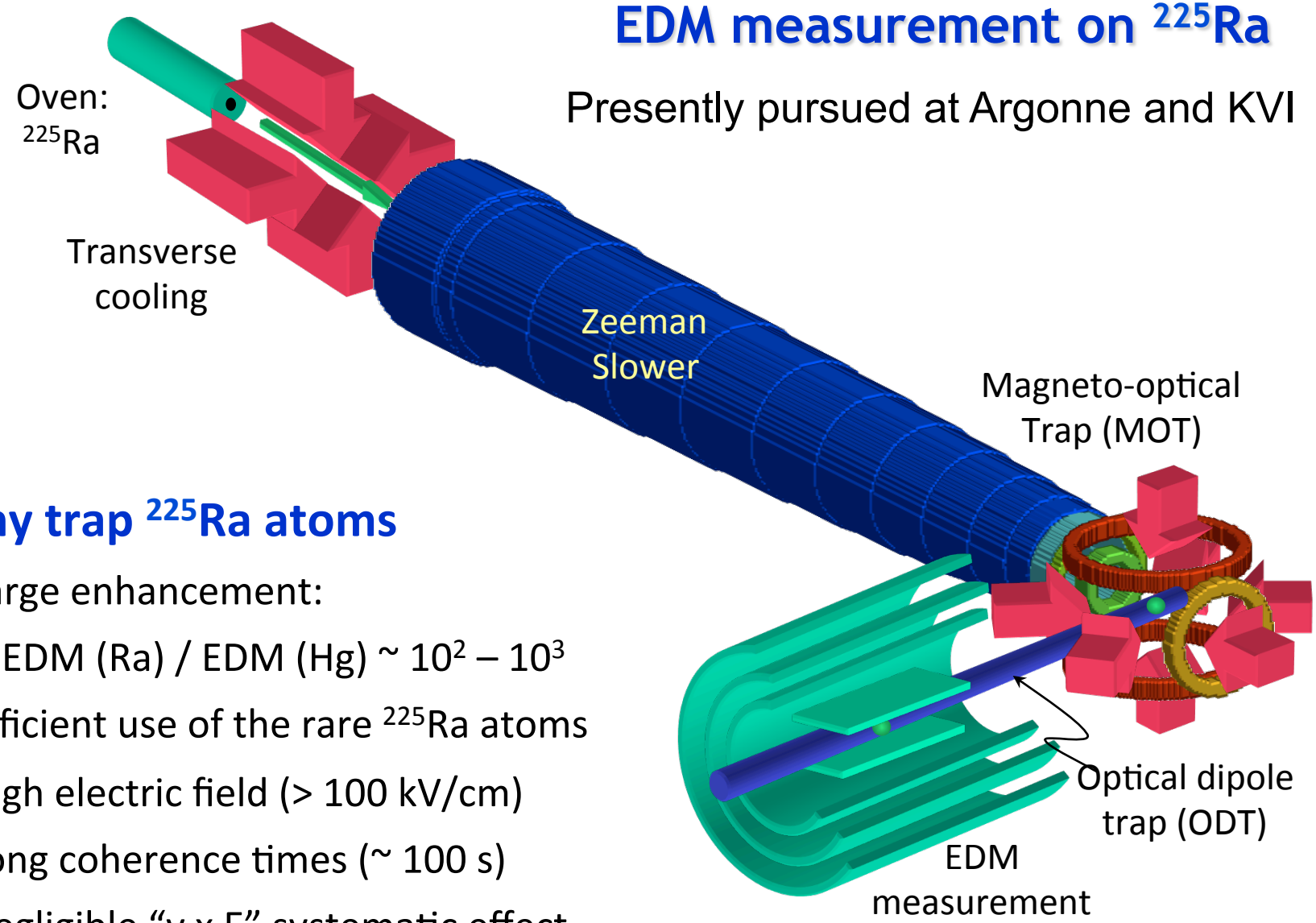
Enhancement Factor: EDM (^{225}Ra) / EDM (^{199}Hg)

Skyrme Model	Isoscalar	Isovector	Isotensor
SIII	300	4000	700
SkM*	300	2000	500
SLy4	700	8000	1000

Schiff moment of ^{225}Ra, Dobaczewski, Engel (2005)
Schiff moment of ^{199}Hg, Ban, Dobaczewski, Engel, Shukla (2010)

EDM measurement on ^{225}Ra

Presently pursued at Argonne and KVI



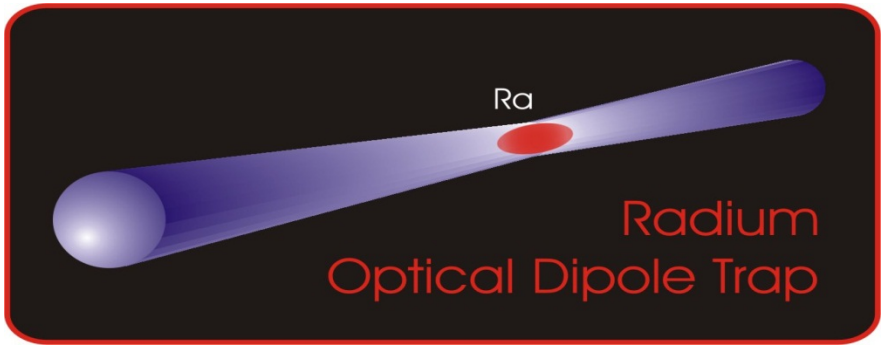
Why trap ^{225}Ra atoms

- Large enhancement:

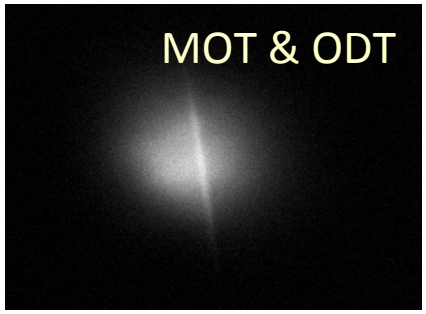
  EDM (Ra) / EDM (Hg) ~ $10^2 – 10^3$
- Efficient use of the rare ^{225}Ra atoms
- High electric field (> 100 kV/cm)
- Long coherence times (~ 100 s)
- Negligible “v x E” systematic effect

Preparation of Cold Radium Atoms for EDM at Argonne

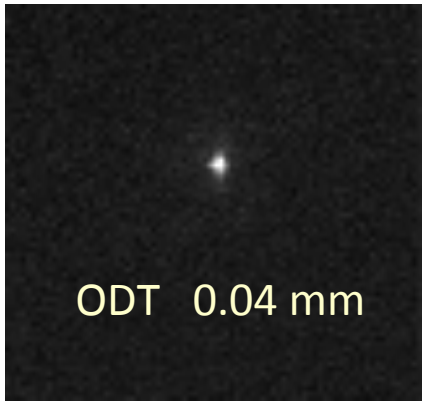
- Magneto-optical trap (MOT) of radium realized (2007);
- Optical dipole trap (ODT) of radium realized (2010);
- Atoms transported from the trap chamber to the measurement chamber (2010);
- Atoms transferred to the measurement trap (2011).



Sideview



Head-on view



Limits and Sensitivities

- Since 2007: Developed relevant techniques.
- Next 5 years: 10 – 100 x 10^{-28} e-cm
- 2020 and beyond: 1 x 10^{-28} e-cm *

  * at an accelerator-based isotope production facility

Yields of EDM-Enhanced Isotopes: ^{225}Ra and ^{223}Rn

Presently available

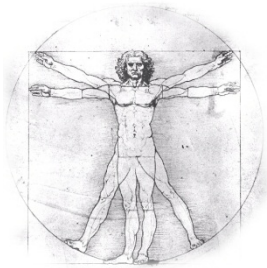
- National Isotope Development Center, ORNL
  - Decay daughters of ^{229}Th
  - ^{225}Ra: 10^7 – 10^8 /s

Projected

- FRIB (B. Sherrill, MSU)
  - Beam dump recovery with a ^{238}U beam
  - Parasitic operation, available ~ 5 months per year
  - ^{225}Ac: 2 x 10^{10} /s
  - ^{223}Ra: 2 x 10^{10} /s

- ISOL@FRIB, Project-X (I.C. Gomes and J. Nolen, Argonne)
  - Protons on thorium target, 1 mA x 1 GeV = 1 MW
  - ^{223}Rn: 10^{11} /s
  - ^{225}Ra: 10^{13} /s

Radon-EDM Experiment



TRIUMF E929

Spokesmen: Timothy Chupp & Carl Svensson

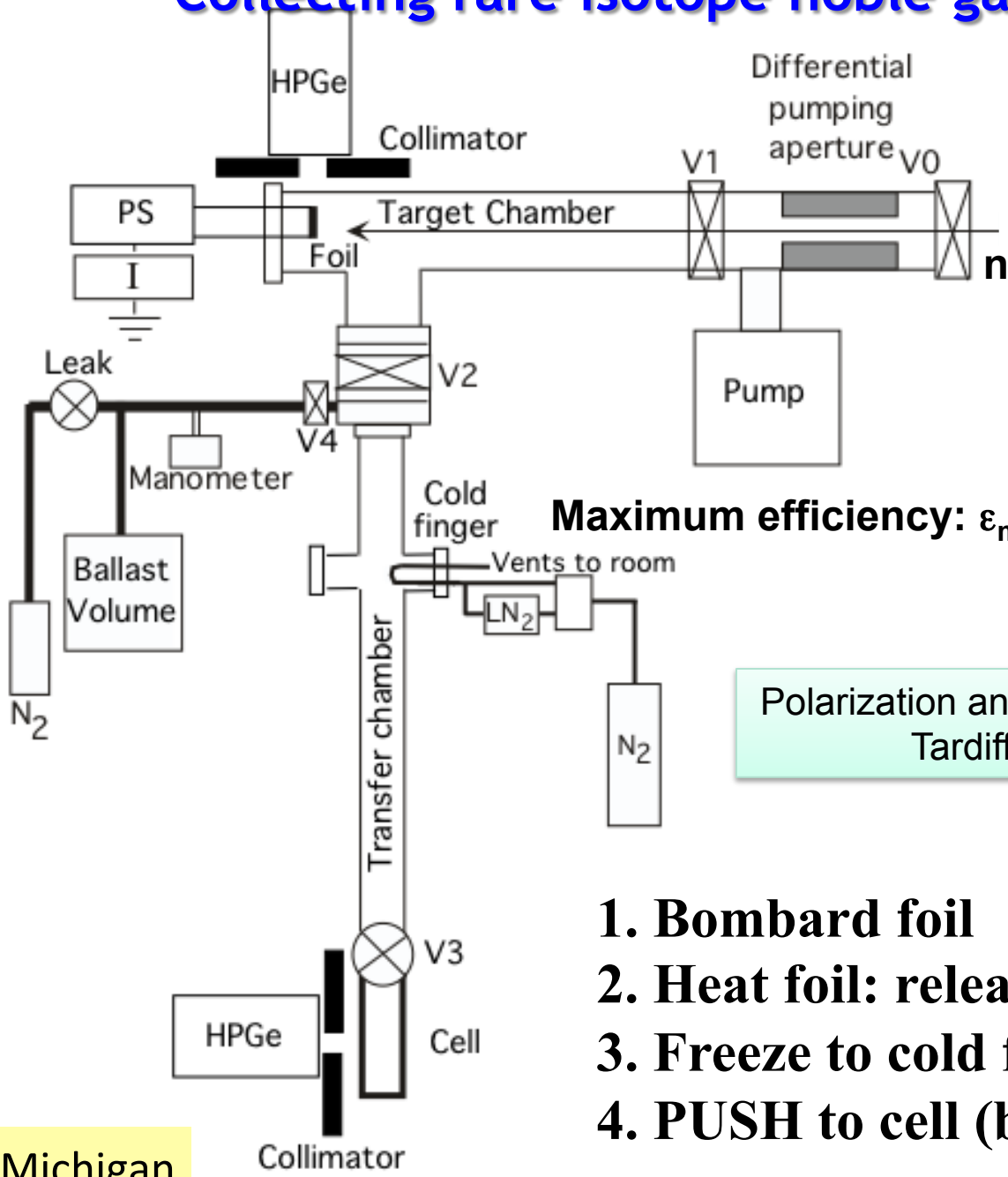
E-929 Collaboration (Guelph, Michigan, SFU, TRIUMF)

TRIUMF

Canada's National Laboratory for Particle and Nuclear Physics

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

Collecting rare isotope noble gases



^{123}Cs (30 keV)
no radon at TRIUMF yet

Maximum efficiency: ε_{max}=75%

Polarization and relaxation rates of radon
Tardiff *et al*. Phys. Rev. A (2008)

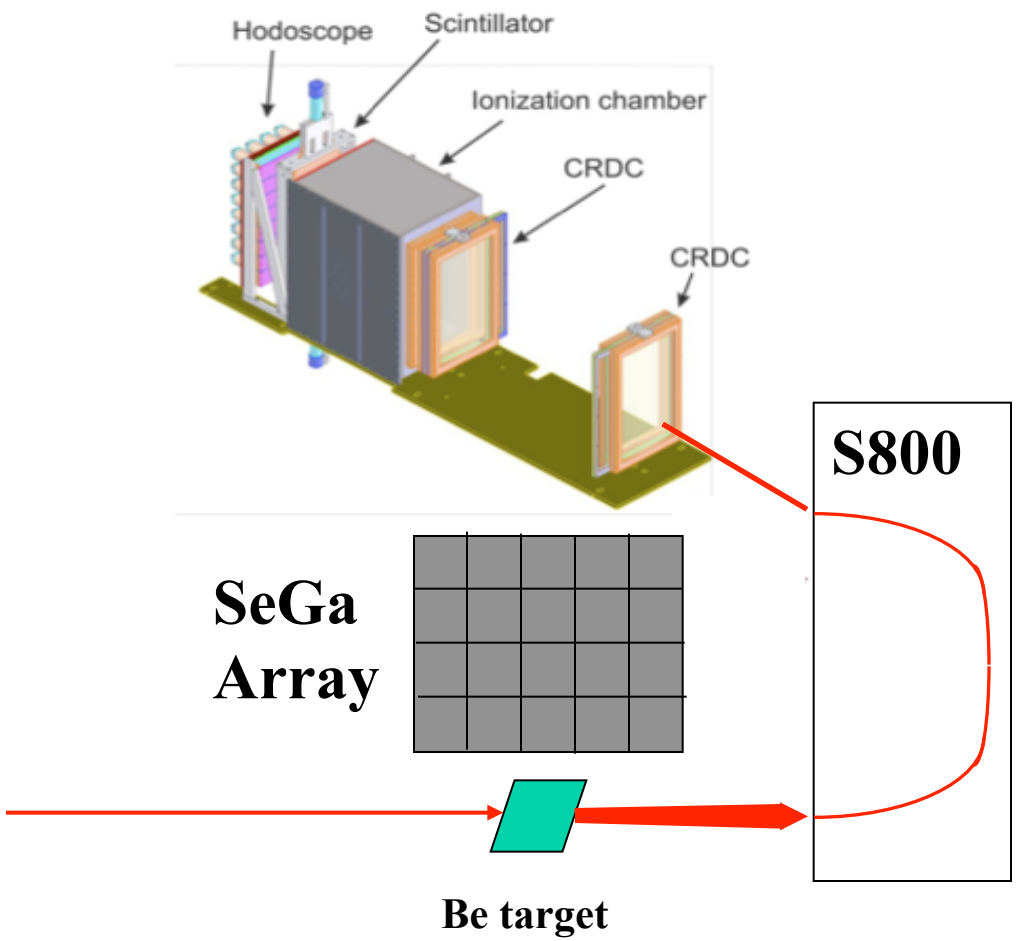
1. **Bombard foil**
2. **Heat foil: release to target chambe**
3. **Freeze to cold finger**
4. **PUSH to cell (buffer gas)**

T. Chupp, Michigan

^{238}U fragmentation-in beam $^{221/223}$Rn* spectroscopy

J. Berryman, A. Gade, B. Sherrill, TC et al.

State of Michigan



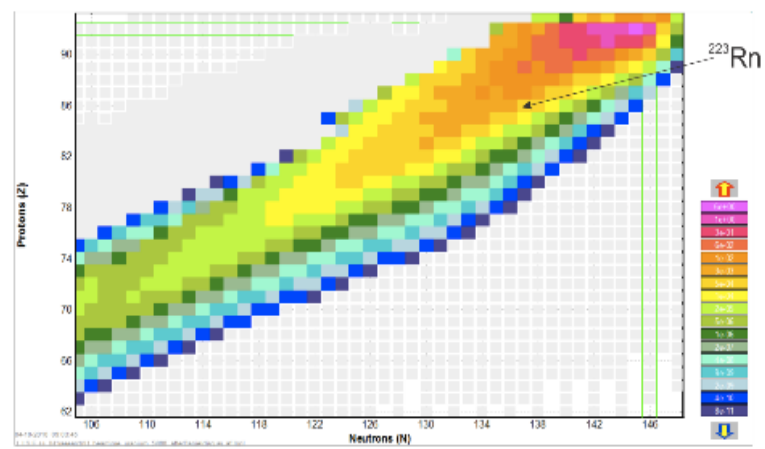


Figure 2. Transmission plot at the focal plane of the S800, calculated with LISE++ for ^{238}U fragmentation on the diamond active target, including fission products. The bottom figure is an expanded view of the top, in the region of the Rn isotopes.

T. Chupp, Michigan

A future for Xenon-129

Current ^{129}Xe limits about 100x greater than ^{199}Hg (1e-29); Hg ~5x more sensitive

- Signal to noise estimates in gas (maser) can reach this level and beyond
- Liquid xenon S/N even better
- BUT interactions of spins/magnetism are limiting
  - Gas: Technical issues
  - Liquid: Shape issues may be addressed with spherical droplets (Munich)

Motivations:

- Need more diamagnetic atom experiments (like radium)
- Possible comagnetometer for n-EDM
  - Japan/TRIUMF (Y. Masuda et al., Phys. Lett. A, 2012)
  - 2-photon (UMichigan)

T. Chupp, Michigan

Summary of EDM Searches on Nucleons and Nuclei

EDM units: 1×10^{-28} e-cm

Sector	Experiment	Current Limit	5-year goal	Beyond 2020	Standard Model	Notes
Neutron	UCN general	300	50 – 100	3 – 5	0.001	No Schiff shielding
Neutron	SNS nEDM			3	0.001	No Schiff shielding
Proton	BNL Storage ring	8,000*		0.01 – 0.1	0.001	No Schiff shielding
Nucleus	Seattle ^{199}Hg cell	0.3	0.03	0.006	0.000,01	
Nucleus	ANL ^{225}Ra trap		10 – 100	1	0.01	Octupole enhanced
Nucleus	Michigan ^{223}Rn cell			2	0.01	Octupole enhanced

* Indirect limit derived from the ^{199}Hg measurement.

Extra slides

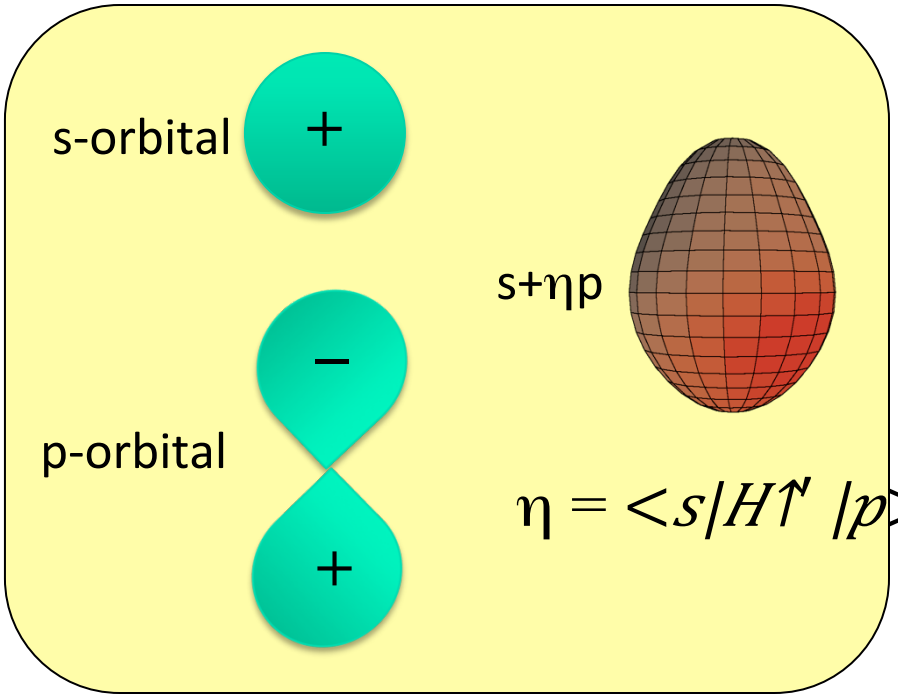
Probing eEDM in a neutral atom or molecule

$$H = -d_{atom} \cdot E_{ext} = -\langle d_e \cdot E_{i} \quad \rightarrow define^{\perp} \; -d_e \cdot E_e,$$

Problem: $\langle E_{int} \rangle = 0$ Insight: $\langle d_e \cdot E_{int} \rangle \neq d_e \cdot \langle E_{int} \rangle$

Enhancement factor! - P.G.H. Sandars, Phys. Lett. (1965)
Commins, Jackson, DeMille, Am. J. Phys. (2007)

$$|E_{eff}| \; Z^3 \alpha^2 (e/a_0^2) \cdot \mathcal{P} \sim \mathcal{P} \cdot 10^{11} \text{ V/cm @ } Z \sim 80$$

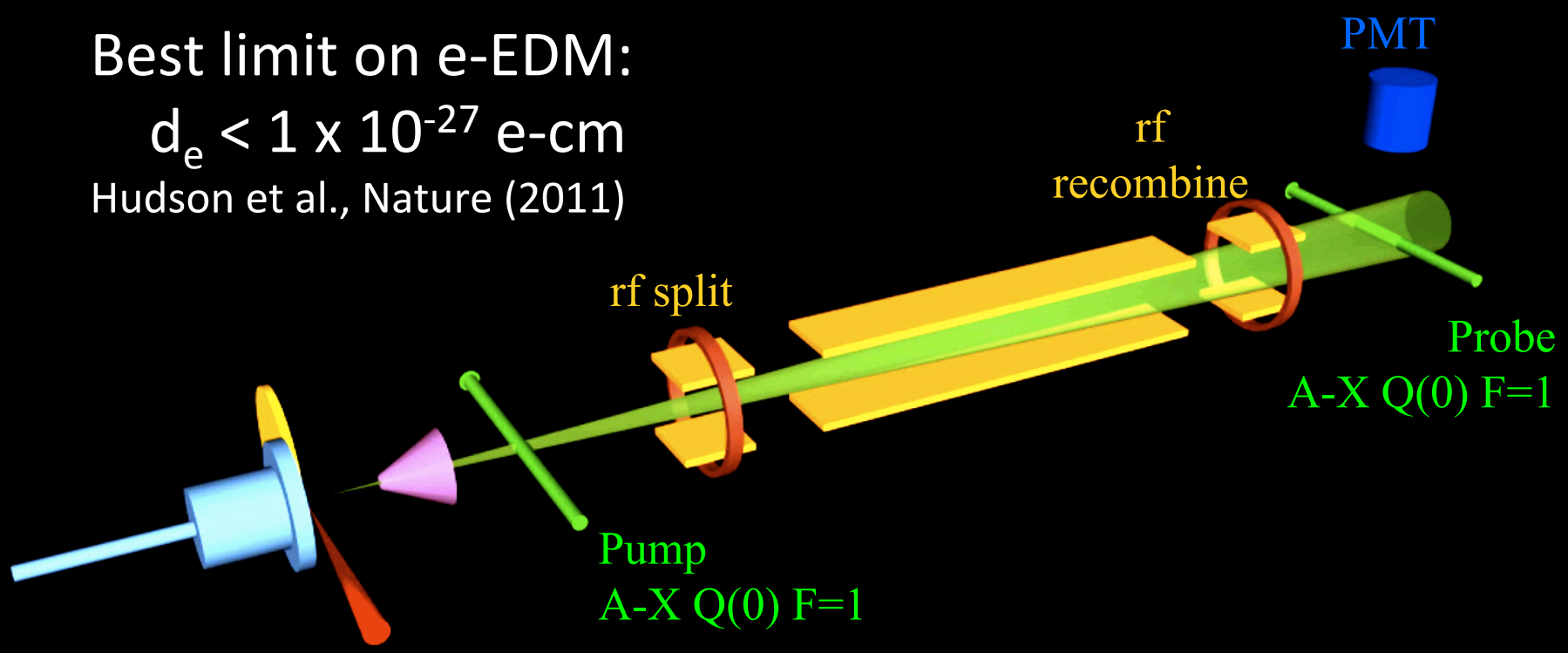


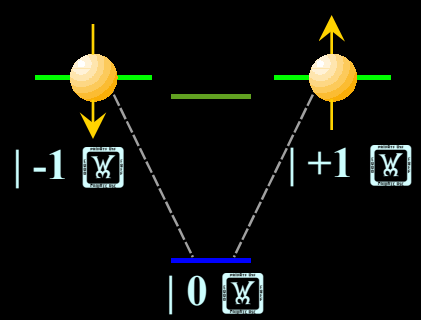
	Tl atom	YbF	ThO
Mixing	s-p	Rotational levels	Ω-doublet
E_ext	100 kV/cm	20 kV/cm	10 V/cm
$\mathcal{P}$	10^{-3}	1	1
E_eff	70 MV/cm	18 GV/cm	80 GV/cm

Best limit on e-EDM:

$d_e < 1 \times 10^{-27}$ e-cm

Hudson et al., Nature (2011)





Limits and Sensitivities

- Current: 10×10^{-28} e-cm
- Next 5 years: 1×10^{-28} e-cm
- 2020 and beyond: 0.01×10^{-28} e-cm

E. Hinds, Imperial London

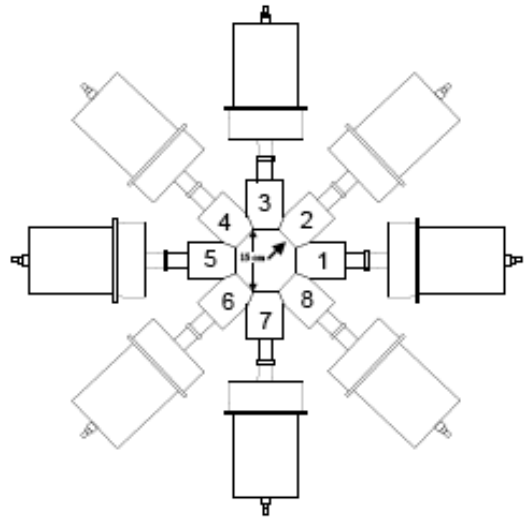
Techniques:

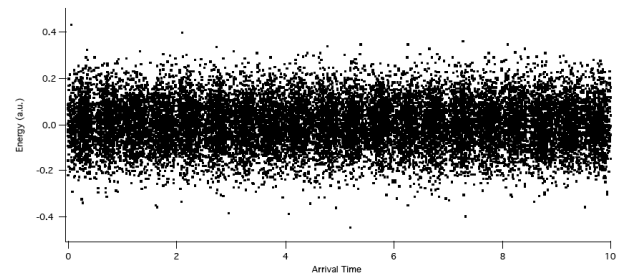
Produce rare ion radon beam

Collect in cell

Comagnetometer

Measure free precesion
(γ anisotropy/β asymmetry/laser)





$^{221/223}$Rn EDM projected sensitivity

Facility	Detection	S_d (100 d)
ISAC	g anisotropy	200 x 10^{-28} e-cm
ISAC	b asymmetry	10 x 10^{-28} e-cm
FRIB	b asymmetry	2 x 10^{-28} e-cm

→ ~ **5x10^{-30} for ^{199}Hg**

T. Chupp, Michigan