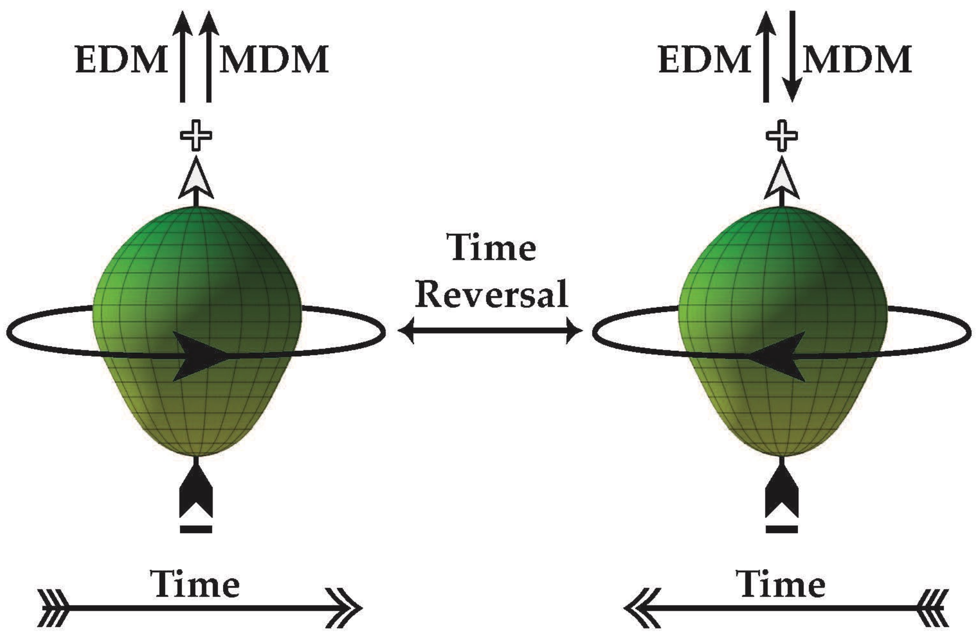
Electric Dipole Moment (2/2)

Yesterday: Motivation & Background, The Atomic Ra EDM Experiment

Today: "Atomic" Parity Violation, Neutrons & Nuclei, & Radioactive Molecules



AIP Emilio Segrè Visual Archives, Born Collection

Maria Goeppert Mayer

Jaideep Taggart Singh (he/him/his)

Michigan State University/FRIB

National Nuclear Physics Summer School 2024

Tuesday July 23, 2024 @ 09:00

Indiana University Bloomington

Swain Hall West 007 (Basement)

FRIB

SCAN ME

Early Career Researchers Should Receive A Yearly Cost-Of-Living Adjustment & A Living Wage!

What is a living wage? According to DOE for grad students: $45k/yr ($22.5/hr)

LIVING WAGES

SC is committed to ensuring that students, trainees, and postdoctoral fellows are paid a fair and equitable wage sufficient to allow a reasonable standard of living. Applicant institutions are strongly encouraged to examine their institutional pay scales to ensure that all personnel earn a living wage. The provision of fellowships, traineeships, stipends, honoraria, subsistence allowances, and other similar payments may be allowable expenses on SC financial assistance awards, per 2 CFR 200.430, § 200.431, and § 200.466. For graduate students, SC considers a reasonable living wage to be an annual income of $45,000, excluding benefits.

DE-FOA-0003177

Living Wage Calculator

Nuclear Science Long Range Plan

NSAC 2023 Long Range Plan Recommendation 1, Bullet 3:

"Raising the compensation of graduate researchers to levels commensurate with their cost of living—without contraction of the workforce—lowering barriers and expanding opportunities in STEM for all, and so boosting national competitiveness."

PIs: ask your team if their stipend now goes as far as yours did "back then!"

Early Career Researchers: consider forming/joining a union!

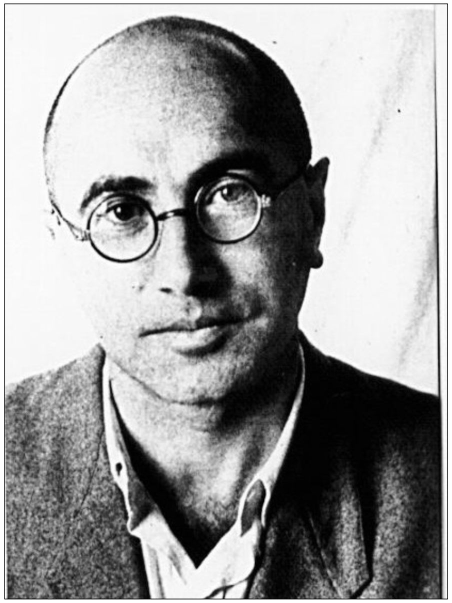
Zel′dovich & Parity Violation

ELECTROMAGNETIC INTERACTION WITH PARITY VIOLATION

Ia. B. ZEL'DOVICH

Submitted to JETP editor September 26, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) **33**, 1531-1533 (December, 1957)



PARITY NONCONSERVATION IN THE FIRST ORDER IN THE WEAK-INTERACTION CONSTANT IN ELECTRON SCATTERING AND OTHER EFFECTS

Ya. B. ZEL' DOVICH

Submitted to JETP editor December 25, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) **36**, 964-966 (March, 1959)

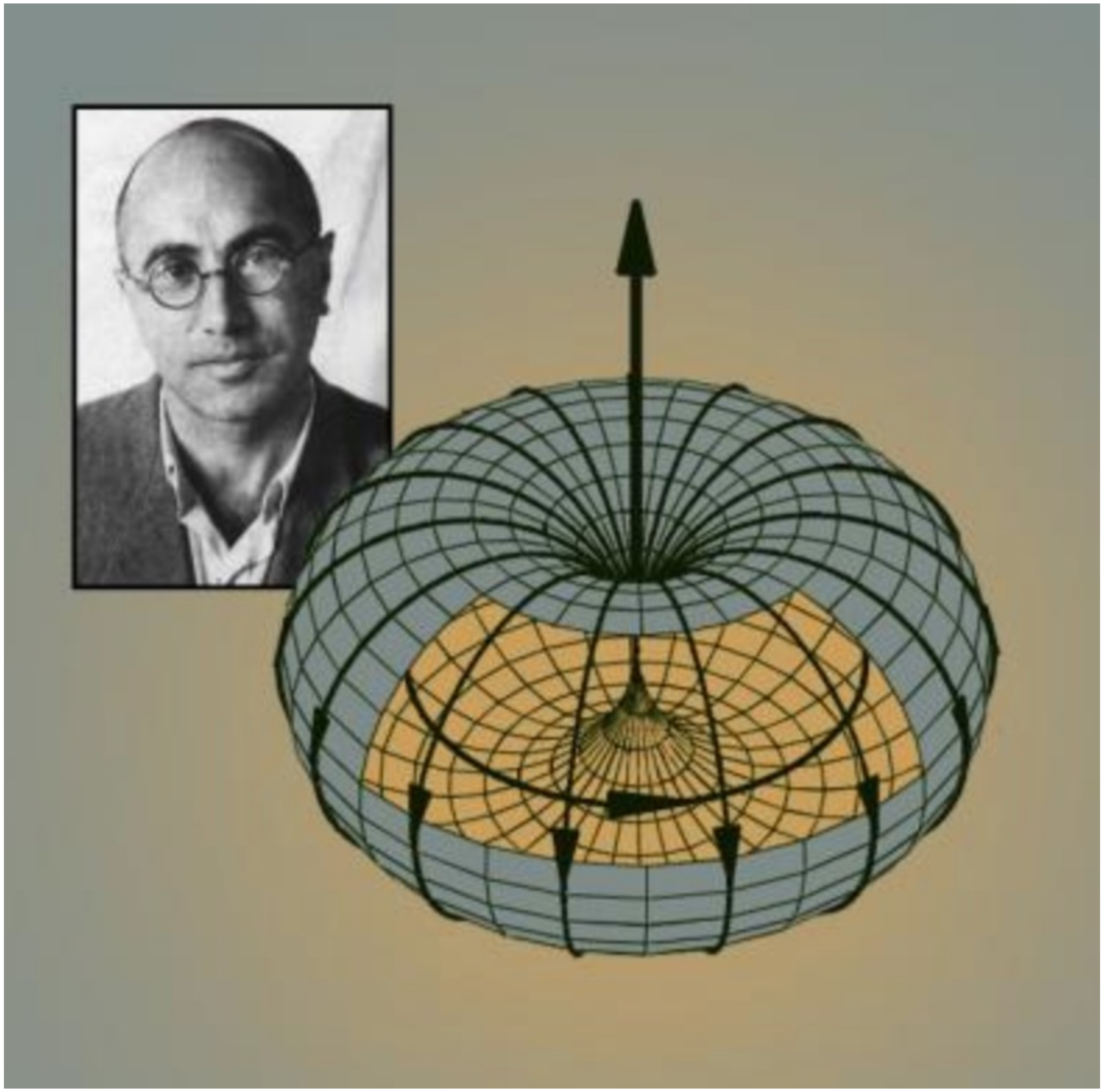
https://phys-astro.sonoma.edu/brucemedalists/yakov-zeldovich

http://www.jetp.ras.ru/cgi-bin/e/index/e/6/6/p1184?a=list

http://www.jetp.ras.ru/cgi-bin/e/index/e/9/3/p682?a=list

Historical Note:
The Wu Experiment was published February 15, 1957
https://doi.org/10.1103/PhysRev.105.1413

Properties of Nuclear Anapole Moments

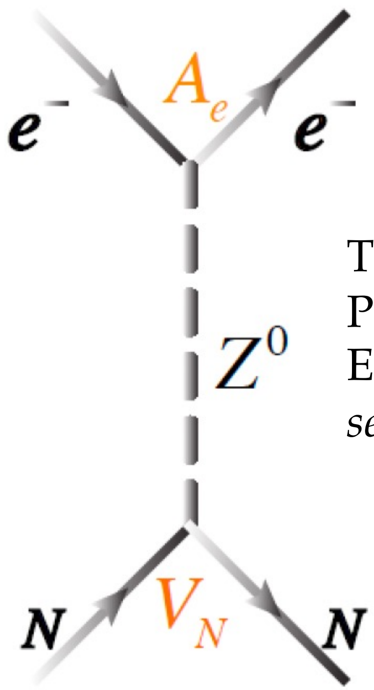


https://www.eurekalert.org/multimedia/925121

- Generated by toroidal currents inside the nucleus
- ***Violates* parity but *conserves* time-reversal**
- Ultimately due to weak interaction effects within the nucleus
- Probed via nuclear-spin dependent interactions with atomic electrons that penetrate the nucleus

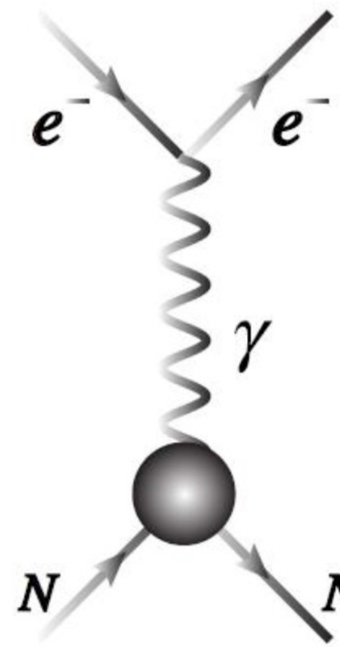
Nuclear Anapole Moments and Atomic Parity Violation

Nuclear-Spin
Independent



This look just like
Parity Violating
Electron Scattering (PVES)!
see C. Palatchi

Main Nuclear-Spin Dependent
Effect in Heavy Atoms
(Nuclear Anapole Moment)



These experiments require the crucial interplay between theory and experiment to interpret the results as well as several measurements across an isotope chain to disentangle different sources of PV effects.

https://indico.cern.ch/event/671322/ - D. Antypas Presentation @ PSAS 2018

Key Concept: Measure the "Mixing" of Quantum States With Opposite Parity

- parity excited state $\updownarrow$ ΔE = energy difference

+ parity excited state

excitation

F = fluorescence photons which indicates that the transition to the excited state occurred

M.A. Bouchiat
photo: Zolotrev

$$\text{Asymmetry} = \frac{F(+E_0) - F(-E_0)}{F(+E_0) + F(-E_0)} = \kappa_{\text{PV}} \frac{Z^3 E_0}{\Delta E}$$

+ parity ground state

Lab electric field (E_0) via the Stark Effect and PV mix the excited states. The fluorescence intensity contains an "interference term" (just like PVES) which can be measured by reversing the electric field direction.

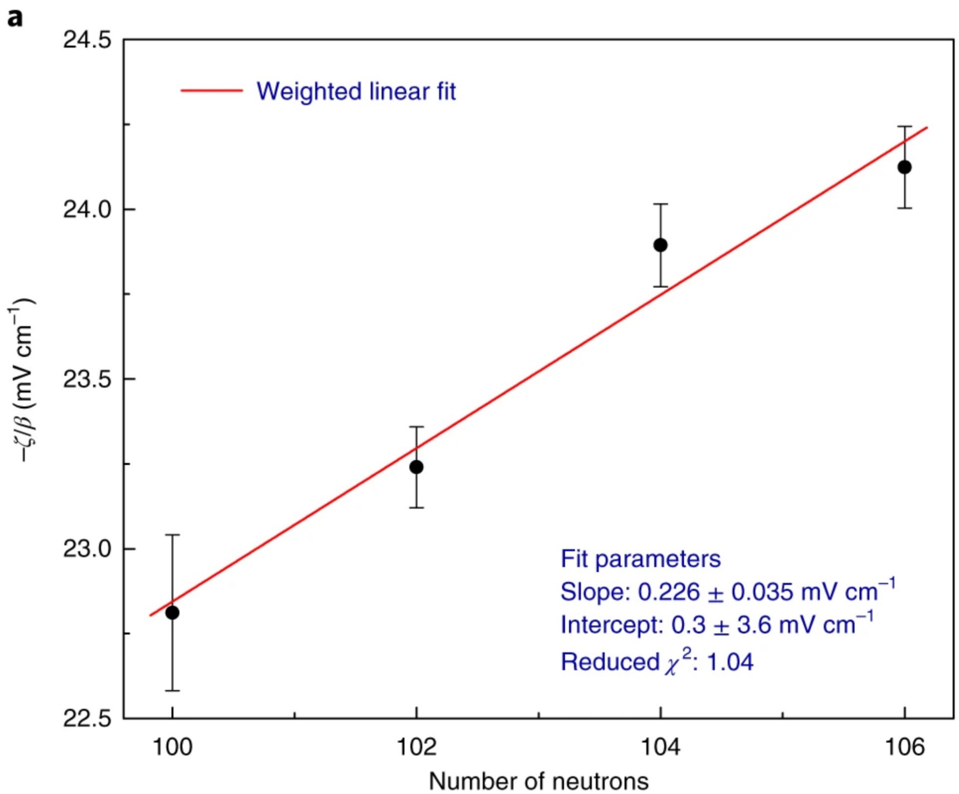
https://www.britannica.com/science/Compton-effect

Physics Letters B 117, 5, pp. 358-364 (1982)

Future Prospects of "Atomic" Parity Violation: Molecules

Key Idea: The energy difference between states of opposite parity can be chosen/manipulated to be very small enhancing the observable PV signal.

Atomic Parity Violation in *I*=0 Yb isotopes (improvements underway for I>0 isotopes)
D. Budker @ Mainz

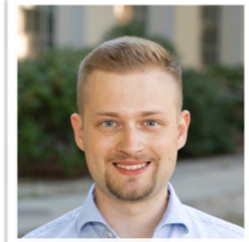


Nature Physics 15, 20–123 (2019)

- Atomic Francium @ TRIUMF
  2022 J. Phys.: Conf. Ser. 2391 012002
- Zombies: Cold beam of polar diatomic molecules
  D. DeMille @ Chicago/ANL
  Phys. Rev. Lett. 120, 142501 (2018)
- Light nuclei in trapped polyatomic molecules:
  E. Norrgard @ NIST
  Phys. Rev. A 102, 052828 (2020)
- Single diatomic molecular ions in a Penning trap:
  J. Karthein @ TAMU
  https://arxiv.org/abs/2310.11192

Single Molecular Ions in a Penning Trap

slide from Jonas Karthein (currently MIT Postdoc to Texas A&M Assistant Prof. Fall 2024)

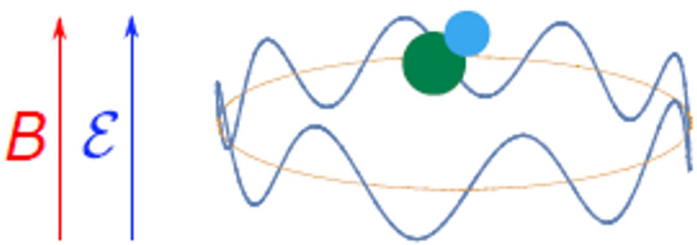

Dr. J. Karthein

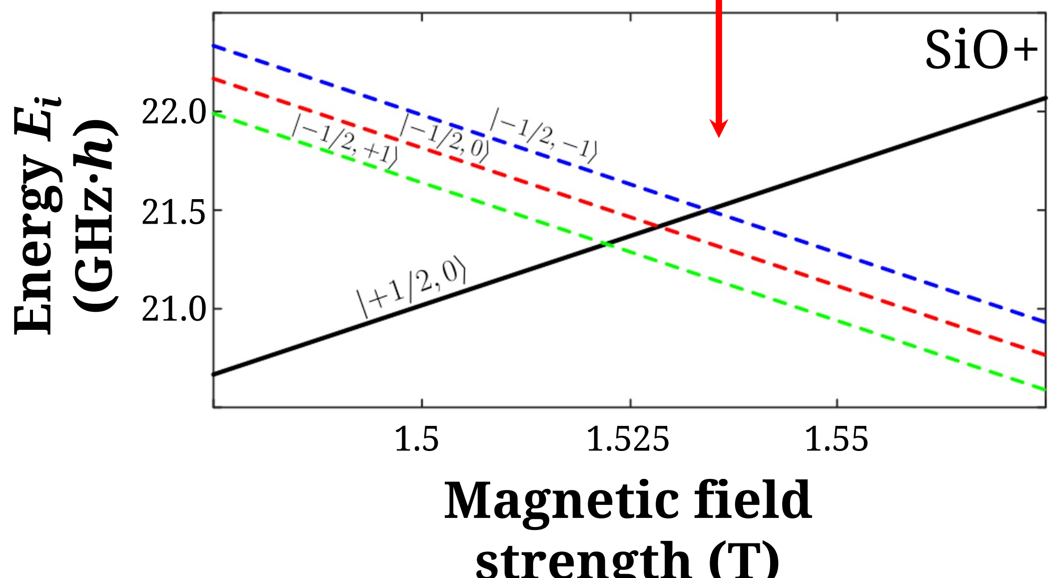
Direct, **high-precision** access to **electroweak** nuclear properties at the intersection of AMO, nuclear and particle physics:

- ➔ Hadronic parity violation
- ➔ "TeV-scale" Z'-boson search
- ➔ Nuclear electroweak structure

$$E_{PV} \sim \frac{\langle \psi_\uparrow^+ | H_\pm | \psi_\downarrow^- \rangle}{E_- - E_+}$$

Degeneracy + Stark mixing
→ amplification by >**10[11]**





Hutzler et al. arXiv 2302.02165 (2023).

https://arxiv.org/abs/2310.11192

Altuntas, DeMille. et al. PRL 120, 142501 (2018).

Intermission

Questions?

1. stuff

SLAC E122 and The 1979 Nobel Prize

Volume 77B, number 3 PHYSICS LETTERS 14 August 1978

PARITY NON-CONSERVATION IN INELASTIC ELECTRON SCATTERING ☆

C.Y. PRESCOTT, W.B. ATWOOD, R.L.A. COTTRELL, H. DeSTAEBLER, Edward L. GARWIN, A. GONIDEC [1], R.H. MILLER, L.S. ROCHESTER, T. SATO [2], D.J. SHERDEN, C.K. SINCLAIR, S. STEIN and R.E. TAYLOR
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94305, USA

J.E. CLENDENIN, V.W. HUGHES, N. SASAO [3] and K.P. SCHÜLER
Yale University, New Haven, CT 06520, USA

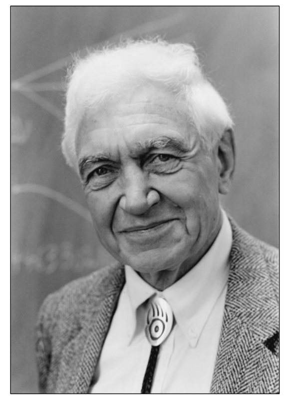
M.G. BORGHINI
CERN, Geneva, Switzerland

K. LÜBELSMEYER
Technische Hochschule Aachen, Aachen, West Germany

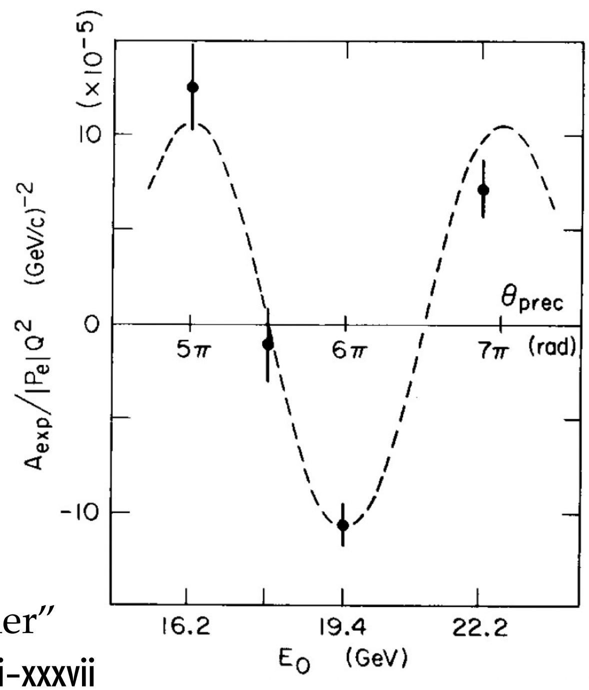
and

W. JENTSCHKE
II. Institut für Experimentalphysik, Universität Hamburg, Hamburg, West Germany

Received 14 July 1978



V. W. Hughes
My Academic "Grandfather"
Annu. Rev. Nucl. Part. Sci. 2000. 50:i–xxxvii



From the 1979 Nobel Prize Press Release (October 15, 1979):

For PVES see C. Palatchi

...Of special interest is a result, published in the summer of 1978, of an experiment at the electron accelerator at SLAC in Stanford, USA. In this experiment the scattering of high energy electrons on deuterium nuclei was studied and an effect due to a direct interplay between the electromagnetic and weak parts of the unified interaction could be observed....

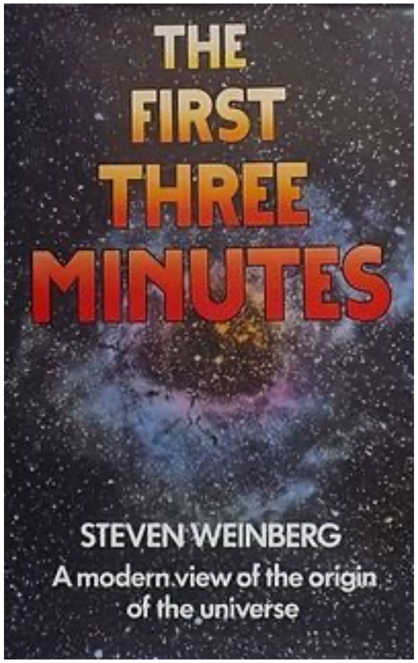
Steven Weinberg (1933-05-03 to 2021-07-23)
1979 Nobel with Sheldon L. Glashow & Abdus Salam

The Nobel Foundation

1. "But I did learn one big thing: that no one knows everything, and you don't have to."
2. "My advice is to go for the messes — that's where the action is."
3. "My third piece of advice is probably the hardest to take. It is to forgive yourself for wasting time."
4. **"Finally, learn something about the history of science, or at a minimum the history of your own branch of science."**

Four Golden Lessons (2003)
https://www.nature.com/articles/426389a

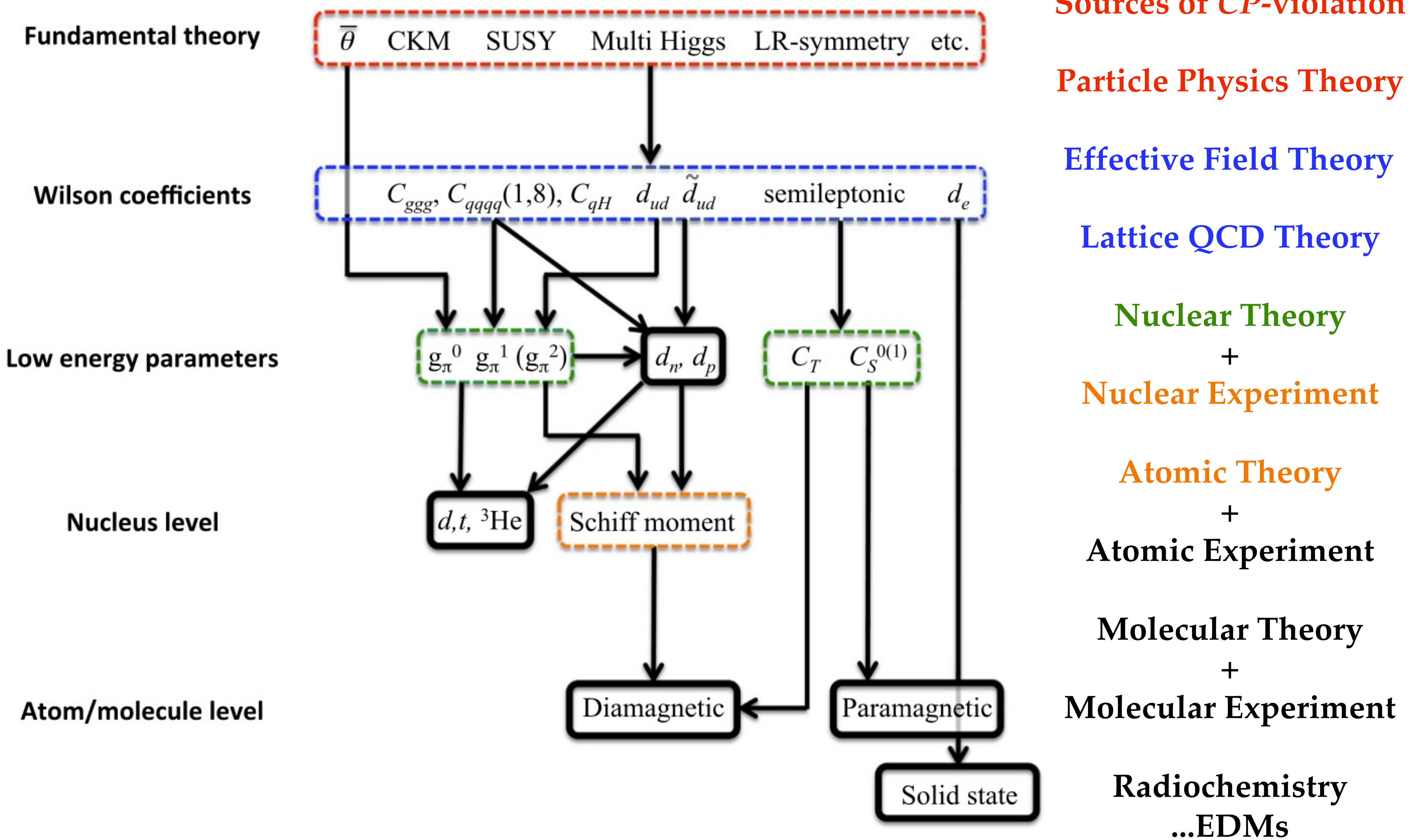
Weinberg, effective field theories, and time reversal violation
U. van Kolck
Nuclear Physics B Volume 1004, July 2024, 116574
https://www.sciencedirect.com/science/article/pii/S0550321324001408



https://en.wikipedia.org/wiki/The_First_Three_Minutes

Connecting New Physics to EDMs

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



Underlying Sources of *CP*-Violation (CPV)

New Particles & Interactions lead to...

...Electron EDM, Quark EDM, Quark "Chromo"-EDMs, Gluon Interactions (Weinberg Operator), & Electron-Quark CPV Interactions which lead to....

Lattice QCD: see H.-W. Lin
Effective Field Theory: see E. Mereghetti

...Asymmetric nuclear charge distributions, Electron-Nucleus CPV Interactions, & Electron EDM which lead to...

...Atomic EDMs and CPV Frequency Shifts in Molecules

Sole Source vs. Global Analysis

$$\Delta\nu = d_e \langle S_e \rangle E_{\text{eff}} \left(E_{\text{lab}}\right) + \kappa_1 \langle S_e \rangle C_S E_{\text{lab}} + \kappa_S \langle S_n \rangle S_{\text{Schiff}} E_{\text{lab}} + \kappa_2 \langle S_n \rangle C_T E_{\text{lab}}$$

<*S*> = mean spin polarization
e = electron
n = nucleus
$\kappa_{1,S,2}$ = depends only on electronic wavefunctions

- Different systems are linear combination of different sources of CPV.
- We need "EDM" measurements in multiple systems to set constraints on different sources of CPV.
- Sole Source Analysis: assume Δν comes only from one CPV source (set all but one CPV source to zero) – this is what we used to do…
- Global Analysis: simultaneous fit for all CPV sources using limits from multiple measurements – this is where the field is heading thanks to this paper: Chupp & Ramsey-Musolf, Phys. Rev. C 91, 035502 (2015)

Model-Dependent Sole-Source Analysis

common New Physics parameters

g_1, g_2, g_3 coupling constants

ϕ_A, ϕ_μ CP–violating phases

$\tan(\beta) = R_d = R_u^{-1}$ Higgs doublet parameter

Pospelov & Ritz
Ann. Phys. 318 119 (2005)

$$\delta_e = -\frac{1}{\sqrt{32\pi^2}}\left[\frac{g_1^2}{12}\sin\phi_A + \left(\frac{5g_2^2}{24}+\frac{g_1^2}{24}\right)\sin\phi_\mu \tan\beta\right]$$

electron EDM

$$\delta_q = -\frac{1}{\sqrt{32\pi^2}}\left[\frac{\sqrt{2}g_3^2}{9}\left(\sin\phi_\mu R_q - \sin\phi_A\right) + \cdots\right]$$

neutron EDM
quark EDMs (short range)

$$\tilde{\delta}_q = -\frac{1}{\sqrt{32\pi^2}}\left[\frac{5g_3^2}{18\sqrt{2}}\left(\sin\phi_\mu R_q - \sin\phi_A\right) + \cdots\right],$$

Hg-199, Ra-225, Xe-129,…
quark chromo-EDMs (long range)

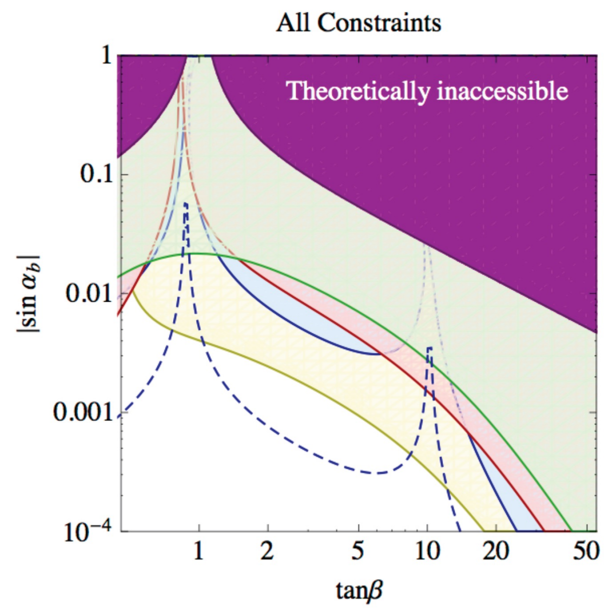
Inoue, Ramsey-Musolf, Zhang
PRD 89, 115023 (2014)

2014 ThO limit for d_e
dashed line - d_e/10

(2015 neutron EDM limit)/10

(2016 ^{199}Hg EDM limit)/2.5
…but large nuclear uncertainties…

(2015 ^{225}Ra EDM limit/10^4)



Model-Independent Global Analysis

TIMOTHY CHUPP AND MICHAEL RAMSEY-MUSOLF PHYSICAL REVIEW C **91**, 035502 (2015)

TABLE VIII. Anticipated limits (95%) on P-odd/T-odd physics contributions for scenarios for improved experimental precision compared to the current limits listed in the first line using best values for coefficients in Table IV and V. We assume $\alpha_{g_\pi^1}$ for ^{199}Hg is 1.6×10^{-17}. For the octupole deformed systems (^{225}Ra and ^{221}Rn/^{223}Rn) we specify the contribution of ^{225}Ra. The Schiff moment for Rn isotopes may be an order of magnitude smaller than for Ra, so for Rn one would require 10^{-26} and 10^{-27} for the fifth and sixth lines to achieve comparable sensitivity to that listed for Ra.

	Current limits (95%)		d_e (e cm) 5.4×10^{-27}	C_S 4.5×10^{-7}	C_T 2×10^{-6}	$\bar{g}_\pi^{(0)}$ 8×10^{-9}	$\bar{g}_\pi^{(1)}$ 1.2×10^{-9}	$\bar{d}_n^{\mathrm{sr}}$ (e cm) 12×10^{-23}
System	Current (e cm)	Projected			Projected sensitivity			
ThO	5×10^{-29}	5×10^{-30}	4.0×10^{-27}	3.2×10^{-7}				
Fr		$d_e < 10^{-28}$	2.4×10^{-27}	1.8×10^{-7}				
^{129}Xe	3×10^{-27}	3×10^{-29}			3×10^{-7}	3×10^{-9}	1×10^{-9}	5×10^{-23}
Neutron/Xe	2×10^{-26}	$10^{-28}/3 \times 10^{-29}$			1×10^{-7}	1×10^{-9}	4×10^{-10}	2×10^{-23}
Ra		10^{-25}			5×10^{-8}	4×10^{-9}	1×10^{-9}	6×10^{-23}
Ra		10^{-26}			1×10^{-8}	1×10^{-9}	3×10^{-10}	2×10^{-24}
Neutron/Xe/Ra		$10^{-28}/3 \times 10^{-29}/10^{-27}$			6×10^{-9}	9×10^{-10}	3×10^{-10}	1×10^{-24}

Leptonic Sector: N >= 2

d_e : electron EDM

C_S : nuclear spin independent eN coupling

***N* CPV low energy observables**
= *N* unknowns
= *N* equations
= *N* experiments

Hadronic Sector: N >= 4

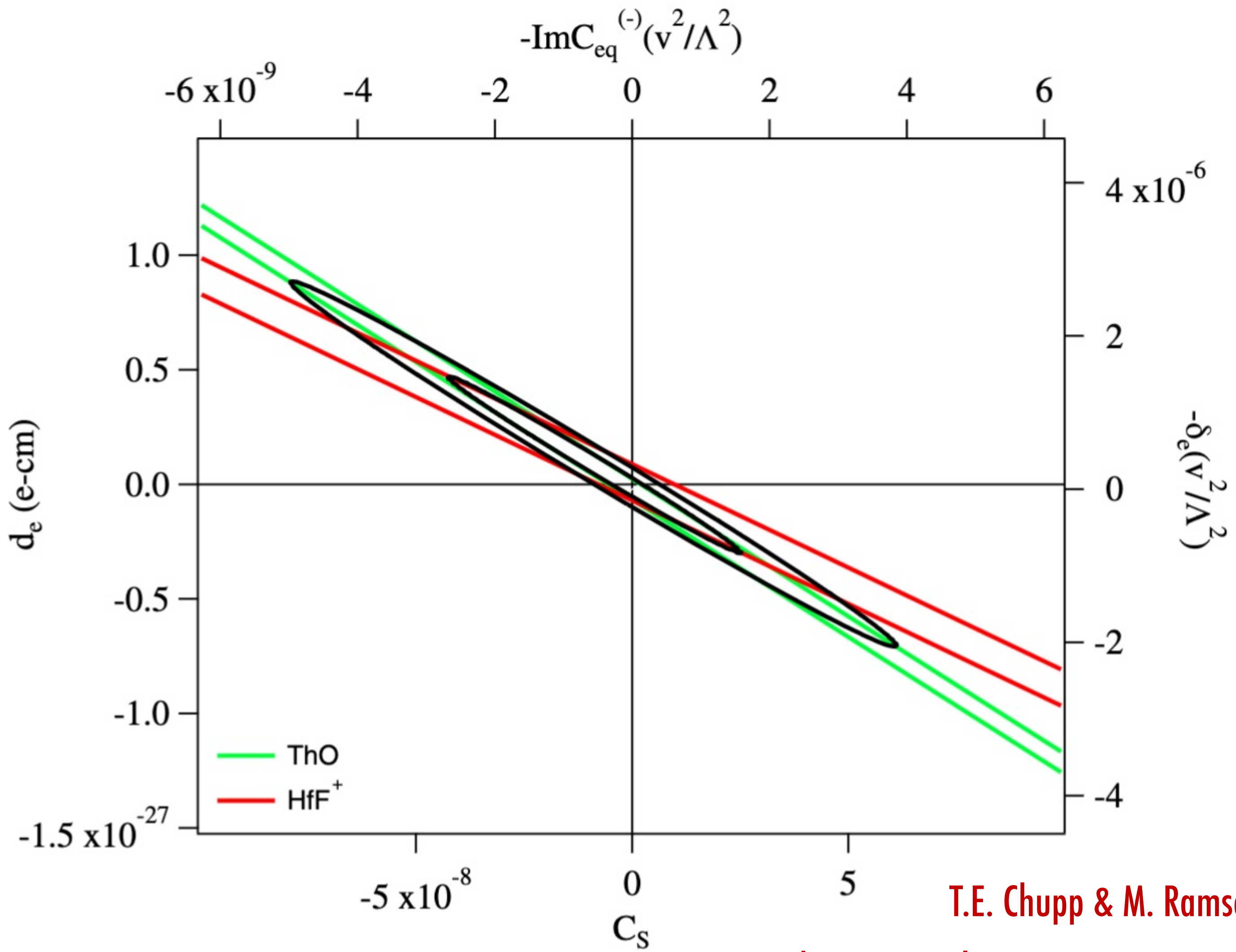
C_T : nuclear spin dependent eN coupling

g_π^0 : isoscalar NN coupling

g_π^1 : isovector NN coupling

d_n^{sr} : short range neutron EDM

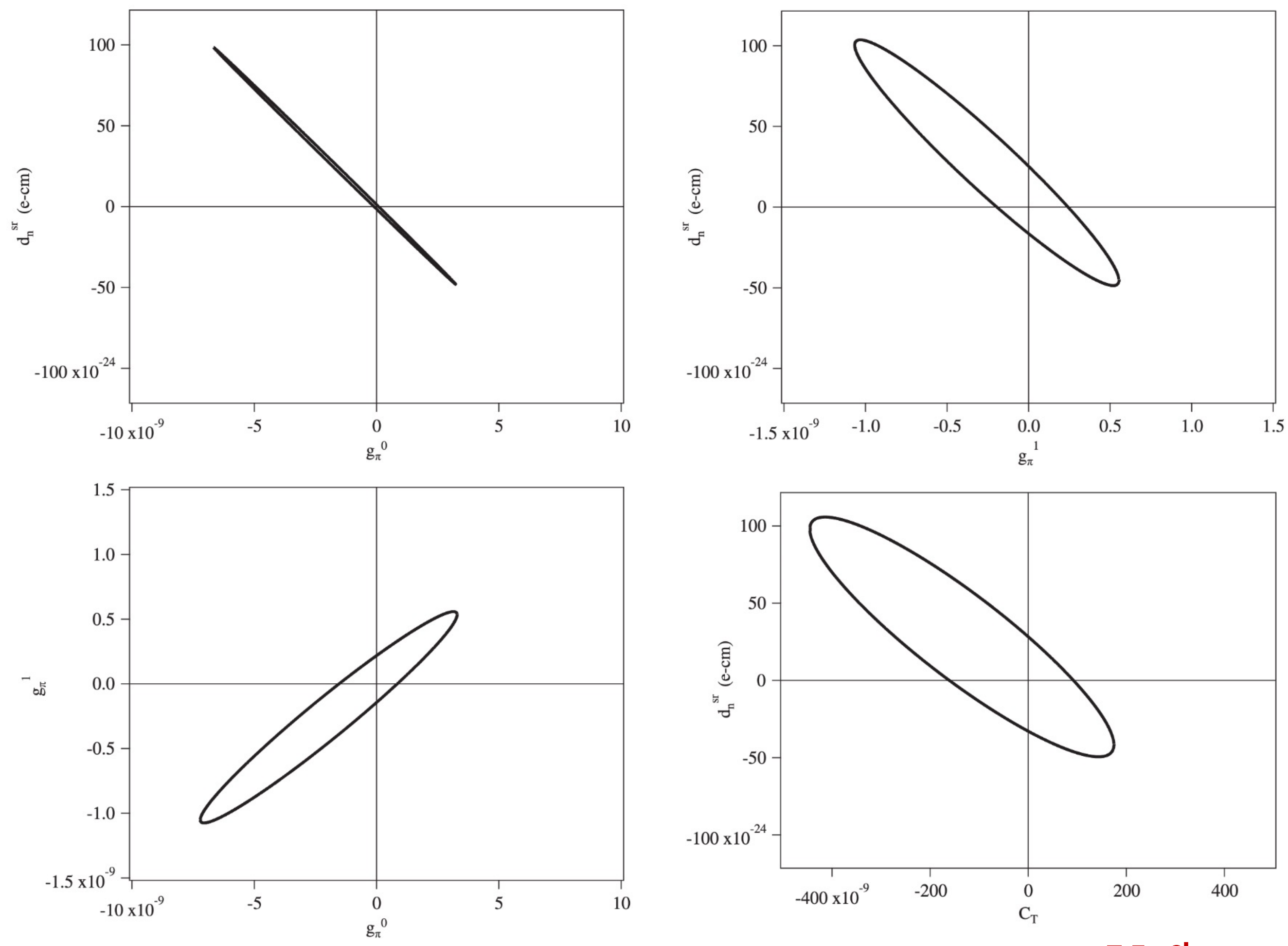
Global Analysis: “Electron EDM” Experiments



T.E. Chupp & M. Ramsey-Musolf PRC 91:035502 (2015)

T.E. Chupp, P. Fierlinger, M. Ramsey-Musolf, JTS, RMP 91:015001 (2019)

Global Analysis In The Hadronic Sector: The Crucial Importance of Neutron EDM



$$S_{\text{Schiff}} = \eta_p d_p + \eta_n d_n + \eta_0 g_0 + \eta_1 g_1$$

η = nuclear wavefunctions
d = single nucleon EDMs
g = CPV πNN interactions

Four hadronic sources needs at least four experiments:

1. **neutron EDM**
2. **atomic ^{199}Hg EDM**
3. **pear-shaped NSM**
4. **^{205}Tl (CeNTREX)**

T.E. Chupp & M. Ramsey-Musolf PRC 91:035502 (2015)

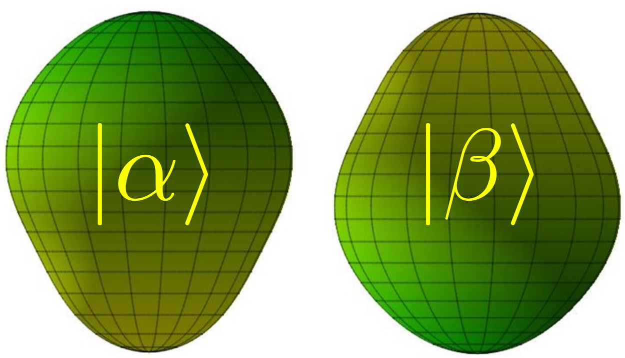
T.E. Chupp, P. Fierlinger, M. Ramsey-Musolf, JTS, RMP 91:015001 (2019)

Sensitivity of Radium-225 Compared to Hg-199

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

$$S \equiv \langle\Psi_0|\, S_z\, |\Psi_0\rangle = \sum_{k\neq 0} \frac{\langle\Psi_0|\, S_z\, |\Psi_k\rangle \langle\Psi_k|\, V_{\not{P}\not{T}}\, |\Psi_0\rangle}{E_0 - E_k} + \text{c.c.}$$

Parity Doublet



55 keV

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

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

- **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 (g_0)	Isovector (g_1)
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)

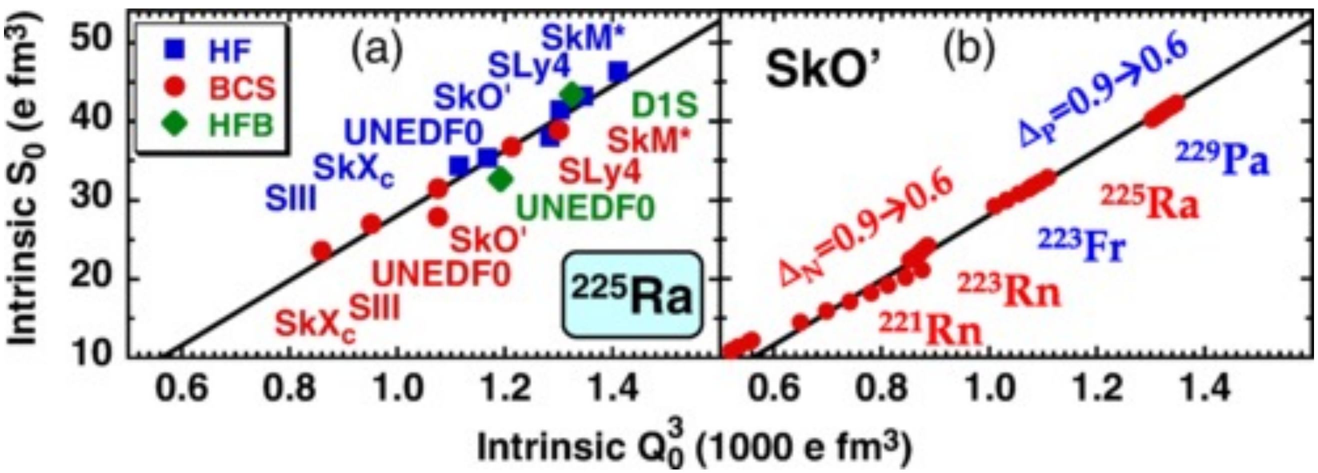
Large Theory Uncertainties: Nuclear Structure Calculations For η Are Super Hard!

type	η (Hg-199)	η (Ra-225)	ratio*3	Hg-199 Ref
SIII	0.005	7.0	4300	PRC 82 015501 (2010)
SkM*	-0.027	21.5	-2400	PRC 82 015501 (2010)
SLy4	-0.006	16.9	-8600	PRC 82 015501 (2010)
SkO′		6.0		
DE05	0.071			PRC 72 045503 (2005)
DS03	0.055			PAN 66 1940 (2003)
"Best"	+/-(0.02)	6.0	+/-(900)?	Prog. PNP 71 21 (2013)

- Isovector coupling (g_1) is given by "chromo"-EDMs
- Nuclei are the most sensitive to this source of new physics
- New Hg-199 calculations are forthcoming... (J. Engel/UNC)

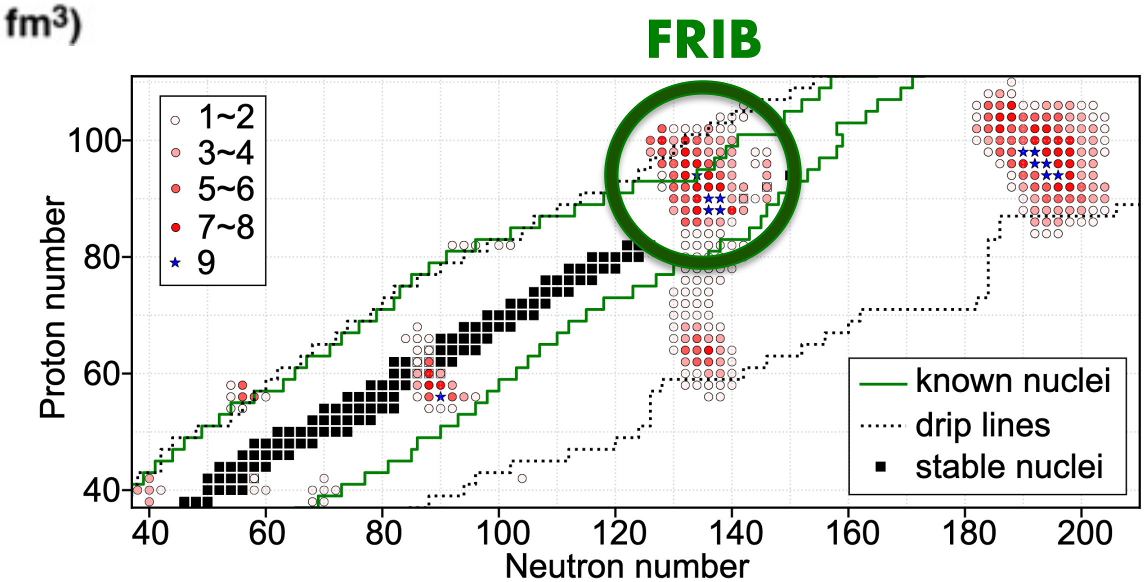
Calibrating the Intrinsic Schiff Moment

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



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!

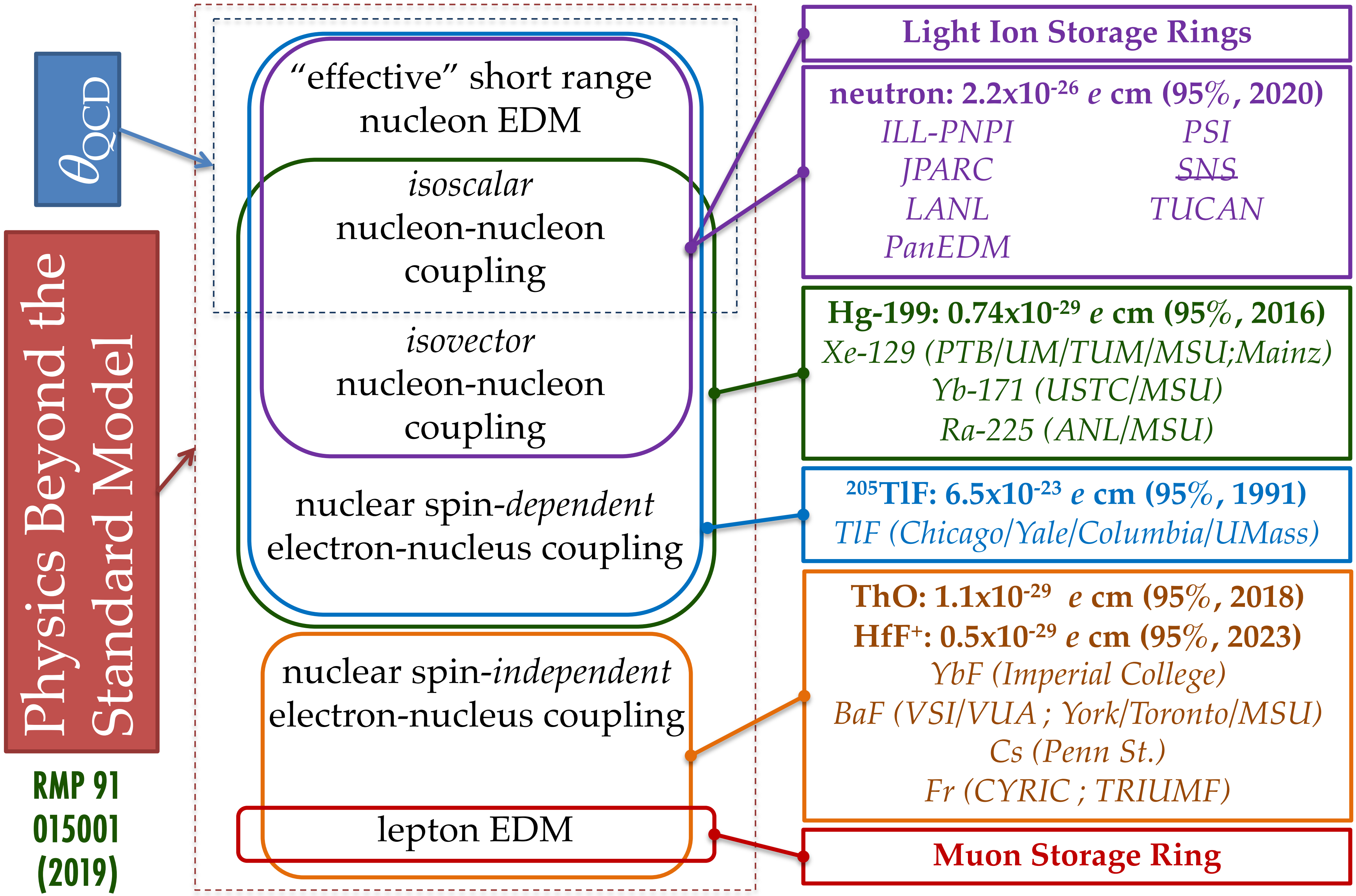


Intermission

Questions?

1. stuff

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



RMP 91 015001 (2019)

"The Best Defense Is A Good Offense"

On the Possibility of Electric Dipole Moments for Elementary Particles and Nuclei

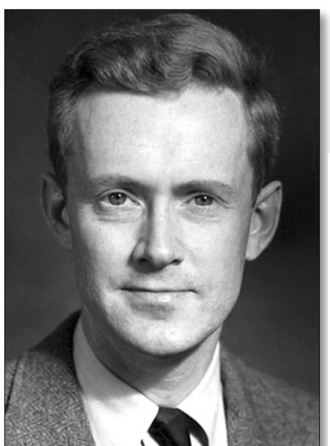
E. M. Purcell and N. F. Ramsey
Department of Physics, Harvard University, Cambridge, Massachusetts

April 27, 1950

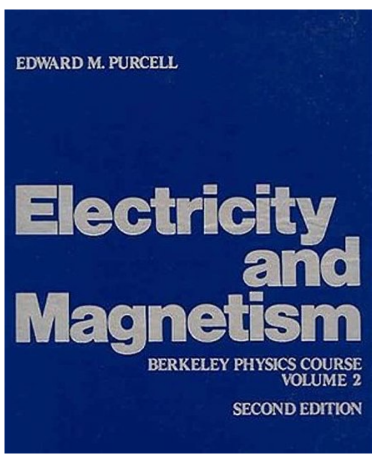
It is generally assumed on the basis of some suggestive theoretical symmetry arguments[1] that nuclei and elementary particles can have no electric dipole moments. It is the purpose of this note to point out that although these theoretical arguments are valid when applied to molecular and atomic moments whose electromagnetic origin is well understood, their extension to nuclei and elementary particles rests on assumptions not yet tested.

https://en.wikipedia.org/wiki/Electricity_and_Magnetism_(book)

Phys. Rev. 78, 807 (1950)

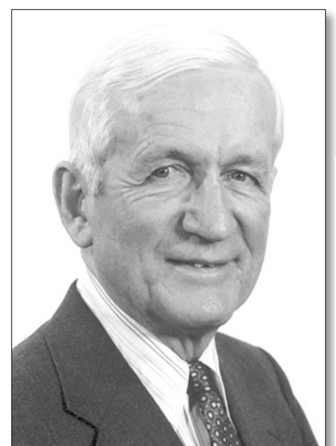


The Nobel Foundation



E.M. Purcell
1952 Nobel
Discovery of NMR

IMHO: Author of the Best Physics Book Ever!

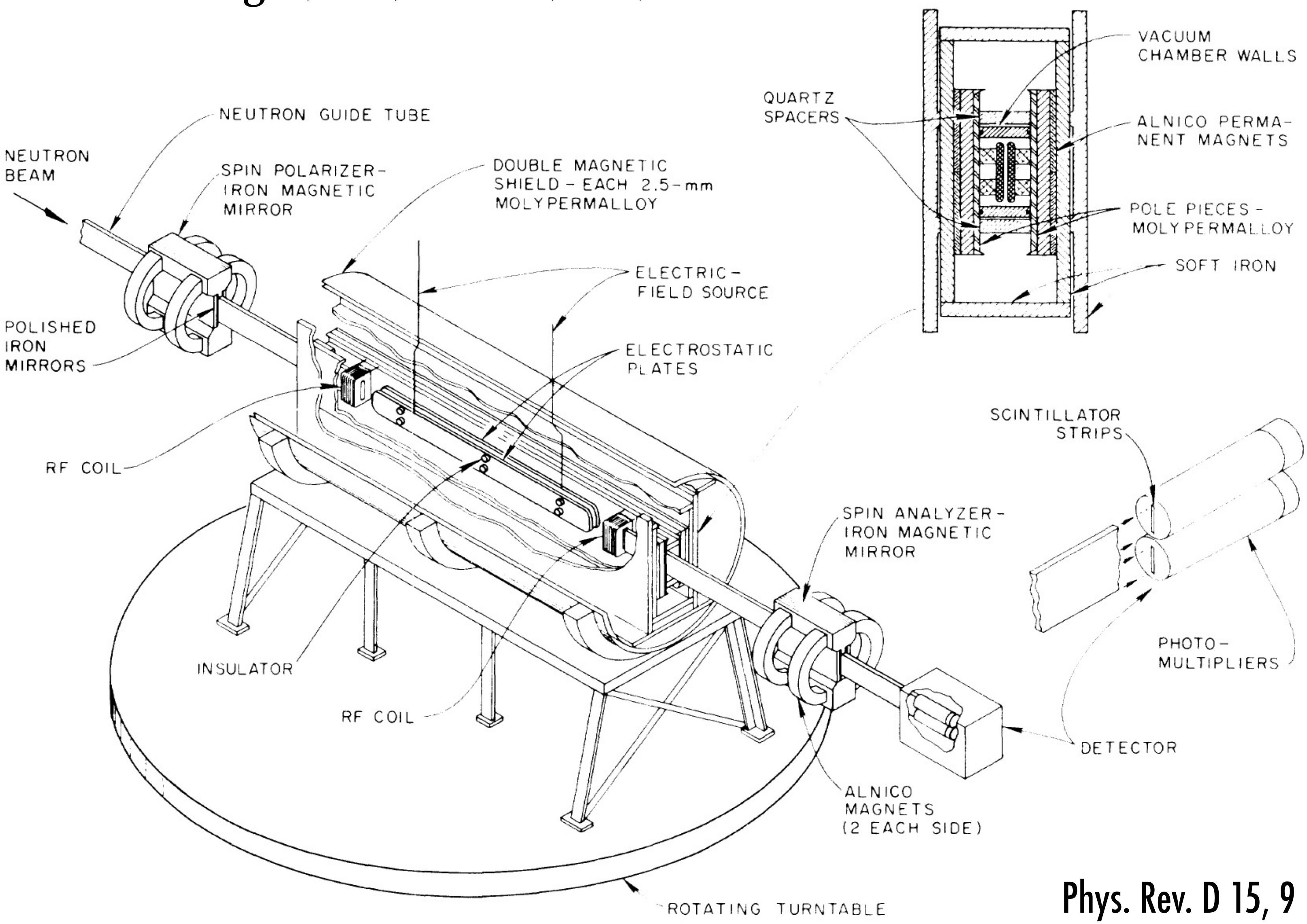


The Nobel Foundation

N.F. Ramsey
1989 Nobel
"for the invention of the separated oscillatory fields method"

Neutron EDM Using a "Beam" of Neutrons

From Oak Ridge (1950) to ILL (1977)



Phys. Rev. D 15, 9 (1977)

Example "False EDM" Systematic: "v x E" Effects

A neutron moving through an electric field sees, in its rest frame, a magnetic field:

$$\mathbf{E}' = \gamma(\mathbf{E} + \mathbf{v} \times \mathbf{B}) - (\gamma - 1)(\mathbf{E} \cdot \hat{\mathbf{v}})\hat{\mathbf{v}}$$

$$\mathbf{B}' = \gamma\left(\mathbf{B} - \frac{\mathbf{v} \times \mathbf{E}}{c^2}\right) - (\gamma - 1)(\mathbf{B} \cdot \hat{\mathbf{v}})\hat{\mathbf{v}}$$

This is results in a velocity-dependent frequency-shift that depends on the sign and magnitude of the *E*-field.

If μ_n is the neutron's magnetic moment, v the neutron velocity, and θ the angle between the electric field and the component of the magnetic field lying in a plane normal to the velocity vector, then the $\vec{E}\times\vec{v}/c$ systematic effect introduces a spurious EDM given by

$$D_{Exv} = -\frac{\mu_n}{e}\frac{v}{c}\sin\theta \sim 10^{-20}\ \text{cm}\times\sin\theta\,. \qquad (6)$$

https://en.wikipedia.org/wiki/Classical_electromagnetism_and_special_relativity

Phys. Rev. D 15, 9 (1977)

Ultra Cold Neutrons (UCN)

see A. Holley

$$T = \frac{mv^2}{2}$$

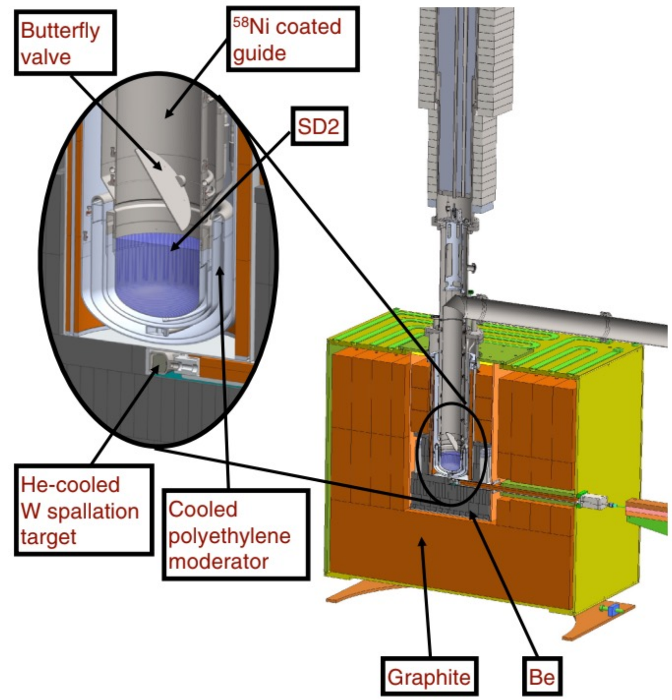
STORAGE OF COLD NEUTRONS

Ya. B. ZEL' DOVICH

Submitted to JETP editor April 3, 1959

J. Exptl. Theoret. Phys. (U.S.S.R.) **36**, 1952-1953 (June, 1959)

UCN @ LANL
Spallation neutrons
w/ solid Deuterium converter



Thermal neutrons:
$T = 290$ K, $v > 10^3$ m/s

UCN:
$T < 4$ mK, $v < 10$ m/s

https://indico.miserver.it.umich.edu/event/5/

http://www.jetp.ras.ru/cgi-bin/e/index/e/9/6/p1389?a=list

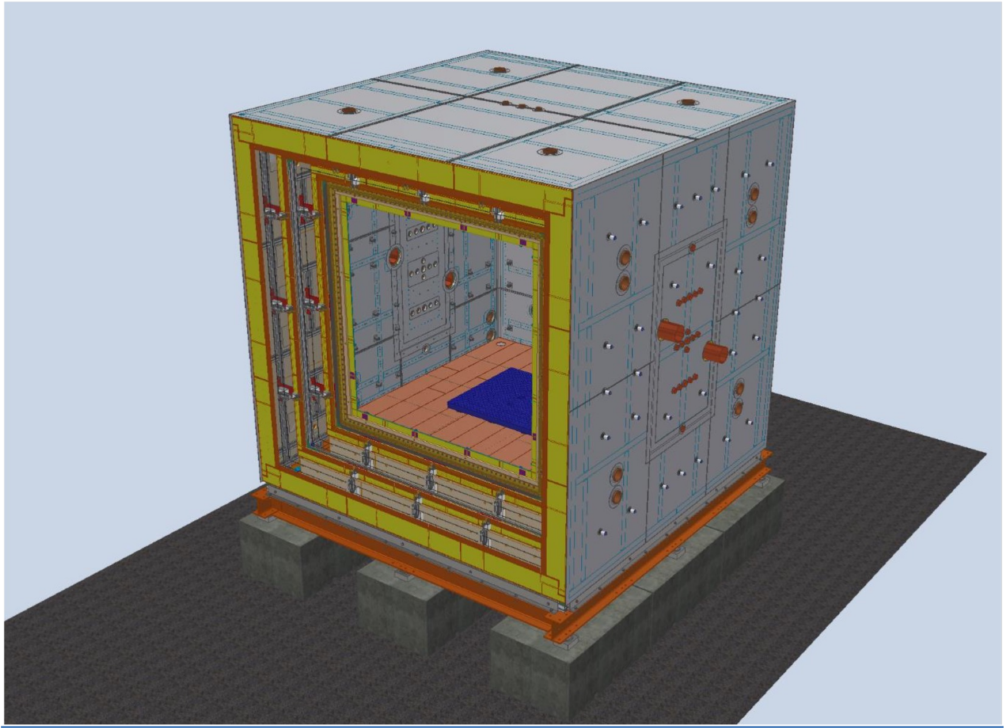
Neutron EDM Using Ultracold Neutrons (UCN)

Worldwide Effort, Some Examples:

- SuperSUN @ ILL (France)
- TUCAN @ TRIUMF (Canada)
- nEDM @ LANL (USA)
- n2EDM @ PSI (Switzerland)
- ~~SNS @ ORNL (USA)~~

present nEDM limit: <= 1E-26 *e* cm
Phys. Rev. Lett. 124, 081803 (2020)
next 5-10 years: ~1E-27 *e* cm

~2 m



4 mu metal layer, 1 Cu layer
Magnetically Shielded Room @ LANL

https://indico.miserver.it.umich.edu/event/5/

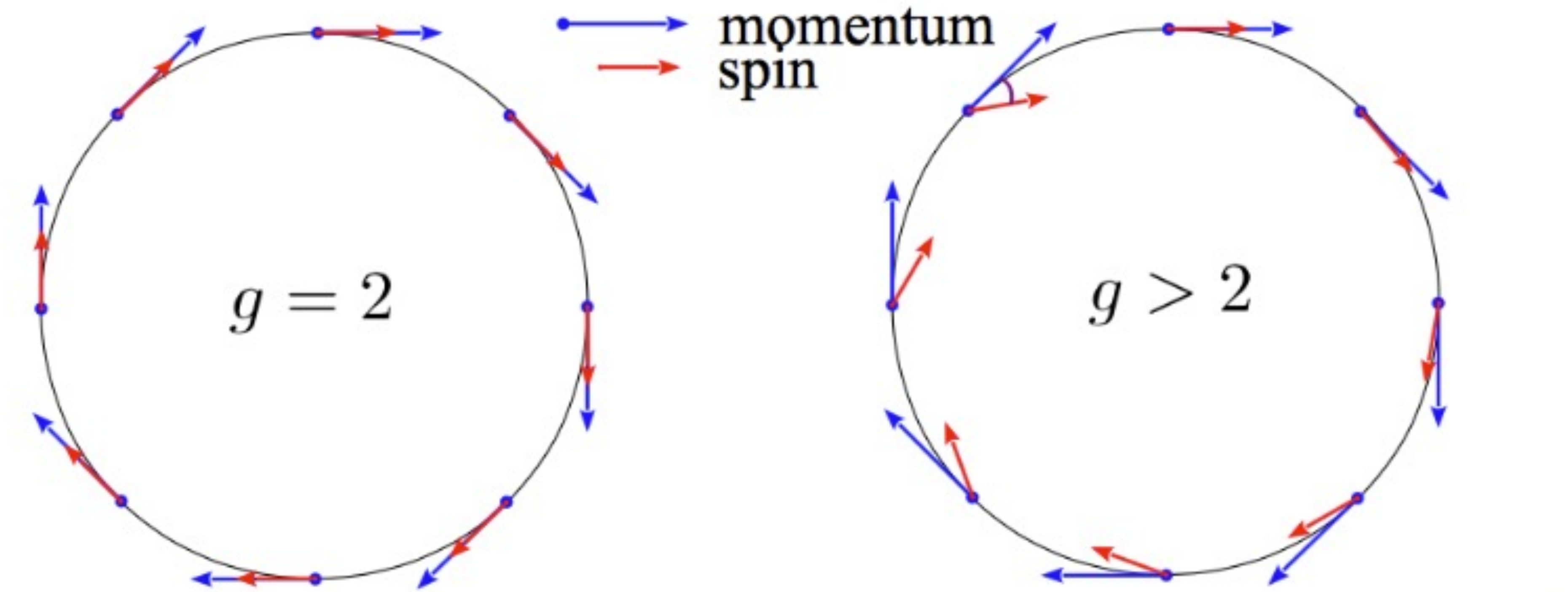
UCNs from:

- superfluid He
- solid Deuterium

Magnetometry:

- Hg-199 atoms
- Cs and/or Rb Atoms
- He-3 atoms
- SQUIDs

Muon Storage Ring Experiments: “g-2” & EDM



Wesley Gohn

If there is a nonzero muon EDM, then the **spin** precesses out of the plane as well:

$$\vec{\omega}_d = -\frac{d}{\hbar J}\left[\vec{v} \times \vec{B} + \vec{E} - \frac{\gamma}{\gamma + 1}\frac{\vec{v} \cdot \vec{E}}{c^2}\vec{v}\right] = -\frac{d\vec{E}'}{\hbar J \gamma}. \qquad (122)$$

RMP 91 015001 (2019)

Schiff Shielding?
Get Rid of the Electrons!

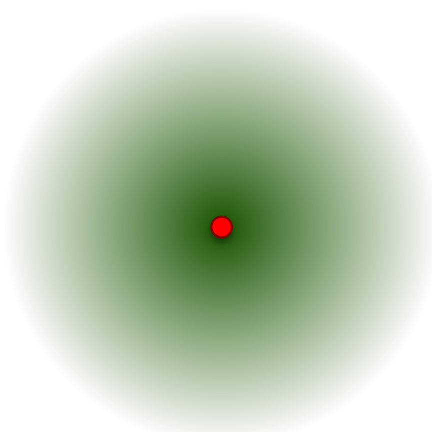
- **Shielding in Diamagnetic Atoms**
  Schiff PR 132:2194 (1963)

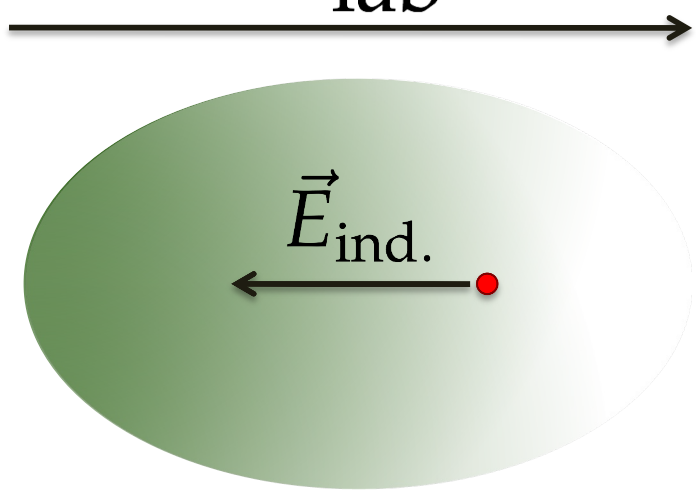
- **Relativistic atoms: The Sandars-Bouchiat Z^3 "Law"**
  Physics Letters 22:290 (1966) & Physics Letters 48B:111 (1974)

- **^{225}Ra vs ^{199}Hg vs. ^{3}He: 2.8 to 1 to 10^{-5}**
  JPB:AMOP 53:195004 (2020) & Phys. Rev. A 106, 022817 (2022)

M. A. Bouchiat

SCAN ME

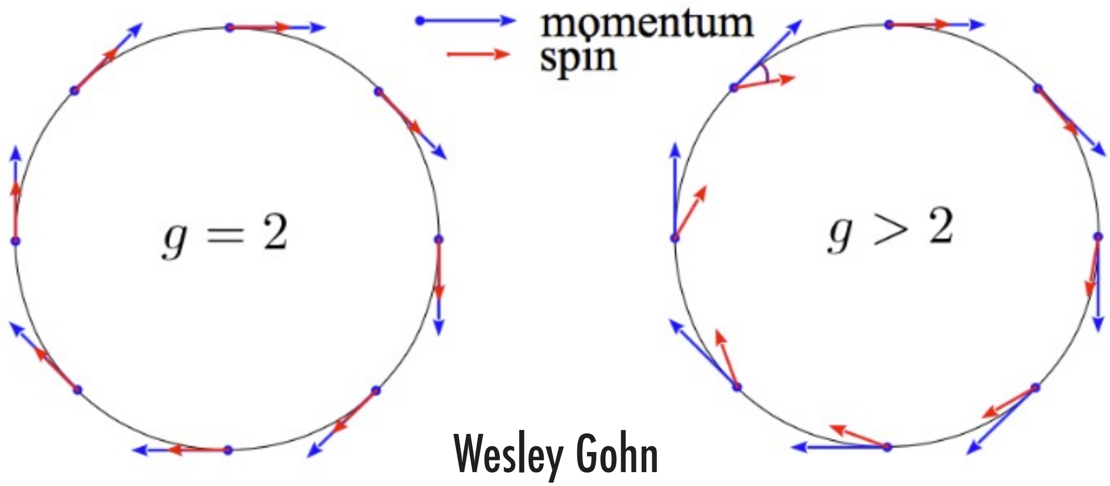




$$\vec{E}_{\text{ind.}} \approx -\vec{E}_{\text{lab}}$$

Light Ion Storage Ring Experiments

- fully ionized Hydrogen, Deuterium, and Helium-3 atoms
- calculable using Lattice QCD (*see H.-W. Lin*)
- confined in storage rings
- longer term goal: ~1E-29 *e* cm



If there is a nonzero nuclear EDM, then the **spin** precesses out of the plane as well.

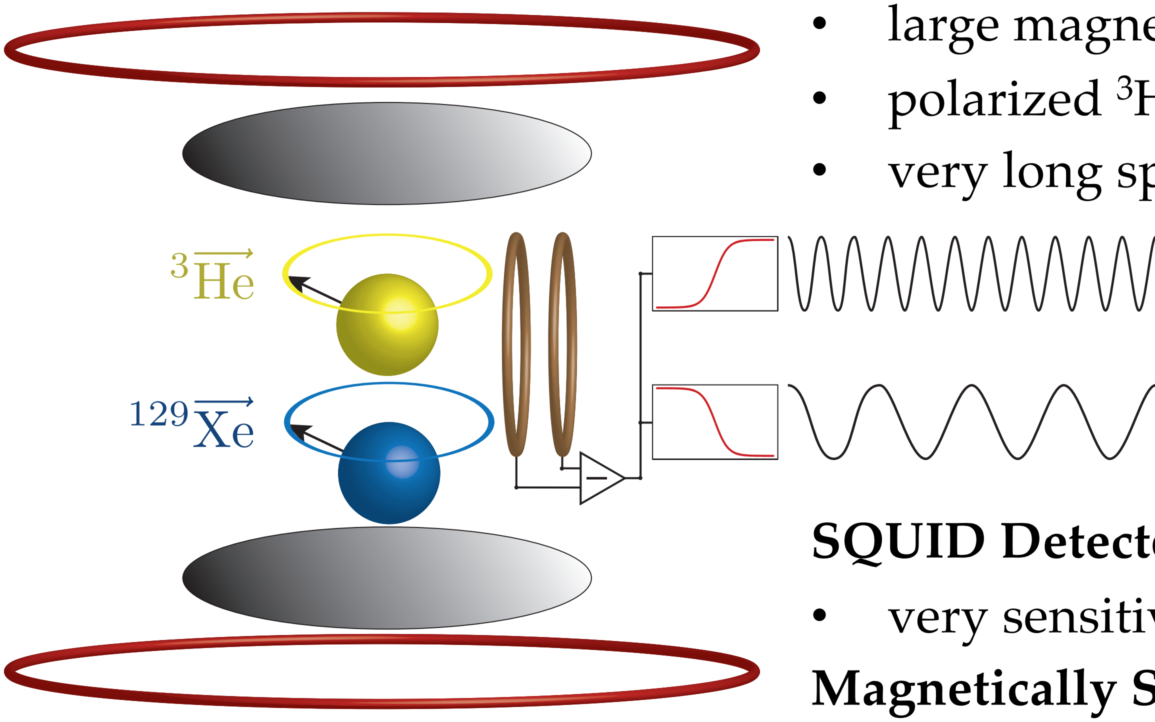
$$\vec{\omega}_d = -\frac{d}{\hbar J}\left[\vec{v} \times \vec{B} + \vec{E} - \frac{\gamma}{\gamma+1}\frac{\vec{v}\cdot\vec{E}}{c^2}\vec{v}\right] = -\frac{d\vec{E}'}{\hbar J \gamma}. \qquad (122)$$

RMP 91 015001 (2019)

2019: Atomic EDM of ^{129}Xe (Stable) in Gas Cell Using SQUID Detection

Polarized Noble Gases

- large magnetizations (30 pT) using SEOP
- polarized ^{3}He for co-magnetometry
- very long spin precession times (10^4 seconds)



^{3}He: smaller EDM + B-field drifts

^{129}Xe: larger EDM + B-fields drifts

SQUID Detectors

- very sensitive detection (6 fT/root-Hz)

Magnetically Shielded Room (BMSR-2 & TUM)

- small (<1 nT) and uniform (<10 pT/cm) residual *B*-field
- high shielding factor (>10^8)

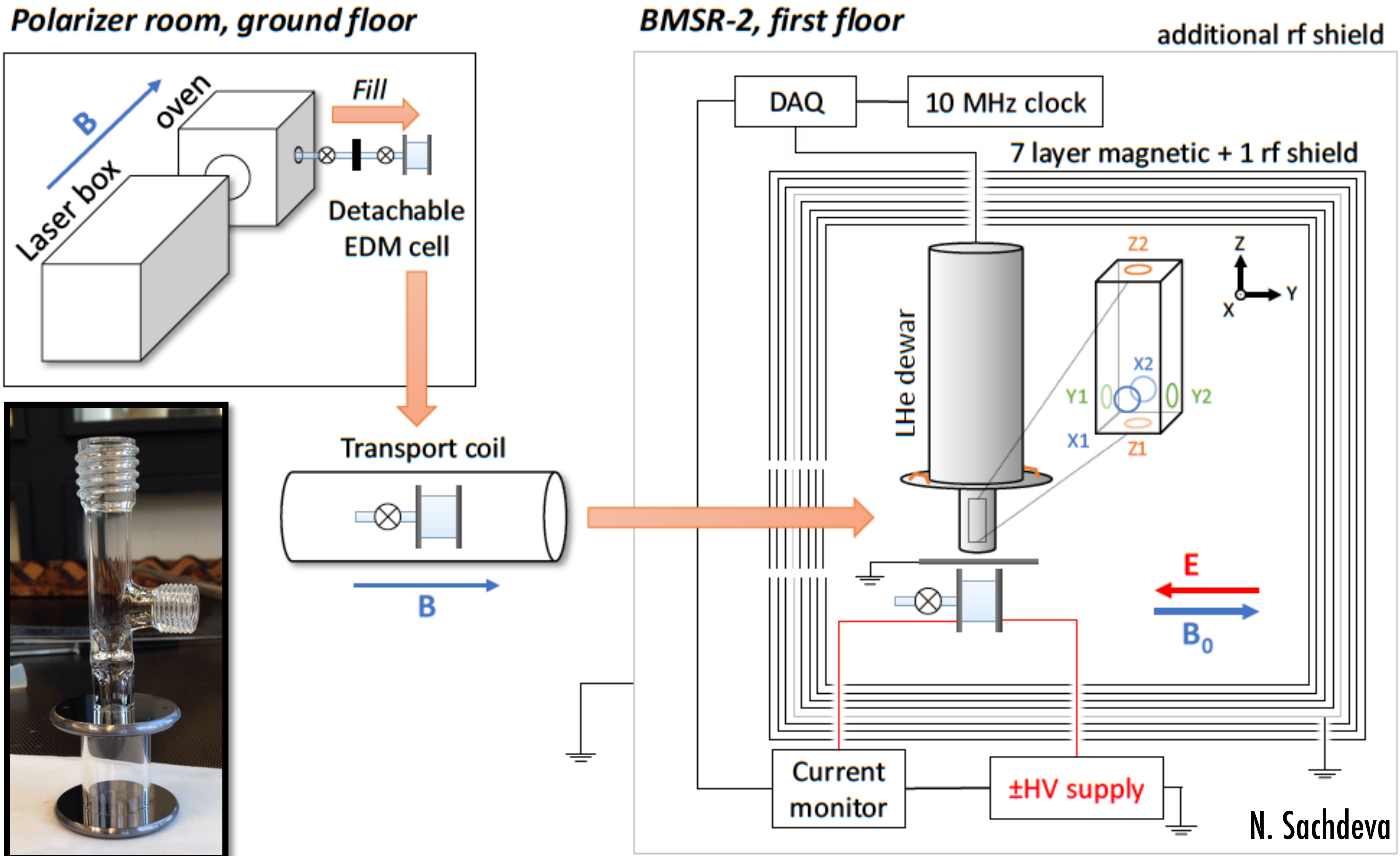
I. Altarev et al. J. Appl. Phys. 117, 233903 (2015)
I. Altarev et al. J. Appl. Phys. 117, 183903 (2015)

Magnetic Field Scales

Object	B-Field (T)
MRI Machine	3E+00
Computer hard drive	2E+00
Loudspeaker	1E+00
Sun spots	2E-01
Refrigerator magnet	5E-03
Earth's magnetic field	5E-05
Cassette tape	2E-05
Bias field for EDM experiment	1E-06
Noble gas (100% @ 1 atm @ 1 mm)	1E-08
Residual field in magnetic shielded room	1E-09
All of my clothes @ 10 cm	1E-10
Human Brain	1E-12
"SQUID" magnetometer noise floor (1 s)	1E-15

Magnetically Shielded Room in Garching, Germany

The Xe-129 EDM Search in Berlin



Main Systematic: Residual Longitudinal Polarization

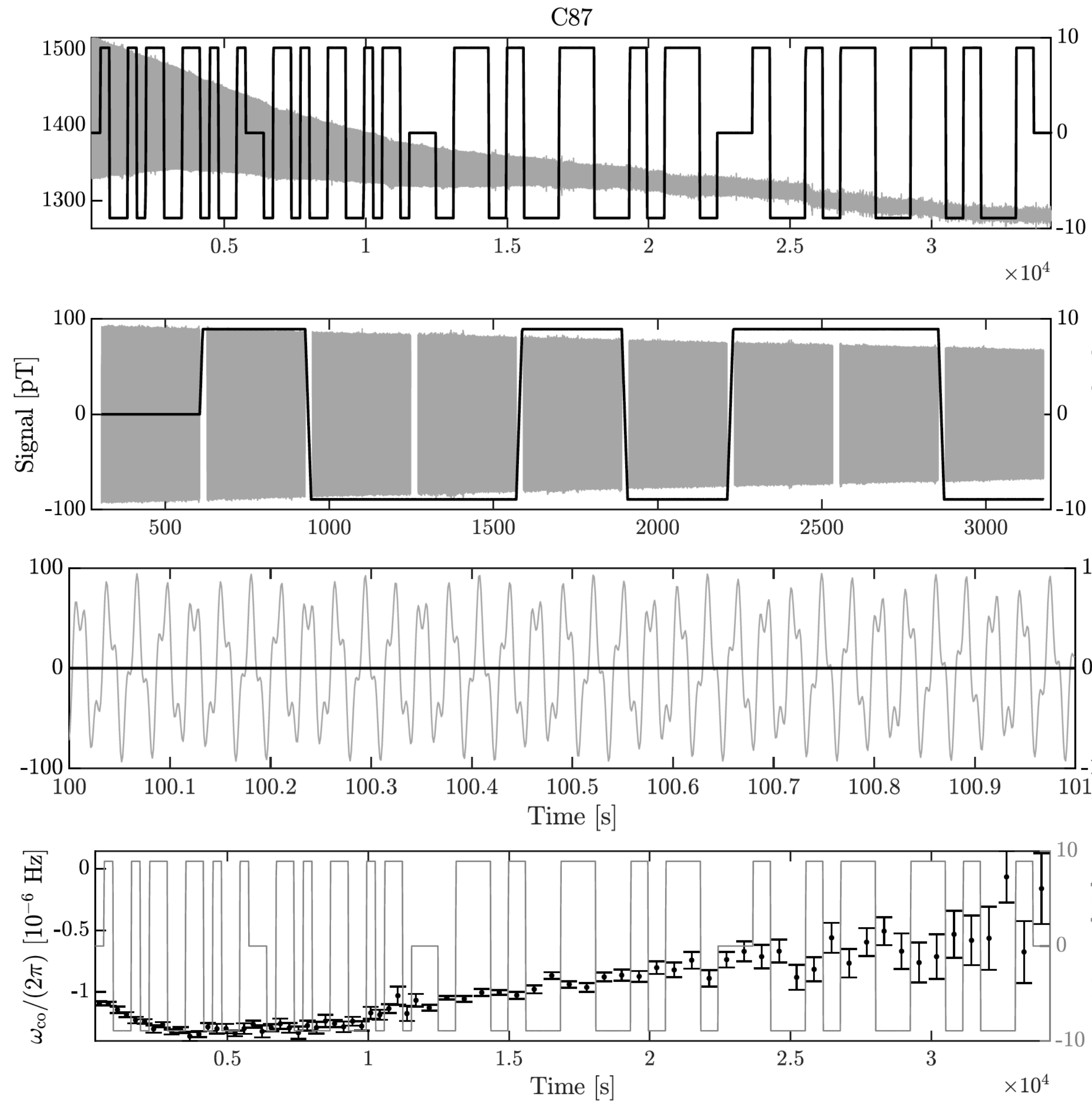
raw signal

filtered signal

zoom in on filtered signal

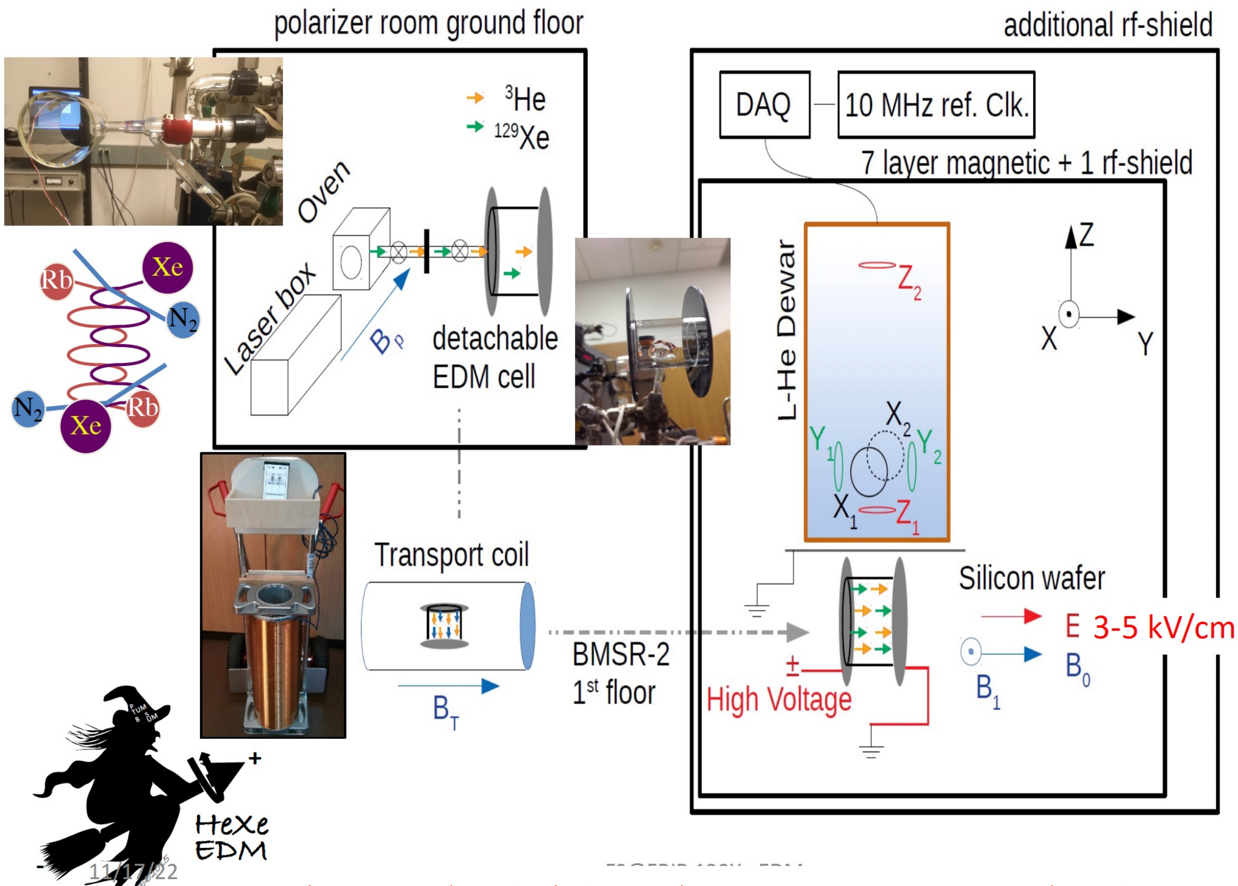
"comagnetometer" signal

$$\omega_{\mathrm{co}} = \omega_{\mathrm{Xe}} - \left[\frac{\gamma_{\mathrm{Xe}}}{\gamma_{\mathrm{He}}}\right]\omega_{\mathrm{He}}$$



PRL 123:143003 (2019)

Next Generation Xe-129 EDM @ LANL



- Developed and carried out in the Magnetically Shielded Rooms (MSR) in FRM-II and PTB-Berlin
- ^{3}He is co-magnetometer
- Explained self-interaction effects in noble gas cells

PRA 100:012502 (2019)

- First proof-of-principle SQUID detection technique gave x5 improved limit

PRL 123:143003 (2019)

T. Chupp (Michigan) & W. Terrano (Arizona St.)

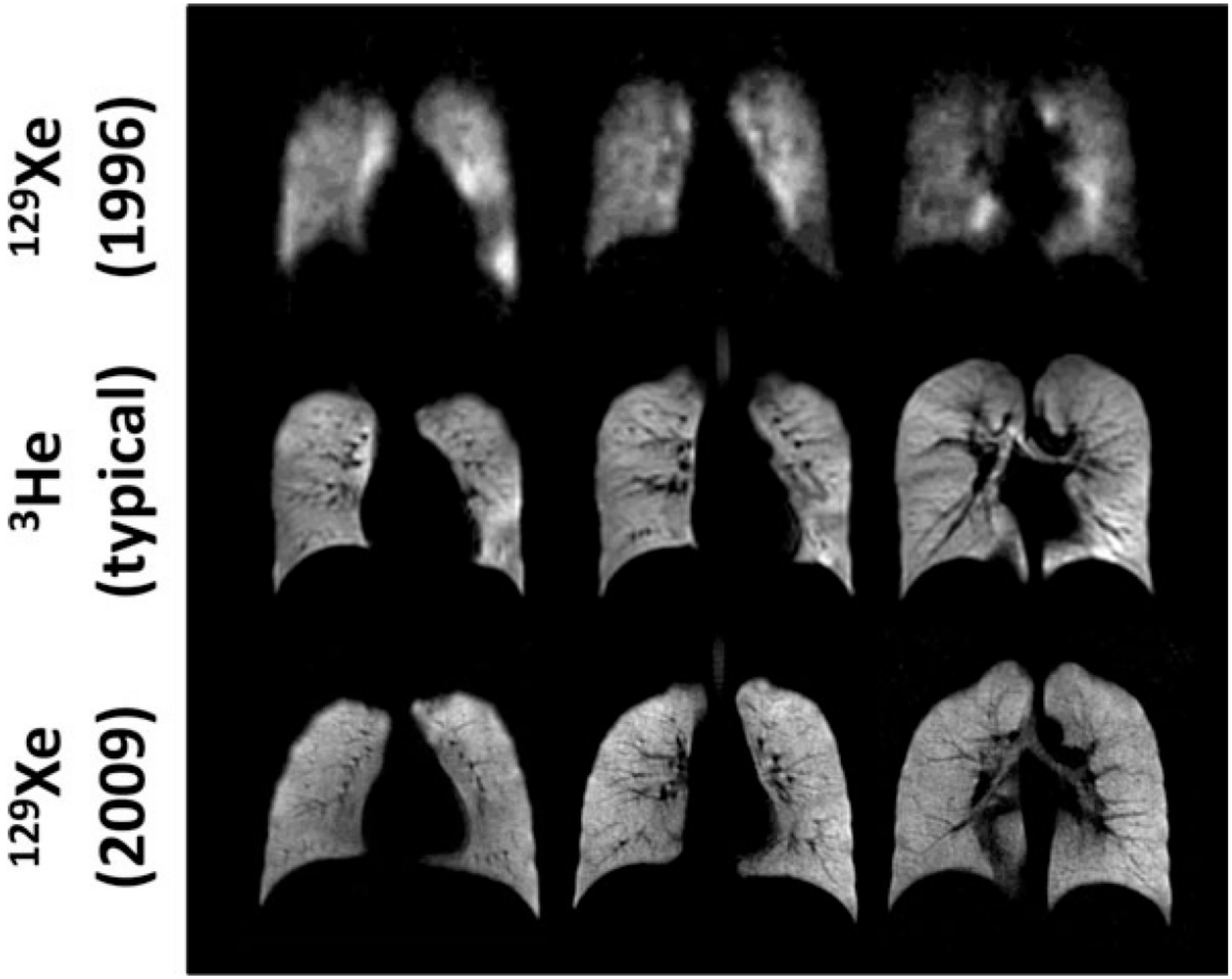
- **EDM(^{129}Xe) < 1.4x10^{-27} *e*-cm (95% C.L.), equivalent to ~1000xEDM(^{199}Hg)**
- Combining the best performing polarizer with the best SQUIDs implies x1000 improved statistical sensitivity is feasible Quantum Sci. Technol. 7 014001 (2022)

Detour: "Hyperpolarized" Noble Gases for MRI

M.A. Bouchiat

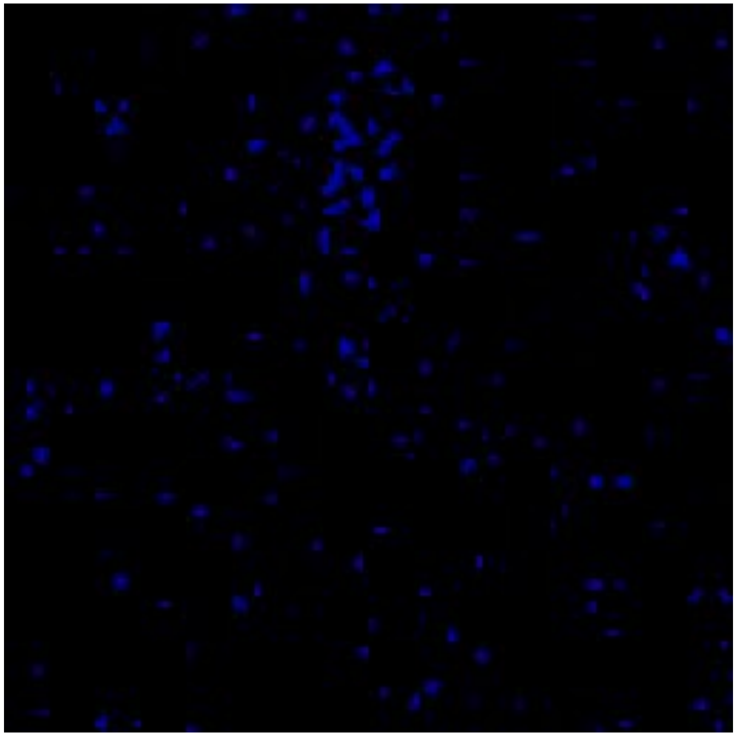
Density = 3 amg
Volume = 30 cm^3
Polarization = 0.01%
M.A. Bouchiat et al.
Phys. Rev. Lett. 5, 373 (1960)

Density = 9 amg
Volume = 400 cm^3
Polarization = 69%
JTS et al.
Phys. Rev. C 91, 055205 (2015)



Mugler & Altes, JMRI 37 313 (2013)

Hyp. Noble Gases for Dynamic Visualizations

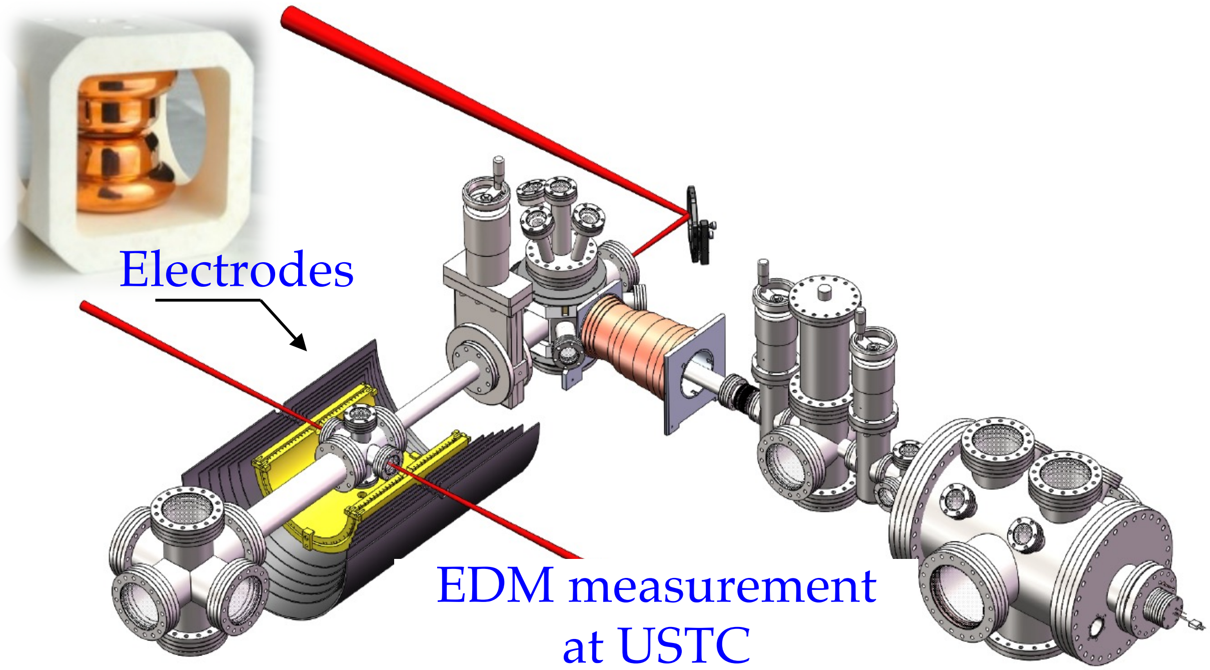


Healthy

Unhealthy

University of Virginia Radiology

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



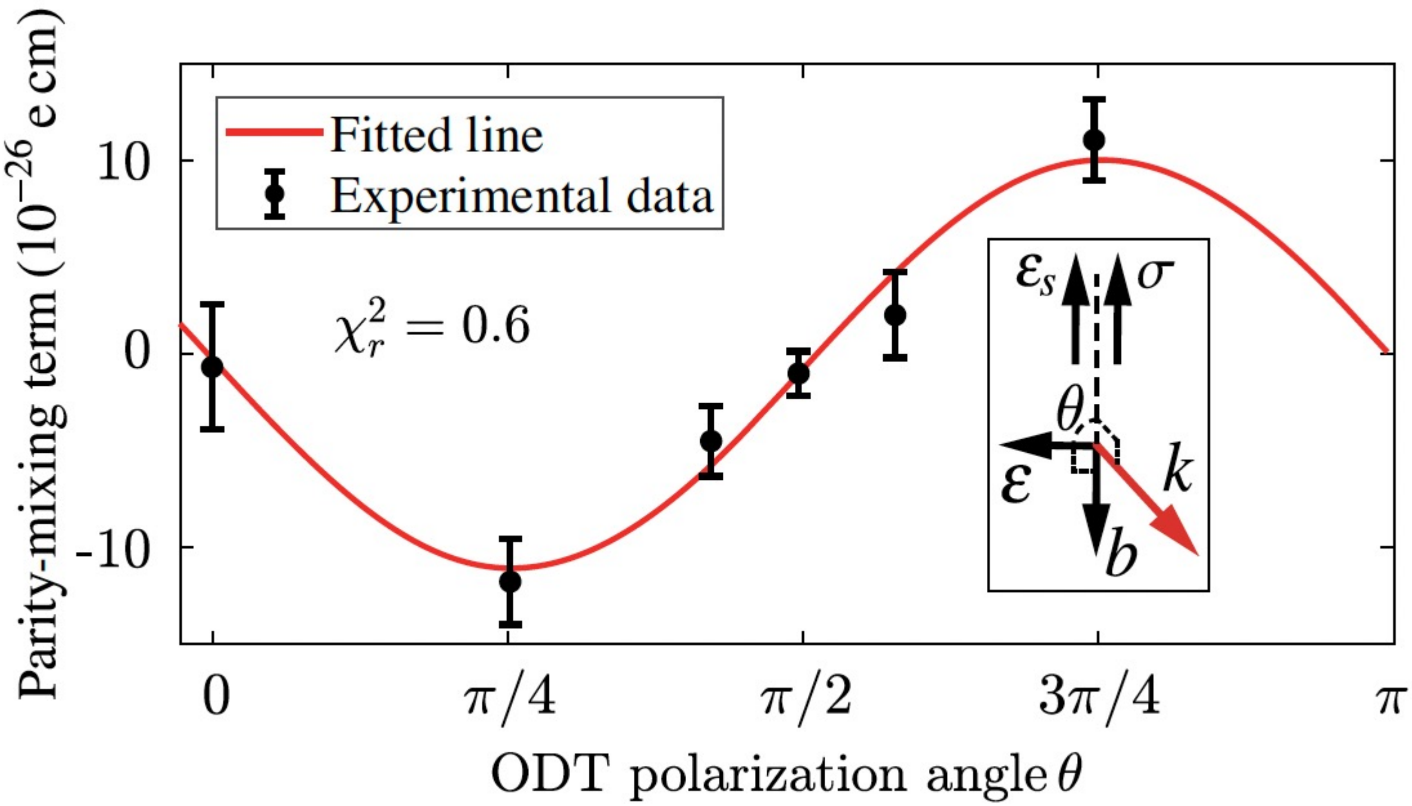
- Pathfinder experiment for ^{223,225}Ra
- Coherent spin precession time > 300 s
- **EDM(^{171}Yb) < 1.5x10^{-26} *e*-cm (95% C.L.), equivalent to ~1000xEDM(^{199}Hg)**

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

Laser Trap Systematics for Yb-171 EDM is Good Enough for Next Generation Ra-225 EDM



b = ODT B-field
ε = ODT E-field
σ = B-field
ε_s = E-field

$$\Delta\nu = \nu_1(\hat{b}\cdot\hat{\sigma})(\hat{\varepsilon}\cdot\hat{\varepsilon}_s) + \nu_2(\hat{b}\cdot\hat{\varepsilon}_s)(\hat{\varepsilon}\cdot\hat{\sigma}), \qquad (3)$$

PRL 129, 083001 (2022)

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

Ra-225: PRC 94:025501 (2016): **$< 1.4\times10^{-23}$ *e* cm (95%)**
(rare pear-shaped nuclei + laser trap experiment)

Xe-129: PRL 123:143003 (2019): **$<1.4\times10^{-27}$ *e* cm (95%)**
(stable + gas cell experiment)

Yb-171: PRL 129:083001 (2022): **$< 1.5\times10^{-26}$ *e* cm (95%)**
(stable + 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.

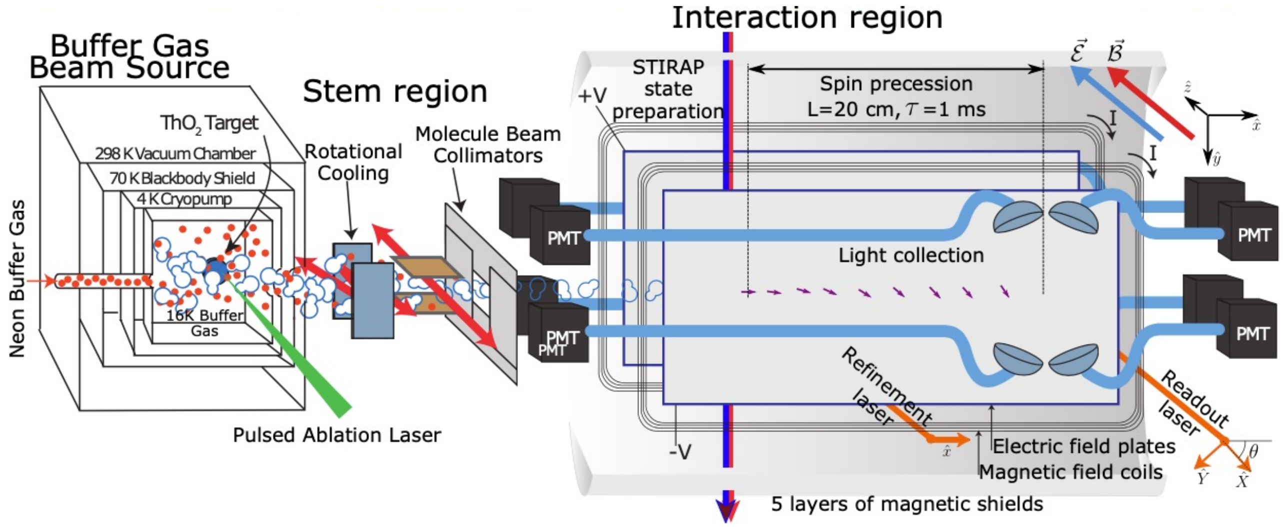
Intermission

Questions?

1. stuff

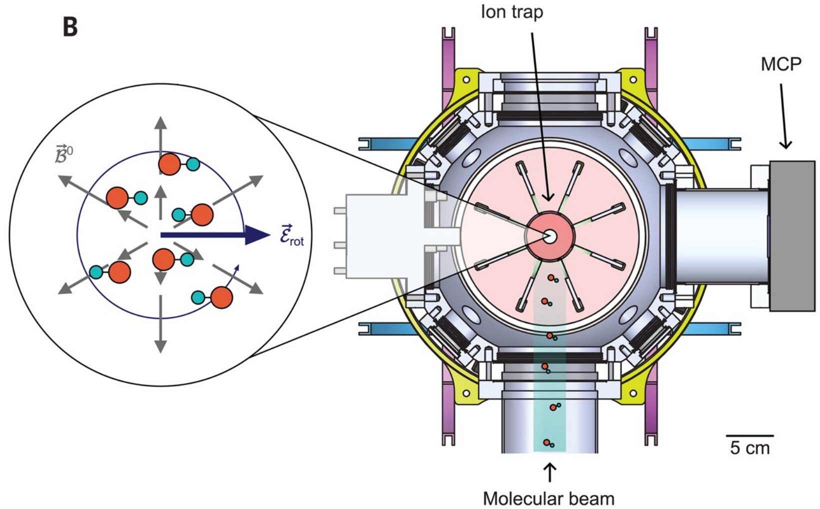
Molecular Electron EDM Experiments: Large Internal E-field and Control of Systematics

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



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

	ACME	JILA
int. time, τ	0.004 sec	2 sec
eff. *E*-field	78 GV/cm	23 GV/cm

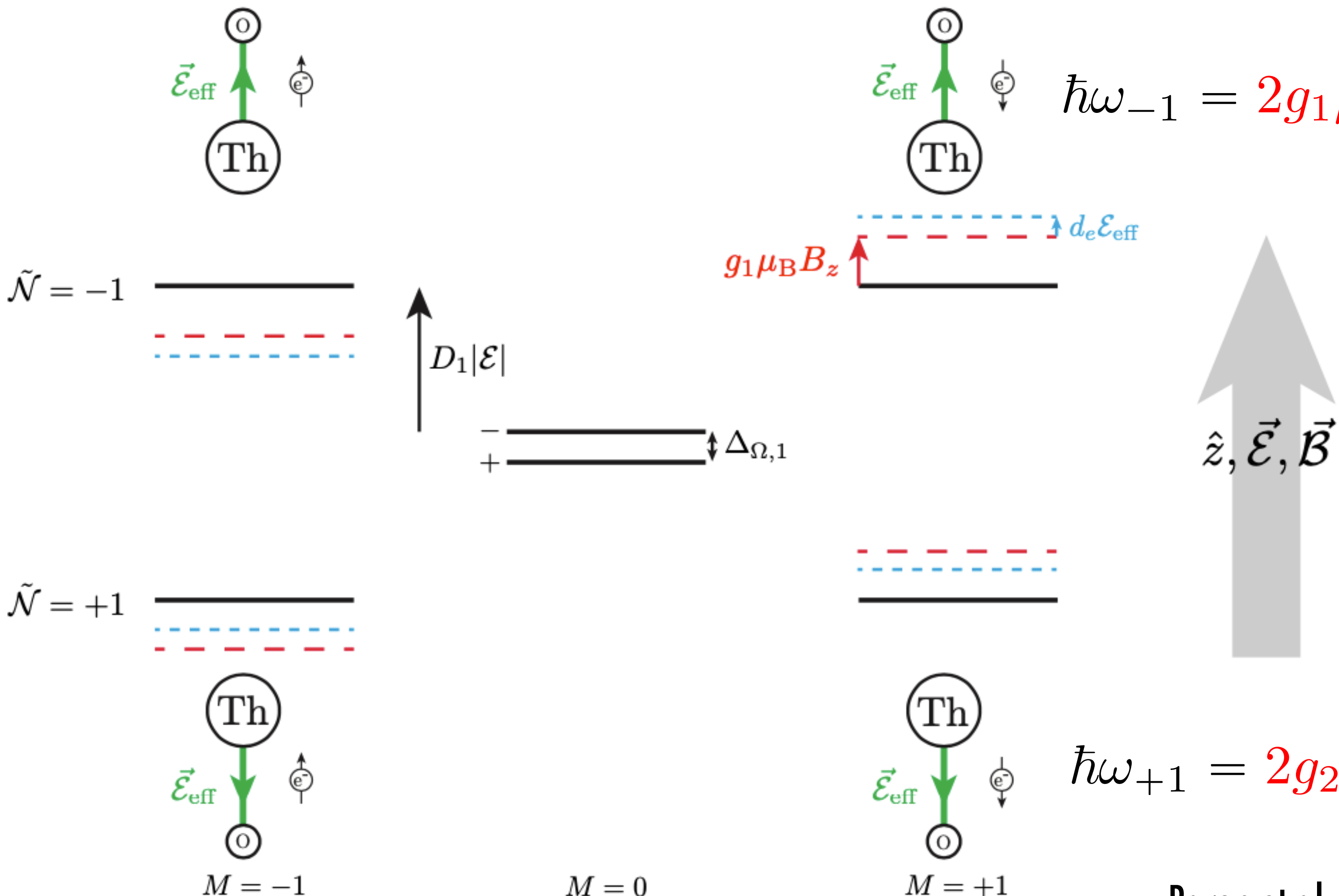


HfF⁺ / ThF⁺
Ion Trap
(JILA)

PRL 119 153001 (2017)
Science 381:46 (2023)

Lab *E*-fields: 0.0005 < GV/cm
R. Ready, et al. NIMA 1014 165738 (2021)

ACME Control of Systematics: Near-Perfect "Internal" Co-Magnetometry



$$\hbar\omega_{-1} = 2g_1\mu_B B_z + 2d_e E_{\text{eff}}$$

$E_{\text{eff}} = 78$ GV / cm

$E_{\text{lab}} <= 140$ V / cm

$$\hbar\omega_{+1} = 2g_2\mu_B B_z - 2d_e E_{\text{eff}}$$

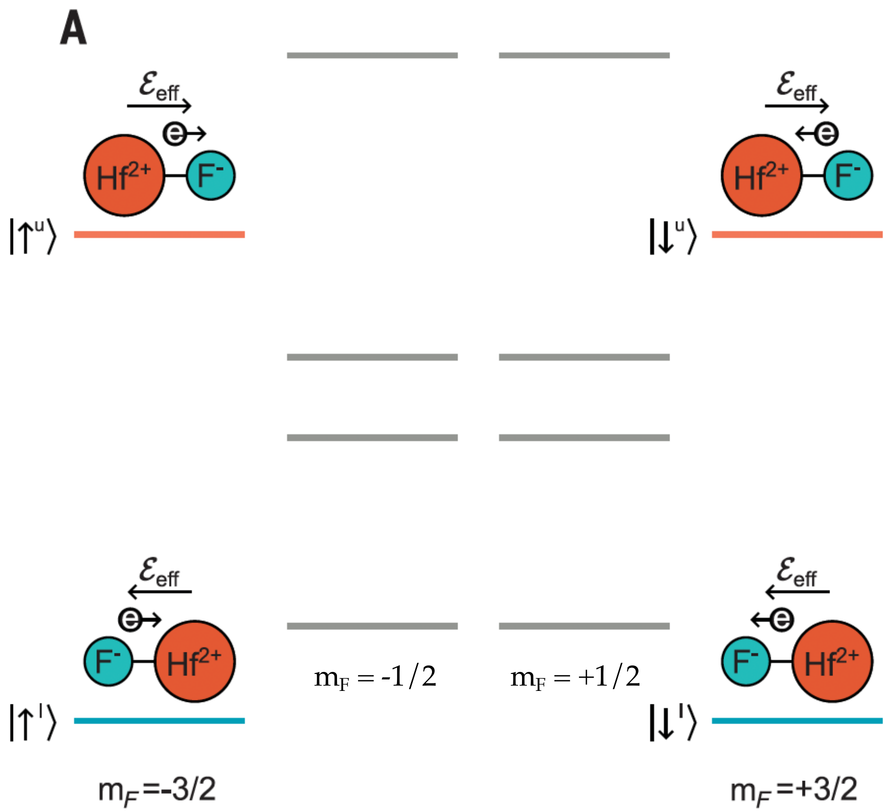
Baron et al. NJP 19:071001 (2017)

Crucially: g_1 is approximately equal to g_2 and has a small dependence on E_{lab}!

JILA Control of Systematics: Near-Perfect "Internal" Co-Magnetometry

E_{lab} = 58 V/cm →

Crucially: g_u is approximately equal to g_l and has a small dependence on E_{lab}!



$$\omega_u = \frac{3g_u\mu_B B_{rot} - 2d_e E_{eff}}{\hbar}$$

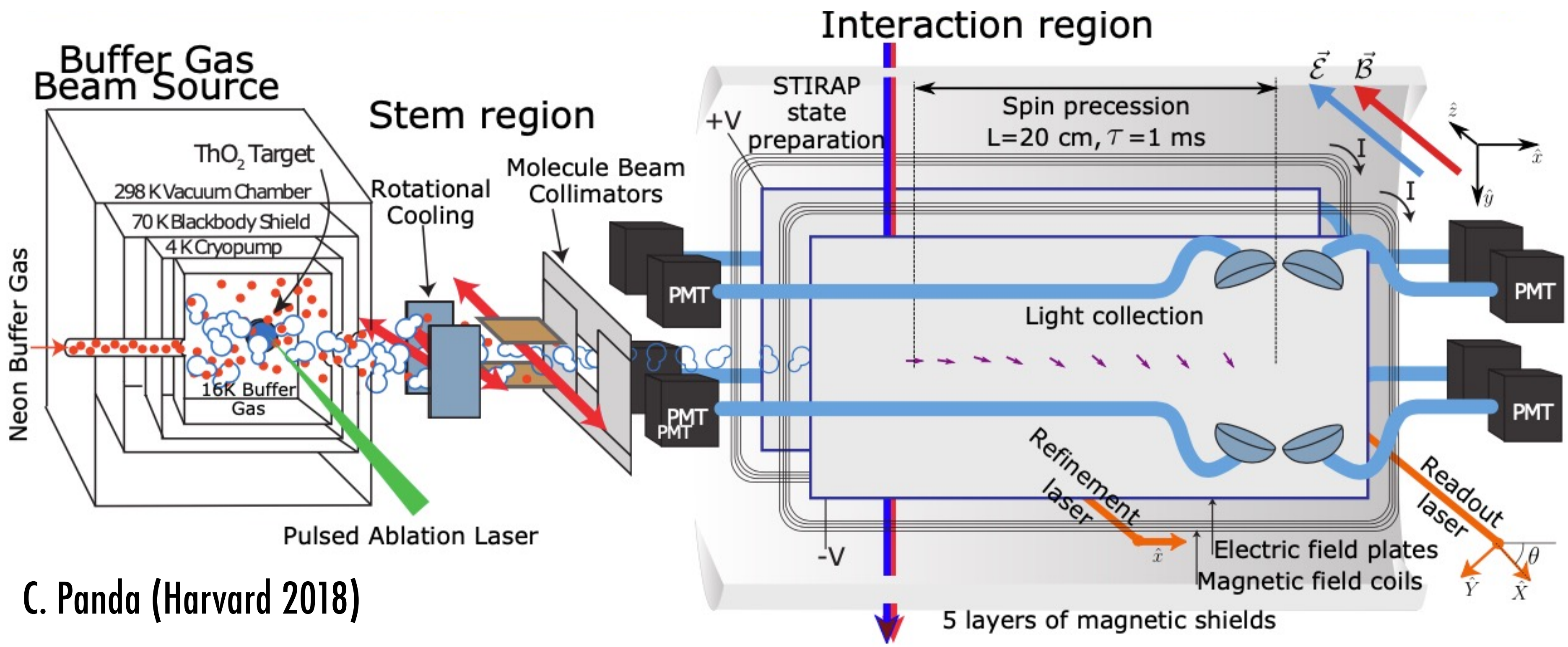
$$I(^{180}\mathrm{Hf}) = 0$$
$$I(^{19}\mathrm{F}) = 1/2$$
$$S(e) = 1/2$$
$$J = 1/2$$

$$\omega_l = \frac{3g_l\mu_B B_{rot} + 2d_e E_{eff}}{\hbar}$$

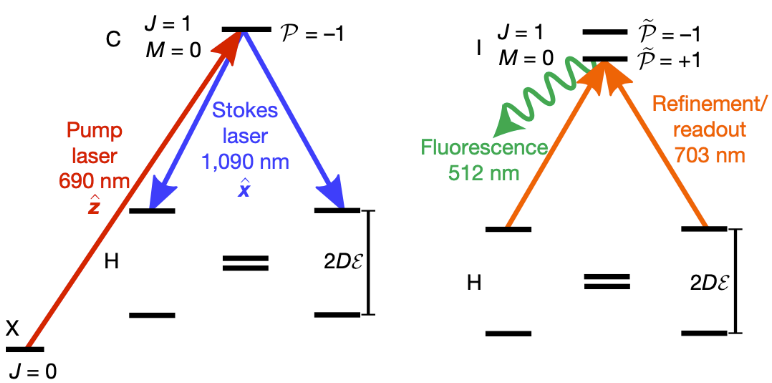
E_{eff} = +/- 23 GV/cm

$$\omega_l - \omega_u = \frac{3(g_l - g_u)\mu_B B_{rot} + 4d_e E_{eff}}{\hbar}$$

The ACME II Experiment: ThO



C. Panda (Harvard 2018)



$$E_{\rm lab} = \pm 80 \text{ V/cm}, \pm 140 \text{ V/cm}$$
$$E_{\rm eff} = 78 \text{ GV/cm}$$
$$T \approx 1 \text{ day}$$
$$\tau \approx 1 \text{ msec}$$
$$N_d \approx 10^4$$

The Path From ACME II to ACME III

ACME-II: d_e = (4.3 +/- 3.1$_{stat}$ +/- 2.6$_{sys}$)x10^{-30} *e* cm (assuming C_S is zero)
Nature 562:355 (2018)

- Reversals included the states probed, the applied *E*- and *B*-fields, the state preparation & probe laser polarizations, and the propagation direction of the state preparation and probe lasers

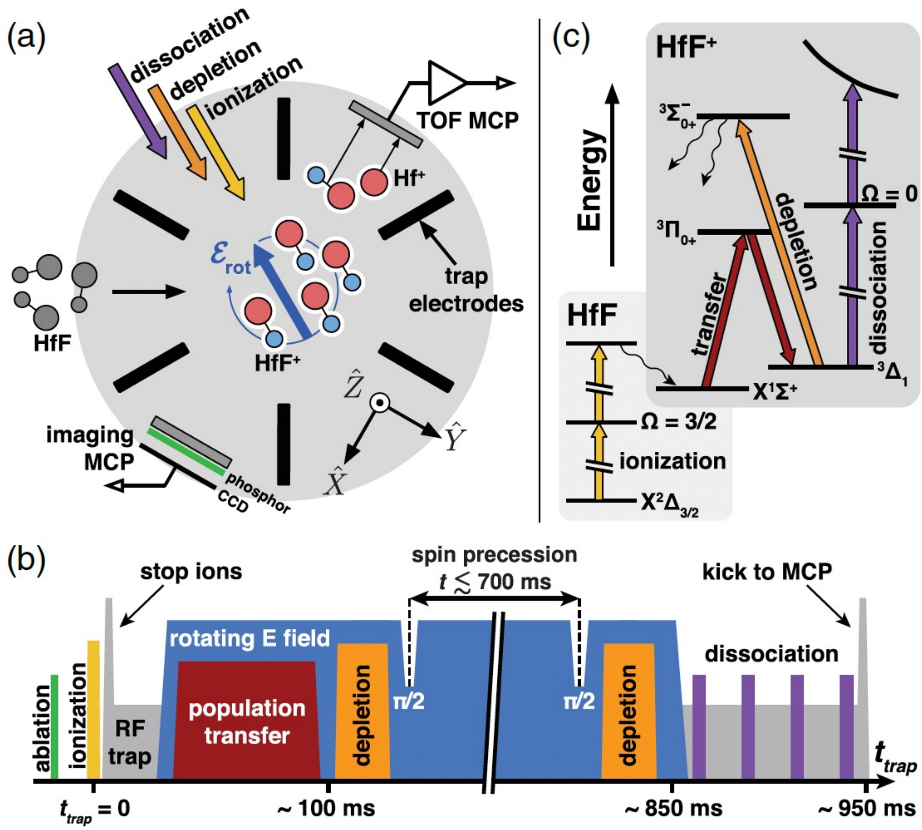
- Leading systematic is a non-reversing lab *E*-field that couples to imperfections in the laser polarizations

ACME-III goal: one more order of magnitude!
Wu et al. NJP 22:023013 (2020) and Z. Lasner (Yale 2019)

- A molecular "lens" to reduce the beam divergence: x16 more molecules probed
- A longer spin precession time (1 ms to 5 ms)
- Improved state preparation
- Improved fluorescence detection
- Additional control of systematics using the magnetically sensitive *Q* state

The General Idea of The JILA Experiment

PRL **119,** 153001 (2017) PHYSICAL REVIEW LETTERS week ending 13 OCTOBER 2017



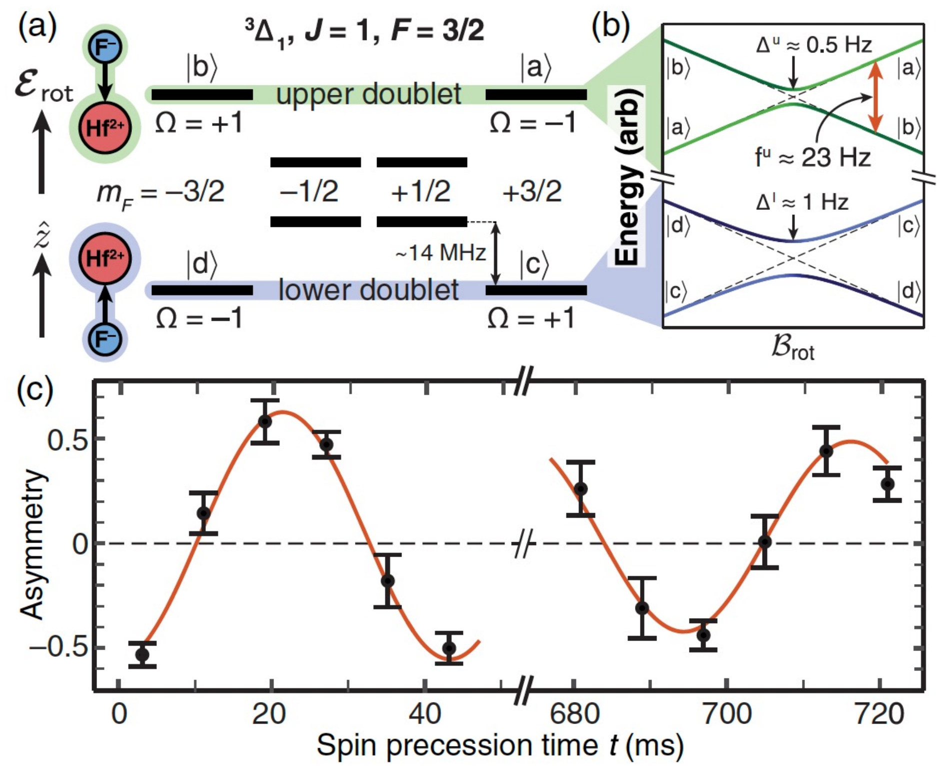
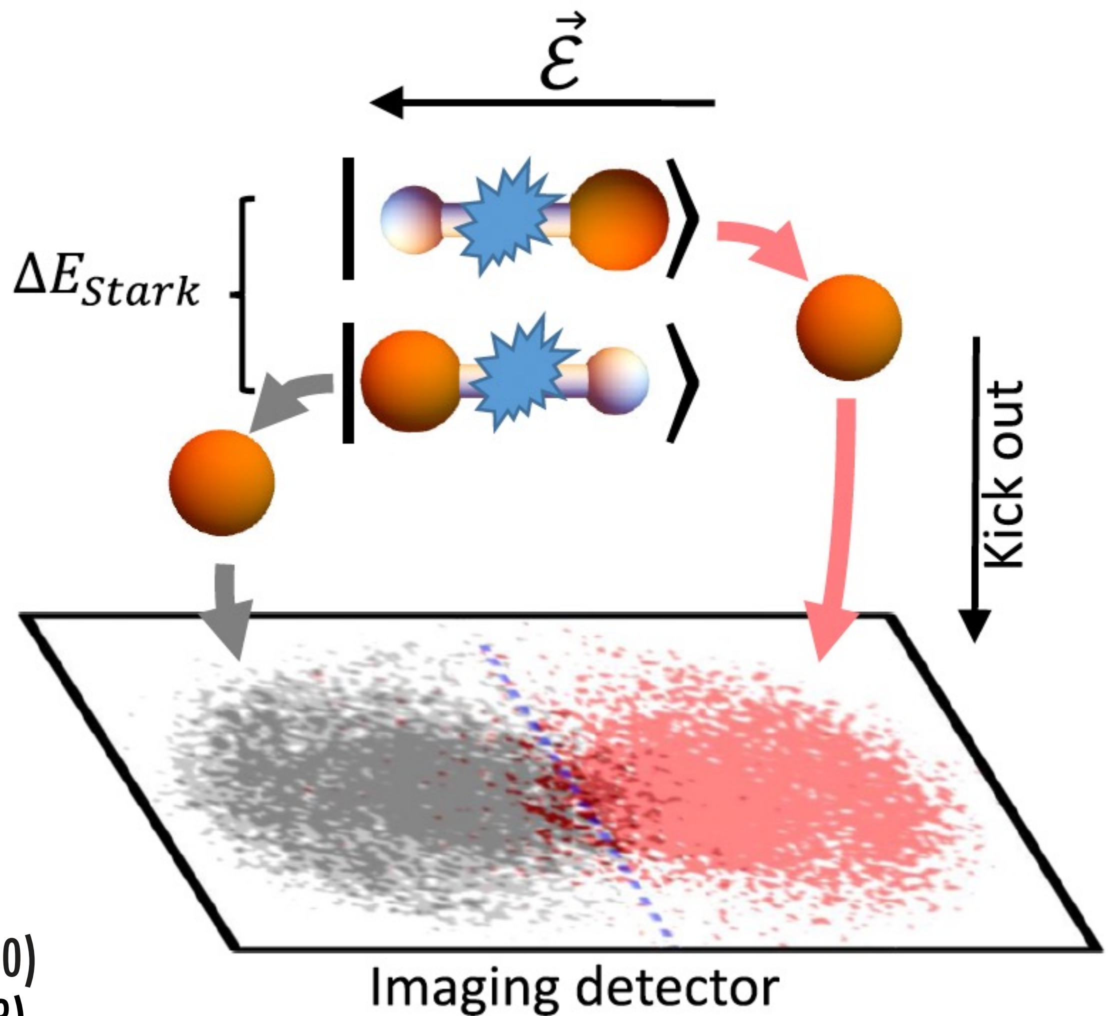


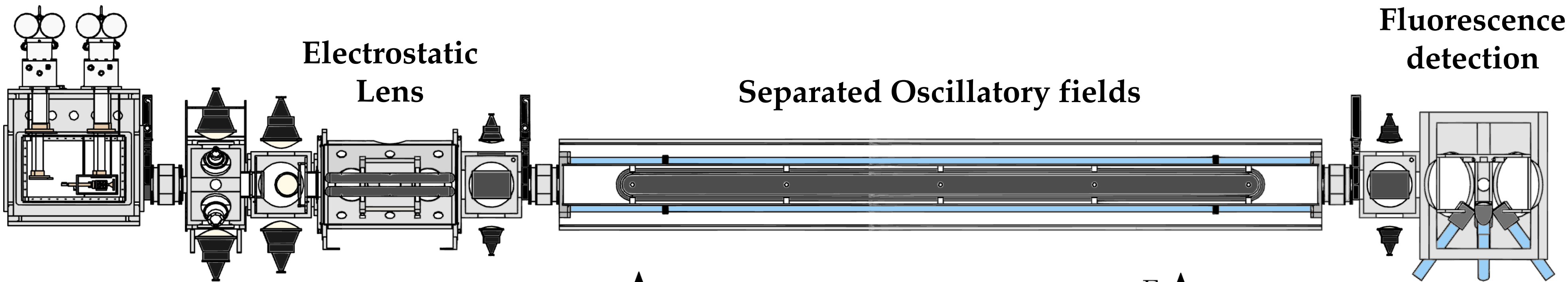
FIG. 2. Electron spin resonance spectroscopy in HfF^+. (a) Level

JILA Main Improvements (2017->2023):
1. Bigger Trap – Longer Coherence Time
2. Measure Both Doublets at the Same Time!

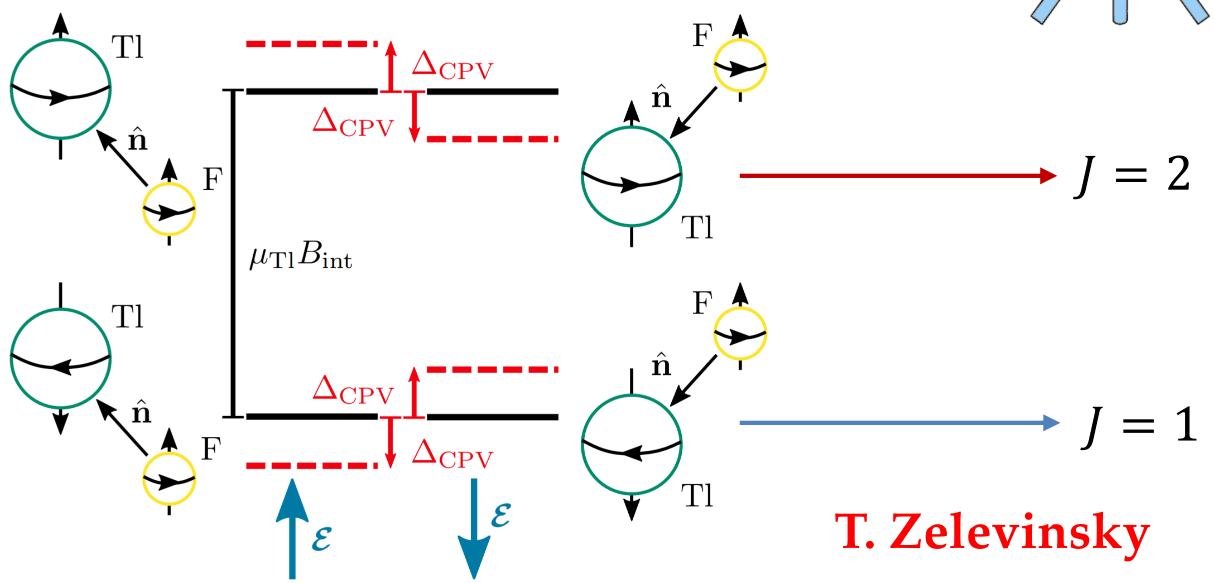


PRL 124 053201 (2020)
Science 381:46 (2023)

Under Construction: CeNTREX @ Argonne
Cold Beam of ^{205}TlF (Stable) Probed With Lasers



- Optical Cycling properties of science state
  PRA 95:062506 (2017)
- Molecular spectroscopy of science state
  PRA 102:052802 (2020)
- Full measurement scheme with "^{19}F comagnetometer"
  Quantum Sci. Technol. 6 044007 (2021)



T. Zelevinsky

- ^{205}Tl has odd proton number: needs nuclear theory
- Data taking starts in ~3 years

Symmetries of Electromagnetic Moments

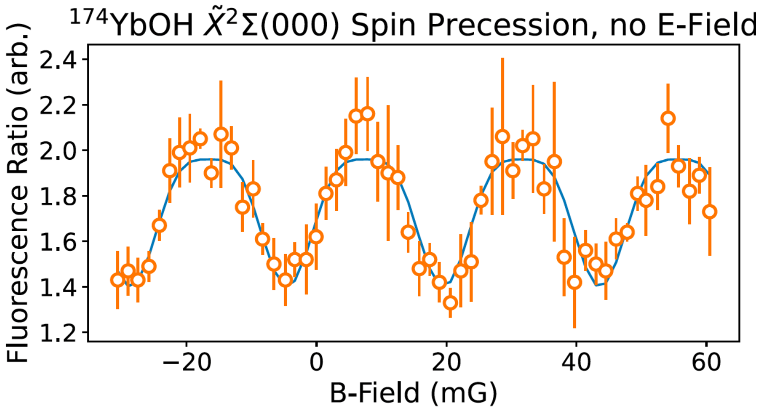
A nucleus with spin *I* has (2*I*+1) symmetry conserving electromagnetic moments:

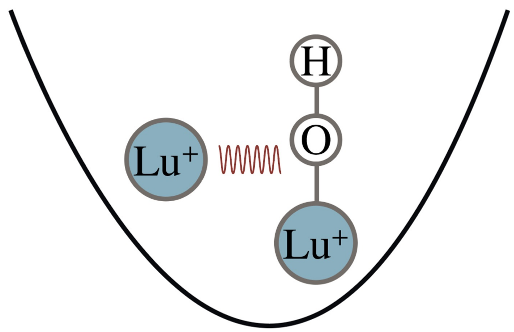
I = 0: electric monopole moment (electric charge) only
I = 1/2: magnetic dipole moment + ...
I = 1: electric quadrupole moment + ...
I = 3/2: magnetic octupole moment + ...

The existence of the following electromagnetic moments violate both time-reversal and parity:

I = 0: magnetic monopole moment (complicated story...)
I = 1/2: electric dipole moment
I = 1: magnetic quadrupole moment

Nuclear Magnetic Quadrupole Moment Searches Using Cold Beams and Molecular Ion Traps

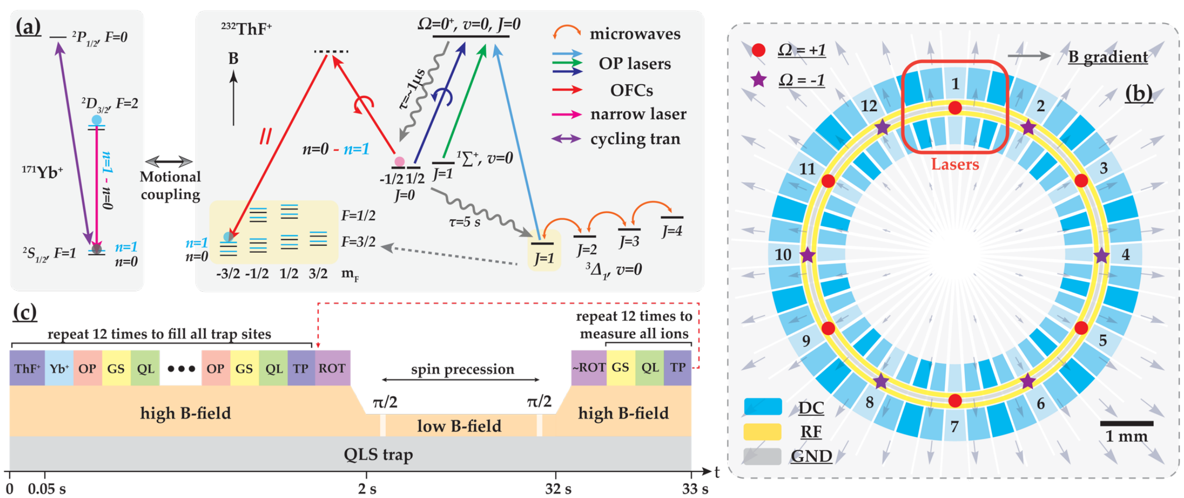




N. Hutzler (Caltech)

M. Grau (Old Dominion)

Y. Zhou (UNLV)



- MQMs are a higher order CPV observable that are enhanced in isotopes with large quadrupole deformations
- MQM searches can directly borrow techniques from molecular electron EDM experiments

PRL 113, 103003 (2014)

- Sensitive to same CPV parameters as Nuclear Schiff Moments
- ^{173}YbOH cold beam experiment under construction
- Trapped molecular ion schemes under development

Phys. Rev. A 109, 033107 (2024)

Intermission

Questions?

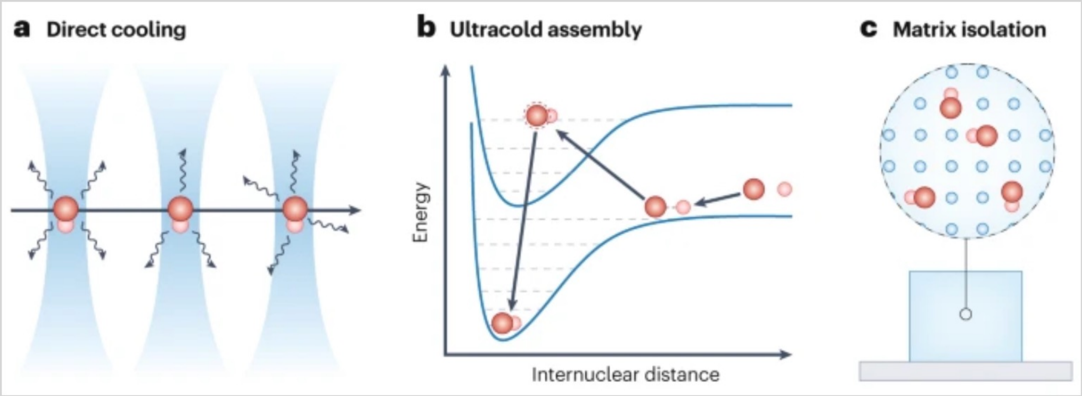
1. stuff

Best of Both Worlds:
Heavy (Rare) 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)
[N.B. the nucleus feels a different E_{eff} than the electrons!]

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, …)

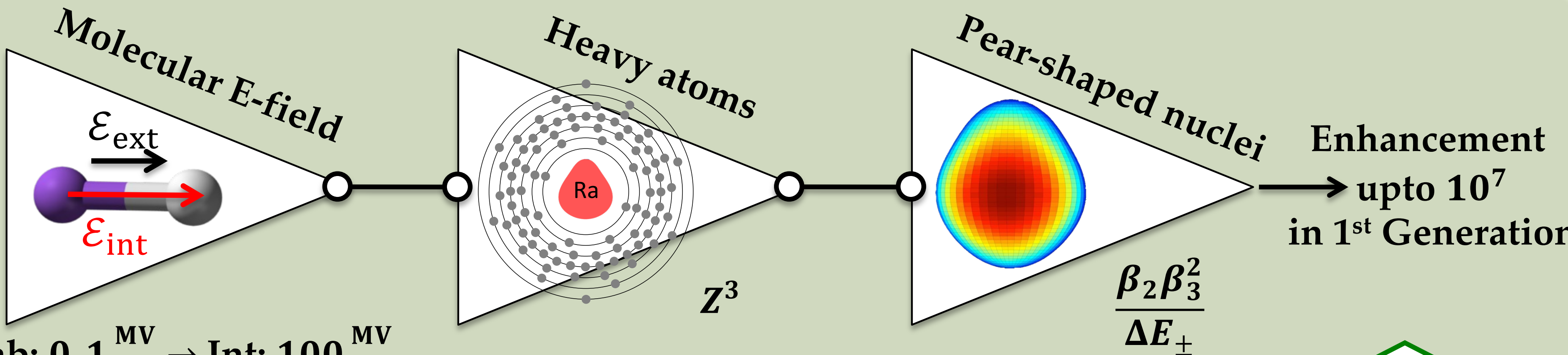


Nature Physics 20, p741-749 (2024)

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?

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



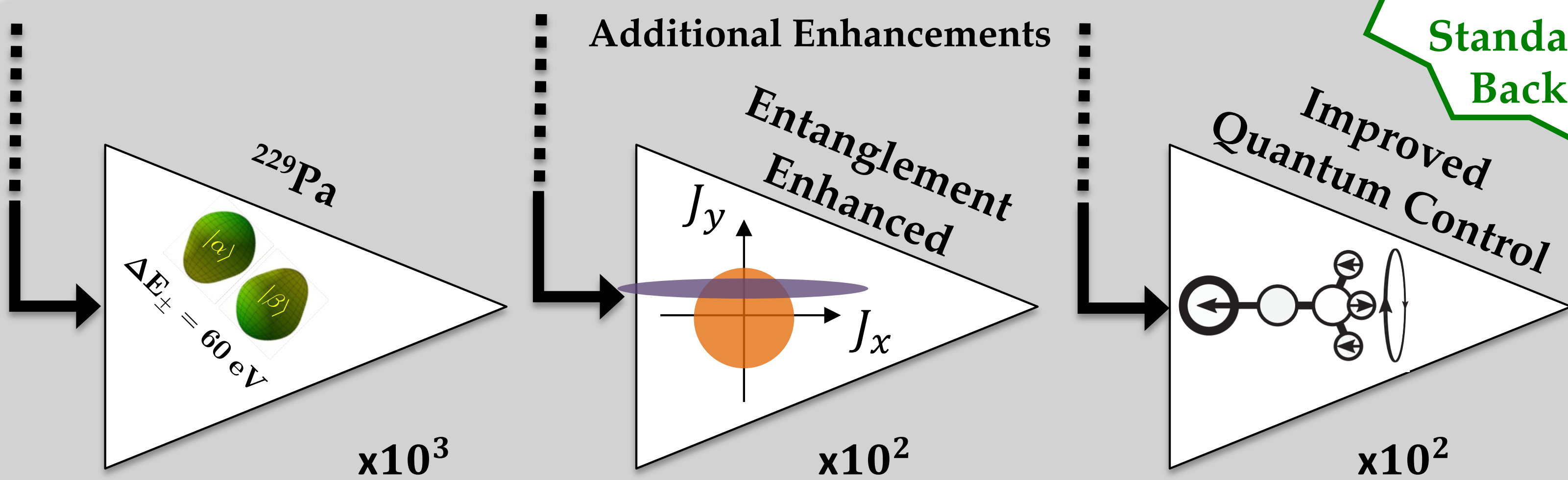
Lab: $0.1\,\frac{\text{MV}}{\text{cm}} \rightarrow$ Int: $100\,\frac{\text{MV}}{\text{cm}}$

Solids: $3\,\frac{\text{MV}}{\text{cm}}$

$$\Delta\nu = \mathcal{E}_{\text{eff}}\,\kappa_{\text{atom}}\,\kappa_{\text{nucleus}} \times (\text{new physics})$$

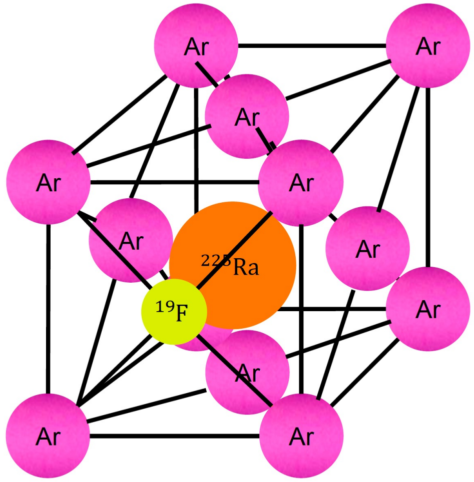
Previously Unimaginable Sensitivity: Standard Model Background

Additional Enhancements



Xing Wu
MSU 2023

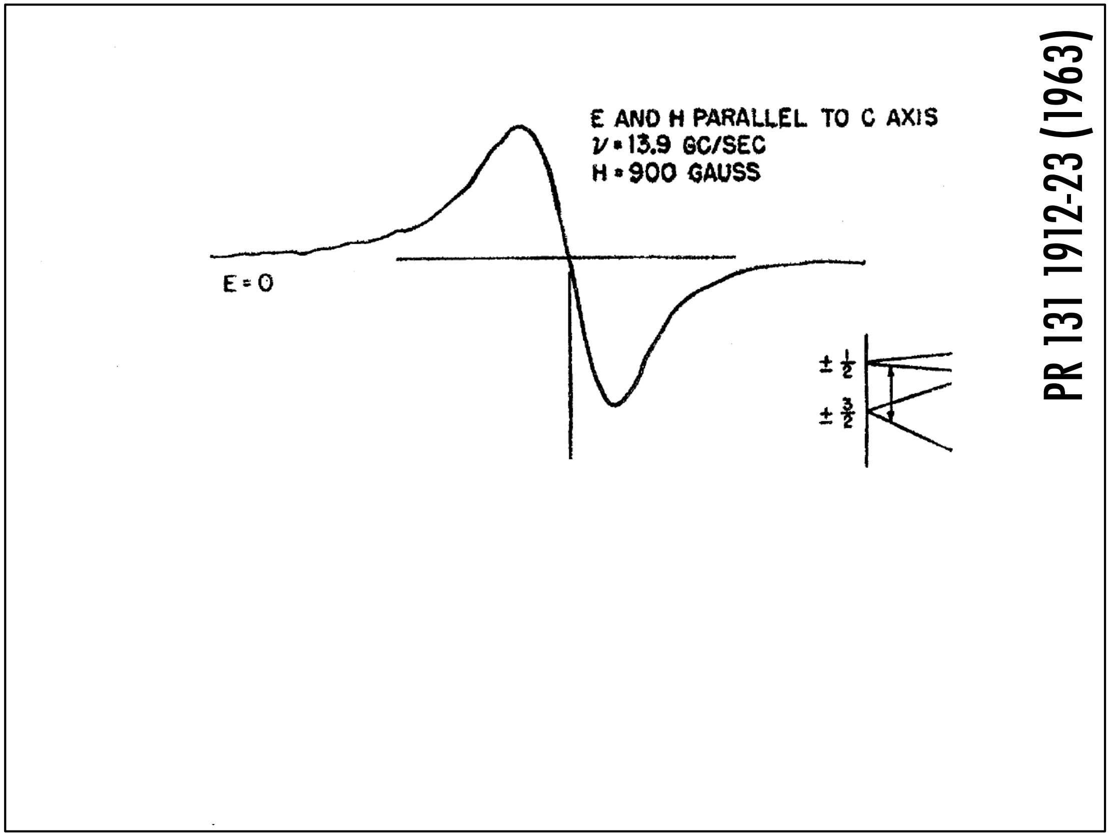
Pear-Shaped Nuclei Implanted In Cryogenic Solids: ^{225}RaF ($\tau_{1/2}$ = 15 days) & ^{229}Pa ($\tau_{1/2}$ = 1.5 days)



- **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**

Controlling Systematics in Solids: The RB-Experiment

Cr^{3+} in Al_2O_3: Royce & Bloembergen Phys. Rev. 131 1912 (1963)



external B-field

Key Concept: In the absence of external fields, the non-degeneracy of a Kramers Doublet is an indication of time-reversal symmetry violation.

"Stark Splitting:" There Are Two Ensembles of Ions!

Cr^{3+} in Al_2O_3: Royce & Bloembergen Phys. Rev. 131 1912 (1963)

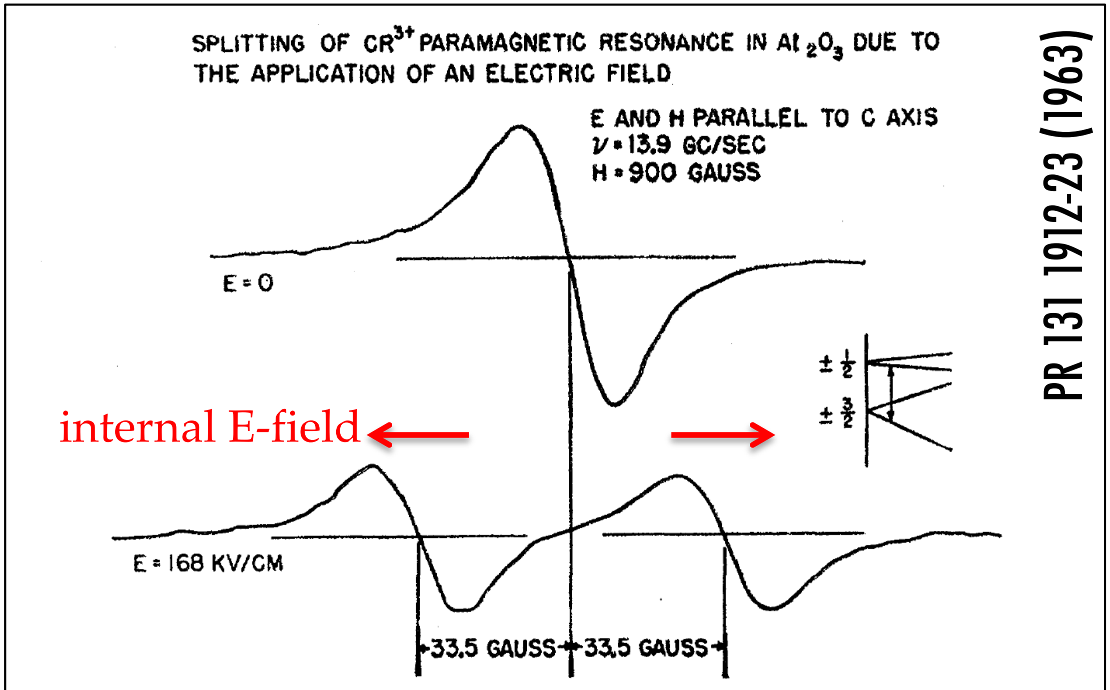


FIG. 1. Experimental absorption derivative curves showing the electric-field-induced splitting of the $\frac{1}{2} \rightarrow \frac{3}{2}$ resonance line of Cr^{3+} in ruby.

external B-field

Key Concept: Under the right conditions, ions (& molecules...) in solids are oriented along the crystal axes.

Apply E-Field Only <u>During</u> State Detection!

Cr^{3+} in Al_2O_3: Royce & Bloembergen Phys. Rev. 131 1912 (1963)

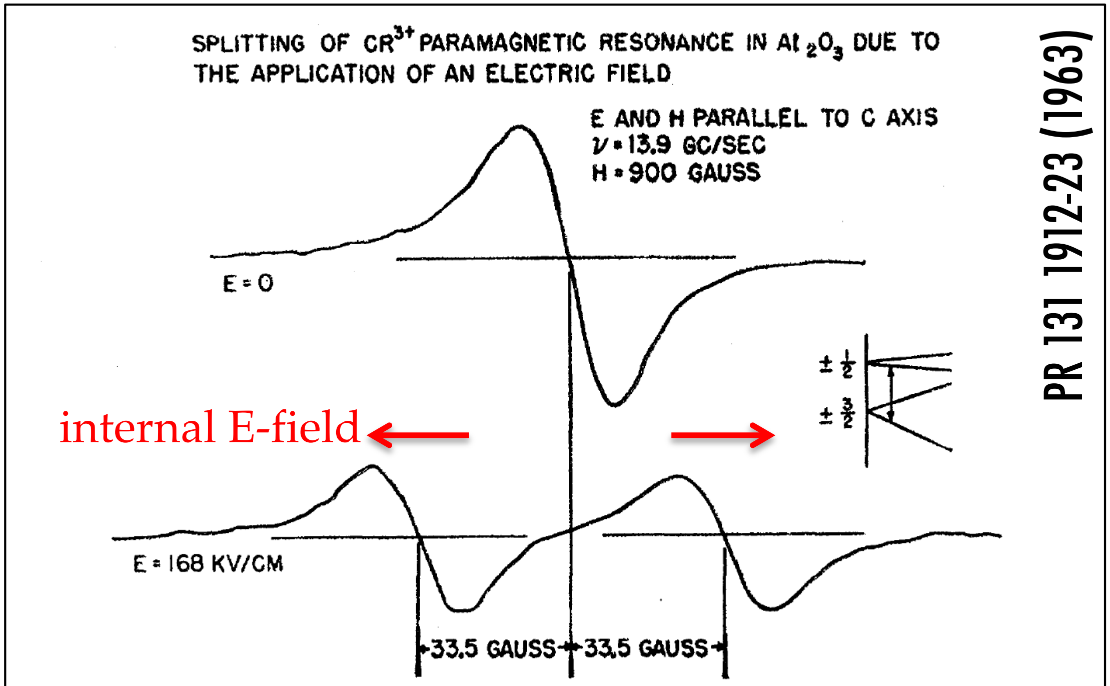
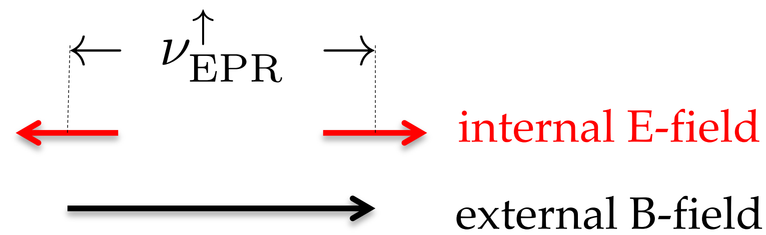
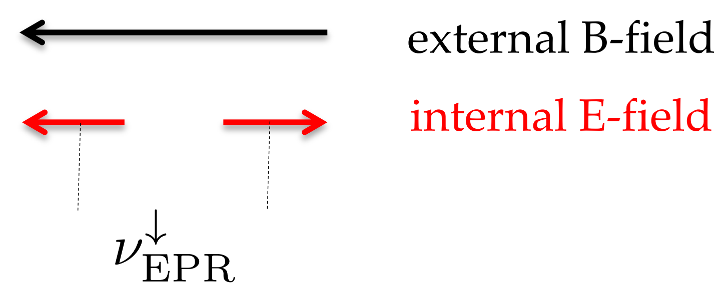


FIG. 1. Experimental absorption derivative curves showing the electric-field-induced splitting of the $\frac{1}{2} \rightarrow \frac{3}{2}$ resonance line of Cr^{3+} in ruby.



$$\Delta\nu_{\mathrm{EPR}} = \frac{4\Delta m d E}{J}$$



Key Concept: Apply a lab *E*-field only during the detection/readout step just to spectroscopically distinguish the two ensembles!

Key Idea to Control Systematics in Solids: Two Nearby Sites Where Effective E-fields Are Opposed

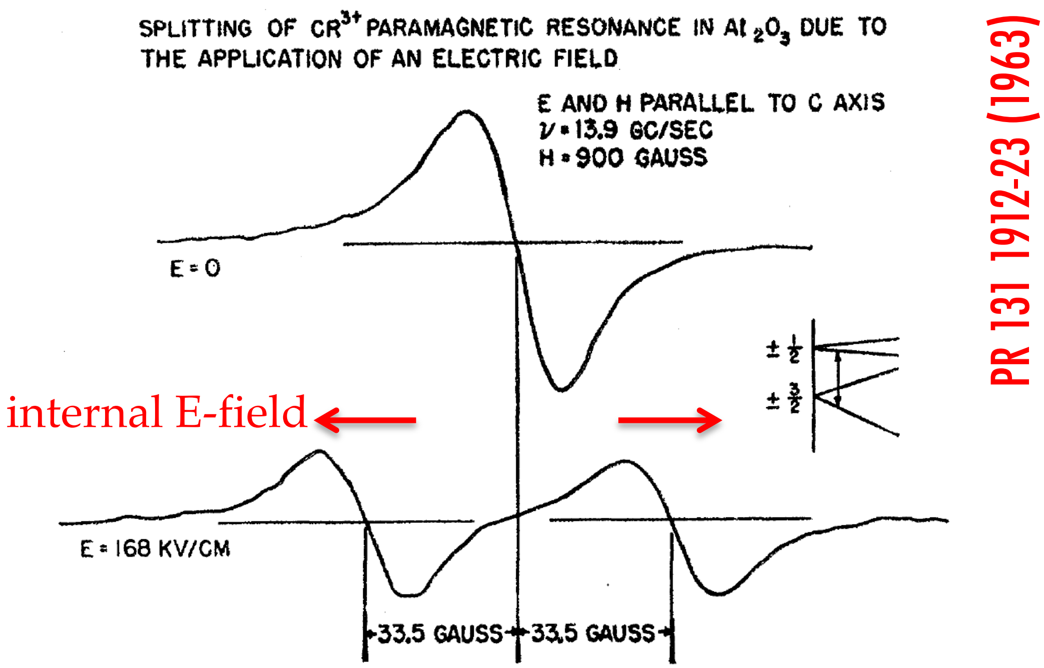
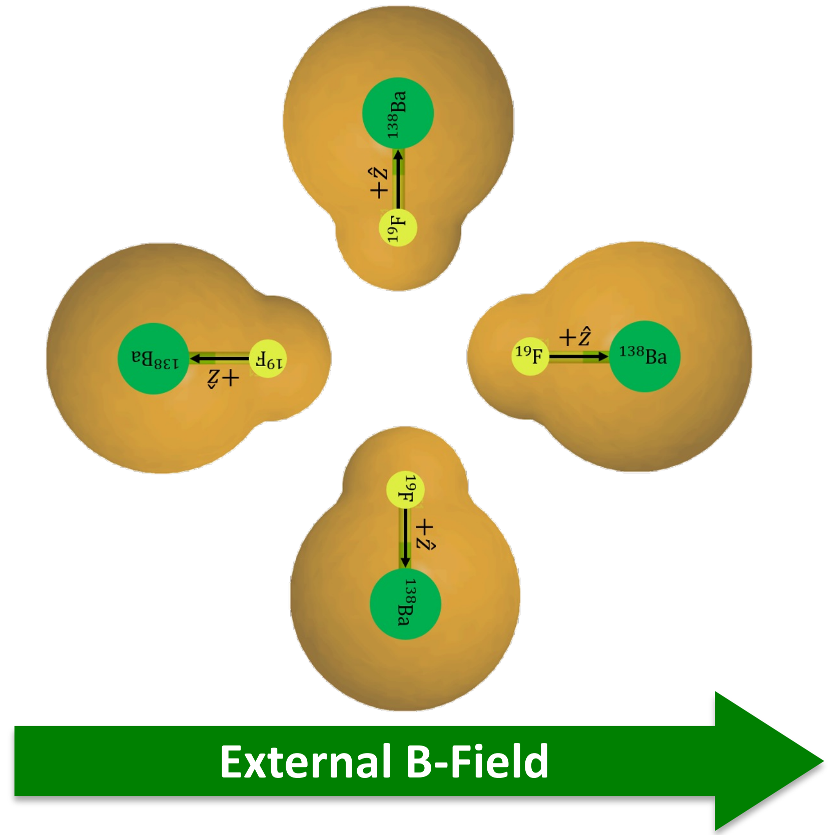


FIG. 1. Experimental absorption derivative curves showing the electric-field-induced splitting of the $\frac{1}{2} \rightarrow \frac{3}{2}$ resonance line of Cr^{3+} in ruby.

external B-field

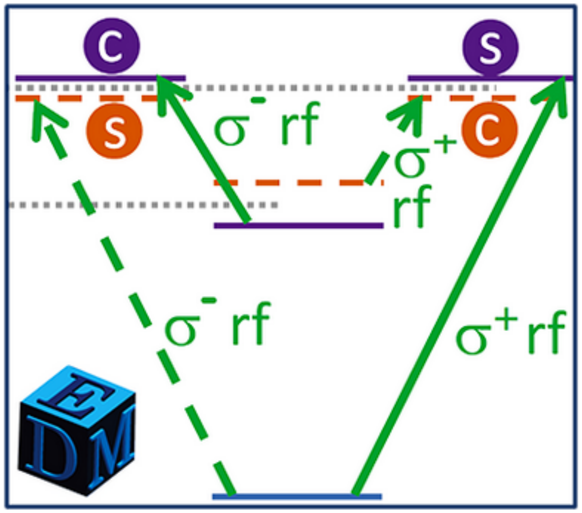


PRA 98:032513 (2018)

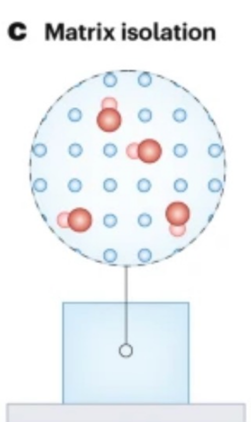
BaF/RaF orientations
(in/out not depicted here)

Key Concept: No lab *E*-field during the spin precession step minimizes the sensitivity of the frequency measurement to external *E*-fields.

One Example of a Modern "RB-Experiment"



EDM³
E. A. Hessels (York, Canada)
A. Vutha (Toronto)
JTS (MSU)



Nature Physics 20, p741–749 (2024)

EDITORS' SUGGESTION

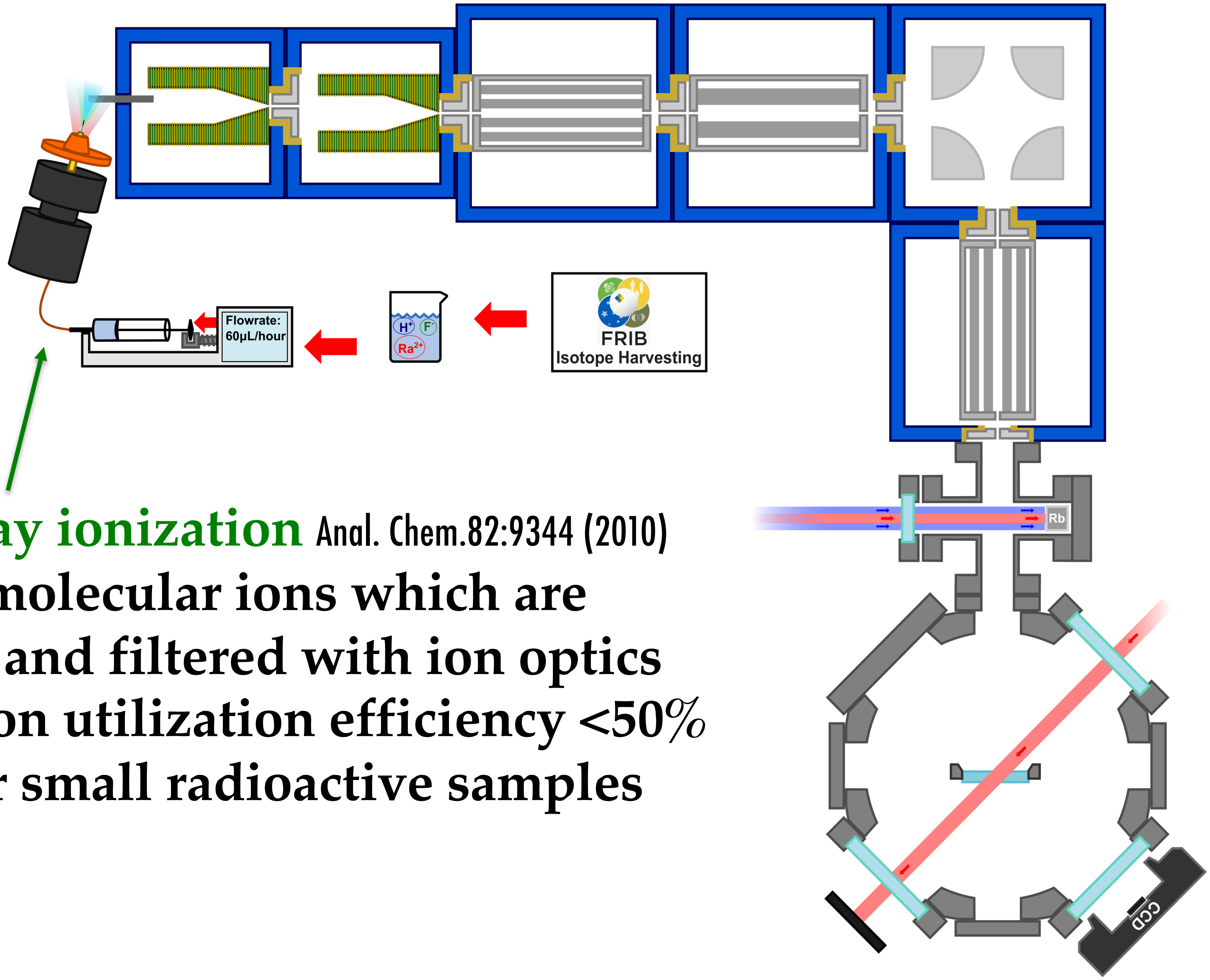
Orientation-dependent hyperfine structure of polar molecules in a rare-gas matrix: A scheme for measuring the electron electric dipole moment

The Stark shift of the hyperfine states of polar molecules embedded in a solid rare-gas matrix is found to depend on the molecular orientation. This finding may significantly improve the measurements of the electron electric dipole moment by using large ensembles of polar molecules trapped in rare-gas matrices with orientation-dependent detections.

A. C. Vutha, M. Horbatsch, and E. A. Hessels

Phys. Rev. A **98**, 032513 (2018)

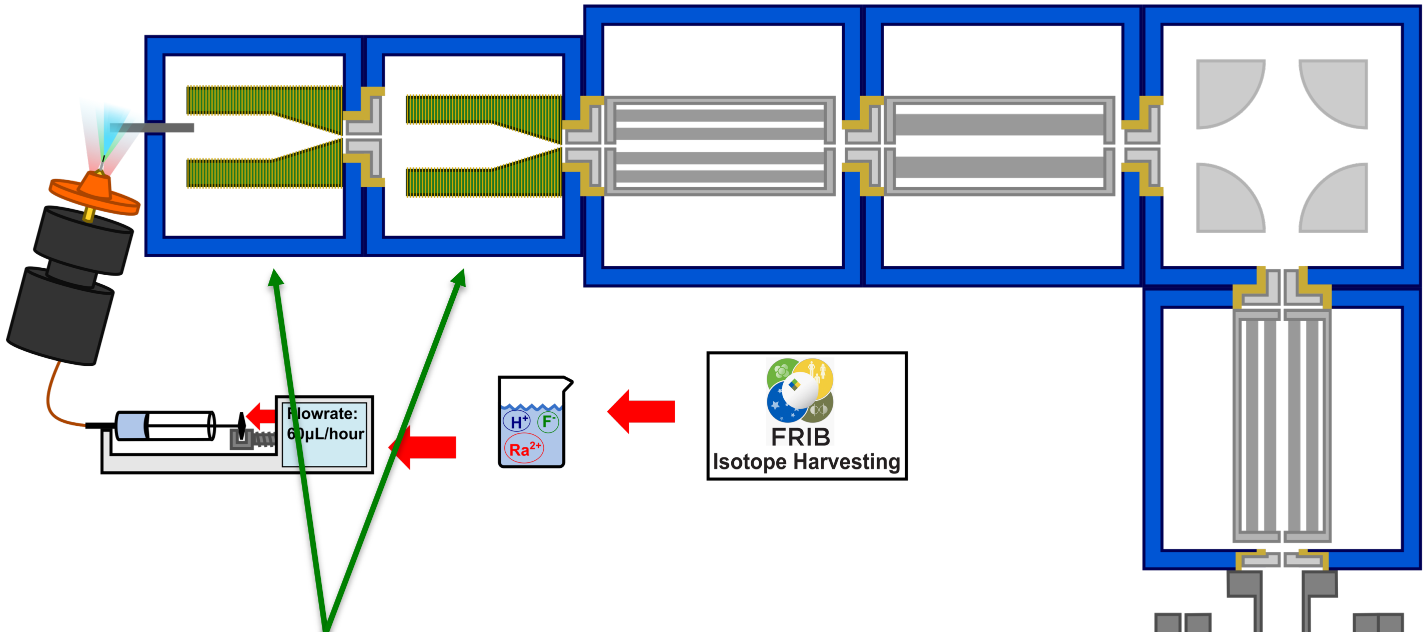
^{225}RaF in Noble Gas Solids ($\tau_{1/2}$ = 15 days)

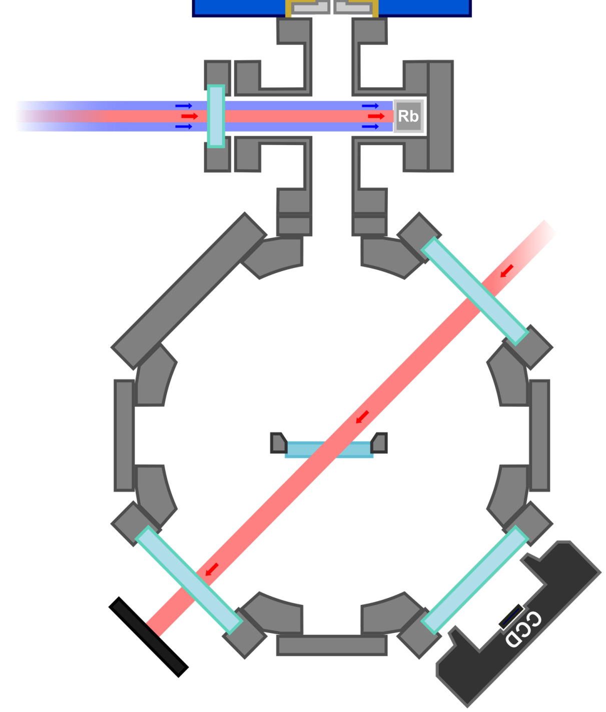


Electrospray ionization Anal. Chem.82:9344 (2010)

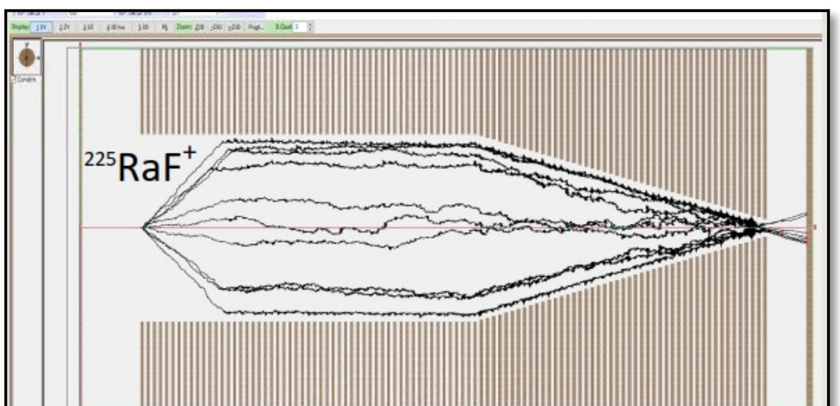
- creates molecular ions which are focused and filtered with ion optics
- ionization utilization efficiency <50%
- ideal for small radioactive samples

^{225}RaF in Noble Gas Solids ($\tau_{1/2}$ = 15 days)

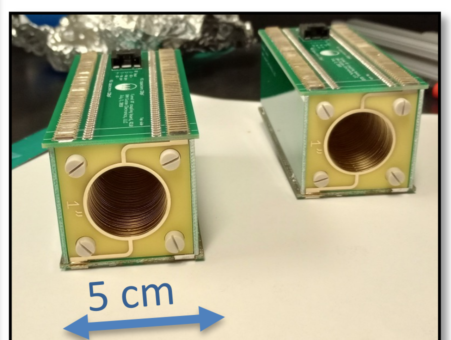




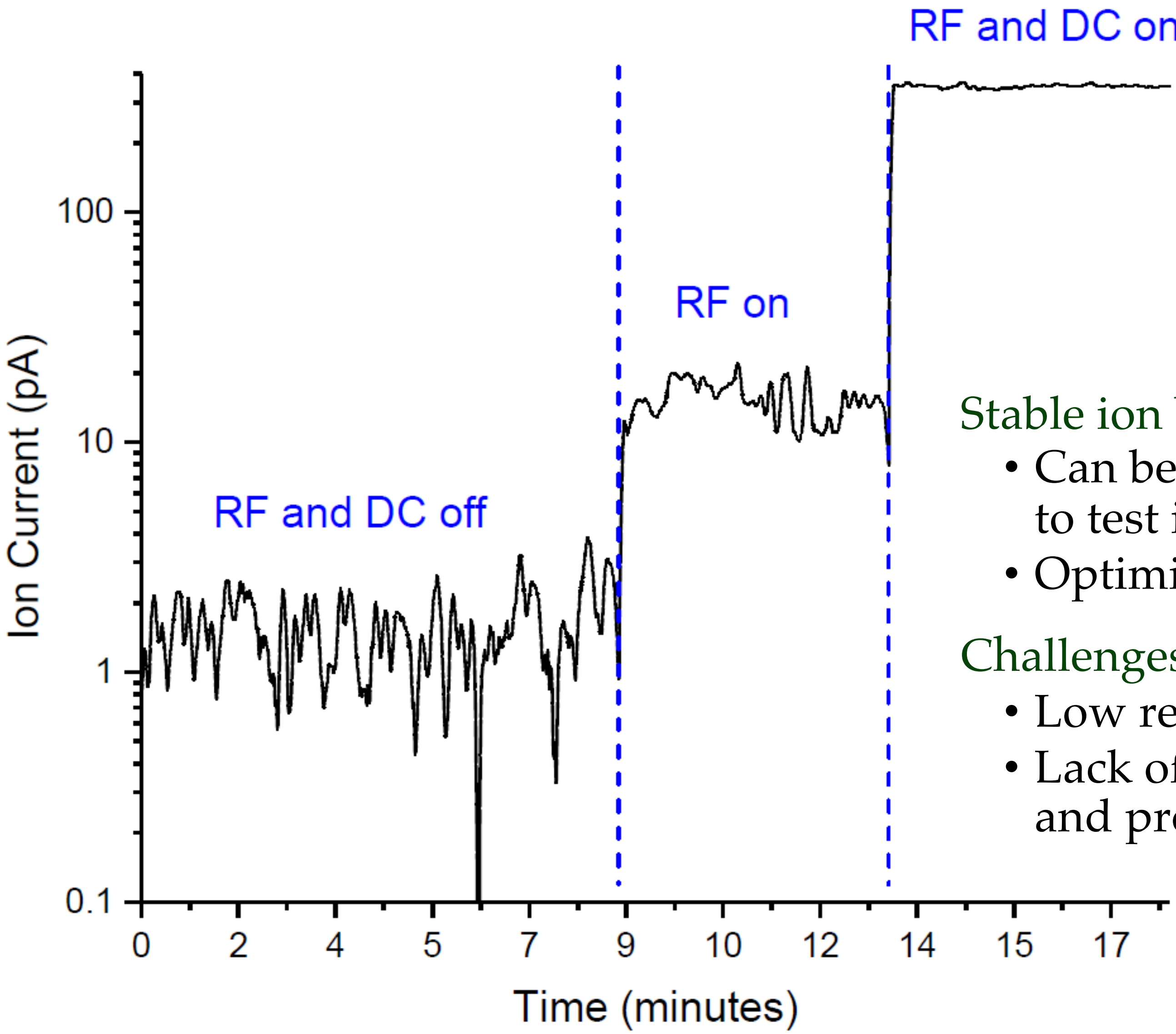
Ion funnels collect ions and separate them from the gas load. Mass Spec. Rev. 29:294 (2010)



GAA Custom Electronics



Ion Funnels Work Well! (~$5k off the shelf)



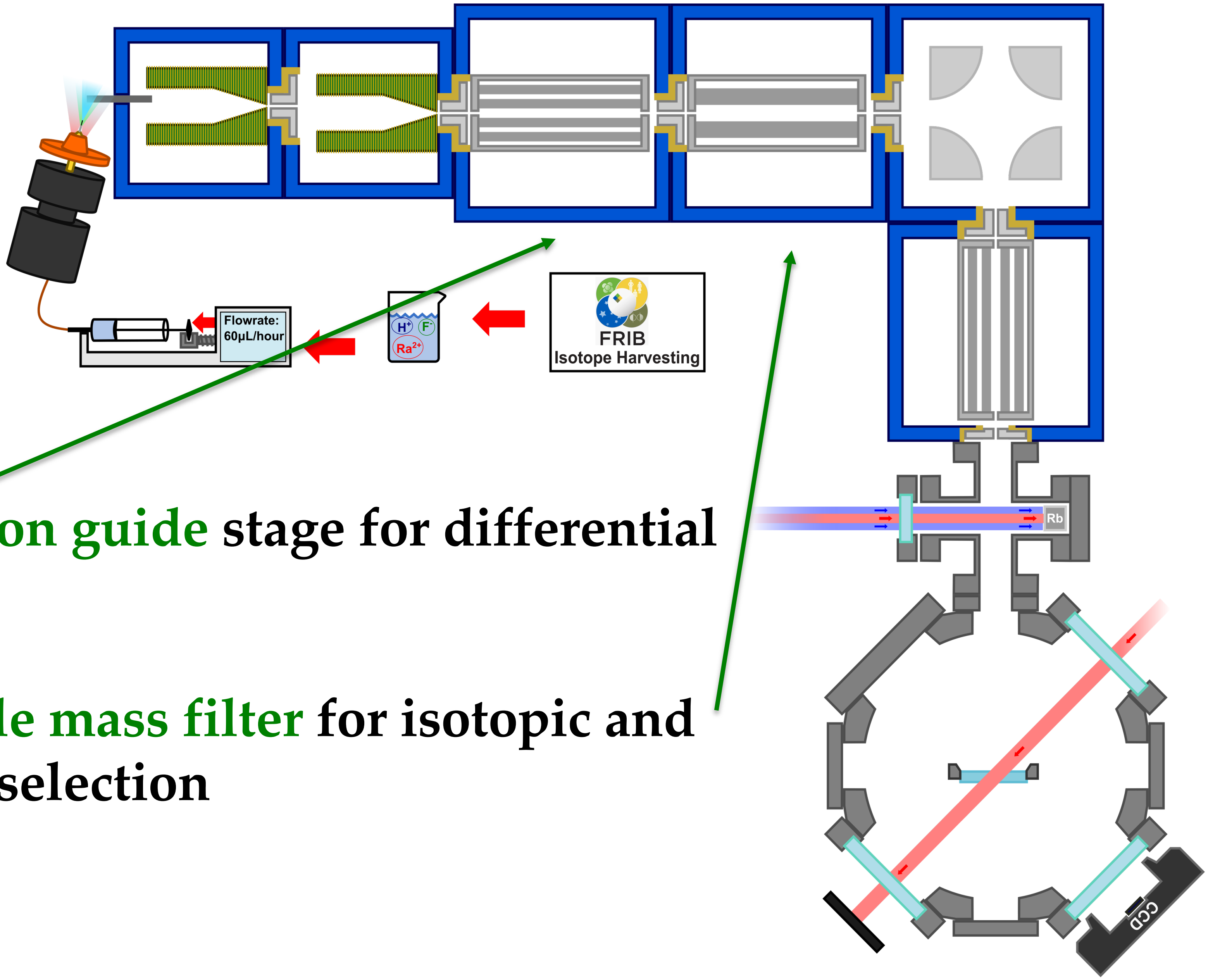
Stable ion beams are possible:

- Can be used during installation to test ion optics
- Optimizing applied bias

Challenges:

- Low reproducibility
- Lack of control over positioning and probe alignment

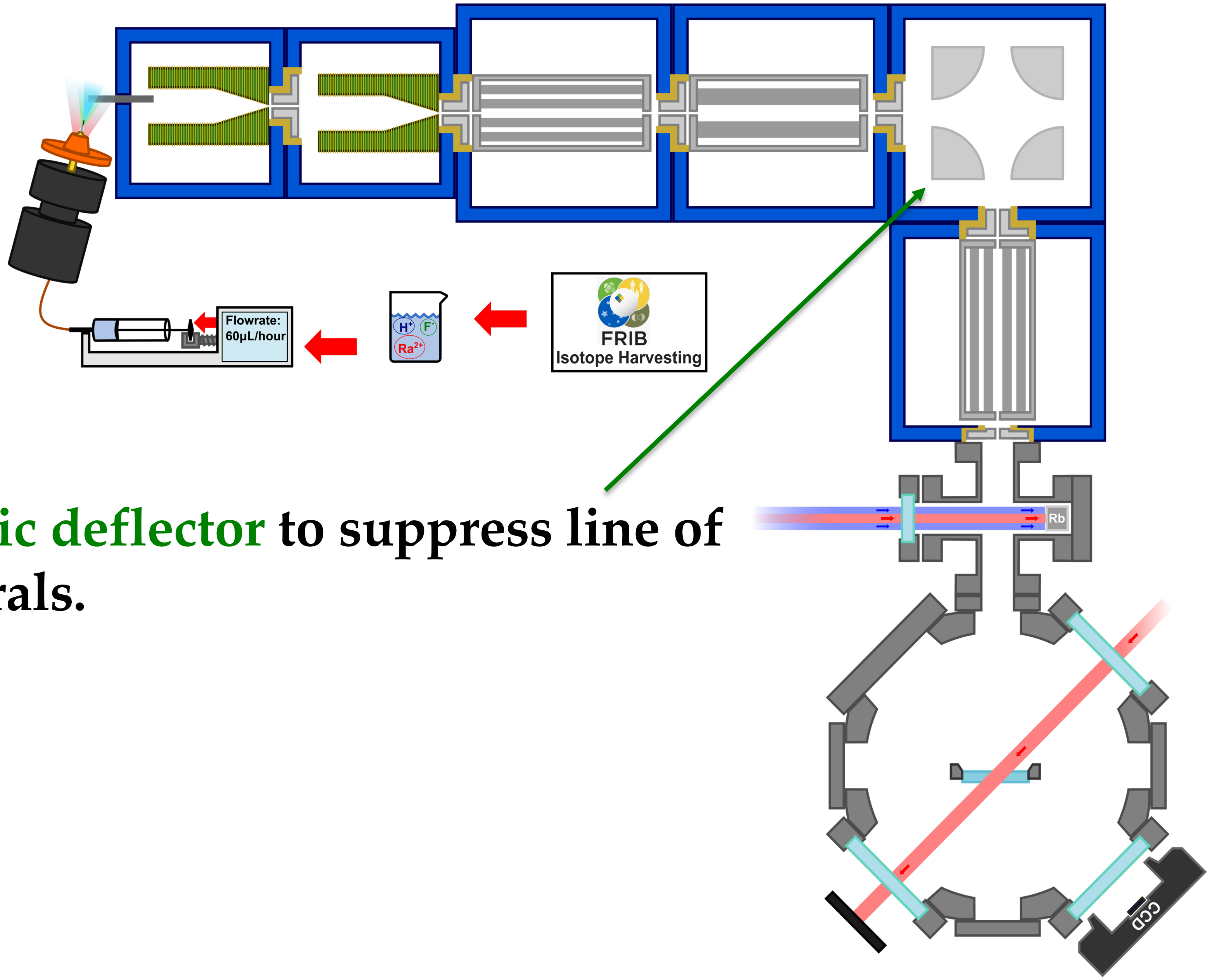
^{225}RaF in Noble Gas Solids ($\tau_{1/2}$ = 15 days)



Octupole ion guide stage for differential pumping

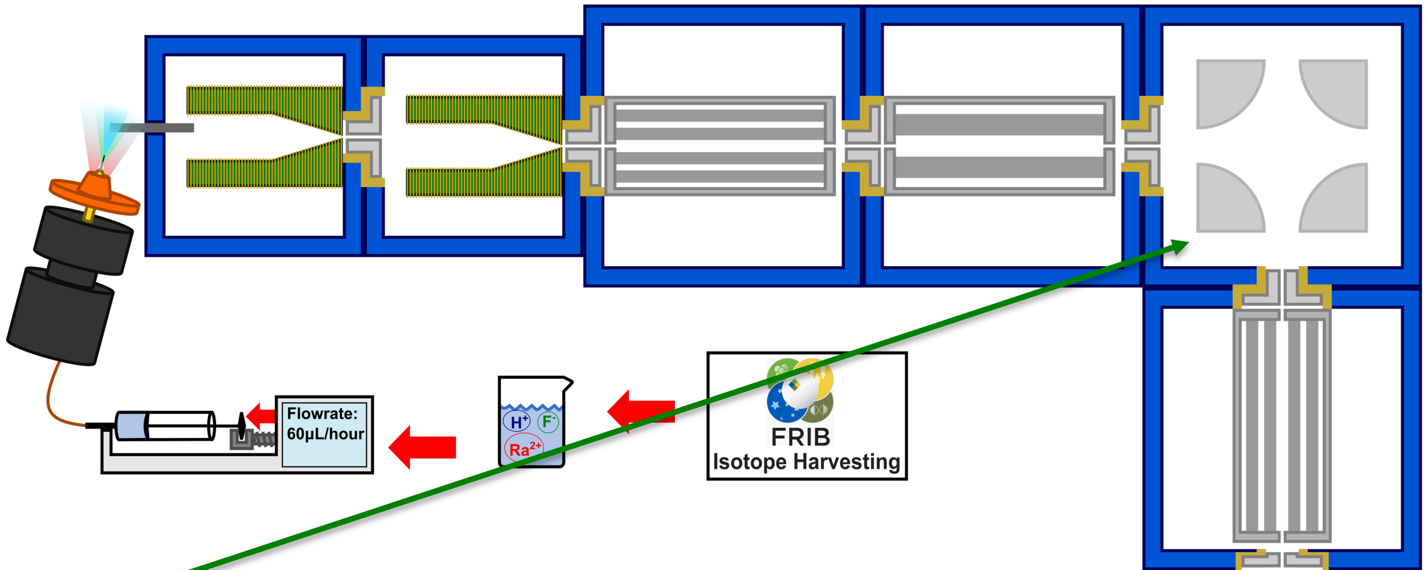
Quadrupole mass filter for isotopic and molecular selection

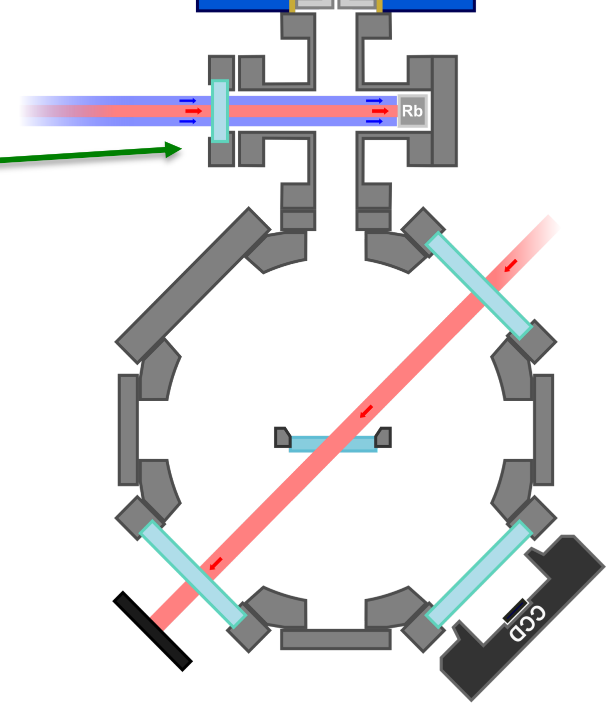
^{225}RaF in Noble Gas Solids ($\tau_{1/2}$ = 15 days)



Electrostatic deflector to suppress line of sight neutrals.

^{225}RaF in Noble Gas Solids ($\tau_{1/2}$ = 15 days)

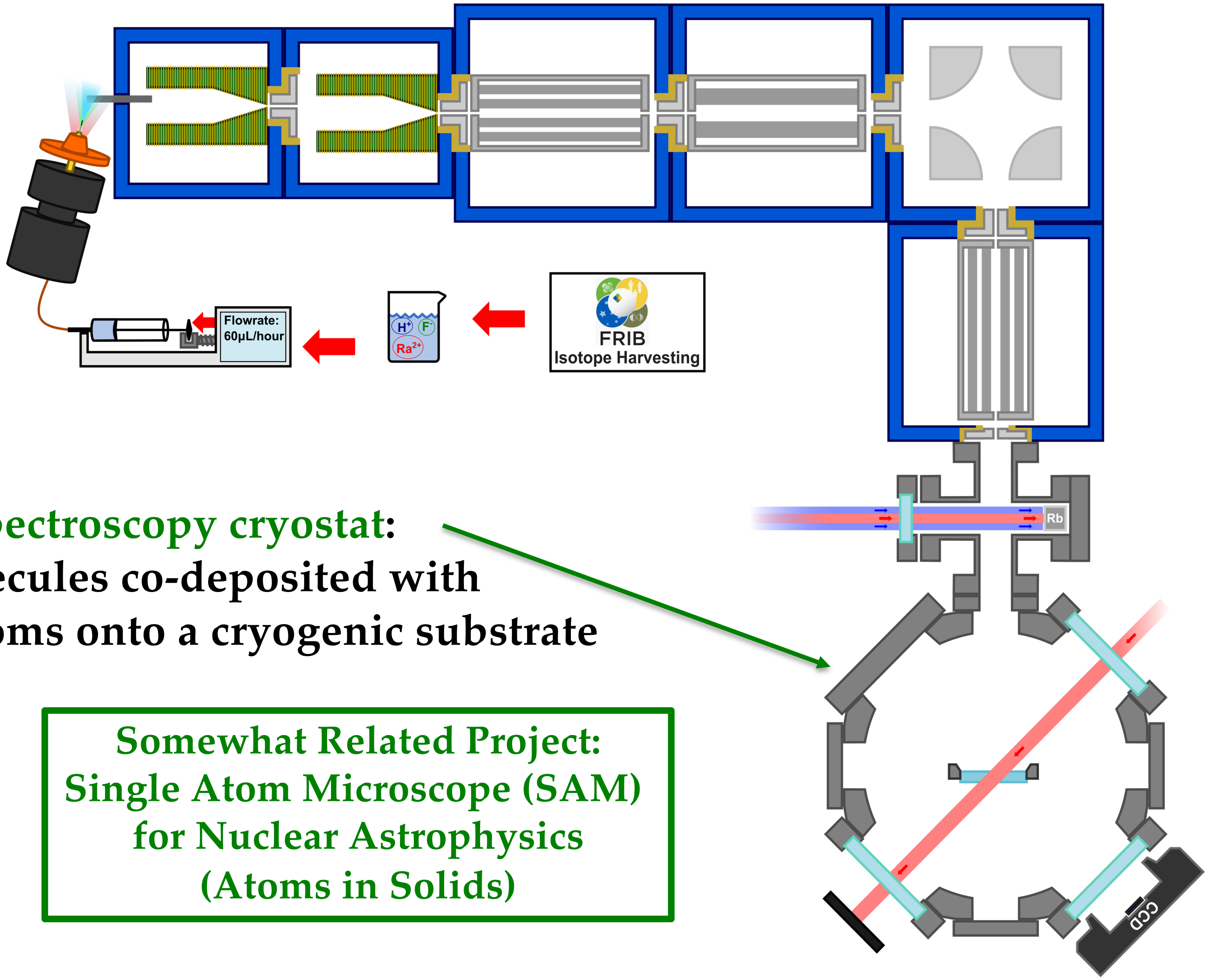




Octupole ion guide for beam shaping into
Rydberg Charge Exchange Cell

Alkali Rydberg atoms for charge exchange to neutralize molecular ions.
(charge exchange cross section scales as n^4)

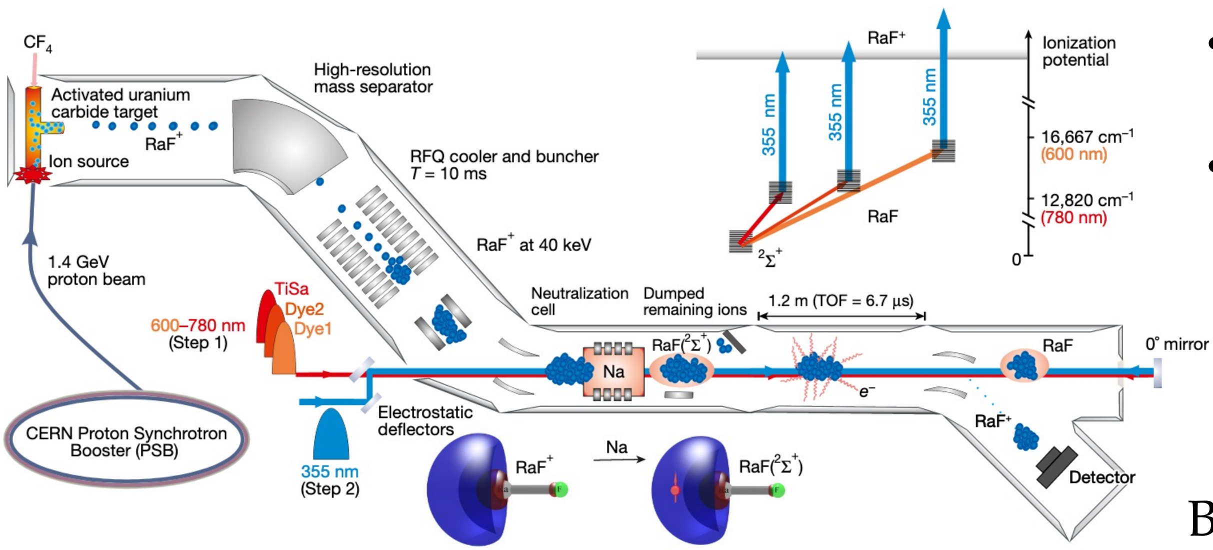
^{225}RaF in Noble Gas Solids ($\tau_{1/2}$ = 15 days)



Molecular spectroscopy cryostat:
Neutral molecules co-deposited with noble gas atoms onto a cryogenic substrate

Somewhat Related Project:
Single Atom Microscope (SAM)
for Nuclear Astrophysics
(Atoms in Solids)

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



- Molecular spectroscopy of RaF is underway!
- RaF is the most laser coolable diatomic molecule!

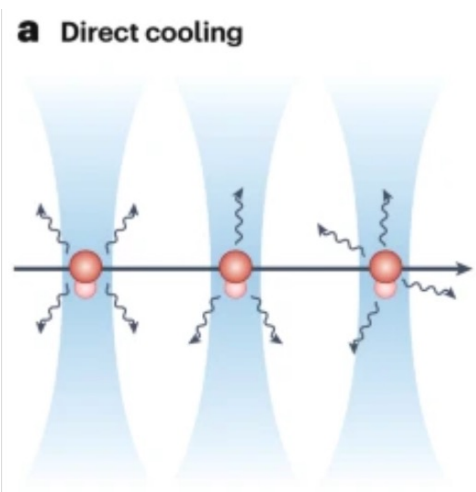
Nature 581:396 (2020)
PRL 127:033001 (2021)

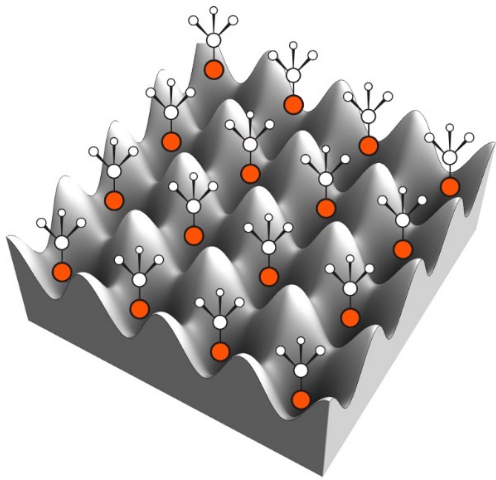
R. Garcia Ruiz (MIT)

Benefits of Polyatomic Molecules

- Laser coolable & trappable
- Highly polarizable
- Comagnetometer states for control of systematics
- High CPV sensitivity
- Laser Cooling of $CaOCH_3$

PRL 119, 133002 (2017)
Quantum Science & Tech. 5, 044011 (2020)
Science 369, 1366–1369 (2020)
Nature Physics 20, p741–749 (2024)

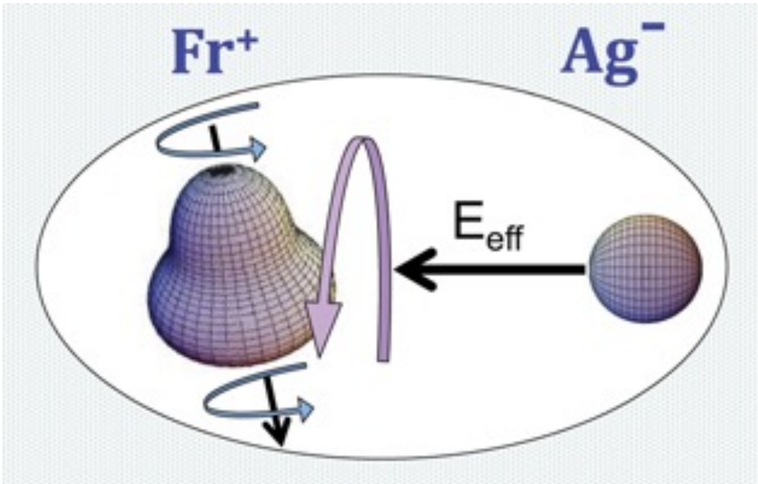




N. Hutzler (Caltech) & J. Doyle (Harvard)

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

Gen-I Estimate:

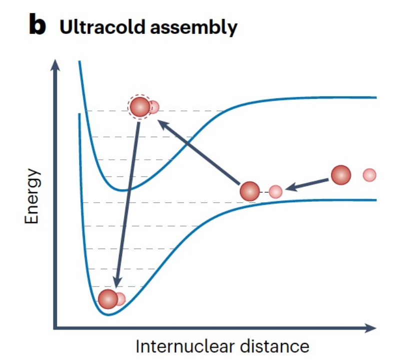


⇒ ~1000x projected improvement vs. ^{199}Hg state of the art

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

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

Theory calculations favorable:
New J. Phys. 23 113039 (2021)
New J. Phys. 24 025005 (2022)

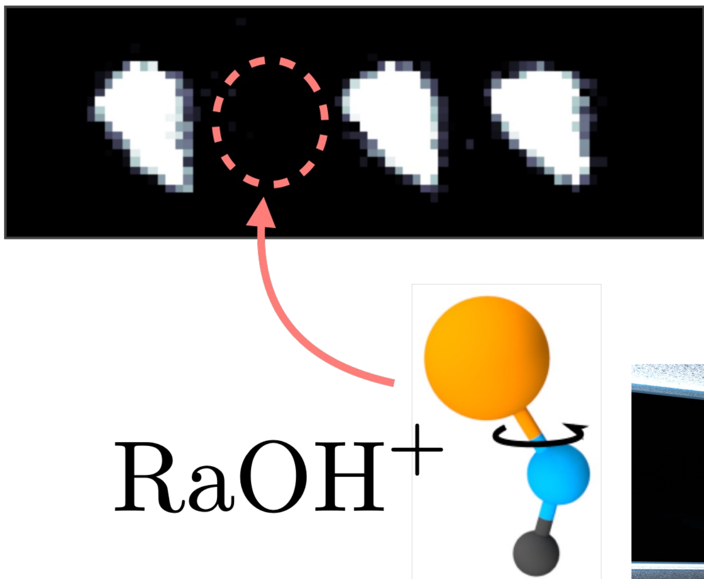


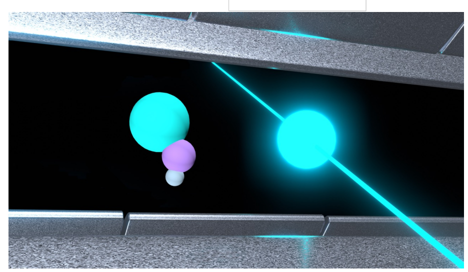
Nature Physics 20, p741-749 (2024)

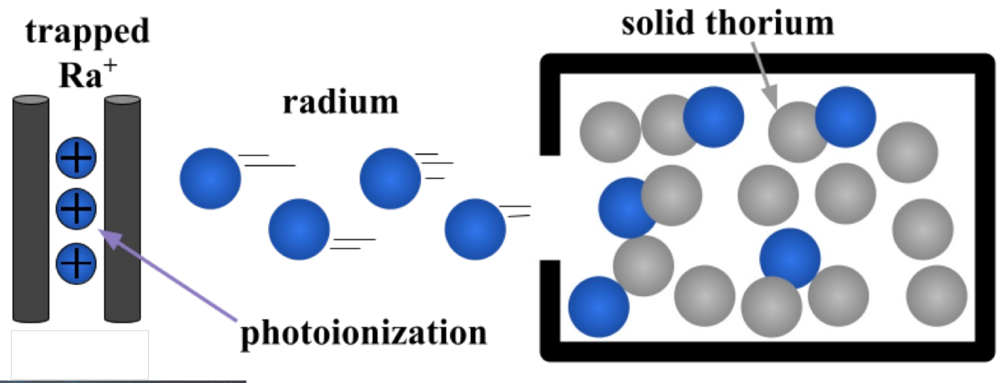
slide from D. DeMille (UChicago/Argonne)

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

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







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

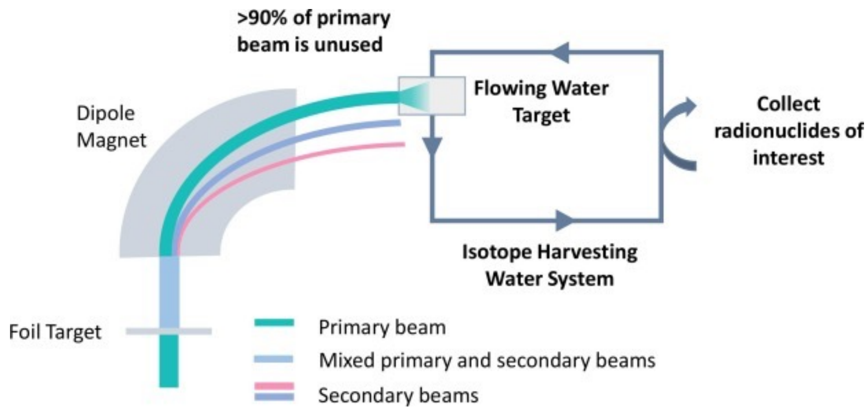
- Spectroscopy and atomic structure measurements of the logic ion Ra^+
  PRL 122, 223001 (2019), PRA 100, 062512 (2019), PRA 100, 062504 (2019), PRA 102, 042822 (2020)
  PRA 105, 042801 (2022)
- Formation of relevant CPV-sensitive single molecular ions
  PRL 126, 023002 (2021)
- Identification of candidate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

slide from A. Jayich (UC Santa Barbara)
DOE ECA 2021

The Nuclear Pear Factory: A Proposed Center

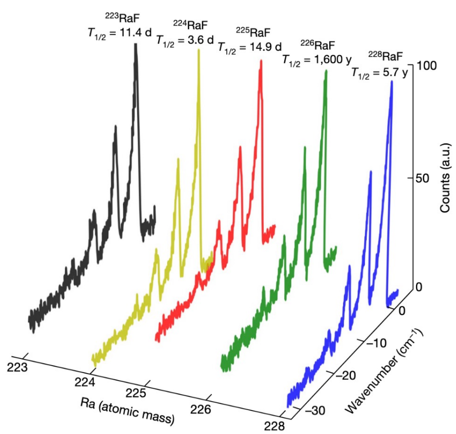
Nature 497:199 (2013)

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

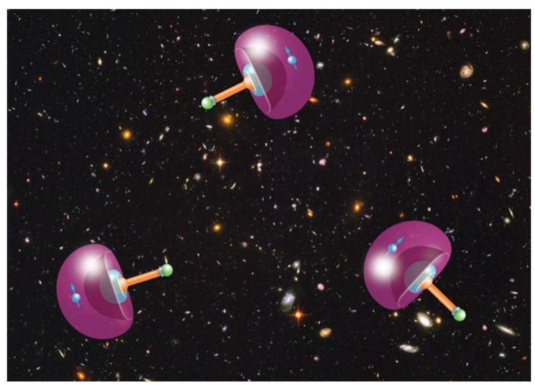


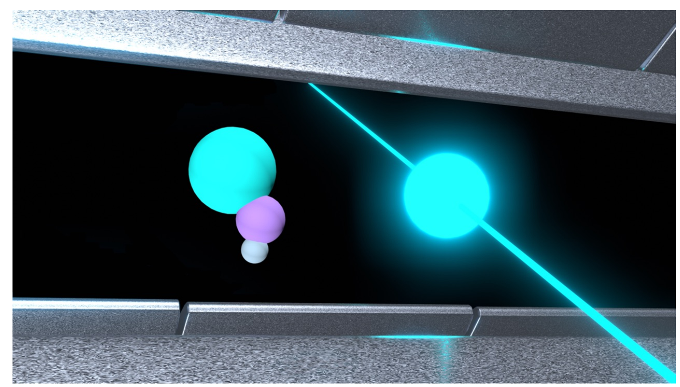
NIMB 478 34 (2020)

N P F



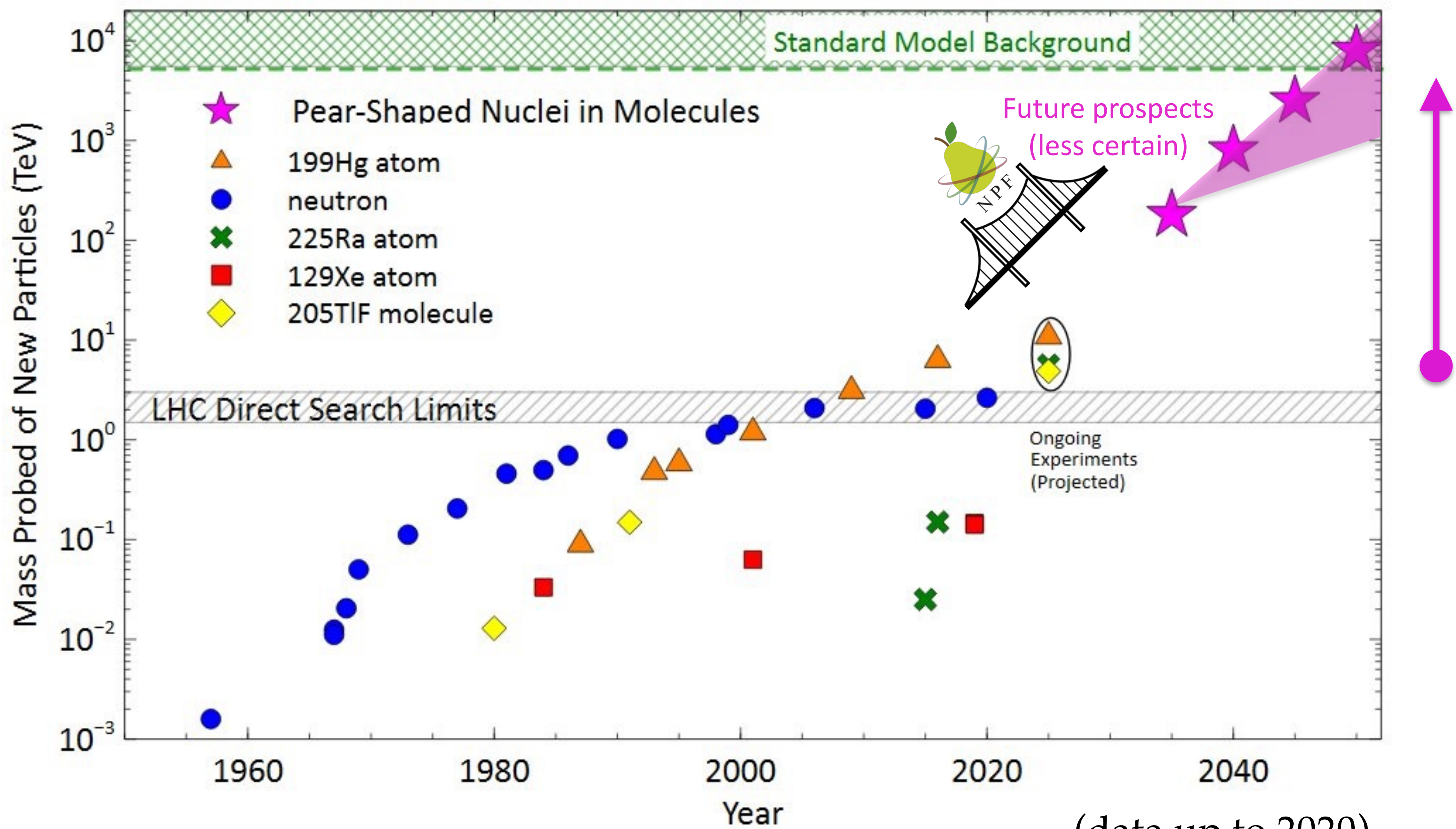
Nature 581:396 (2020)





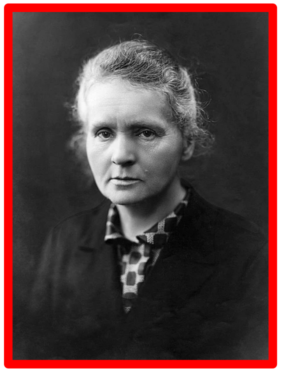
https://physics.aps.org/articles/v14/103 & A.M. Jayich

Exploring The Entire New Physics Discovery Window With Standard Model Sensitivity Within Your Lifetime!



(data up to 2020)

We Are Following In The Footsteps Of Giants Towards A Transformational Discovery Within Our Lifetime



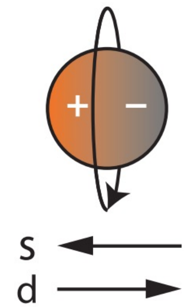
88 $^1S_0$
Ra
Radium
(226)
$[Rn]7s^2$
5.2784

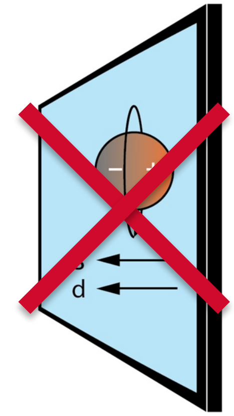
91 $^4K_{11/2}$
Pa
Protactinium
231.04
$[Rn]5f^26d7s^2$
5.89

87 $^2S_{1/2}$
Fr
Francium
(223)
$[Rn]7s$
4.0727

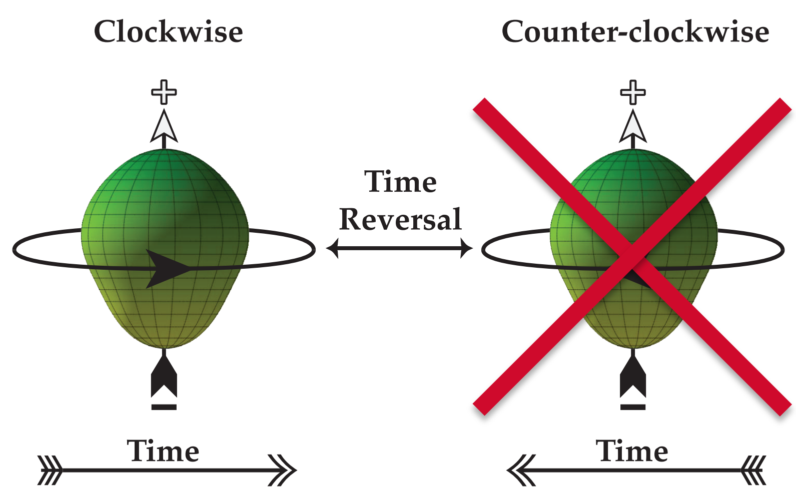
C.S. Wu

M.A. Bouchiat





NPF



M. Curie (2/5), L. Meitner (0/49), & M. Perey (0/5)

Wikipedia, NIST, AIP Emilio Segre Visual Archives, M. Zolotrev

Thanks For Your Attention! More Questions?

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**

U.S. DEPARTMENT OF ENERGY | Office of Science

DOE Early Career Award 2018
DE-SC0019015 (EDM3)
DE-SC0019455 (Ra EDM)

GORDON AND BETTY MOORE FOUNDATION

ALFRED P. SLOAN FOUNDATION 1934

NSF

NSF CAREER 2017
 # 1654610 (SAM)