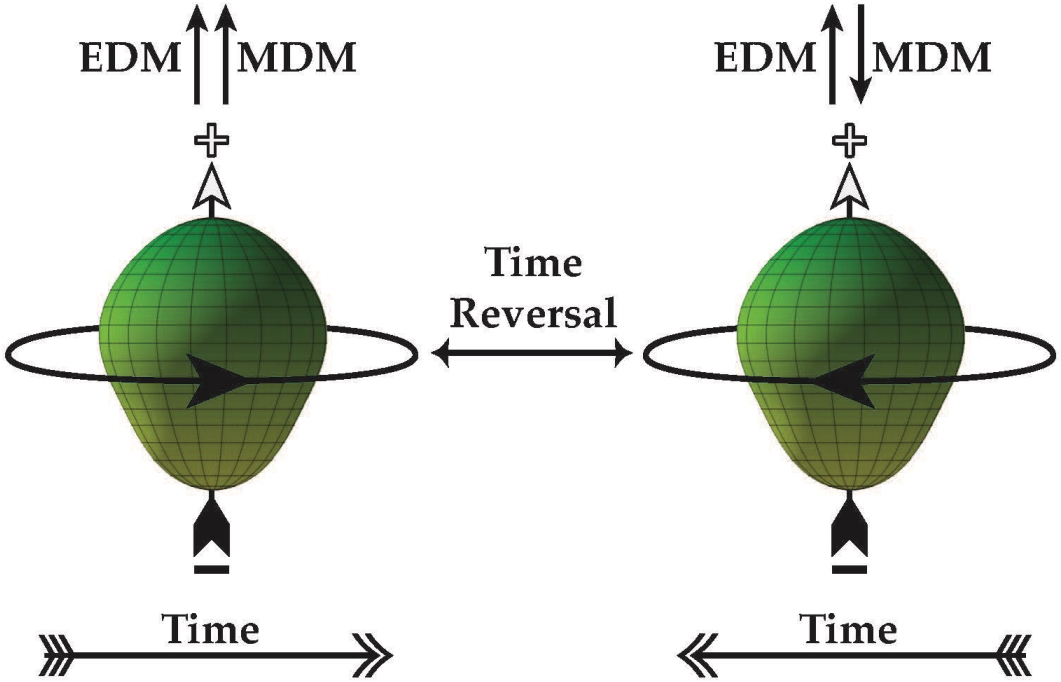
Community-Building Efforts From The FRIB Perspective



NPF

Jaideep Taggart Singh
FRIB / Michigan State University

INT Program INT-24-1
Fundamental Physics with Radioactive Molecules
UW-INT Room C520 April 9, 2024

FRIB

Marie-Anne Bouchiat

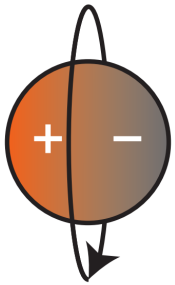
SCAN ME

Selected Recent History

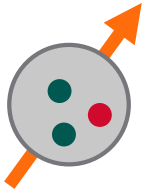
- **2019 Summer**: FRIB-TA Topical Program: Hadronic Electric Dipole Moments in the FRIB Era: (C.-Y. Liu, A. Shindler, JTS, V. Zelevinsky)
- **2021 Summer** : APS Moore/MIT: New Opportunities for Fundamental Physics Research w/ Radioactive Molecules (R. F. Garcia Ruiz, N. Hutzler, J. Dilling, R. Berger)
- **2021 Winter:** Preproposal to NSF for a Science & Technology Center
- **2022 Summer:** Workshop at DAMOP
- **2022 Summer:** Preproposal to NSF for a Physics Frontiers Center
- **2022 Fall:** Workshop on Fundamental Symmetries @ FRIB
- **2022 Winter:** Full Proposal to NSF for a Physics Frontiers Center
- **2023 Spring:** Reverse Site Visit for PFC Finalists (not selected)
- **2024 Spring:** This INT Workshop

Let's keep up the momentum and keep working with each other!

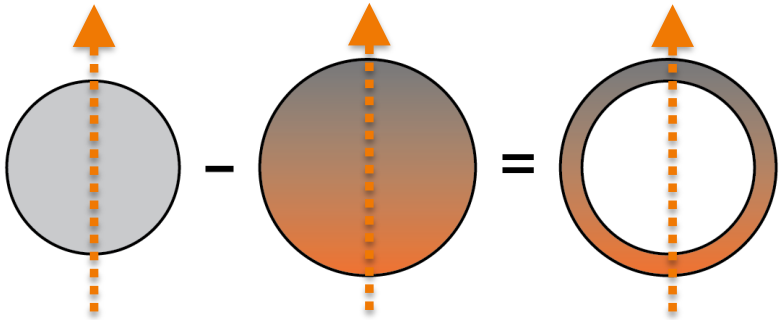
Key Ingredient: New Physics Beyond The Standard Model That Violates Time-Reversal Symmetry*



Electron Electric Dipole Moment (EDM)



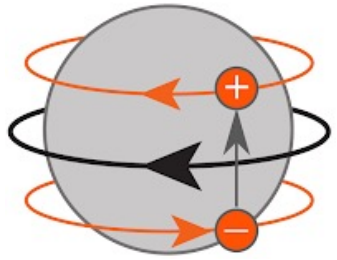
Neutron EDM



Charge Distribution

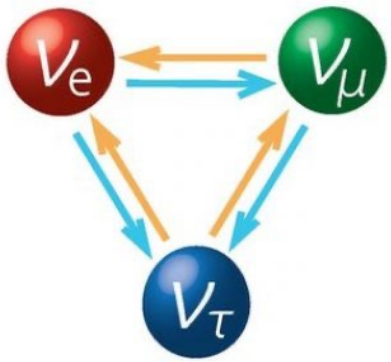
EDM Distribution

Nuclear Schiff Moment



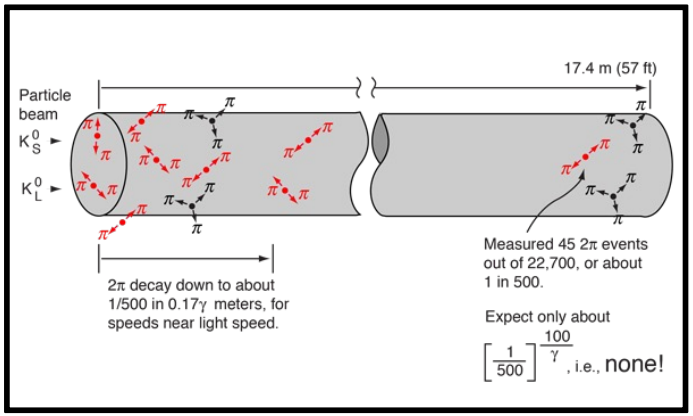
Nuclear Magnetic Quadrupole Moment

Neutrinos (Leptogenesis)

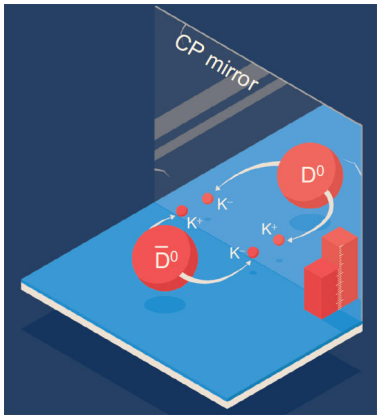


https://the-gist.org/2016/09/can-neutrino-oscillation-explain-the-universe/

Rare Decays of Mesons



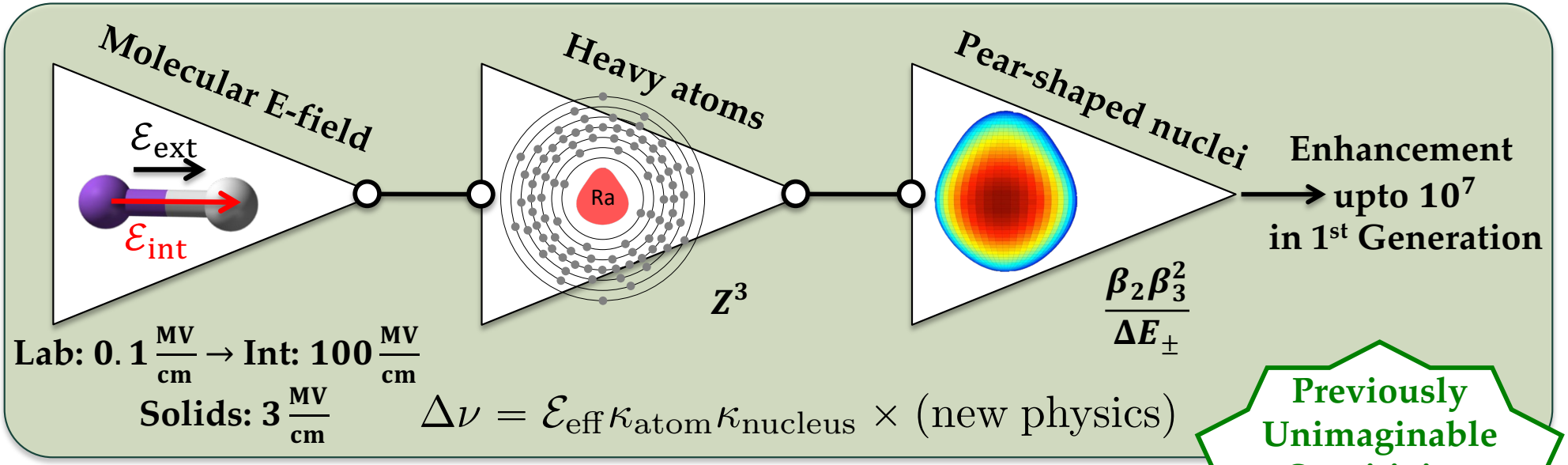
Hyperphysics



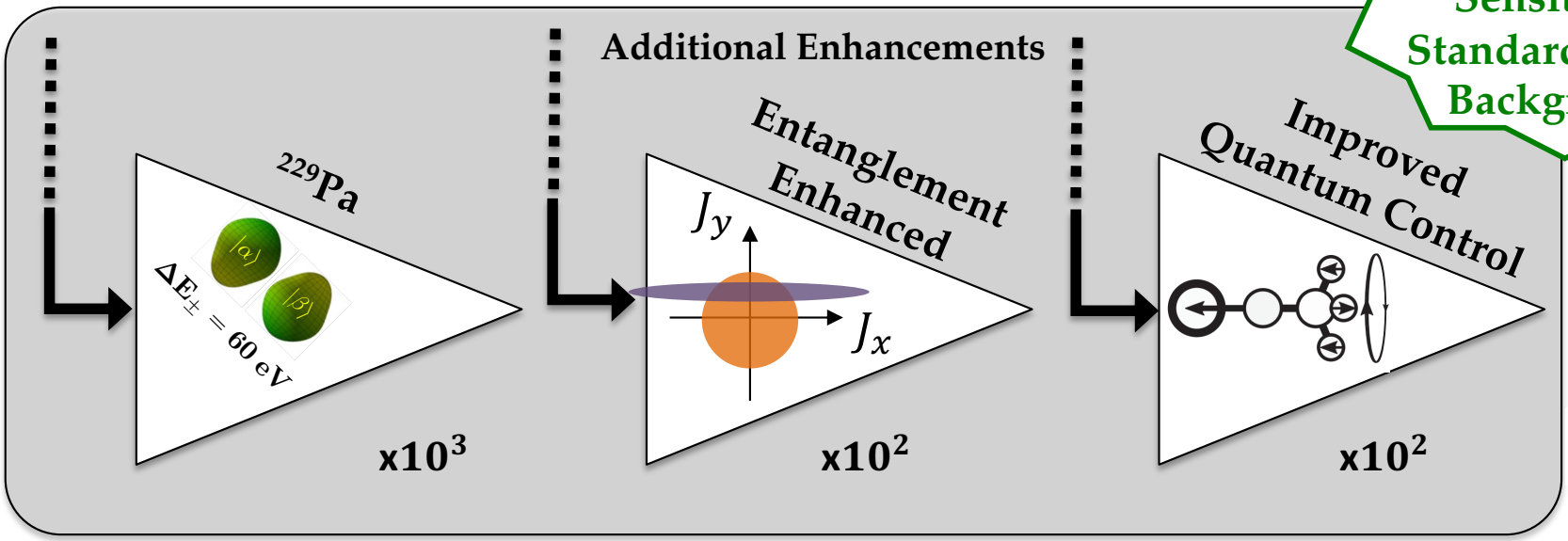
CERN

*time-reversal (T) violation implies charge-parity (CP) violation by the CPT Theorem

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



Previously Unimaginable Sensitivity: Standard Model Background



Xing Wu

External Context: 2023 Long Range Plan

Sidebar 6.2 Radioisotope harvesting at FRIB for fundamental physics

The Facility for Rare Isotope Beams (FRIB) will yield the discovery of new, exotic isotopes and the measurement of reaction rates for nuclear astrophysics, and will produce radioactive isotopes that can be used for a broad range of applications, including medicine, biology, and fundamental physics.

Converting waste to wealth

Pear-shaped nuclei enable new-physics searches

Sidebar 6.4 Nuclear Decay and Quantum Sensors: From Neutrinos to Safeguards

Other experiments have developed superconducting quantum sensors that are sensitive enough to measure the tiny energy kick that a lithium atom gets from the neutrino following beryllium-7 electron-capture decay. The Beryllium Electron capture in Superconducting Tunnel junctions (BeEST) experiment currently performs such precision decay measurements to observe tiny changes in the observed recoil energies (Figure 1). These changes could be caused by a hypothetical new type of neutrinos: so-called sterile neutrinos. BeEST has set world-leading laboratory-based limits on whether these sterile neutrinos, which are candidates for dark matter, can have masses below 1 MeV.

Note: the need for radiochemistry support and key isotopes for the FRIB Fundamental Symmetries user community will only increase!

Facility for Rare Isotope Beams @ MSU

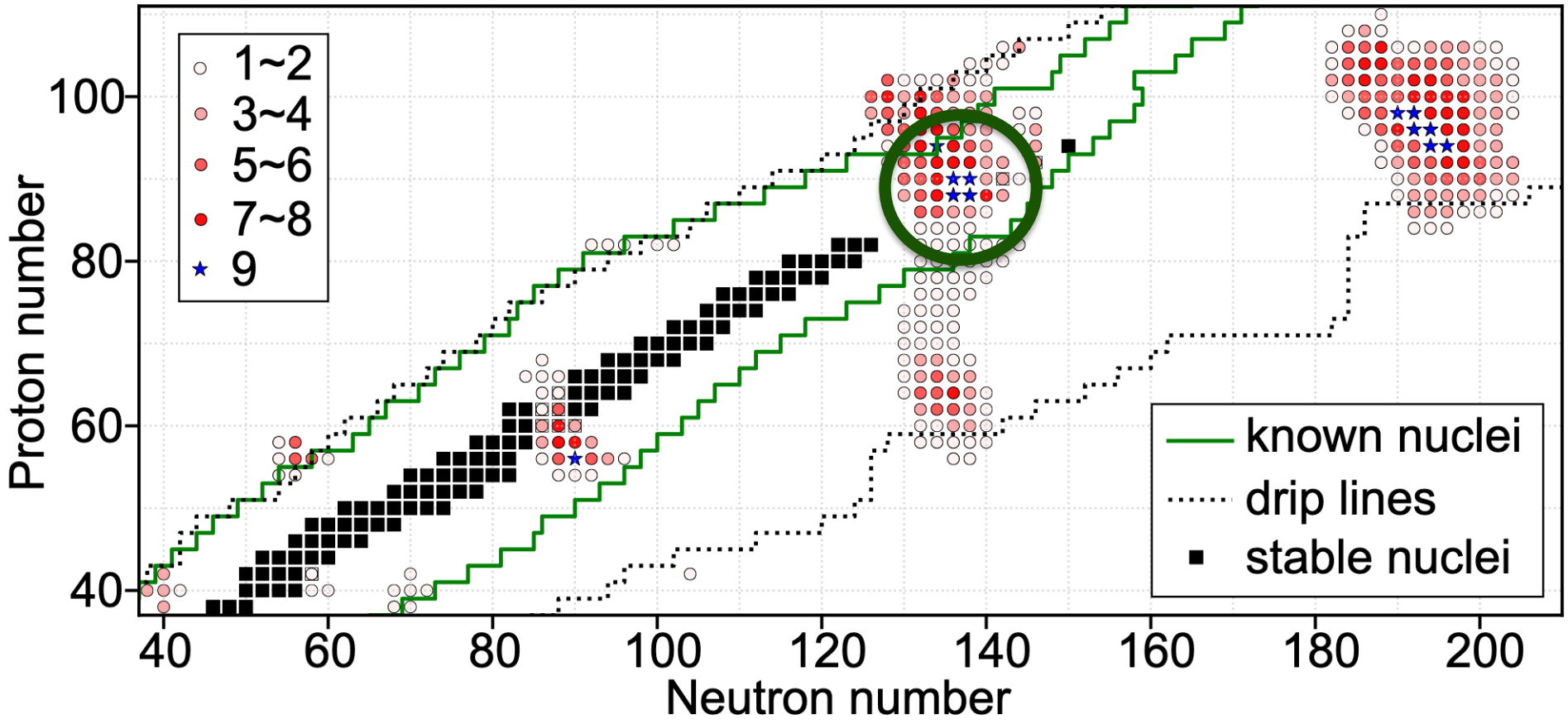
Google Maps & Wikipedia Commons

Facility for Rare Isotope Beams @ MSU

We Are 25% of the Logo -
We Should Aim To Be 25% of the Science!

"Fundamental Symmetries"

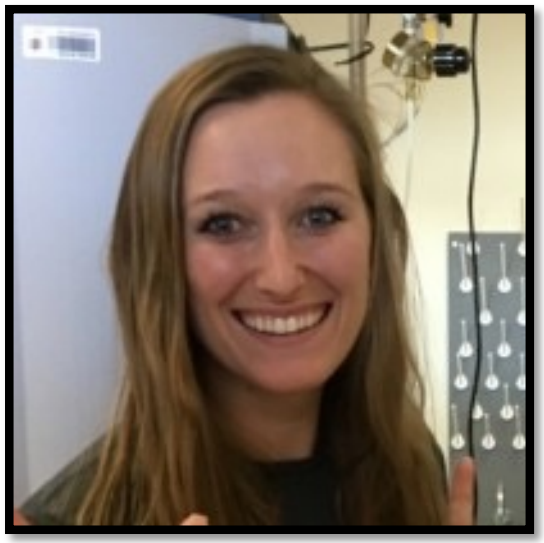
FRIB Will Produce These Rare Heavy Pear-Shaped Nuclei in Practical Quantities (Some for the First Time)



Phys. Rev. C, 102:024311, Aug 2020

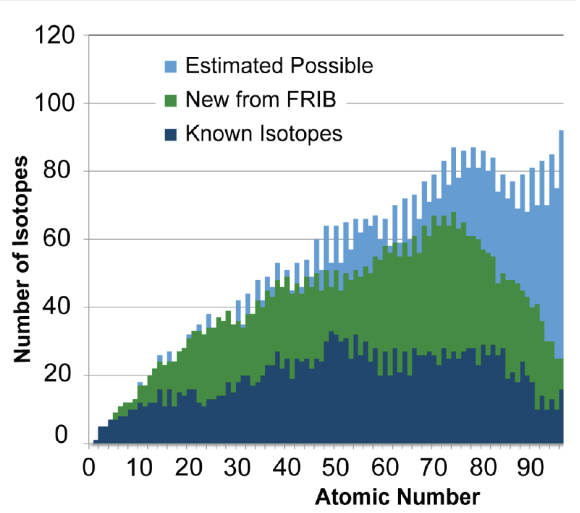
"Isotope Harvesting" at
The Facility for Rare Isotope Beams (MSU/East Lansing)

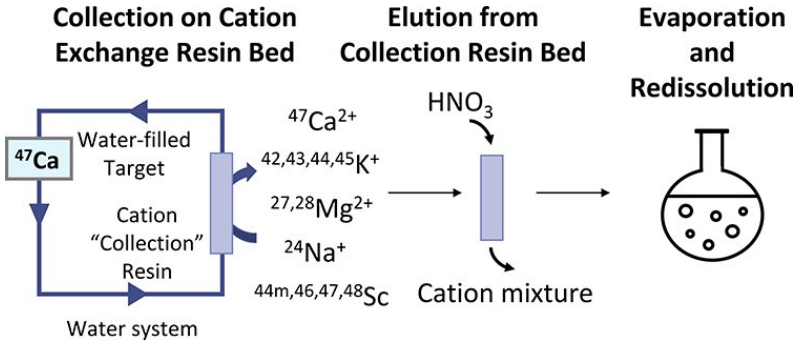
Prof. Greg Severin



Prof. Alyssa Gaiser

Prof. Katharina Domnanich





Recovery of 92% to 99% of ^{47}Ca

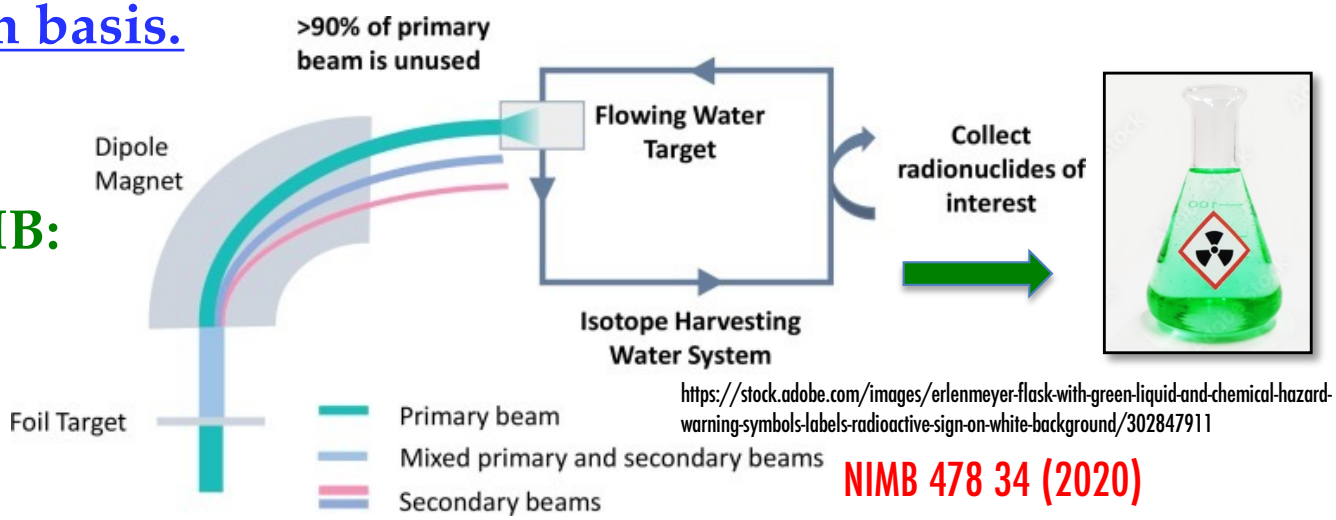
Abel et al., ACS Omega 5(43) 27864 (2020)

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 on a per atom basis.

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



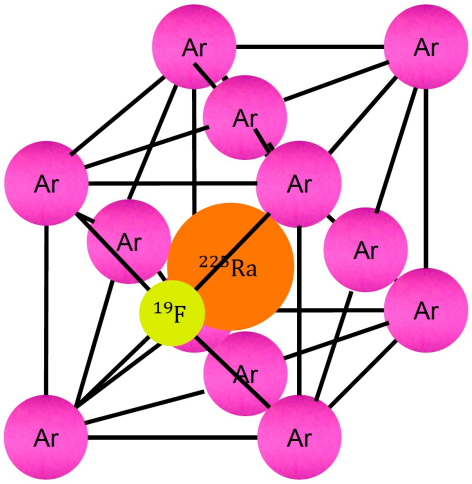
https://stock.adobe.com/images/erlenmeyer-flask-with-green-liquid-and-chemical-hazard-warning-symbols-labels-radioactive-sign-on-white-background/302847911

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?

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 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**

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

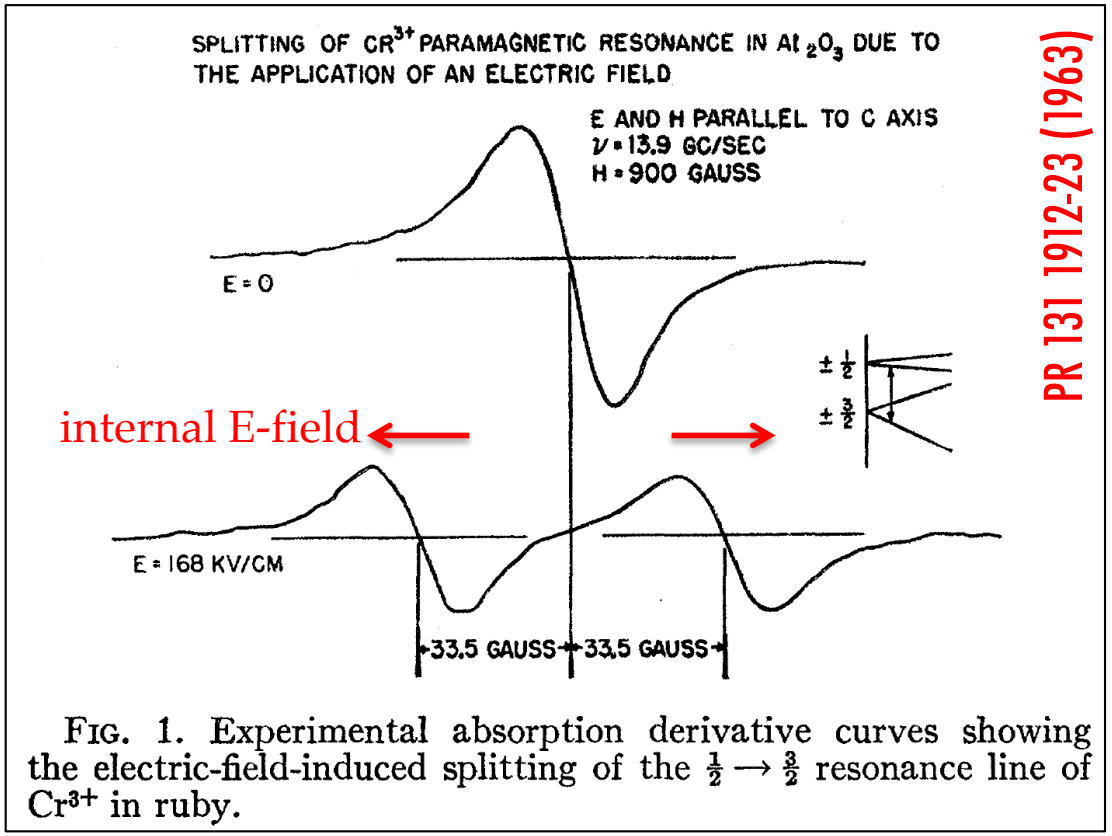
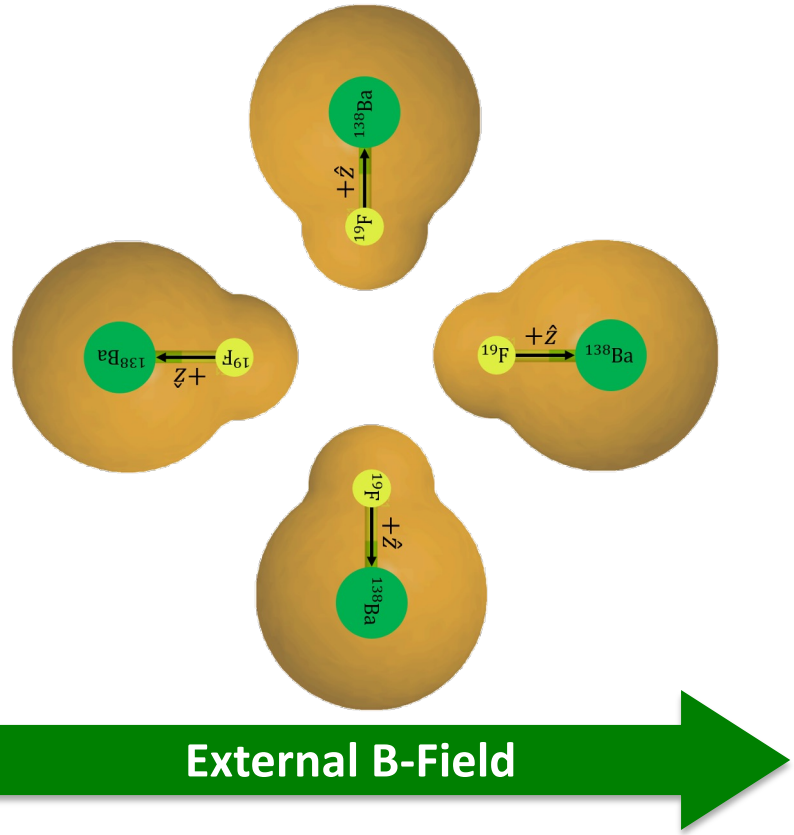


FIG. 1. Experimental absorption derivative curves showing the electric-field-induced splitting of the $\frac{1}{2} \rightarrow \frac{3}{2}$ resonance line of Cr^{3+} in ruby.

PR 131 1912-23 (1963)



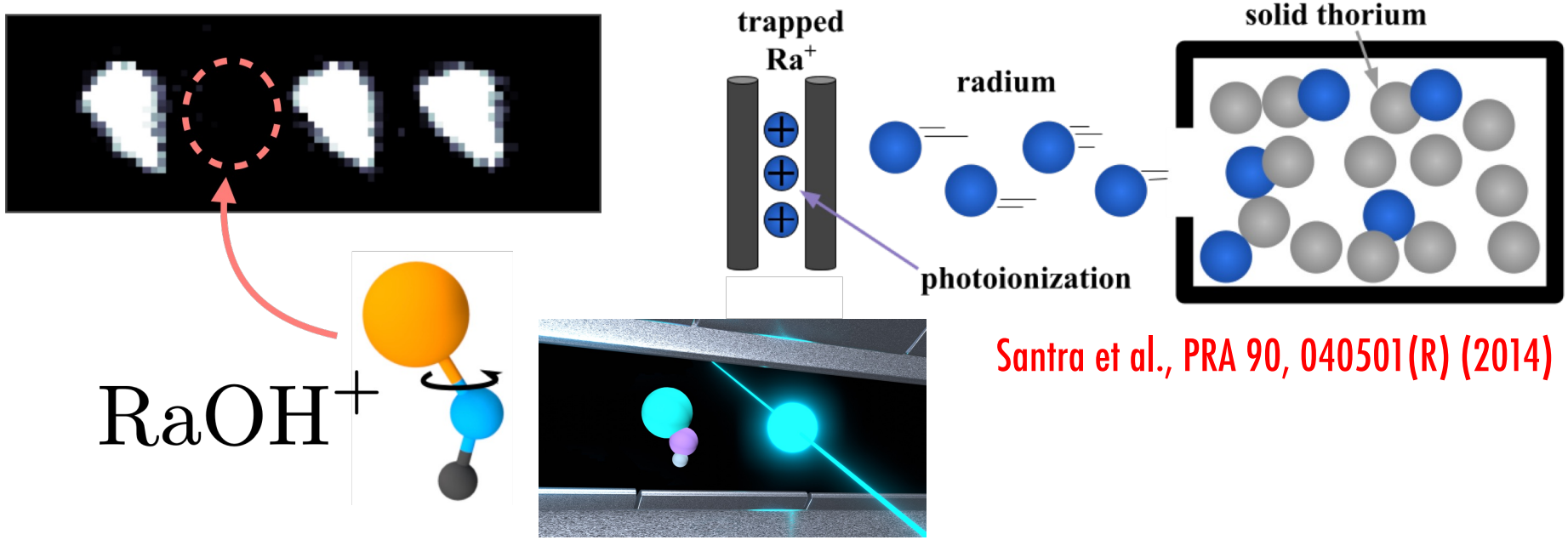
external B-field

PRA 98:032513 (2018)

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

The two ensembles can be spectroscopically resolved by the application of a modest external E-field (applied only during readout).

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

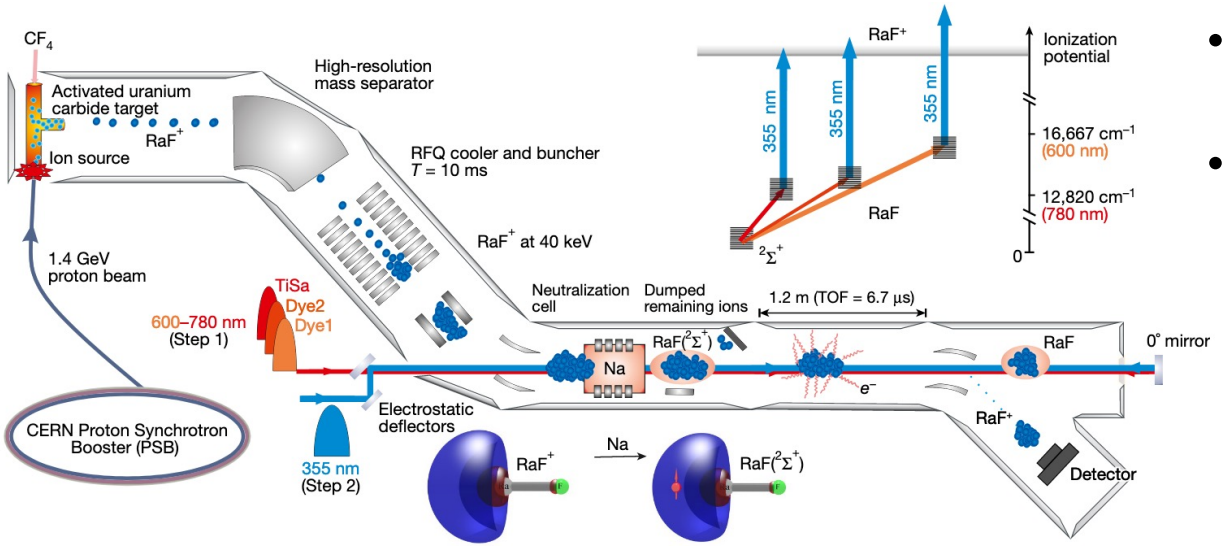


Santra et al., PRA 90, 040501(R) (2014)

- 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)

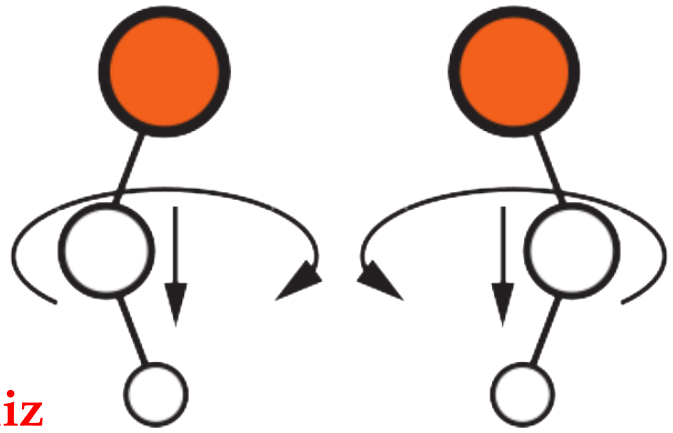
slide from A. Jayich

Direct Laser Cooling of Neutral Molecules Into a Laser Trap: ^{225}RaF, ^{225}RaOH, ^{225}RaOCH$_3$ ($\tau_{1/2}$ = 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)



Benefits of Polyatomic Molecules

- Laser coolable & trappable
- Highly polarizable
- Comagnetometer states for control of systematics
- High $\mathcal{T}$ sensitivity

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

slide from Ronald Garcia Ruiz and Nick Hutzler

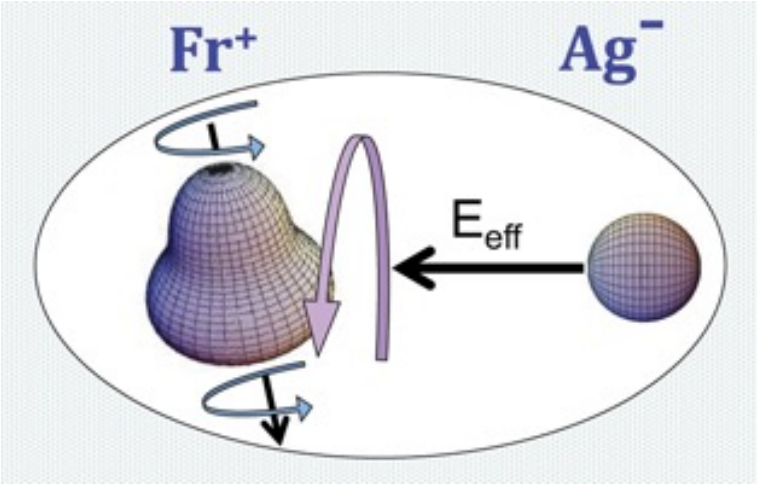
Ultracold Assembly of Neutral Molecules Within A Laser Trap: ^{223}FrAg ($\tau_{1/2}$ = 22 minutes)

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

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

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

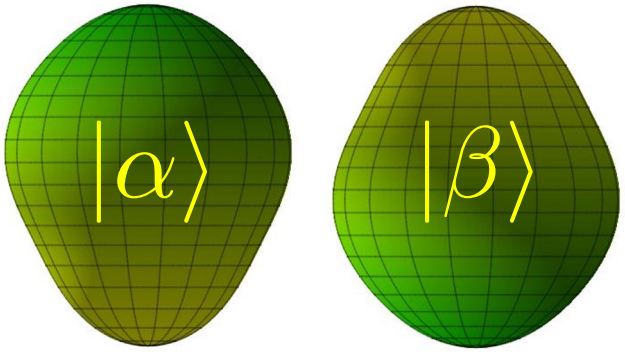
slide from
Adrian Yearby

Choose an isotope with large deformations

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

Unknown

Parity Doublet



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

ΔE

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

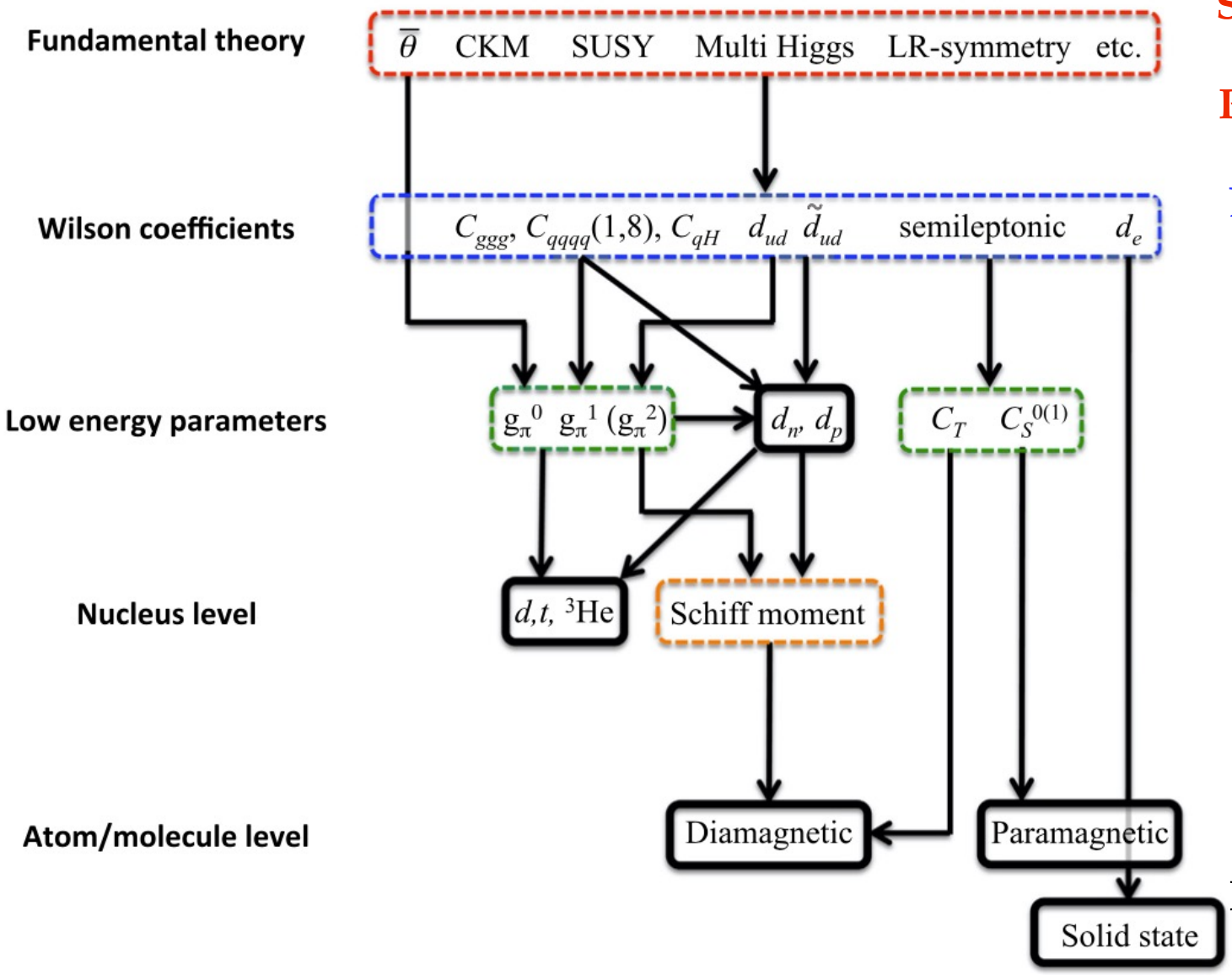
Pa-229: Haxton & Henley PRL 51:1937 (1983)
I. Ahmad et al Phys. Rev. C 92:024313 (2015)
Dobaczewski et al PRL 121, 232501 (2018)

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!

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

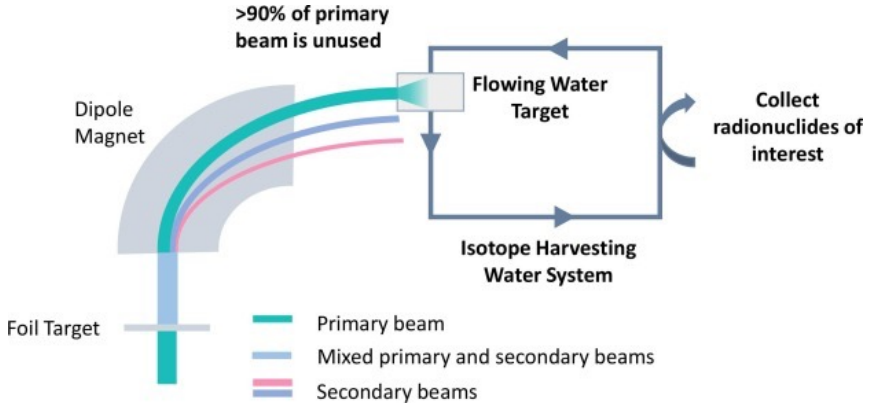
Molecular Theory
+
Molecular Experiment

Radiochemistry
...EDMs

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)

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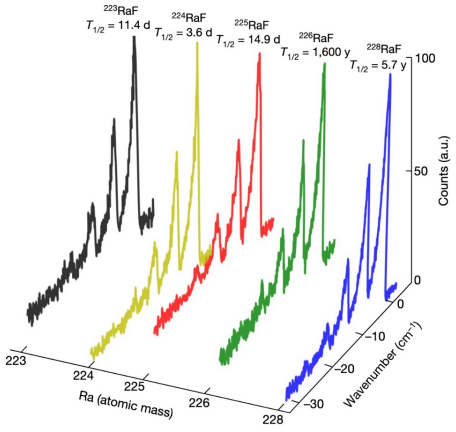
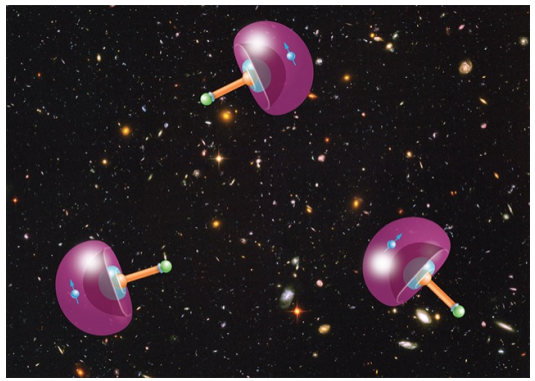
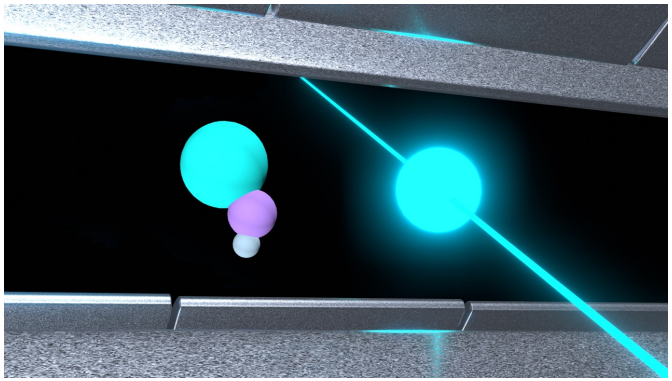


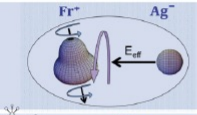
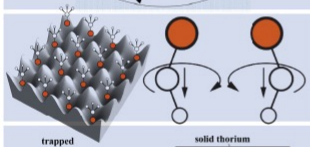
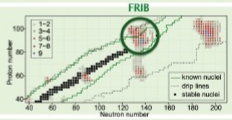
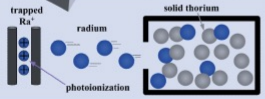
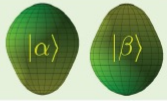
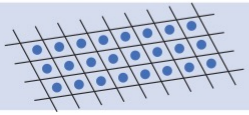
Nature 581:396 (2020)





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

Major Scientific Activities Of The Nuclear Pear Factory

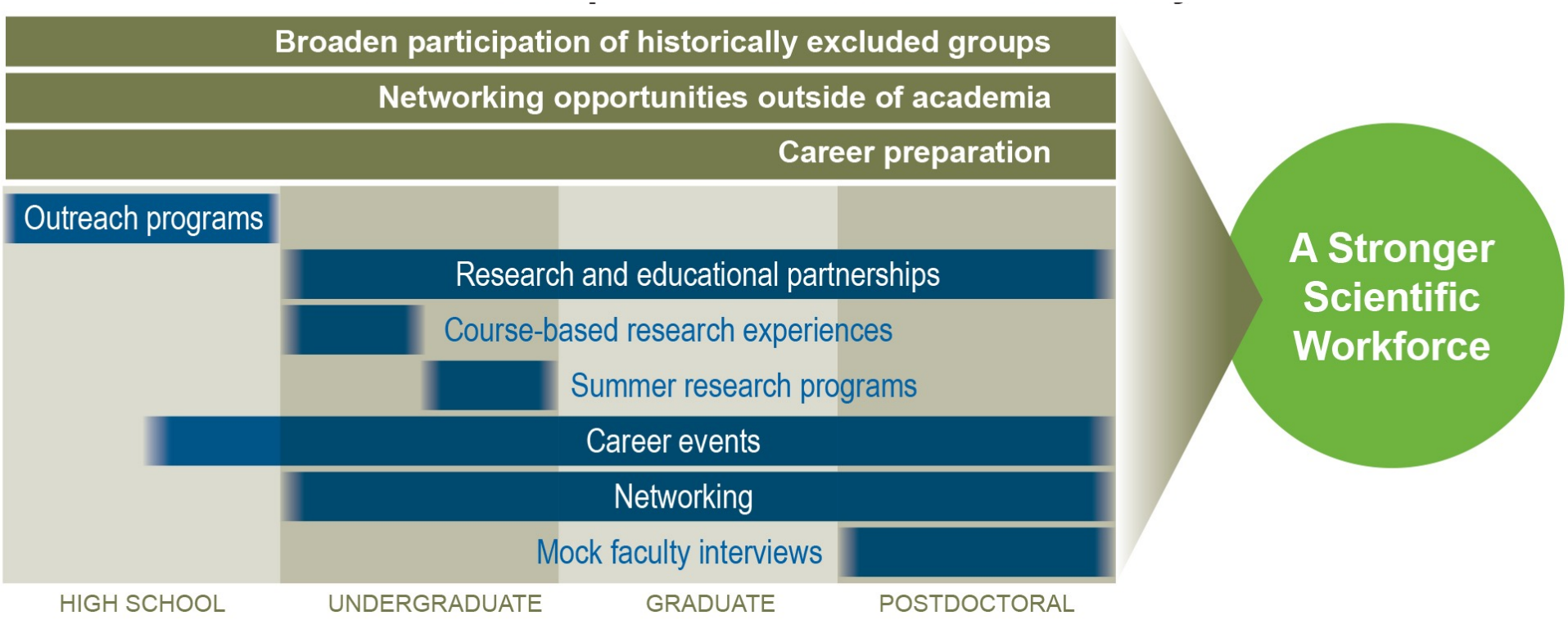
Major Activity 1	Building a Quantum Control and Sensing Toolkit	Calibrating and Benchmarking the Sensitivity to New Physics	Major Activity 2
	Ultracold Molecular Assembly	Atomic & Molecular Theory	
	Direct Laser Cooling and Trapping of Molecules	Nuclear Structure of the Actinide Region	
	Trapped Molecular Ions	Search for the Nearly Degenerate Parity Doublet in Protactinium-229	
	Solid State Systems	Atomic & Molecular Spectroscopy	

6 Year Goal: Lay the foundation (theory, radiochemistry, spectroscopy, etc.) to launch at least two experiments with a new physics sensitivity of x1000 beyond the current state of the art in the hadronic sector

- broad program naturally allows for risk mitigation
- annual meeting & community-driven workshops
- virtual seminars & collaboration visits
- shared infrastructure
- seed funding for junior faculty and emerging areas

"A major strength of this proposal is its synergy between theorists and experimentalists."
– Reviewer 3

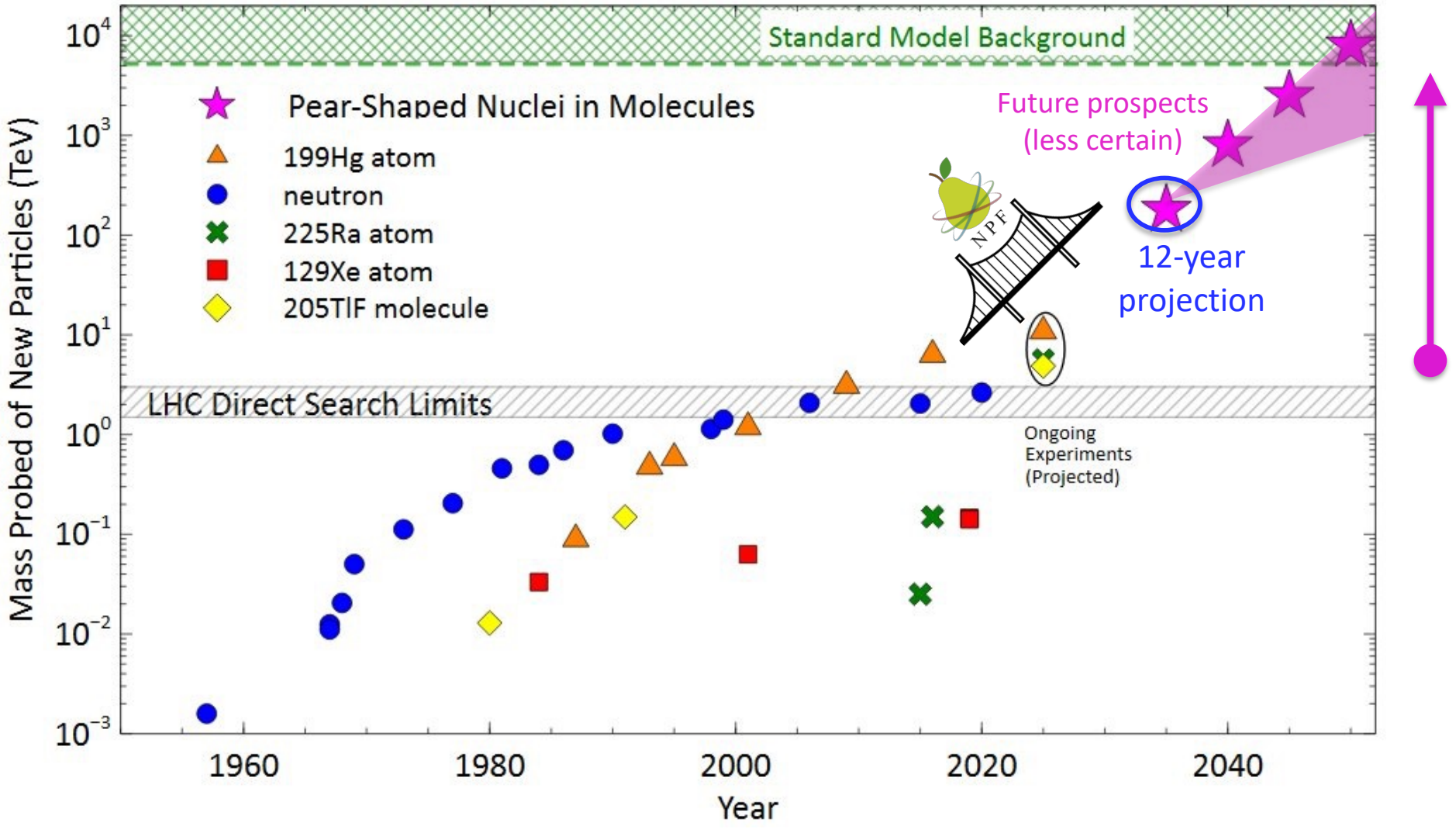
Broadening the Participation of Historically Excluded Groups That May One Day Realize Our Scientific Dream



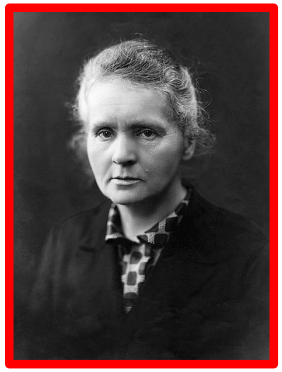
- Actively recruit and retain students to broaden participation from historically excluded groups: (1) financial support, (2) academic/research support, (3) inclusive climate (codes of conduct, community agreements, climate survey)
- Success = a STEM career in either industry or academia

"The broader impacts of the proposal are excellent, including activities at the pre-college, college, graduate school, and postdoc levels." – Reviewer 6

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



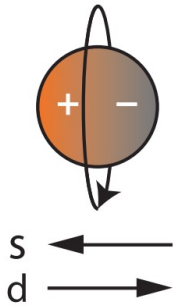
We Are Following In The Footsteps Of Giants Towards A Transformational Discovery Within Our Lifetime

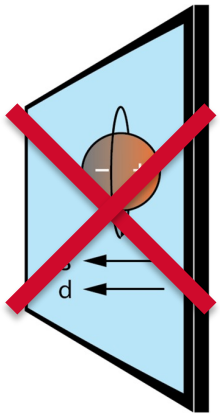


88 $^1S_0$
Ra
Radium
(226)
$[Rn]7s^2$
5.2784

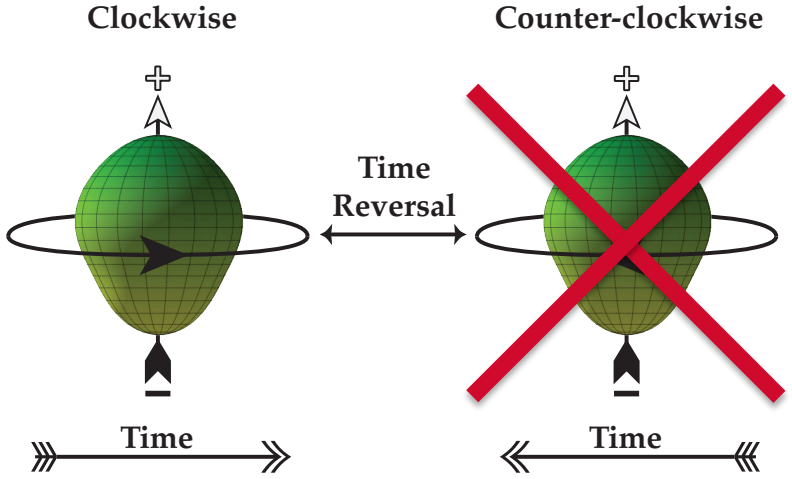
C.S. Wu

M.A. Bouchiat





91 $^4K_{11/2}$
Pa
Protactinium
231.04
$[Rn]5f^2 6d7s^2$
5.89



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

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

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

The Future is Very Exciting - Come Join Us!

Ra EDM Postdoc Opening
Opportunity @ Argonne
contact: Peter Mueller

SLAM!

Short-Lived Atoms and Molecules!
https://www.slamcommunity.com/
contact: Nick Hutzler (Caltech)

Xing Wu

Postdoc and Staff Scientist Openings in Radioactive Molecules @ FRIB/MSU
contacts: Xing Wu (wux@frib.msu.edu)
Jaideep Taggart Singh (singhj@frib.msu.edu)

Staff Scientist @ FRIB

https://inspirehep.net/jobs/2700553

Discussion Questions

- How do we build a sustainable community?
- How do we strengthen our international collaborations?
- How do we strengthen experimental/theory collaborations?
- What radiochemistry needs does the community have?
- What experimental infrastructure is needed at FRIB and elsewhere?
- **Pointed question: How to we avoid "going it alone"/"duplicating efforts" and "competing ourselves" out of existence? [Tension between "individual PI" effort vs. "large (by AMO standards)" collaborative efforts]**