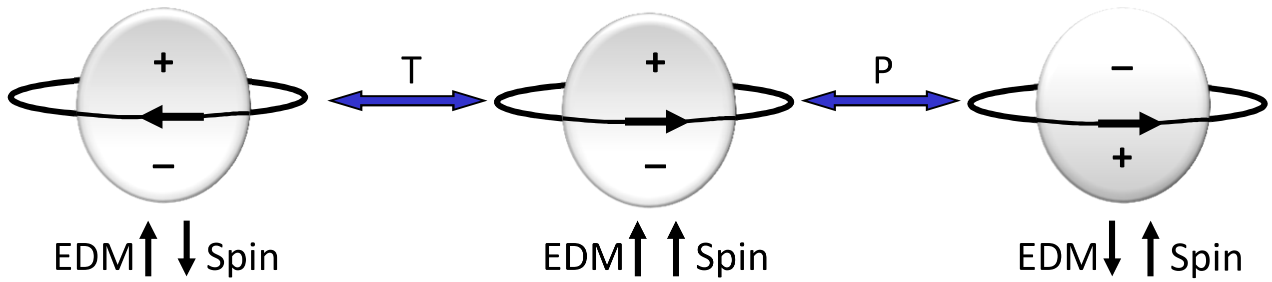


EDM Searches at Project X

Zheng-Tian Lu

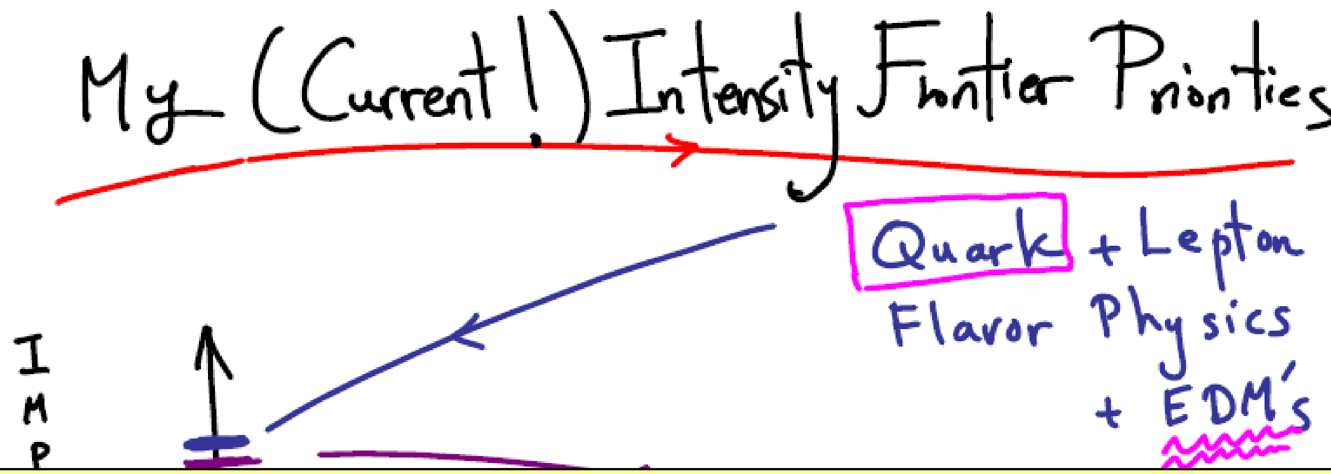
Physics Division, Argonne National Laboratory

Department of Physics, University of Chicago

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

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

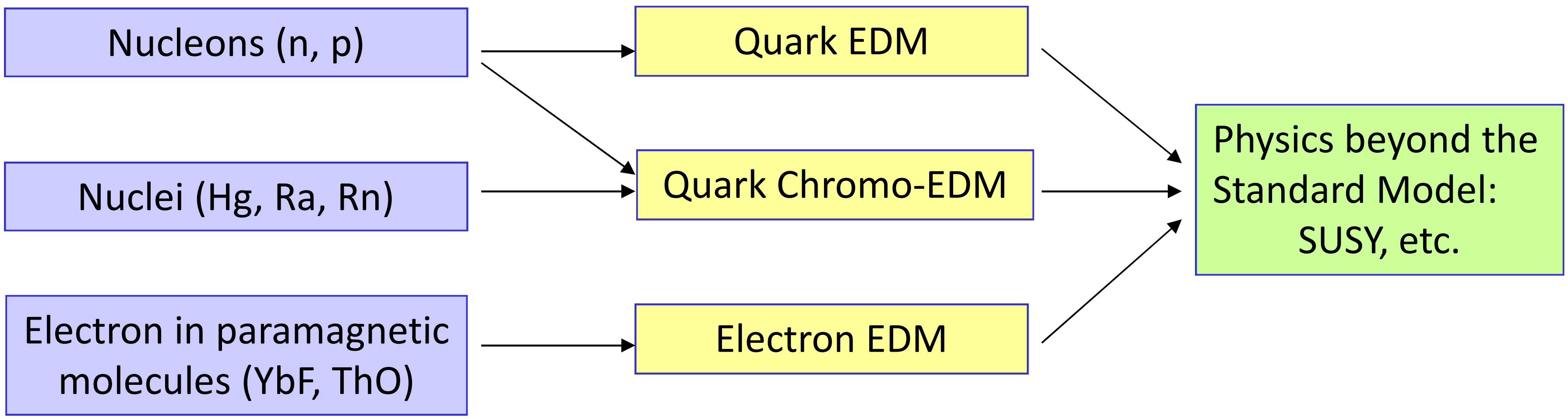


"The existence of an EDM can provide the "missing link" for explaining why the universe contains more matter than antimatter."

"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)

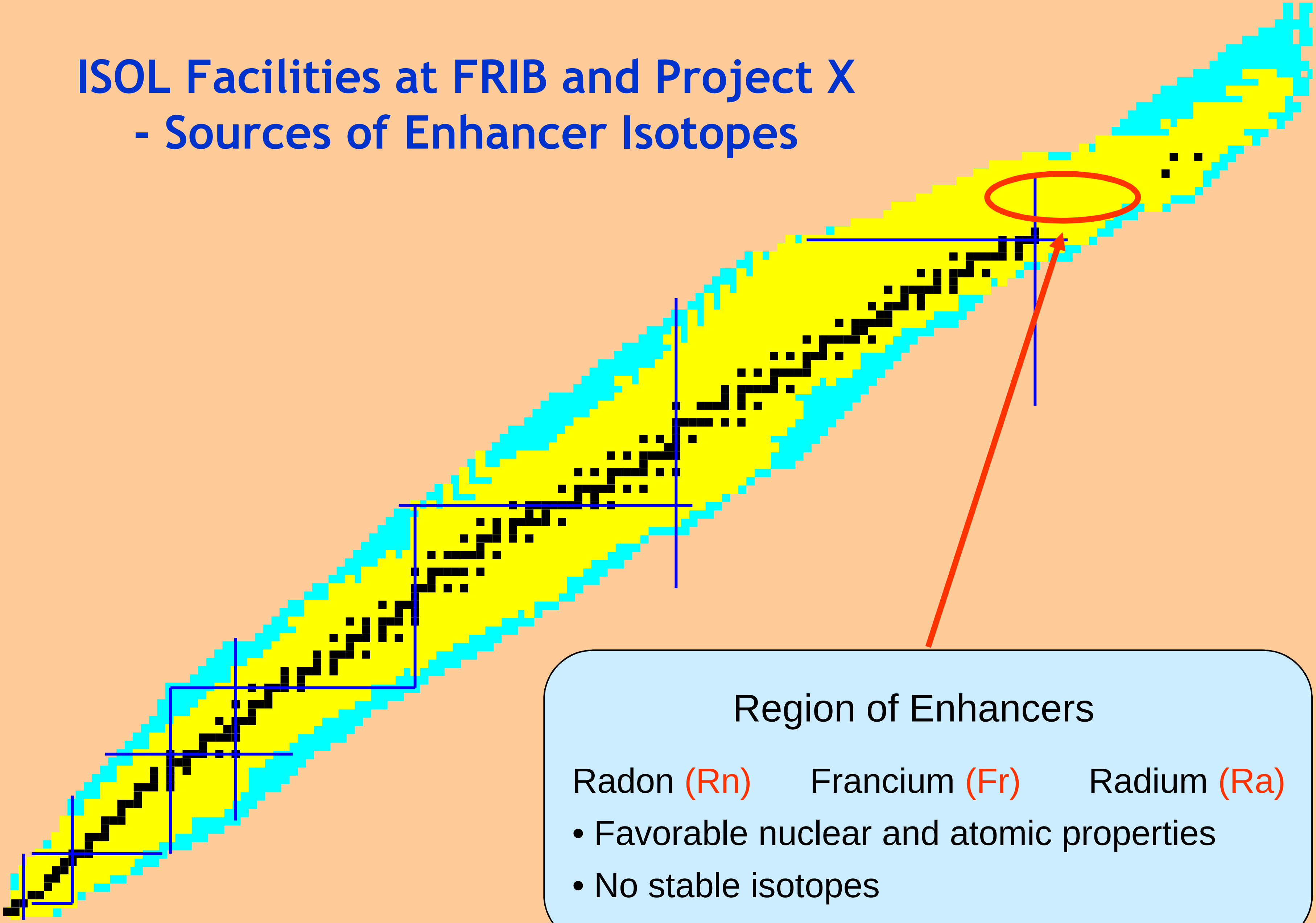
EDM Searches in Three Sectors



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)

ISOL Facilities at FRIB and Project X
- Sources of Enhancer Isotopes



Region of Enhancers

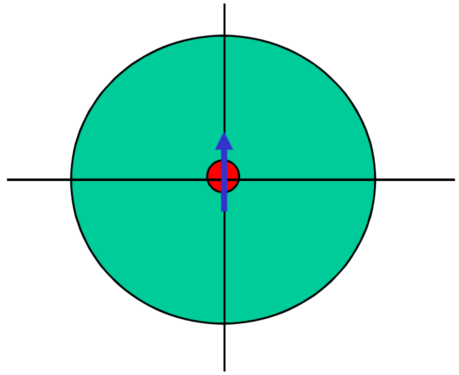
Radon (Rn) Francium (Fr) Radium (Ra)

- Favorable nuclear and atomic properties
- No stable isotopes

Measurability of Nuclear EDM

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

Schiff shielding



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

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

since nuclear charge distribution differs from EDM distribution.

$$d_{atom} \propto d_{nucleus} \cdot \left(r_d^2 - r_c^2\right) \cdot r_{atom}^{-1} \cdot r_c^{-1}$$

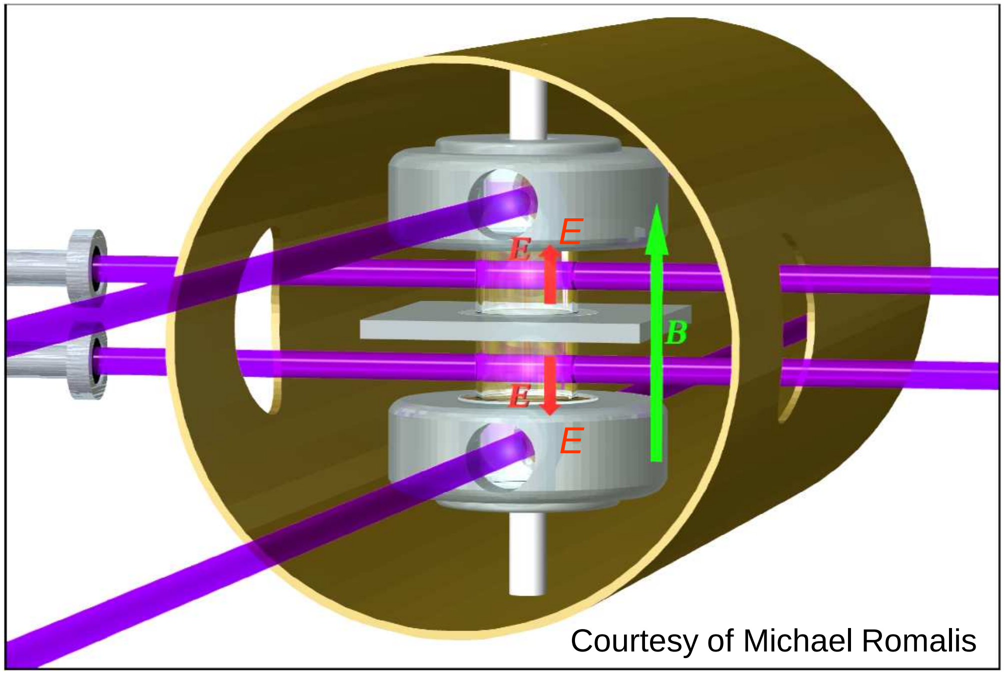
simplified

Schiff moment — rigorous →

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

The Seattle EDM Measurement (1980's - present)

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



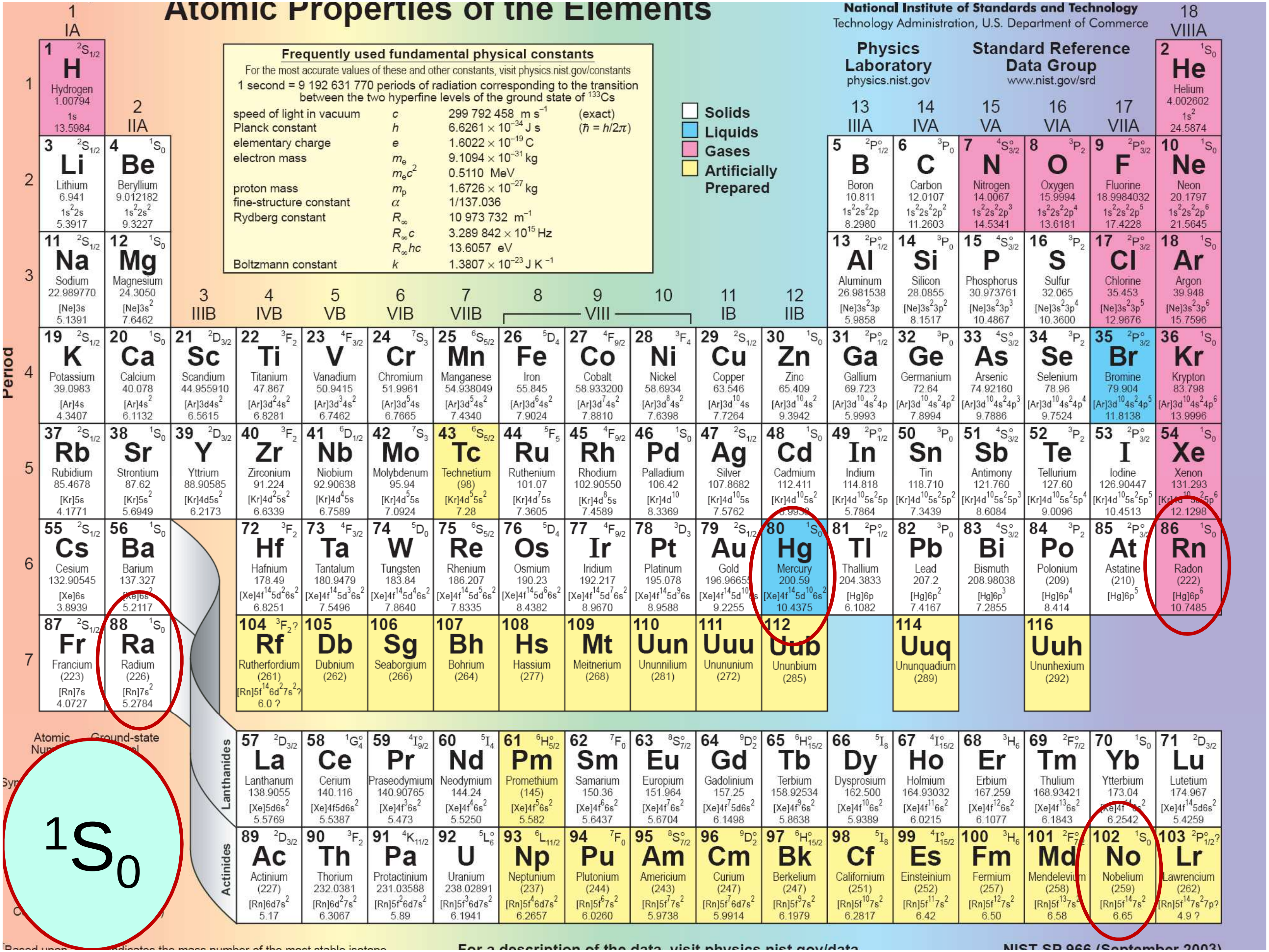
$$f_+ = \frac{2\mu B + 2dE}{h} \approx 15\ \text{Hz}$$

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

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

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 133Cs
speed of light in vacuum c 299 792 458 m s⁻¹ (exact)
Planck constant h 6.6261 × 10⁻³⁴ J s (ħ = h/2π)
elementary charge e 1.6022 × 10⁻¹⁹ C
electron mass mₑ 9.1094 × 10⁻³¹ kg
mₑc² 0.5110 MeV
proton mass mₚ 1.6726 × 10⁻²⁷ kg
fine-structure constant α 1/137.036
Rydberg constant R∞ 10 973 732 m⁻¹
R∞c 3.289 842 × 10¹⁵ Hz
R∞hc 13.6057 eV
Boltzmann constant k 1.3807 × 10⁻²³ J K⁻¹
Solids
Liquids
Gases
Artificially Prepared
Period
Lanthanides
Actinides
For a description of the data, visit physics.nist.gov/data
NIST SP 966 (September 2003)

$^1S_0$

EDM of ^{225}Ra enhanced

^{225}Ra:

I = ½

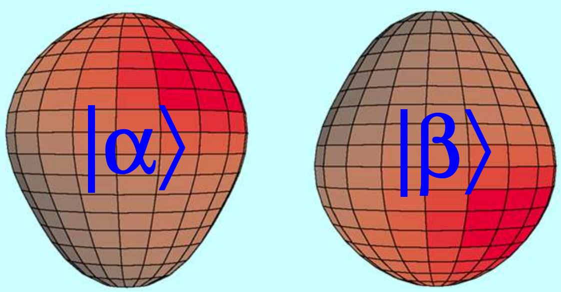
$t_{1/2}$ = 15 d

- 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)

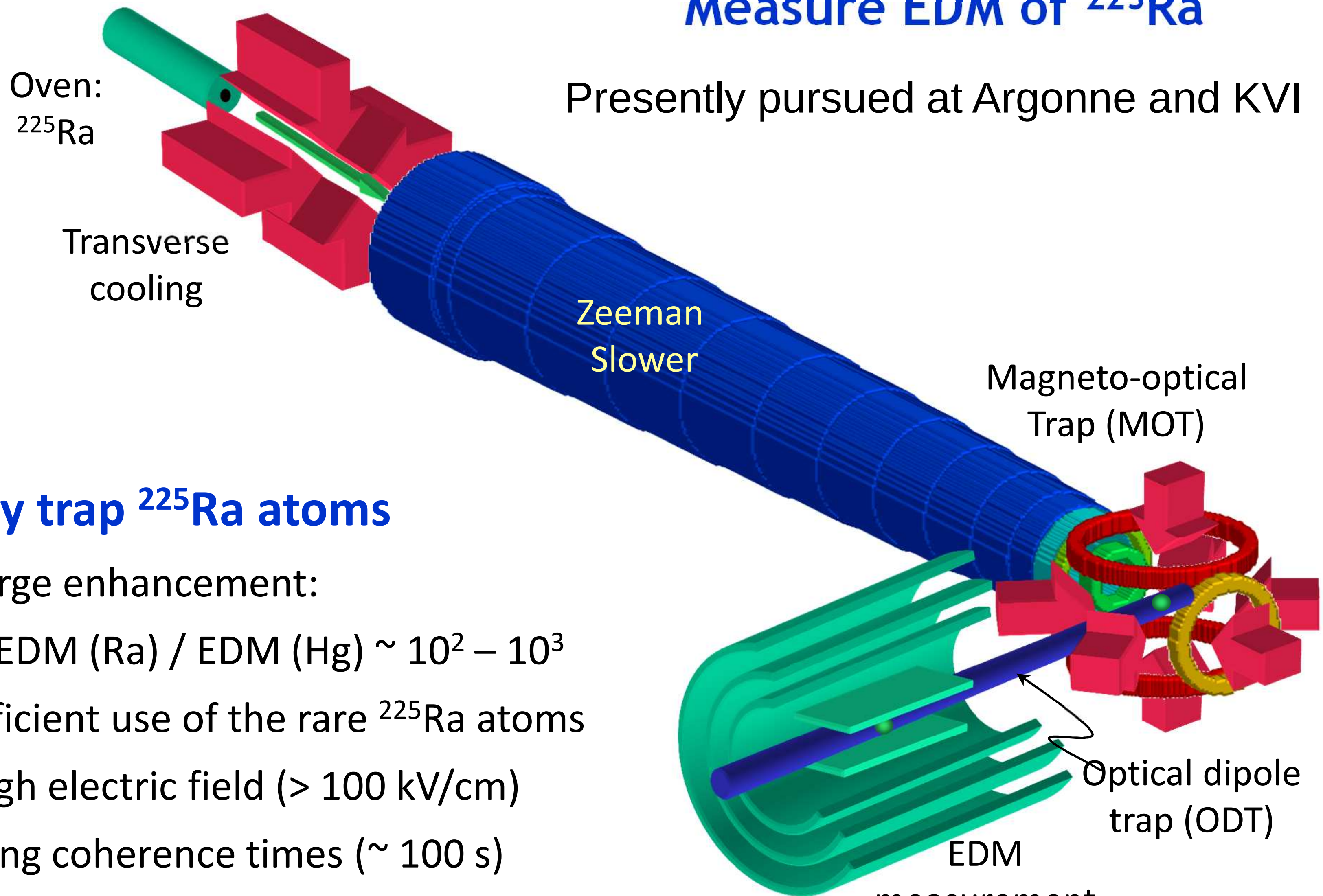
Skyrme Model	Isoscalar	Isovector	Isotensor
SIII	300	4000	700
SkM*	300	2000	500
SLy4	700	8000	1000

Schiff moment of ^{225}Ra, Dobaczewski, Engel (2005)

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

Measure EDM of ^{225}Ra

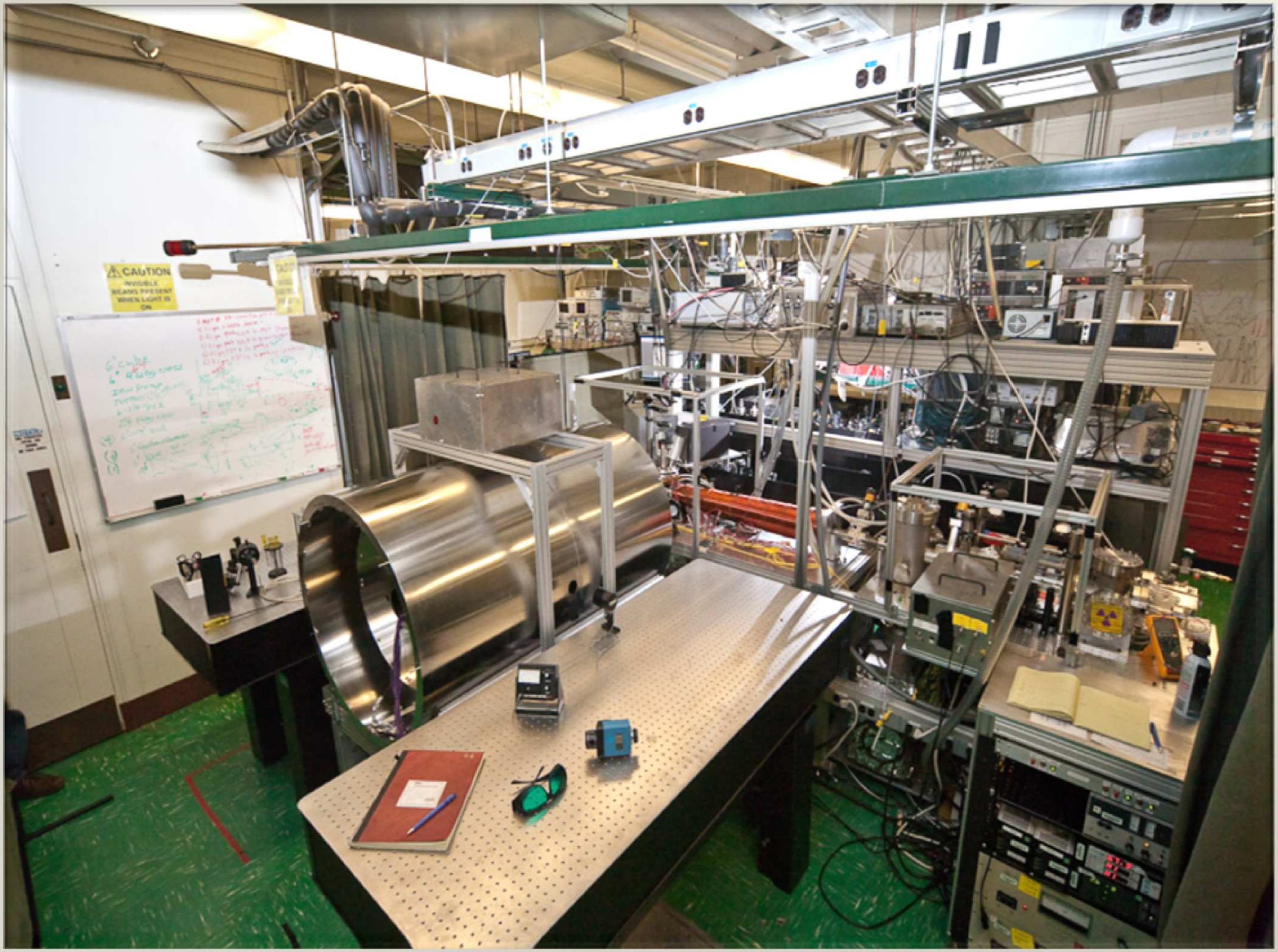
Presently pursued at Argonne and KVI



Why trap ^{225}Ra atoms

- Large enhancement:

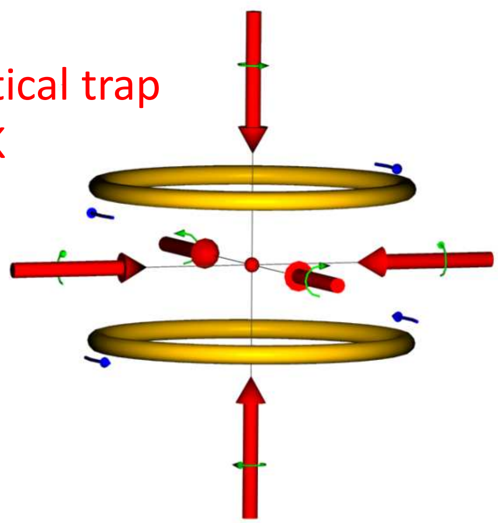
  EDM (Ra) / EDM (Hg) ~ $10^2 – 10^3$
- Efficient use of the rare ^{225}Ra atoms
- High electric field (> 100 kV/cm)
- Long coherence times (~ 100 s)
- Negligible “v x E” systematic effect


CAUTION

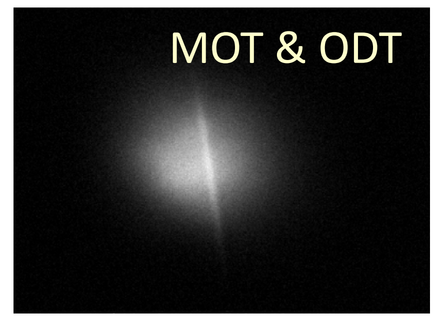
Preparation of Cold Radium Atoms for EDM at Argonne

- 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 observed.

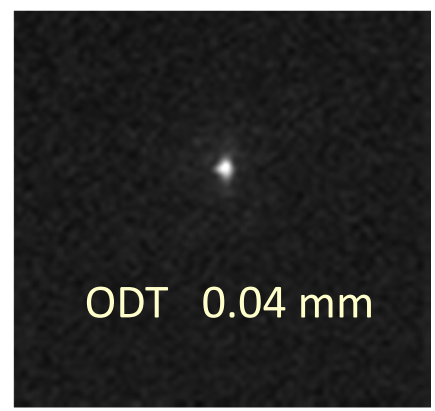
Magneto-optical trap
1 mm, 40 μK

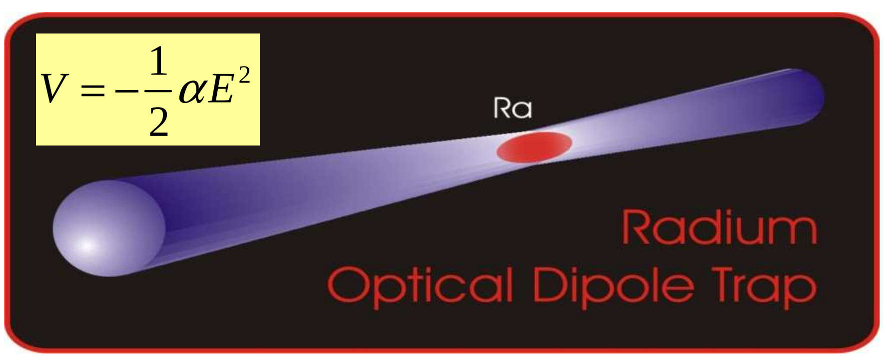


Sideview

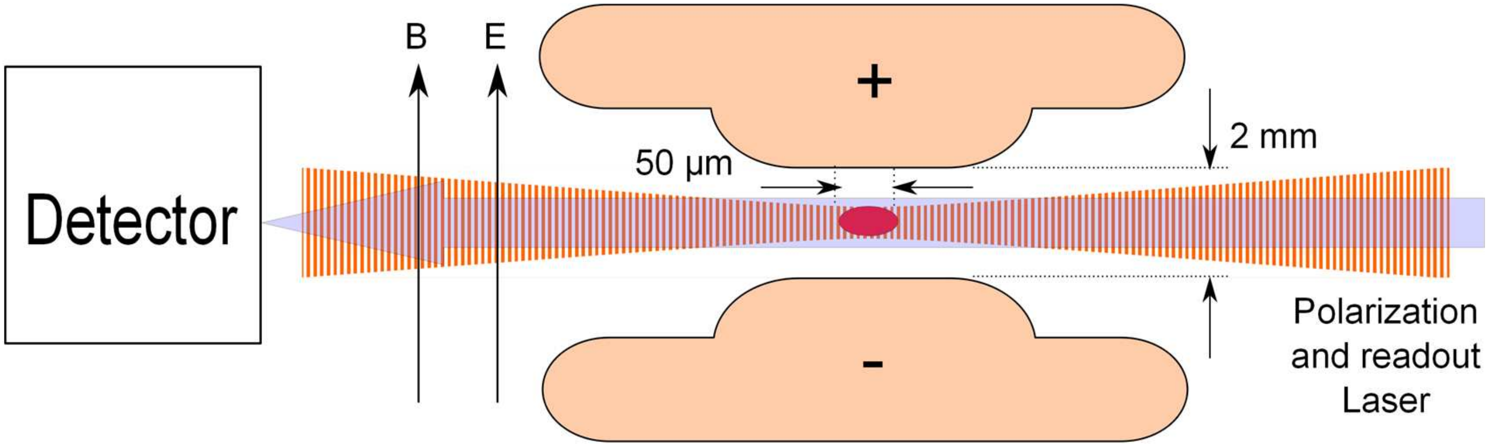


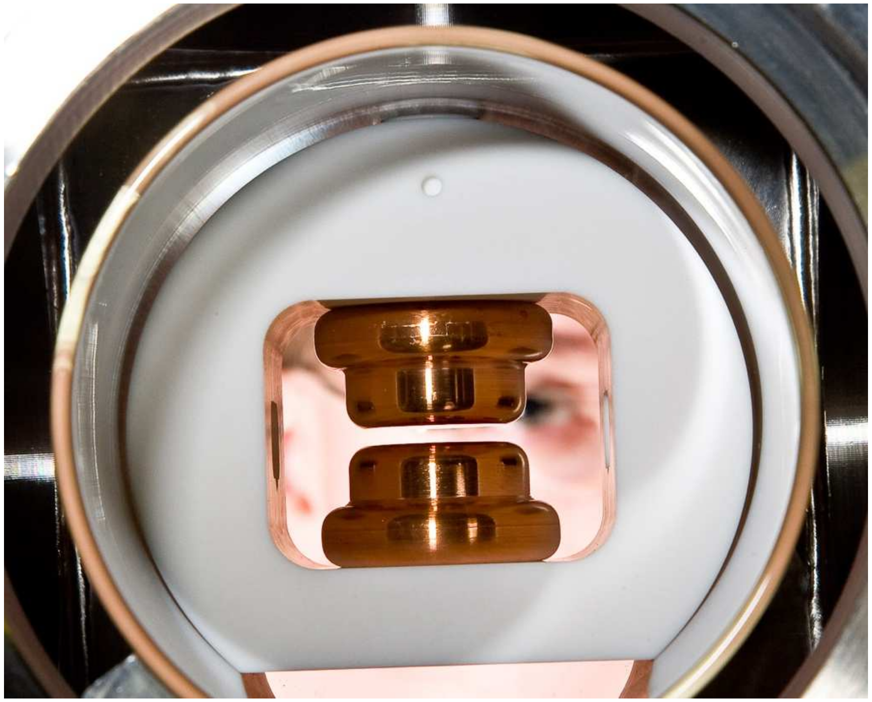
Head-on view



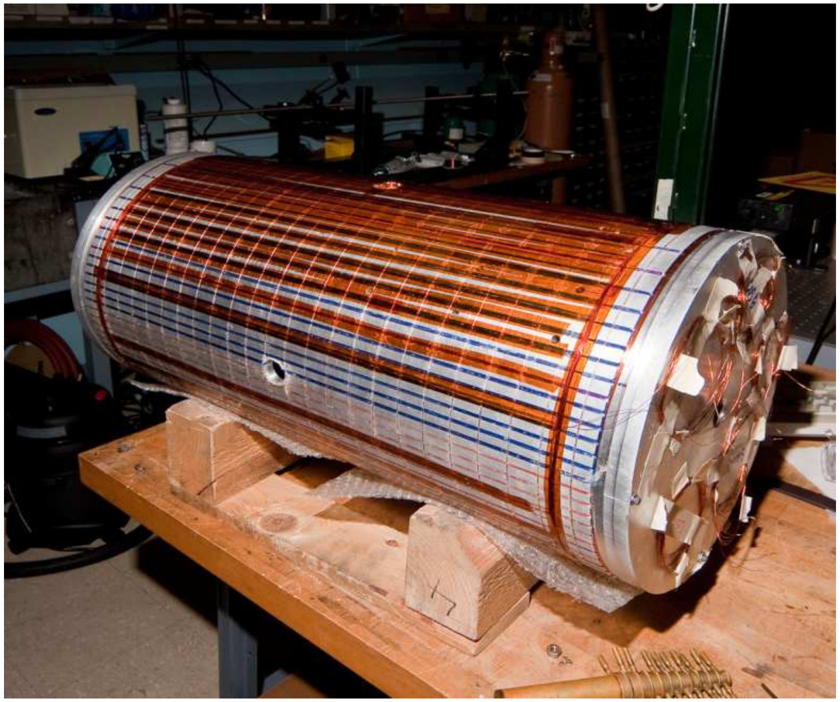


B & E fields ready to be installed





100 kV/cm



B gradient < 10 μG/cm

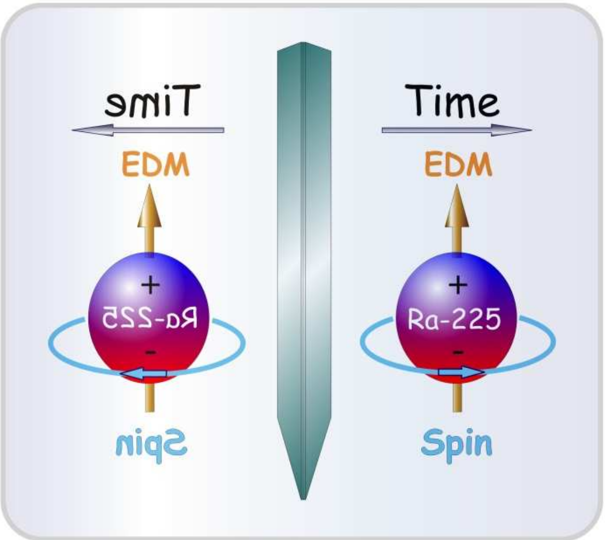
Radium EDM Search at Argonne

Progress

- 2007 – Magneto-optical trap (MOT) of radium realized;

  J.R. Guest *et al.*, Phys. Rev. Lett. (2007)
- 2010 – Optical dipole trap (ODT) of radium realized;
- 2011 – Atoms transferred to the measurement trap;

  R.H. Parker *et al.* Phys. Rev. C (2012)
- 2012 – Spin precession of Ra-225 observed.

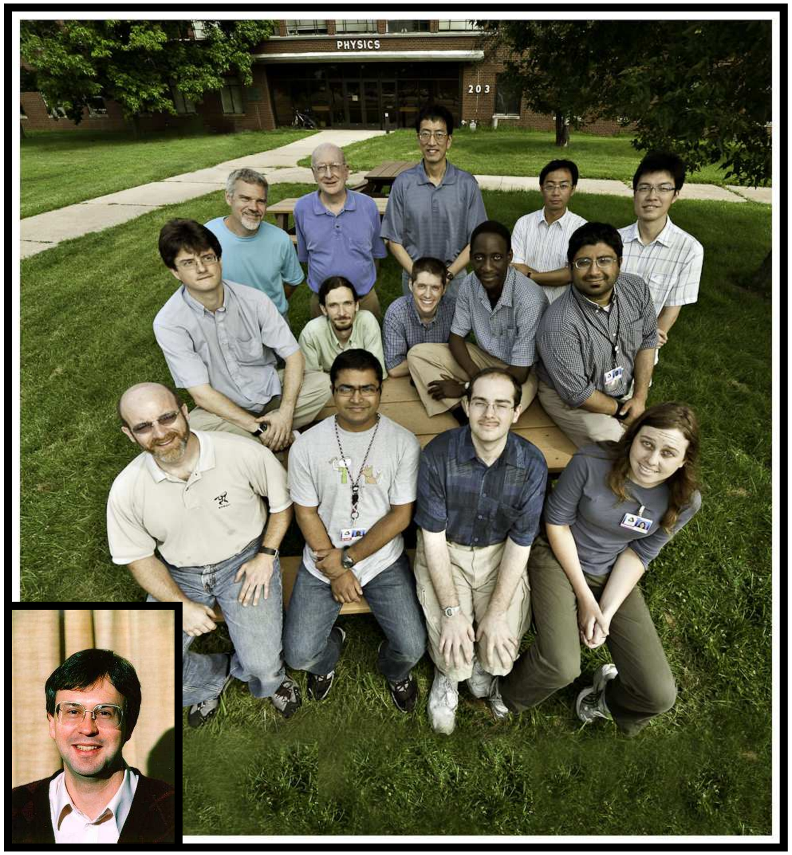


Outlook

- 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

Argonne Atom Trappers (2010)

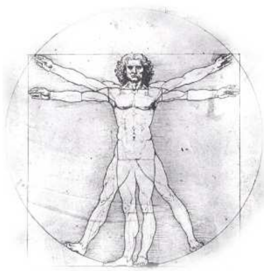


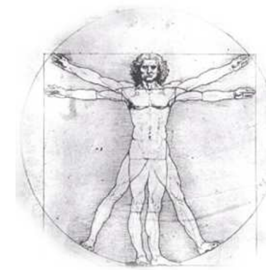
Argonne "Cold" Atom Trappers (2011)

Kevin Bailey, Matt Dietrich, John Greene, Roy Holt, Mukut Kalita (U Kentucky), Wolfgang Korsch (U Kentucky), Nathan Lemke, Zheng-Tian Lu, Peter Mueller, Tom O'Connor, Richard Parker, Jaideep Singh

We acknowledge support by DOE, Office of Nuclear Physics

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

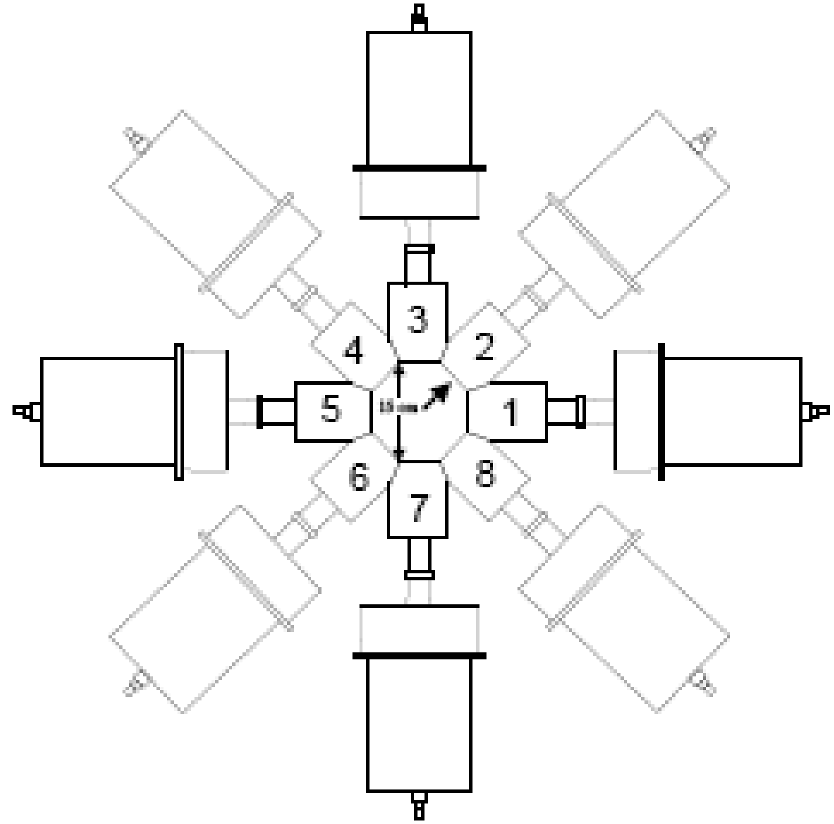
Techniques:

Produce rare ion radon beam

Collect in cell

Comagnetometer

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



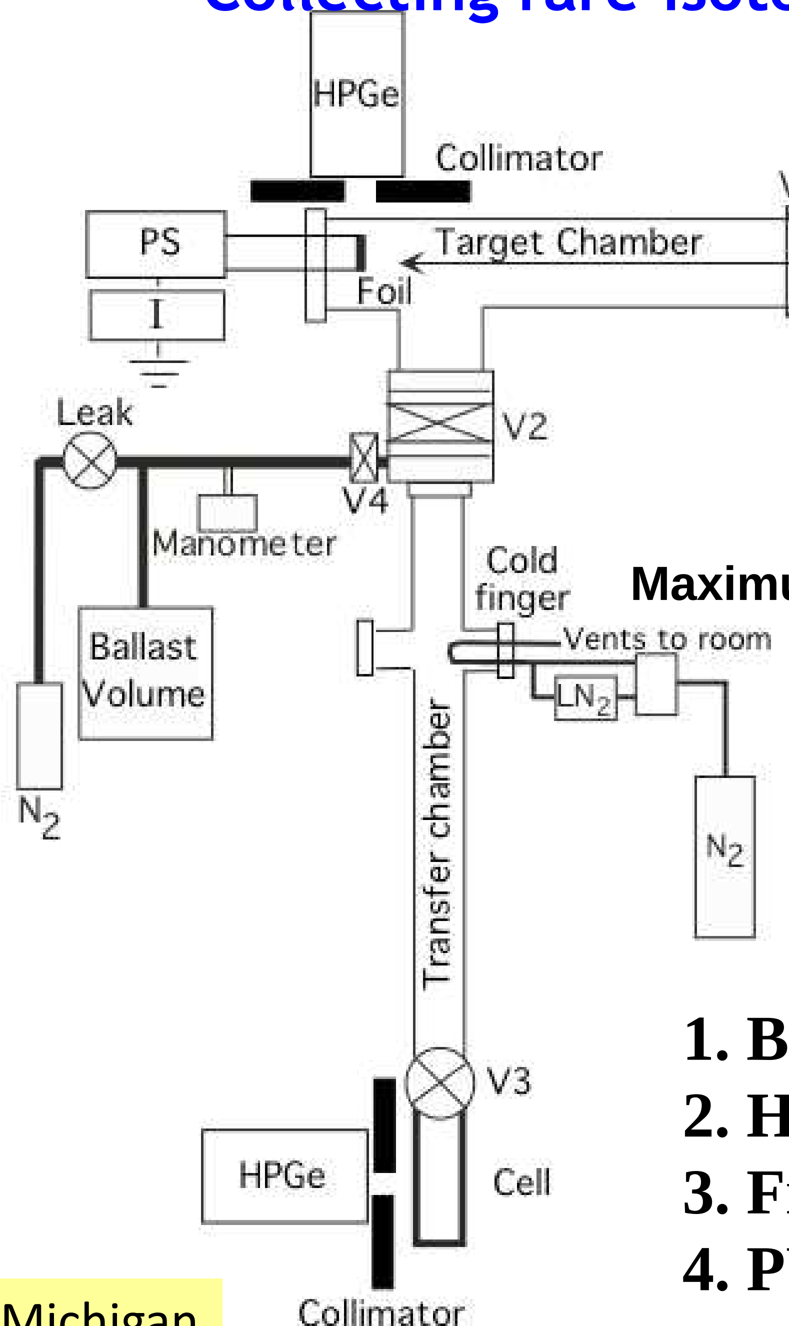
$^{221/223}$Rn EDM projected sensitivity

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

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)

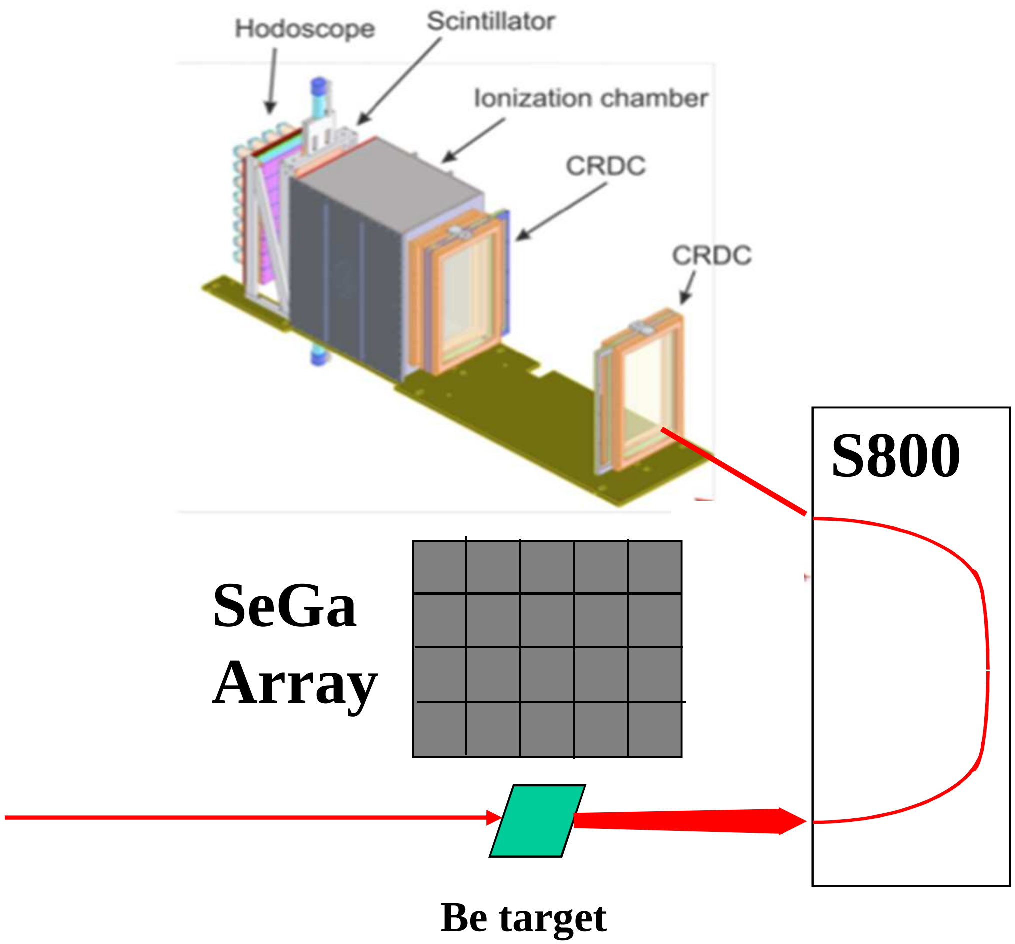
1. **Bombard foil**
2. **Heat foil: release to target chambe**
3. **Freeze to cold finger**
4. **PUSH to cell (buffer gas)**

T. Chupp, Michigan

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

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

State of Michigan



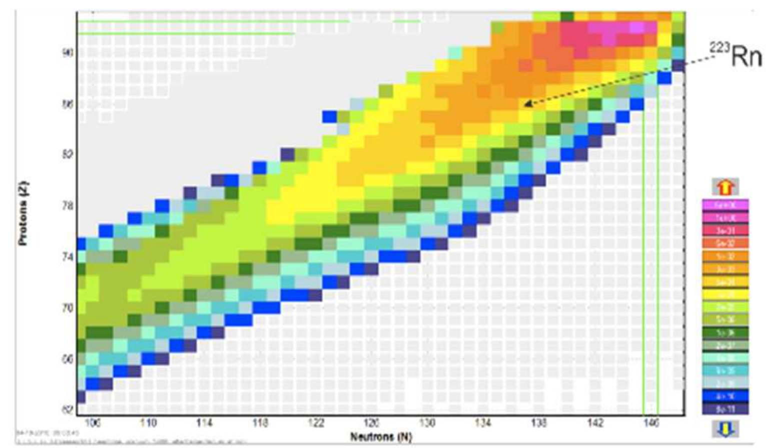
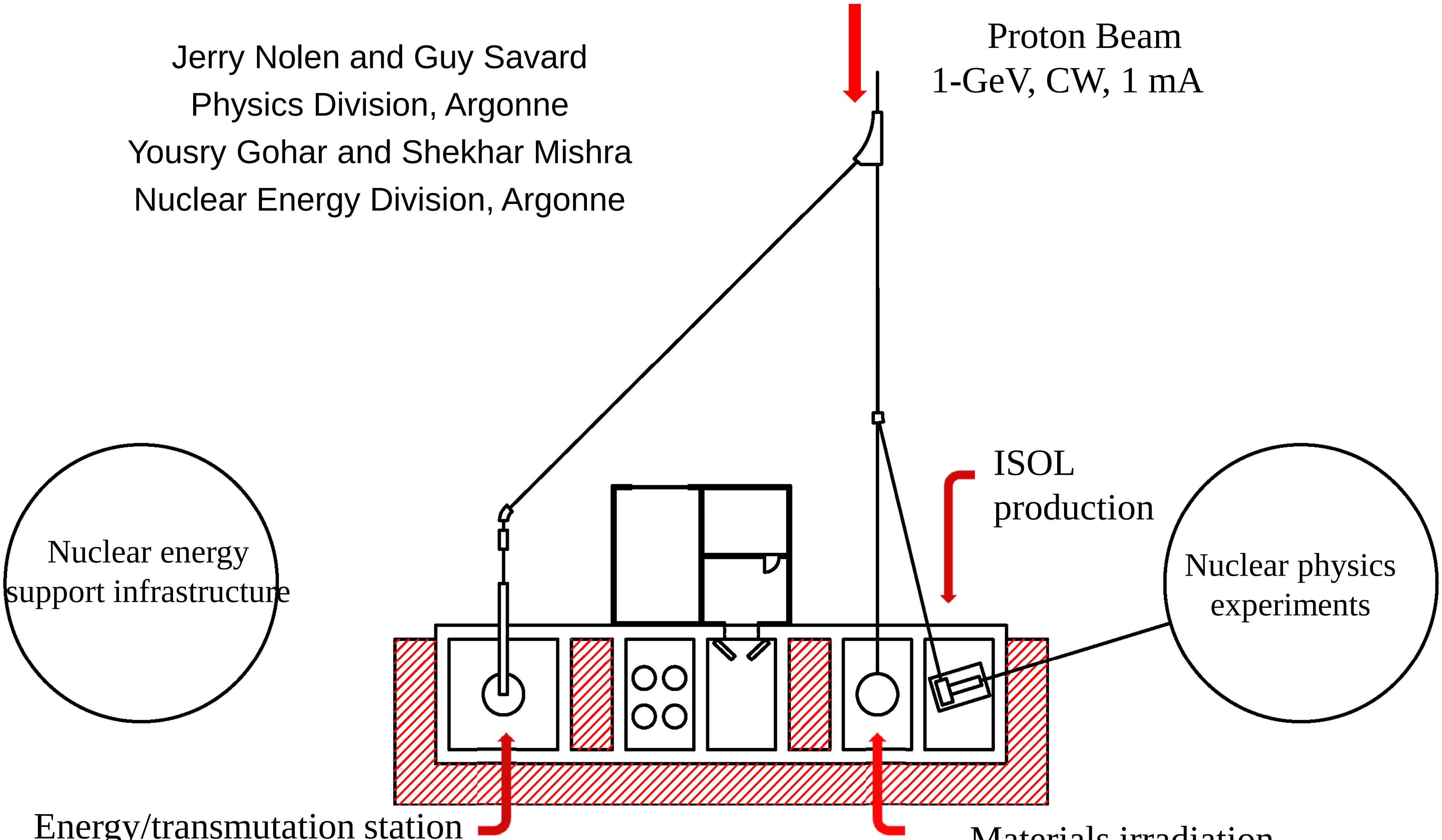


Figure 2. Transmission plot at the focal plane of the S800, calculated with LISE++ for ^{238}U fragmentation on the diamond active target, including fission products. The bottom figure is an expanded view of the top, in the region of the Rn isotopes.

T. Chupp, Michigan

Draft Layout of the Project X Joint Nuclear Facility

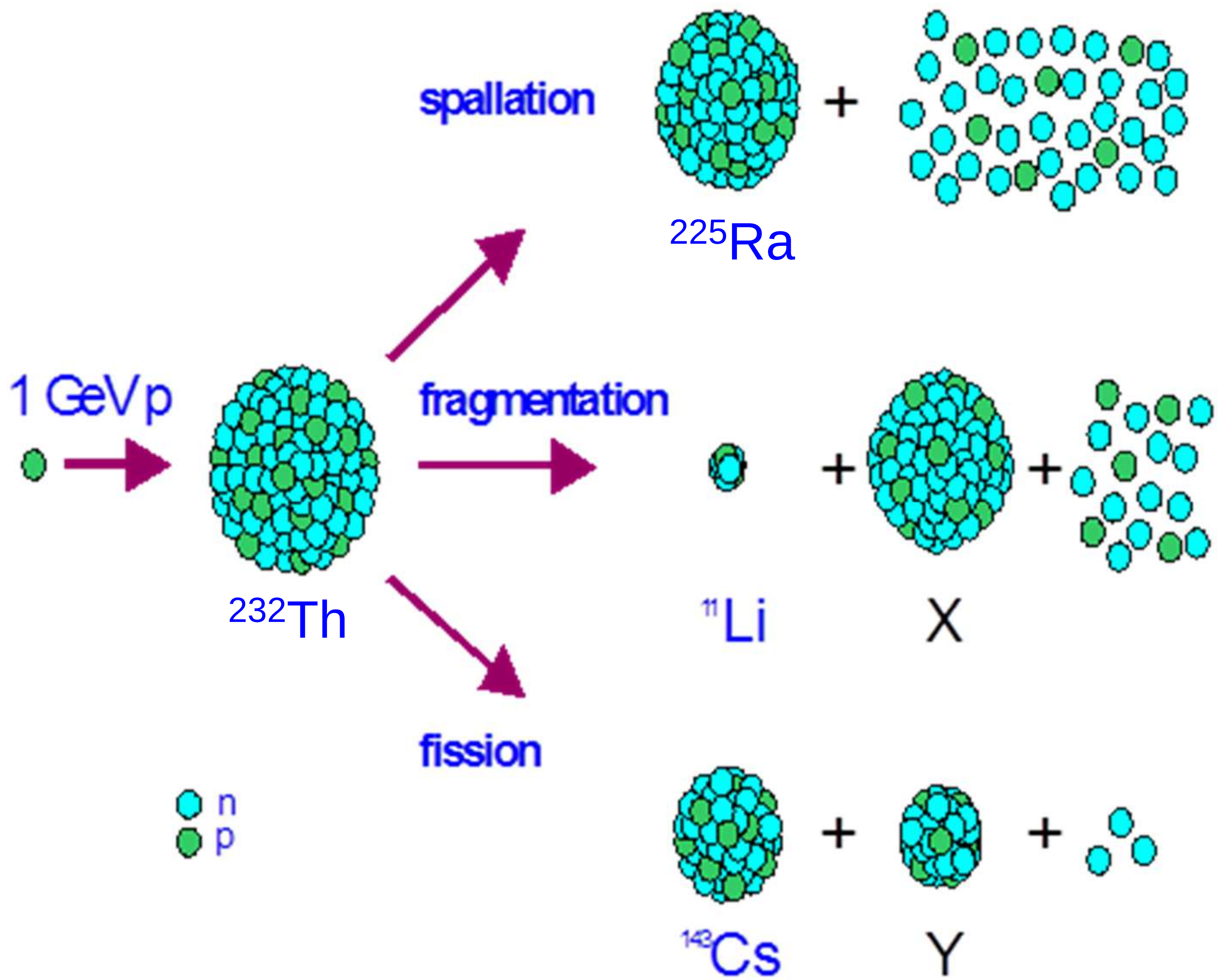
Jerry Nolen and Guy Savard
Physics Division, Argonne
Yousry Gohar and Shekhar Mishra
Nuclear Energy Division, Argonne



Project X Joint Nuclear Facility,
August, 2010

J. Nolen, Argonne

Reaction mechanisms

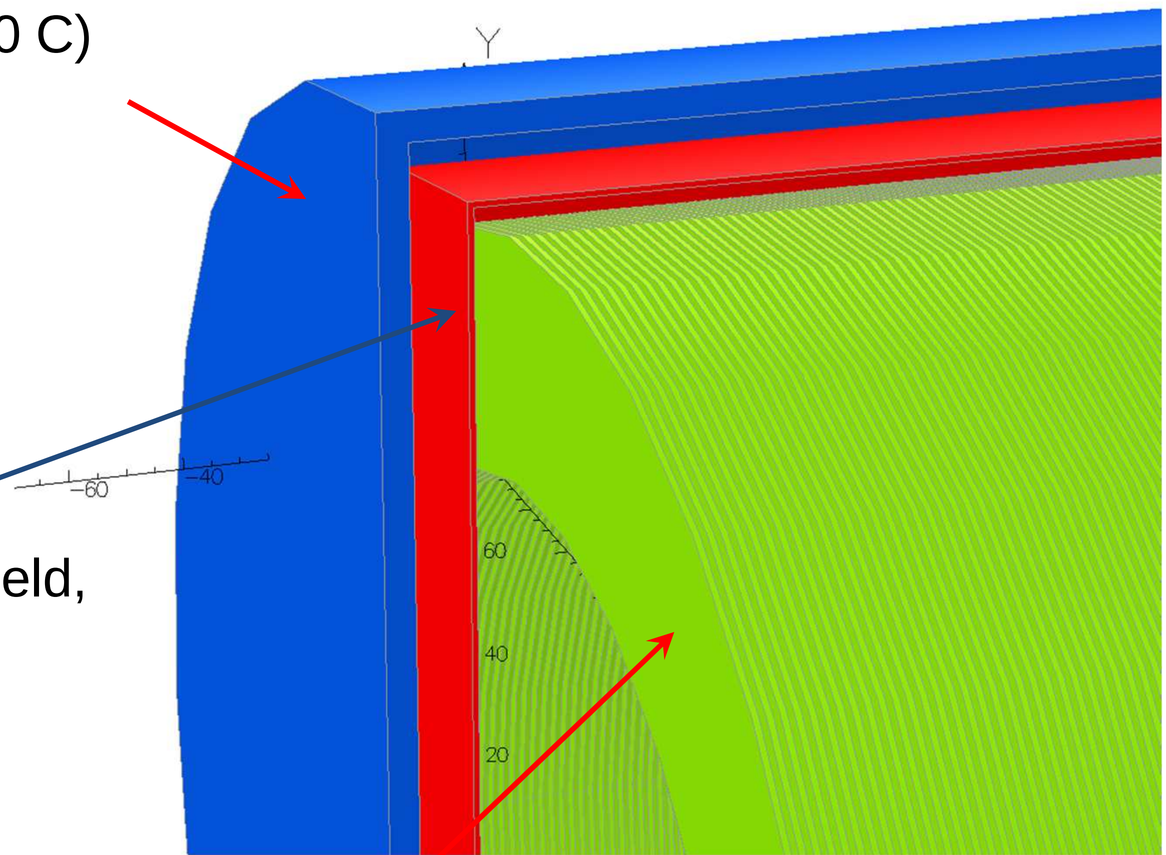


500-kW thorium target concept

J. Nolen, Argonne

500-kW thorium target concept - close-up

Carbon felt insulation w/ graphite liner (1800 C)
and water-cooled outside (30 C)



Tungsten container, heat shield,
2200 C

1-mm thick Th rings @ 1-mm spacing, 400 total, 2000 C

J. Nolen, Argonne

Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Nuclear Instruments and Methods in Physics Research B 204 (2003) 286–292
NIM B
Beam Interactions with Materials & Atoms
www.elsevier.com/locate/nimb

Optimization of ISOL targets based on Monte-Carlo simulations of ion release curves

B. Mustapha *, J.A. Nolen

Physics Division, Argonne National Laboratory, 9700 S. Cass Avenue, Argonne IL, 60439, USA

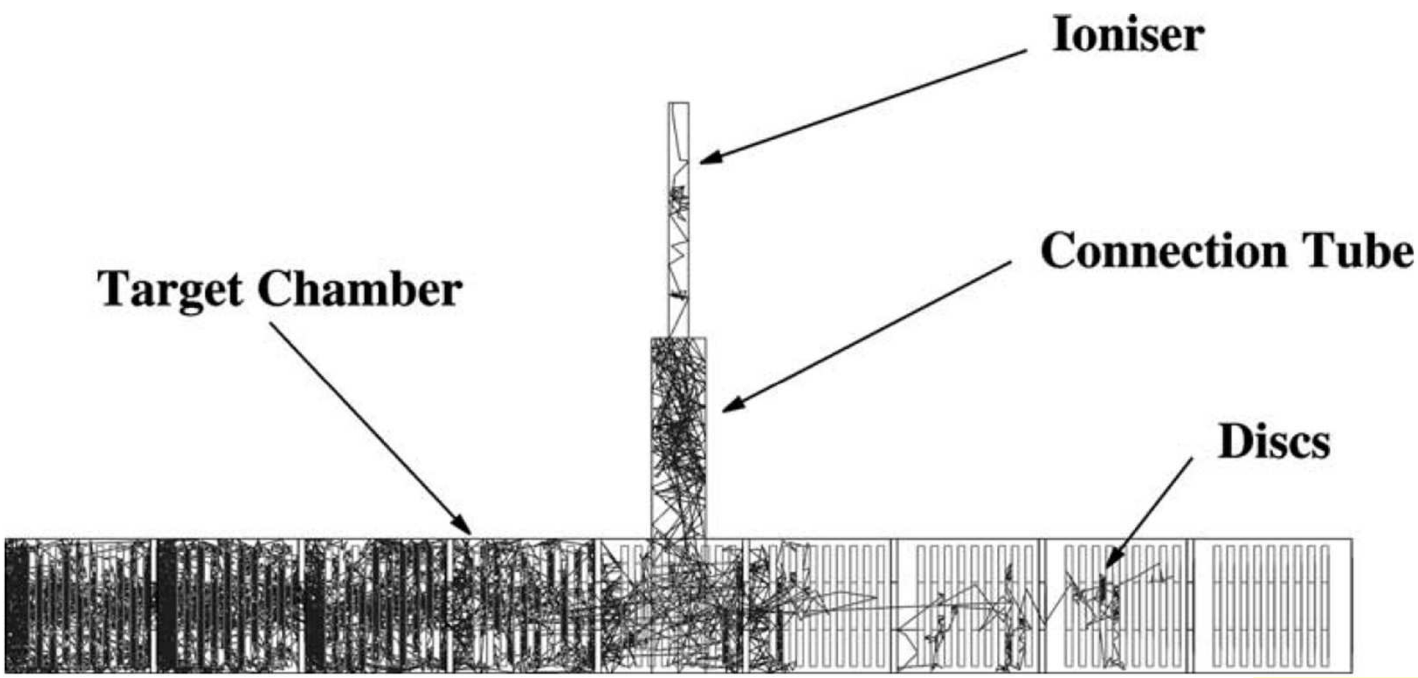
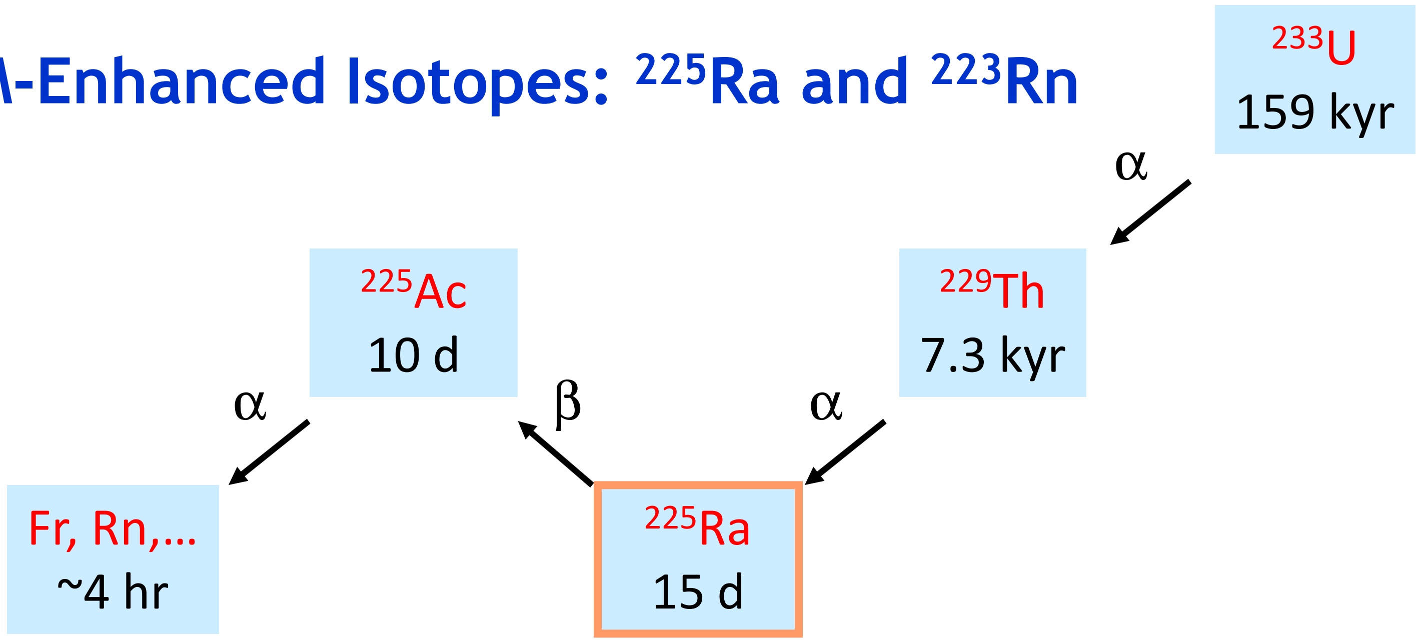


Fig. 1. Geometry of the RIST target showing the path of one particle from proc

J. Nolen, Argonne

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

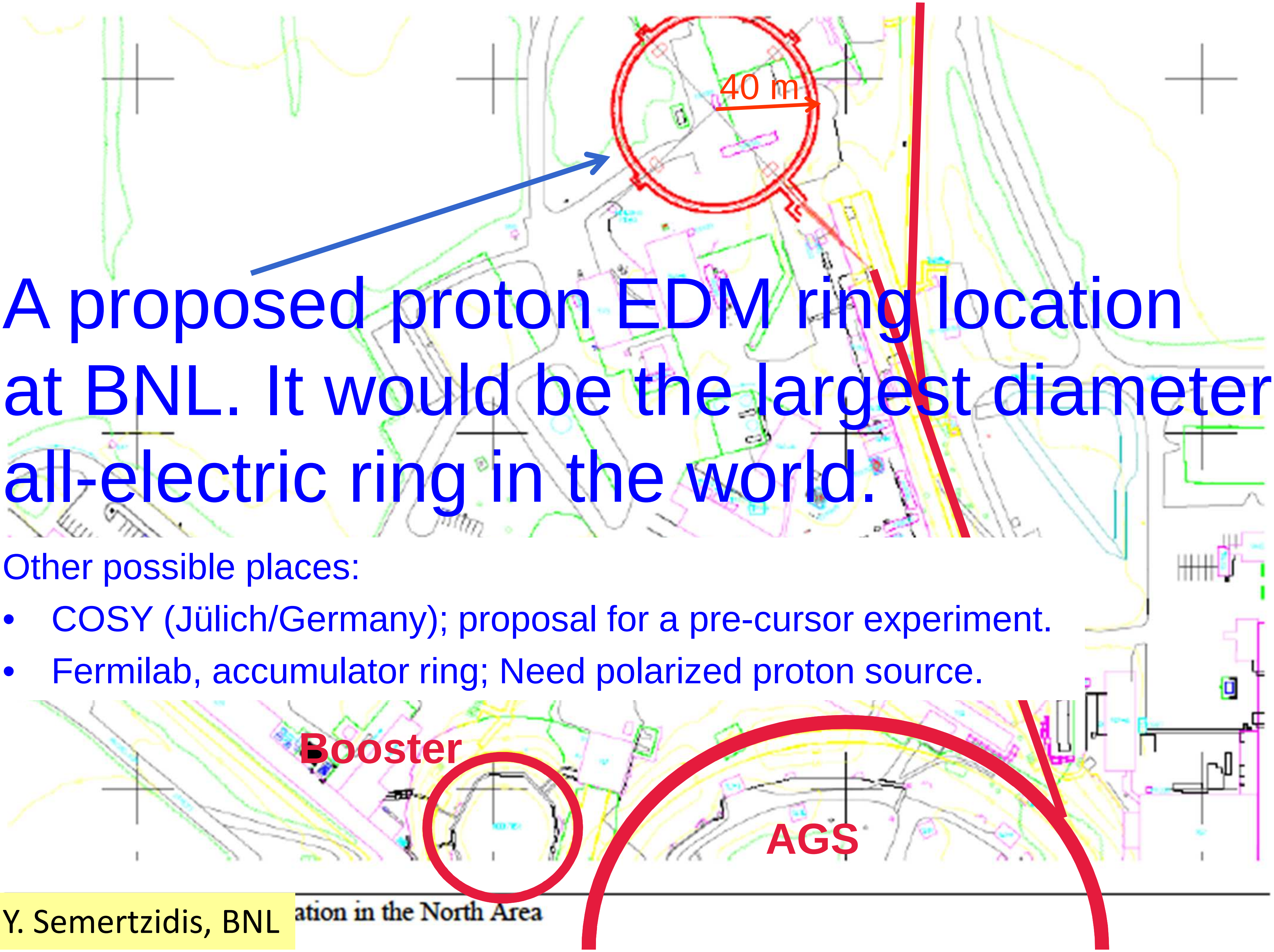
- FRIB (B. Sherrill, MSU)
  - Beam dump recovery with a ^{238}U beam ^{225}Ra: 6 x 10^9 /s
  - Dedicated running with a ^{232}Th beam ^{225}Ra: 5 x 10^{10} /s

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

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

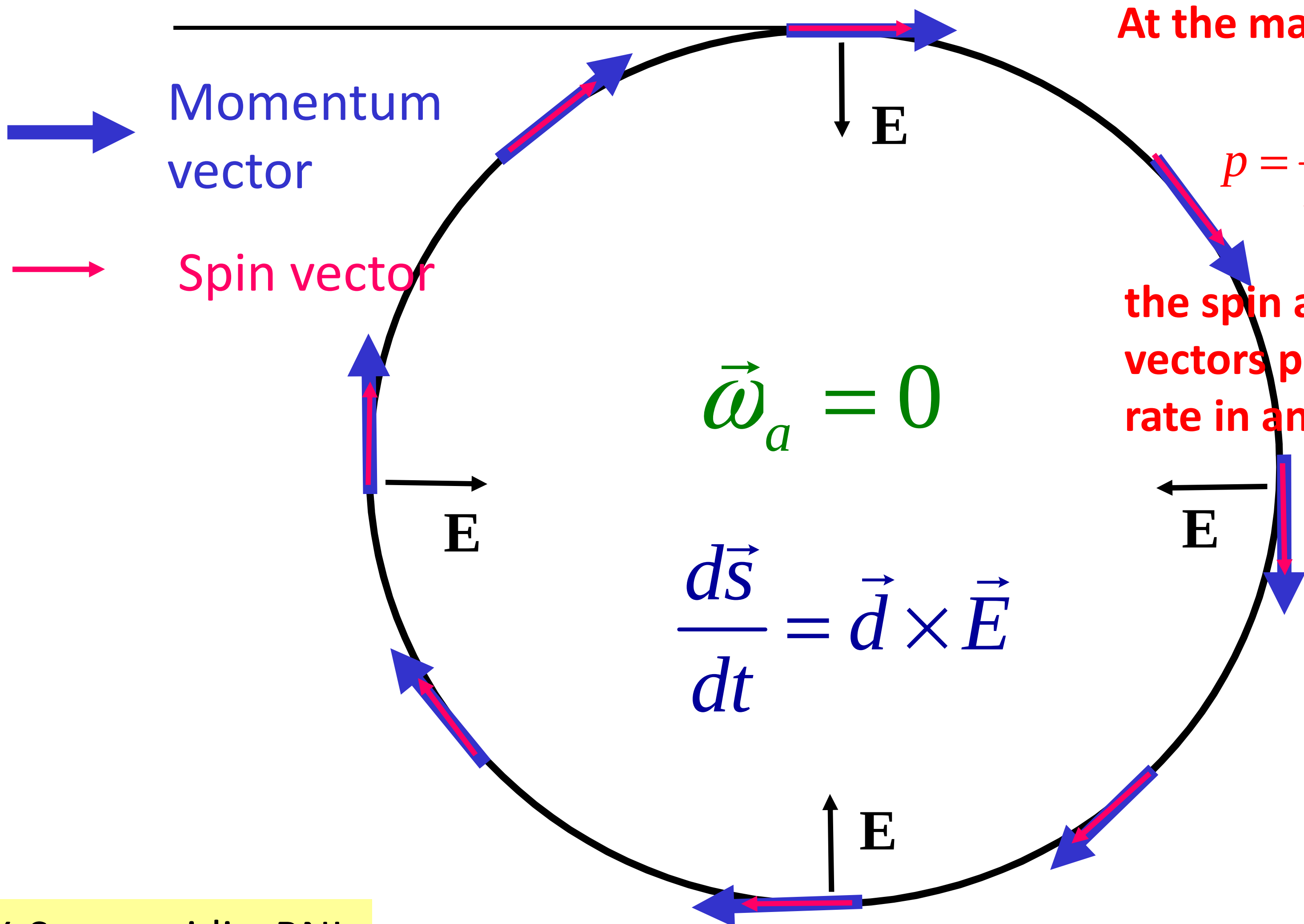
Other possible places:

- 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



$$\vec{\omega}_a = 0$$

$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

At the magic momentum

$$p = \frac{m}{\sqrt{a}} = 0.7 GeV/c$$

the spin and momentum vectors precess at same rate in an E-field

Y. Semertzidis, BNL

The miracles that make the pEDM

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

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

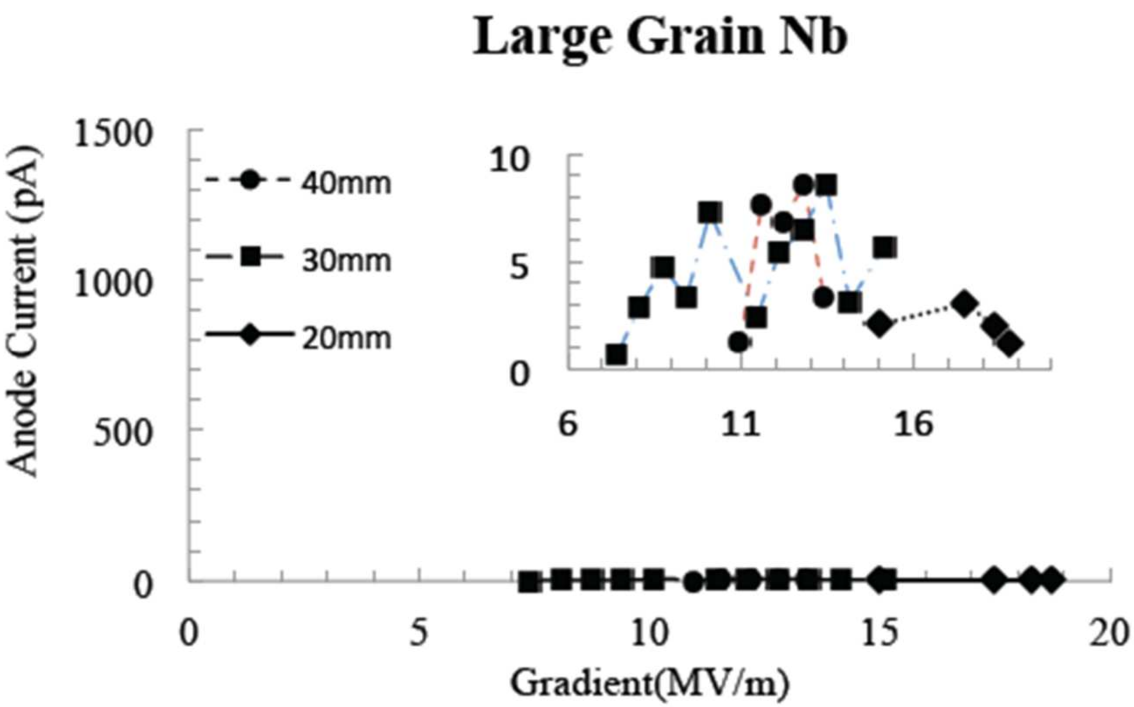
3. Weak vertical focusing in an all-electric ring: Spin Coherence Time allows for 10^3s beneficial storage; prospects for much longer SCT with mixing

4. Co-magnetometer: Counter-rotating beams. The vertical splitting of the counter-rotating beams is proportional to the average radial B-field

Y. Semertzidis, BNL

Reported progress in the all-electric Storage Ring EDM for the proton

- Recent E-field results from JLab are very encouraging: negligible dark current at the required E-field (10 MV/m, at 30 mm plate gap)
- Smaller ring may be possible (staging)



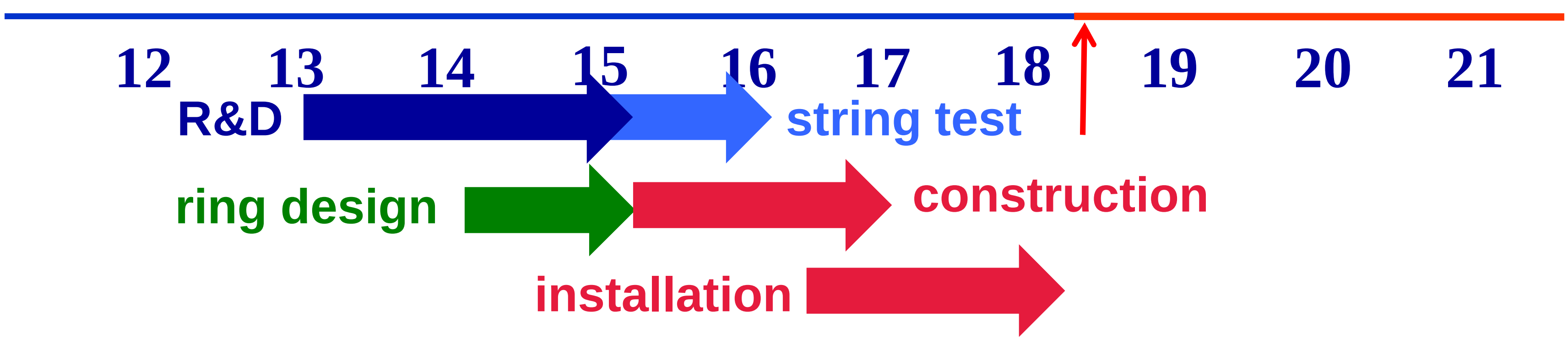
PRSTAB 15,083502, 2012

Y. Semertzidis, BNL

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



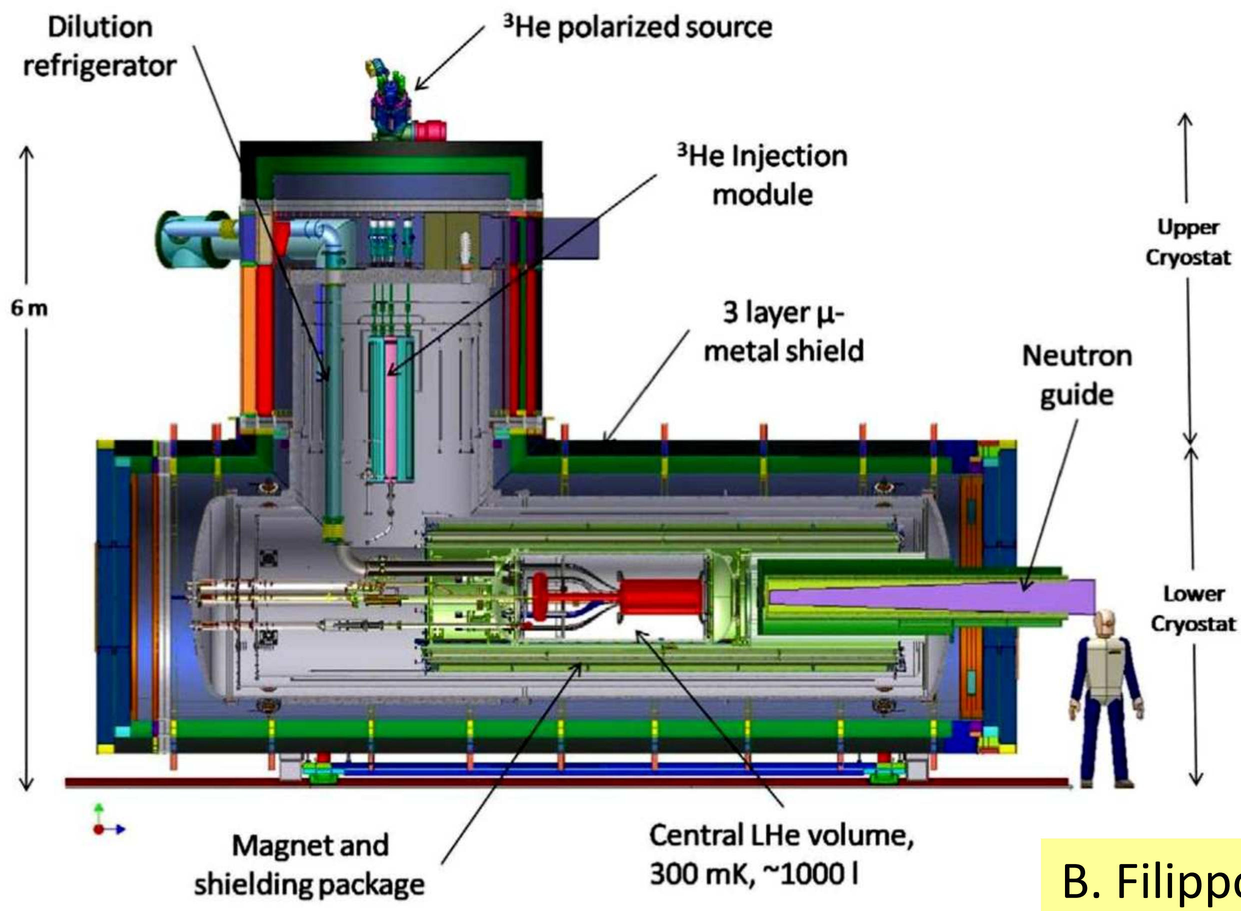
Limits and Sensitivities

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

Y. Semertzidis, BNL

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

Next Generation nEDM Experiments

Cryogenic UCN source, room temperature storage cells

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

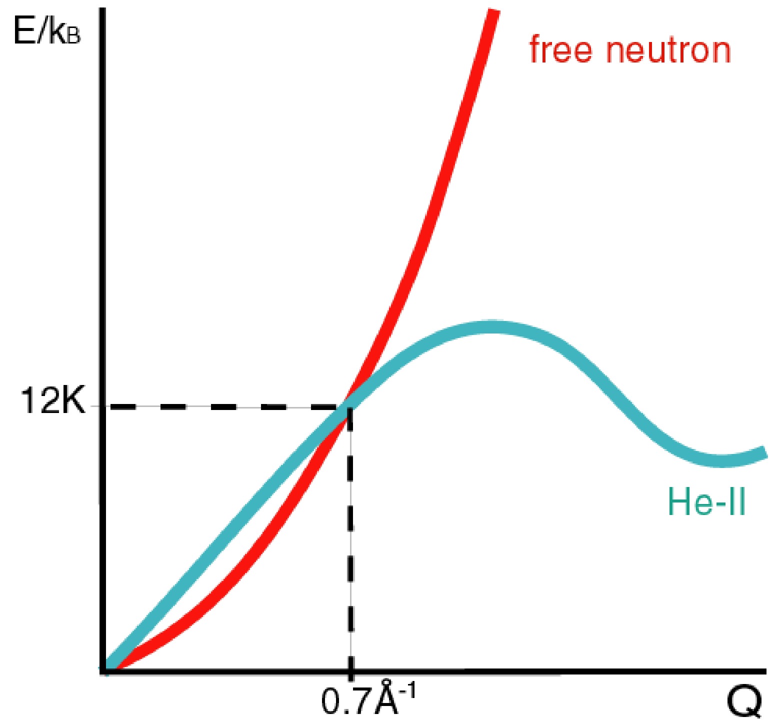
Super-fluid He source/storage cell

- 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)

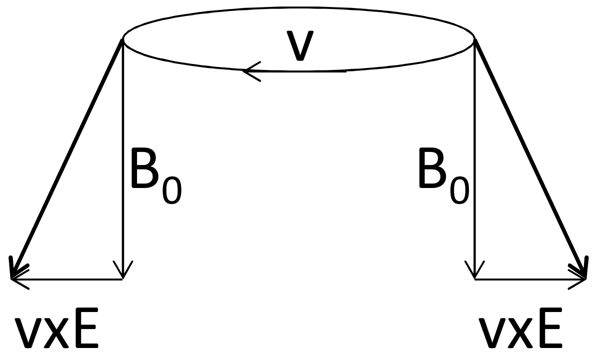
Key Features of SNS experiment

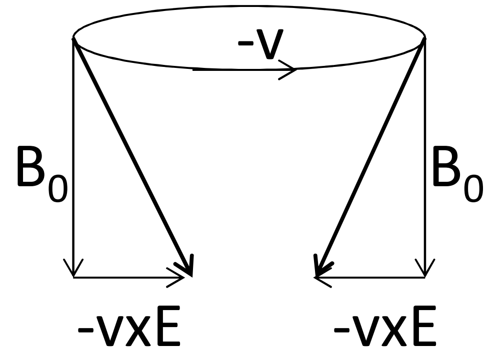
- Sensitivity: 10^{-28} e-cm, 100 times better than existing limit
- Production of UCN in superfluid helium
- Polarized ^{3}He co-magnetometer
  - Also functions as neutron spin precession monitor via spin-dependent n-^{3}He capture cross section
    - Detected via wavelength-shifted scintillation light 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

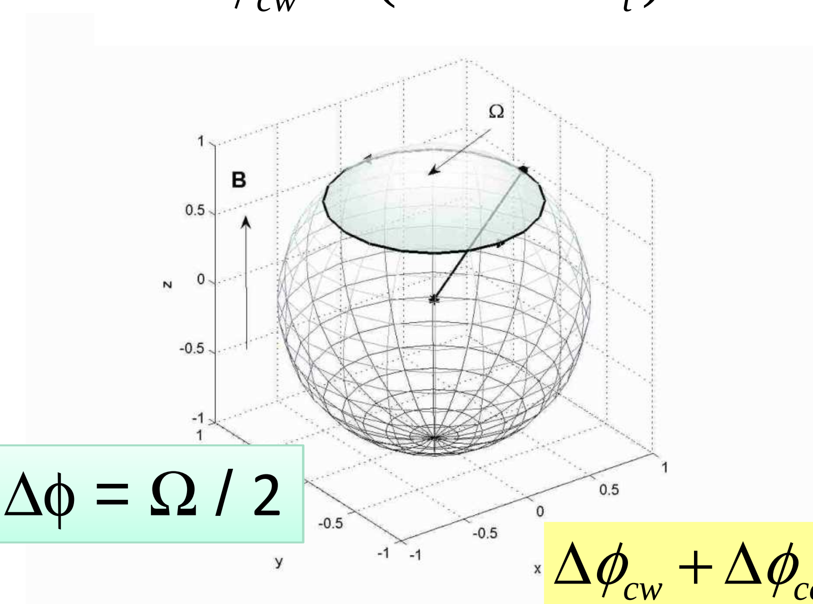
Pendlebury et al., PRA (2004)

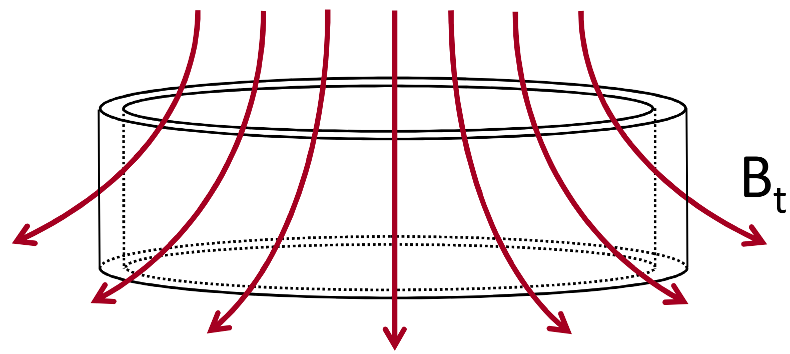




$$\Delta\phi_{cw} \propto (\mathrm{v}\times E + B_t)^2$$

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





$$\Delta\phi = \Omega / 2$$

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

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

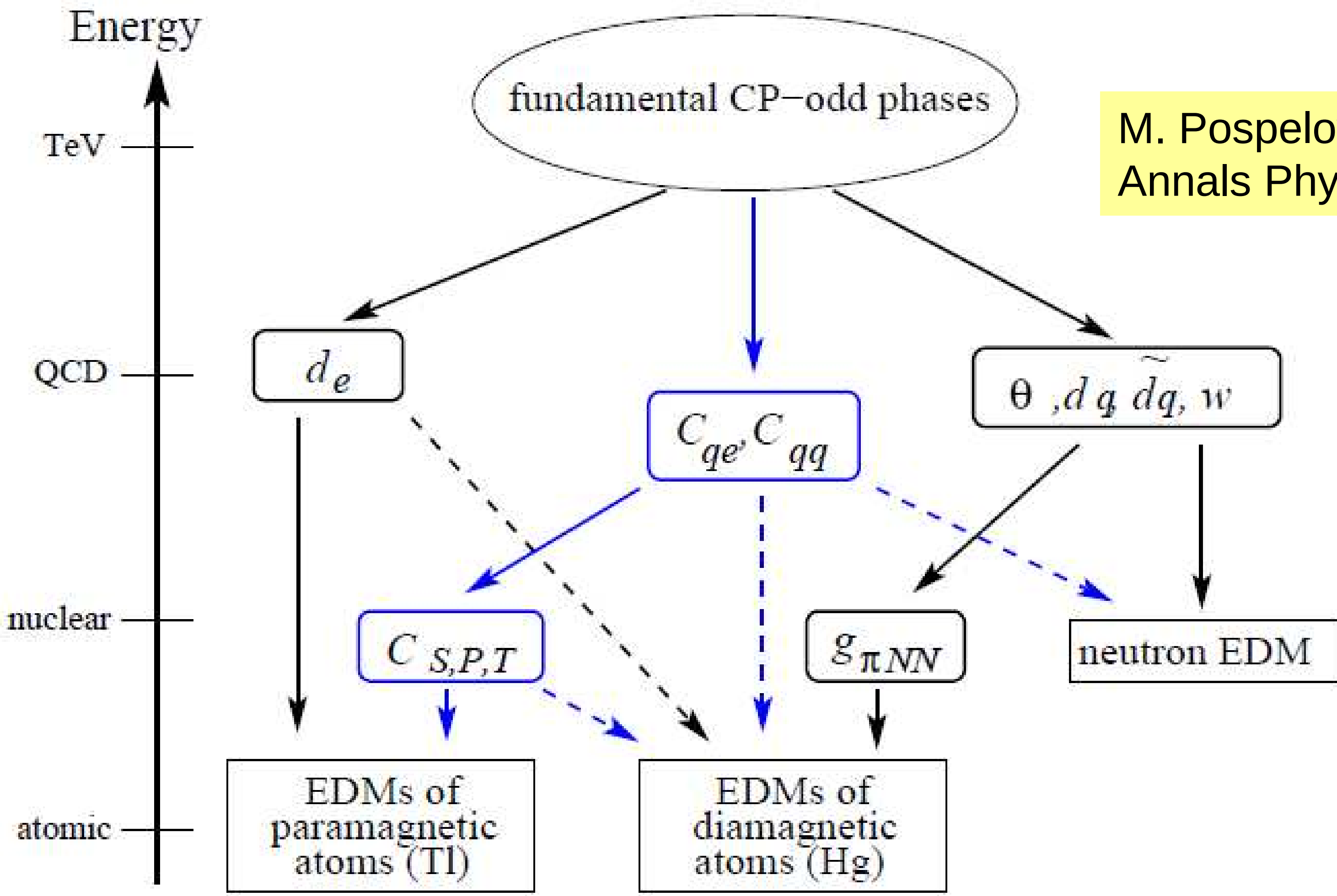
Summary of EDM Searches on Nucleons and Nuclei

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.

Origin of Elementary EDMs



M. Pospelov, A. Ritz, Annals Phys.(2005)

"Clearly, if EDM is found, we will need multiple systems to identify the origin of new CP violation." -- B. Filippone, Caltech