Radioactive molecules for Nuclear Science

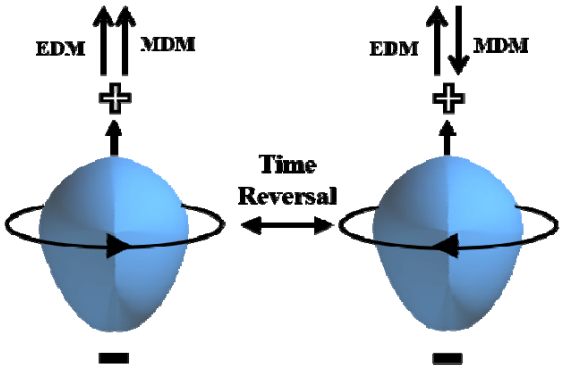
Ronald Fernando Garcia Ruiz

MIT

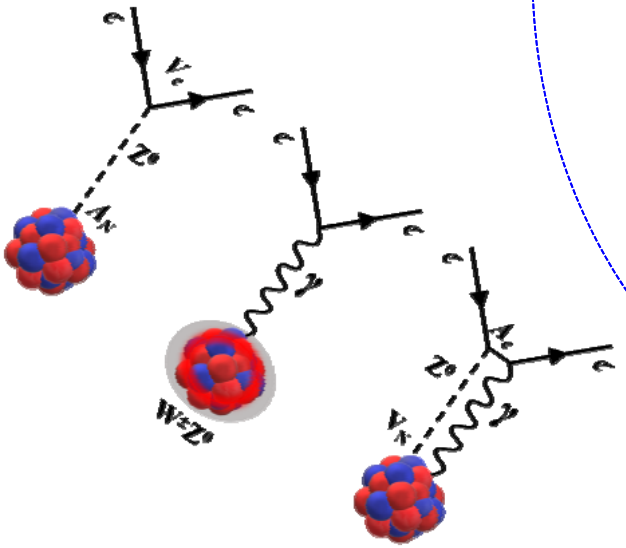
TRIUMF Science Week
July 2022

Radioactive molecules offer a unique window into our study of nuclei and fundamental interactions

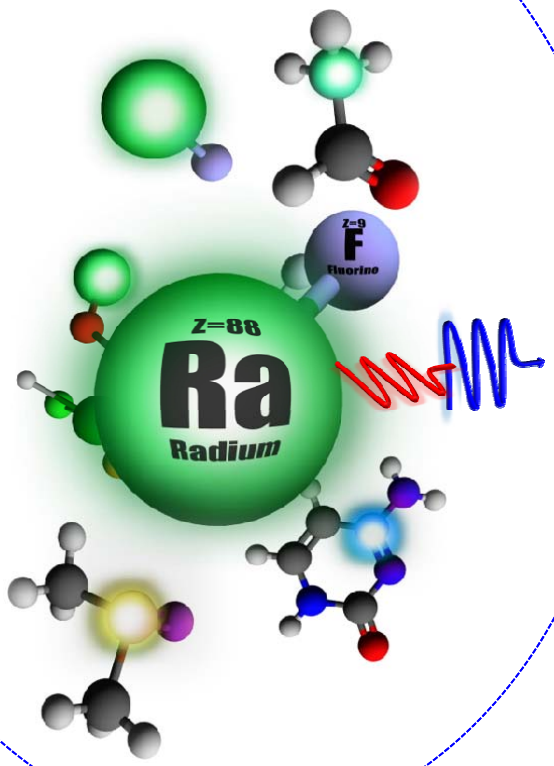
Fundamental Symmetries



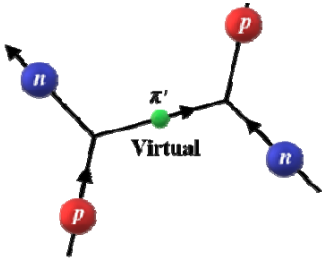
Hadronic parity violation



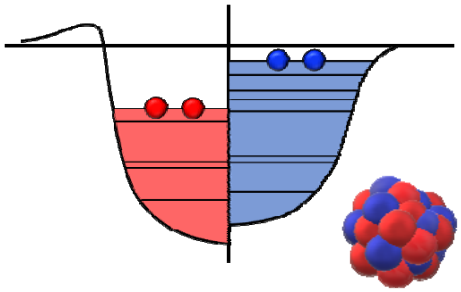
Radioactive molecules



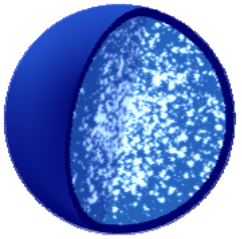
Nuclear Force



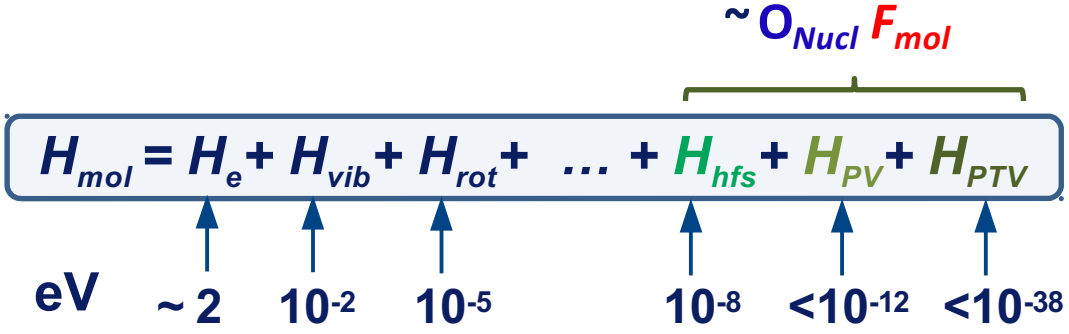
Nuclear structure

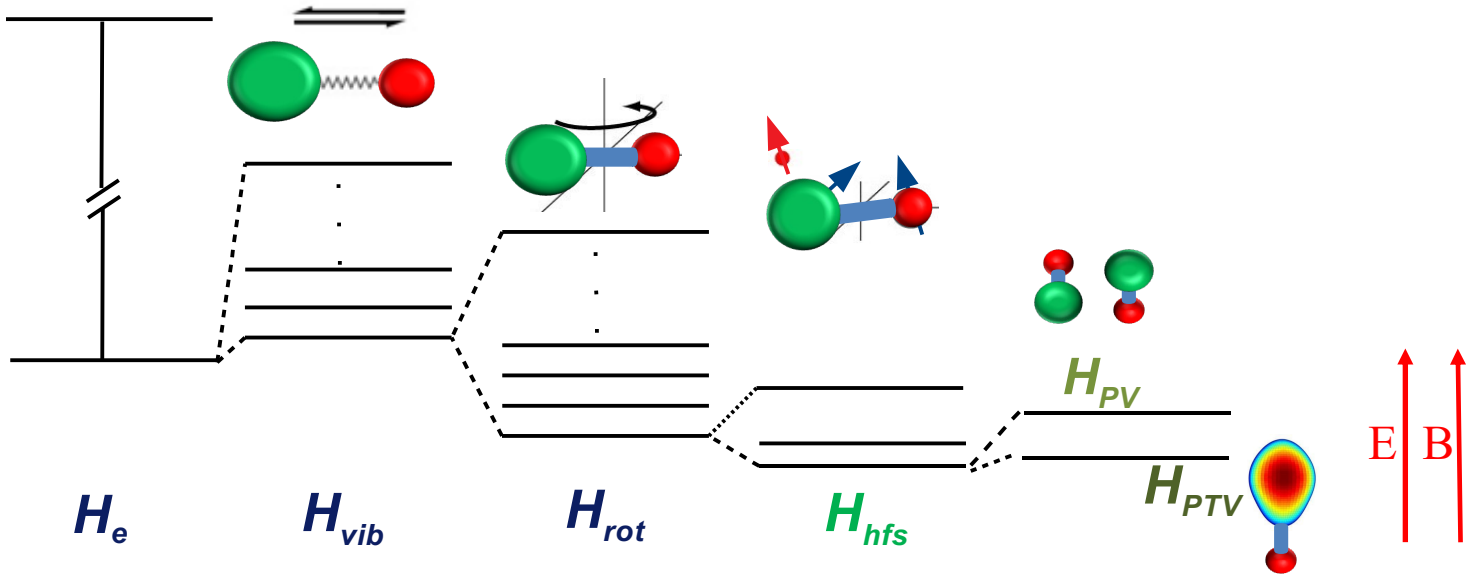


Nuclear matter

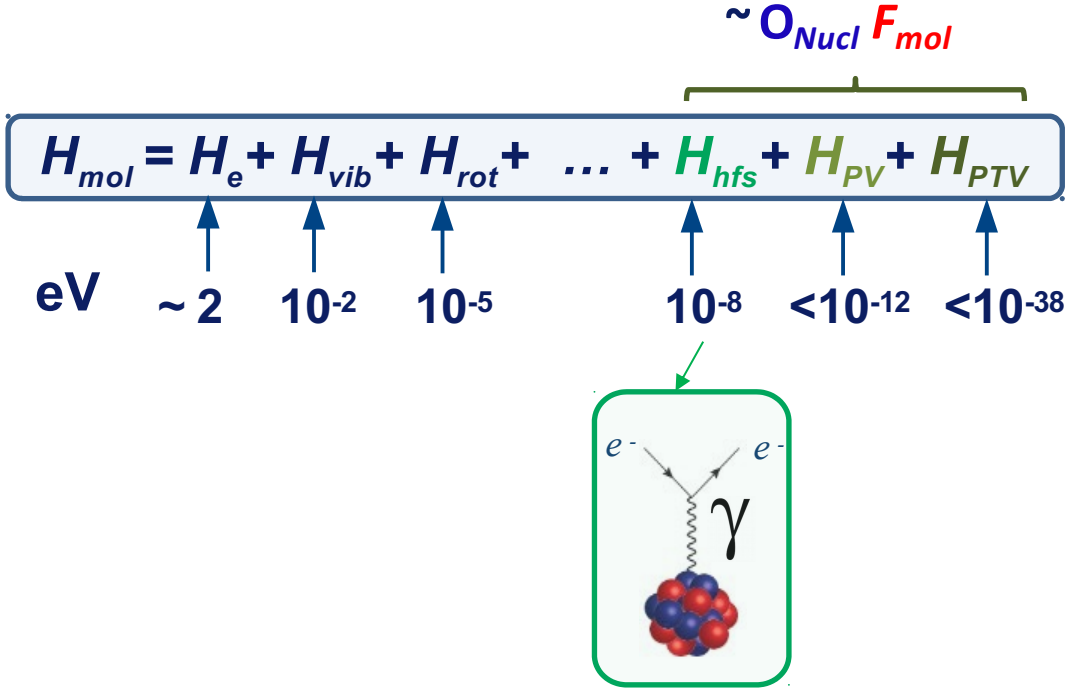


Why radioactive molecules?





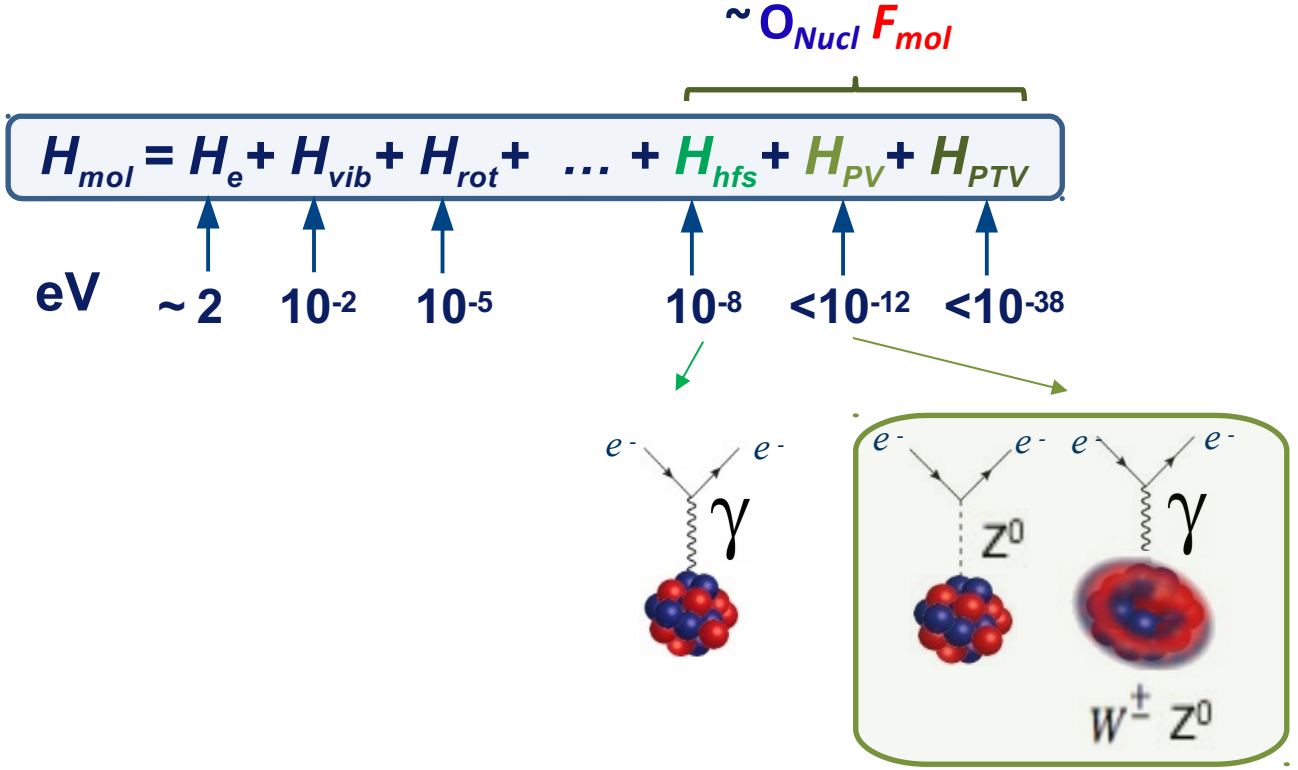
Why radioactive molecules?



P,T-even

Nuclear matter
Nuclear structure
BSM searches

Why radioactive molecules?



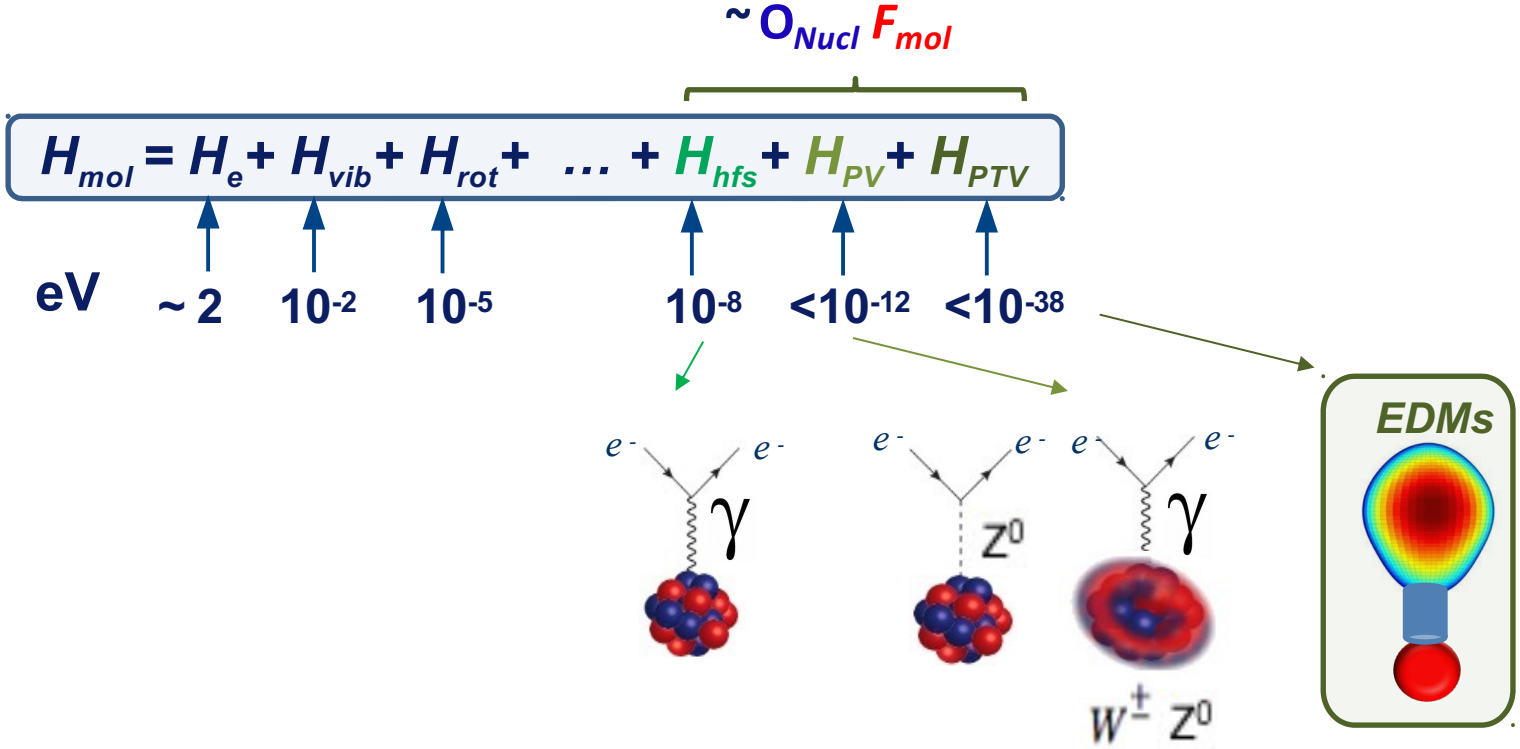
P,T-even

Nuclear matter
Nuclear structure
BSM searches

P-violation

Electro weak structure
Precision Standard Model tests
Dark Mater properties?
New forces?

Why radioactive molecules?



P,T-even

Nuclear matter
Nuclear structure
BSM searches

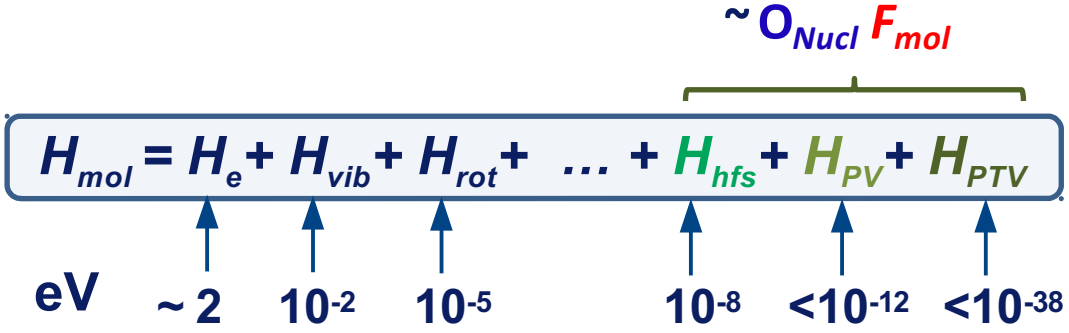
P-violation

Electro weak structure
Precision Standard Model tests
Dark Mater properties?
New forces?

T-violation

Matter-antimatter asymmetry
New particles?

Why radioactive molecules?



How to look for new physics?

Deviations from Standard Model predictions

H_{hfs}

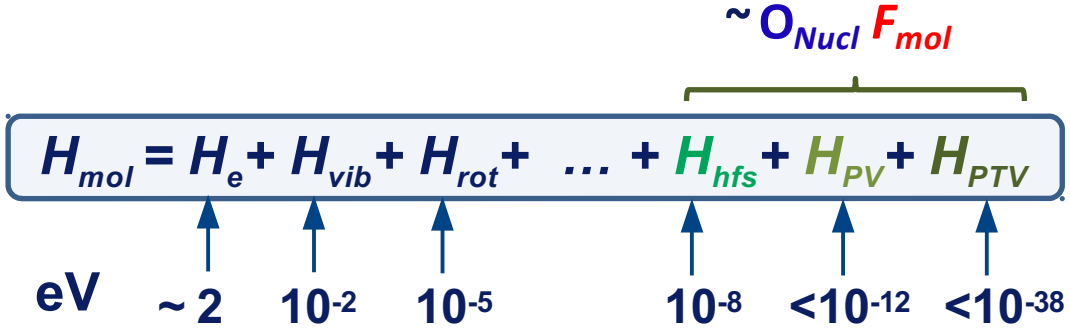
Unknown properties of the Standard Model

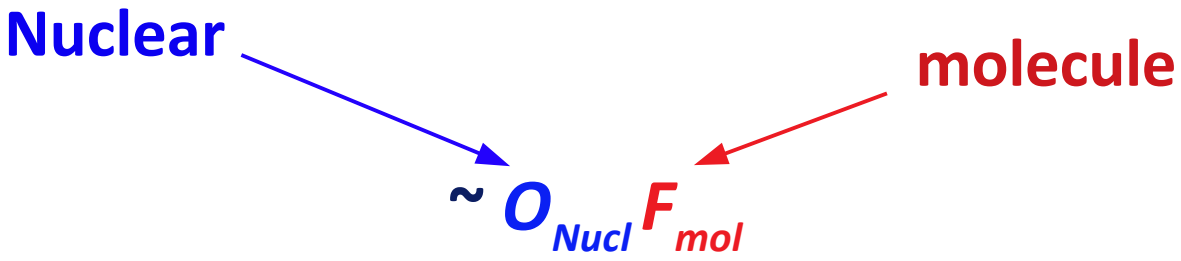
H_{PV}

A discovery that the Standard Model does not predict

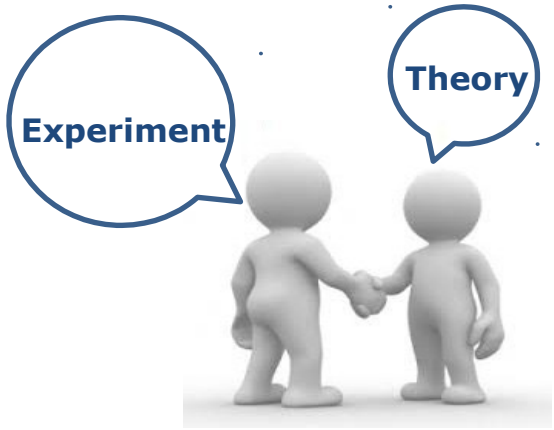
H_{PTV}

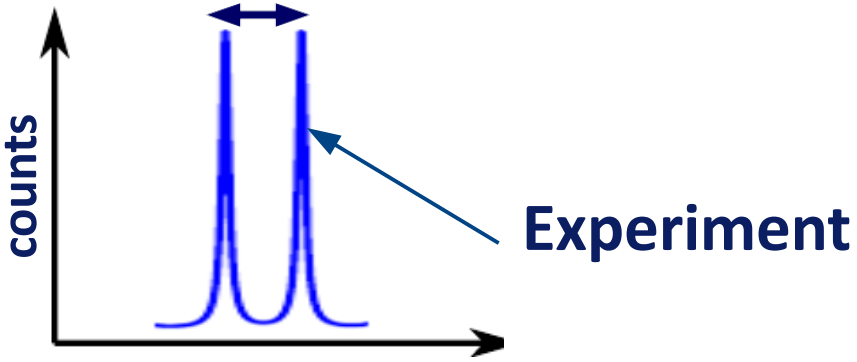
Why radioactive molecules?



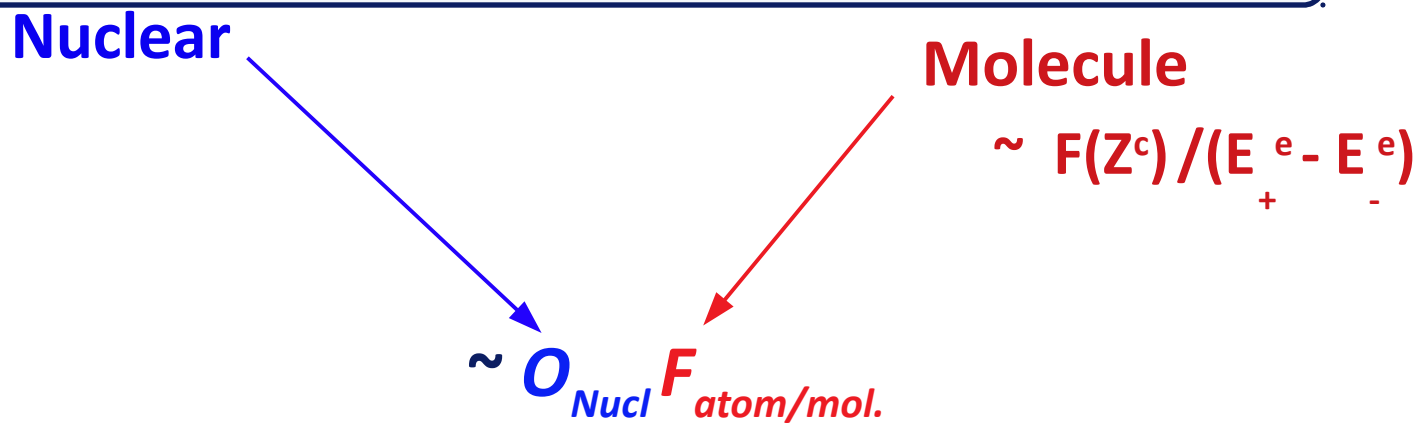


Nuclear & Atomic & Molecular





Why radioactive molecules?



- Molecule > 10^3

Why radioactive molecules?

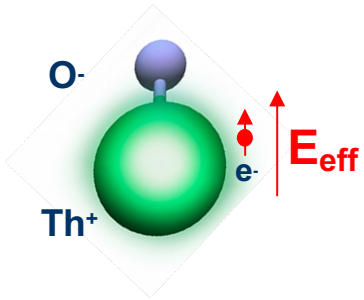
Nuclear

Molecule

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

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

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



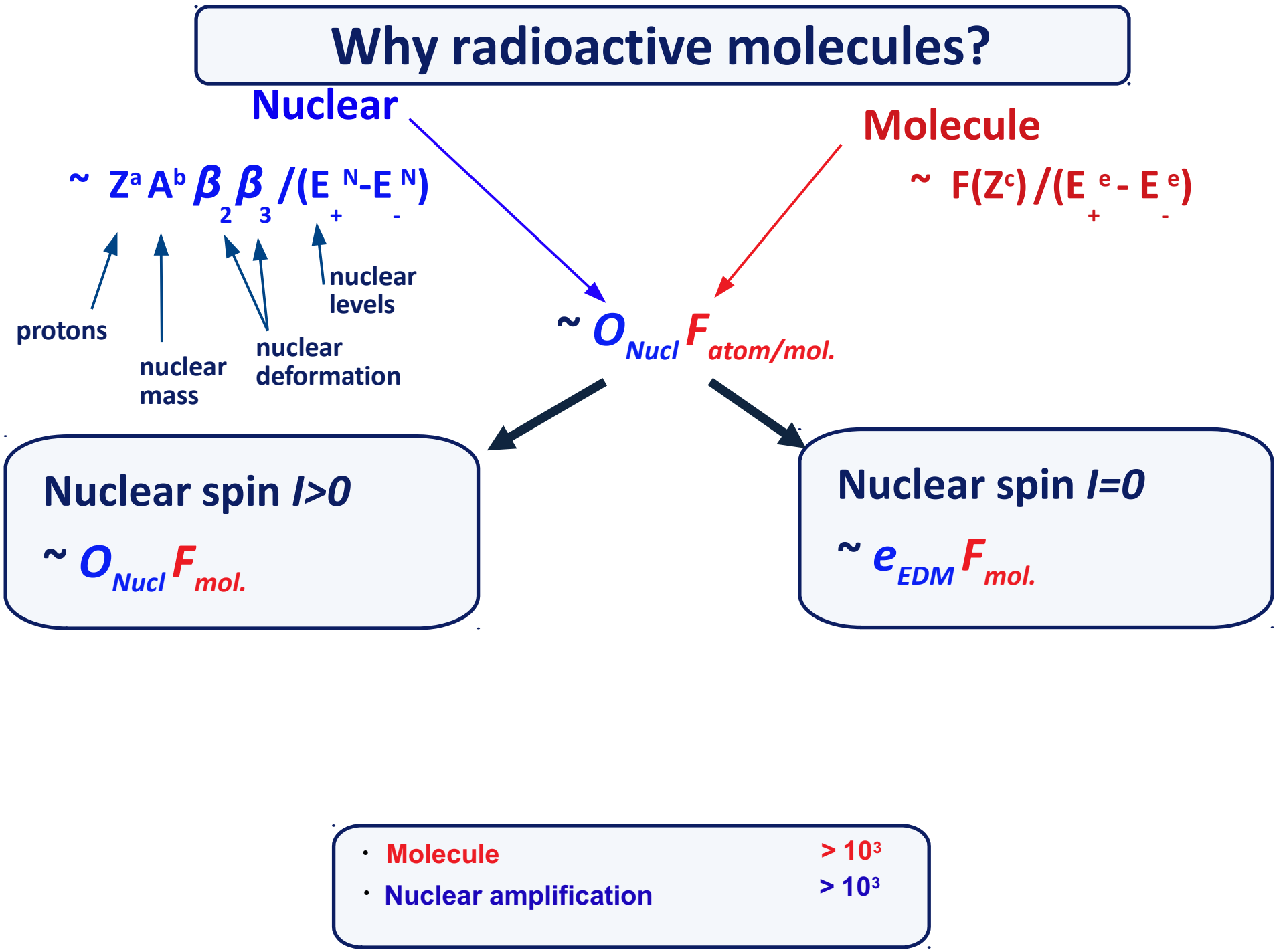
[ACME, Nature 562, 355 (2018)]

Nuclear spin *I=0*

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

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

Why radioactive molecules?



- 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

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

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

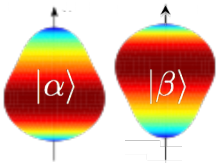
- ✓ Large Z, A
- ✓ Nuclear spin I >0
- ✓ β_2 $\beta_3 > 0$

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

· Molecule	> 10^3
· Nuclear amplification	> 10^3

^{225}Ra



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

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

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

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

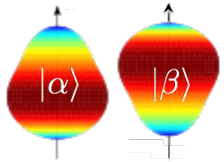
Radioactive molecules => Best of all words!

Nuclear X Molecule

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

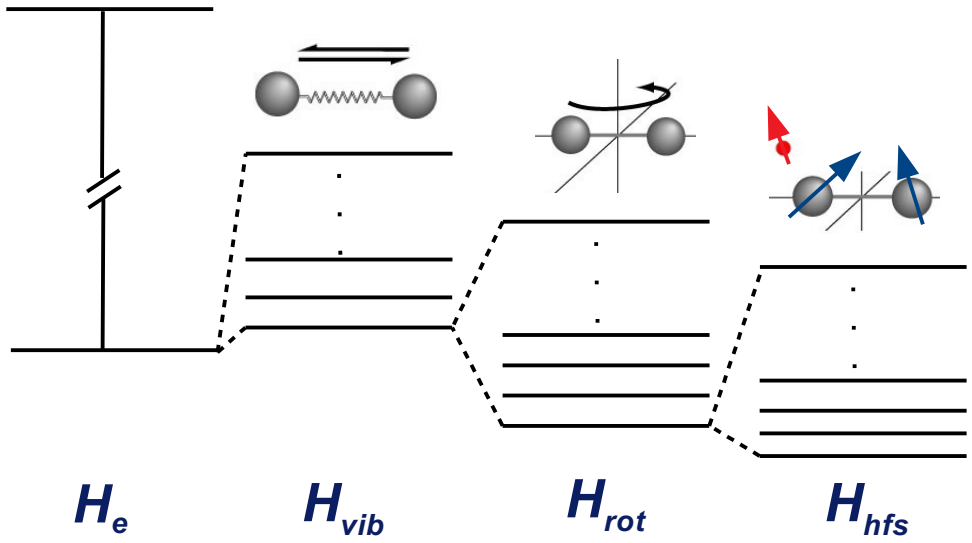
• Molecule	$> 10^3$
• Nuclear amplification	$> 10^3$

^{225}Ra



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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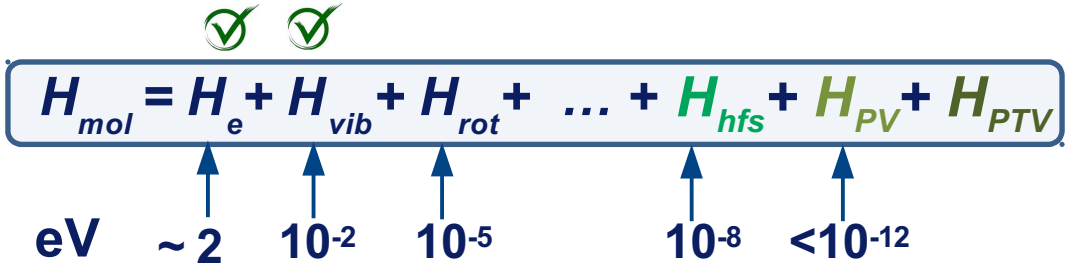
Article | Open Access | Published: 27 May 2020

Spectroscopy of short-lived radioactive molecules

R. F. Garcia Ruiz ✉, R. Berger ✉, […]

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

12k Accesses | **22** Citations | **163** Altmetric | Metrics



S. Udrescu

A. Brinson

S. Wilkins

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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

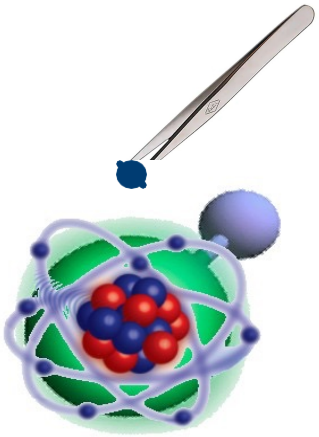
CHEMISTRY WORLD

Molecular experiments hope to reveal new physics

BY ANDY EXTANCE | 5 JUNE 2020

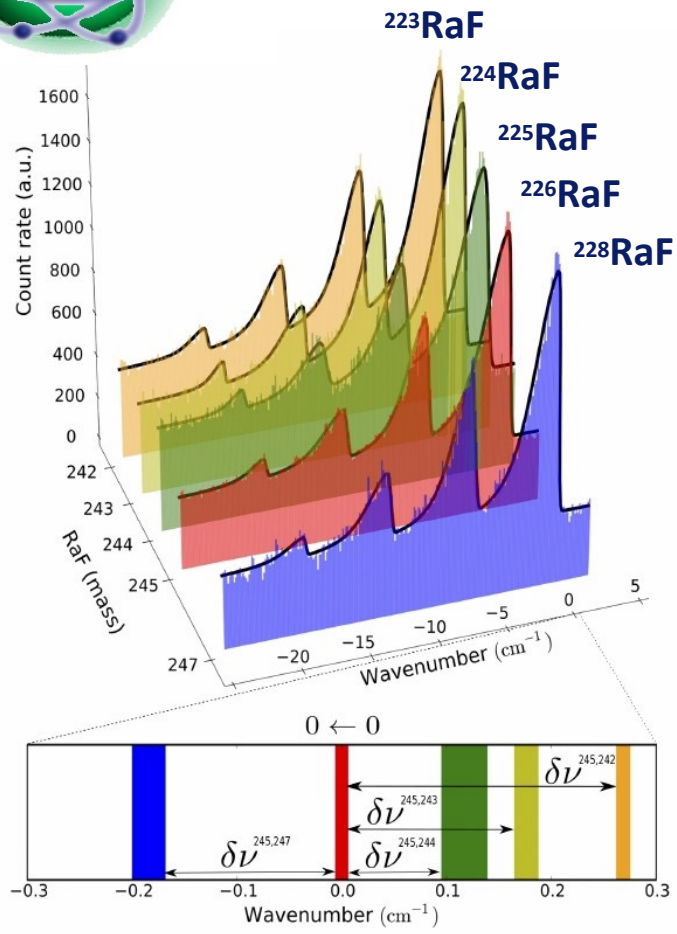
Detecting extremely short-lived radium fluoride can explore standard model's limits

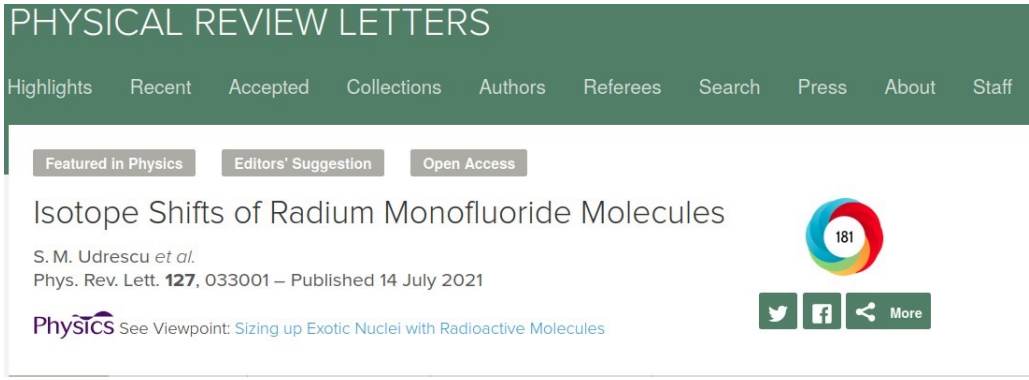
Recent Results (RaF)



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

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



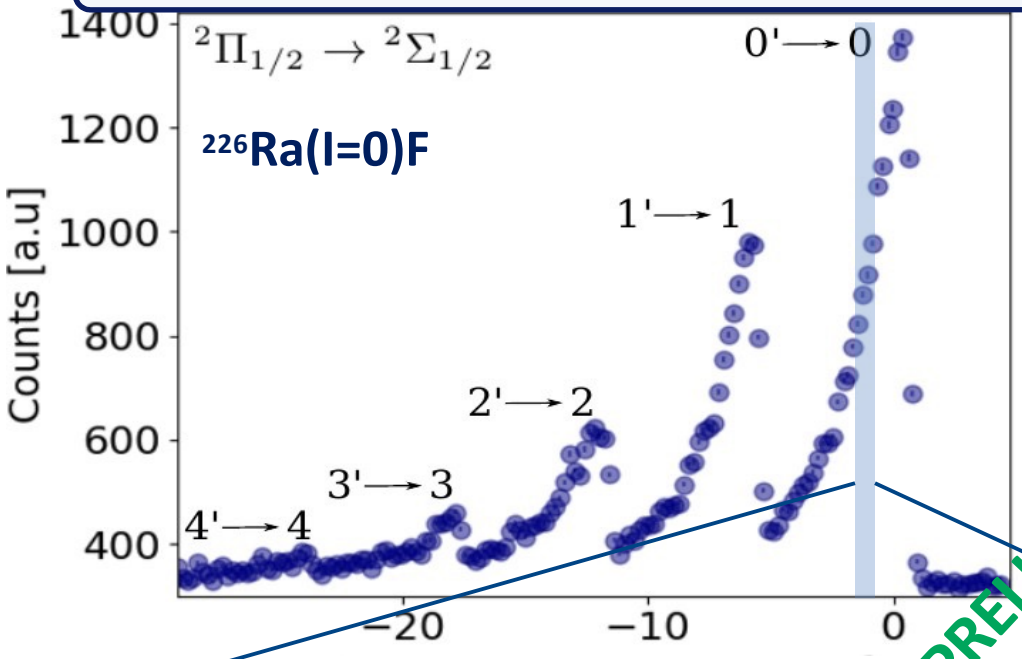


S. Udrescu

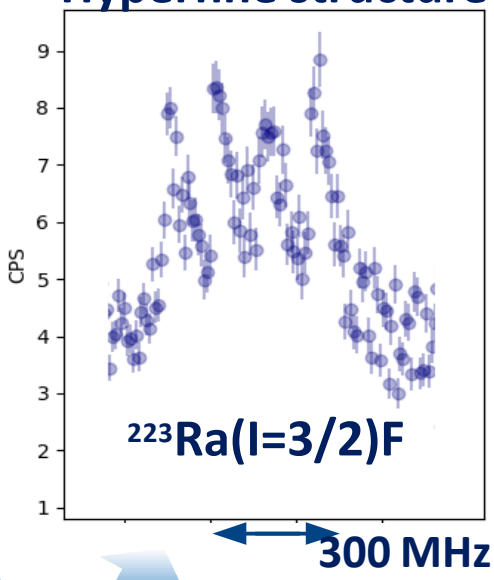
A. Brinson

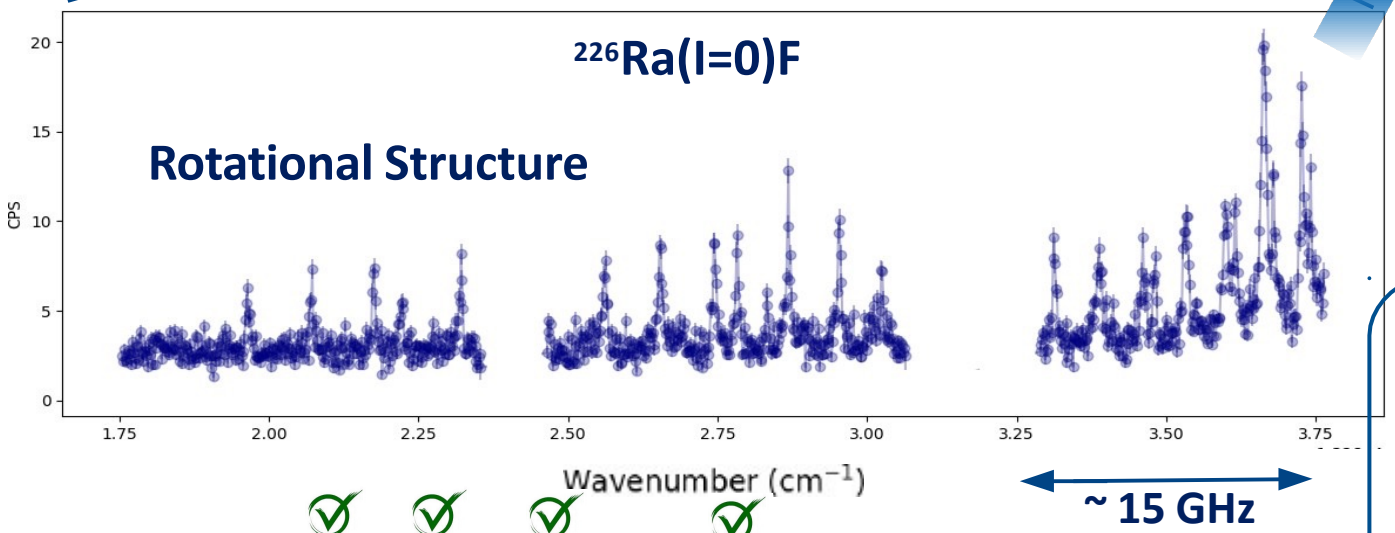
S. Wilkins

Recent results: Precision experiments (RaF)



PRELIMINARY



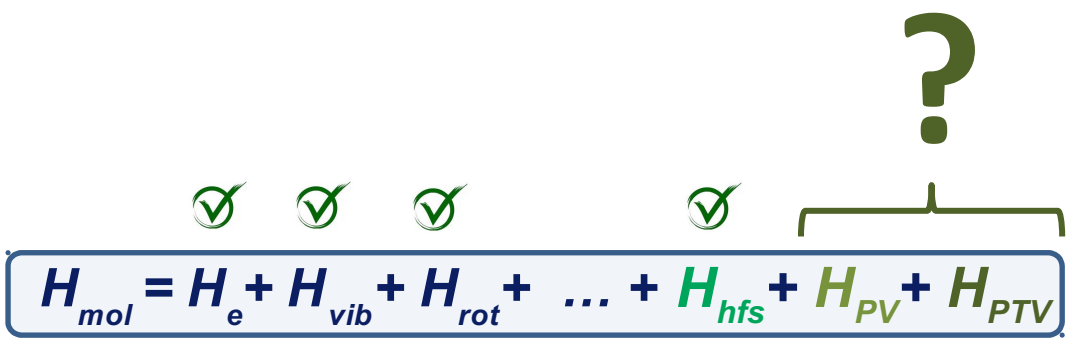


$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$


S. Wilkins

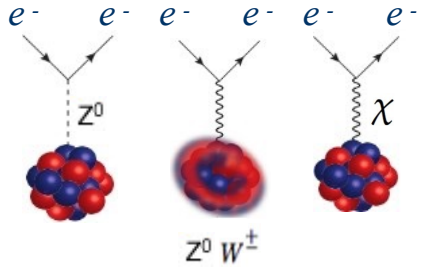

S. Udrescu

What's next?



A single molecule in a Penning trap

$H_{PV} \sim F(Z^c) / (E_+^{\,e} - E_-^{\,e})$



Atoms: $(E_+ - E_-) \sim 1$ eV

Molecules: $(E_+ - E_-) \sim 10^{-5}$ eV

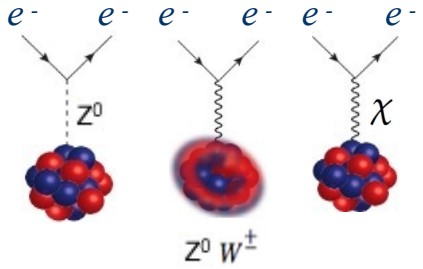
[Phys Rev Lett 120, 142501 (2018)]
[Phys. Rev. Lett. 119, 223201 (2017)]
Demille's group

$$|s'\rangle = |s\rangle + \frac{\langle s| V_{PV} |p\rangle}{E_- - E_+} |p\rangle$$
γ

- Parity and Time reversal violation $> 10^3$
- Nuclear amplification $> 10^3$
-

A single molecule in a Penning trap

$H_{PV} \sim F(Z^c) / (E_+{}^e - E_-{}^e)$

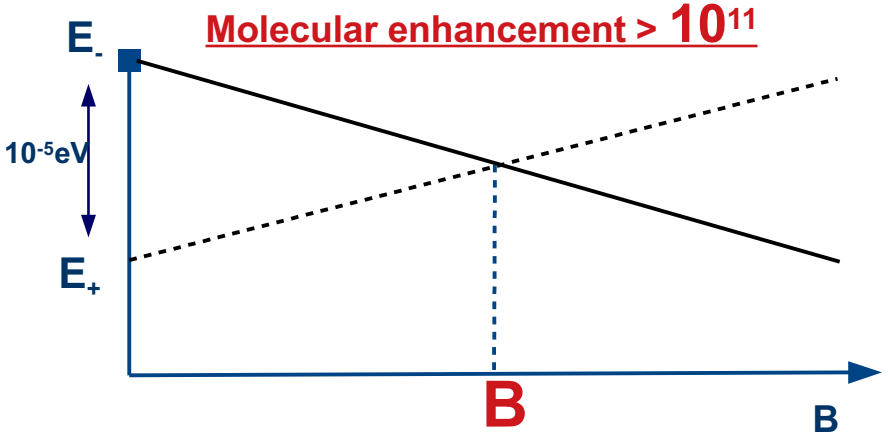


Atoms: $(E_+ - E_-) \sim 1$ eV

Molecules: $(E_+ - E_-) \sim 10^{-5}$ eV

[Phys Rev Lett 120, 142501 (2018)]
[Phys. Rev. Lett. 119, 223201 (2017)]
Demille's group

$$|s'\rangle = |s\rangle + \sum_{\gamma} \frac{\langle s| V_{PV} |p\rangle}{E_- - E_+} |p\rangle$$



Molecular enhancement > 10^{11}

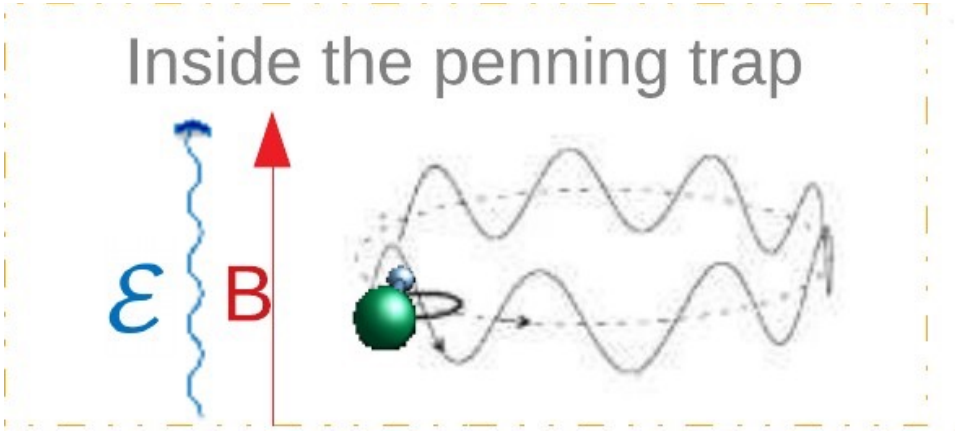
- Parity and Time reversal violation > 10^3
- Nuclear amplification > 10^3
- Parity violation > 10^{11}

A single molecule in a Penning trap

$H_{PV} \sim F(Z^c)/(E_+{}^e - E_-{}^e)$

In collaboration with K. Blaum (MPIK), D. Demille (U Chicago), J. Dilling (ORNL), G. Gwinner (Manitoba), N. Hutzler (Caltech), R. Ryngle (FRIB)

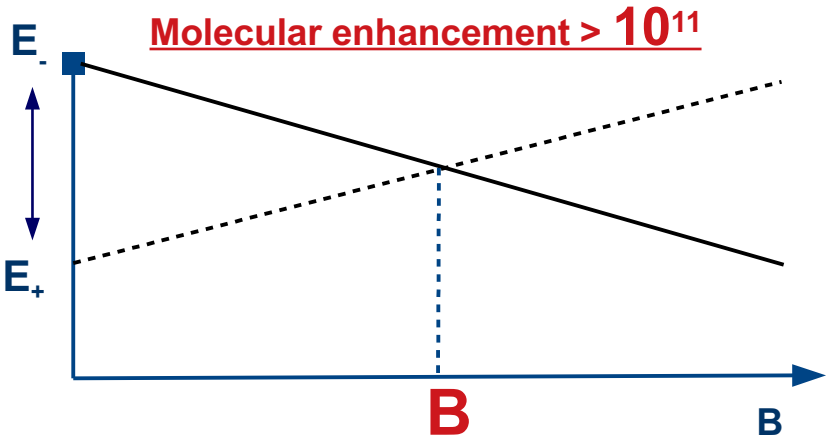
TRIUMF



J. Karthein

S. Udrescu

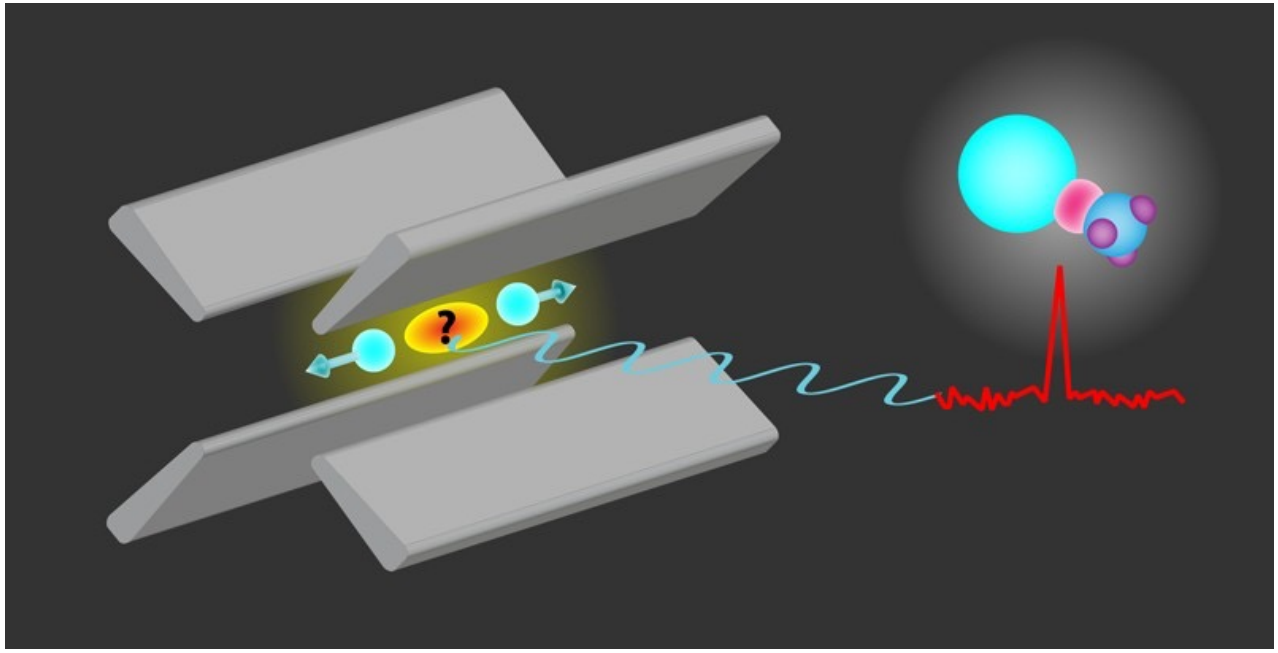
S. Moroch



- Parity and Time reversal violation $> 10^3$
- Nuclear amplification $> 10^3$
- Parity violation $> 10^{11}$

Designer Molecules for Fundamental-Symmetry Tests

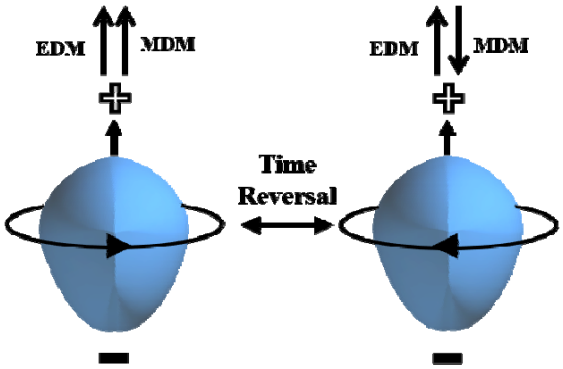
→ $RaOH^+$ and $RaOCH_3^+$ [Fan et al. Phys. Rev. Lett. 126, 023002 (2021)]
[Yu & Hutzler Phys. Rev. Lett. 126, 023003 (2021)]



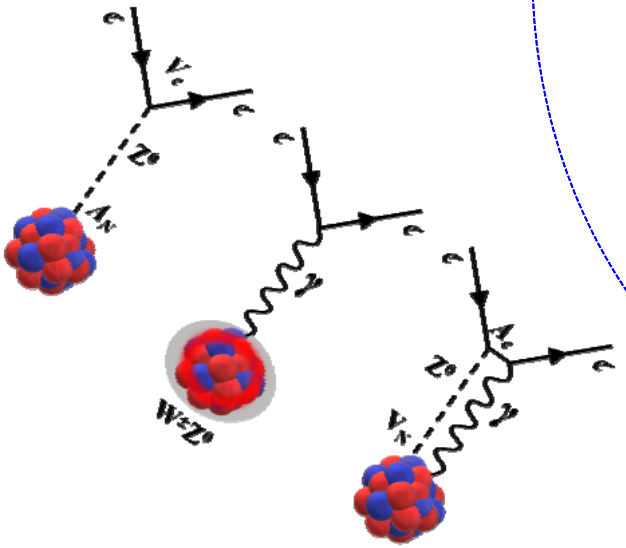
→ RaAg: Assembling molecules from cold atoms [Fleig & Demille]

Summary and Outlook

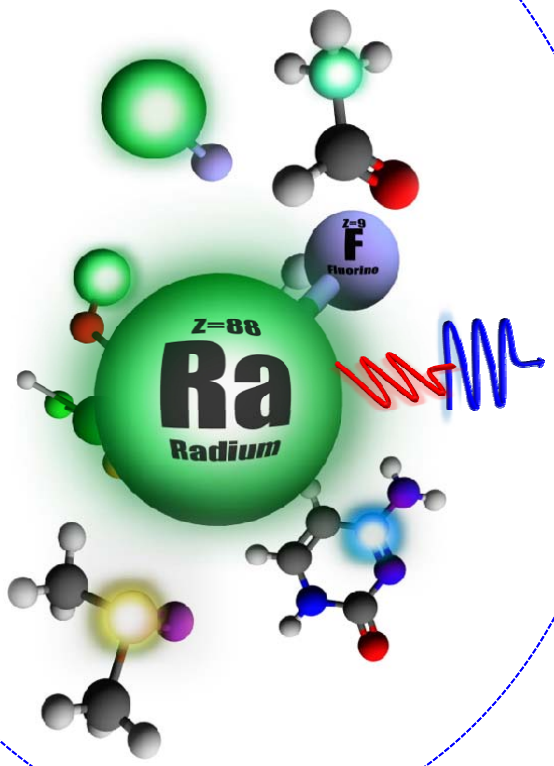
Fundamental Symmetries



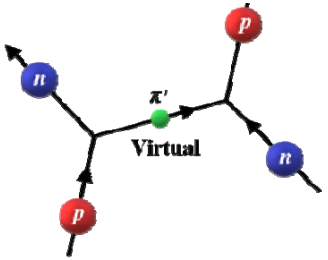
Hadronic parity violation



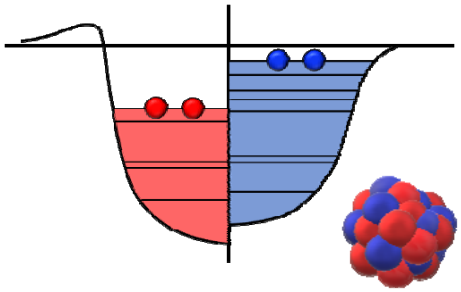
Radioactive molecules



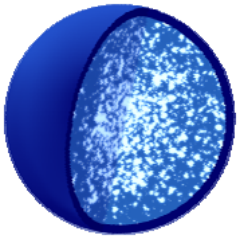
Nuclear Force



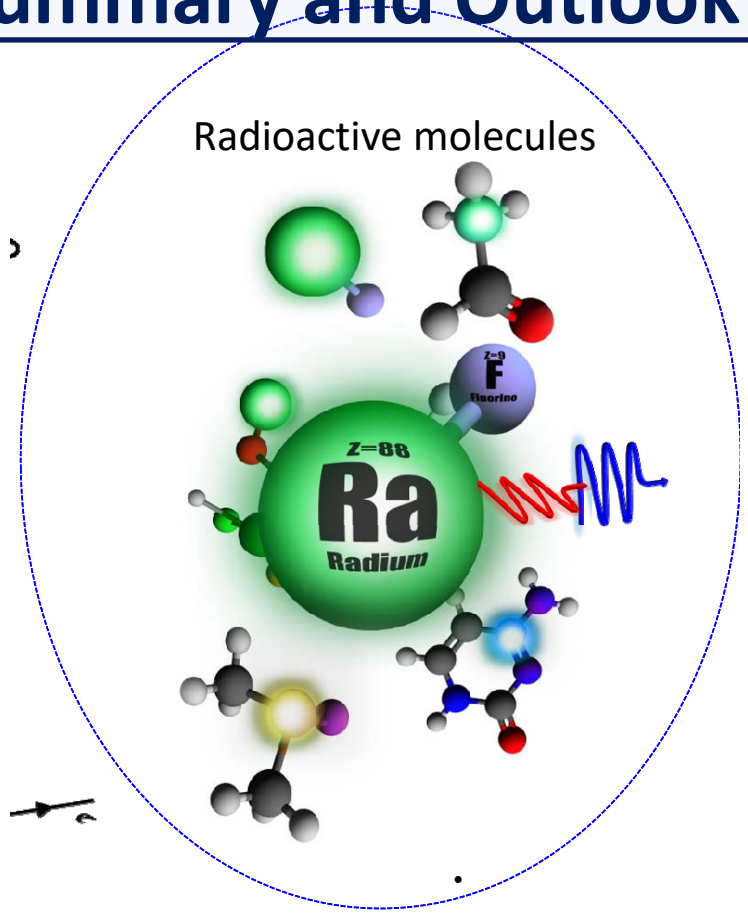
Nuclear structure



Nuclear matter

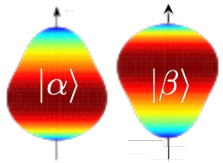


Summary and Outlook



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

^{225}Ra



Radioactive molecules => Best of all words!

Nuclear X Molecule

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