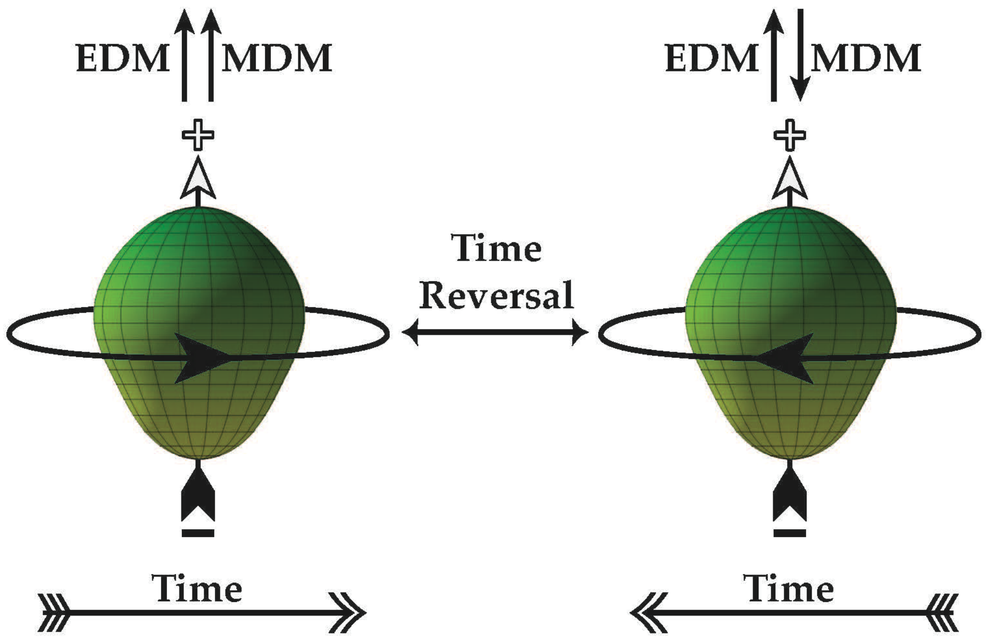
The Nuclear Pear Factory: Searching for Time-Reversal Violation Using Pear-Shaped Nuclei in the FRIB Era



Jaideep Taggart Singh

Michigan State University / FRIB

DNP T1-6: 0900-0930, June 30, 2023

2023 CAP Congress, Fredericton, NB, Canada

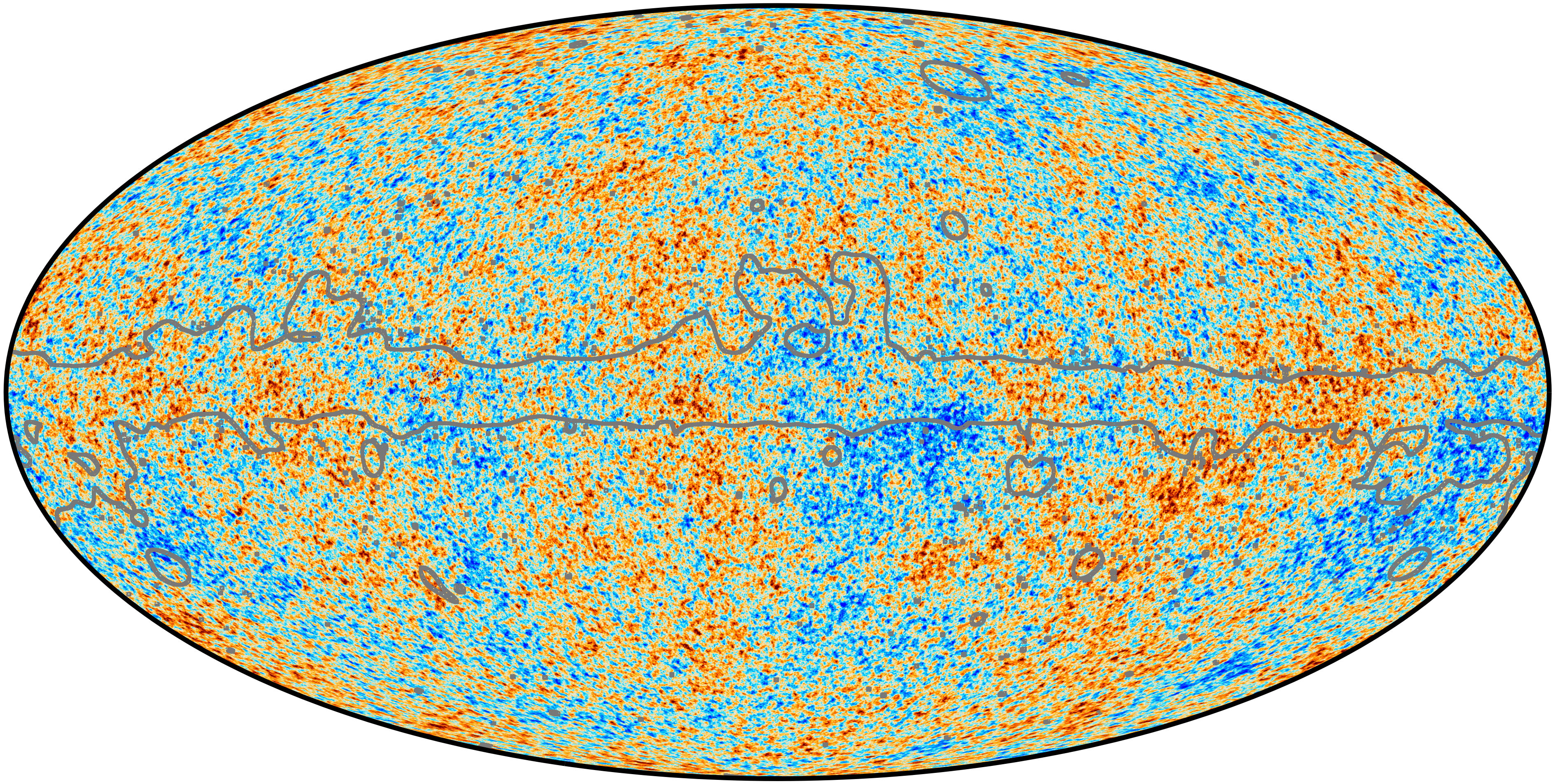
University of New Brunswick, UNB Kinesiology (Rm. 201)

Marie-Anne Bouchiat

SCAN ME

FRIB

Cosmic Microwave Background Anisotropy: More matter than antimatter in the visible universe



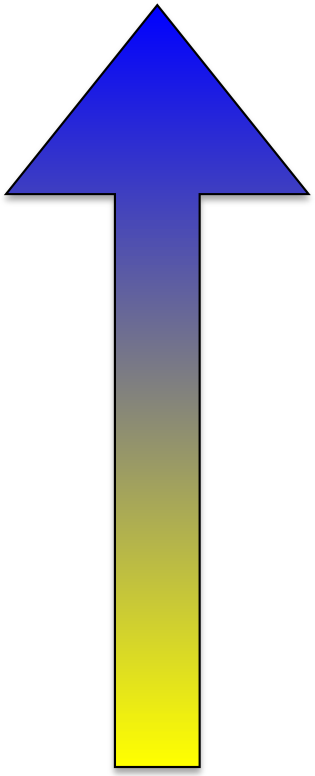
-300 300 μK

~100 ppm fluctuations

Planck 2018
https://www.cosmos.esa.int/web/planck/picture-gallery

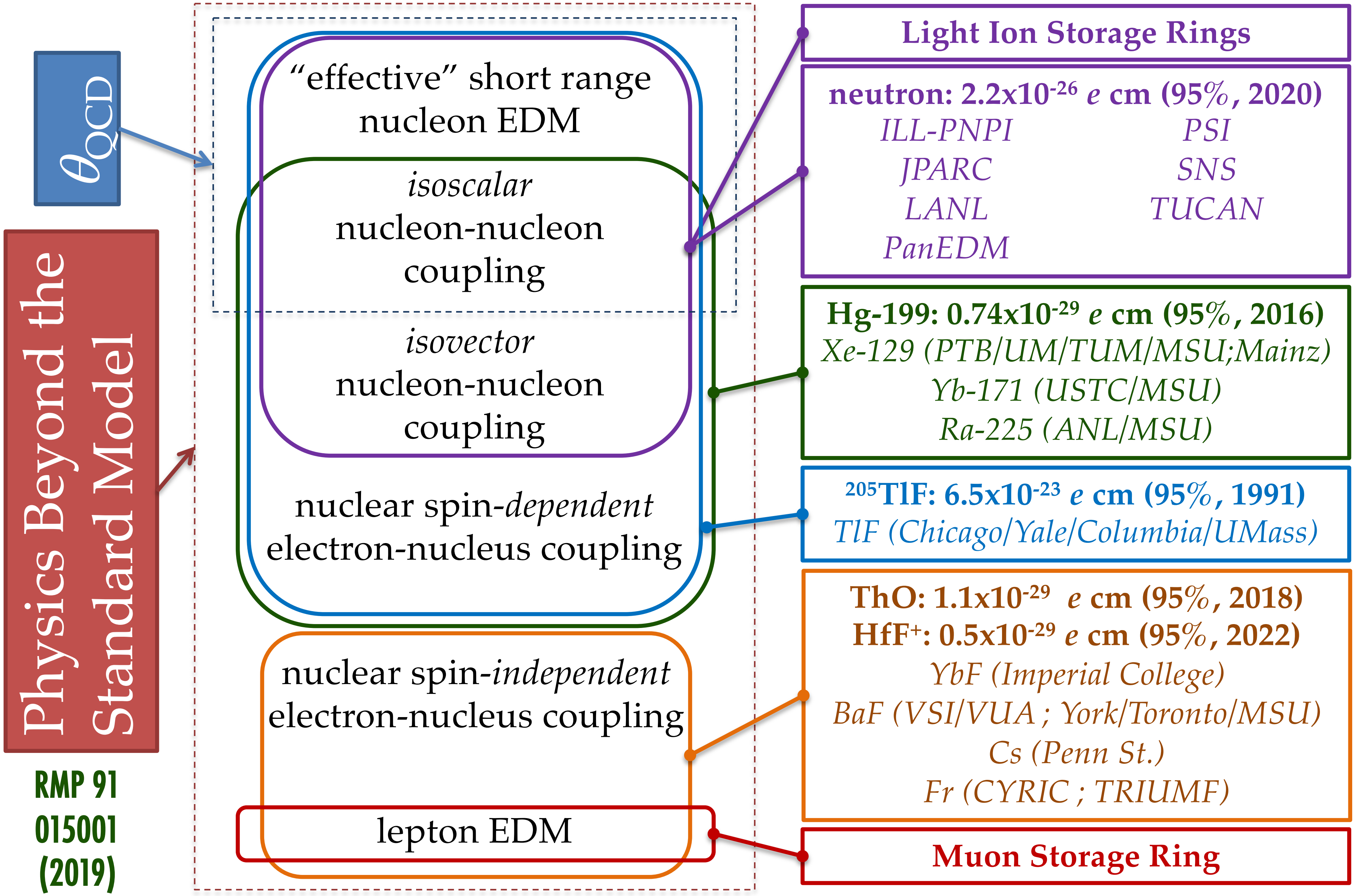
EDM: Measures the Separation of Charges

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



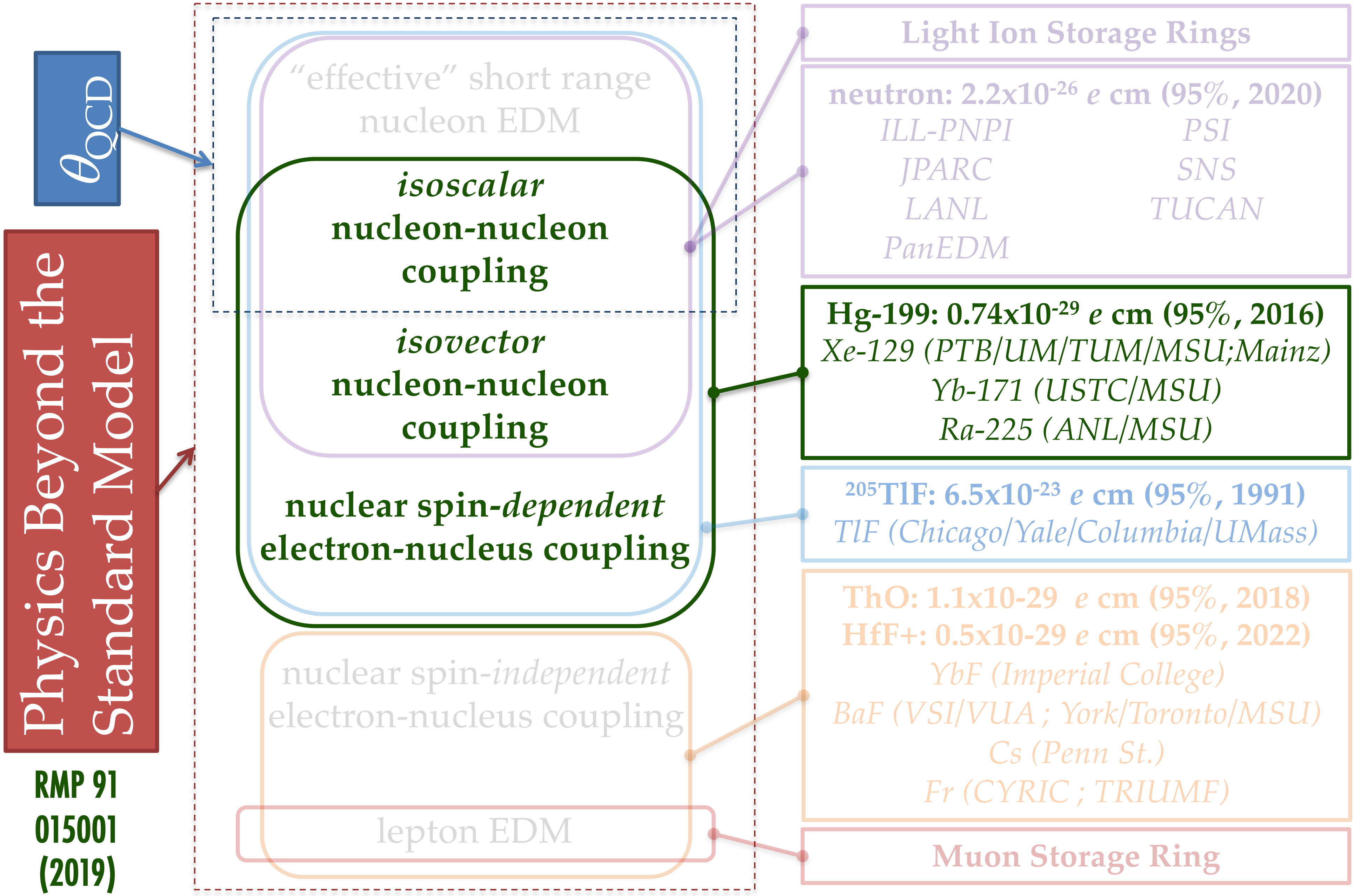
$\vec{d}$

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



RMP 91 015001 (2019)

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



RMP 91 015001 (2019)

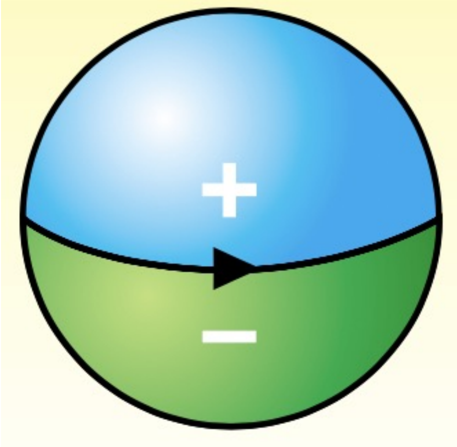
2023 EDM Limits: Free of SM "Backgrounds"

Chupp, Fierlinger, Ramsey-Musolf, JTS RMP 91:015001 (2019) & Nature 562:355 (2018) & PRL 124:081803 (2020) & arxiv:2212.11841

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 (Chicago/Harvard/Northwestern)
	0.05		trapped HfF^{+} (JILA/Boulder)
Hg-199	0.074	$\sim 10^{-6}$	atoms in vapor cell (UW-Seattle)

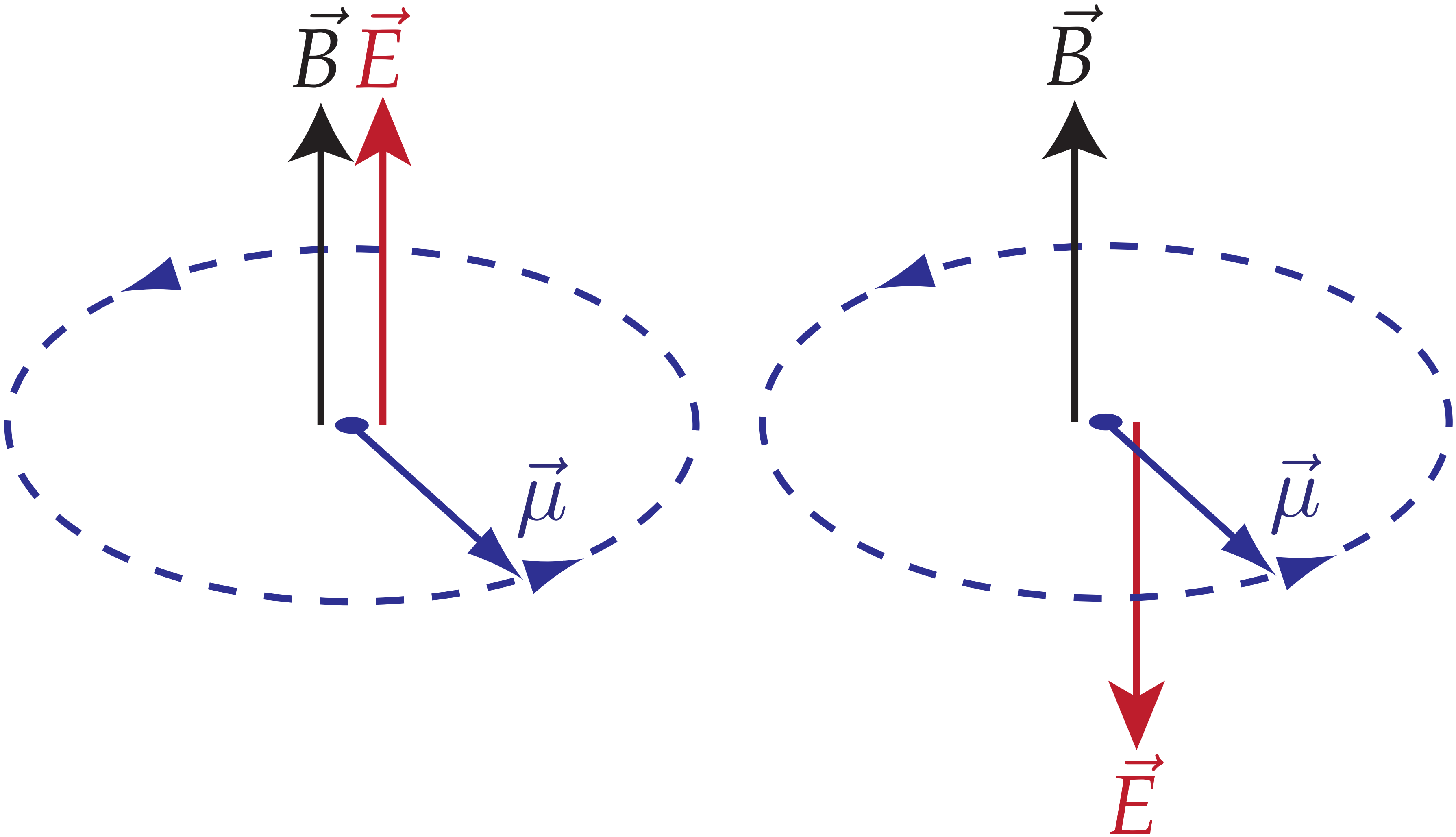
Imagine a Hg-199 atom that is composed of two oppositely charged hemispherical shells each with charge magnitude *e*:

If the Hg-199 atom 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.



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

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

Quantum Projection Noise:

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

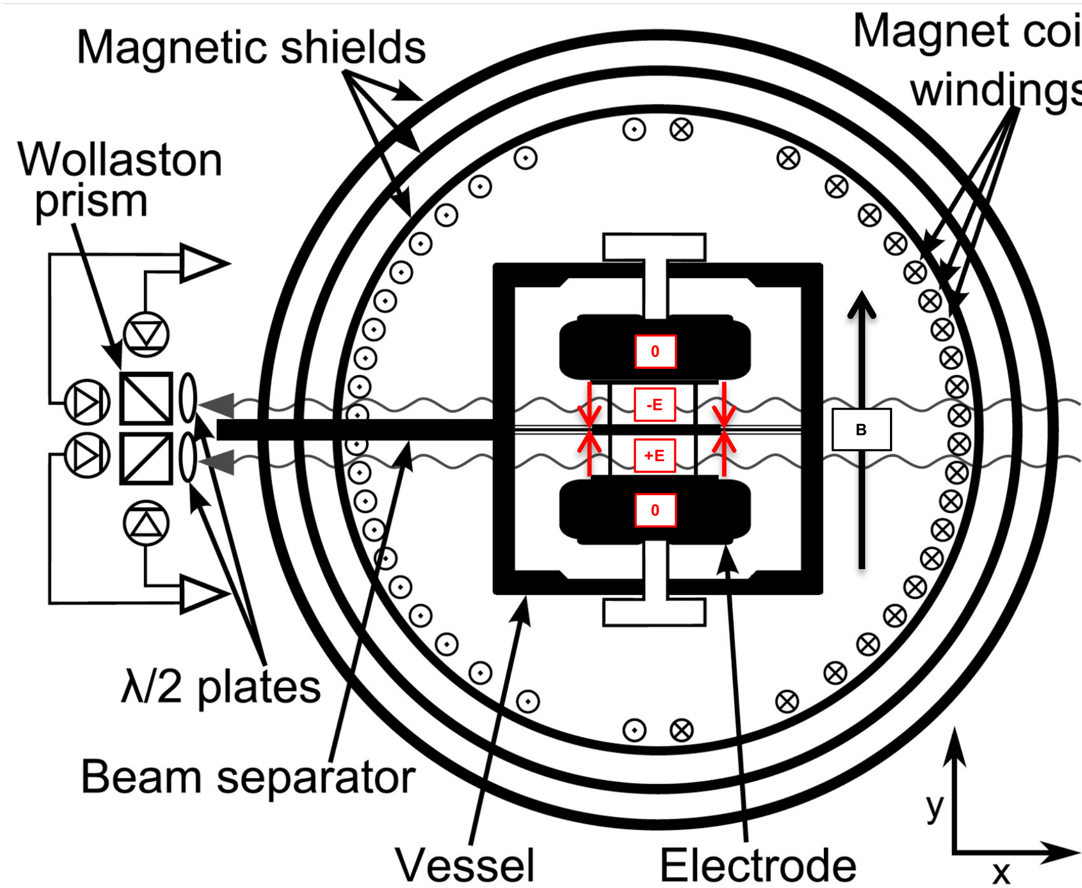
Electric field

number of detected particles

integration time

interrogation time

The Gold Standard: Hg-199 EDM Search



- **diamagnetic**, $^1S_0$ ground state
- $I = ½$, 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.

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

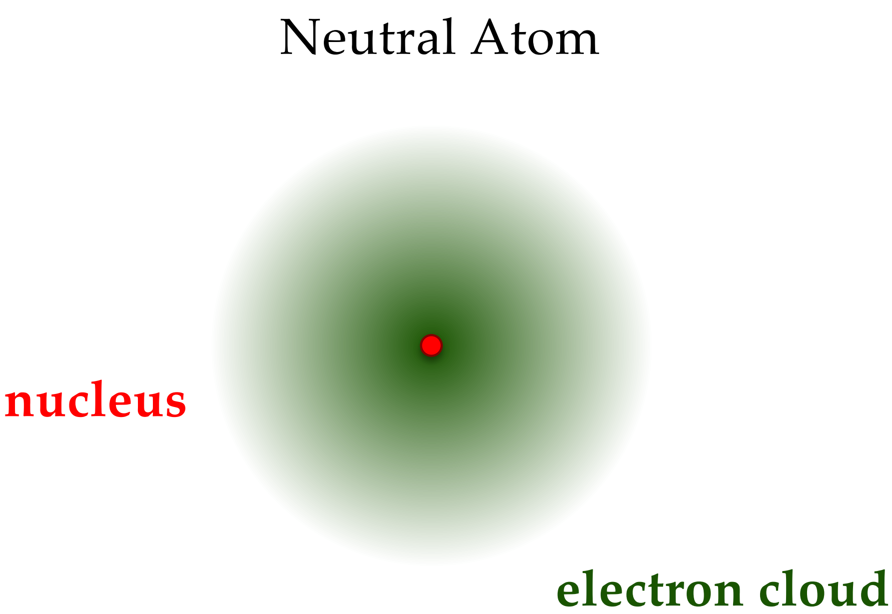
$$\Delta\nu \leq 0.1 \text{ nHz}$$

The best limit on atomic EDM:

EDM(^{199}Hg) < 0.74x10^{-29} *e*-cm (95% C.L.)

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

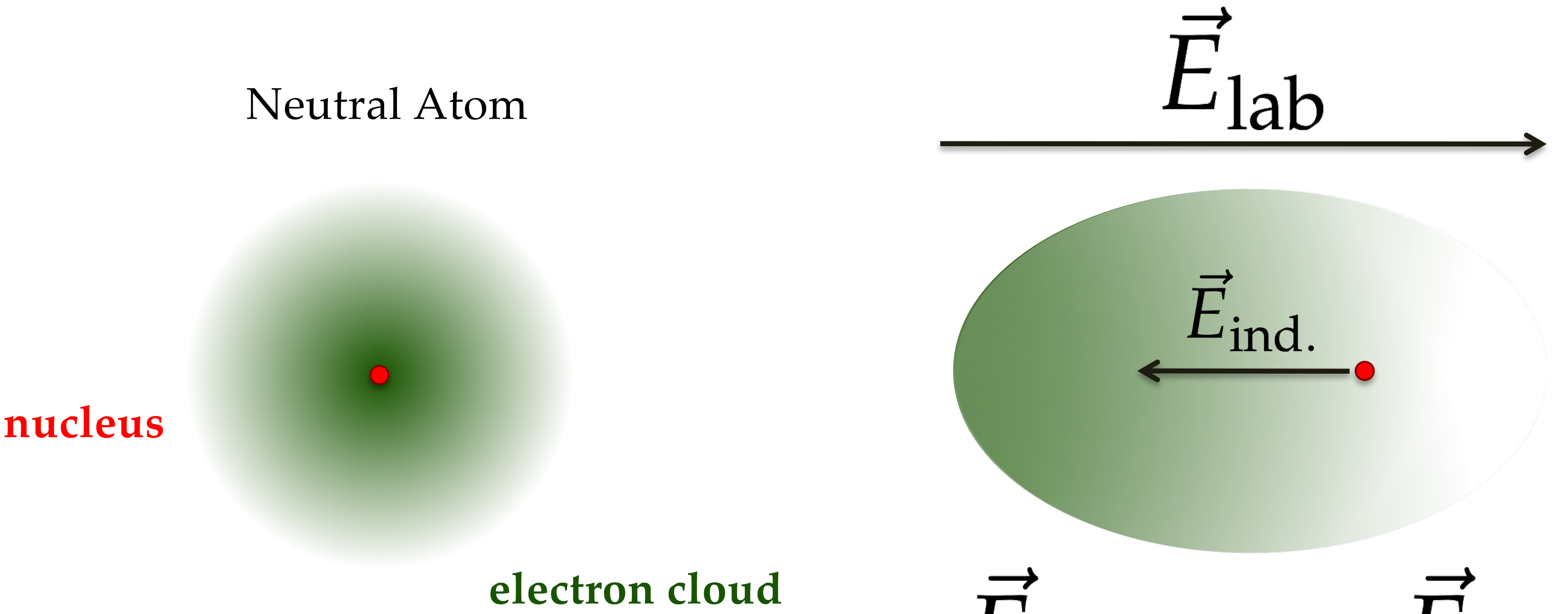
Diamagnetic Atoms: All electrons are paired.



Schiff Shielding in Diamagnetic Atoms

- **Shielding in Diamagnetic Atoms**

  Schiff PR 132:2194 (1963)



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

Shielding Imperfect with Relativistic Atoms & Finite Nuclei

- **Shielding in Diamagnetic Atoms**

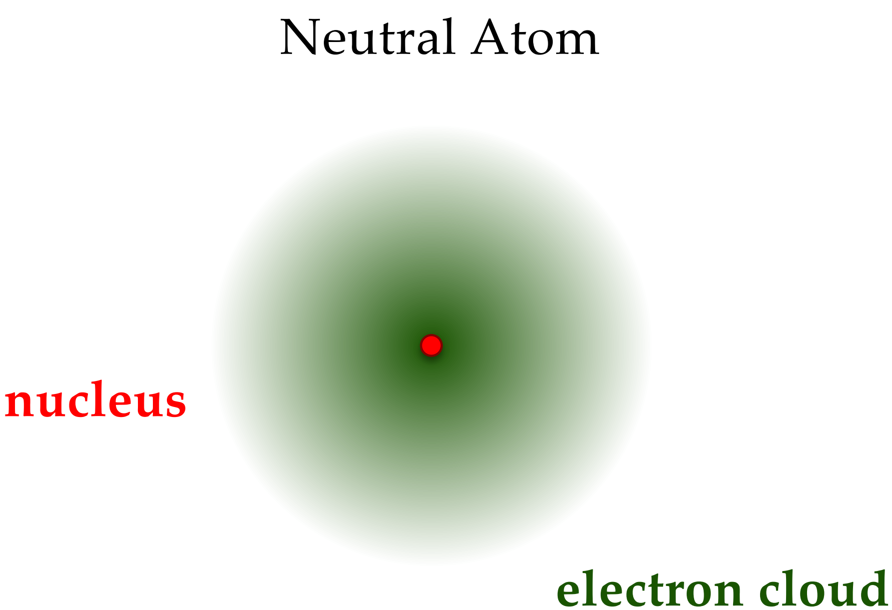
  Schiff PR 132:2194 (1963)

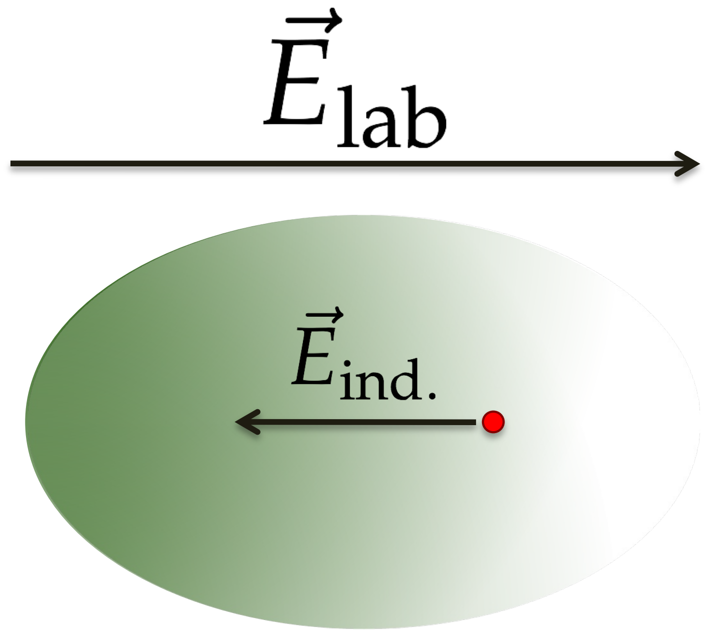
- **Relativistic atomic structure (^{225}Ra/^{199}Hg ~ 3)**

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

Schiff Moment

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





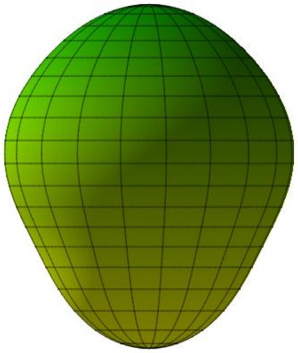
$$\vec{E}_{\text{ind.}} \approx -\vec{E}_{\text{lab}}$$

Nuclear Schiff Moment in the Lab Frame

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

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

1. Body-frame nuclear deformation with large intrinsic Schiff moment
2. Difference in lab-frame nuclear energy levels
3. The CP-violating physics that we seek to measure (unknown)



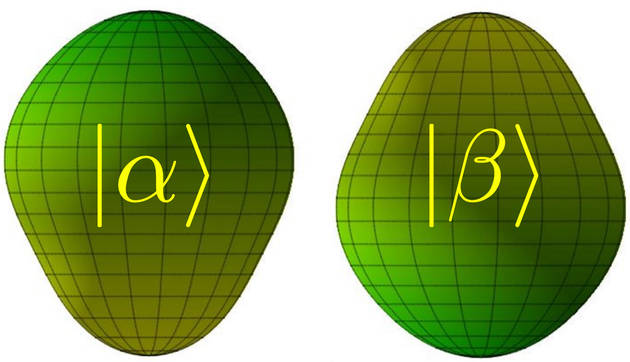
Example of large intrinsic Schiff moment: Pear-shaped nucleus in the "body-frame"

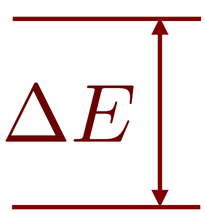
Enhanced Nuclear Moments with Parity Doublets

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

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

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**

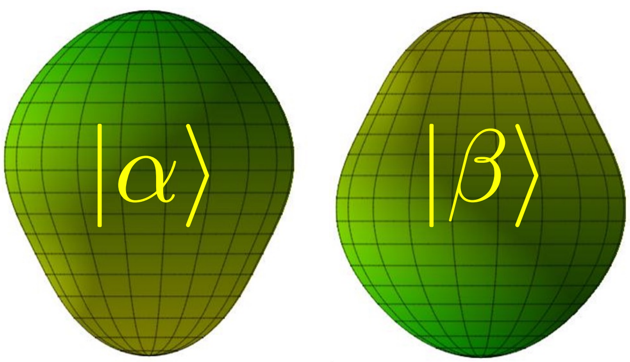
Haxton & Henley PRL 51:1937 (1983)

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



ΔE

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

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

- **Nearly degenerate parity doublet**

  Haxton & Henley PRL 51:1937 (1983)

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

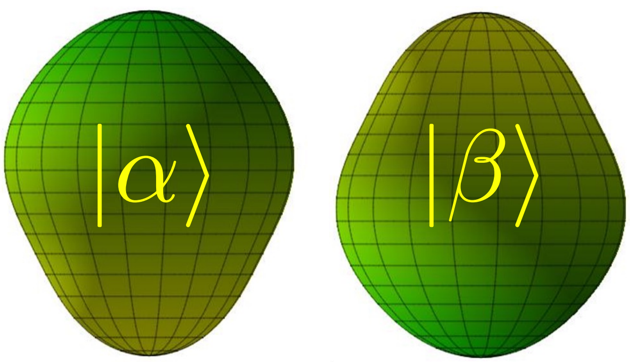
  Auerbach, Flambaum, & Spevak PRL 76:4316 (1996)

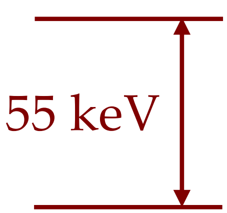
Enhanced Sensitivity in Radium-223/Radium-225

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

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

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**

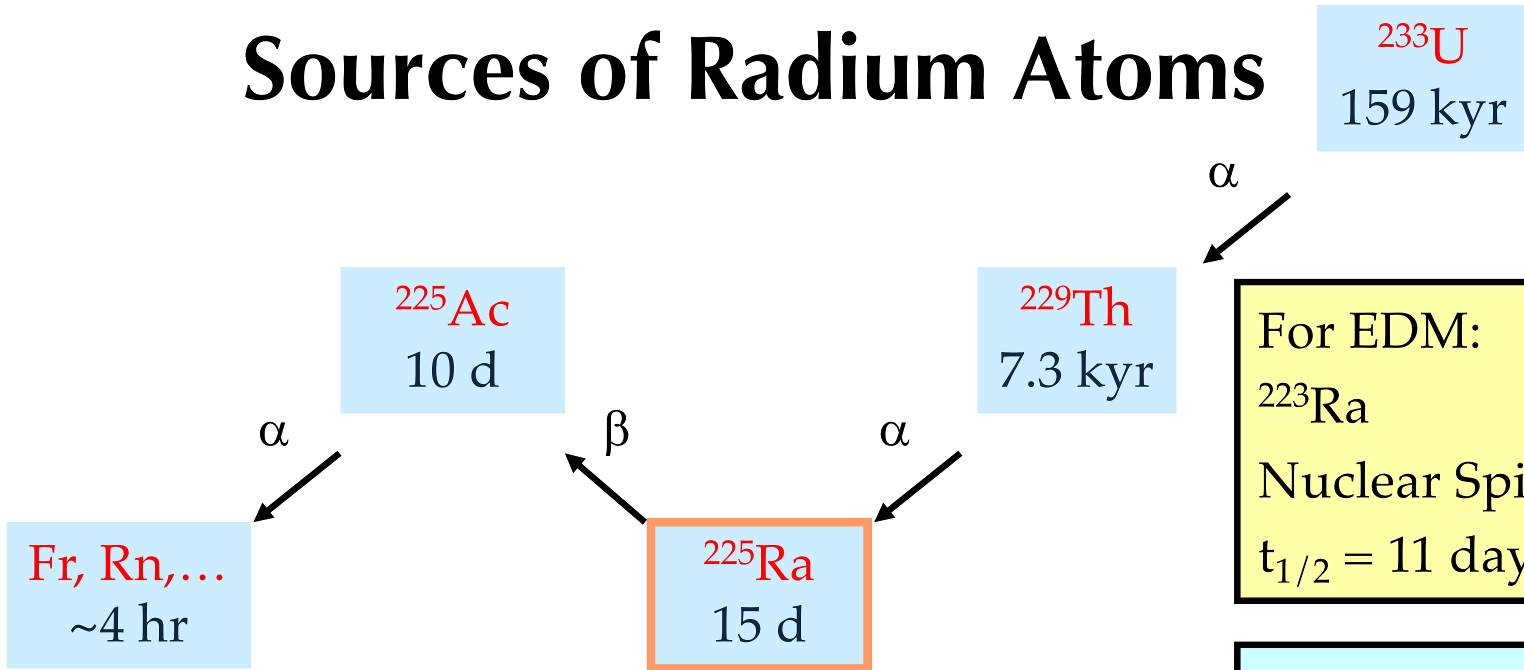
  Auerbach, Flambaum, & Spevak PRL 76:4316 (1996)

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



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

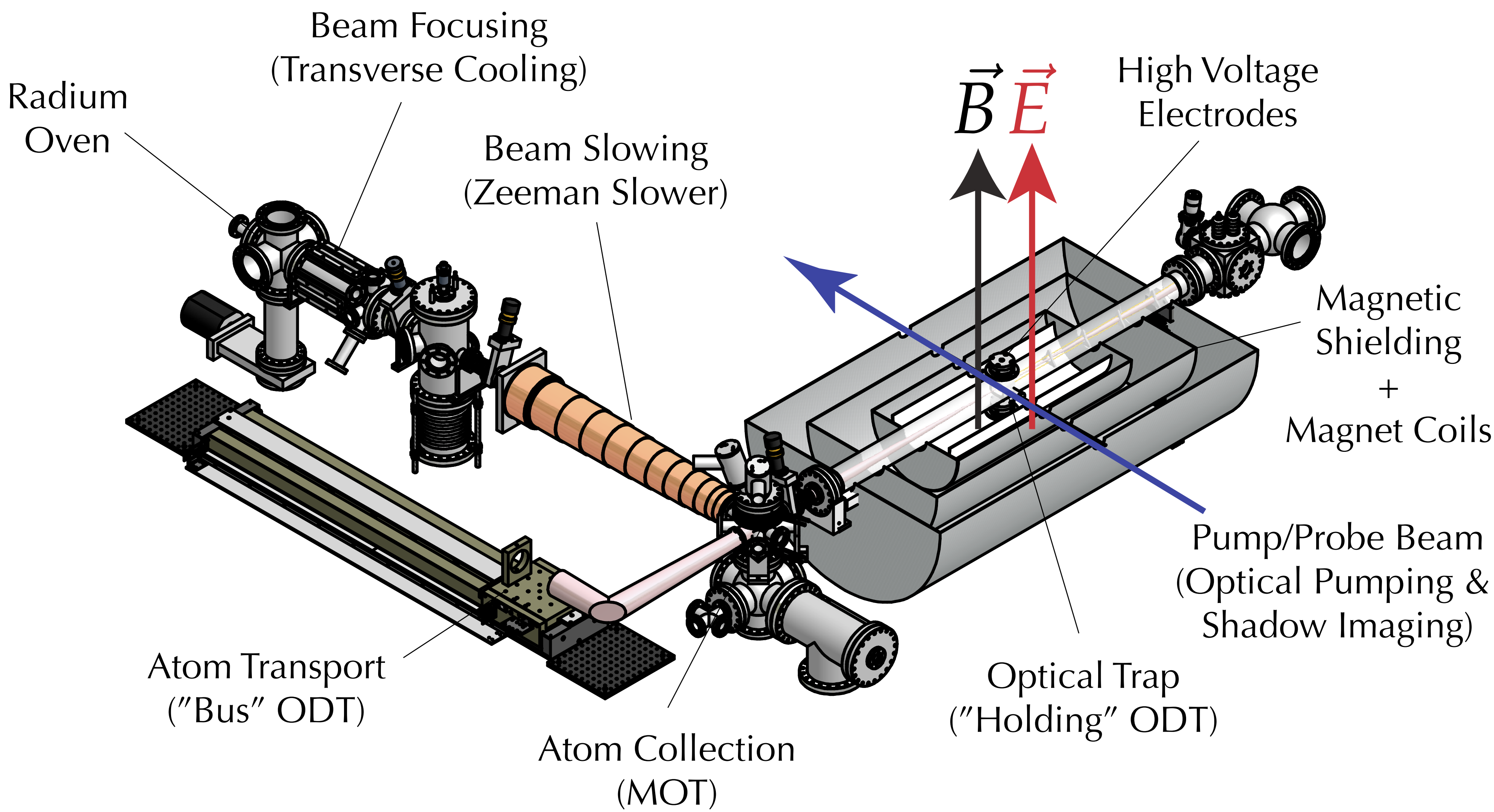
For EDM:
^{225}Ra
Nuclear Spin = ½
$t_{1/2}$ = 15 days

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

- 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
- **^{225}Ra is reserved for cancer research (targeted alpha therapy using ^{225}Ac), but we have a plan to use a ^{229}Th source.**

Eventually, the Facility for Rare Isotope Beams will produce ^{225}Ra, ^{229}Pa, etc.

The Laser Trap Ra EDM Experiment @ Argonne



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.

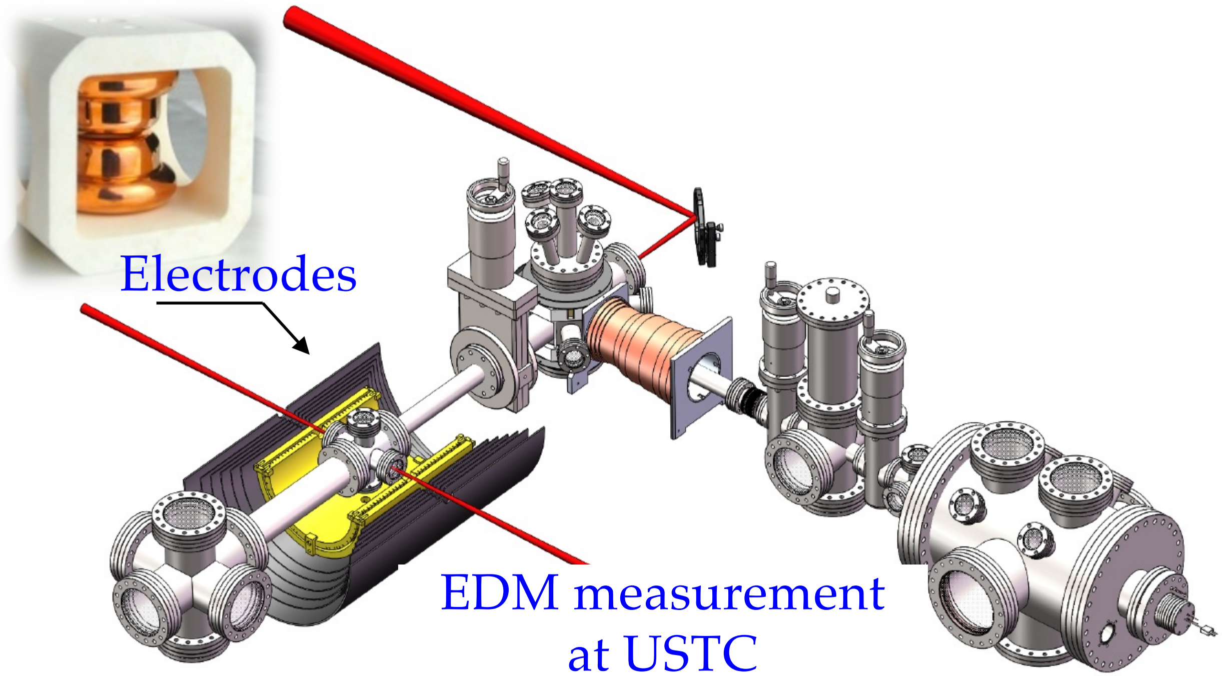
More efficient detection of atoms: optical cycling

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

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

Goal is <10^{-26} *e* cm over 4 years and then 10^{-28} *e* cm long term

2022: Atomic EDM of ^{171}Yb (Stable) in a Laser Trap Using Laser Probing



- Pathfinder experiment for ^{223,225}Ra
- Coherent spin precession time > 300 s
- **EDM(^{171}Yb) < 1.5x10^{-26} *e*-cm (95% C.L.), equivalent to ~1000xEDM(^{199}Hg)**

PRL 129, 083001 (2022)

slide from Z.-T. Lu

- Determined the magic ODT (optical dipole trap) wavelength
  PRA 102, 062805 (2020)
- Developed a quantum non-demolition (QND) method with a spin-detection efficiency of 50%
  Phys. Rev. App. 19, 054015 (2023)
- Observed the systematic due to parity mixing in ODT, and suppressed the effect by averaging measurements with ODTs in opposite directions
- Upgrades underway to improve sensitivity by x100

Recent Results in Xe-129 and Yb-171 (Not Pear-Shaped)

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)

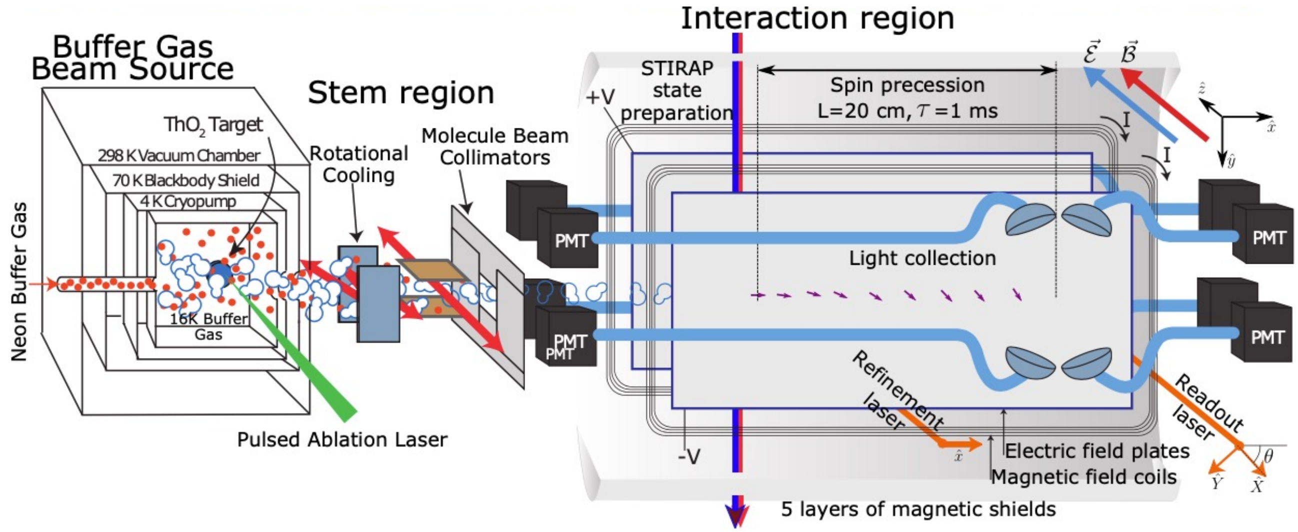
Yb-171: PRL 129:083001 (2022): **< 1.5×10^{-26} *e* cm (95%)**
(laser trap experiment, very similar to Ra experiment)

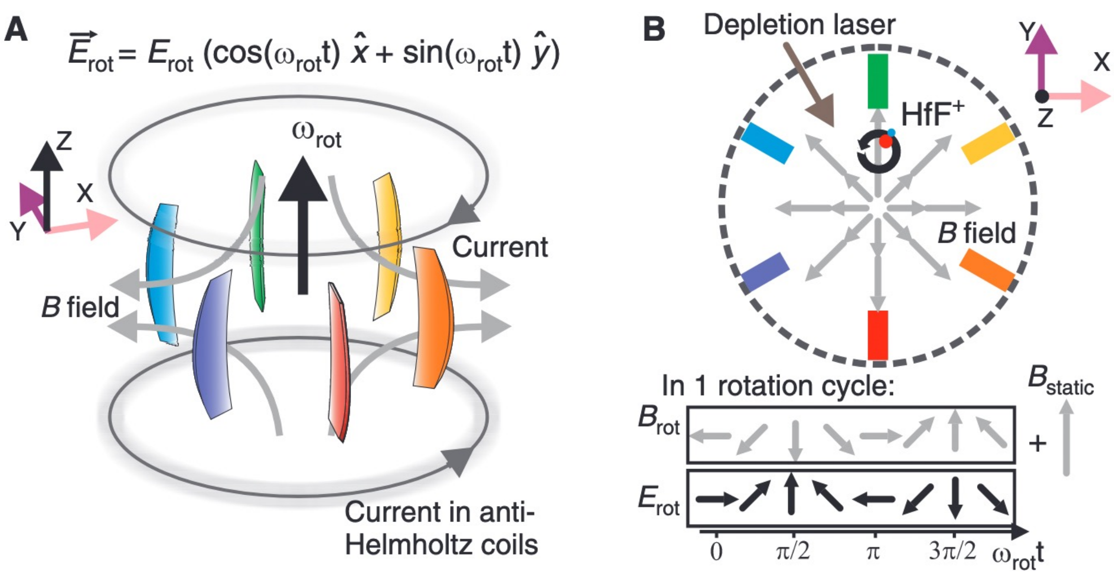
- The new physics constraints within the hadronic sector for all three of these experiments are roughly equal.
- The Yb experiment validates the laser trap approach for Ra for at least another three orders of magnitude.

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

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

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

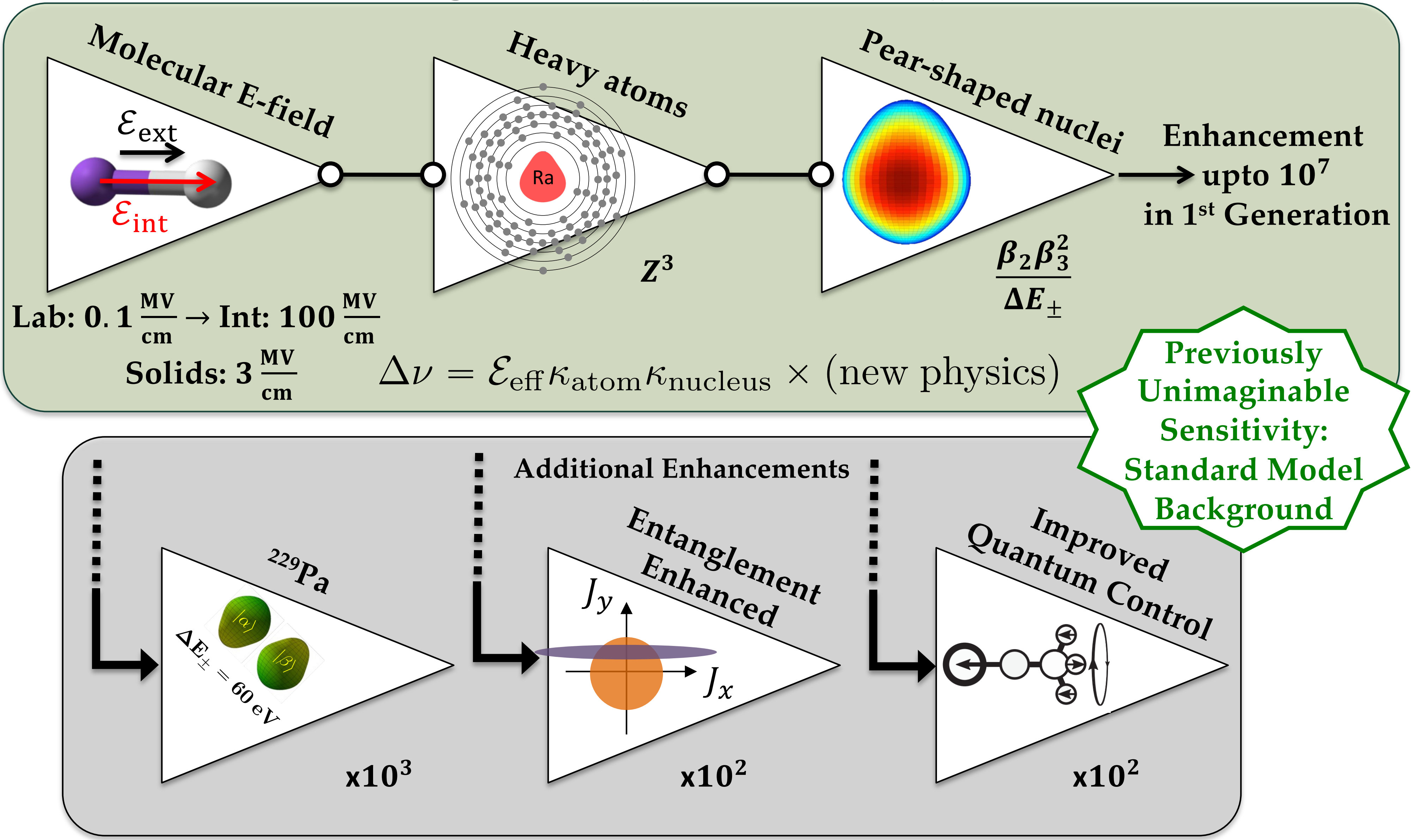




HfF+/ThF+
Ion Trap
(JILA)

Science 342 (6163) 1220 (2013)
PRL 119 153001 (2017)
arxiv:2212.11841 (2022)

New Laboratory: Trapped Radioactive Molecules Containing Heavy Pear-Shaped Nuclei

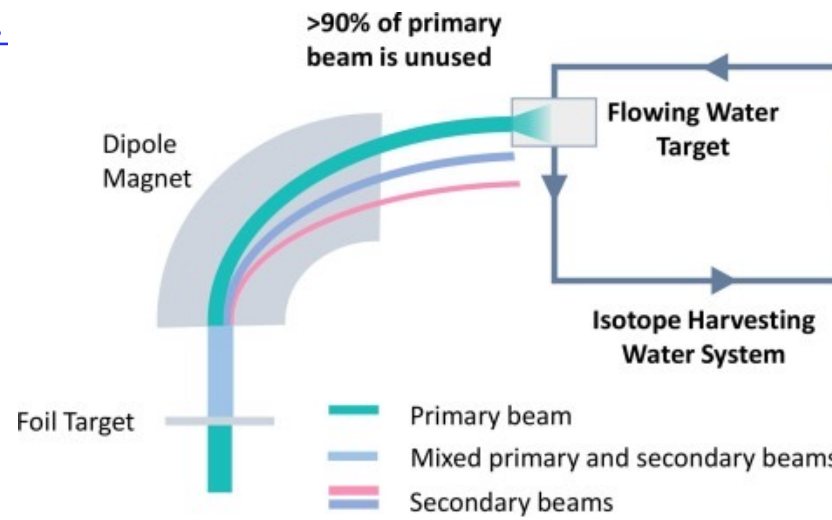


Opportunity for Nuclear Schiff Moments: Short-Lived Pear-Shaped Nuclei Inside Molecules

Enhancements: nuclear Schiff moment enhancement of x1000 (^{225}Ra)
to maybe(!?!) x1000000 (^{229}Pa)
and ~100 MV/cm effective internal E-field (lab < 1 MV/cm)

Potential: x10^{5} to x10^{10} more new physics sensitivity than the ^{199}Hg experiment <u>on a per atom basis.</u>

Opportunity:
Isotope harvesting @ FRIB:
from "Beam to Beaker"
(^{225}Ra, ^{229}Pa, ...)



NIMB 478 34 (2020)

Challenges:

- How do we get the harvested isotopes from "Beaker" into an experiment?
- How do we calibrate the new physics sensitivity of these "enhancer isotopes" inside of molecules?
- How do we efficiently form & probe short-lived radioactive molecules?

Facility for Rare Isotope Beams @ MSU

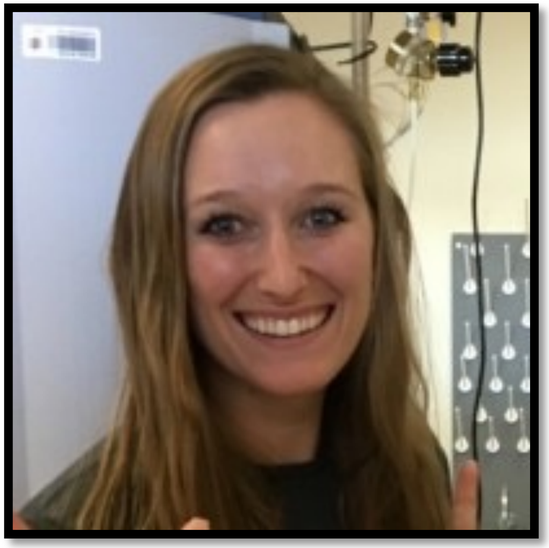
Michigan State University
East Lansing, MI
Bad at American Football
<u>Home of FRIB</u>

University of Michigan
Ann Arbor, MI
Good at American Football
no FRIB

Google Maps & Wikipedia Commons

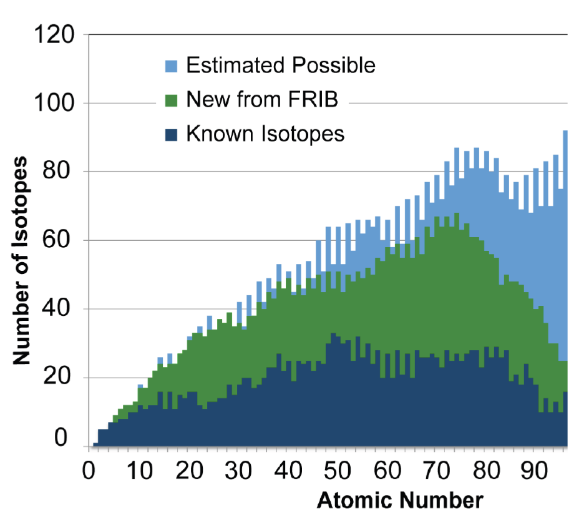
"Isotope Harvesting" at
The Facility for Rare Isotope Beams (MSU/East Lansing)

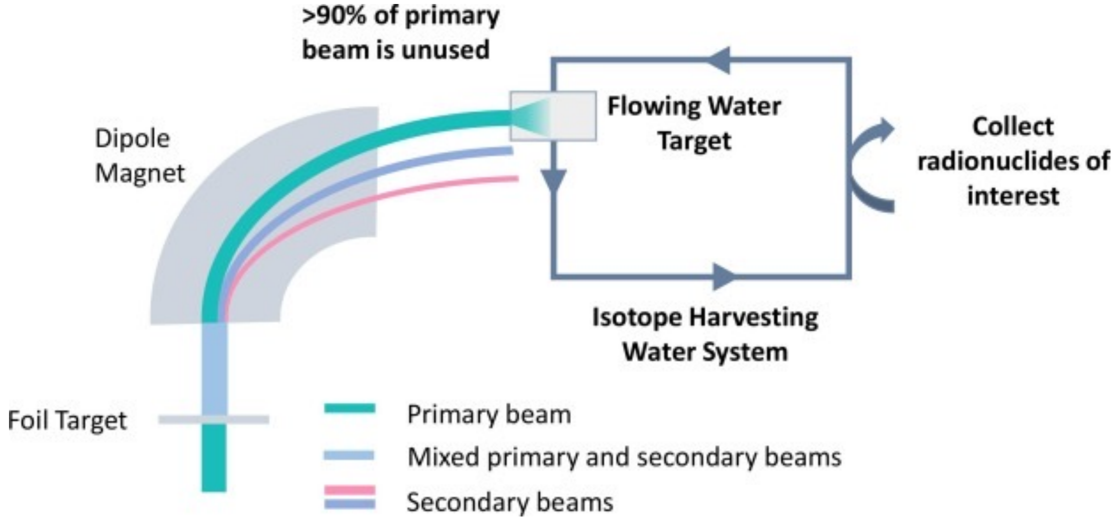
Prof. Greg Severin



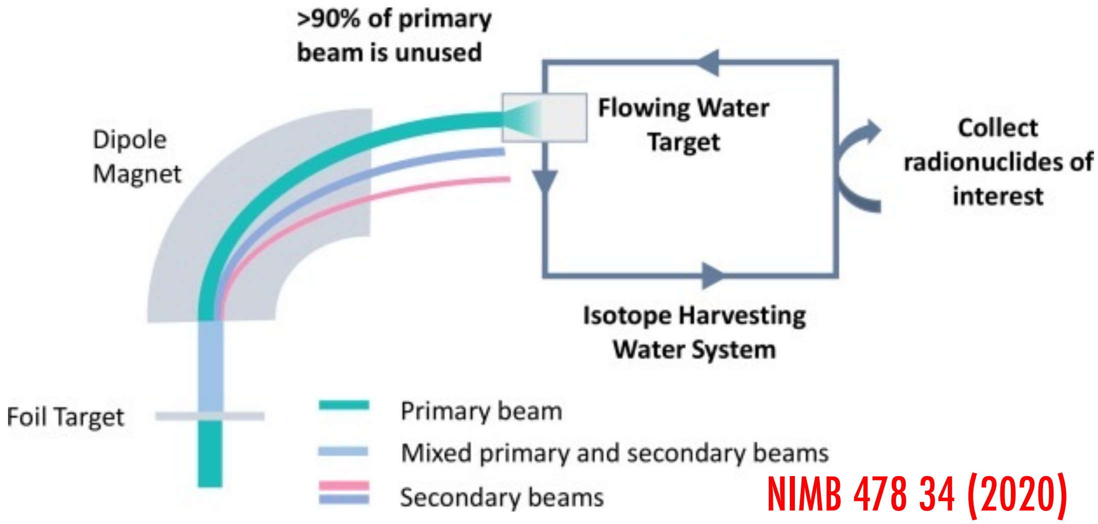
Prof. Alyssa Gaiser

Prof. Katharina Domnanich



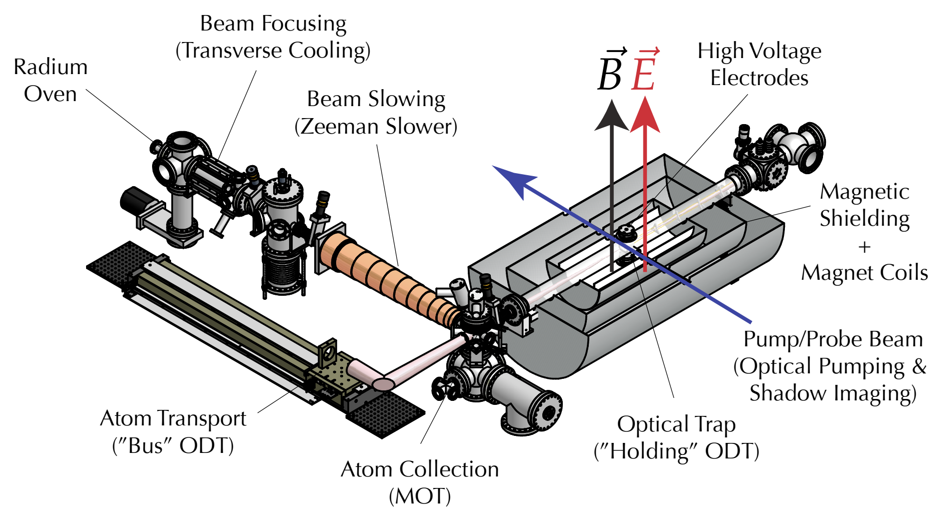


$upport Needed For “Beaker to Experiment”



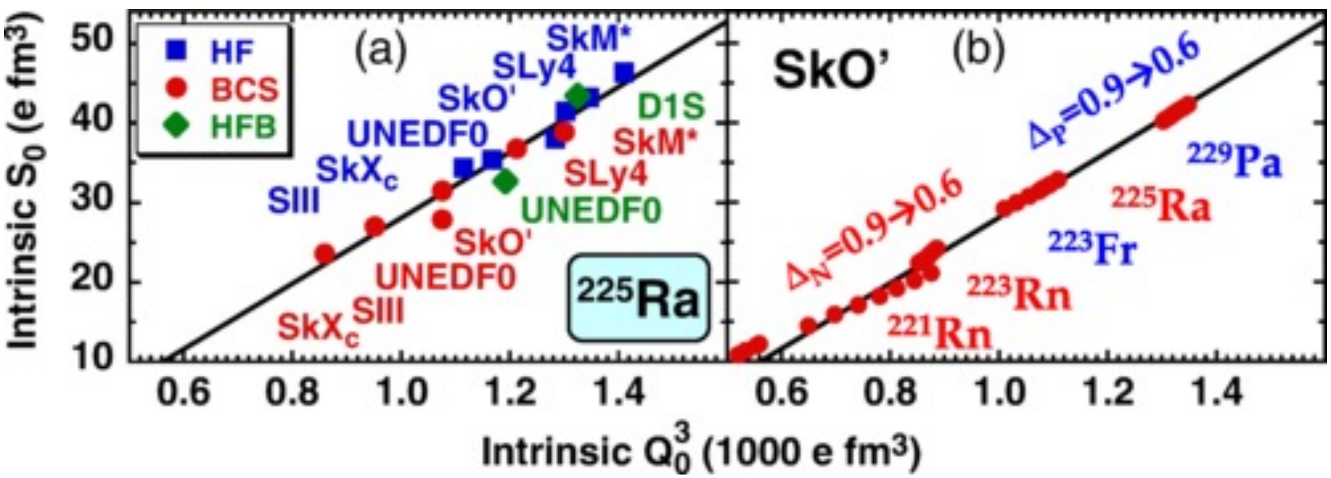
NIMB 478 34 (2020)

- FRIB Operations is supported by DOE-NP
- Isotope Harvesting @ FRIB is supported by DOE-Isotopes



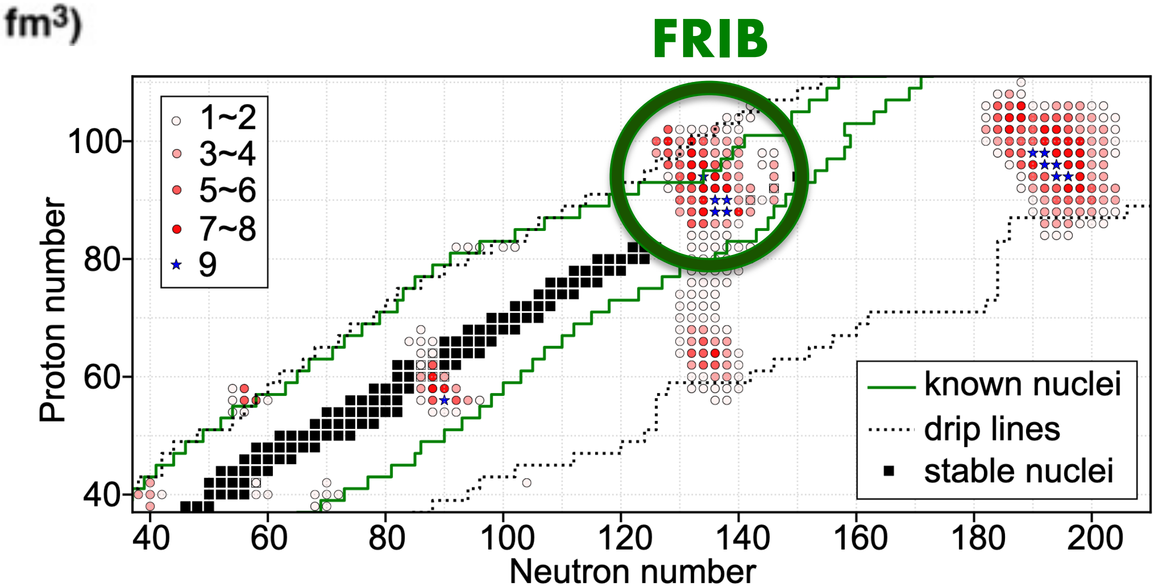
Calibrating the Intrinsic Schiff Moment

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



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

Nuclear structure measurements combined with nuclear theory can calibrate the new physics sensitivity of "enhancer" isotopes with uncertainty quantification!



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

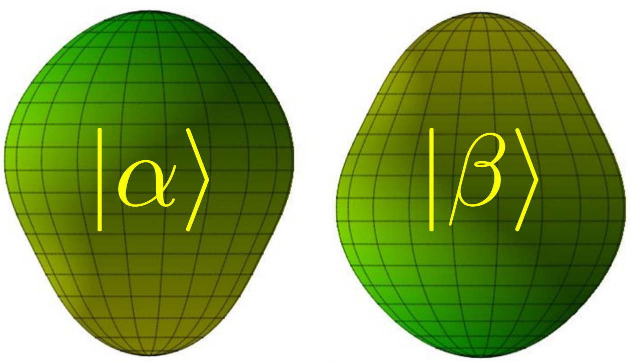
$$S_z = \frac{\langle er^2 z\rangle}{10} - \frac{\langle r^2\rangle \langle ez\rangle}{6}$$

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



$$\Delta E$$

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

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

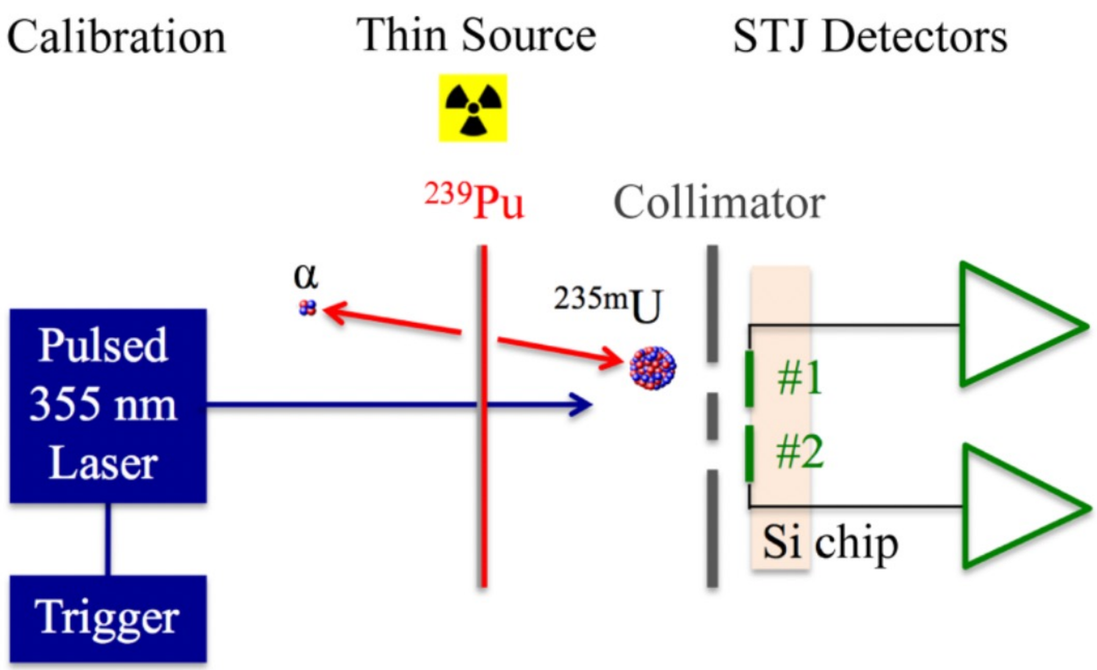
Pa-229: Haxton & Henley PRL 51:1937 (1983)
I. Ahmad et al Phys. Rev. C 92:024313 (2015)
Dobaczewski et al PRL 121, 232501 (2018)

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!

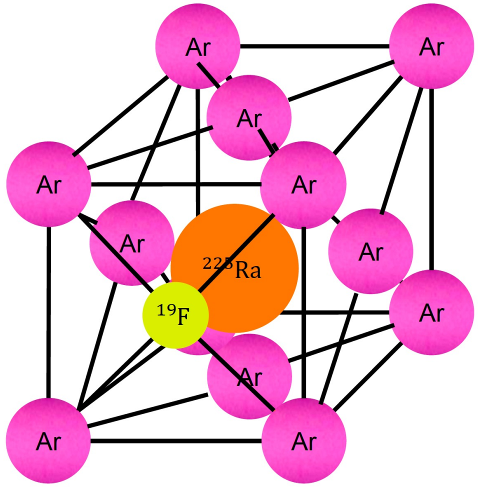
We have used superconducting high-resolution radiation detectors to measure the energy level of metastable ^{235m}U as 76.737 ± 0.018 eV. The ^{235m}U isomer is created from the α decay of ^{239}Pu and embedded directly into the detector. When the ^{235m}U subsequently decays, the energy is fully contained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



PRC 97 054310 (2018)

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.

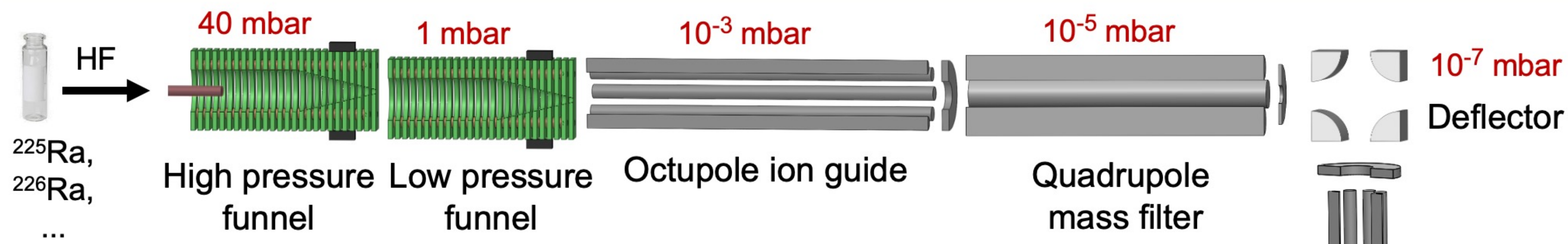
Pear-Shaped Nuclei Implanted In Cryogenic Solids: ^{225}RaF ($t_{1/2}$ = 15 days) & ^{229}Pa ($t_{1/2}$ = 1.5 days)

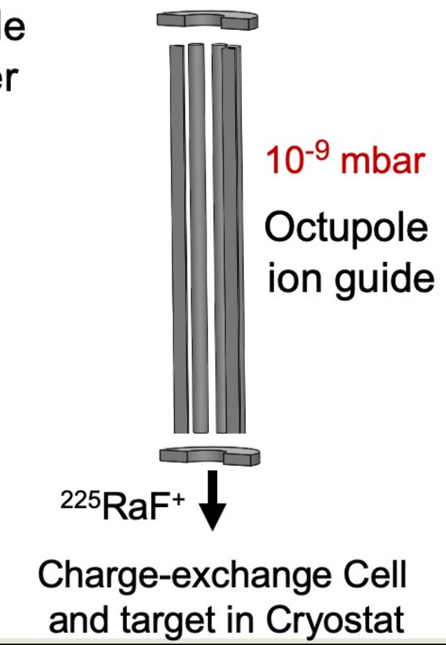


- **Efficient trapping of a wide variety of species**
- **Very high number densities**
- Stable and chemically inert confinement
- Transparent in the optical regime for optical probing
- Under certain conditions, polar molecules orient themselves along the crystal axes which allows for control of systematics: PRA 98:032513 (2018)
- **Challenge: quantum control in rare gas solids**
- Ions implanted in optical crystals allowing for optically-addressable nuclear spins Hyp. Int. 240:29 (2019), arXiv:2305.05781 (2023), arXiv:2304.10331 (2023)
- Implanted ions can sit at two distinct sites with opposite pointing internal E-fields which allows for control of systematics PR 131 1912 (1963)
- **Efforts are underway to form & implant molecules & ions into solids**

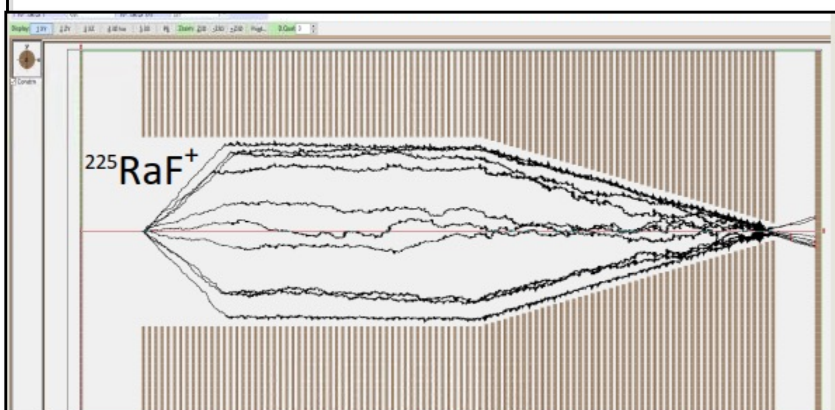
JTS DOE ECA 2018

RaF & RaOH in Noble Gas Solids (MSU/York/Toronto)



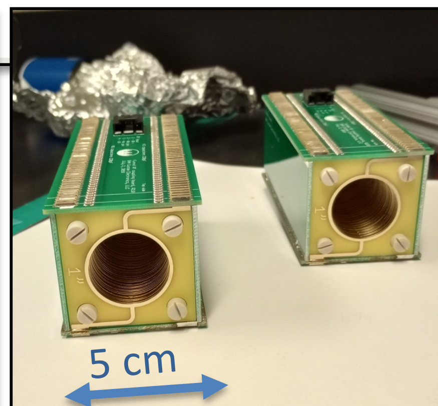


1. Ionization of liquid sample
2. Reduction of residual gas pressure in ion funnels and ion guides
3. Isotope mass separation to remove contaminants
4. Deflection by 90° to suppress neutrals propagating in line of sight
5. Second octupole for differential pumping
6. Neutralization in Charge-Exchange Cell
7. Implantation in cryogenic target

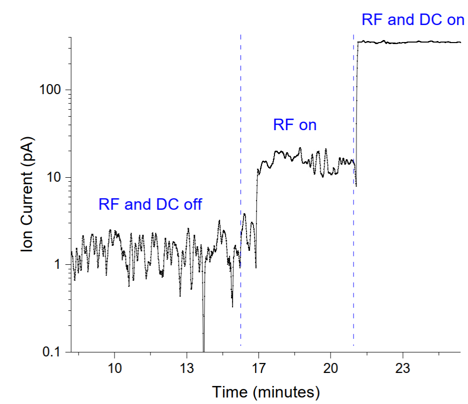


N. Nusgart, ICAP 2022

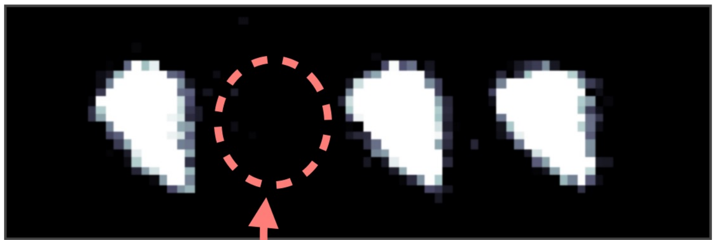
Ion funnels

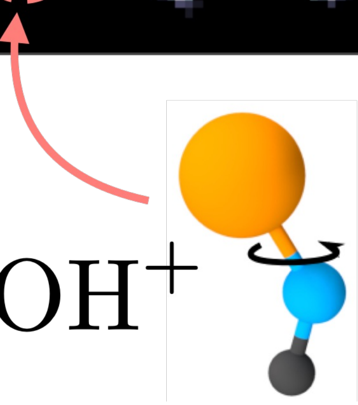


GAA Custom Electronics

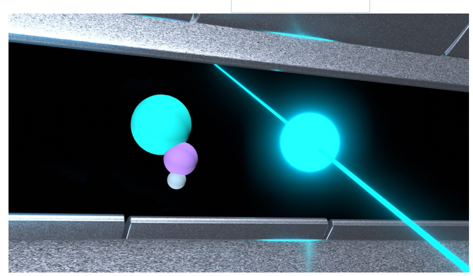


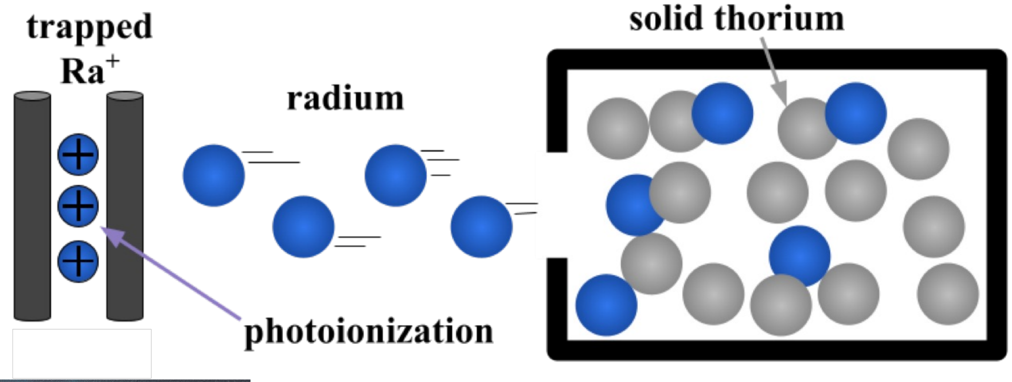
Quantum Logic Spectroscopy of Single Molecular Ions: $^{225}RaOH^+$, $^{225}RaSH^+$, & $^{225}RaOCH_3^+$ ($t_{1/2}$ = 15 days)





$RaOH^+$



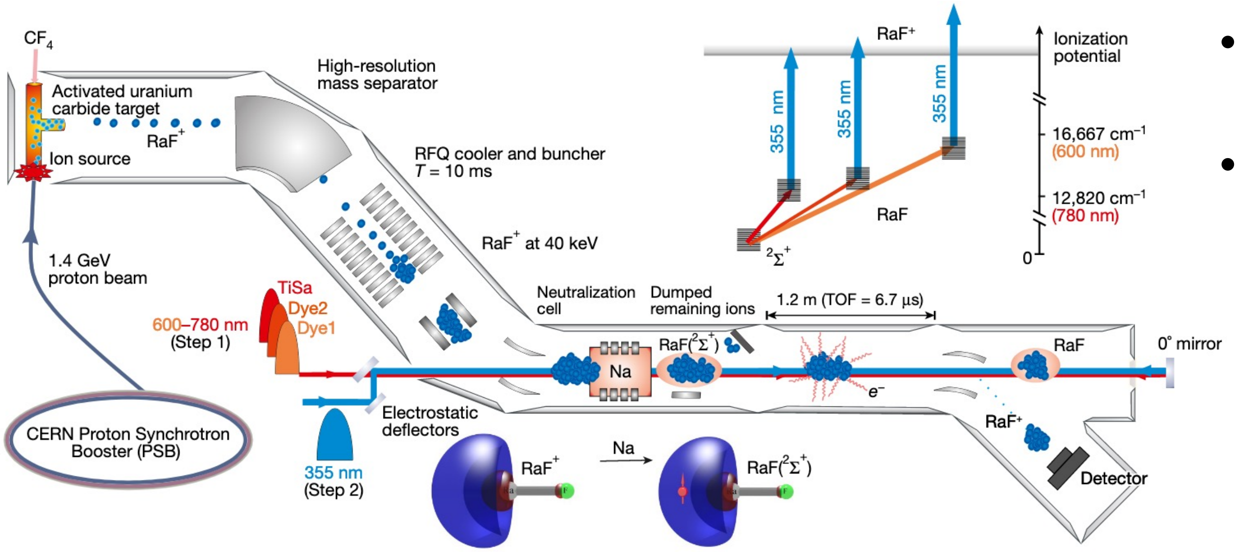


Santra et al., PRA 90, 040501(R) (2014)

- Spectroscopy and atomic structure measurements of the logic ion Ra^+
  PRL 122, 223001 (2019), PRA 100, 062512 (2019), PRA 100, 062504 (2019), PRA 102, 042822 (2020)
  PRA 105, 042801 (2022)
- Formation of relevant CPV-sensitive single molecular ions
  PRL 126, 023002 (2021)
- Identification of candidate molecular ions with pear-shaped nuclei with enhanced CPV sensitivity
  PRL 126, 023003 (2021)

slide from A. Jayich

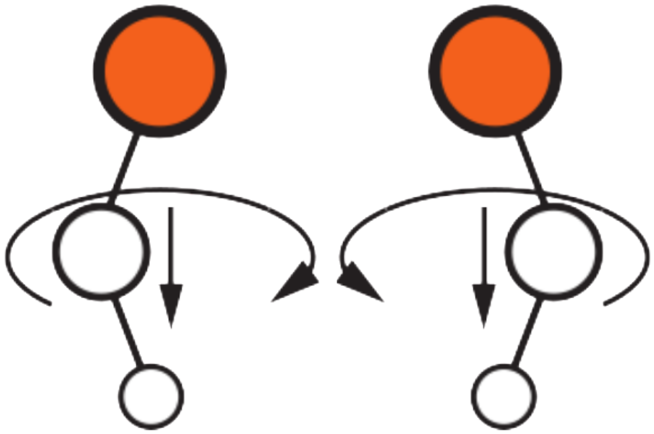
Direct Laser Cooling of Neutral Molecules Into a Laser Trap: ^{225}RaF & ^{225}RaOH ($t_{1/2}$ = 15 days)

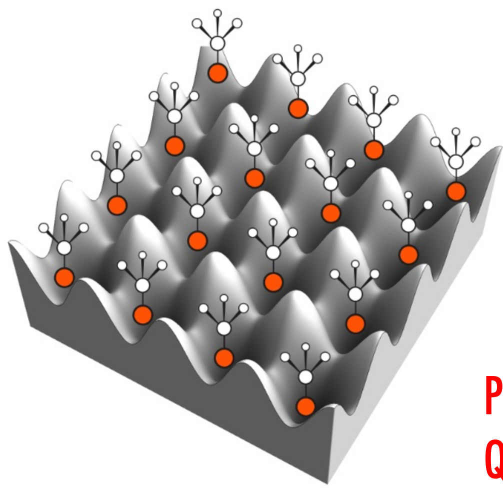


- Molecular spectroscopy of RaF is underway!
- Laser cooling of RaF appears feasible and scheme is under development

Nature 581:396 (2020)
PRL 127:033001 (2021)

slide from R. Garcia Ruiz





Benefits of Polyatomic Molecules
- Laser coolable & trappable
- Highly polarizable
- Comagnetometer states for control of systematics
- High CPV sensitivity

PRL 119, 133002 (2017)
Quantum Science & Tech. 5, 044011 (2020)

slide from N. Hutzler

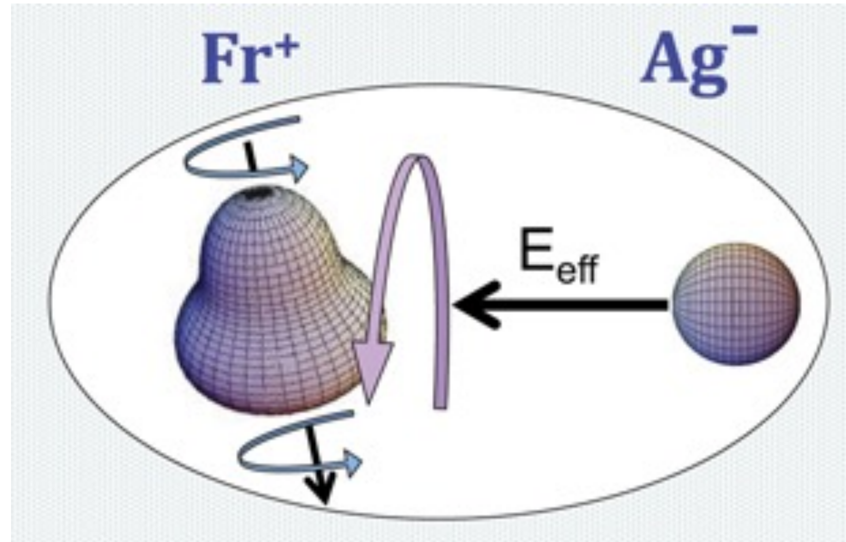
Ultracold Assembly of Neutral Molecules Within A Laser Trap: ^{223}FrAg ($t_{1/2}$ = 22 minutes)

- **Included in Gen-I Estimate:**
  - --300x NSM enhancement
  - --near-ideal molecular structure
  - --t_{coh} ~10 s [Cornish, Zwierlein, etc.]
  - -- ~100% detection efficiency
  - --n = 10^4 molecules

⇒ ~1000x projected improvement vs. ^{199}Hg state of the art

Needs major involvement of radiochemists, thermal ion beam source experts, radiological safety experts, …
to develop ^{223}Fr+ ion source

slide from D. DeMille



All these parameters *ALREADY DEMONSTRATED* with stable bi-alkalis (!)

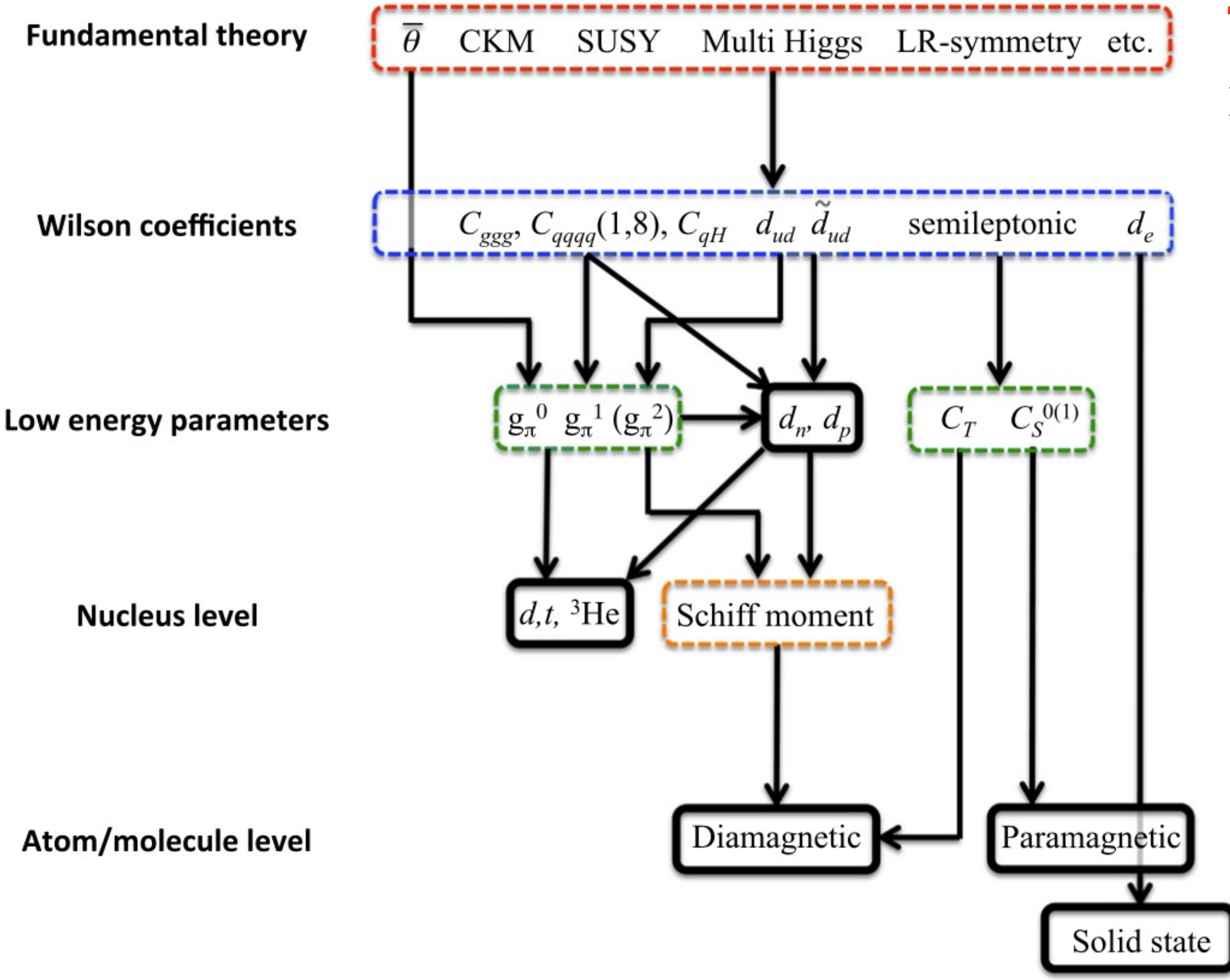
Theory calculations favorable:

New J. Phys. 23 113039 (2021)
New J. Phys. 24 025005 (2022)

odd-proton nuclei like ^{223}Fr probe largely orthogonal parameter space vs. odd-neutron species

Connecting New Physics to EDMs

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



Sources of *CP*-violation

Particle Physics Theory

Effective Field Theory

Lattice QCD Theory

Nuclear Theory
+
Nuclear Experiment

Atomic Theory
+
Atomic Experiment

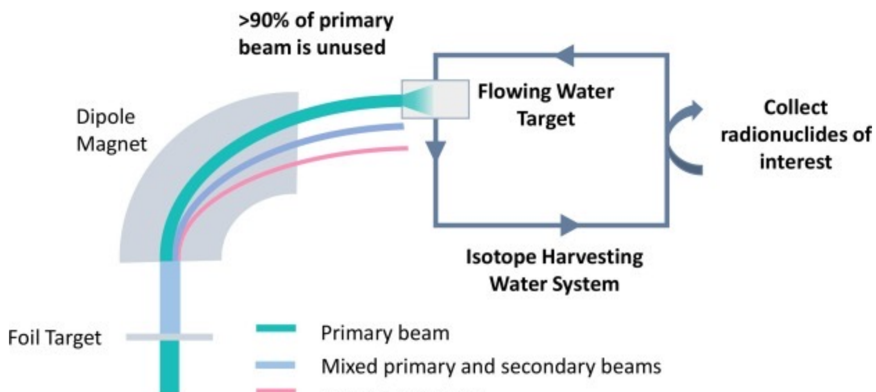
Molecular Theory
+
Molecular Experiment

EDM Measurements

The Nuclear Pear Factory: A Proposed Center

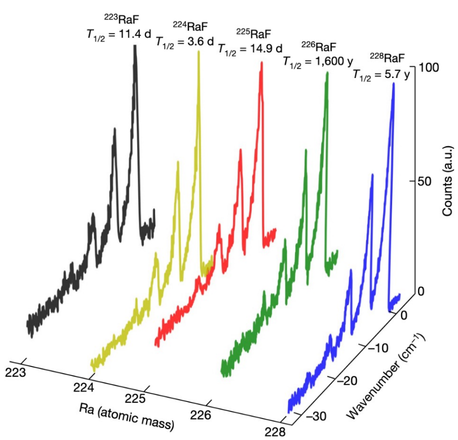
Nature 497:199 (2013)

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.

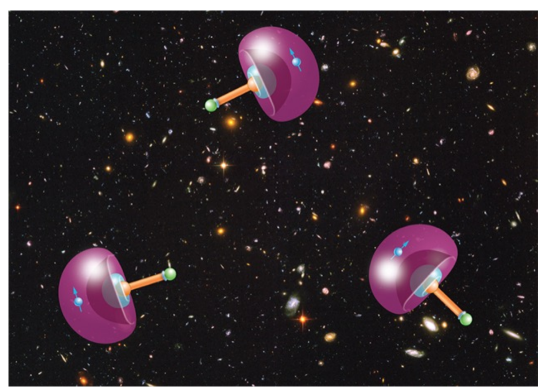


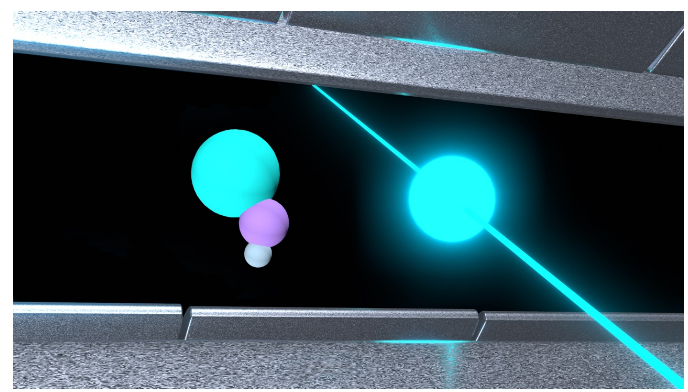
NIMB 478 34 (2020)

N P F



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. Pear-shaped nuclei such as Radium-225 and Protactinium-229 have significantly enhanced sensitivity to *CP*-violation originating within the nuclear medium.
3. **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.**
4. **Isotope harvesting and radiochemistry at FRIB enables access to these enhancer isotopes in practical quantities for ultrasensitive EDM searches.**
5. **We propose a center, The Nuclear Pear Factory, to realize the unprecedented discovery potential made possible by short-lived radioactive molecules.**

singhj@frib.msu.edu **web: spinlab.me** **twitter: @spinlabmsu**

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