Exotic molecules for fundamental physics at ISOLDE

Figure modified from https://sphereofinfluence360.com/

R. F Garcia Ruiz, R. Berger for the RaF collaboration at ISOLDE

November 2021

Why (radioactive) molecules?

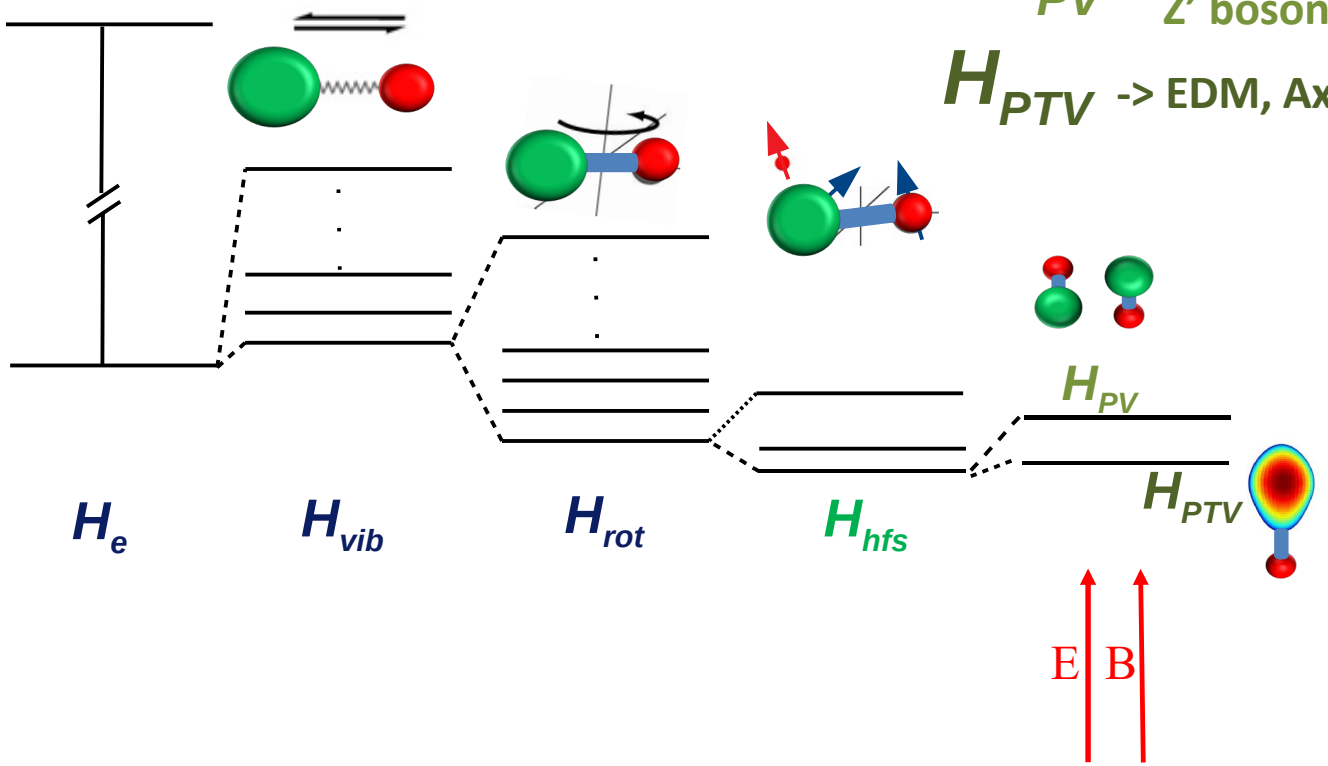
-> Extremely sensitive systems to measure parity- and time-reversal violation

$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$

	H_e	H_{vib}	H_{rot}	H_{hfs}	H_{PV}	H_{PTV}
eV	~ 2	10^{-2}	10^{-5}	10^{-8}	$<10^{-12}$	$<10^{-38}$

H_{PV} -> Electroweak physics, Z' bosons, ...

H_{PTV} -> EDM, Axions, ...



Why (radioactive) molecules?

Nuclear

Molecule

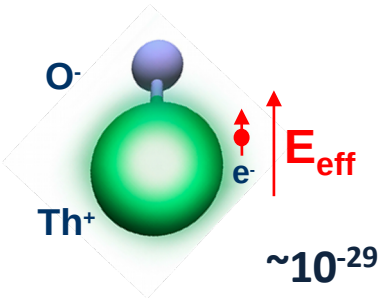
$\sim F(Z^c) / (E^e_+ - E^e_-)$

$H_{PV}, H_{PTV} \sim O_{Nucl} F_{atom/mol.}$

Nuclear spin $I=0$

$\sim e_{EDM} F_{mol.}$

ThO: $E_{eff} \sim 80$ GV/cm



$\sim 10^{-29}$ e cm

[ACME, Nature 562, 355 (2018)]

- **Molecule** **$> 10^3$**

Why radioactive molecules?

Nuclear

$\sim Z^a A^b \beta_2 \beta_3 / (E^N_+ - E^N_-)$

- protons
- nuclear mass
- nuclear deformation
- nuclear levels

Molecule

$\sim F(Z^c) / (E^e_+ - E^e_-)$

$H_{PV}, H_{PTV} \sim O_{Nucl} F_{atom/mol.}$

Nuclear spin $I>0$

$\sim O_{Nucl} F_{mol.}$

Nuclear spin $I=0$

$\sim e_{EDM} F_{mol.}$

- Molecule $> 10^3$
- Nuclear amplification $> 10^3$

Why radioactive molecules?

Nuclear

$\sim Z^a A^b \beta_2 \beta_3 / (E^N_+ - E^N_-)$

protons — nuclear mass — nuclear deformation — nuclear levels

Molecule

$\sim F(Z^c) / (E^e_+ - E^e_-)$

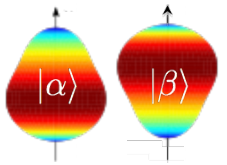
$H_{PV}, H_{PTV} \sim O_{Nucl} F_{atom/mol.}$

- ✓ Large Z, A
- ✓ Nuclear spin I >0
- ✓ $\beta_2 \beta_3 > 0$

Only for radioactive, short-lived nuclei!

- ➢ ^{225}Ra (Z=88), $T_{1/2}$= 15 days
- ➢ ^{227}Th (Z=90), $T_{1/2}$= 19 days
- ➢ ^{229}Pa (Z=91), $T_{1/2}$= 1.5 days

^{225}Ra



[Gaffney et al. Nature 497, 199 (2013)]

- Molecule > 10^3
- Nuclear amplification > 10^3

Why radioactive molecules?

Nuclear

$\sim Z^a A^b \beta_2 \beta_3 / (E^N_+ - E^N_-)$

protons

nuclear mass

nuclear deformation

nuclear levels

Molecule

$\sim F(Z^c) / (E^e_+ - E^e_-)$

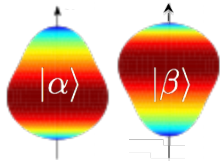
$H_{PV}, H_{PTV} \sim O_{Nucl} F_{atom/mol.}$

Radioactive molecules => Best of all worlds!

Nuclear X Molecule

- ✓ Large Z, A
- ✓ Nuclear spin I >0
- ✓ $\beta_2 \beta_3 > 0$

^{225}Ra

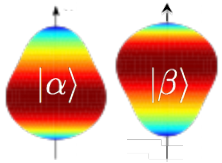


- Molecule $> 10^3$
- Nuclear amplification $> 10^3$

RaF: An ideal candidate

Why ISOLDE?

- ^{225}Ra (Z=88), $T_{1/2}$= 15 days
- Octupole deformation discovered at ISOLDE



[Gaffney et al. Nature 497, 199 (2013)]

- Large production of RaF (>10^7 mol/s) at ISOLDE

- ✓ Large Z, A
- ✓ Nuclear spin I >0
- ✓ β_2 β_3 > 0

+ predicted to be good laser cooling!

[Isaev, Hoekstra, Berger Phys. Rev. A 82, 052521 (2010)]

… BUT experimental knowledge of short-lived, radioactive molecules was lacking

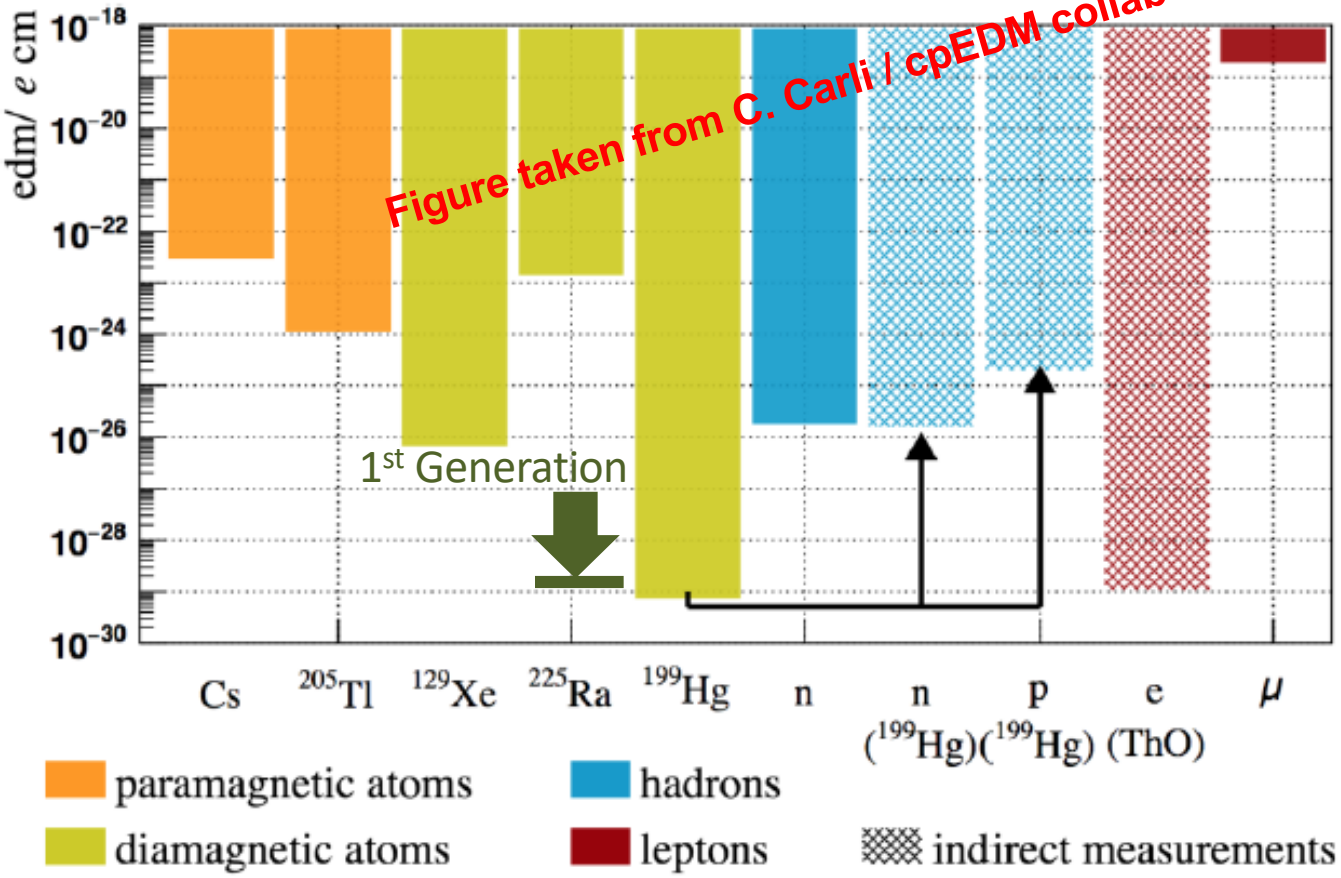
Single molecule sensitivity RaF

P,T violation:

H_{PTV}

$$\delta EDM = \frac{\hbar}{e}\frac{1}{P|E_{int}|\tau\sqrt{\dot{N}T}}$$

RaF
1st Generation → ~10^{-29} e cm



Single molecule sensitivity RaF

P violation:

H_{PV}

$$\frac{\Delta W}{W} \simeq \frac{1}{2\sqrt{2N_0}tW}$$

(Flux)(time)

Interaction time

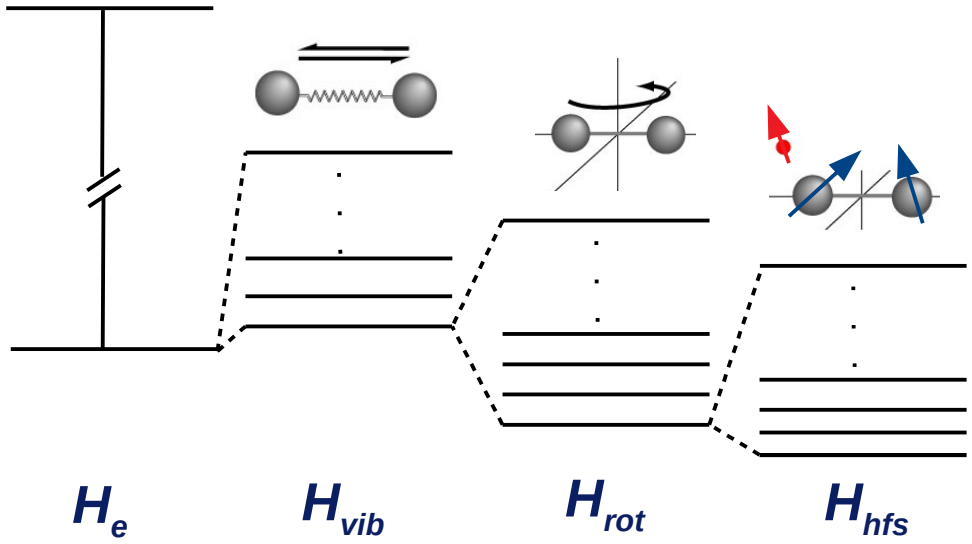
With W(RaF)~50 Hz
- **Flux → 1 molecule/s**
- **1 h measurement time**
- **t=1 ms**

=> 10% uncertainty

https://arxiv.org/abs/1302.5682

Recent Results (RaF)

[Garcia Ruiz, Berger et al. Nature 581, 396 (2020)]



$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

eV	~ 2	10^{-2}	10^{-5}	10^{-8}	$<10^{-12}$

S. Udrescu

A. Brinson

S. Wilkins

Recent Results (RaF)

“Hot” molecules can be super cool!

nature

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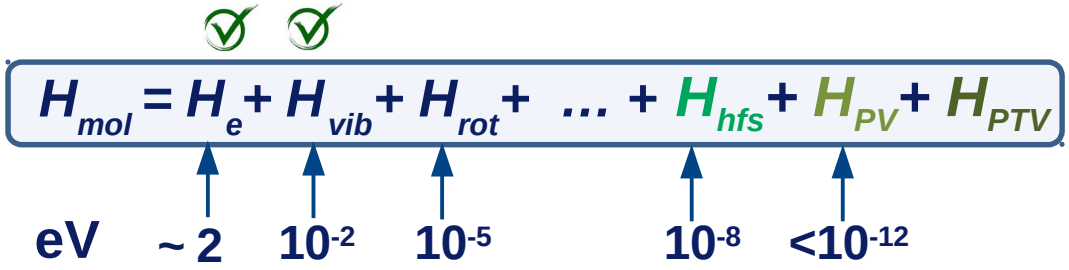
Article | Open Access | Published: 27 May 2020

Spectroscopy of short-lived radioactive molecules

R. F. Garcia Ruiz ✉, R. Berger ✉, […]

Nature **581**, 396–400 (2020) | Cite this article



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DOI:10.1063/PT.6.1.20200611a
11 Jun 2020 in Research & Technology

Spectroscopy of molecules with unstable nuclei

Pinning down the energy transitions of radium monofluoride, and eventually other short-lived molecules, could reveal the ways they are influenced by the properties of heavy radioactive nuclei.

Andrew Grant

physicsworld

ATOMIC AND MOLECULAR | RESEARCH UPDATE

Exotic radioactive molecules could reveal physics beyond the Standard Model

05 Jun 2020

CHEMISTRY WORLD

Molecular experiments hope to reveal new physics

BY ANDY EXTANCE | 5 JUNE 2020

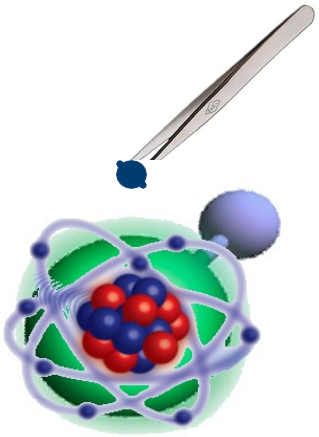
Detecting extremely short-lived radium fluoride can explore standard model’s limits

S. Udrescu

A. Brinson

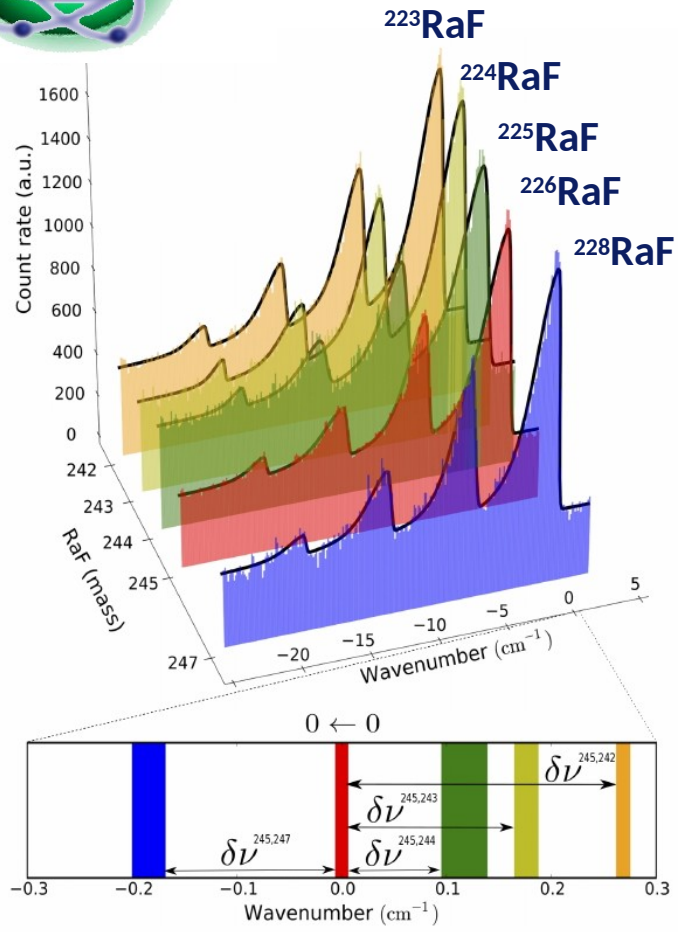
S. Wilkins

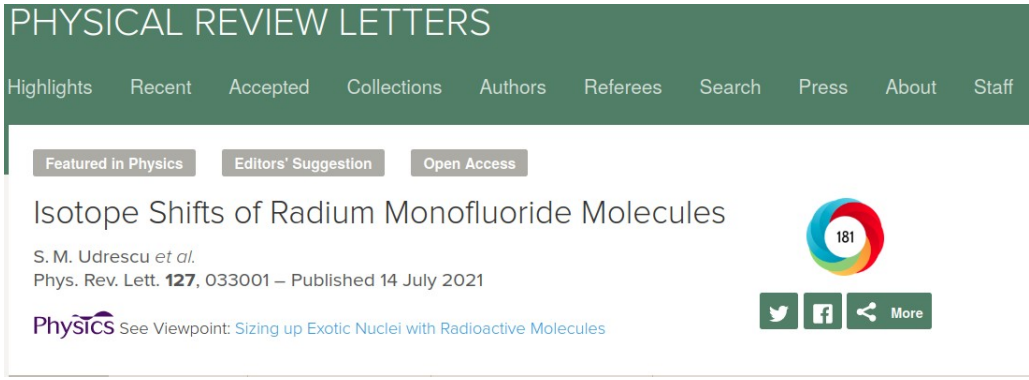
Recent Results (RaF)



New opportunities for nuclear structure studies of the heaviest elements (e.g. ThO, PaO,…)

[Udrescu et al. Phys. Rev. Lett. 127, 033001 (2021)]



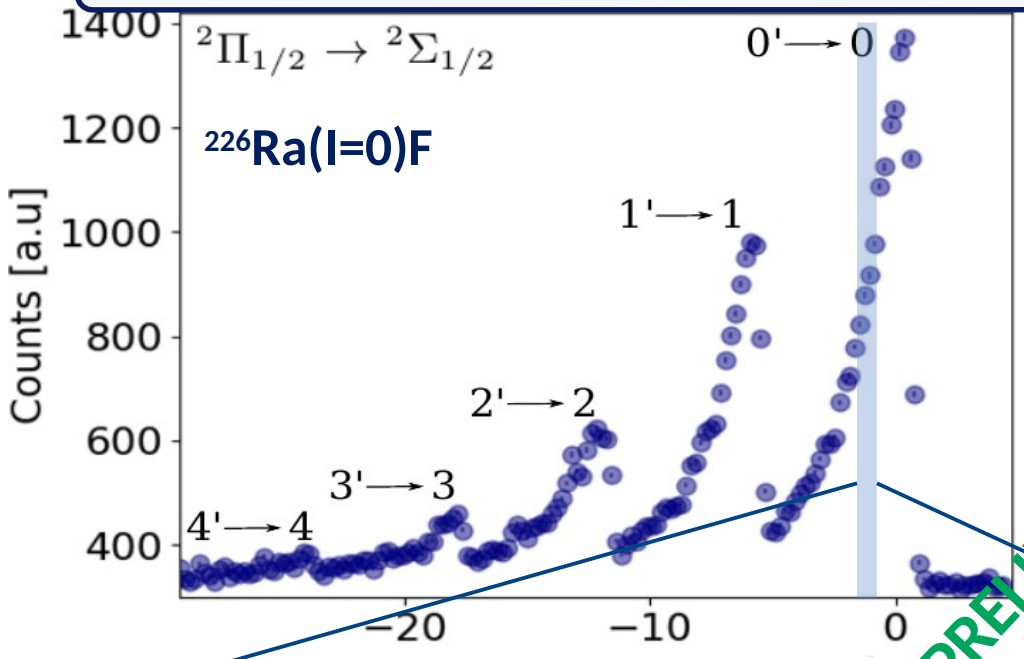


S. Udrescu

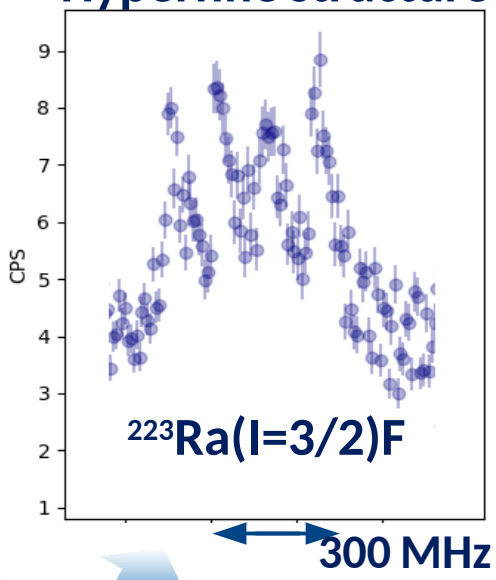
A. Brinson

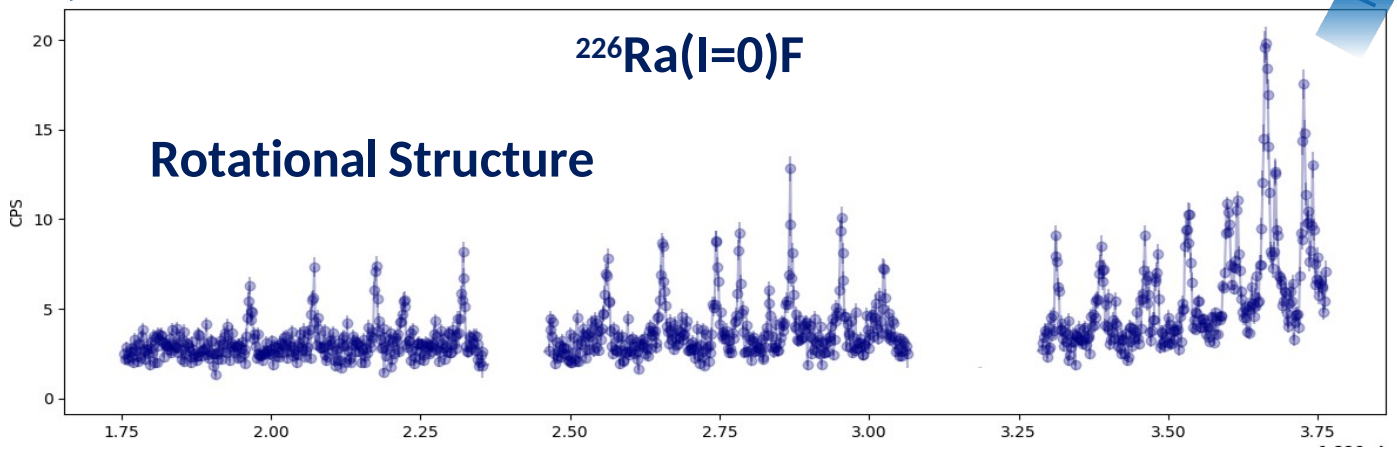
S. Wilkins

Recent results: Precision experiments (RaF)



PRELIMINARY



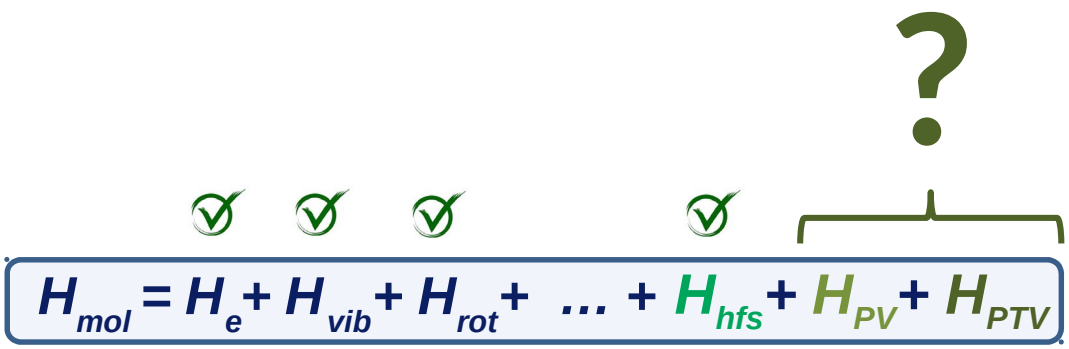


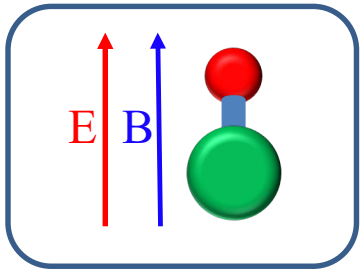
Experiment is ongoing as we speak

✓ ✓ ✓ ✓

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

Symmetry-violating measurements with RaF



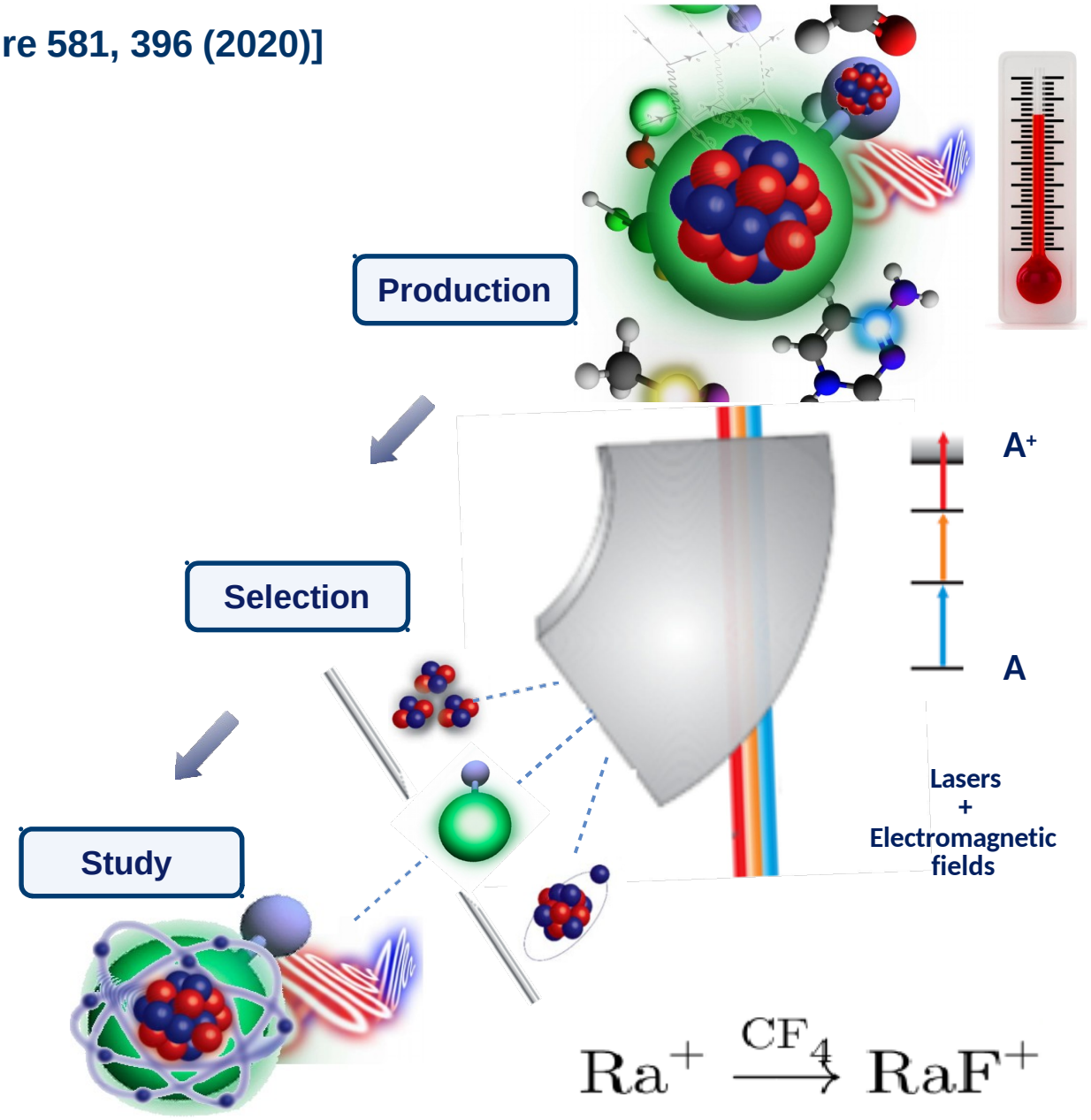


Slow, and cold molecules are needed!

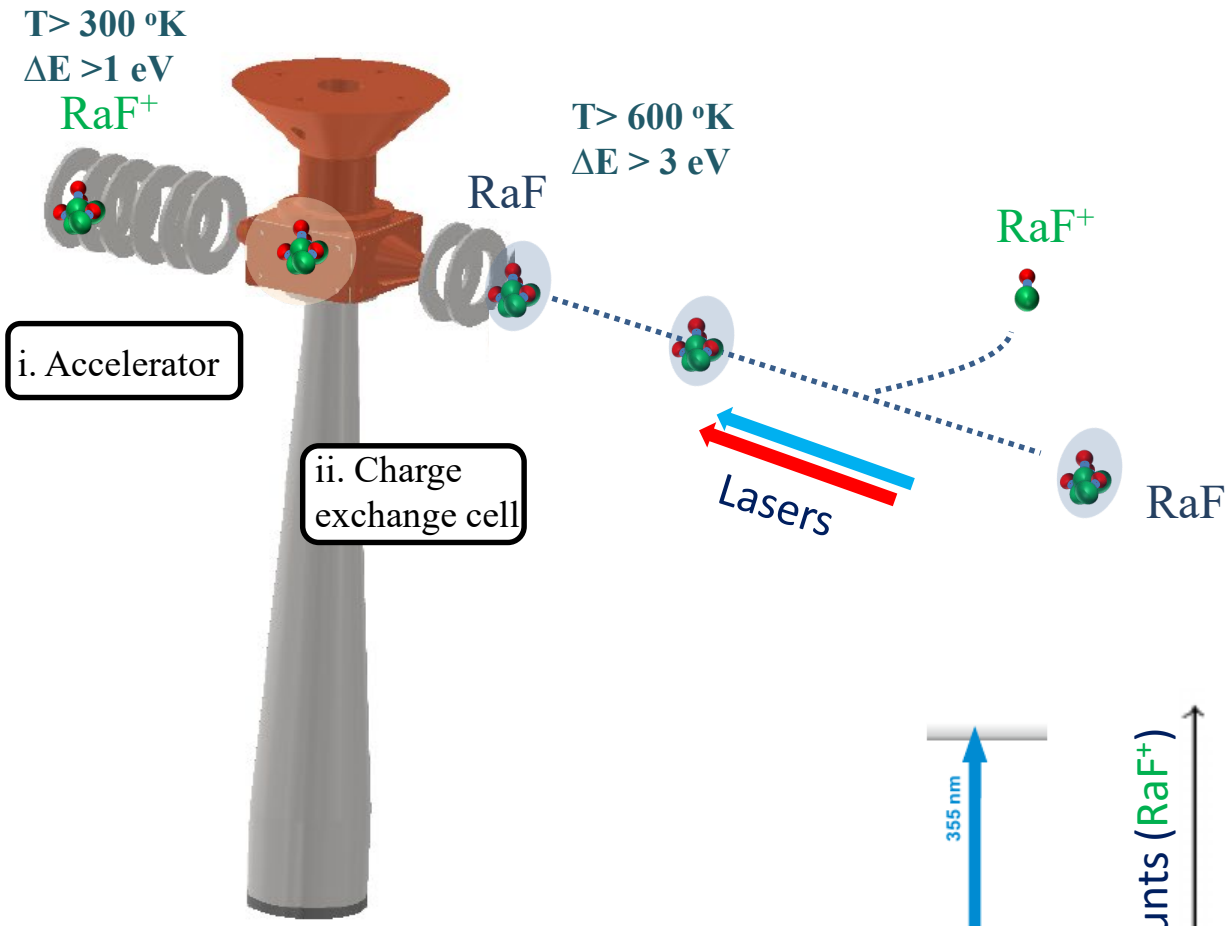
Recent Results (RaF)

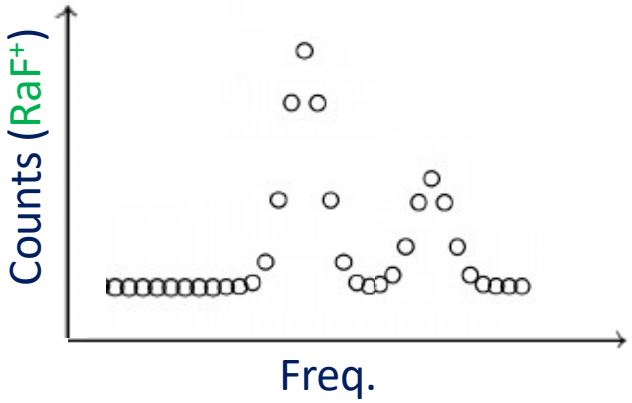
[Garcia Ruiz, Berger et al. Nature 581, 396 (2020)]

Traps
+
lasers

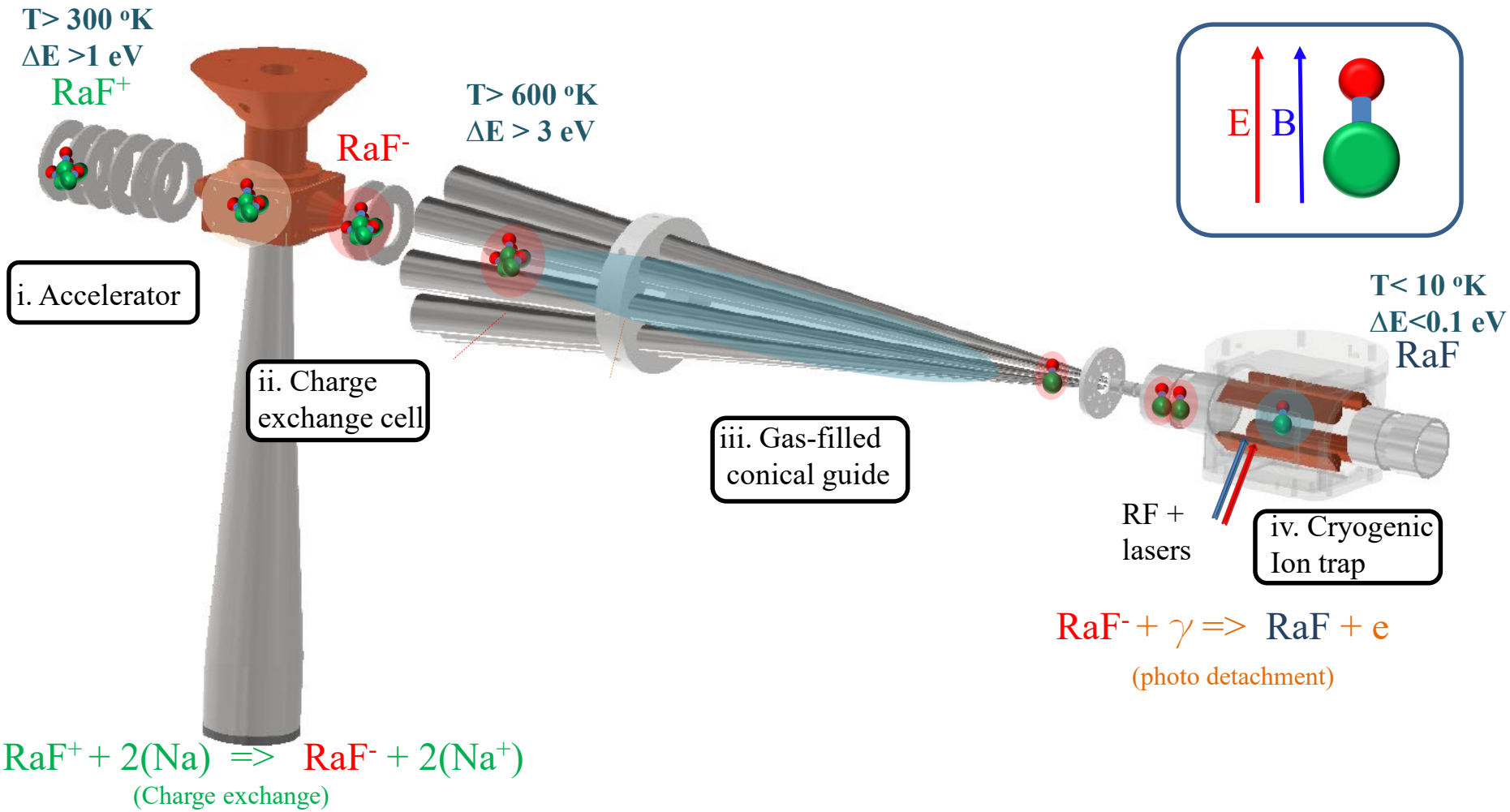


Symmetry-violating measurements with RaF





Symmetry-violating measurements with RaF



Timeline

2021	2022	2023	2024
Design and simulations	Acquisition and construction of experimental equipment	Commissioning and experimental test with BaF	Proof-of-principle with RaF- ions. Trapping and cooling of RaF	Symmetry violating measurements

Radioactive molecules offer unique opportunities to test the violation of fundamental symmetries and look for new physics

News › News › Topic: Experiments

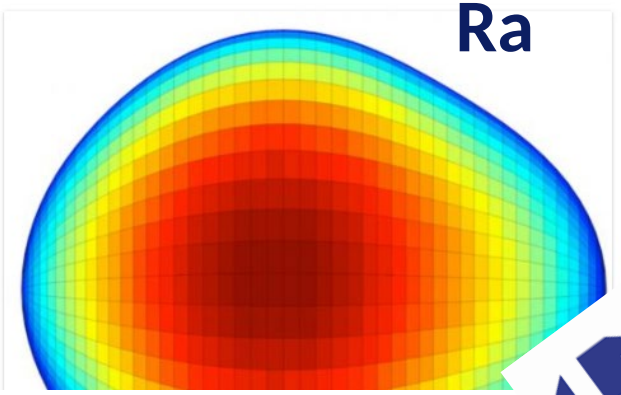
Voir en français

First observations of short-lived pear-shaped atomic nuclei

An international team at the ISOLDE radioactive-beam facility at CERN has shown that some atomic nuclei can assume asymmetric, "pear" shapes

8 MAY, 2013 | By Stephanie Hills

Ra



News › News › Topic: Physics

Voir en français

ISOLDE scores a first with laser spectroscopy of short-lived radioactive molecules

The result represents an essential step towards using these molecules for fundamental physics research and beyond

27 MAY, 2020

RaF

ISOLDE

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

ISOLDE @ CERN offers an ideal place to perform these studies

New Opportunities for Fundamental Physics Research with Radioactive Molecules Workshop

June 28, 2021

Cambridge, Massachusetts

Massachusetts Institute of Technology

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http://web.mit.edu/RadioMolecules/