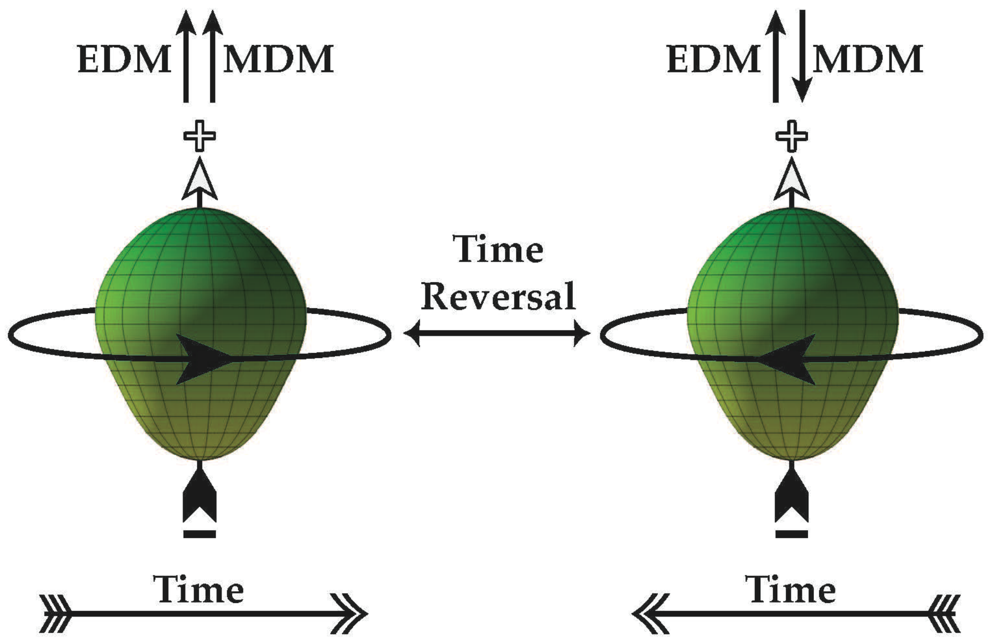
The Search for Permanent Electric Dipole Moments Using Pear-Shaped Nuclei in the FRIB Era



Jaideep Taggart Singh

Michigan State University / FRIB

1530-1600, August 31, 2022, Poinsettia / Quince

EW: Tests of Symmetries and the Electroweak Interaction

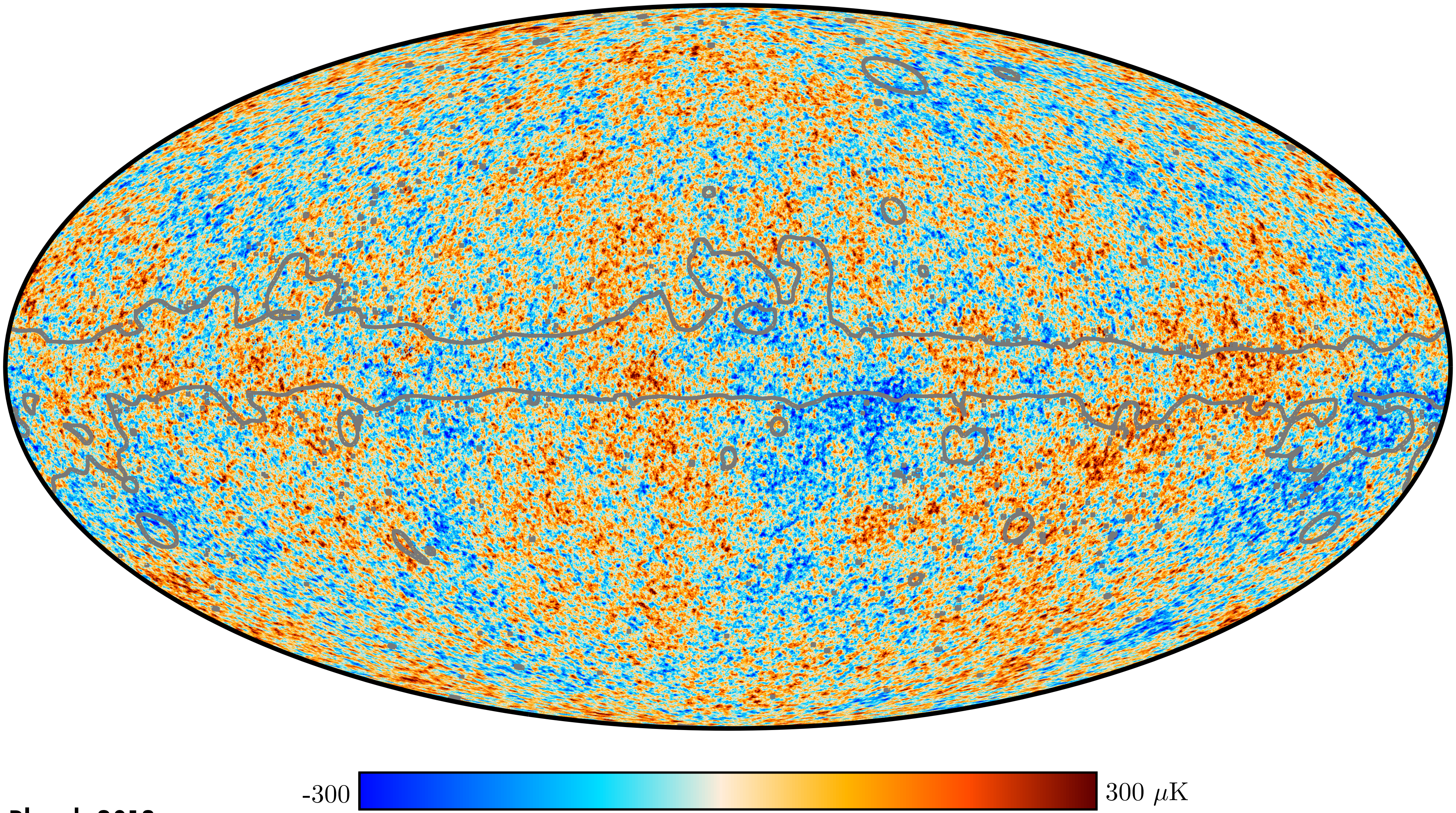
14th Conference on the Intersections of Particle and Nuclear Physics (CIPANP 2022)

FRIB

Marie-Anne Bouchiat

SCAN ME

Cosmic Microwave Background Anisotropy



Planck 2018

https://www.cosmos.esa.int/web/planck/picture-gallery

08/30: HUFFENBERGER – CMB

Sakharov's Conditions: Need *CP*-Violation

The Nobel Foundation

VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

The theory of the expanding Universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from anti-matter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the Universe is asymmetrical with respect to the number of particles and antiparticles (C asymmetry). In particular, the absence of antibaryons and the proposed absence of baryonic neutrinos implies a non-zero baryon charge (baryonic asymmetry). We wish to point out a possible explanation of C asymmetry in the hot model of the expanding Universe (see [1]) by making use of effects of CP invariance violation (see [2]). To explain baryon asymmetry, we propose in addition an approximate character for the baryon conservation law.

1. A baryon number violating interaction exists.
2. Departure from thermal equilibrium.
3. ***Both C- & CP-symmetry must be violated.***

Standard Model *CP*-Violation: Not Enough

$$\eta = \frac{\text{matter} - \text{antimatter}}{\text{relic photons}} \propto \sin(\delta)$$

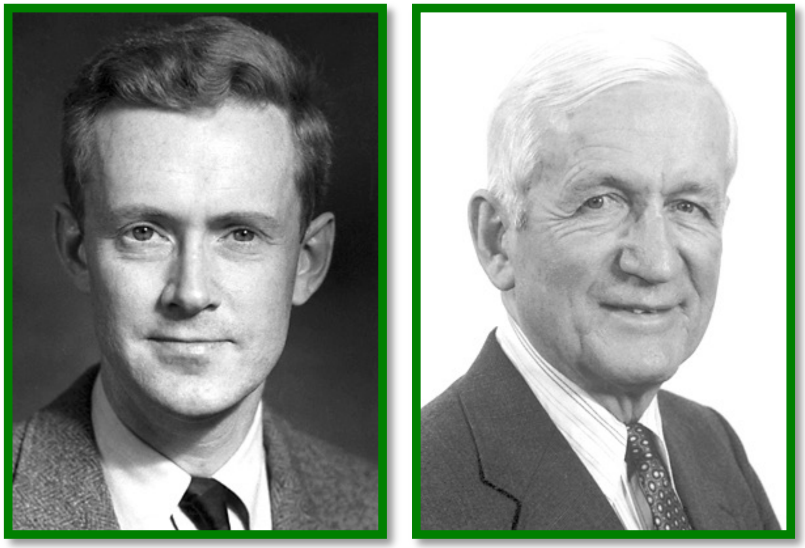
$$\eta_{\text{exp}} \approx 10^{-9}$$ PDG2022

$$\eta_{\text{CKM}} \approx 10^{-26}$$ Huet & Sather PRD 51:379 (1995)

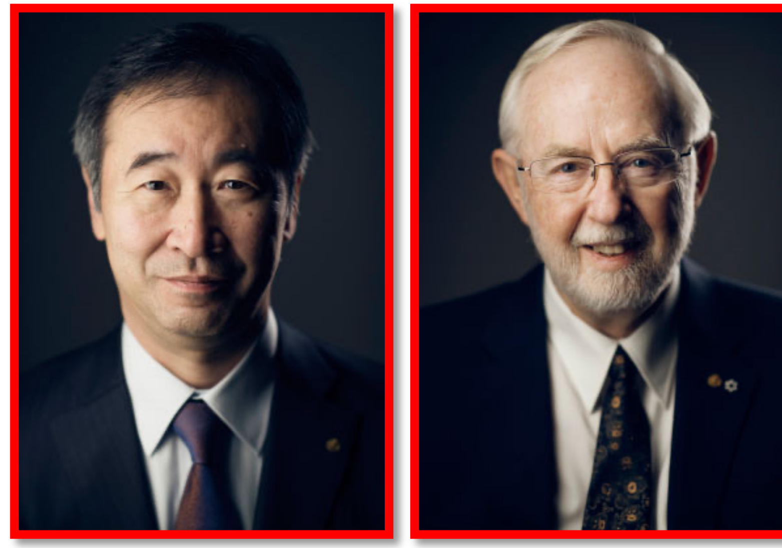
$$V = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}\exp(-i\delta) \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}\exp(+i\delta) & +c_{12}c_{23} - s_{12}s_{23}s_{13}\exp(+i\delta) & s_{23}c_{13} \\ +s_{12}s_{23} - c_{12}c_{23}s_{13}\exp(+i\delta) & -c_{12}s_{23} - s_{12}c_{23}s_{13}\exp(+i\delta) & c_{23}c_{13} \end{bmatrix}$$

$$\delta = CP\text{-violating “phase”}$$

Where do we look for more *CP*-violation?



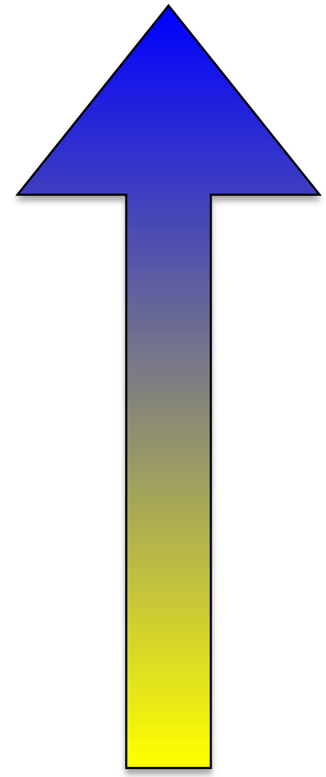
The Nobel Foundation



The Nobel Foundation

- Decays of *B*-mesons [Belle II] – **08/30: ZLEBCIK – CPV @ Belle II**
- Rare decays of b-hadrons [LHCb] – **08/30: VILLA – CPV @ LHCb**
- Angular correlations in the 3γ–decay of ortho-positronium [MSU/Wittenberg]
- D-coefficient in nuclear beta-decay [The MORA Project]
- Nuclear magnetic quadrupole moments [Caltech]
- Polarized neutron transmission through polarized nuclei – **08/31: SCHAPER - NOPTREX**
- Neutrinos have mass! (PMNS matrix) [T2K! + 0ν2β] – **All the NU Sessions**
- ***electric dipole moments: If CPT is good*, then *T*-violation can be used to search for new sources of *CP*-violation!**

EDM: Measures the Separation of Charges

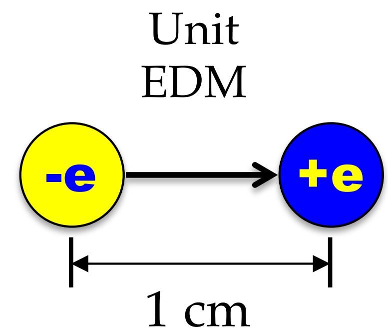


$\vec{d}$

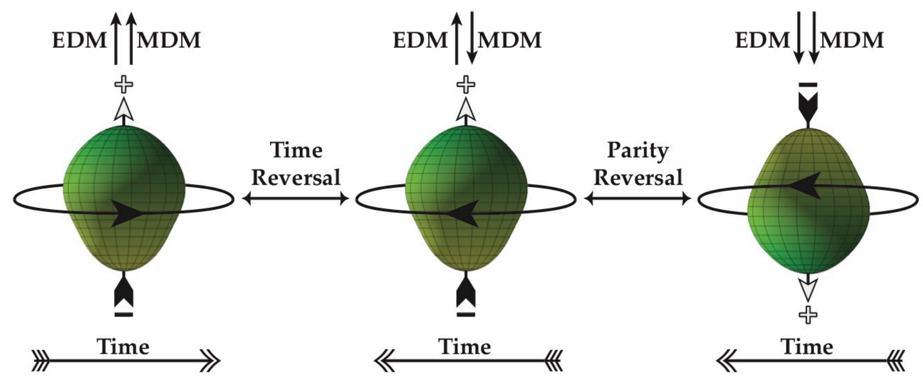
“Thunder Cloud as Generator #2” (1971) by Paterson Ewen [Art Gallery of Ontario]

EDMs to E-fields as MDMs to B-fields

$$\mathcal{H} = -\mu\left(\frac{\vec{S}\cdot\vec{B}}{S}\right) - d\left(\frac{\vec{S}\cdot\vec{E}}{S}\right)$$



	P-parity	T-time reversal
$\vec{S}$	$+$	$-$
$\vec{B}$	$+$	$-$
$\vec{E}$	$-$	$+$
$\vec{S}\cdot\vec{B}$	$+$	$+$
$\vec{S}\cdot\vec{E}$	$-$	$-$

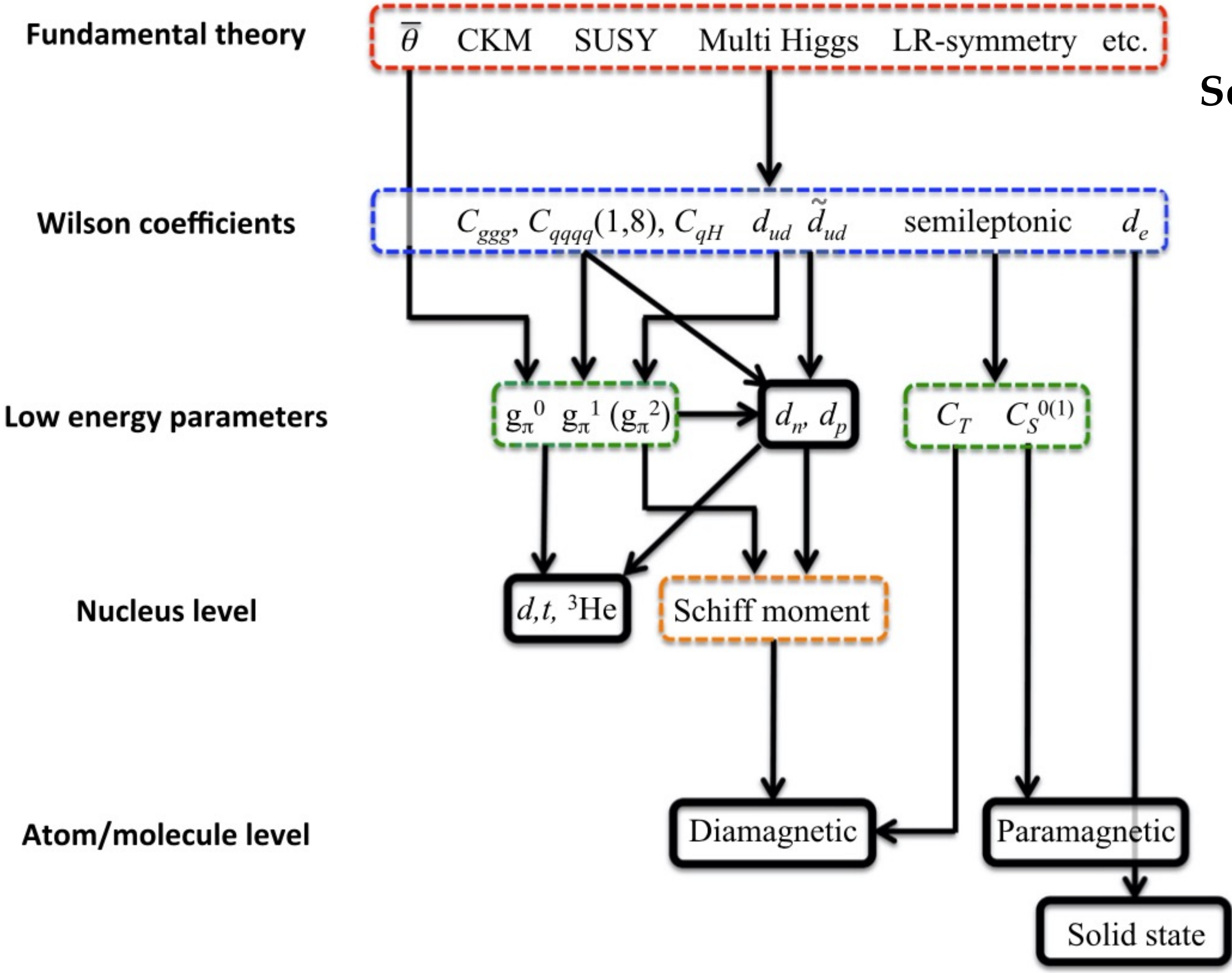


Theorist: …trivial application of the Wigner-Eckart Theorem…

Experimentalist: ...blah blah blah Wigner-someone something…

Connecting BSM Sources of $\not{CP}$ to EDMs

T.E. Chupp, P. Fierlinger, M. Ramsey-Musolf, JTS, RMP 91:015001



Theorists:
Sources of *CP*-violation

Lattice QCD is absolutely essential here! **08/31: SHINDLER**

Experiments:
What we measure

Different Sources of ~~CP~~ ⇔ EDM of Different Systems

Physics Beyond the Standard Model

RMP 91 015001 (2019)

nuclear spin-*independent* electron-nucleus coupling

lepton EDM

ThO: 1.1×10^{-29} *e* cm (95%, 2018)

HfF^+ (JILA/Boulder)

YbF (Imperial College)

BaF (VSI/VUA ; York/Toronto/MSU)

Cs (Penn St.)

Fr (CYRIC ; TRIUMF)

Muon Storage Ring

Different Sources of $\not{CP}$ ↔ EDM of Different Systems

θ_{QCD}

Physics Beyond the Standard Model

RMP 91 015001 (2019)

"effective" short range nucleon EDM

isoscalar nucleon-nucleon coupling

isovector nucleon-nucleon coupling

nuclear spin-*independent* electron-nucleus coupling

lepton EDM

Light Ion Storage Rings

neutron: 2.2x10^{-26} *e* cm (95%, 2020)

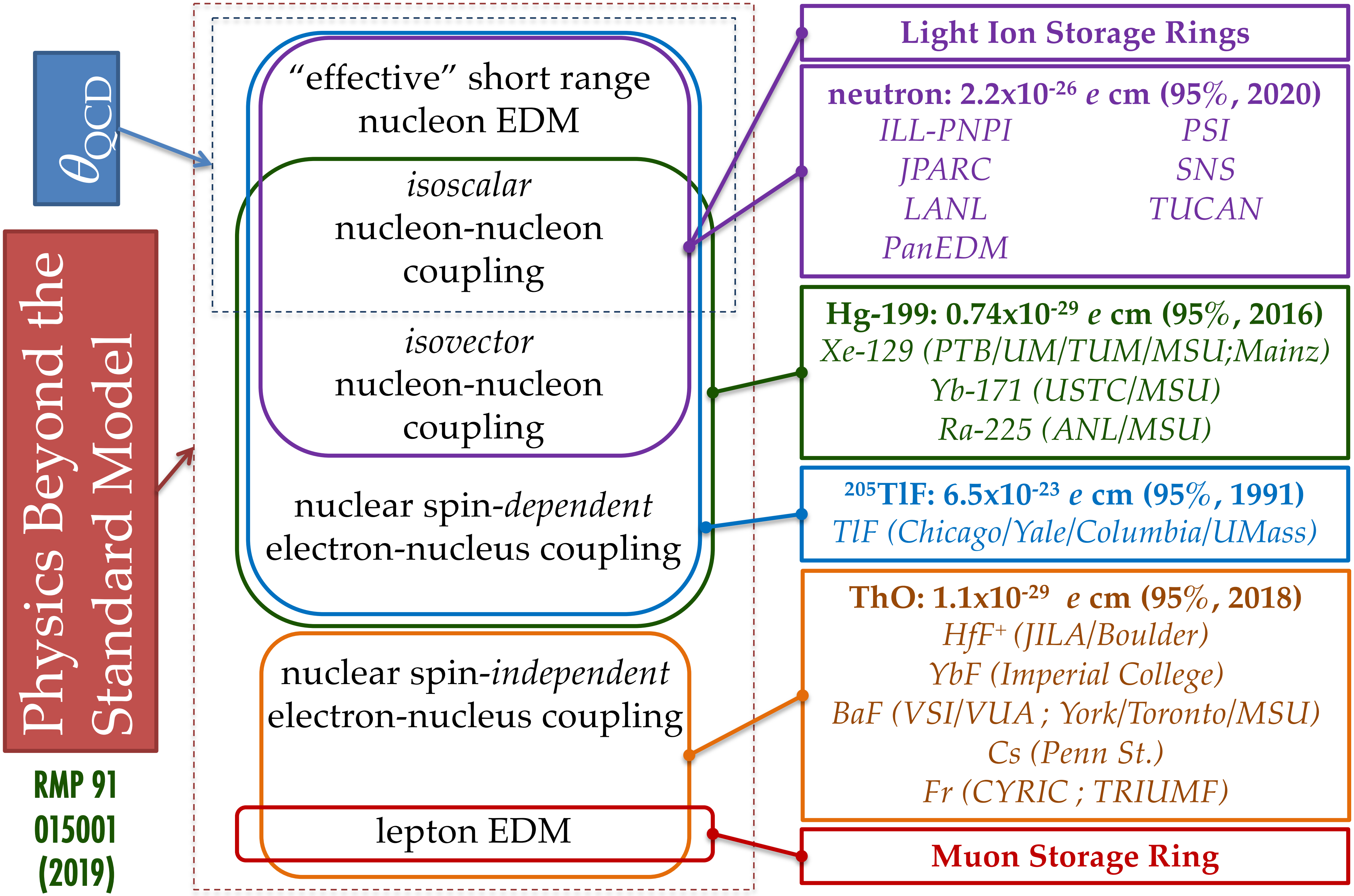
ILL-PNPI *PSI*
JPARC *SNS*
LANL *TUCAN*
PanEDM

ThO: 1.1x10^{-29} *e* cm (95%, 2018)

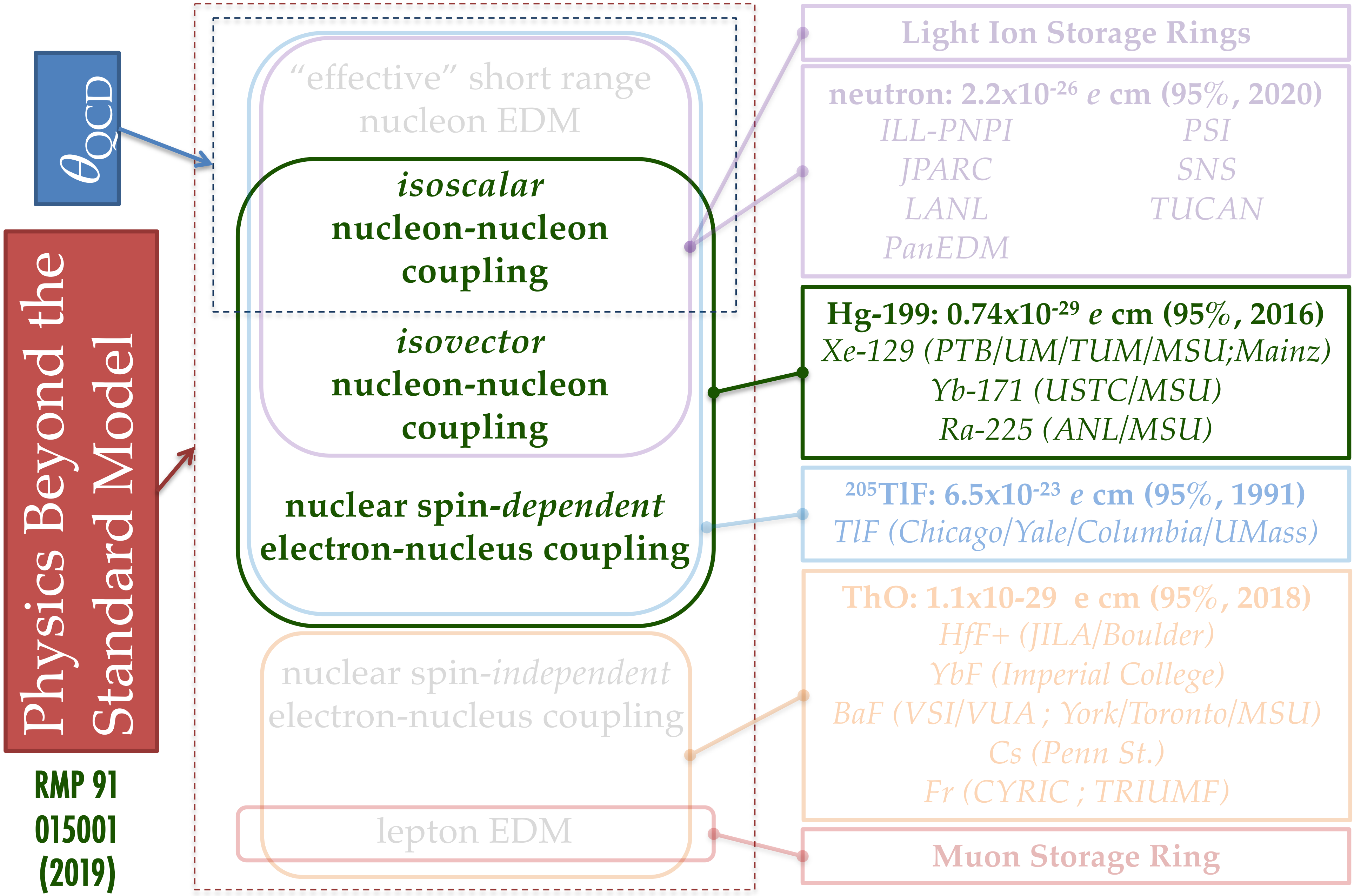
HfF$^+$ (JILA/Boulder)
YbF (Imperial College)
BaF (VSI/VUA ; York/Toronto/MSU)
Cs (Penn St.)
Fr (CYRIC ; TRIUMF)

Muon Storage Ring

Different Sources of $\not{CP}$ ↔ EDM of Different Systems



Different Sources of $\not{C}\not{P}$ ↔ EDM of Different Systems



RMP 91 015001 (2019)

2022 EDM Limits: Free of SM "Backgrounds"

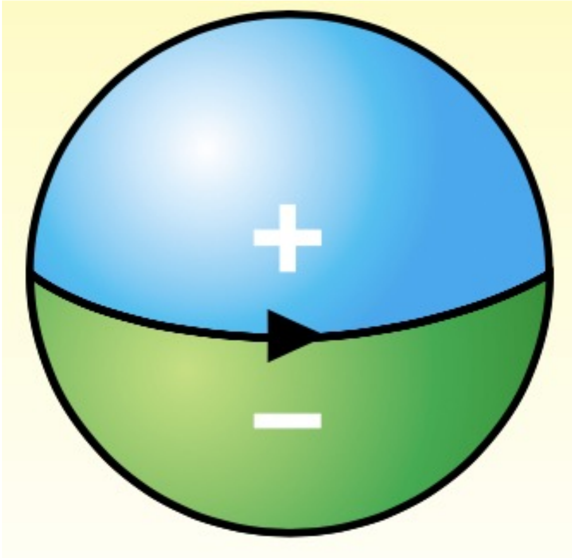
Chupp, Fierlinger, Ramsey-Musolf, JTS RMP 91:015001 (2019) & Nature 562:355 (2018) & PRL 124:081803 (2020)

System	Best Limit (95%) 1E-28 *e* cm	SM estimate 1E-28 *e* cm	Method (Location)
Neutron	220	$\sim 10^{-4}$	ultracold neutrons in a bottle (PSI)
"Electron"	0.11	$\sim 10^{-10}$	cold ThO beam (Harvard/Yale)
Hg-199	0.074	$\sim 10^{-6}$	atoms in vapor cell (UW-Seattle)

Imagine a neutron that is composed of two oppositely charged hemispherical shells:

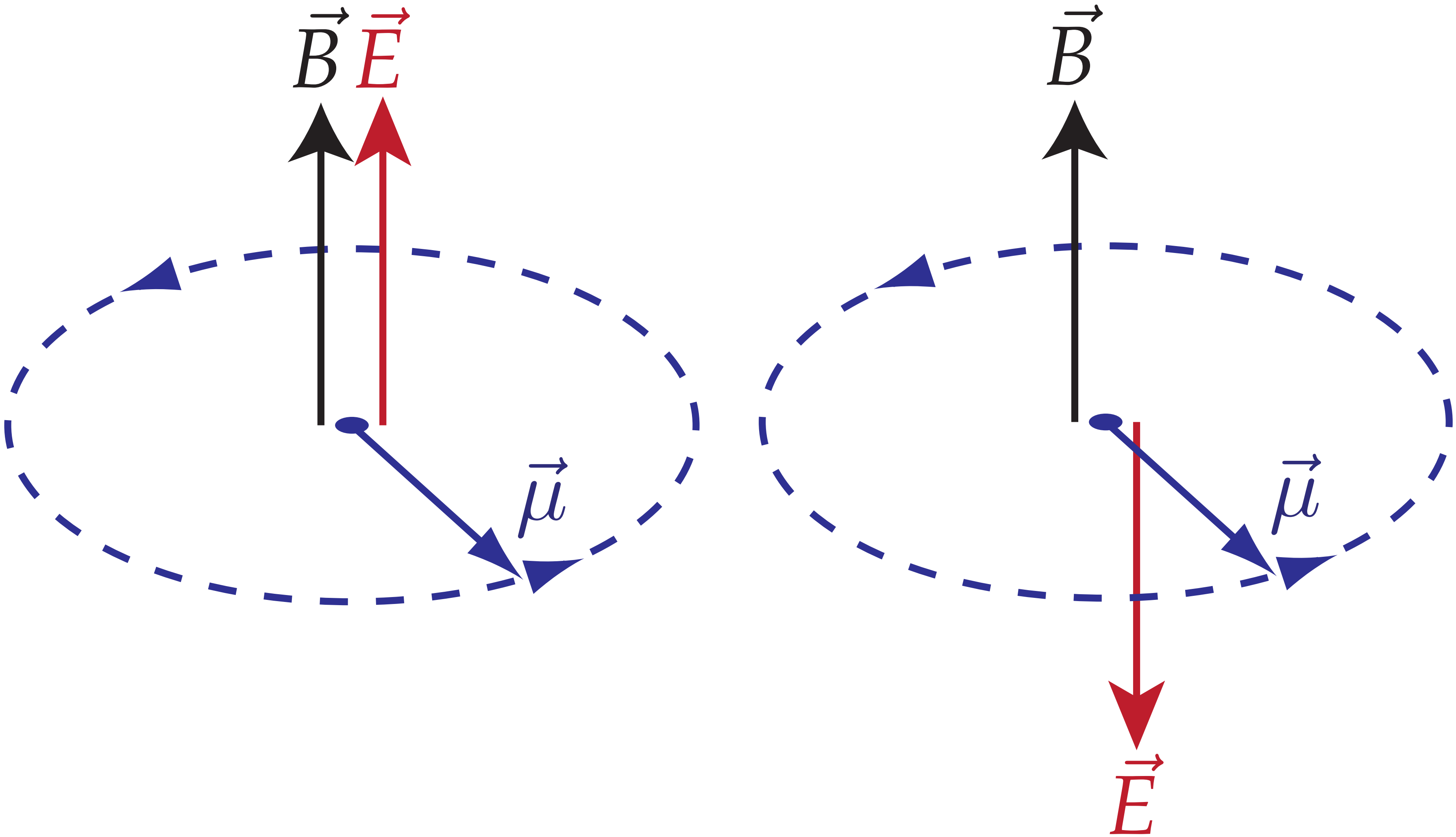
If the neutron was the size of the Earth, then the maximum thickness of these shells would be less than the diameter of a strand of human hair.

08/31: BISON – Neutron EDM
08/31: EW Neutron EDM (1300-1500), PIEGSA (Next Talk!)



Physics Today, June 2003

Always Measure Frequency
Example: Spin Precession of a Spin-1/2 Particle



$$h\nu_\uparrow = 2(\mu B_\uparrow + dE) \qquad h\nu_\downarrow = 2(\mu B_\downarrow - dE)$$

Statistical Sensitivity

$$\Delta\nu = \nu_{\uparrow} - \nu_{\downarrow} = \frac{4dE}{h} \qquad \sigma_{\nu} = \frac{\Gamma_{\text{linewidth}}}{\text{SNR}}$$

Quantum Projection Noise:

$$\frac{\sigma_d}{\sqrt{N_m}} = \frac{\hbar}{4E\sqrt{N_d T \tau}}$$

Electric field (E)

number of detected particles (N_d)

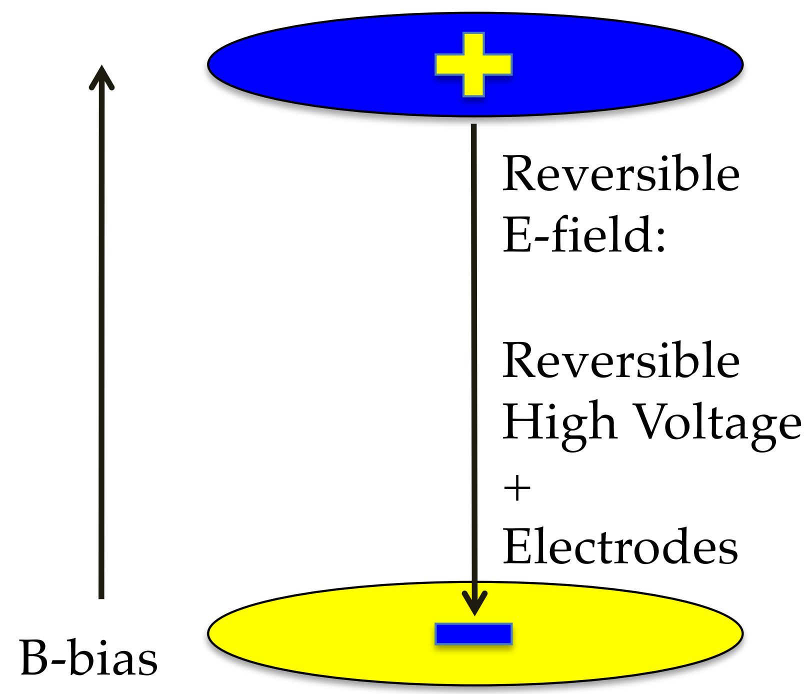
integration time (T)

interrogation time (τ)

Magnetic Field Instabilities: Annoying

$$\Delta\nu = \nu_{\uparrow} - \nu_{\downarrow} = \frac{4dE}{h} + \boxed{\frac{2\mu(B_{\uparrow} - B_{\downarrow})}{h}}$$

Instabilities adds noise & limits the statistical precision.



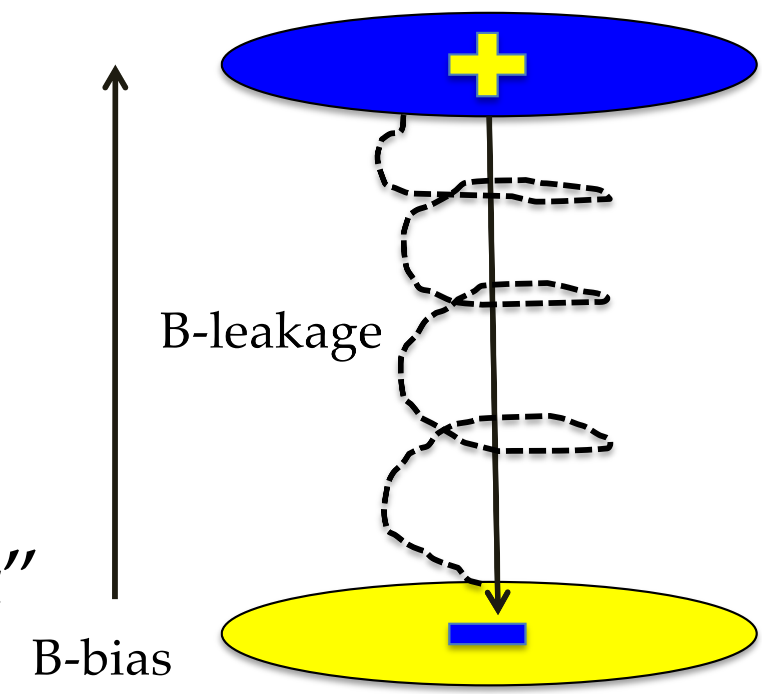
Electric Field-Correlated Systematic: Killer

$$\Delta\nu = \nu_{\uparrow} - \nu_{\downarrow} = \frac{4dE}{h} + \boxed{\frac{2\mu(B_{\uparrow} - B_{\downarrow})}{h}}$$

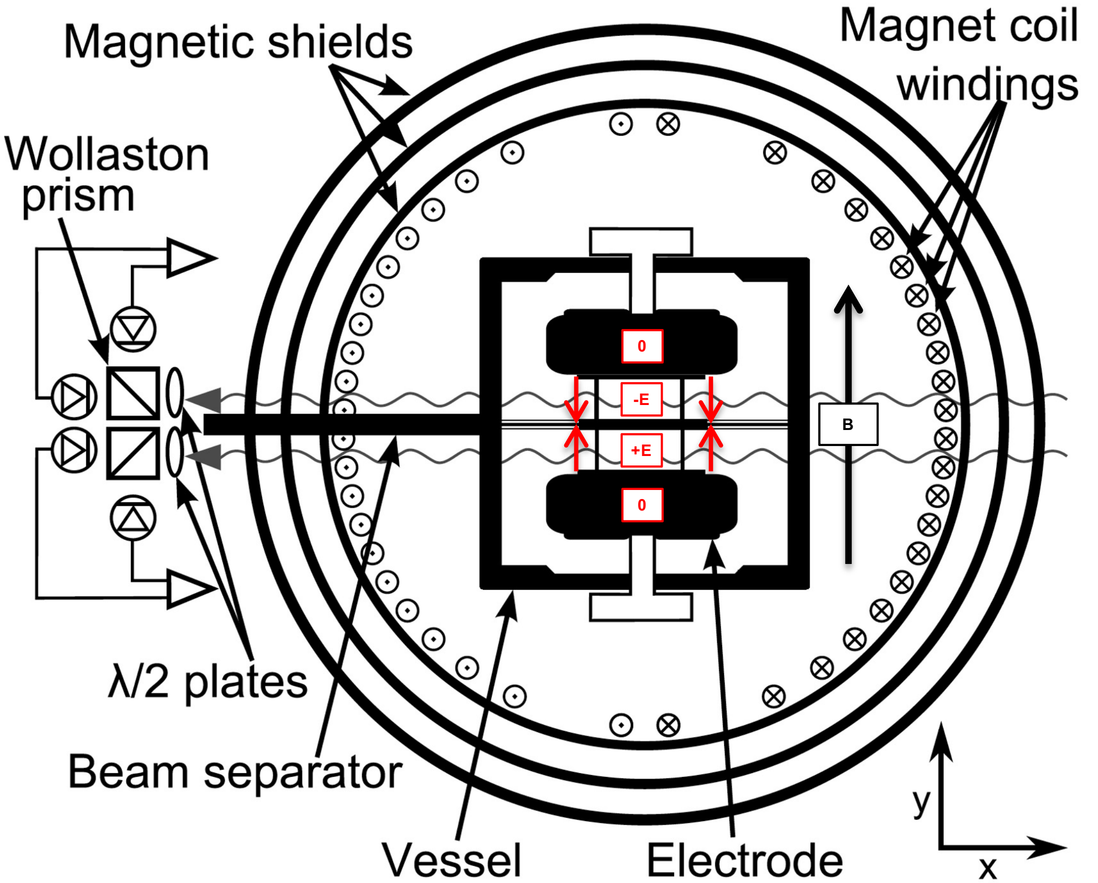
challenge!

Instabilities adds noise & limits the statistical precision.

"False" effects, things which change sign with the electric field, are nasty: "leakage current"



The Gold Standard: Hg-199 EDM Search



- **diamagnetic**, $^1S_0$ ground state
- $I = 1/2$, no elect. quad. moment
- **high Z**, (80) rel. atomic struct.
- **stable**, (17% n.a.) 92% enriched
- **high vapor pressure**, ($10^{13}/cm^3$)
- **modest electric field**, 10 kV/cm
- **30+ year old experiment!**

Limiting systematic appears to be ~10 nm scale motion of vapor cells when HV is switched in the presence of 2nd order *B*-field gradients.

08/31: CHEN – Hg EDM

$$\nu = 8.3\ \text{Hz}$$

$$\Delta\nu \leq 0.1\ \text{nHz}$$

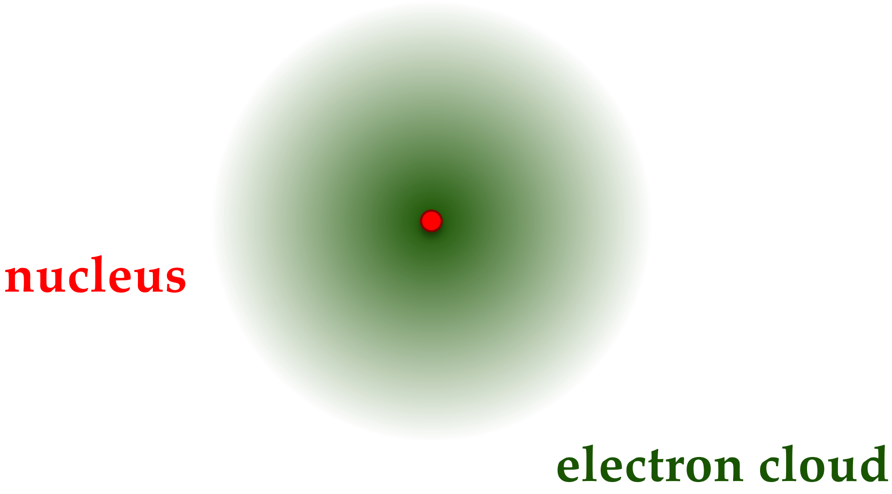
The best limit on atomic EDM:

EDM(^{199}Hg) < 0.74×10^{-29} *e*-cm (95% C.L.)

Graner et al., PRL 116:161601 (2016)

Diamagnetic Atoms: All electrons are paired.

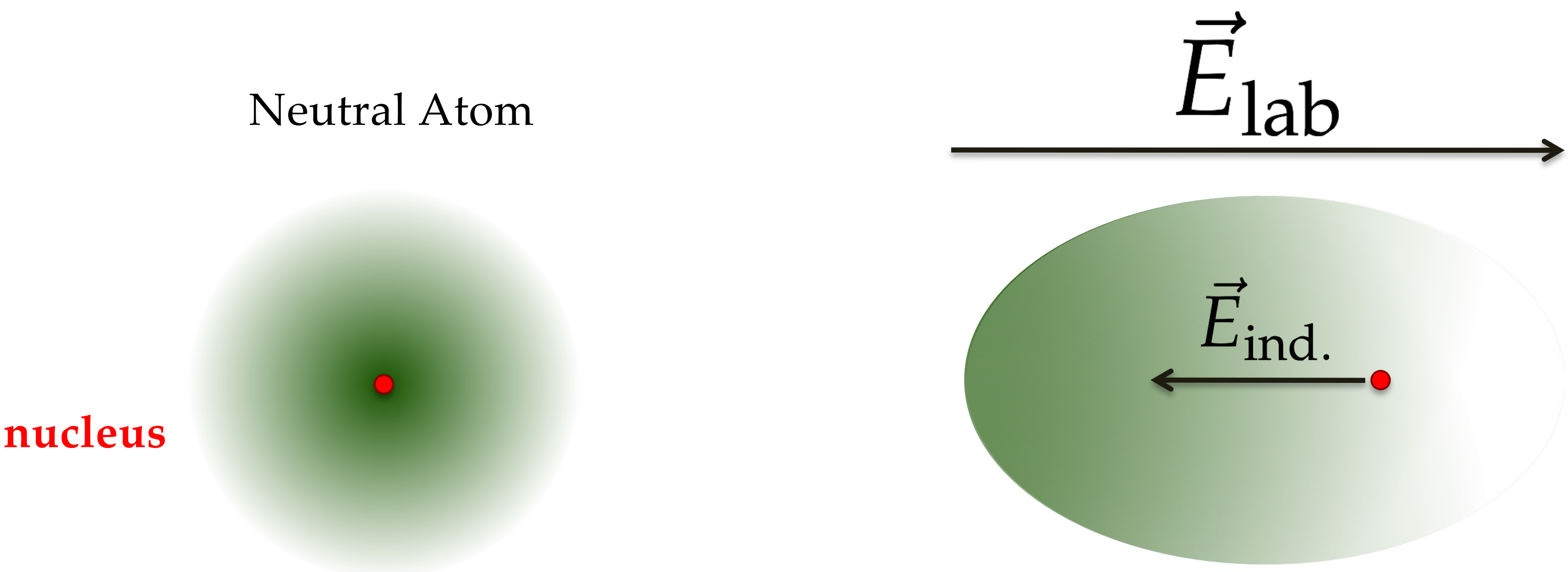
Neutral Atom



Schiff Shielding in Diamagnetic Atoms

- **Shielding in Diamagnetic Atoms**

    Schiff PR 132:2194 (1963)



$$\vec{E}_{\mathrm{ind.}} \approx -\vec{E}_{\mathrm{lab}}$$

Shielding Imperfect with Relativistic Atoms & Finite Nuclei

- **Shielding in Diamagnetic Atoms**

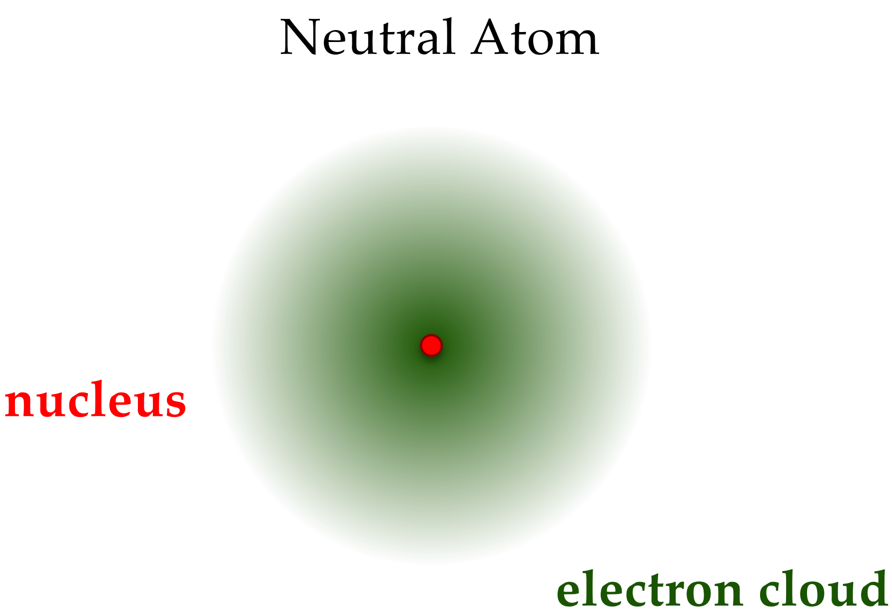
  Schiff PR 132:2194 (1963)

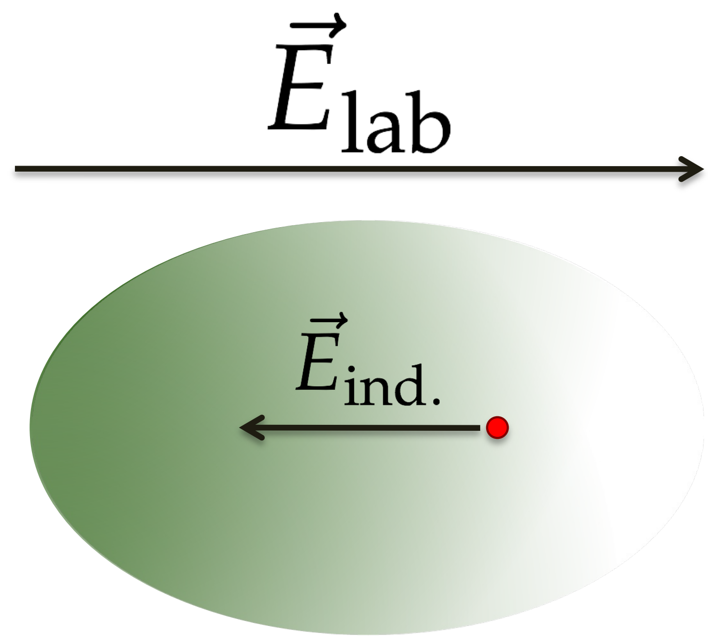
- **Relativistic atomic structure ($^{225}Ra/^{199}Hg \sim 3$)**

  PRA 66:012111 (2002) & PRL 120:203001 (2018) & PRA 92:022502 (2015)

Schiff Moment

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





$$\vec{E}_{\text{ind.}} \approx -\vec{E}_{\text{lab}}$$

Nuclear Schiff Moment in the Lab Frame

$$S_z = \frac{\langle er^2 z \rangle}{10} - \frac{\langle r^2 \rangle \langle ez \rangle}{6}$$

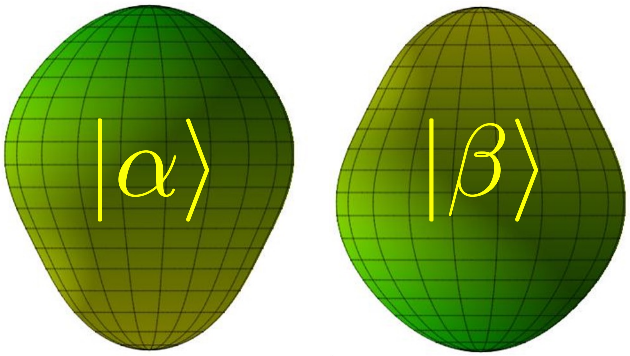
$$S \equiv \langle \Psi_0 | S_z | \Psi_0 \rangle = \sum_{k \neq 0} \frac{\langle \Psi_0 | S_z | \Psi_k \rangle \langle \Psi_k | V_{PT} | \Psi_0 \rangle}{E_0 - E_k} + \text{c.c.}$$

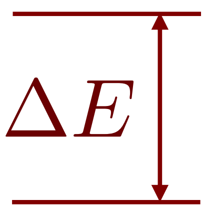
Enhanced Nuclear Moments with Parity Doublets

$$S_z = \frac{\langle e r^2 z \rangle}{10} - \frac{\langle r^2 \rangle \langle e z \rangle}{6}$$

$$S \equiv \langle \Psi_0 | S_z | \Psi_0 \rangle = \sum_{k \neq 0} \frac{\langle \Psi_0 | S_z | \Psi_k \rangle \langle \Psi_k | V_{PT} | \Psi_0 \rangle}{E_0 - E_k} + \text{c.c.}$$

Parity Doublet





$$|\Psi_1\rangle = \frac{|\alpha\rangle - |\beta\rangle}{\sqrt{2}}$$

$$|\Psi_0\rangle = \frac{|\alpha\rangle + |\beta\rangle}{\sqrt{2}}$$

- **Nearly degenerate parity doublet**

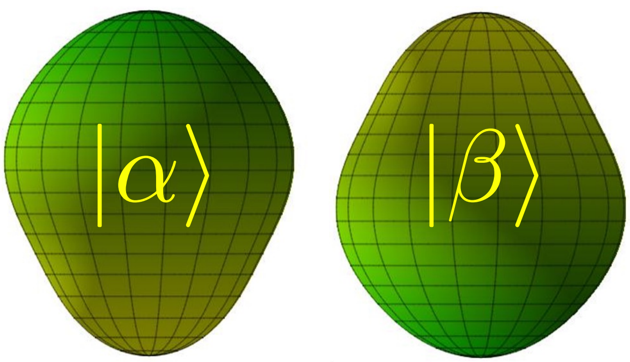
Haxton & Henley PRL 51:1937 (1983)

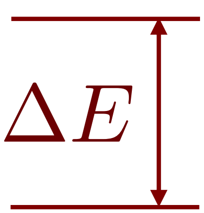
Enhanced Schiff Moments in Deformed Nuclei

$$S_z = \frac{\langle e r^2 z \rangle}{10} - \frac{\langle r^2 \rangle \langle e z \rangle}{6}$$

$$S \equiv \langle \Psi_0 | S_z | \Psi_0 \rangle = \sum_{k \neq 0} \frac{\langle \Psi_0 | S_z | \Psi_k \rangle \langle \Psi_k | V_{PT} | \Psi_0 \rangle}{E_0 - E_k} + \text{c.c.}$$

Parity Doublet





$$|\Psi_1\rangle = \frac{|\alpha\rangle - |\beta\rangle}{\sqrt{2}}$$

$$|\Psi_0\rangle = \frac{|\alpha\rangle + |\beta\rangle}{\sqrt{2}}$$

- **Nearly degenerate parity doublet**

  Haxton & Henley PRL 51:1937 (1983)

- **Large intrinsic Schiff moment due to octupole deformation**

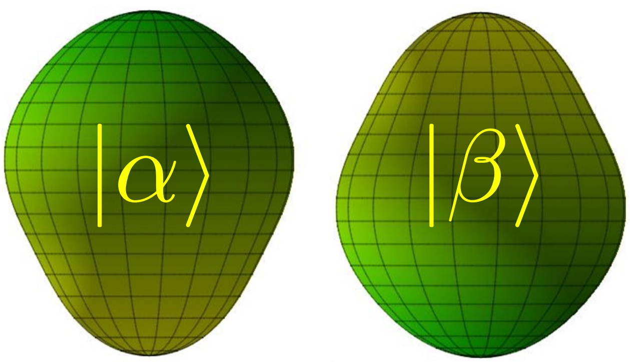
  Auerbach, Flambaum, & Spevak PRL 76:4316 (1996)

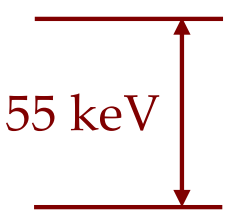
Enhanced Sensitivity in Radium-223/Radium-225

$$S_z = \frac{\langle er^2 z\rangle}{10} - \frac{\langle r^2\rangle\langle ez\rangle}{6}$$

$$S \equiv \langle\Psi_0|\, S_z\, |\Psi_0\rangle = \sum_{k\neq 0} \frac{\langle\Psi_0|\, S_z\, |\Psi_k\rangle \langle\Psi_k|\, V_{PT}\, |\Psi_0\rangle}{E_0 - E_k} + \text{c.c.}$$

Parity Doublet





$$|\Psi_1\rangle = \frac{|\alpha\rangle - |\beta\rangle}{\sqrt{2}}$$

$$|\Psi_0\rangle = \frac{|\alpha\rangle + |\beta\rangle}{\sqrt{2}}$$

- **Nearly degenerate parity doublet**

  Haxton & Henley PRL 51:1937 (1983)

- **Large intrinsic Schiff moment due to octupole deformation**

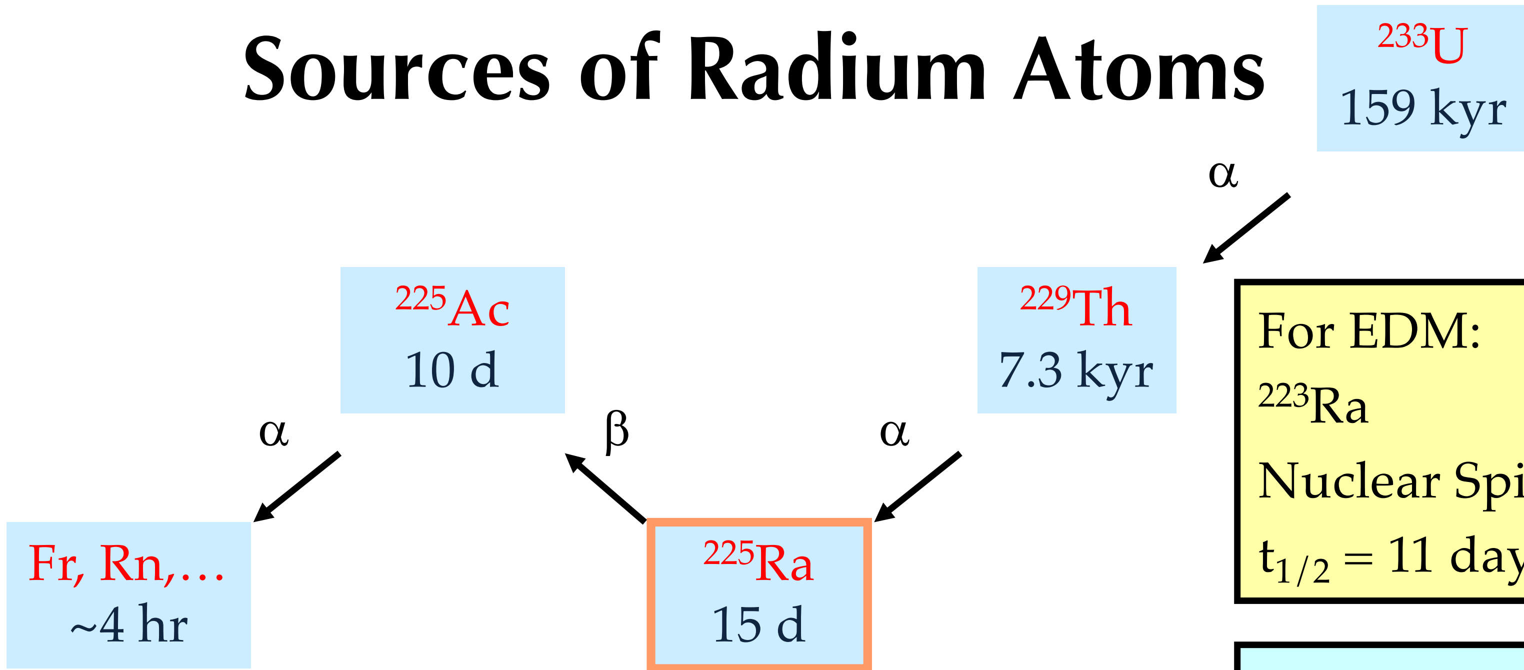
  Auerbach, Flambaum, & Spevak PRL 76:4316 (1996)

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

Skyrme Model	Isoscalar	Isovector
SIII	300	4000
SkM*	300	2000
SLy4	700	9000

^{225}Ra: Dobaczewski & Engel PRL 94:232502 (2005)
^{199}Hg: Ban et al. PRC 82:015501 (2010)

Sources of Radium Atoms



- 2 mCi (50 ng) ^{225}Ra sources from:

  National Isotope Development Center (Oak Ridge, TN)
- Test source: 1 μCi (1 mg) ^{226}Ra
- Integrated Atomic Beam Flux ~ 10^8/s

09/02: SHERRILL – FRIB

Facility for **R**are **I**sotope **B**eams (2022 to 2027)

Yield for ^{225}Ra ~ (10^9 to 10^{10})/s

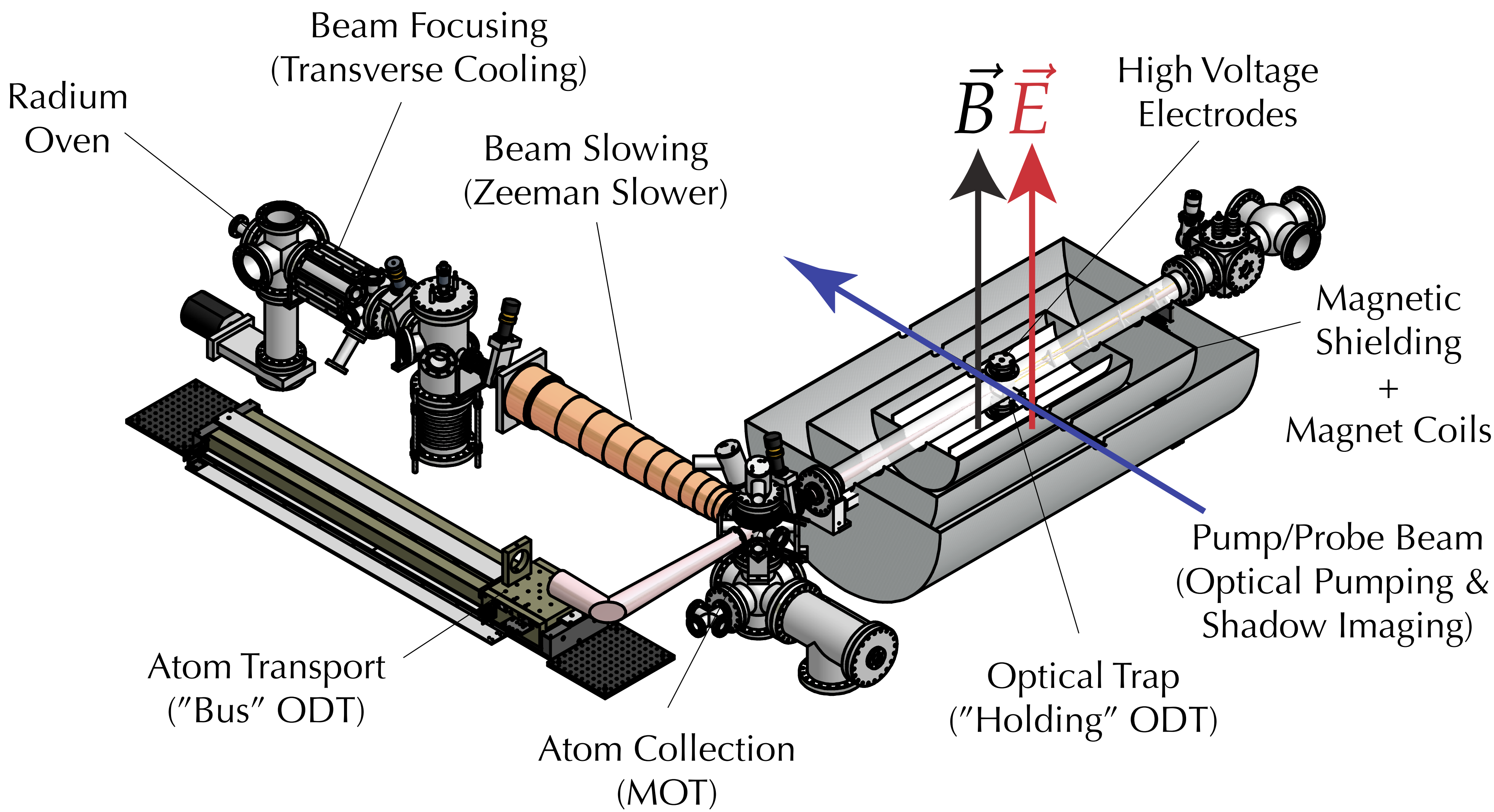
Yield for ^{229}Pa ~ (10^{10} to 10^{11})/s

For EDM:
^{223}Ra
Nuclear Spin = $^3/_2$
$t_{1/2}$ = 11 days

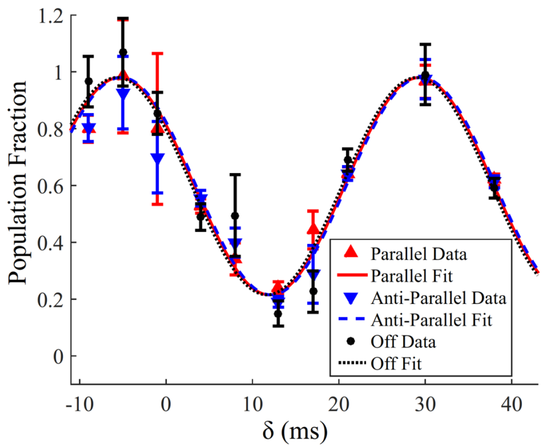
For EDM:
^{225}Ra
Nuclear Spin = ½
$t_{1/2}$ = 15 days

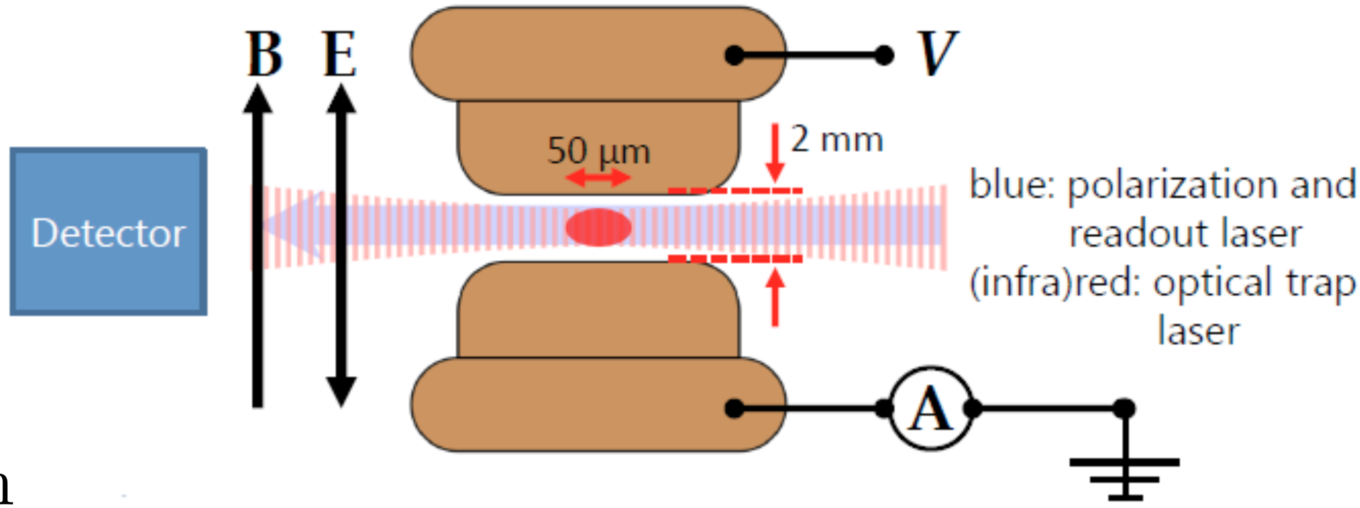
For Testing:
^{226}Ra
Nuclear Spin = 0
$t_{1/2}$ = 1600 yrs

The Laser Trap Ra EDM Experiment @ ANL



The Laser Trap Ra EDM Experiment @ ANL





$$E_{\text{lab}} = \pm 70\ \text{kV/cm}$$

$$T \approx 3\ \text{days}$$

$$\tau \approx 20\ \text{sec}$$

$$N_d \approx 10^2$$

^{225}Ra

Nuclear Spin = ½

$t_{1/2}$ = 15 days

Low vapor pressure

EDM search using atoms held in Optical Lattice

Romalis & Fortson PRA 59:4547 (1999)
Chin et al. PRA 63:033401 (2001)
Bishof et al. PRC 94:025501 (2016)

- Atoms concentrated in a very small region
- Long coherence time (100 s)
- negligible "v x E" systematics
- High electric field (>100 kV/cm) in vacuum
- Light-induced systematic effects can be controlled!

Ra EDM: Completely Statistics Limited

Dec 2014: PRL 114:233002: |d(Ra-225)| < 50x10^{-23} *e* cm (95%)

June 2015: PRC 94:025501: |d(Ra-225)| < 1.4x10^{-23} *e* cm (95%)

Effect	Current uncertainty	α scenario uncertainty	β scenario uncertainty
E-squared effects	1×10^{-25}	7×10^{-29}	7×10^{-31}[a]
B-field correlations	1×10^{-25}	5×10^{-27}	3×10^{-29}[a]
Holding ODT power correlations	6×10^{-26}	9×10^{-30}	9×10^{-32}[a]
Stark interference	6×10^{-26}	2×10^{-27}	3×10^{-29}[a]
E-field ramping	9×10^{-28}	2×10^{-29}	N/A
Blue laser power correlations	7×10^{-28}	1×10^{-31}	1×10^{-31}
Blue laser frequency correlations	4×10^{-28}	8×10^{-30}	8×10^{-30}
$\mathbf{E} \times \mathbf{v}$ effects	4×10^{-28}	7×10^{-30}	N/A
Leakage current	3×10^{-28}	9×10^{-29}	N/A
Geometric phase	3×10^{-31}	7×10^{-30}	5×10^{-33}
Total	2×10^{-25}	5×10^{-27}	4×10^{-29}[a]

[a]This uncertainty will improve with the statistical sensitivity of the experiment.

More efficient detection of atoms: STIRAP + optical cycling

More efficient laser cooling and trapping: 1 ppm to 100 ppm

Higher electric field: 70 kV/cm to >200 kV/cm

Goal is <10^{-25} *e* cm over 3 years and then 10^{-28} *e* cm long term

Recent Results in Xe-129 and Yb-171

Ra-225: PRC 94:025501 (2016): **< 1.4×10^{-23} *e* cm (95%)**
(laser trap experiment)

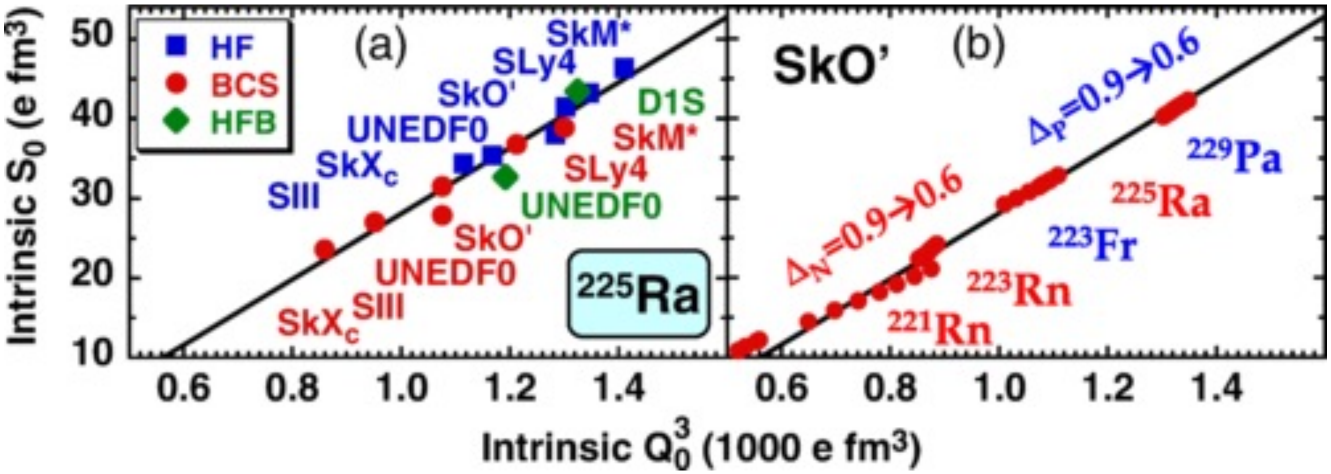
Xe-129: PRL 123:143003 (2019): **<1.4×10^{-27} *e* cm (95%)**
(gas cell experiment)

Yb-171: PRL 129:083001 (2022): **< 1.5×10^{-26} *e* cm (95%)**
(laser trap experiment, very similar to Ra experiment)

Punchlines: The new physics constraints within the hadronic sector for all three of these experiments are roughly equal. The Yb experiment validates the laser trap approach for Ra for at least another three orders of magnitude.

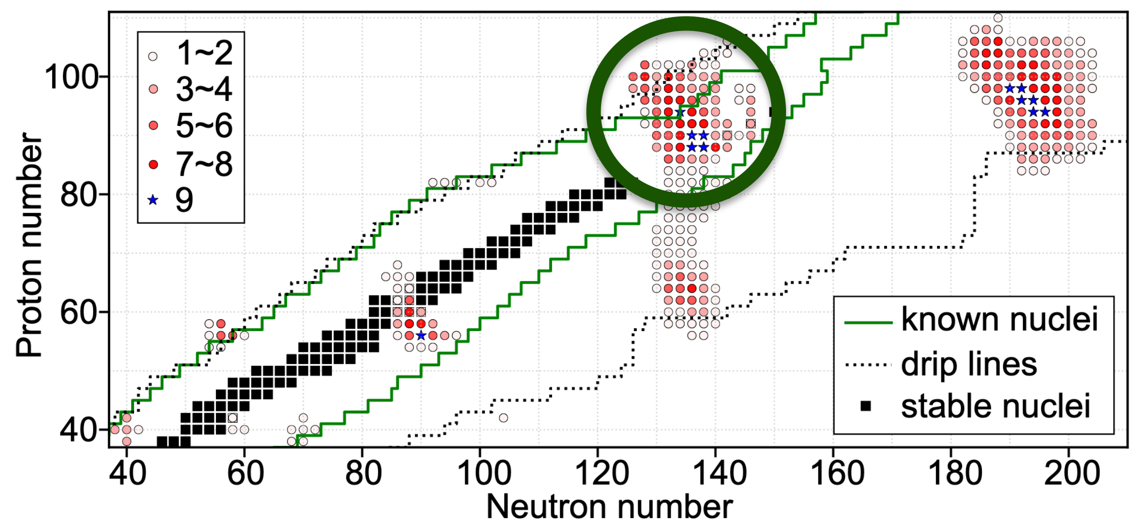
Calibrating the Intrinsic Schiff Moment

$$S \equiv \langle \Psi_0 | S_z | \Psi_0 \rangle = \sum_{k \neq 0} \frac{\langle \Psi_0 | S_z | \Psi_k \rangle \langle \Psi_k | V_{PT} | \Psi_0 \rangle}{E_0 - E_k} + \text{c.c.}$$



PRL 121, 232501 (2018)
Phys. Rev. C, 102:024311 (2020)

The Intrinsic Schiff Moment (numerator) varies by a factor of a few if not zero, but the Parity Doublet Splitting (denominator) could vary by orders of magnitude!



Protactinium-229 (^{229}Pa) *may* be unusually sensitive!

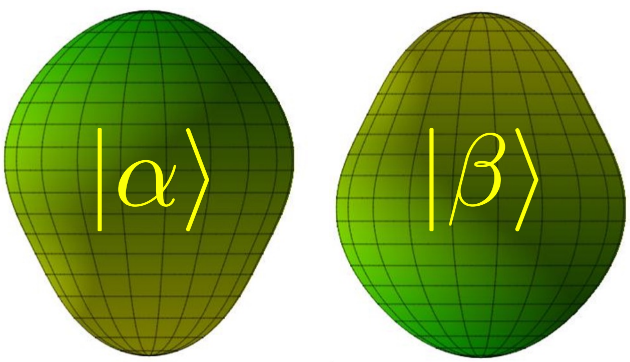
$$S_z = \frac{\langle e r^2 z \rangle}{10} - \frac{\langle r^2 \rangle \langle e z \rangle}{6}$$

Choose an isotope with large deformations

$$S \equiv \langle \Psi_0 | S_z | \Psi_0 \rangle = \sum_{k \neq 0} \frac{\langle \Psi_0 | S_z | \Psi_k \rangle \langle \Psi_k | V_{PT} | \Psi_0 \rangle}{E_0 - E_k} + \text{c.c.}$$

Unknown

Parity Doublet



$$|\Psi_1\rangle = \frac{|\alpha\rangle - |\beta\rangle}{\sqrt{2}}$$

ΔE

$$|\Psi_0\rangle = \frac{|\alpha\rangle + |\beta\rangle}{\sqrt{2}}$$

Pa-229: Haxton & Henley PRL 51:1937 (1983)
I. Ahmad et al Phys. Rev. C 92:024313 (2015)
Dobaczewski et al PRL 121, 232501 (2018)

Isotope	ΔE (keV)	$\tau_{1/2}$ (sec)	sensitivity
Hg-199	1800	stable	1
Rn-223	~10^2?	10^3	10^2
Ra-225	55	10^6	10^3
Pa-229	**(0.06 +/- 0.05)?**	**10^5**	**10^6**

FRIB will make lots of Pa-229!

Planned Pa-229 Nuclear Spectroscopy @ FRIB!

We have used superconducting high-resolution radiation detectors to measure the energy level of metastable ^{235m}U as 76.737 ± 0.018 eV. The ^{235m}U isomer is created from the α decay of ^{239}Pu and embedded directly into the detector. When the ^{235m}U subsequently decays, the energy is fully contained within the detector and is

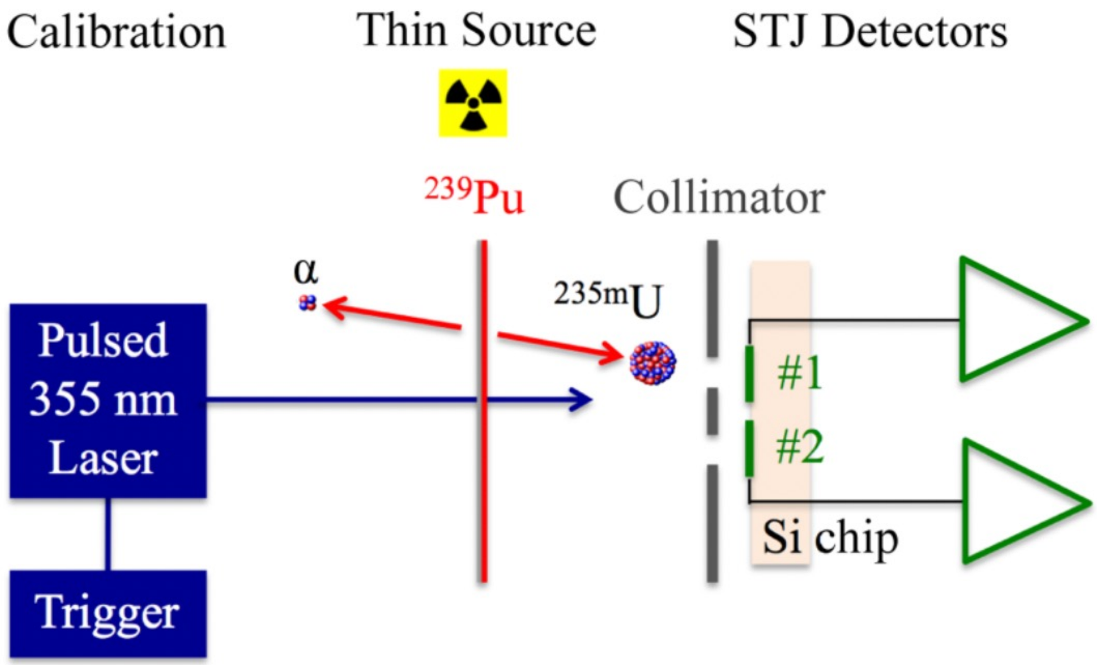


FIG. 1. Schematic of experimental setup: ^{235m}U recoil ions produced by the decay of ^{239}Pu are embedded in the STJ detectors, which measure their subsequent decay into the ^{235}U ground state.

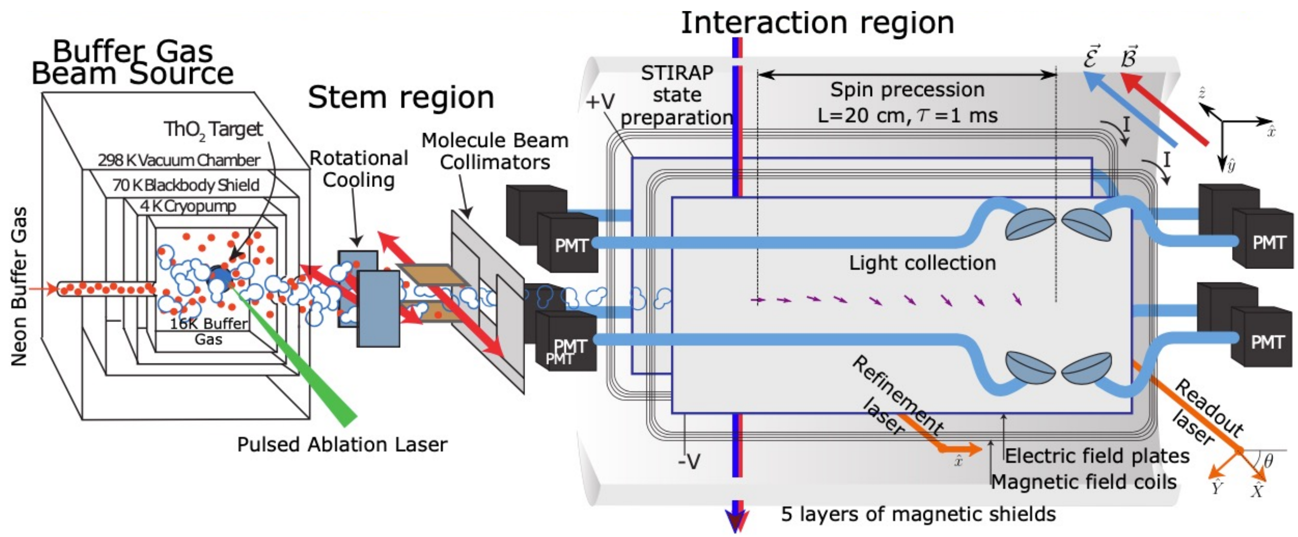
PRC 97 054310 (2018)

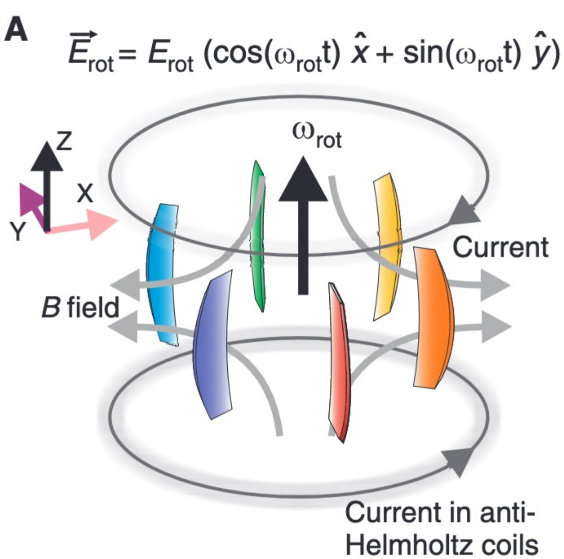
09/01: FRIEDRICH - BeEST

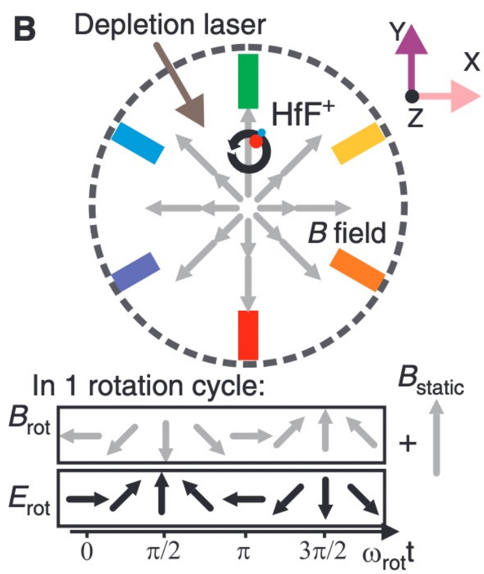
Molecular Electron EDM Experiments: Large Internal E-field and Control of Systematics

ACME – ThO*
Neutral Beam
(Harvard / Northwestern / Chicago)

C. Panda (Harvard 2018)
Nature 562 355 (2018)







HfF^+ / ThF^+
Ion Trap
(JILA)

Science 342 (6163) 1220 (2013)
PRL 119 153001 (2017)

FRIB Opportunity:
Short-Lived Radioactive Molecule Experiments!

Opportunity: nuclear Schiff enhancement ~10^{3+}
and ~100 MV/cm effective E-field
(compared to <1 MV/cm lab E-fields)

Potential: x10^5 to x10^{10} more physics sensitivity than the Hg-199 experiment <u>on a per atom basis</u> (atoms from FRIB)

Key Challenge: how do we efficiently produce and probe short-lived radioactive molecules? **09/02: GARCIA RUIZ – Radioactive Molecules**

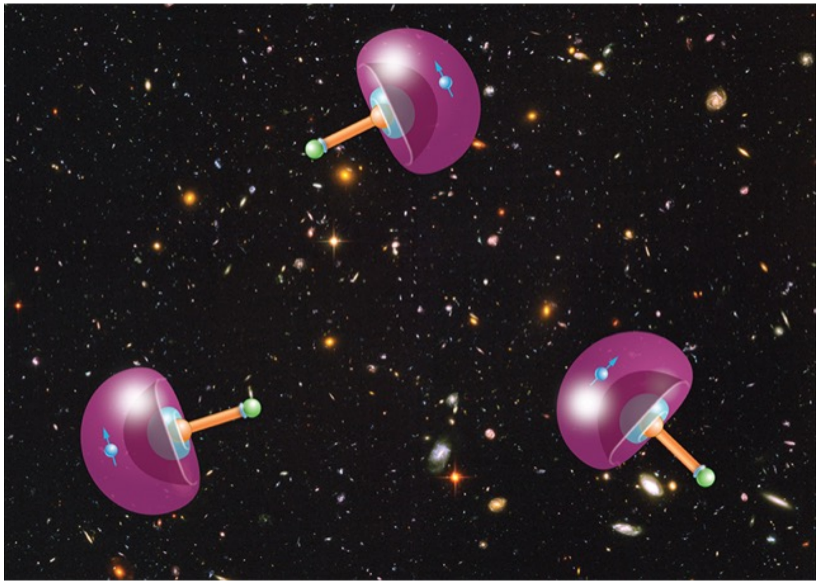
Punchline: we need an OFFLINE AREA to form beams of HARVESTED ISOTOPES for use in LONG INTEGRATION TIME experiments @ FRIB!

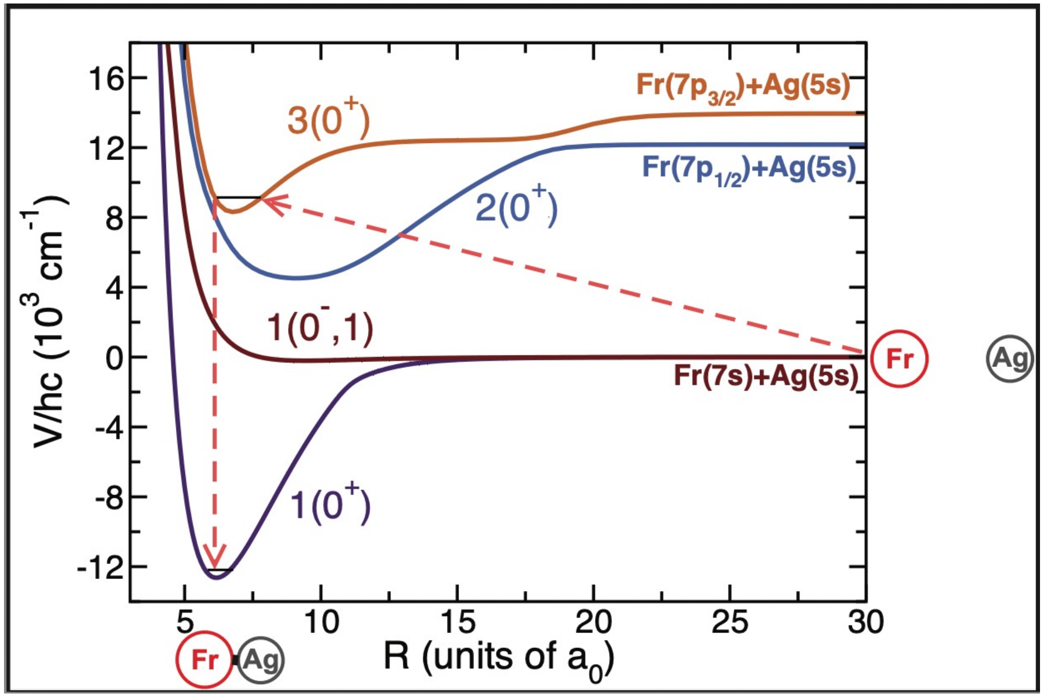
Neutral Molecule Laser Trap (ANL/Chicago/MIT/Temple)

Opportunity: Uses demonstrated modern quantum manipulation techniques
Challenge: Efficient loading of trap
Status: Laser spectroscopy underway!

Nature 581:396 (2020)
PRL 127:033001 (2021)
New J. Phys. 24 025005 (2022)

https://physics.aps.org/articles/v14/103



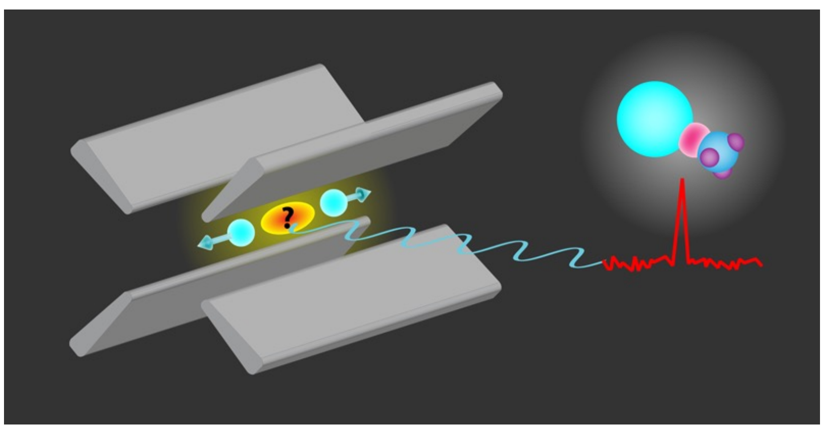


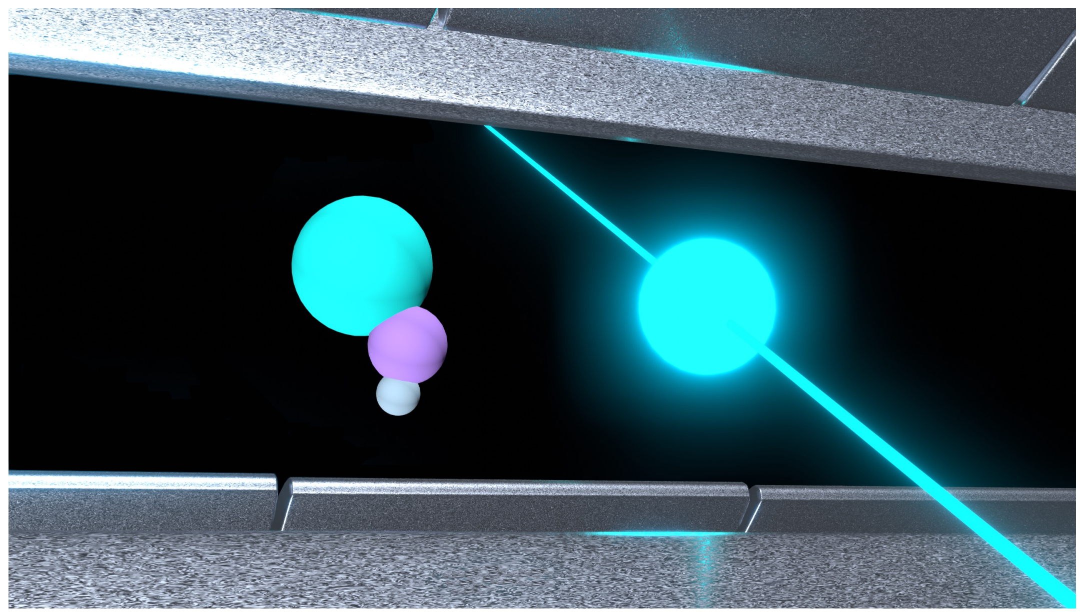
Molecular Ion Trap (UCSB/Caltech)

Opportunity: Uses demonstrated modern quantum manipulation techniques in a “general” purpose ion trap.
Challenge: Probes only one molecular ion at a time
Status: Molecule formation, trapping, and spectroscopy all underway!

A.M. Jayich

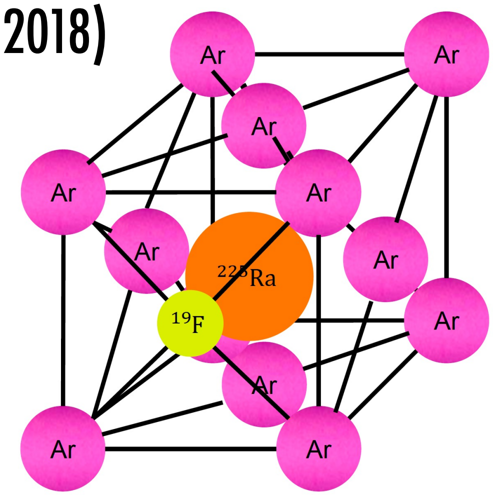
Fan et al. PRL 126:023002 (2021)
Yu & Hutzler PRL 126:023003 (2021)
https://physics.aps.org/articles/v14/3



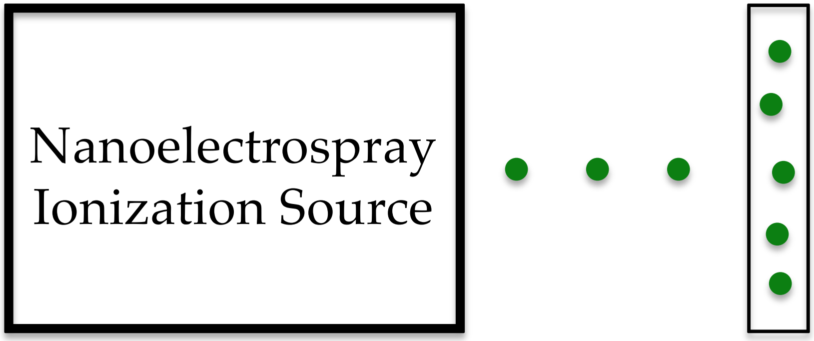


Molecules in Noble Gas Solids (York/Toronto/MSU)

- **Efficient trapping of a wide variety of species**
- Stable and chemically inert confinement
- Transparent in the optical regime for optical probing
- long T_1: solid Xe-129 (I=1/2) 10^2 s @ 10 G & 77 K
  Gatzke, Cates, et al. PRL 70 693 (1993) 10^6 s @ 10^3 G & 4.2 K
- long T_2: 10^3 s for 1 ppm diamagnetic (μ_N) spin impurities
  Van Vleck PR 74 1168 (1948)
- Under certain conditions, polar molecules orient themselves along the crystal axes: Vutha et al. PRA 98:032513 (2018)
- **Very high number densities**
- **Challenge: quantum control in medium**

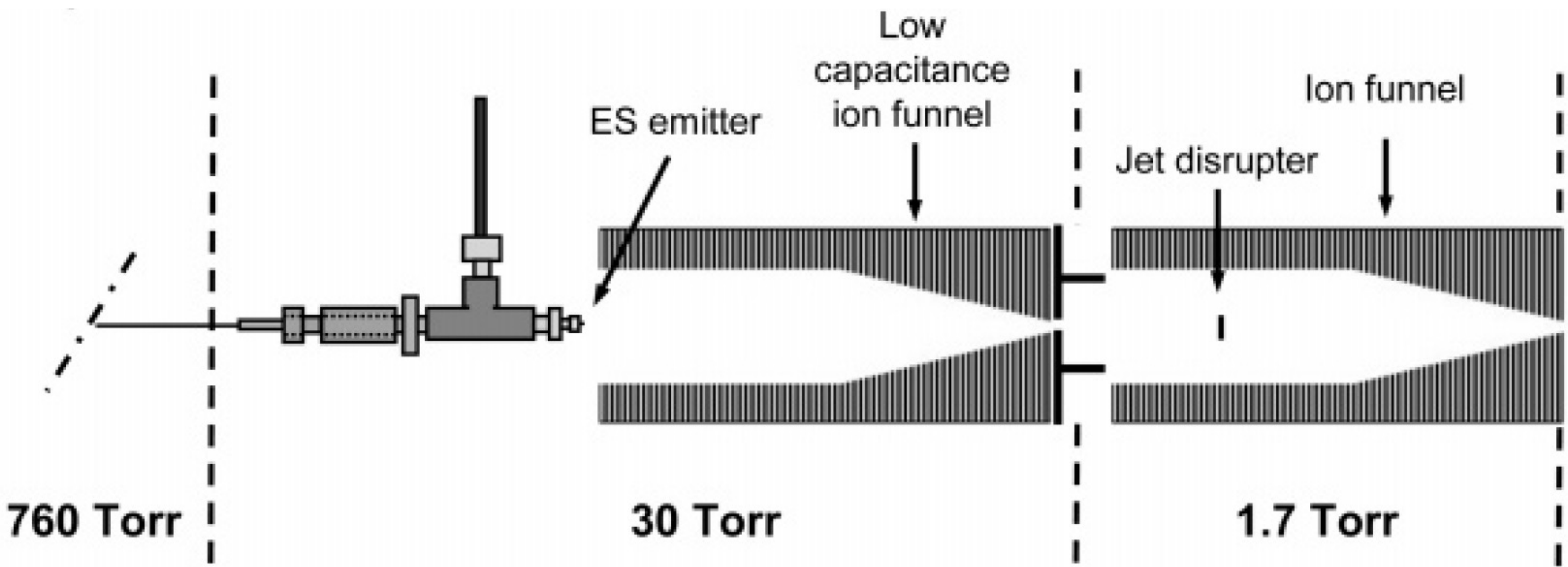


Deposit Molecules into Noble Gas Solids (MSU)



Efficiencies of 10-50% have been reported in these ion sources.

J. Am. Soc. Mass Spectrom. (2015) 26:55-62



^{229}Pa Ions in Optical Crystals (MSU)

JTS Hyp. Int. 240:29 (2019)

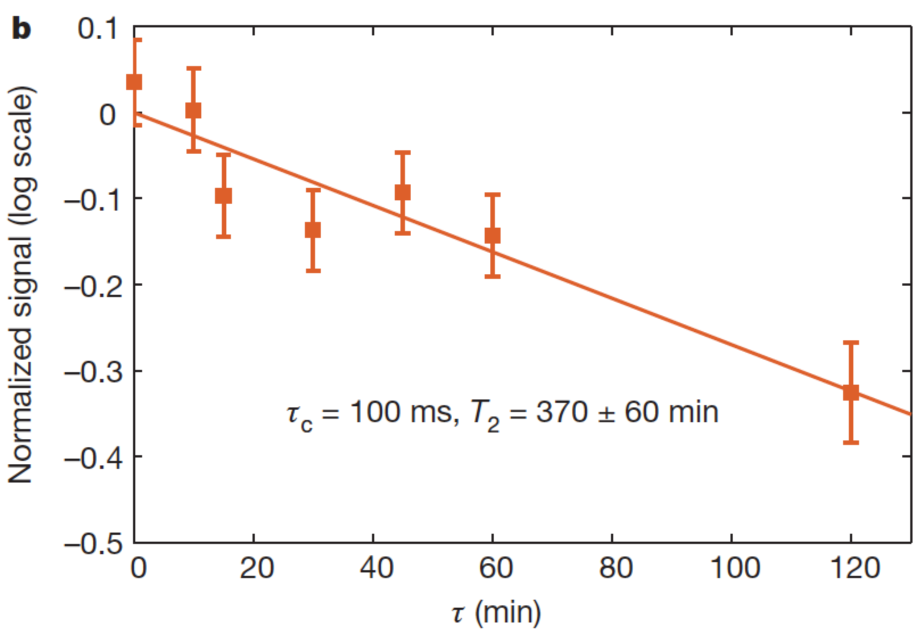
- Large intrinsic sensitivity to BSM physics
  - **high Z** (^{199}Hg, ^{205}Tl, ^{225}Ra, ^{221,223}Rn, **^{229}Pa**)
  - **octupole deformed nucleus** (^{225}Ra, ^{221,223}Rn, **^{229}Pa**)
- Large *E*-field or *B*-field gradient (MQM) to amplify observable
  - **local crystal fields (1-10 MV/cm) (solids)**
- Repeat the measurement as many times as possible
  - ~~large number of nuclei (stable)~~
  - **long integration time (FRIB: steady supply for short $\tau_{1/2}$)**
  - **long trapping time: nuclei "stored" in the solid**
  - **long coherence time possible?**
- High efficiency extraction of experimental signal
  - **near unity capture and trapping efficiency in solid**
  - **optical detection via laser probing**
  - **optically-accessible nuclear spins**
  - **inhomogenous broadening – address each nucleus individually?**
- **Control of systematics**

Long Coherence Times of Lanthanide Ion Nuclei

doi:10.1038/nature14025
8 JANUARY 2015 | VOL 517 | NATURE | 177

Optically addressable nuclear spins in a solid with a six-hour coherence time

Manjin Zhong[1], Morgan P. Hedges[1,2], Rose L. Ahlefeldt[1,3], John G. Bartholomew[1], Sarah E. Beavan[1,4], Sven M. Wittig[1,5], Jevon J. Longdell[6] & Matthew J. Sellars[1]



Under the right experimental conditions (magnetic field of 1.35 T and temperature of 2 K) , using a specially designed pulse sequence (KDD_x), **the T_2 of $^{151}Eu^{3+}$ (I=5/2) embedded in Y_2SiO_5 was measured to be over 6 hours.**

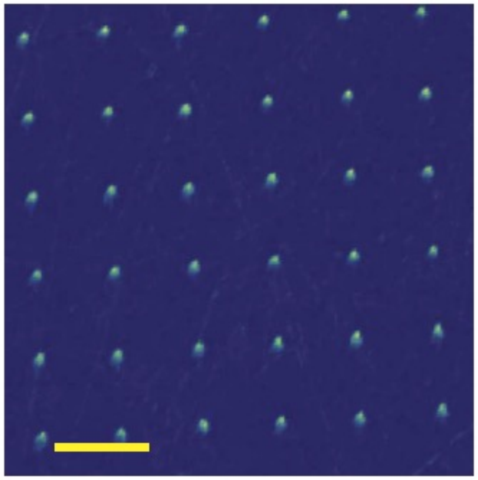
Single Ion Implantation & Manipulation

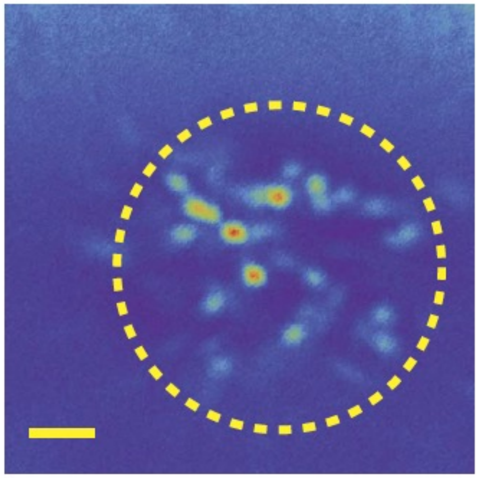
Received 19 Jan 2014 | Accepted 15 Apr 2014 | Published 14 May 2014

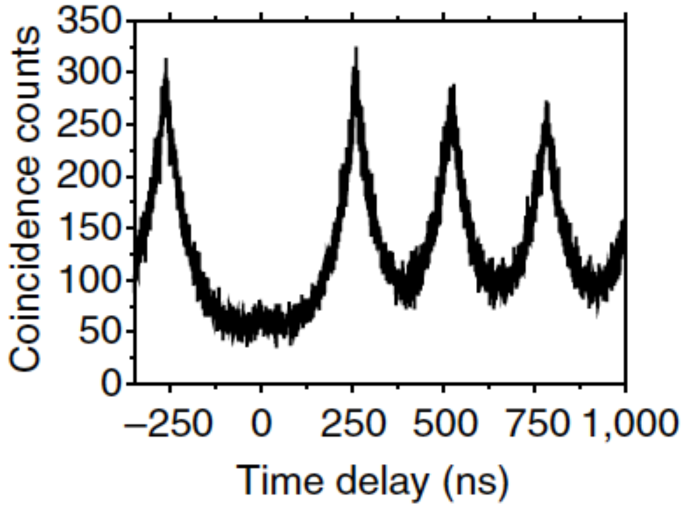
DOI: 10.1038/ncomms4895

Coherent properties of single rare-earth spin qubits

P. Siyushev[1,*], K. Xia[1,*], R. Reuter[1], M. Jamali[1], N. Zhao[2], N. Yang[3], C. Duan[4], N. Kukharchyk[5], A.D. Wieck[5], R. Kolesov[1] & J. Wrachtrup[1]







Left: well-controlled ion implantation of Ce^{3+} (yellow bar = 10 microns)

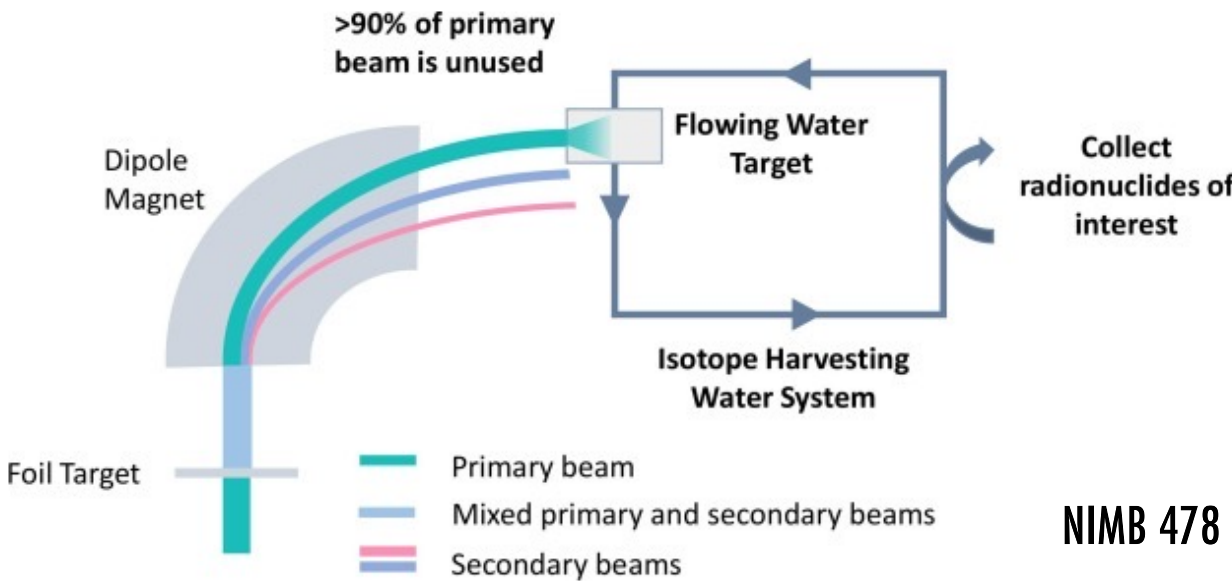
Middle: individual Ce site (yellow bar = 2 microns)

Right: antibunching in photon correlation data indicates single emitter

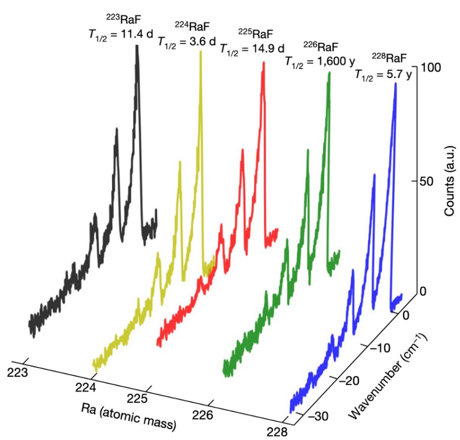
The Nuclear Pear Factory: A Proposed NSF Center

Nature 497:199 (2013)

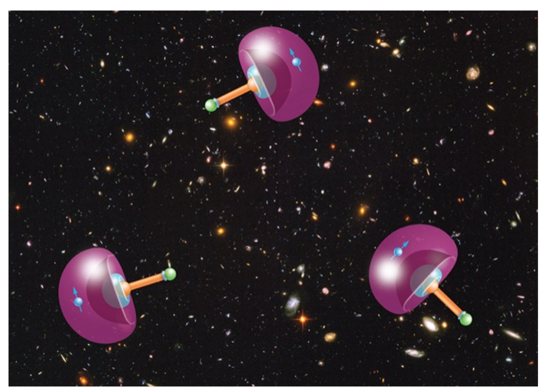
A joint Experiment/Theory & AMO/Nuclear effort to calibrate the new physics sensitivity of pear-shaped nuclei and to carry out the requisite precursory work leading to ultrasensitive EDM searches.

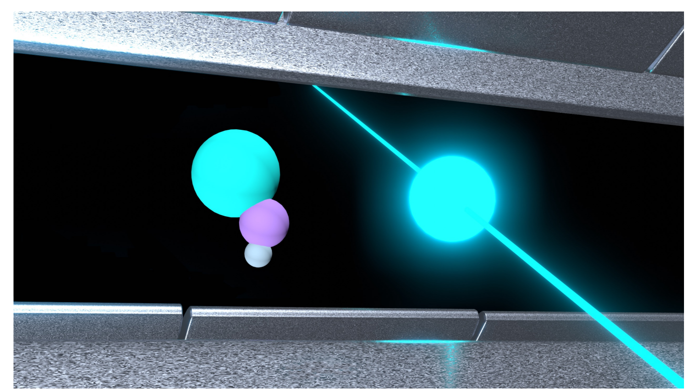


NIMB 478 34 (2020)



Nature 581:396 (2020)





https://physics.aps.org/articles/v14/103 & A.M. Jayich

Thanks For Your Attention!

1. Detecting a non-zero EDM would be an unambiguous signature of physics Beyond the Standard Model of Particle Physics.
2. Searches in a variety of complementary systems are needed since the source of any new possible *CP*-violation is not known and to confirm results with different systematics.
3. Pear-shaped nuclei such as Radium-225 and Protactinium-229 have significantly enhanced sensitivity to *CP*-violation originating within the nuclear medium.
4. Polar molecules have and will continue to revolutionize searches for *CP*-violation in both the leptonic and (soon!) the hadronic sectors.
5. **Short-lived radioactive molecules potentially have x10^5 to x10^{10} more new physics sensitivity than Hg-199 in the hadronic sector on a per atom basis.**
6. **Isotope harvesting and radiochemistry at FRIB enables access to these enhancer isotopes in practical quantities for ultrasensitive EDM searches.**

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Junior Faculty Search @ Michigan State/FRIB: Fundamental Symmetries With Rare Isotopes

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