An Electron EDM Search in HfF^+:

Probing P & T-violation Beyond the Standard Model

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Experiment: Laura Sinclair, Russell Stutz & Eric Cornell

Theory: Ed Meyer & John Bohn

JILA, NIST, and University of Colorado

JILA | AMO Physics Center | NSF

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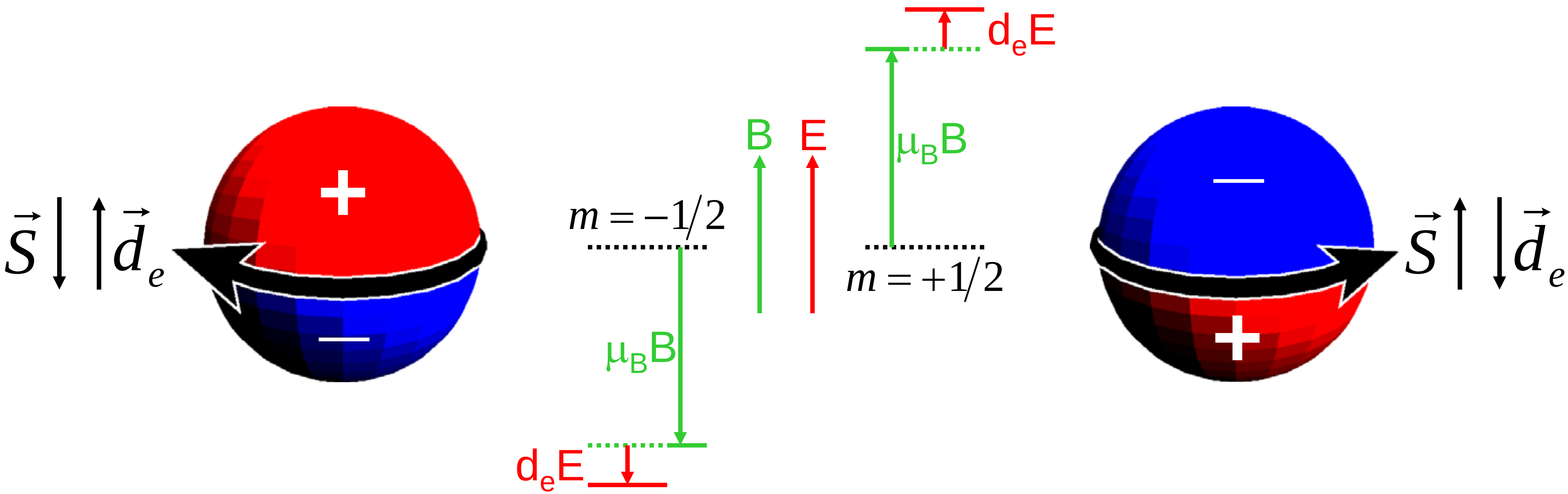
e^- EDM Search @ JILA

e^- Energy Levels

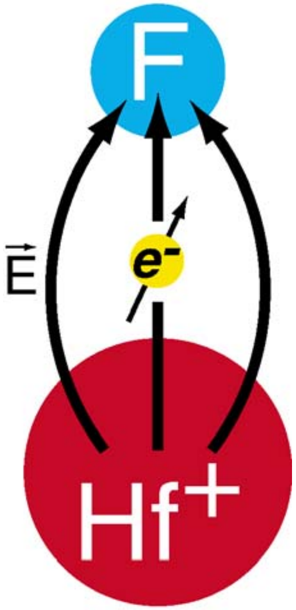
$$\underbrace{H_B \propto \vec{S}\cdot\vec{B}}_{\text{P-even,T-even}} \qquad \underbrace{H_E \propto \vec{S}\cdot\vec{E}}_{\text{P-odd,T-odd}}$$



Frequency Shift: $\Delta\omega = \dfrac{2d_e E}{\hbar}$

Frequency Resolution: $\Delta\omega = \dfrac{1}{\tau\sqrt{N}}$

Advantages of Molecules



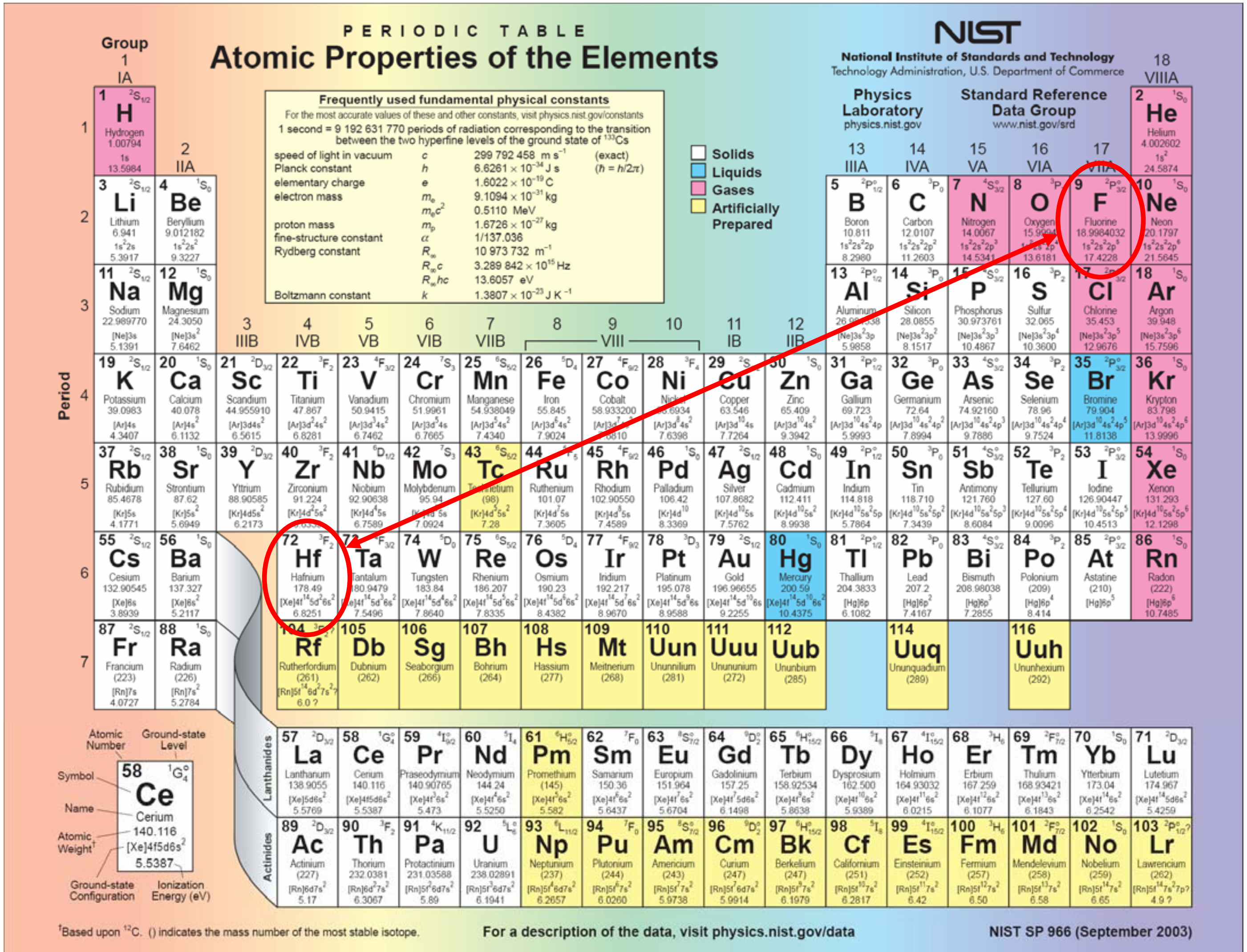
1. ***Large*** internal electric fields.
   - Effective E-field seen by e^-, E_{eff} ~ 10^{10} V/cm.
   - Compared to ***maximum*** E_{lab} ~ 10^5 V/cm.
2. ***Accessible*** internal electric fields.
   - Easy to polarize, need only E_{lab} ~ 1 V/cm.
3. Rejection of systematic errors.
   - Magnetic field ***insensitive*** transitions.
   - E_{eff} ***independent*** of E_{lab}.

Advantages of Ions

1. ***Easy*** to trap.
2. ***Long*** spin coherence times.

Molecular Ion of Choice: HfF^+

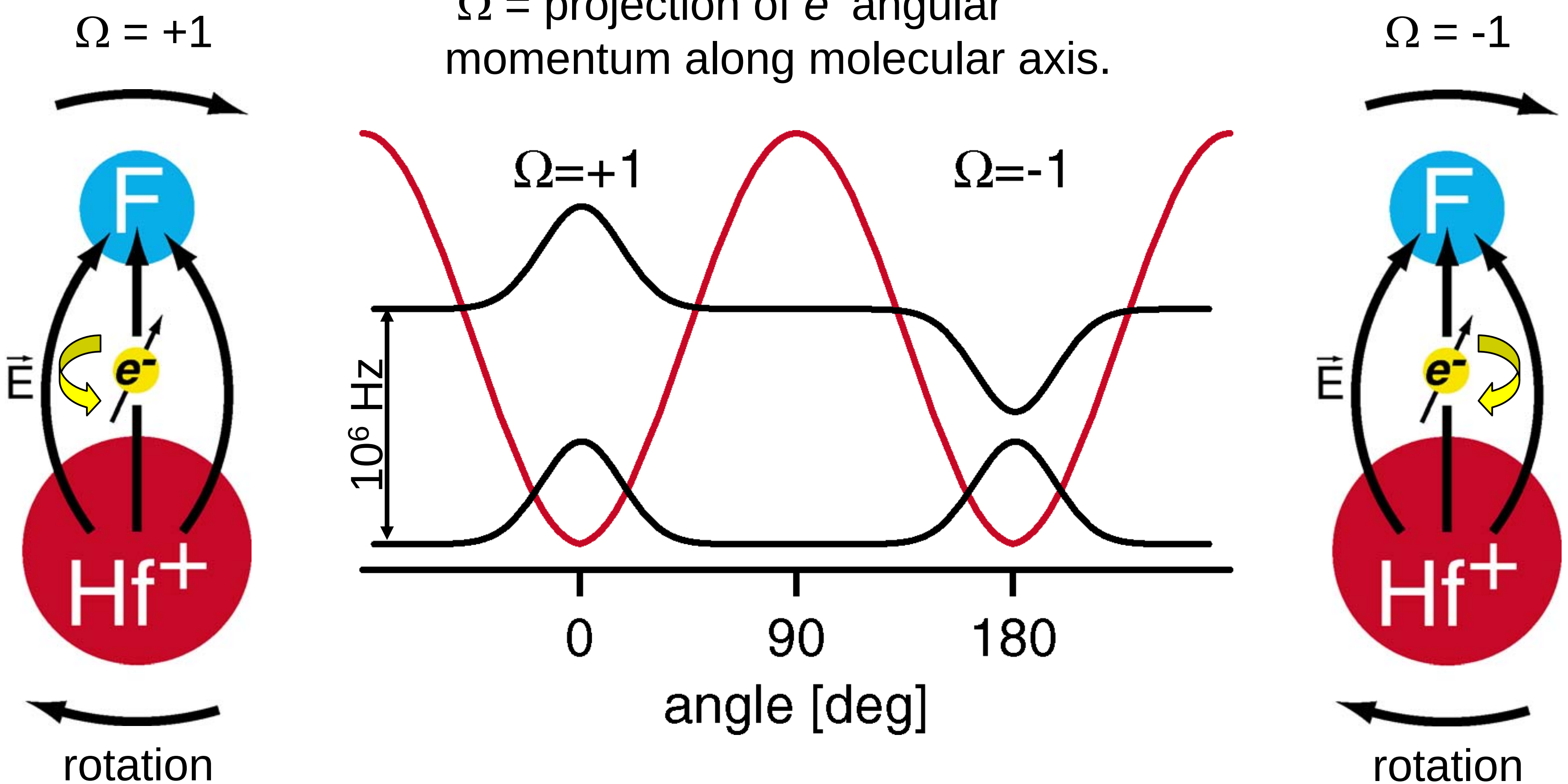
HfF^+ Theory {
- Meyer *et. al.*, PRA **73**, 062108 (2006).
- Petrov *et. al.*, arXiv:physics/0611254 (2006).



Polar Molecules

- Molecules do ***not*** have permanent electric dipole moments.
- Molecules do have closely spaced levels of opposite parity.
  - Ω-doubling ~10^6 Hz vs. s/p splitting ~10^{14} Hz in atoms.

Ω = projection of e^- angular momentum along molecular axis.



HfF^+ in the $^3\Delta_1$ State

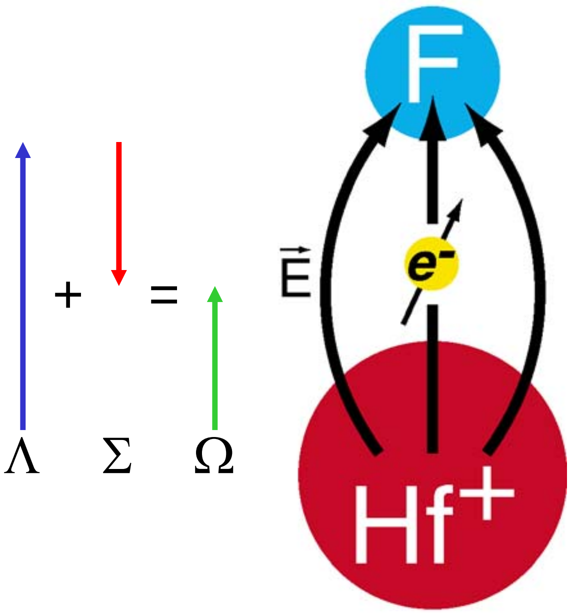
- Net e^- spin: $|\Sigma|=1$
- Small magnetic moment: $\mu_m \ll \mu_B$
- Hf nucleus: I=0 & I=1/2 isotopes

$^3\Delta_1$

spin: $\Sigma = \pm 1$

orbital: $\Lambda = \pm 2$

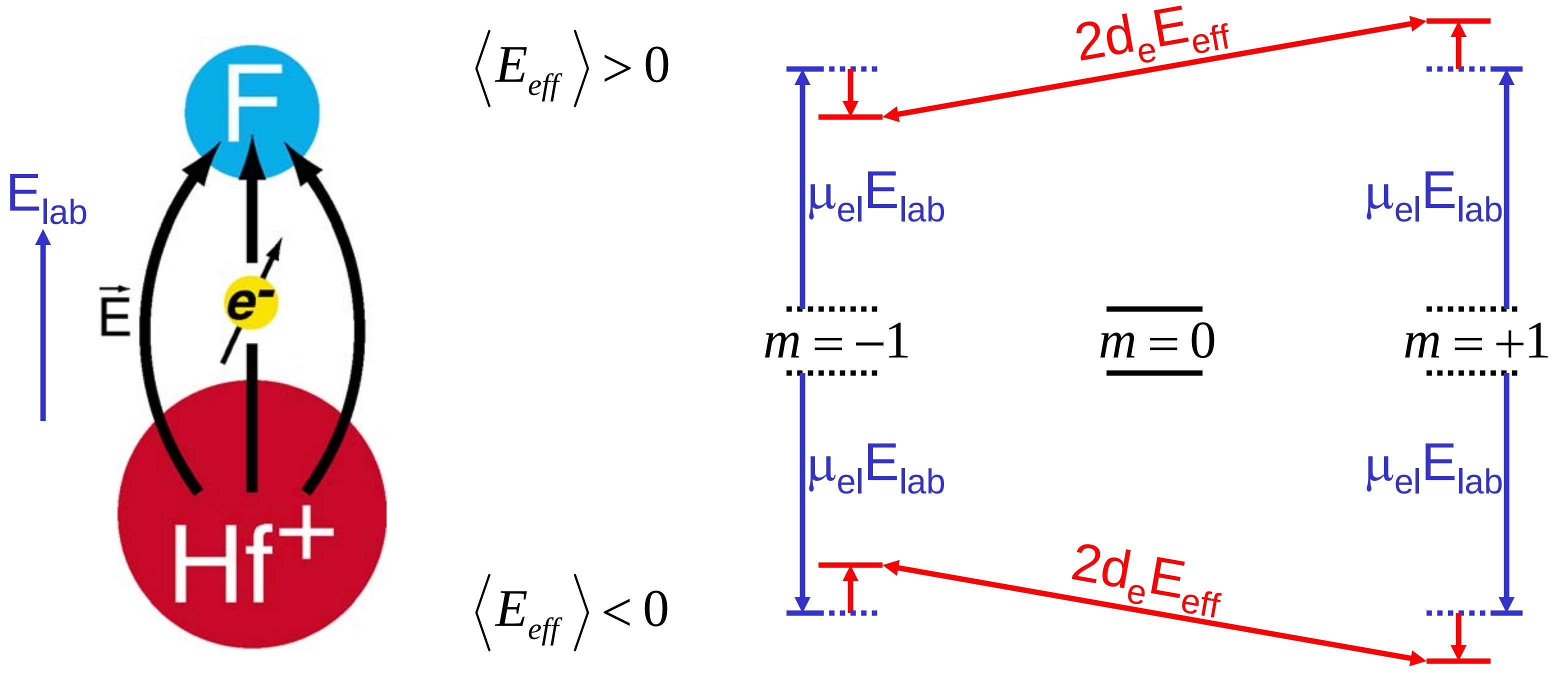
spin + orbital: $\Omega = \Lambda + \Sigma = \pm 1$



Ω-doublet splitting ↕ $m=-1$ $m=0$ $m=+1$

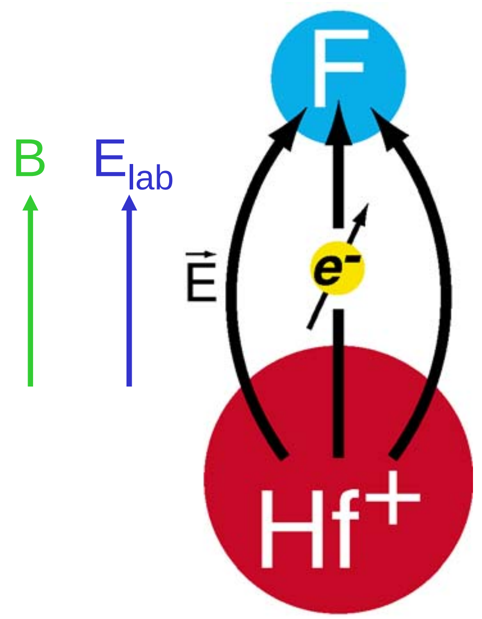
Intramolecular Electric Fields

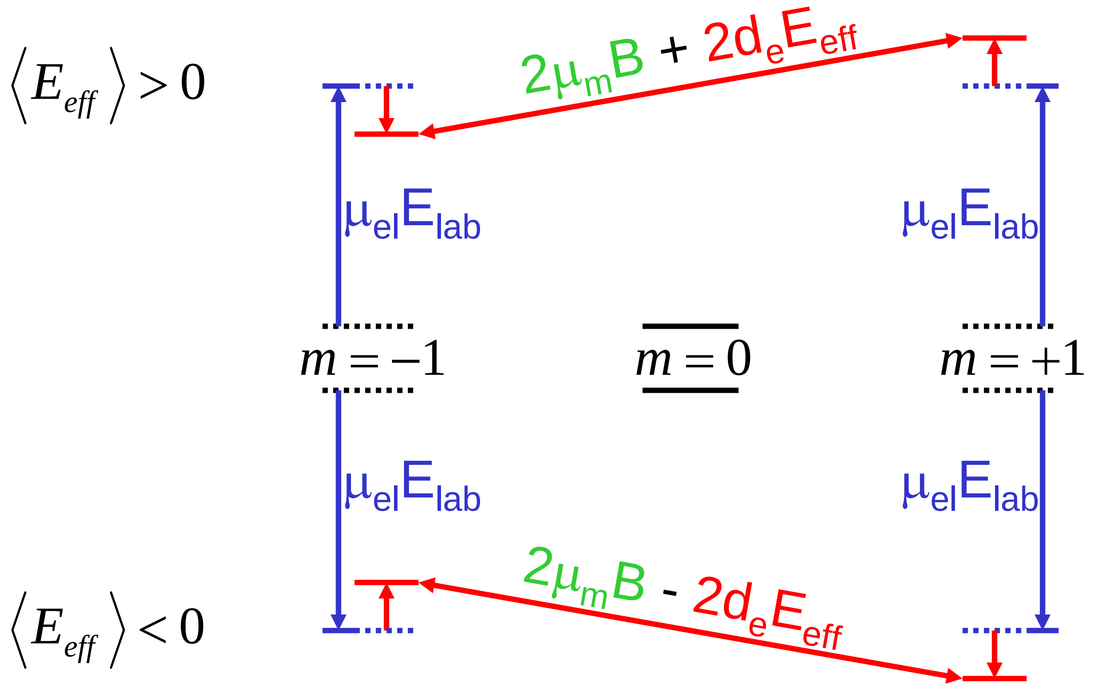
- E_{lab} mixes states of opposite parity inducing a net molecular dipole moment in the lab frame.
- Sign of E_{eff} is set by sign of induced molecular dipole moment.



Systematic Checks

- Measure frequency splitting in both Ω-doublet levels.
  - Zeeman shift is ***common mode***.
- Vary magnitude of E_{lab}.
  - Linear Stark shift implies fully mixed states of opposite parity and E_{eff} nominally ***independent*** of E_{lab}.

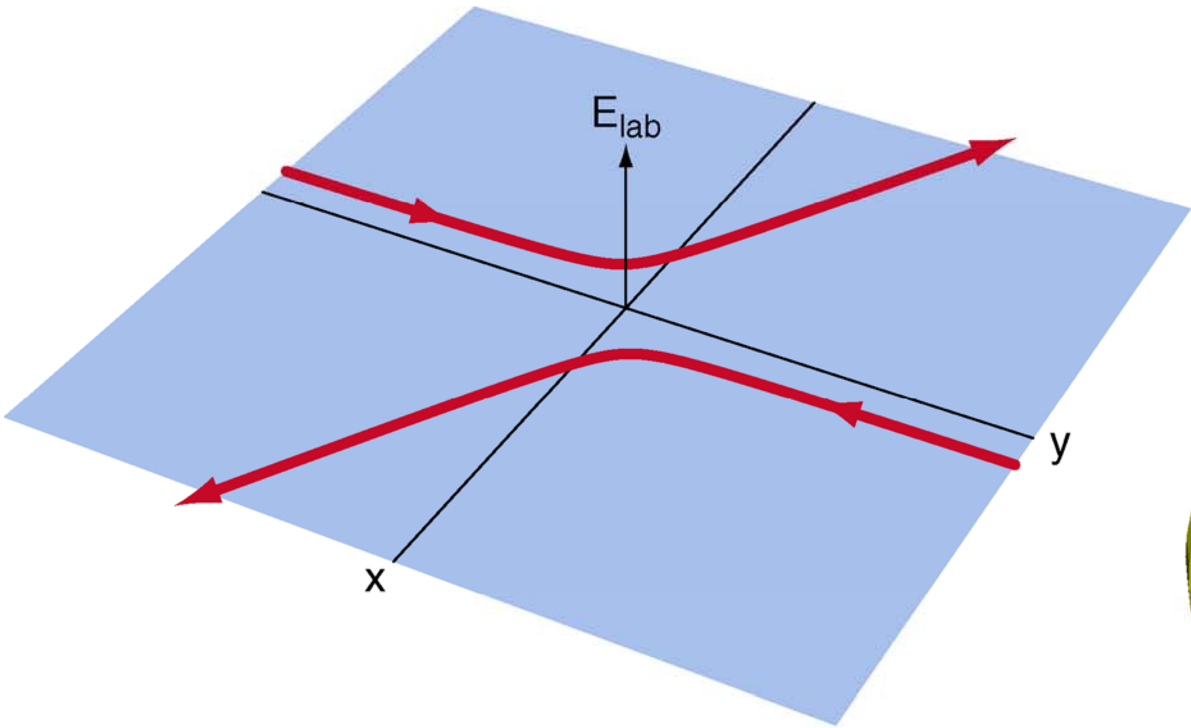


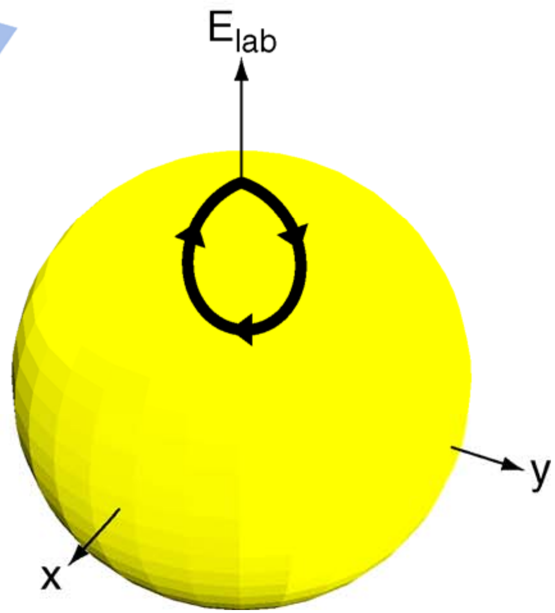


Ion-Ion Collisions & Decoherence

- Electric field between two ions during a collision tips the quantization axis and generates a geometric phase shift.
- Sets limits on ion number, N~100, and interrogation time, τ~1s.

$$\Delta\varphi \propto \Omega \propto T^4$$

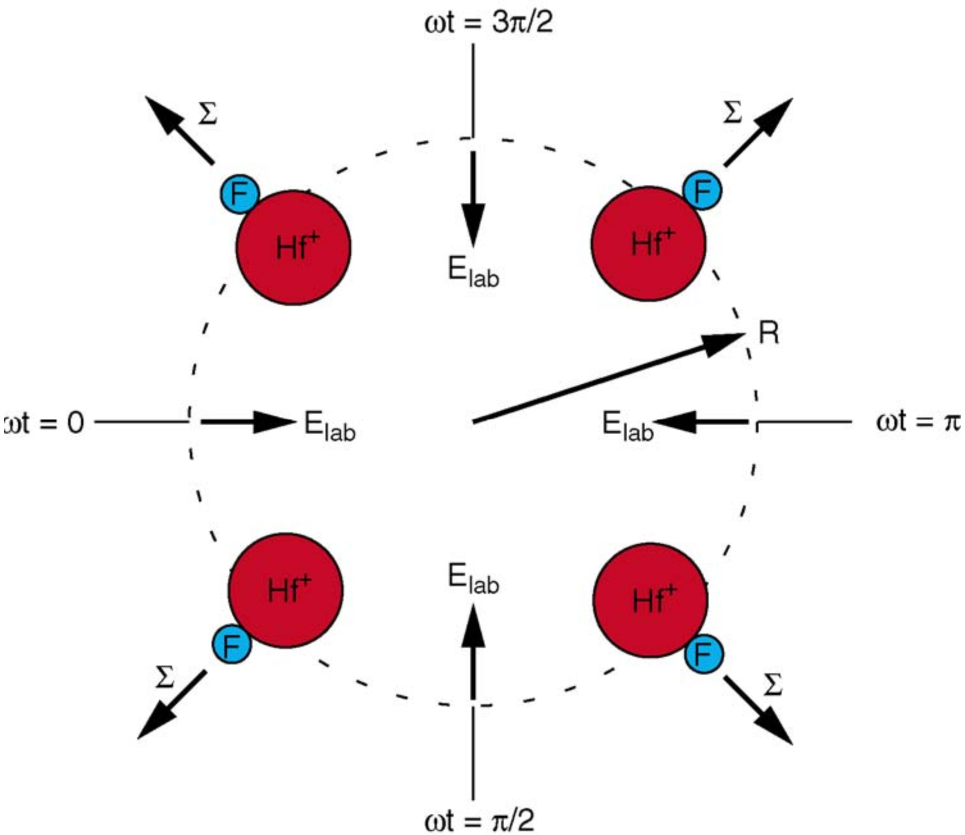


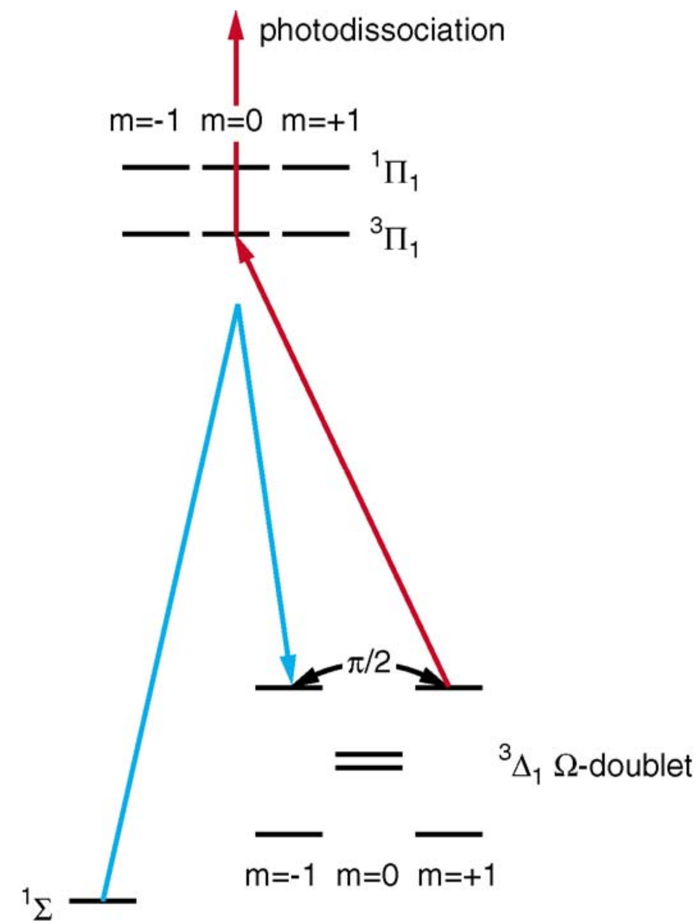


Envisioned Experimental Sequence

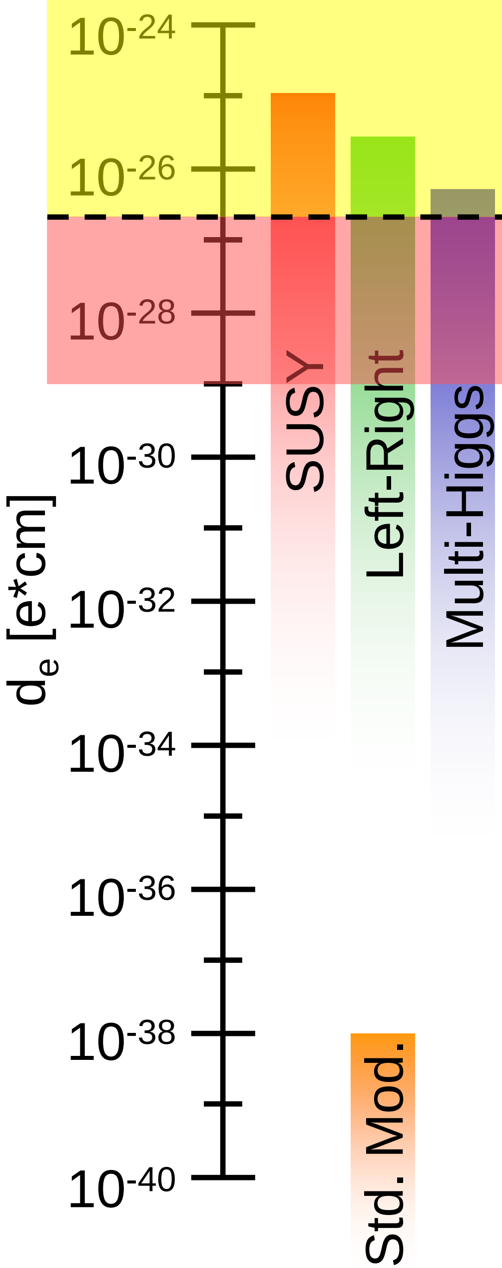
1. Apply rotating E_{lab}.
2. Raman π pulse.
3. Ramsey $\pi/2$ pulse.
4. Coherent evolution.
5. Ramsey $\pi/2$ pulse.
6. Raman π pulse.
7. Photodissociation: $HfF^+ \rightarrow Hf^+ + F$.
8. Separately detect Hf^+ and HfF^+.

$$\vec{E}_{lab}(t) \propto E_{lab}\left[\cos(\omega t)\hat{x} + \sin(\omega t)\hat{y}\right]$$





e^- EDM Sensitivity Estimate



$|d_e| < 1.6 \times 10^{-27}$ e*cm [~10^{-18} Debye]
E.D. Commins Tl Exp. Limit [PRL **88**, 071805 (2002)]

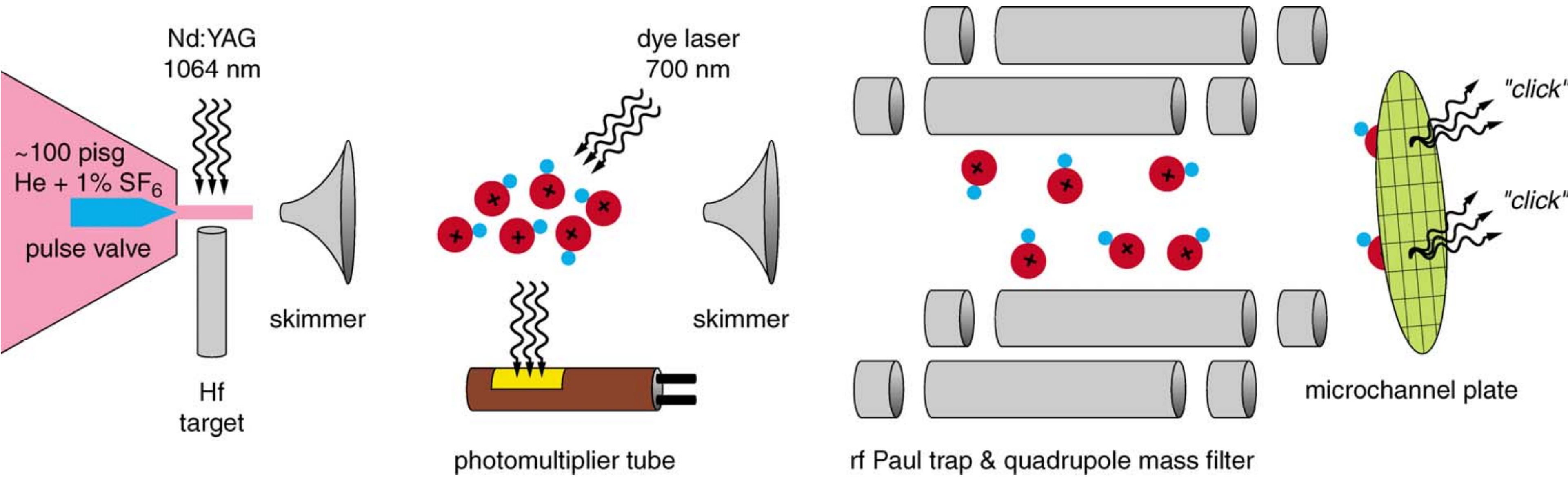
$|d_e| < 10^{-29}$ e*cm / day$^{1/2}$

$$\left|d_e\right| < \frac{\hbar}{2E_{eff}\tau\sqrt{N}}$$

Projected sensitivity: $|d_e| < 10^{-29}$ e*cm / day$^{1/2}$
- Theoretical calculations: $E_{eff} \sim 2 \times 10^{10}$ V/cm
- Expected spin coherence time: $\tau \sim 1$ second
- Expected counting statistics: $N \sim 3 \times 10^6$ ions / day

Systematic Checks
- Change Ω-doublet levels.
- Vary E_{lab} while E_{eff} remains constant.

Experimental Setup



Laser Ablation in a Supersonic Jet

- Create HfF^+.
- Cool rotational, vibrational, and translational motion.

Fluorescence Spectroscopy

- Measure rotational temperature of neutral HfF molecular beam.

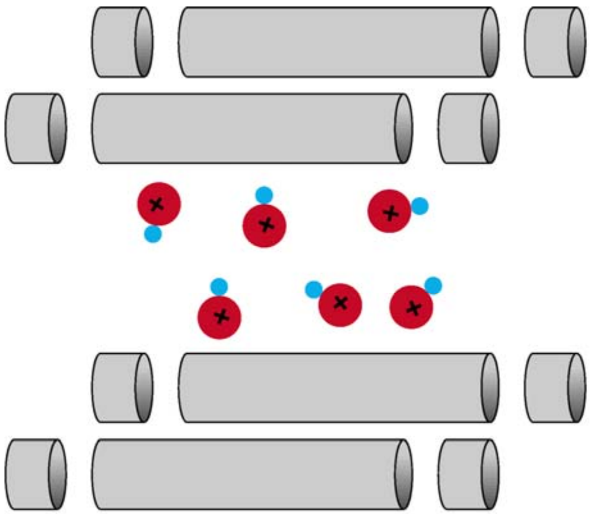
Mass Spectrometry

- Trap Hf^+, HfF^+, HfF_2^+, and HfF_3^+.

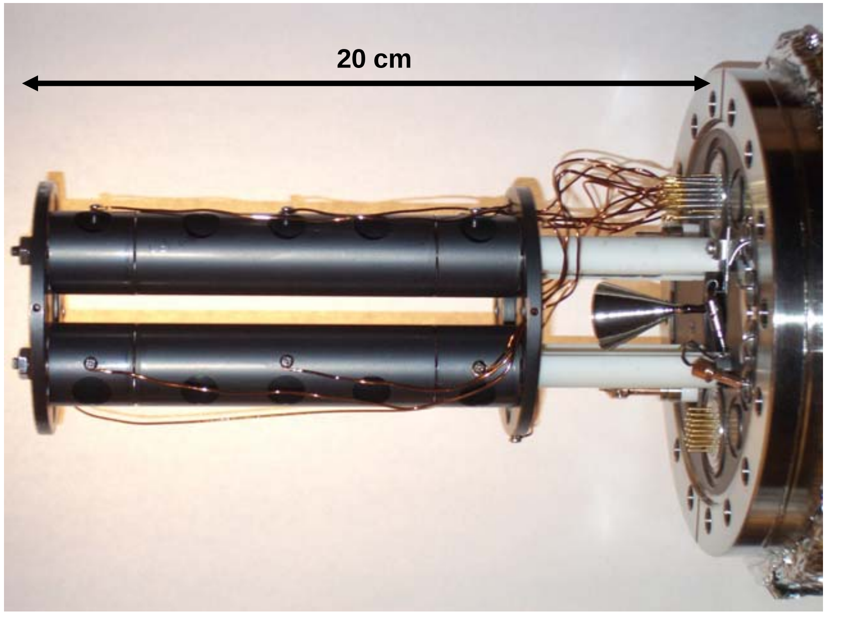
Ion Beam Imaging

- Measure translational temperature of ion beam.

Mass Spectrometry

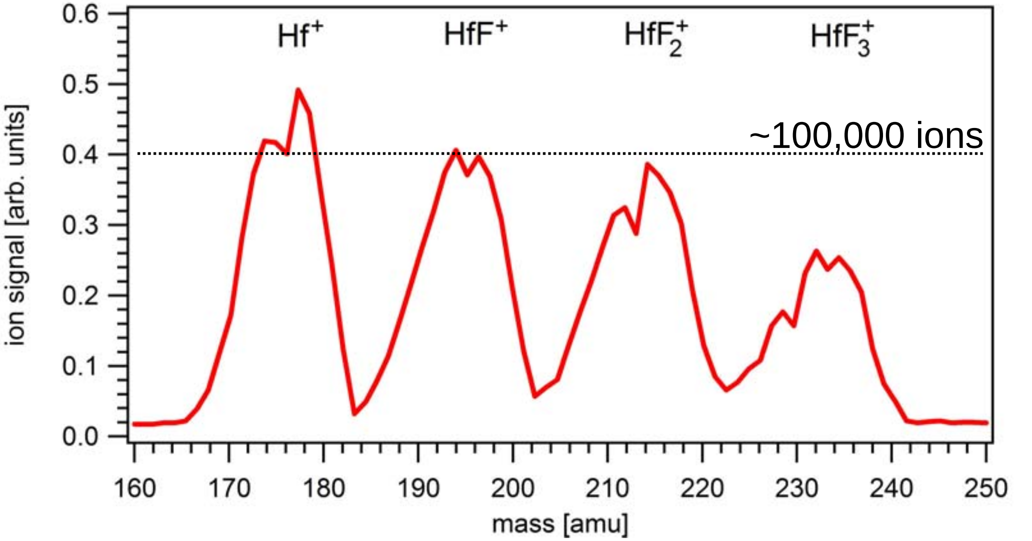


rf Paul trap & quadrupole mass filter

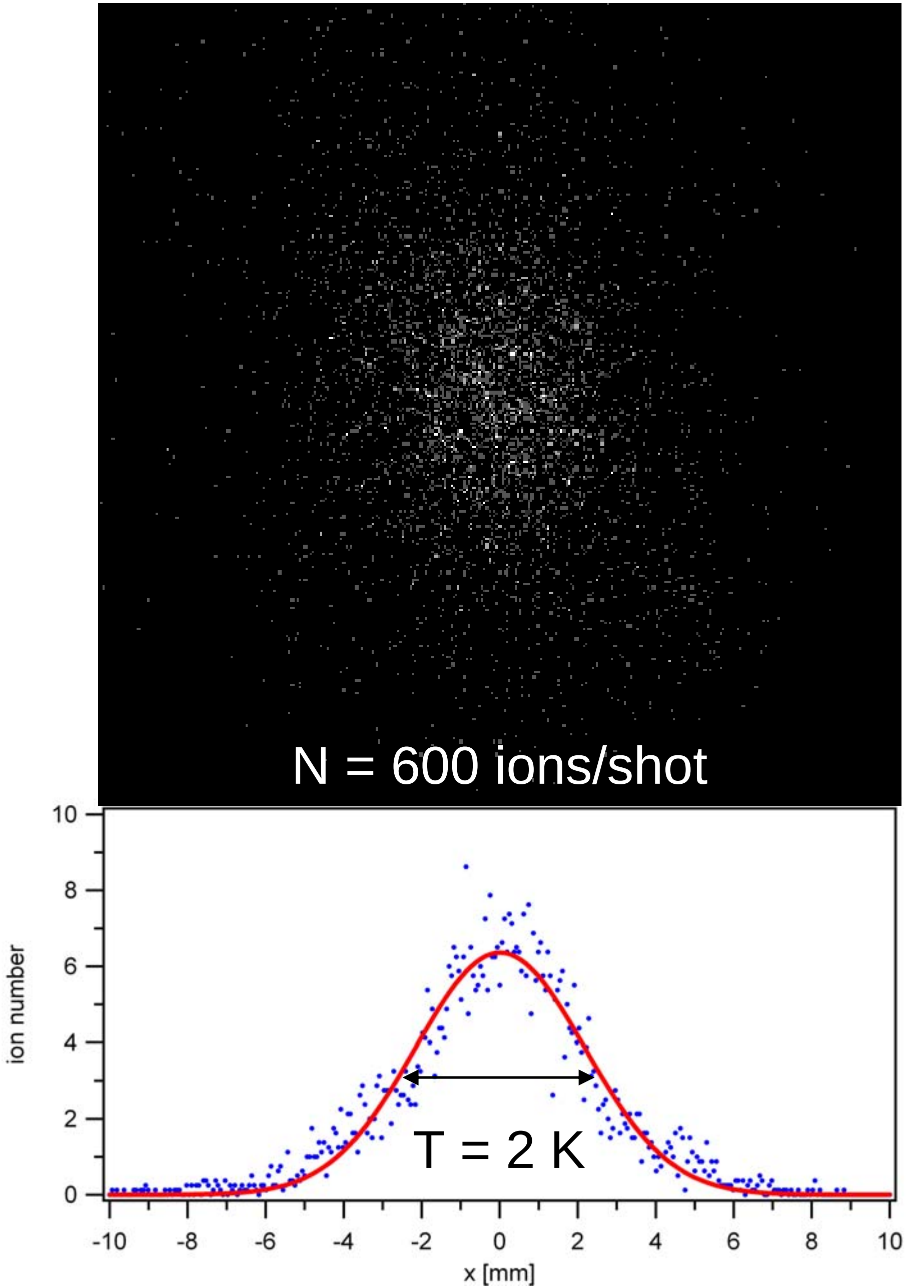


Exothermic Chemical Reactions

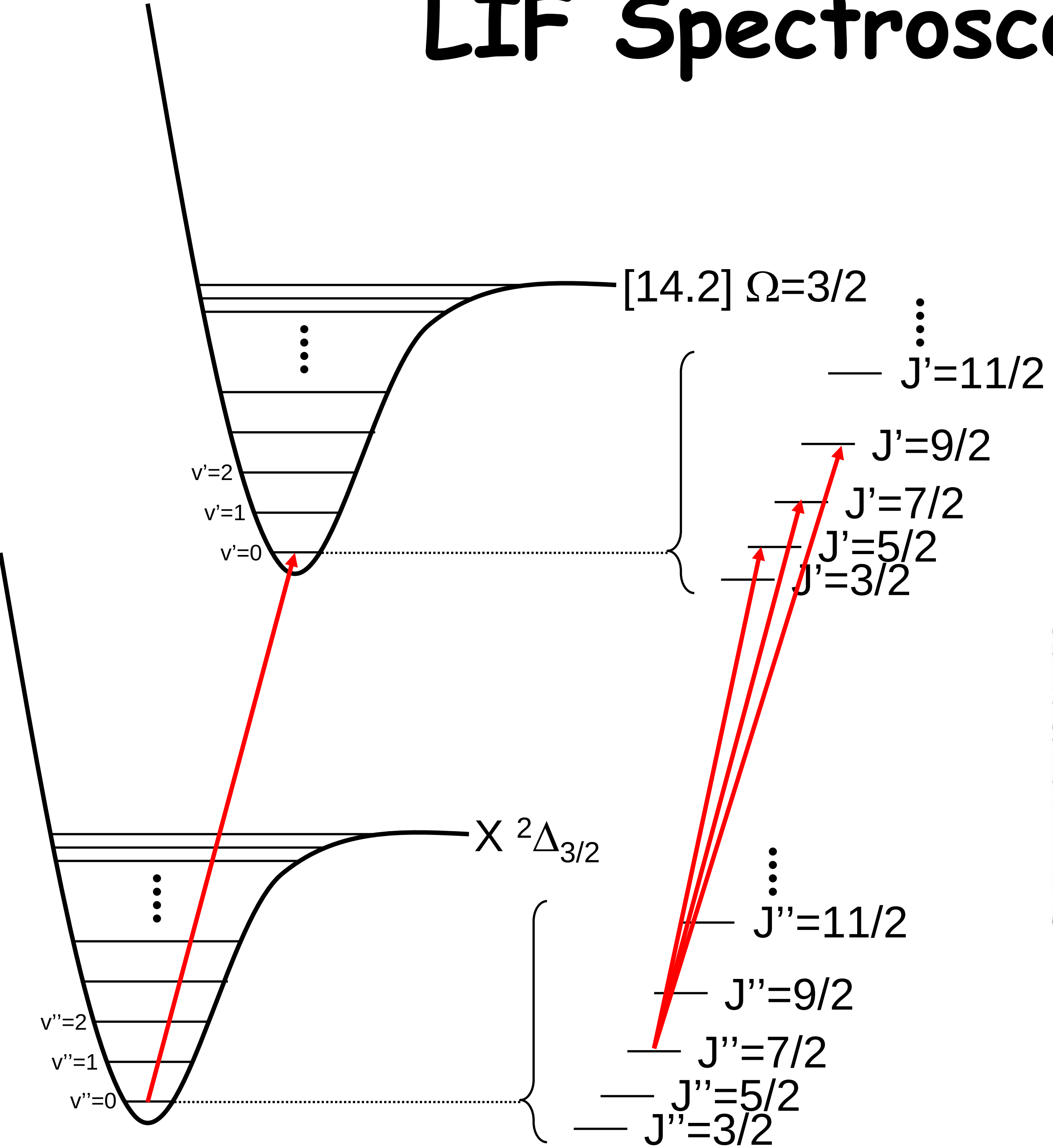
$$Hf^+ + SF_6 \rightarrow HfF^+ + SF_5$$
$$Hf^+ + SF_6 \rightarrow HfF_2^+ + SF_4$$
$$Hf^+ + SF_6 \rightarrow HfF_3^+ + SF_3$$



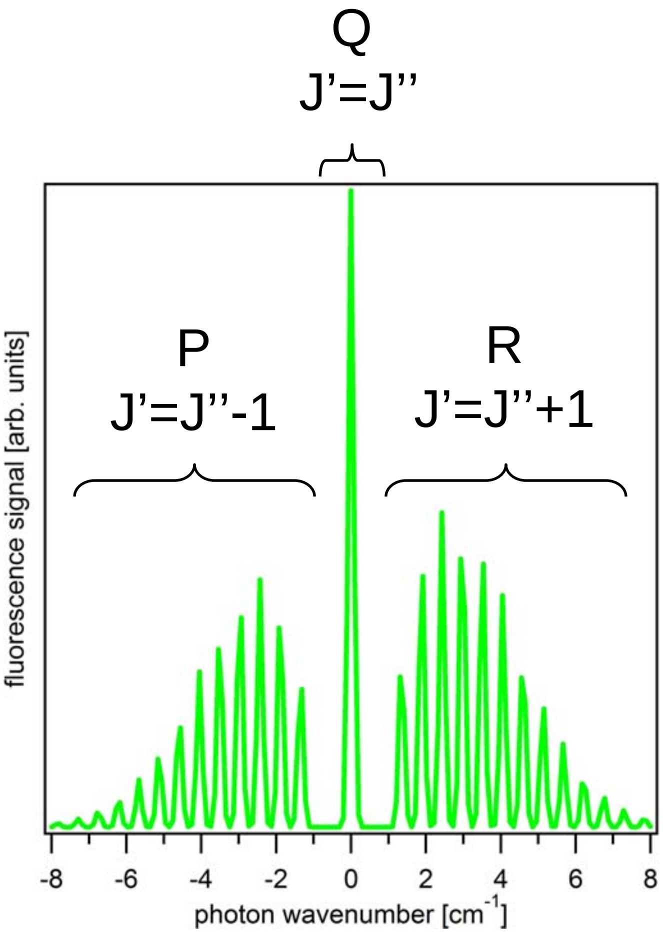
Ion Beam Imaging



LIF Spectroscopy



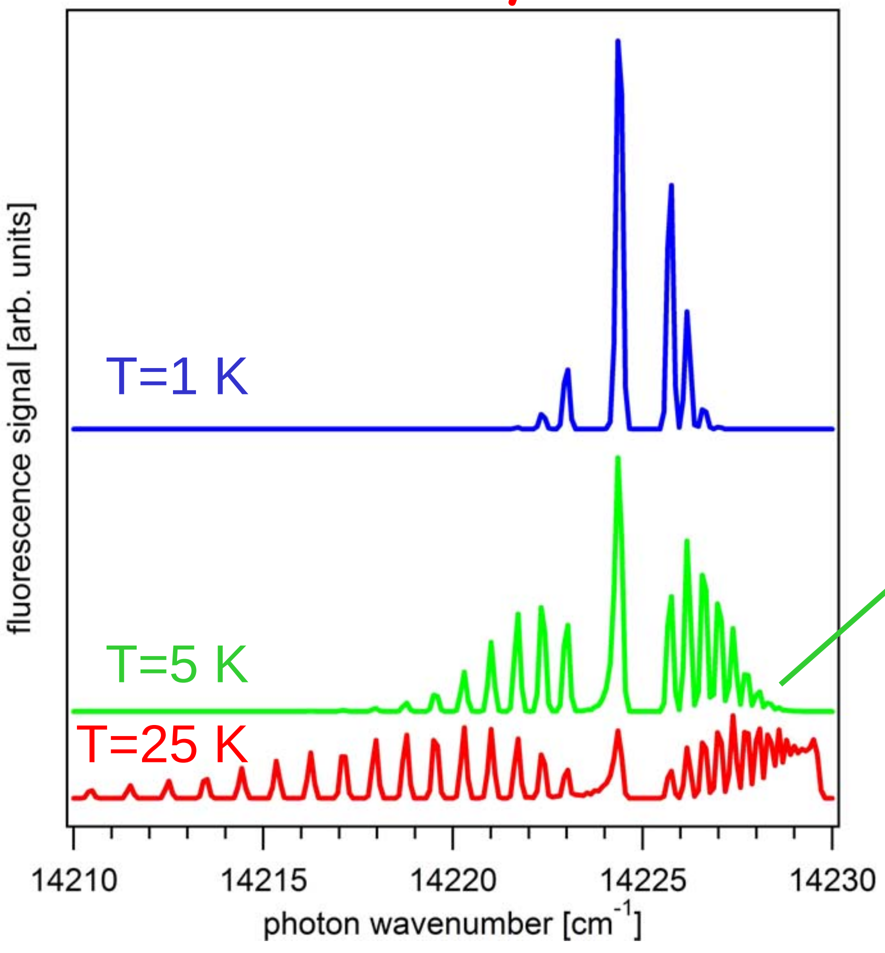
- 3 transitions per J level.
- Count lines to measure rotational temperature.



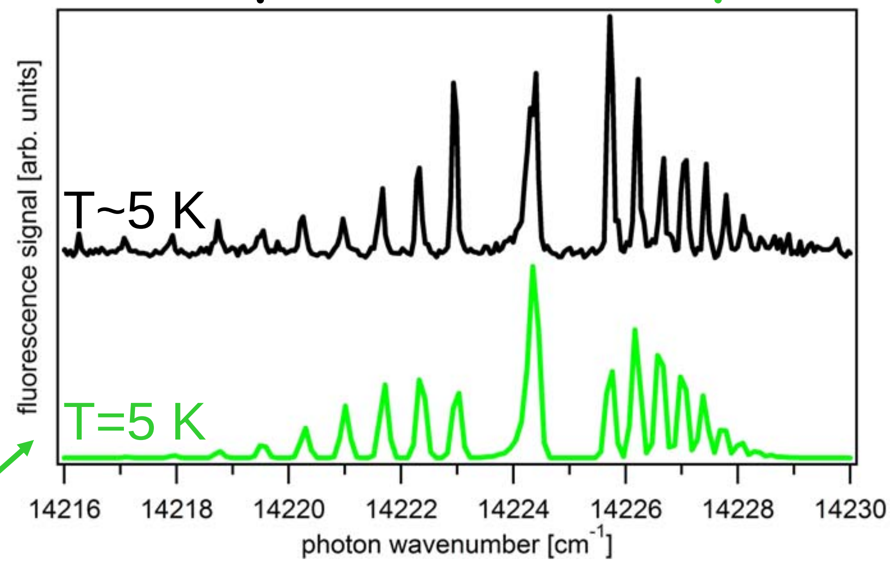
New Neutral HfF Spectroscopy

[14.2] $\Omega=3/2 \leftarrow X\ ^2\Delta_{3/2}$ $(0\leftarrow0)$

Theory



Experiment & Theory

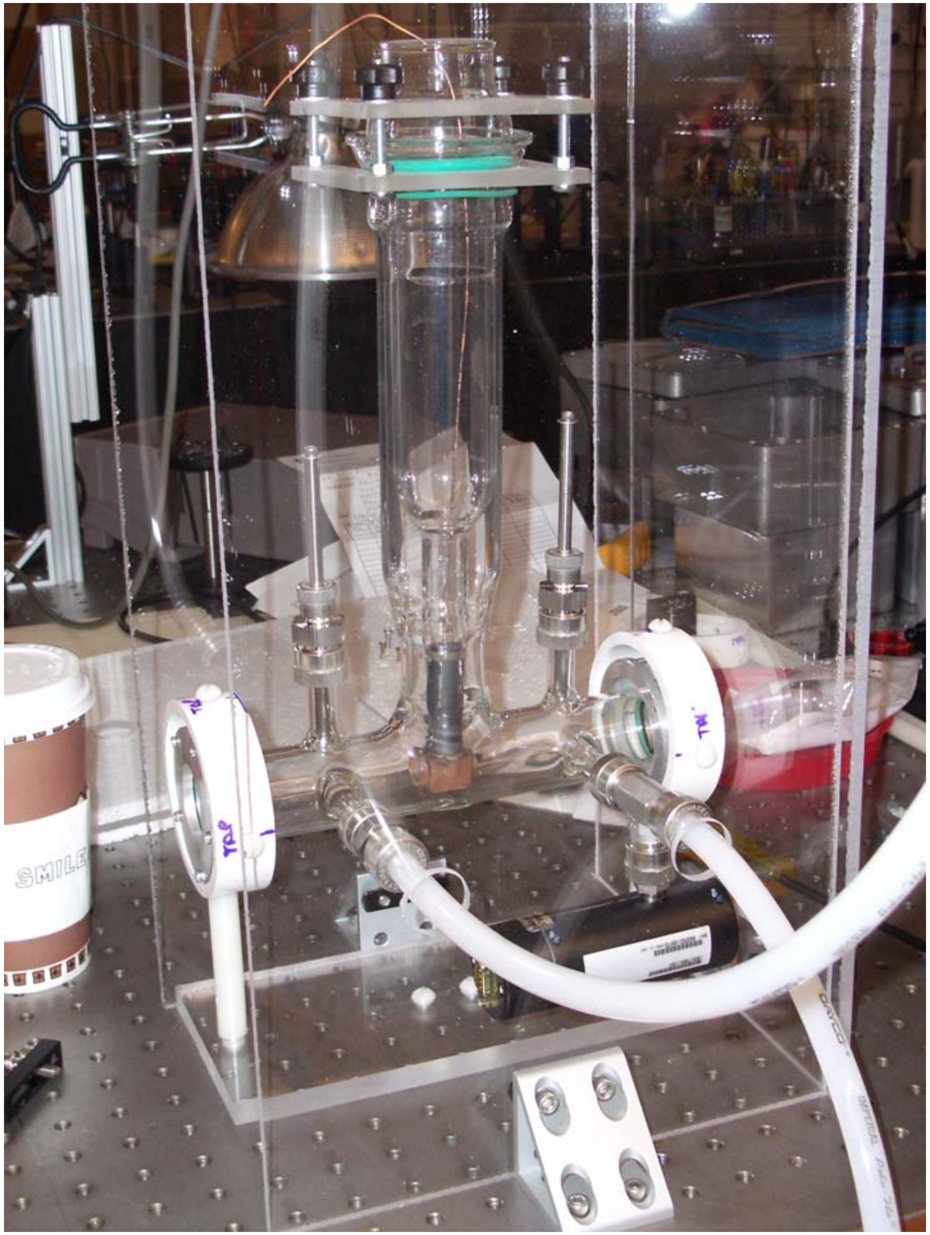


Difference in rotation constants gives chirp in line spacing.

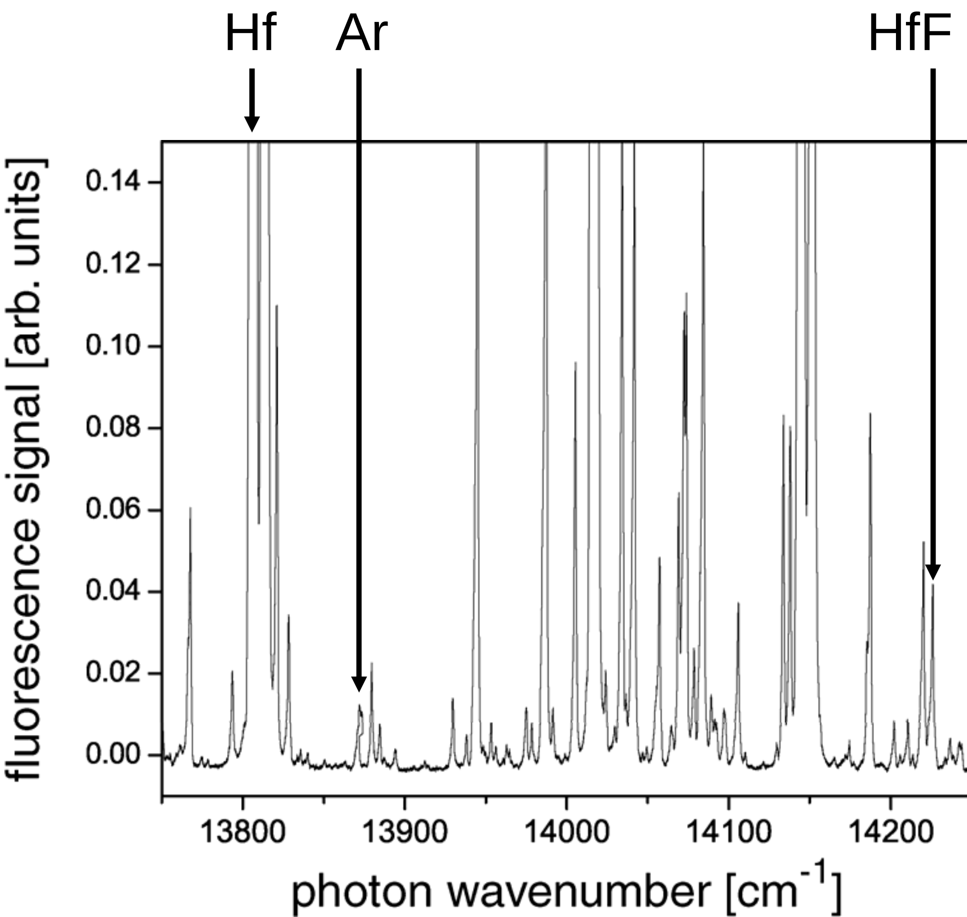
- $B'' = 0.2805\ cm^{-1}$
- $B' = 0.2660\ cm^{-1}$

See also: J. Mol. Spect. **225**, 1 (2004).

Traditional Discharge Spectroscopy

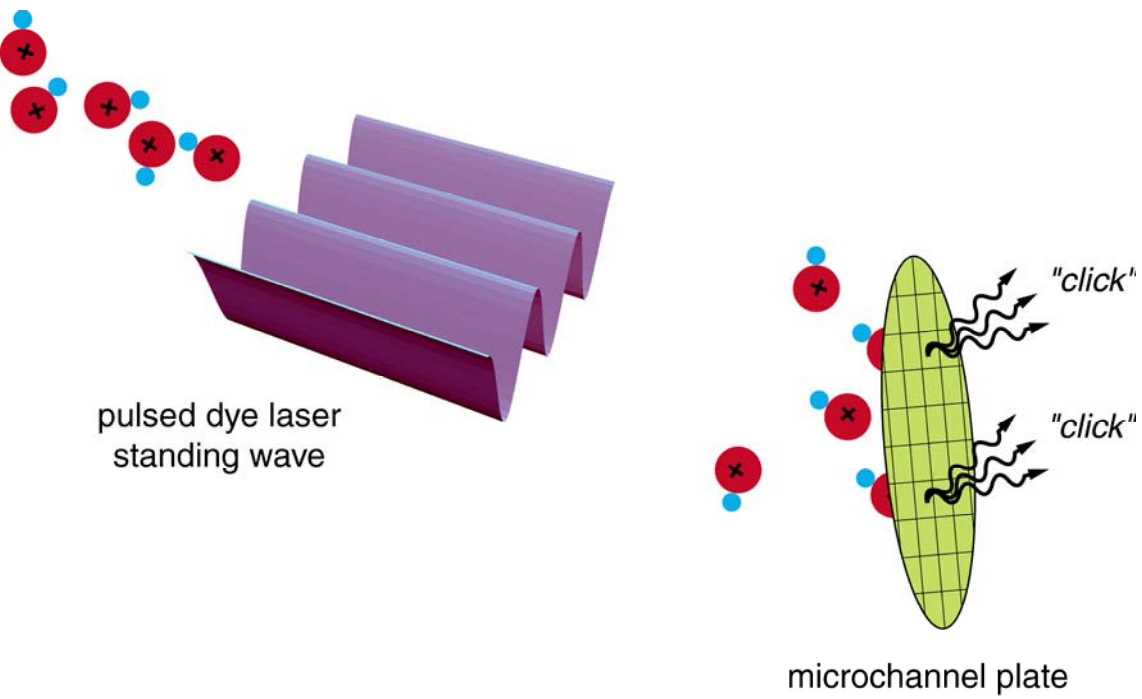


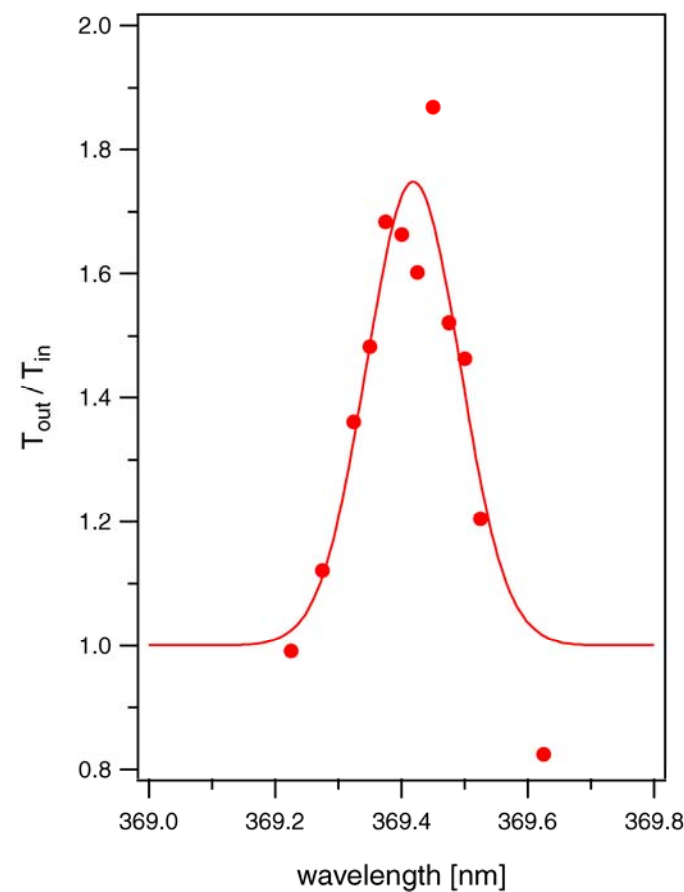
- Neutral and ionic atomic lines.
- Neutral moleclar lines.
- Unassigned lines well above noise.



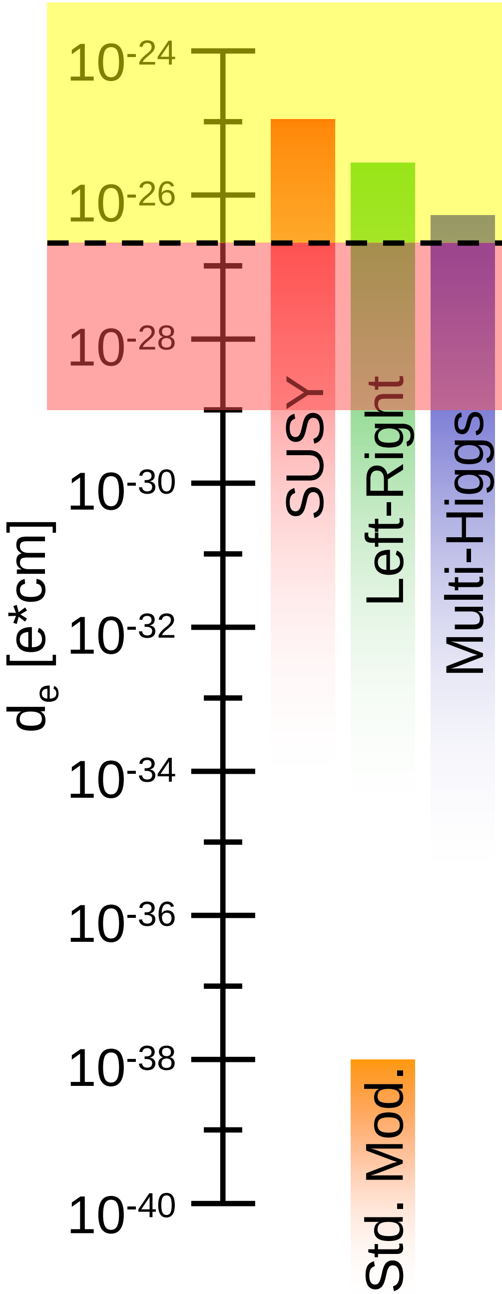
Novel Ion-Sensitive Spectroscopy

- ***Near resonance***, optical potential from pulsed standing wave has:
  - ~10 K depth.
  - ~300 GHz power broadened linewidth.
- Microchannel plate only detects ions.
- Test idea on known Yb^{+} transition at 370 nm.





e^- EDM Search Outlook



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- Created & trapped HfF^+ molecular ions.
- Characterized temperature of supersonic beam.

- Projected sensitivity: $|d_e| < 10^{-29}$ e*cm / day$^{1/2}$
  - Theoretical calculations: $E_{eff} \sim 2 \times 10^{10}$ V/cm
  - Expected spin coherence time: $\tau \sim 1$ second
  - Expected counting statistics: $N \sim 3 \times 10^6$ ions / day

- Currently searching for HfF^+ electronic transitions…
- Next, begin measuring spin coherence times…

e⁻ EDM Search @ JILA

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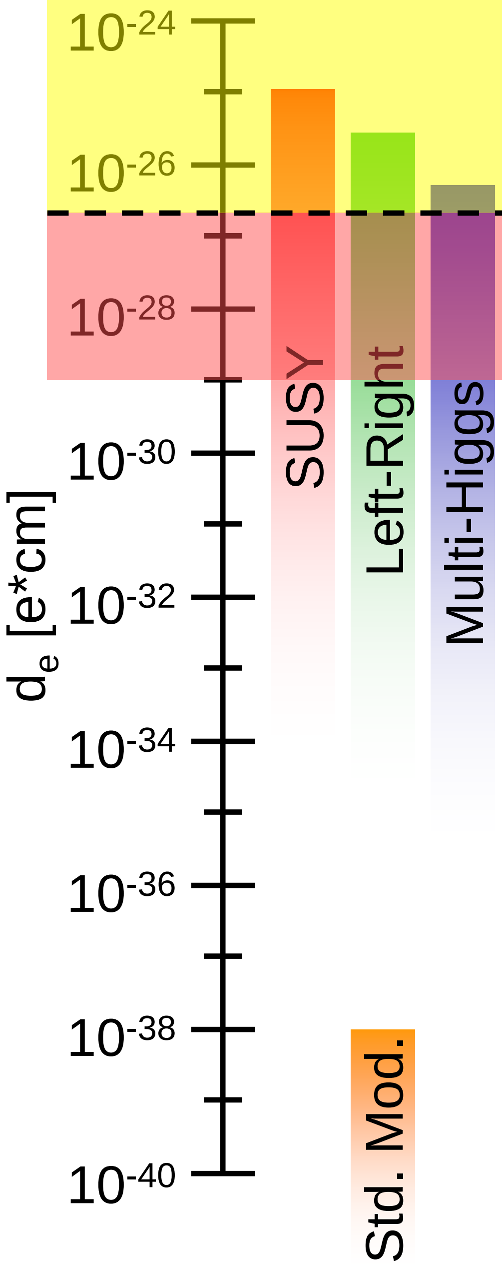

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