Radioactive molecules as laboratories for fundamental physics

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MIT

TRIUMF Science Week
August 2020

Radioactive molecules as laboratories for fundamental physics

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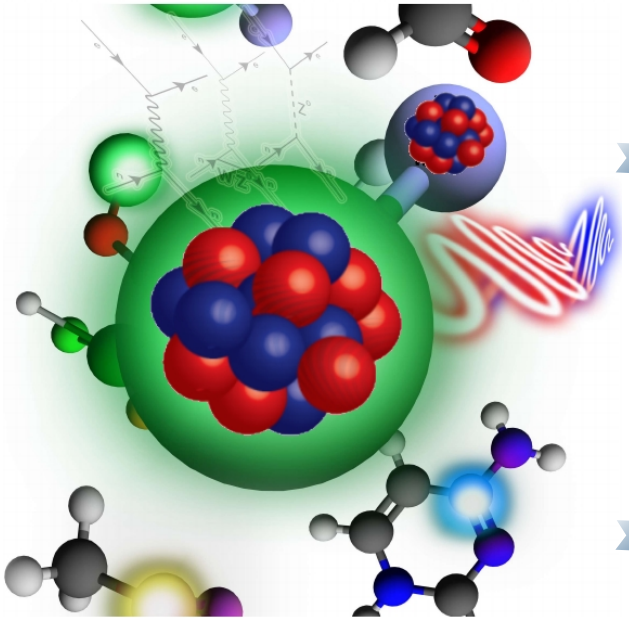
- Why (radioactive) Molecules?
- Recent Results (RaF)
- Summary & Outlook

Radioactive Molecules



Nuclear EM structure

Astrophysics

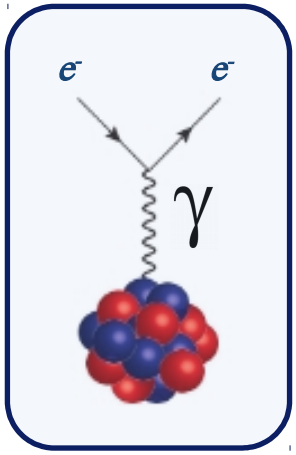
Nuclear EW structure

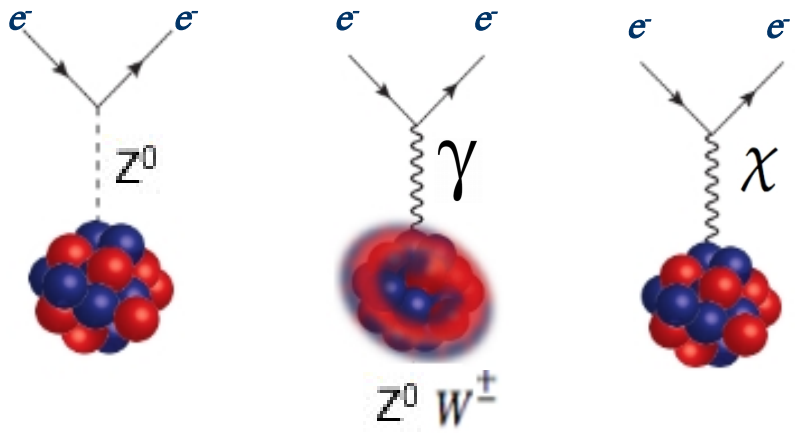
Nuclear chemistry

Fundamental symmetries

Quantum chemistry

Why (radioactive) molecules?





Long range

Electromagnetic structure

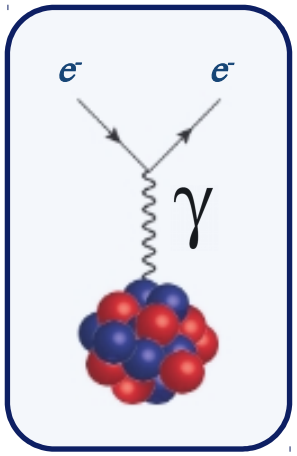
Short range (< 0.1 fm)

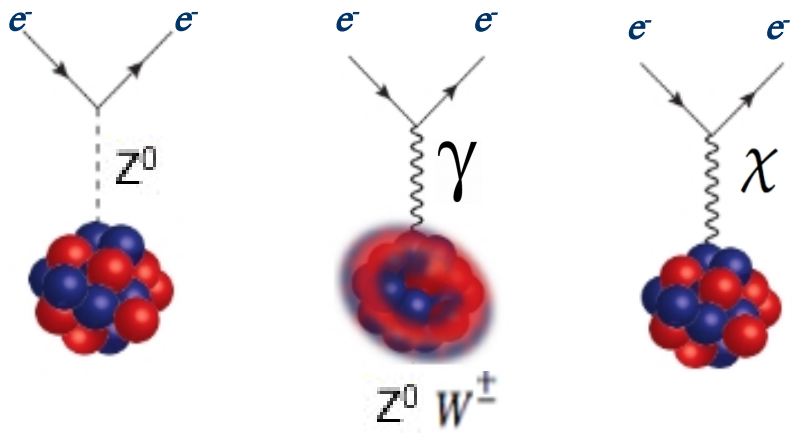
Electroweak structure

Atoms $\langle r^2 \rangle, I, \mu, Q, \ldots$

- Nuclear force → QCD
- Emergence of nuclear phenomena
- Understanding of nuclear matter

Why (radioactive) molecules?





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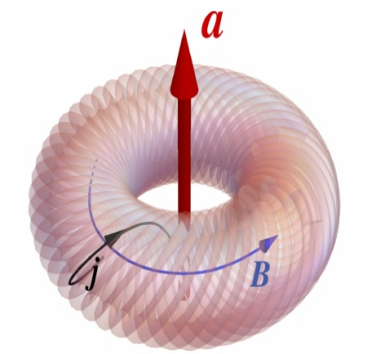

[Safronova et al. RMP 90, 025008 (2018)]
[Wood et al. Science 275, 1759 (1997)]

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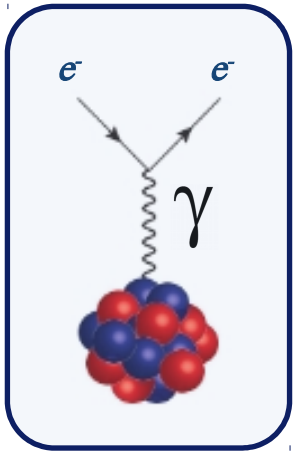

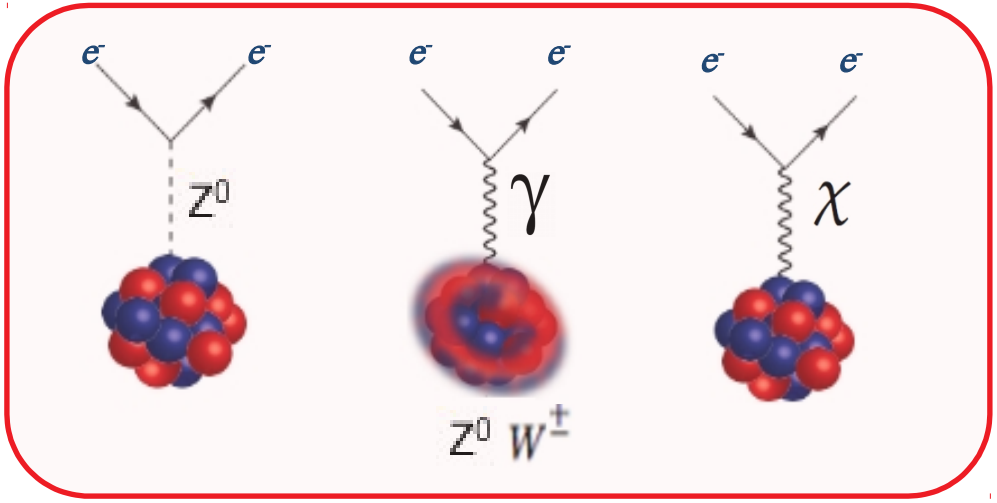

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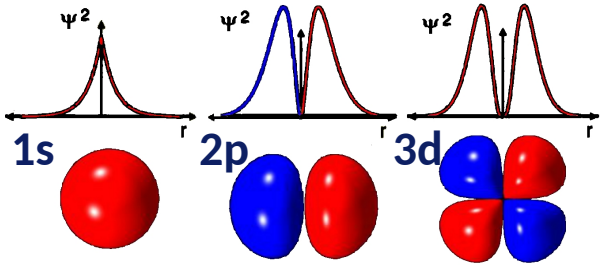
Molecules A_{AM} , eEDM , S_{schiff} , MQM

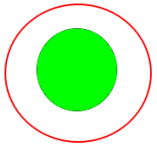
- Fundamental symmetries, BSM physics
- Matter / Antimatter asymmetry
- Dark matter

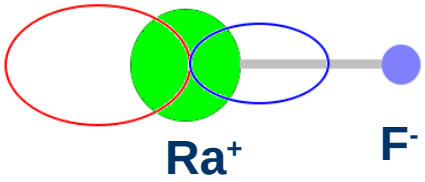
Why (radioactive) molecules?

Atoms



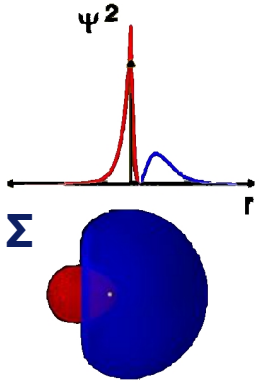
$\langle r^2 \rangle$ $I, \mu, Q, \ldots$





A_{AM} , $eEDM$, S_{schiff} , MQM

Molecules



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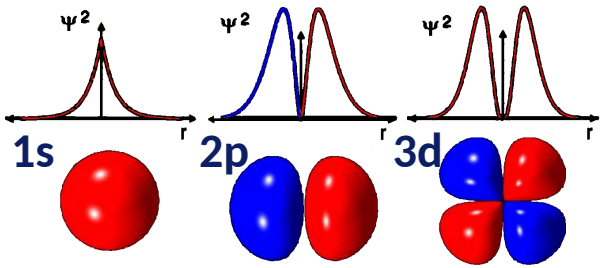

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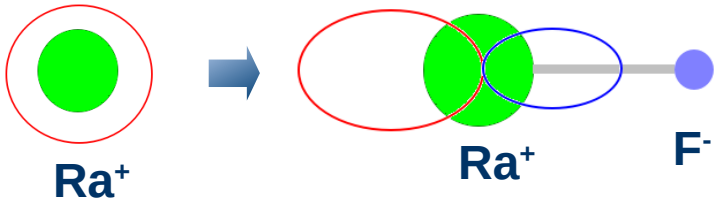

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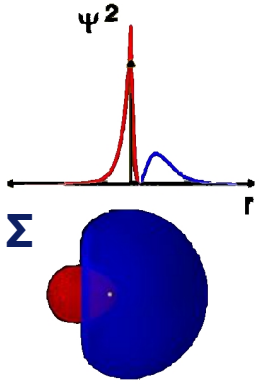


$$E_{PNC} \sim \frac{\langle \text{P-odd}|H_{\text{w}}|\text{P-even}\rangle}{E_- - E_+}$$

Atoms: (E_+ - E_-) ~ 1 eV

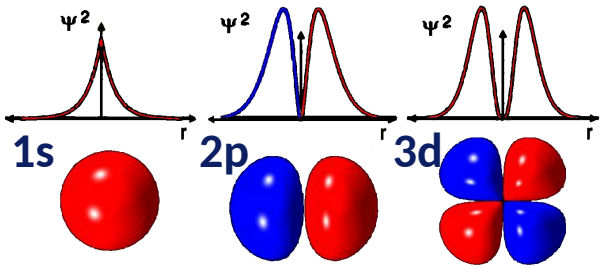
Molecules: (E_+ - E_-) ~ 10^{-5} ev

- **Parity violation > 10^{11}**

[Phys Rev Lett 120, 142501 (2018)]
[Phys. Rev. Lett. 119, 223201 (2017)]

Why (radioactive) molecules?

Atoms



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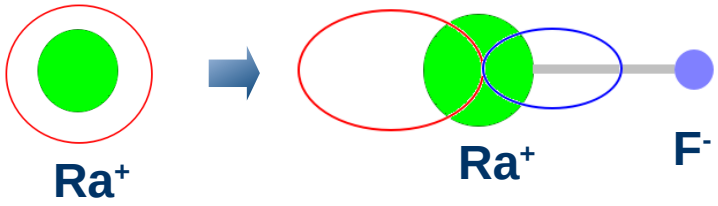

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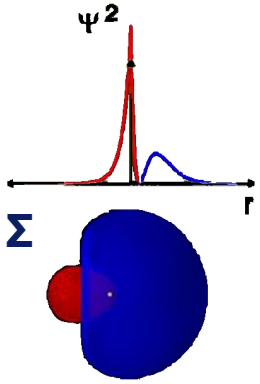

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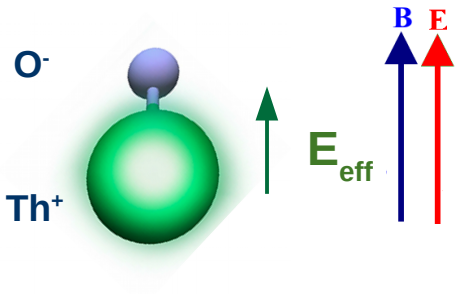


E_{ext} ~1 V/cm

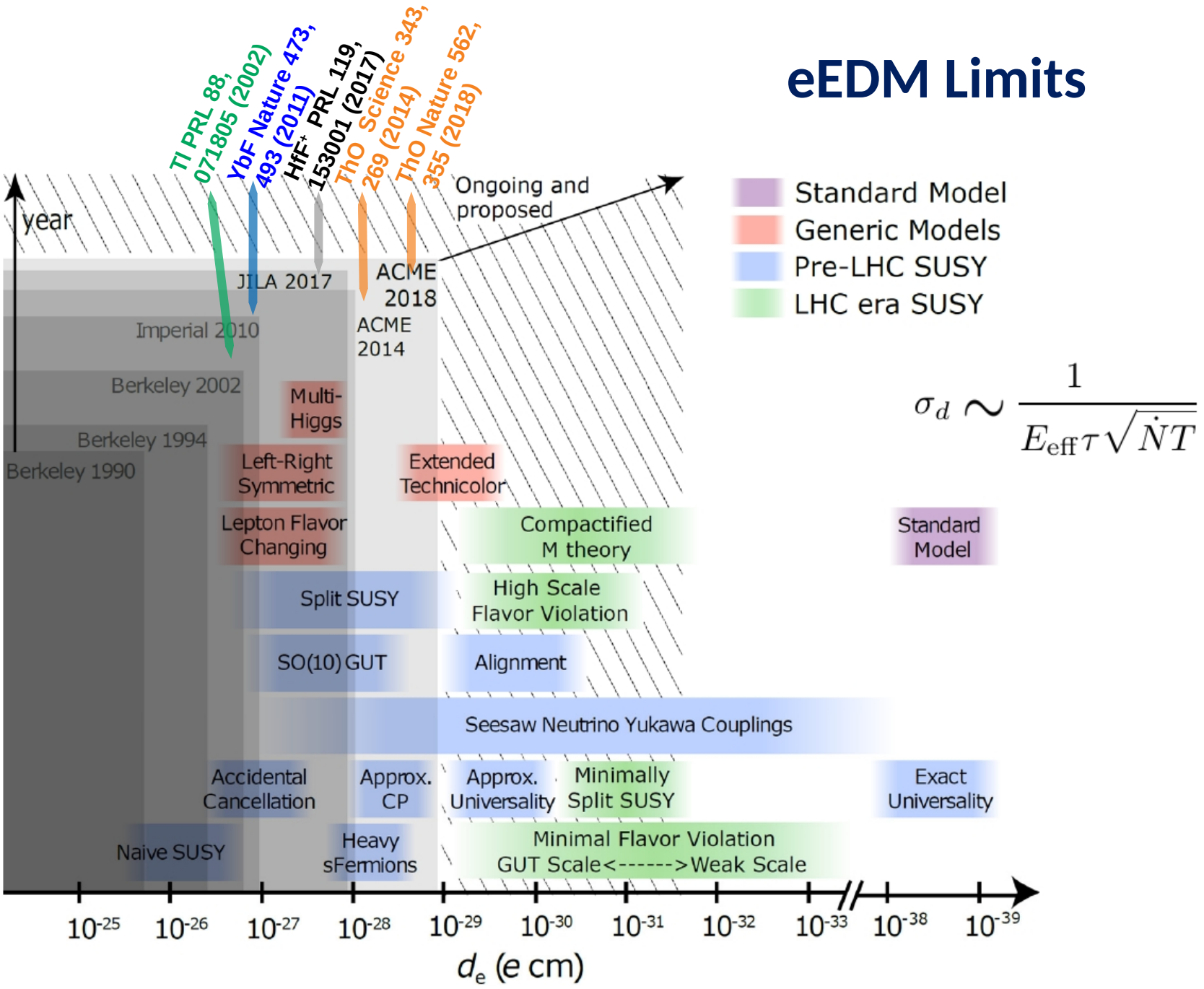
E_{eff} ~80 GV/cm

$\sim Z^n$

- Parity and Time reversal violation > 10^3

[ACME, Nature 562, 355 (2018)]
[Baron et al. Science 343, 269 (2014)]
[Sandars Phys. Rev. Lett. 18, 1396 (1967)]

eEDM Limits



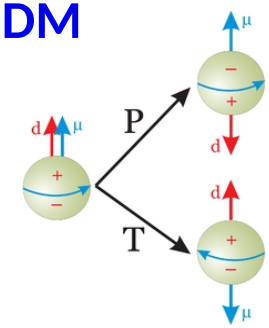
$$\sigma_d \sim \frac{1}{E_{\text{eff}}\tau\sqrt{\dot{N}T}}$$

[Source: D. DeMille. Manipulating Quantum Systems: An Assessment of Atomic,Molecular, and Optical Physics in the United States (2019)]

Why (radioactive) molecules?

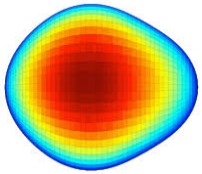
P,T- violation

EDM



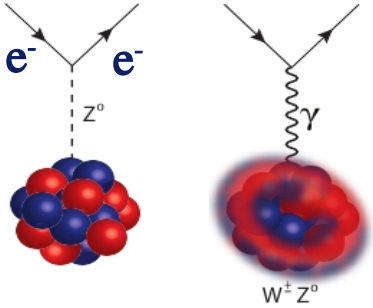
$\sim Z^3 R(Z)$

S_{schiff}



$\sim Z^3 \beta_2\beta_3 A^{2/3} / (E_+ - E_-)$

P- violation

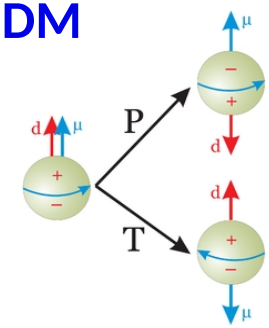


$\sim Z^3$ $\sim Z^2 A^{2/3} R(Z)$

Why (radioactive) molecules?

P,T- violation

EDM



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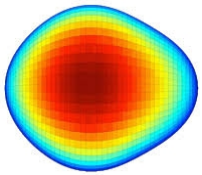

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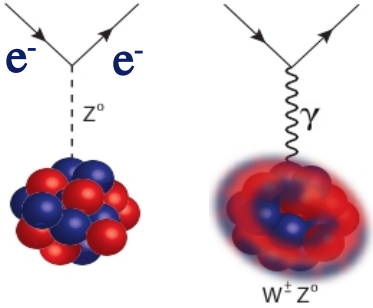
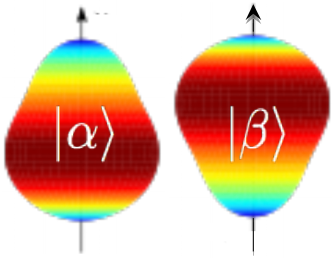


$\sim Z^3$ $\sim Z^2 A^{2/3} R(Z)$

[Gaffney et al. Nature 497, 199 (2013)]
[Parker et al. Phys. Rev. Lett. 114, 233002 (2015)]



^{225}Ra

$\Delta E = 55$ keV

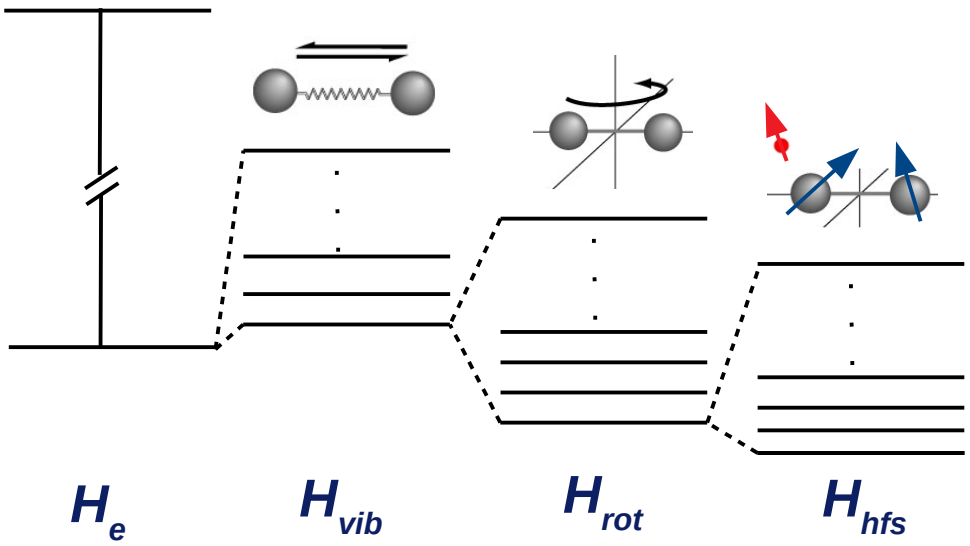
Radioactive nuclei →

- Max. Z, A, $I>0$
- Max. β_2, β_3
- Min. $(E^N_+ - E^N_-)$

Radioactive molecules: Best of all worlds

Recent Results (RaF)

Collinear resonance ionization spectroscopy of Ra(Z=88)F molecules
[Garcia Ruiz, Berger et al. CERN-INTC-2018-017 (2018)]



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

eV	~ 2	10^{-2}	10^{-5}	10^{-6}	10^{-8}	$<10^{-12}$	$<10^{-15}$

$$\sigma_d \sim \frac{1}{E_{\mathrm{eff}}\tau\sqrt{\dot{N}T}}$$

$\sim Z^3$

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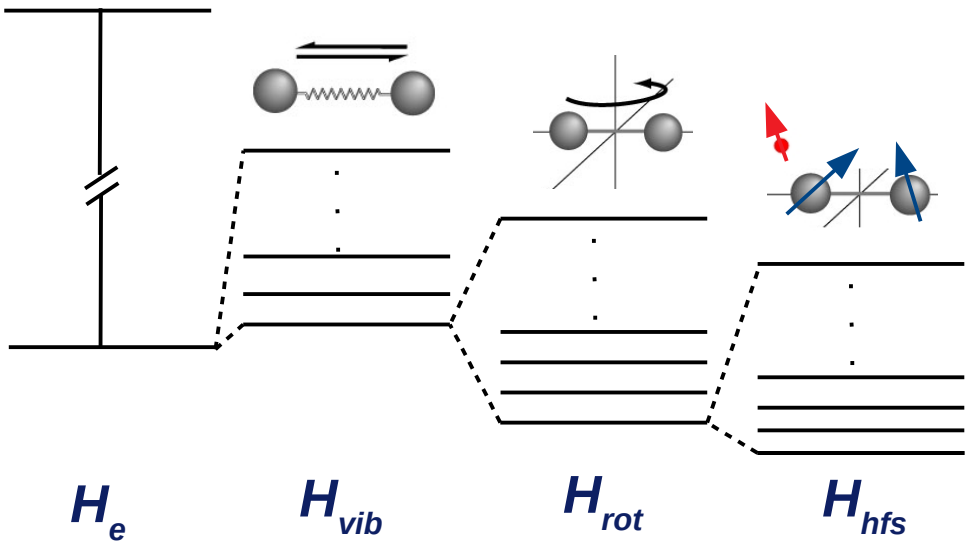

I. Low-lying structure?
II. Feasibility of laser cooling?
1. Dominant f_{00}?
2. Short-lived excited state ($T_{1/2}$)?
3. Electronic states of lower energy (E)?

$$\sigma_d \sim \frac{1}{E_{\mathrm{eff}}\tau\sqrt{\dot{N}T}}$$

$\sim Z^3$ >1 s ?

SrF: First evidence of laser cooling
[Shuman et al. Nature 467, 820-823 (2010)]

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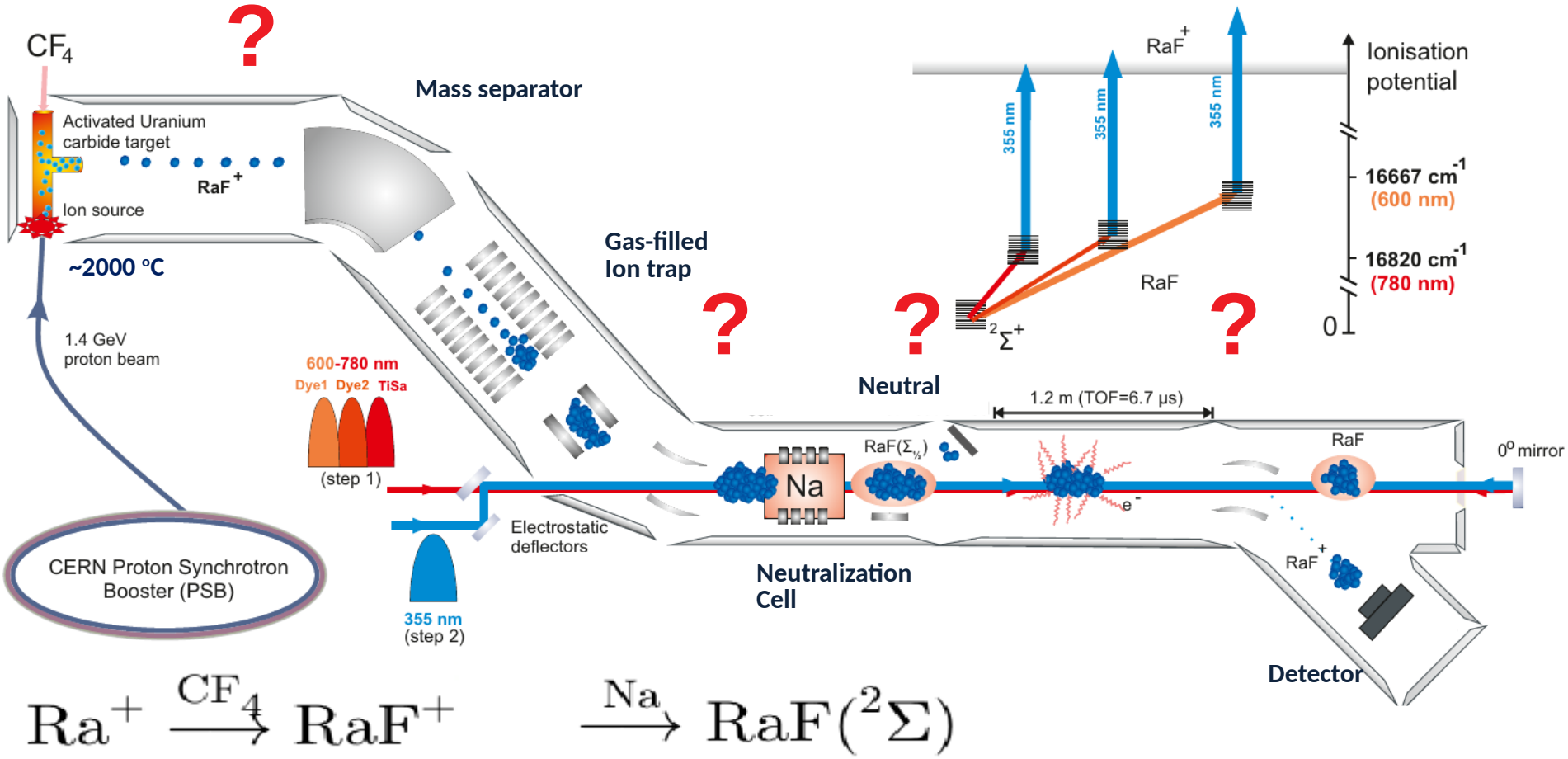


$$\mathrm{Ra}^{+} \xrightarrow{\mathrm{CF_4}} \mathrm{RaF}^{+} \xrightarrow{\mathrm{Na}} \mathrm{RaF}(^2\Sigma)$$

Production → **State preparation** → **Study**

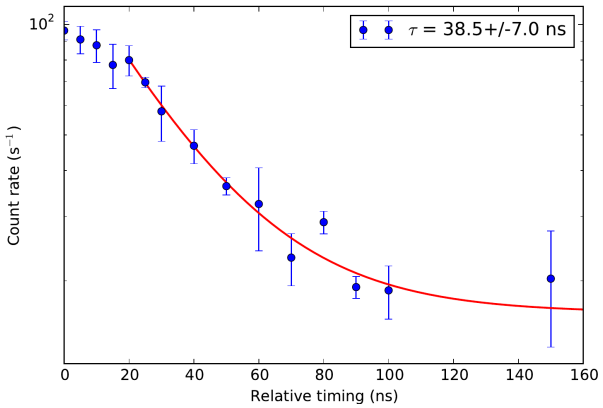
[Garcia Ruiz et al. Nature 581, 396 (2020)]

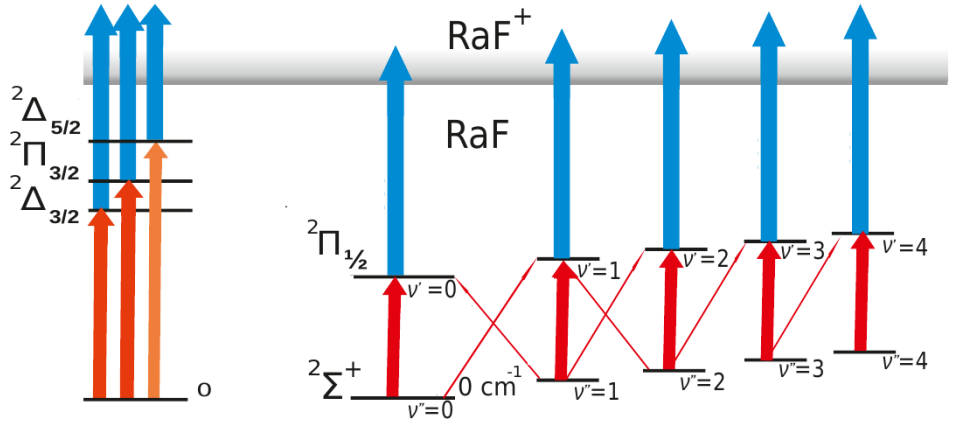
Recent Results (RaF)

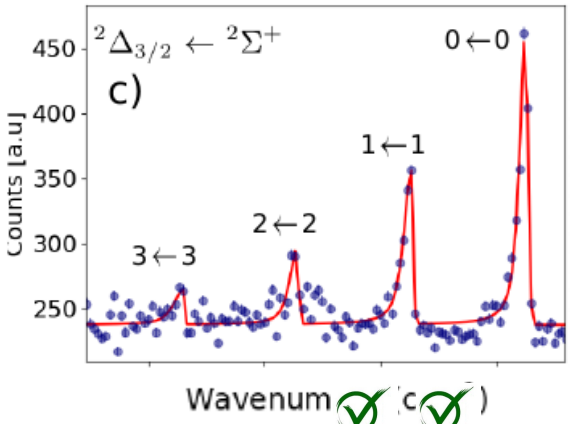
I. Low-lying structure ✓

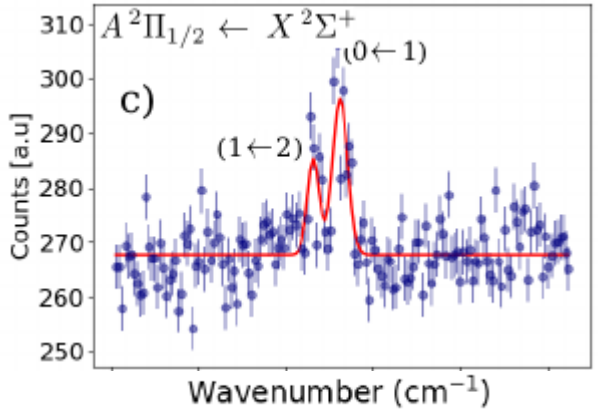
II. Feasibility of laser cooling?

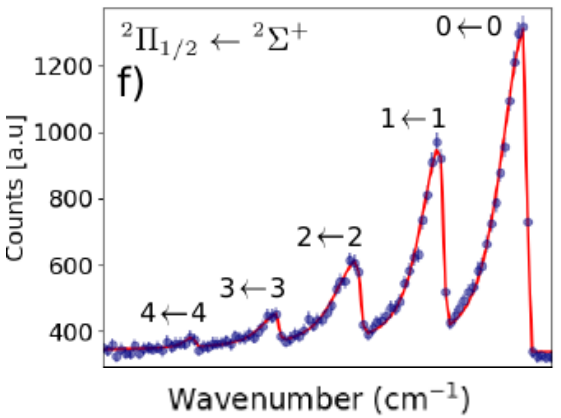
1. Dominant f_{00}? → $f_{00}/f_{ij} > 0.97$ ✓
2. Short-lived excited state ($T_{1/2}$)? → $T_{1/2} < 50$ ns ✓
3. Electronic states of lower energy (E)? → 2000 cm^{-1} above ✓











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

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

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"Hot" molecules can be super cool!

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

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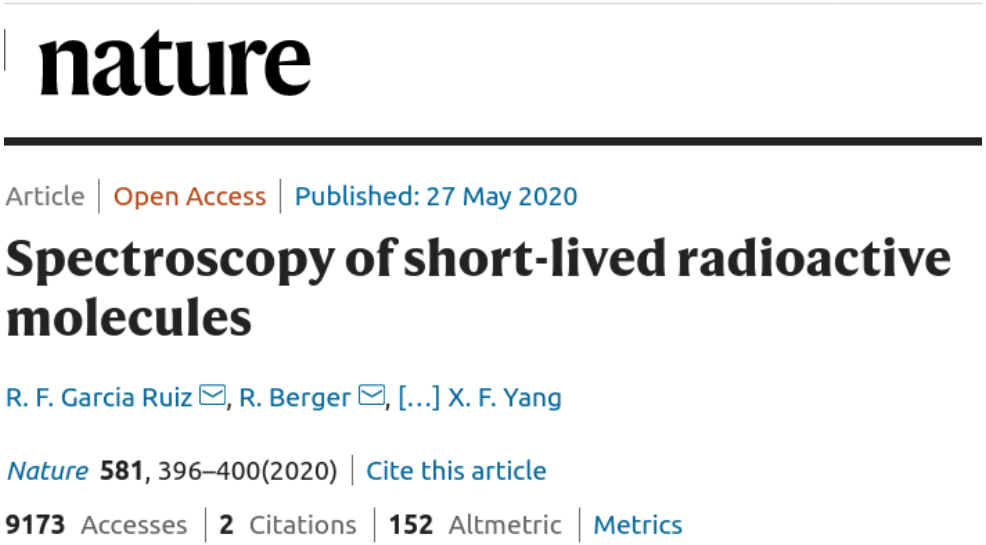

nature

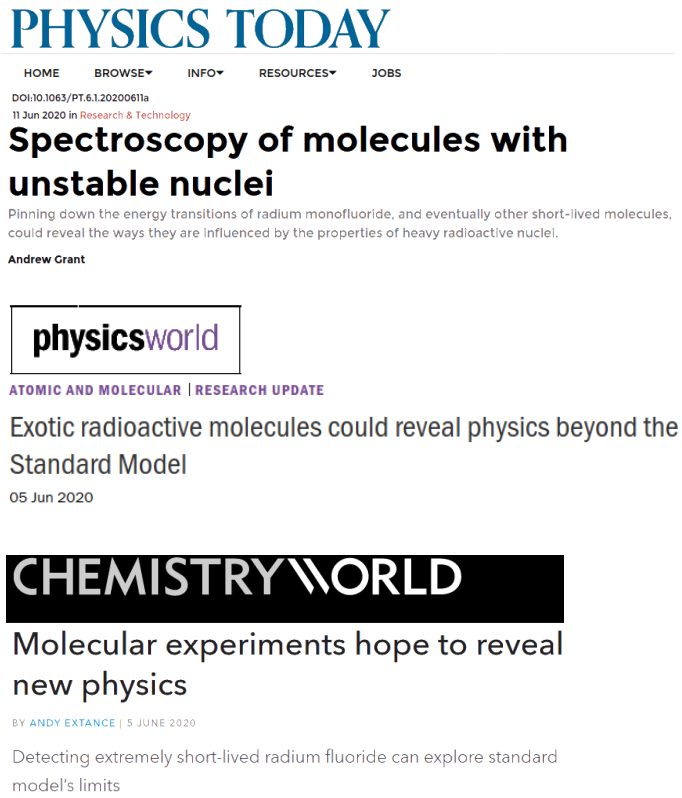
Article | Open Access | Published: 27 May 2020

Spectroscopy of short-lived radioactive molecules

R. F. Garcia Ruiz, R. Berger, [...] X. F. Yang

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

9173 Accesses | **2** Citations | **152** Altmetric | Metrics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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

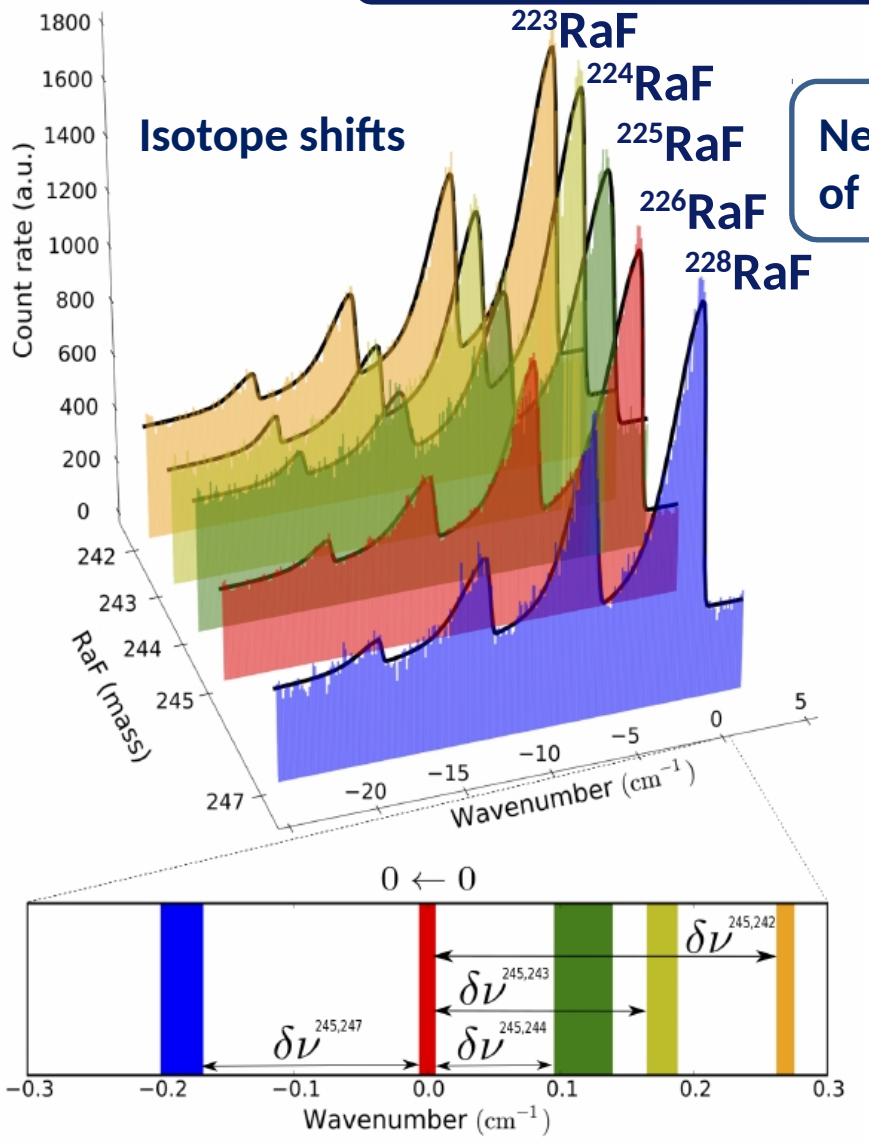
BY ANDY EXTANCE | 5 JUNE 2020

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

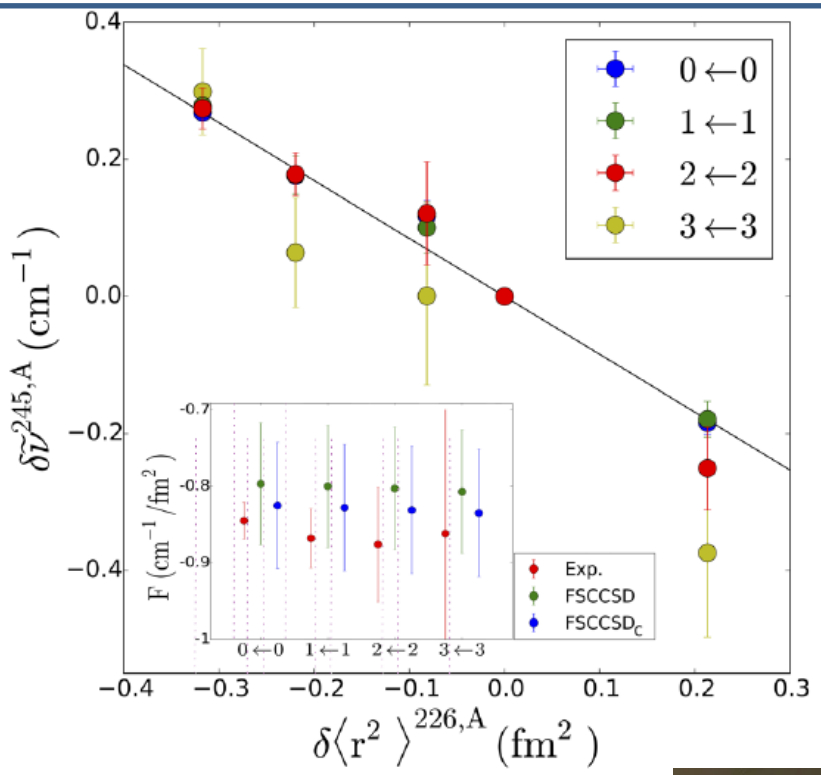
$$H_{mol} = H_e + H_{vib} + H_{rot} + H_{hfs} + H_{PV} + H_{PTV}$$ ✓ ✓

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

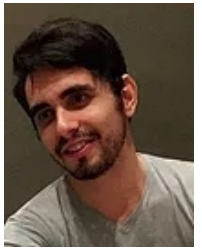
Recent Results (RaF)



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



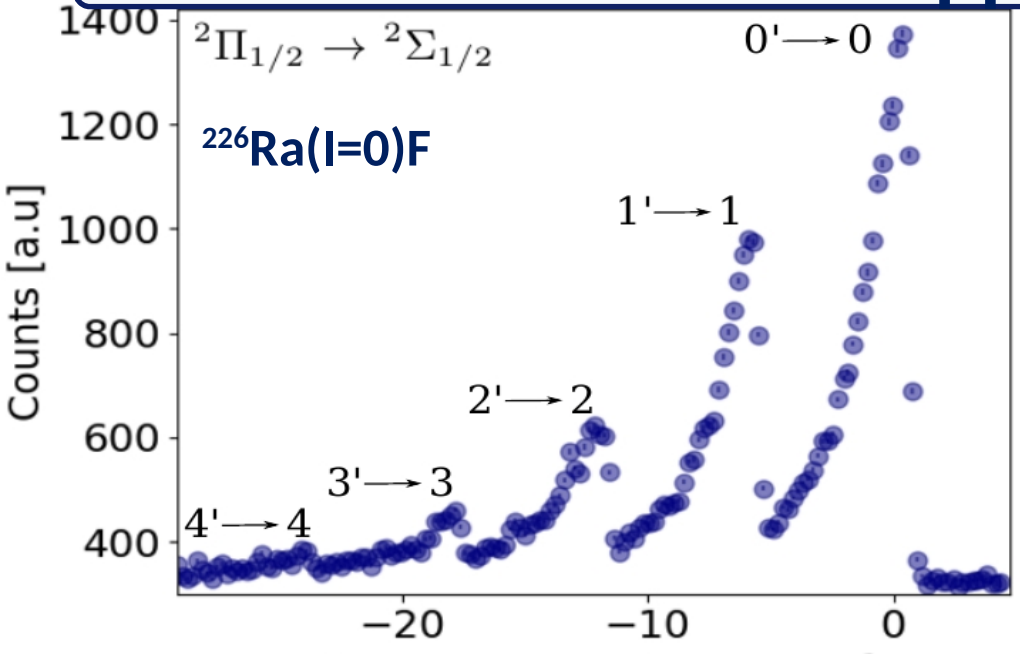
[Udrescu et al. *In preparation* (2020)]



S. Udrescu

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

Recent results: Sub-Doppler spectroscopy (RaF)



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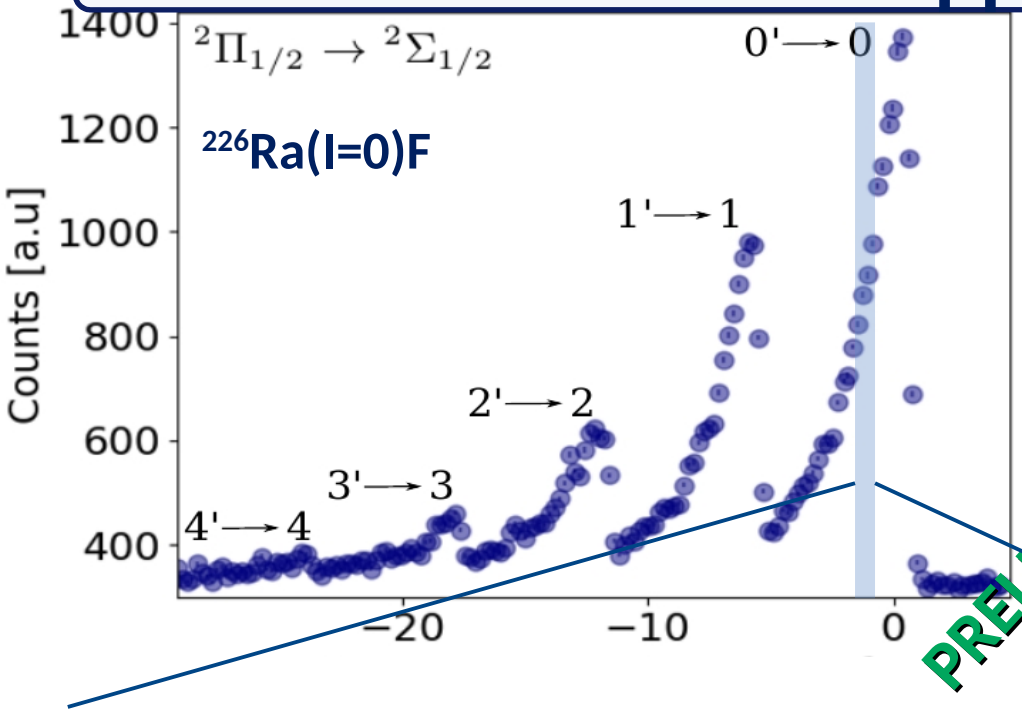
eV	~ 2	10^{-2}	10^{-5}	10^{-6}	10^{-8}	$<10^{-12}$	$<10^{-15}$

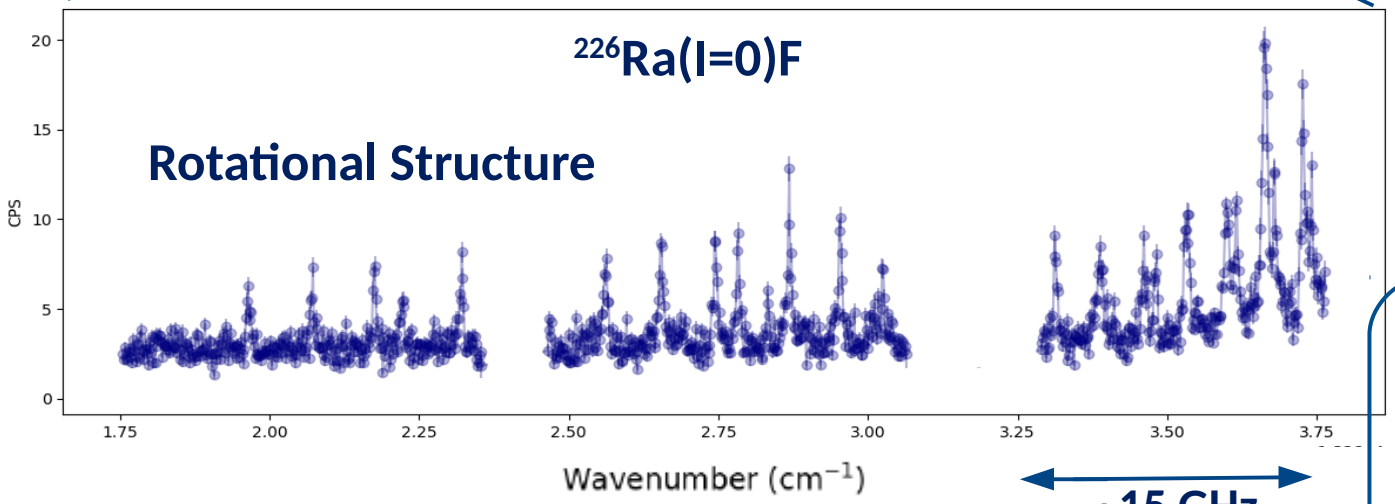
Graduate students @ MIT

A. Brinson

S. Udrescu

Recent results: Sub-Doppler spectroscopy (RaF)

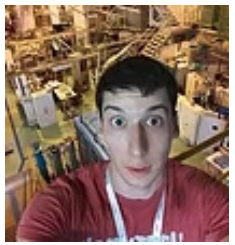




~ 15 GHz

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

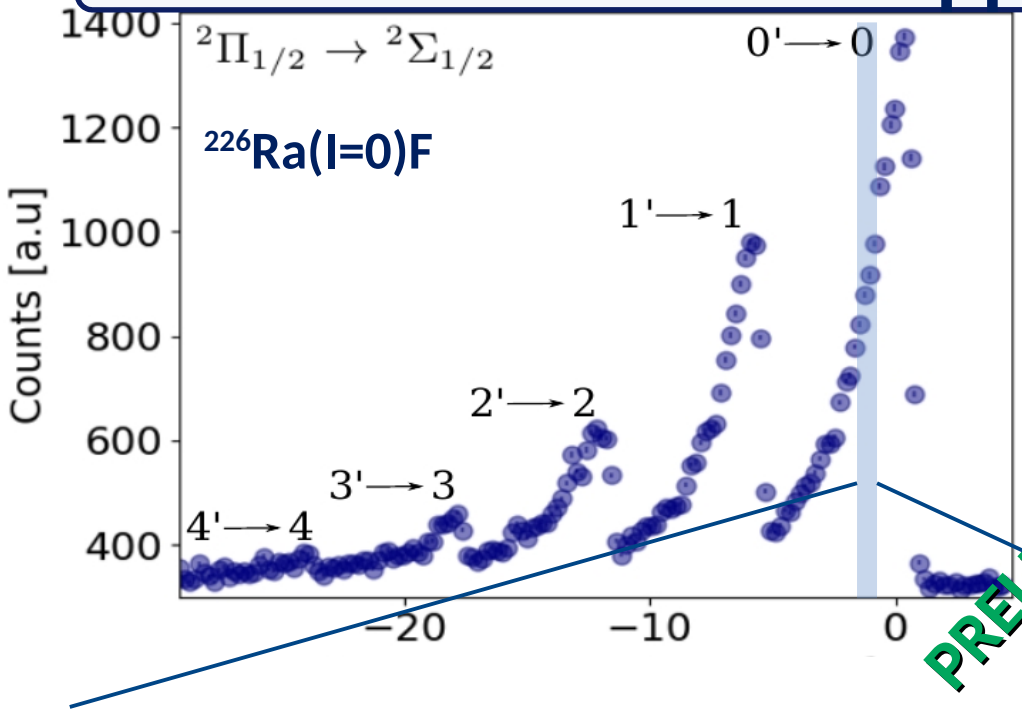
Graduate students @ MIT



A. Brinson

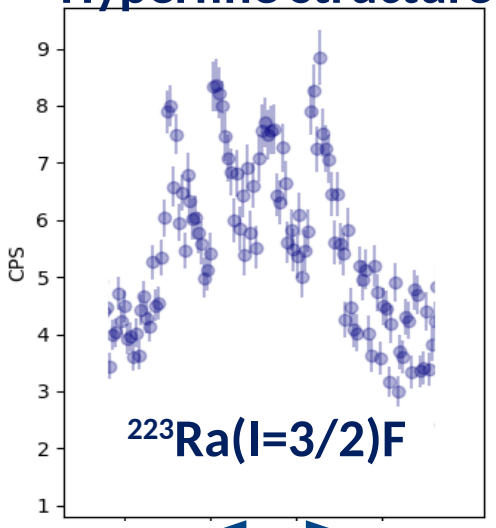
S. Udrescu

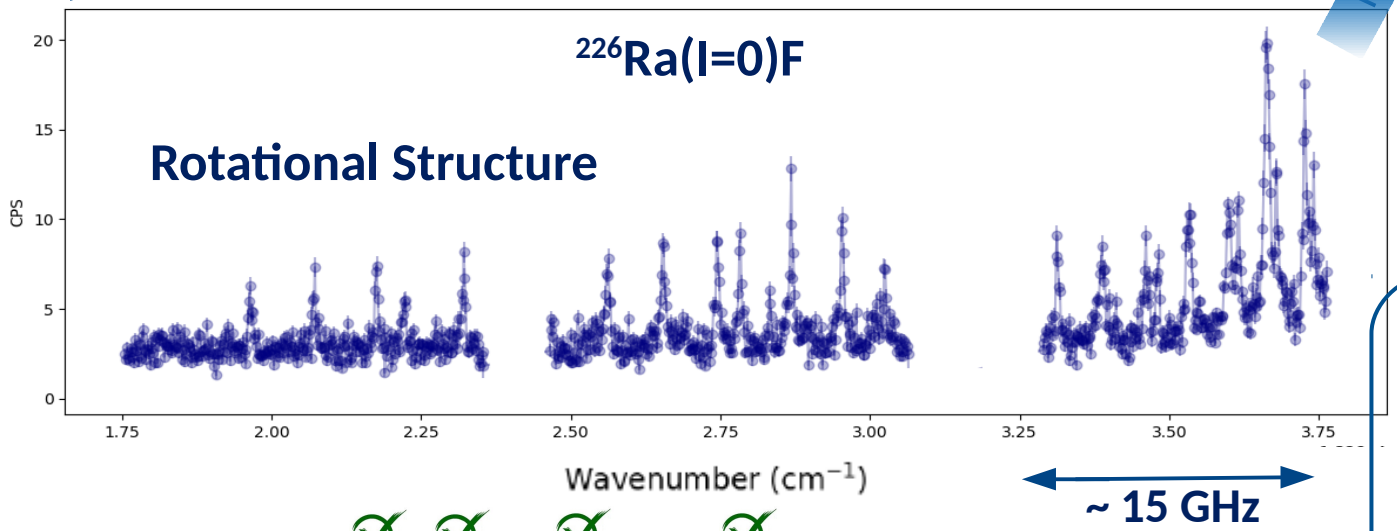
Recent results: Sub-Doppler spectroscopy (RaF)



PRELIMINARY

Hyperfine structure





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

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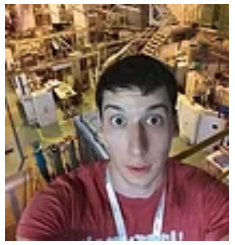
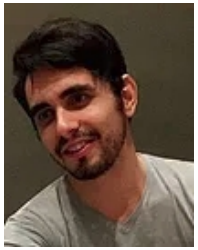


A. Brinson

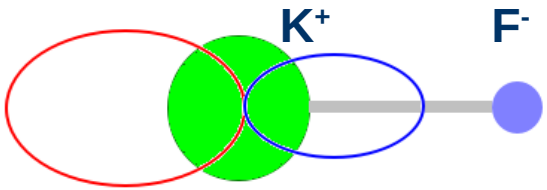


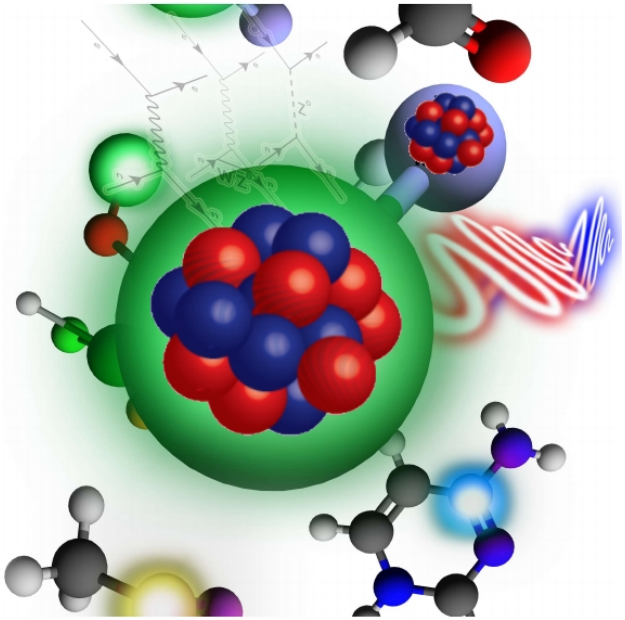
S. Udrescu

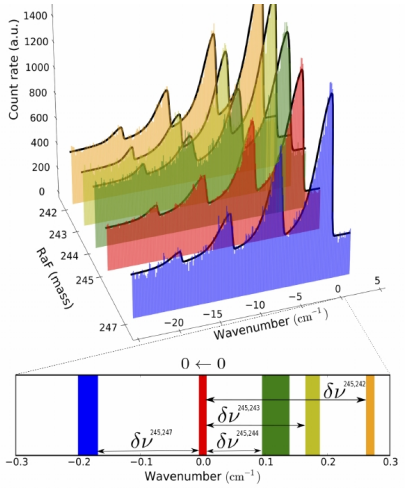
Summary and Outlook

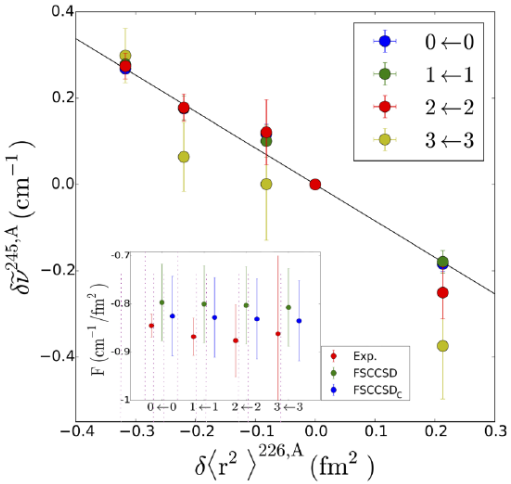
Radioactive Molecules

Nuclear EM structure







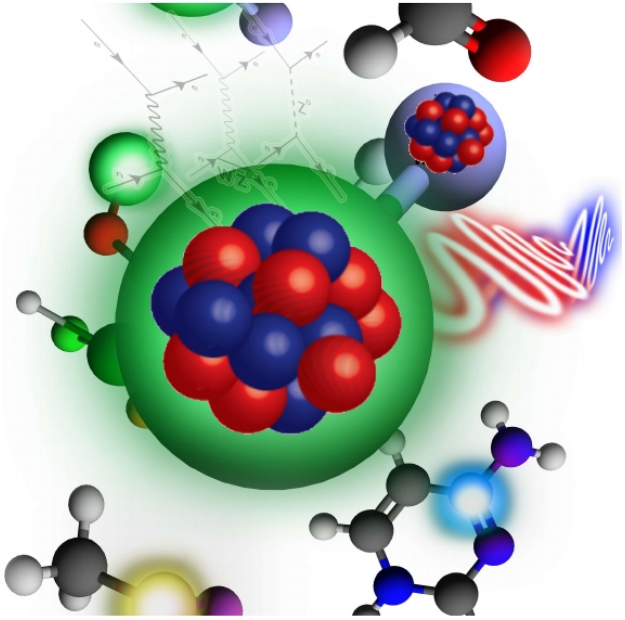


Summary and Outlook

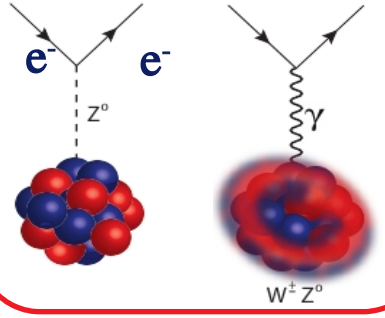
Radioactive Molecules

Nuclear EM structure

Nuclear EW structure



P- violation



$$E_{PNC} \sim \frac{\langle \text{P-odd}|H_{\text{w}}|\text{P-even}\rangle}{E_- - E_+}$$

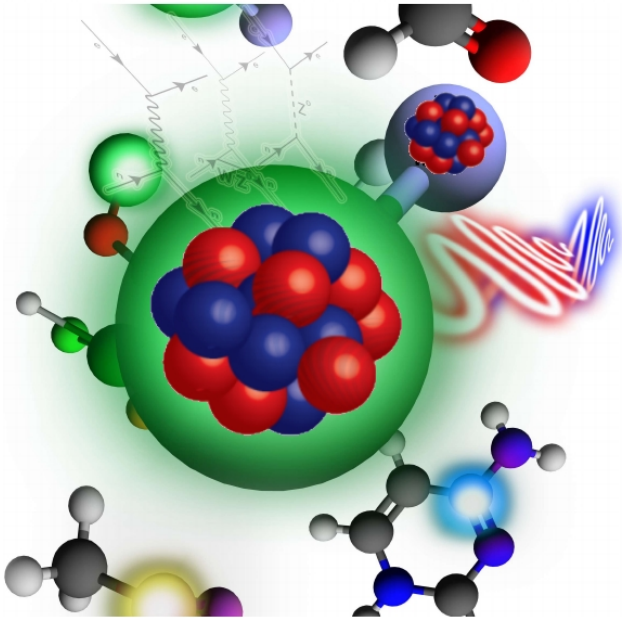
Molecular enhancement > 10^{11}

Summary and Outlook

Radioactive Molecules

Nuclear EM structure

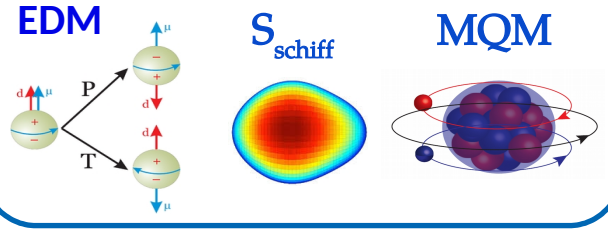
Nuclear EW structure



→ AcF, RaO, PaO, RaOH, ….

Fundamental symmetries

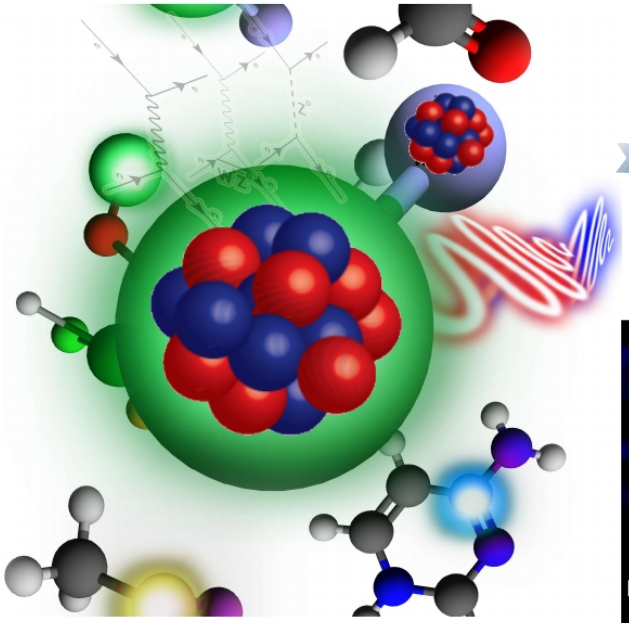
P,T- violation



Molecular + Nuclear amplification
→ E_{eff} > 10 GV/cm

Summary and Outlook

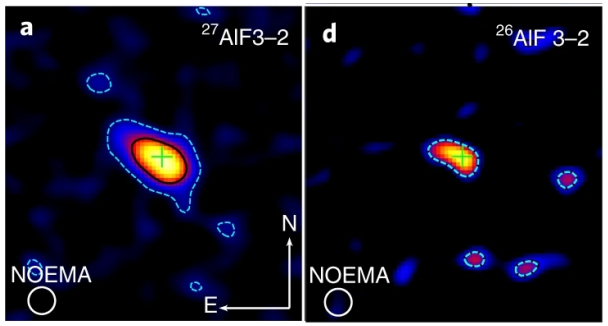
Radioactive Molecules



Nuclear EM structure

Nuclear EW structure

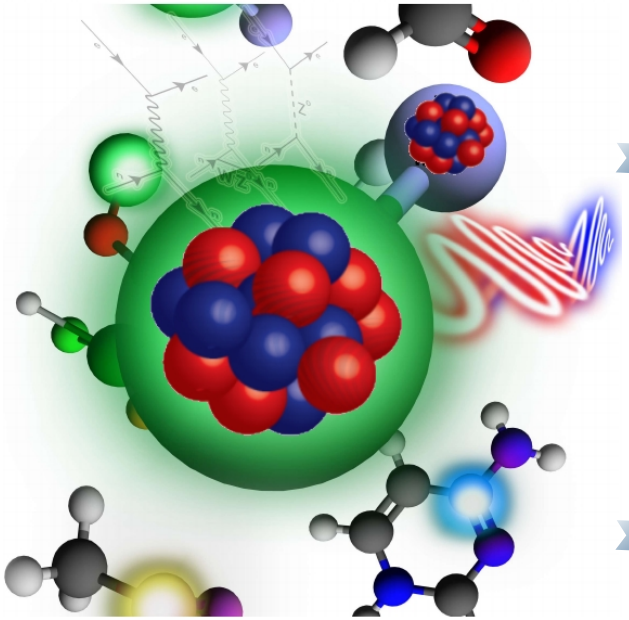
Astrophysics



Fundamental symmetries

Summary and Outlook

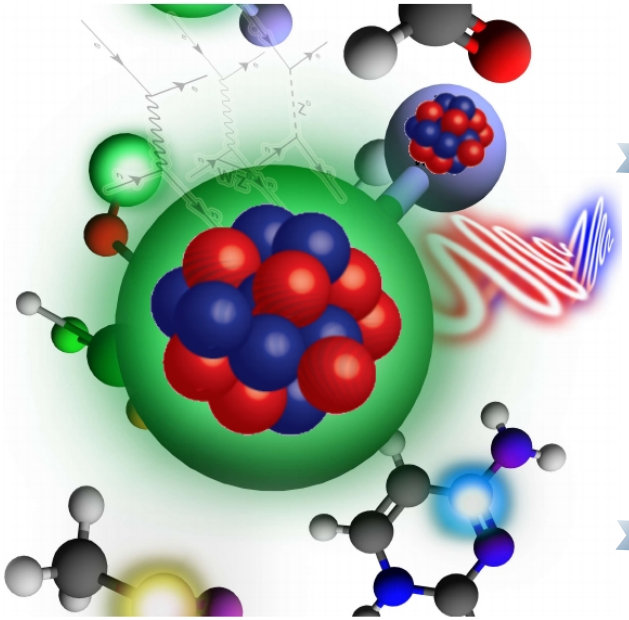
Radioactive Molecules



- Nuclear EM structure
- Astrophysics
- Nuclear EW structure
- Nuclear chemistry
- Fundamental symmetries
- Quantum chemistry

Summary and Outlook

Radioactive Molecules



Nuclear EM structure

Astrophysics

Nuclear EW structure

Nuclear chemistry

Fundamental symmetries

Quantum chemistry

Lots of opportunities!

TRIUMF EEC NEW LETTER OF INTENT

Detailed Statement of Proposed Research for Experiment S2068-LOI

Radioactive Molecules for Nuclear Structure and Fundamental Physics Research

R.F. Garcia Ruiz[1,2], J. Behr[3], R. Berger[4], J. Dilling[3,5], R. de Groote[6], K. Flanagan[7], N. Hutzler[8], A. Kwiatkowski[3], S. Malbrunot-Ettenauer[2], G. Neyens[2,9], S. Wilkins[2]

...collaboration in the making!

Thanks to…

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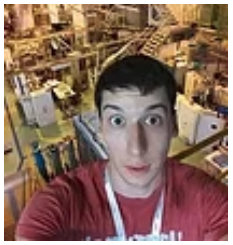
P.-G. Reinhard (Erlangen-Nürnberg),
G. Hagen (ORNL),
J. Holt (TRIUMF),
R. Stroberg (U. Washington)...

Quantum chemistry: *R. Berger (U. Marburg, Germany),*
T. Isaev (PNPI NRCKI, St. Petersburg)

ISOLTRAP (F. Wienholtz) , **RILIS** (S. Wilkins, K. Chrysalidis)
Target group (S. Rothe), **ISOLDE Technical group**

Graduate students @ MIT



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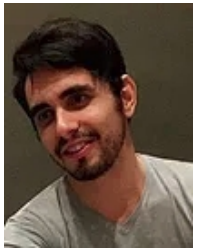

S. Udrescu

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