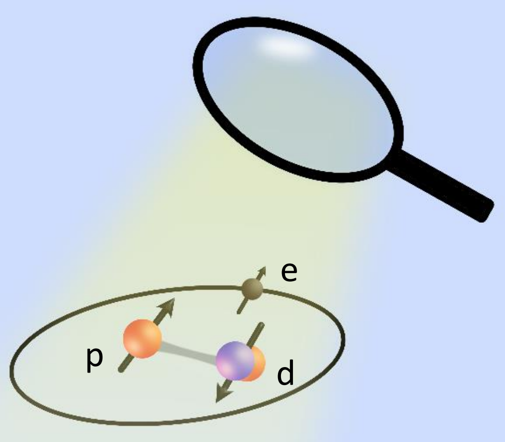
Max-Planck-Institut
für Kernphysik
Heidelberg

Precision Spectroscopy Single HD^+ Ions in a Penning Trap

Matthew Bohman

α TRAP

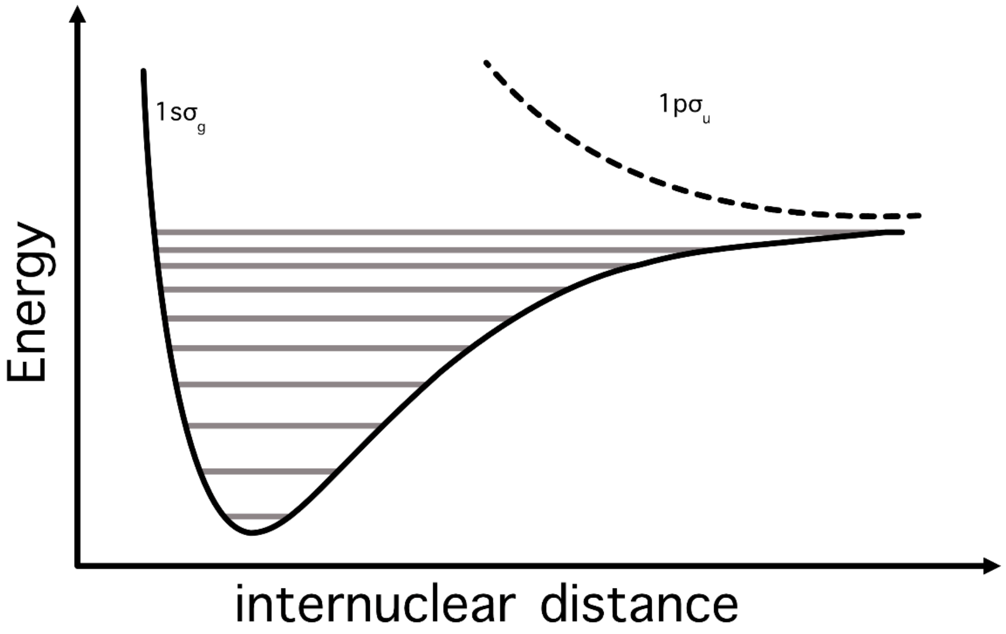
The Simplest Molecules



Simple molecules let us investigate the properties of fundamental particles and how they interact

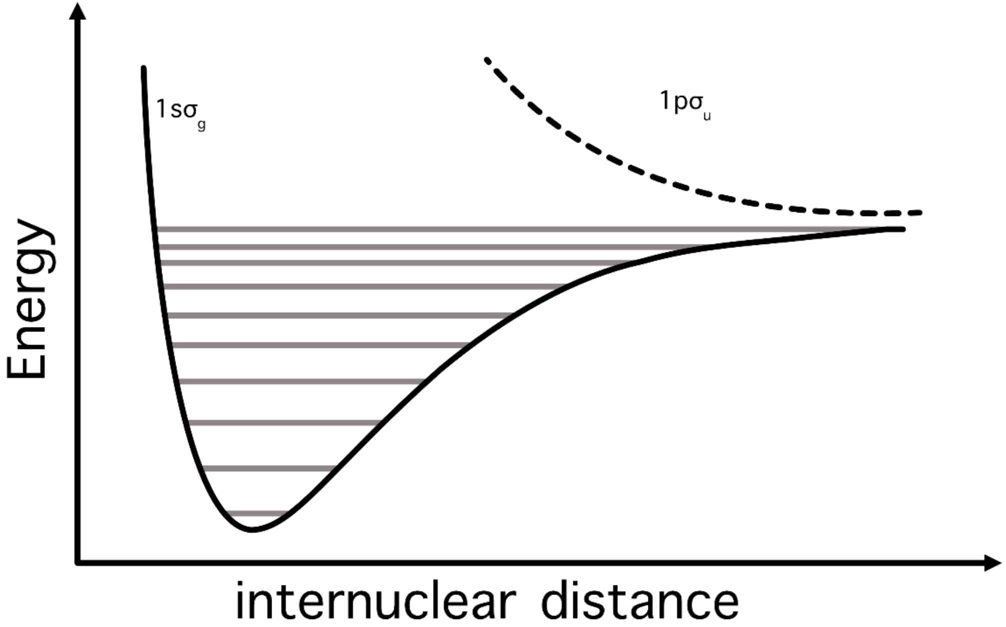
- Highly calculable with bound state quantum electrodynamics (QED)
- Determination of fundamental constants
- High precision tests of the Standard Model

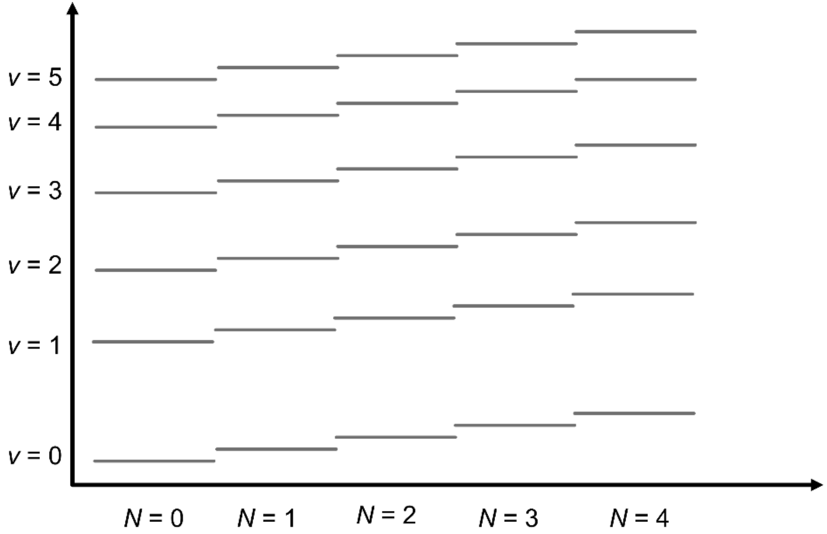
Diatomic MHI Observables



- Single, bound electronic energy level
- Hundreds of unique rotational, vibrational energy levels
- Each level has unique hyperfine structure (HFS)

Diatomic MHI Observables





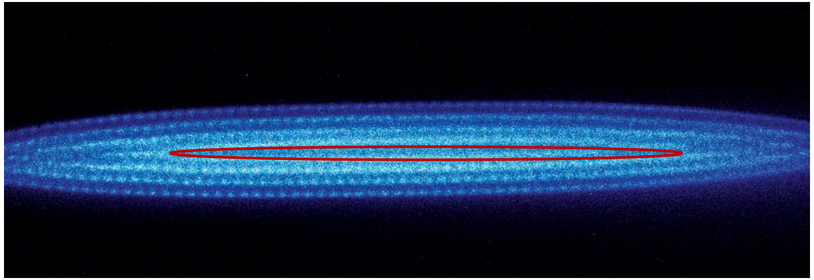
Status of MHI Experiments

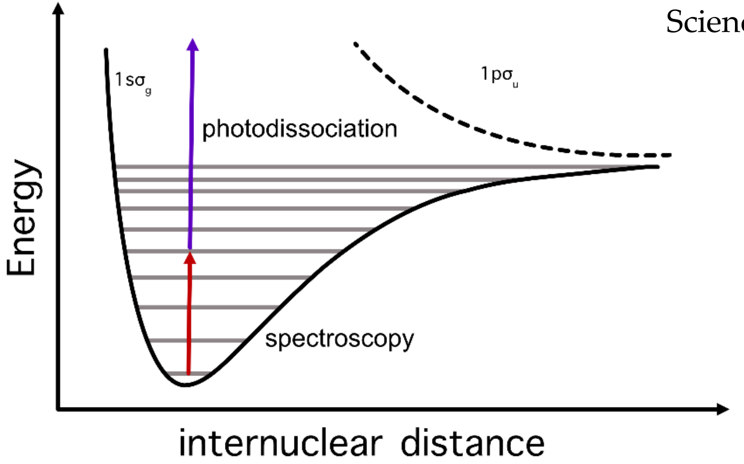
Coulomb Crystal Experiments

- HHU Düsseldorf
- VU Amsterdam
- LKB Paris
- Wuhan

In RF traps, a small number MHI (<100) is trapped in a Coulomb crystal of laser cooled Be+ ions

Detection via photodissociation -> discrete drop in fluorescence



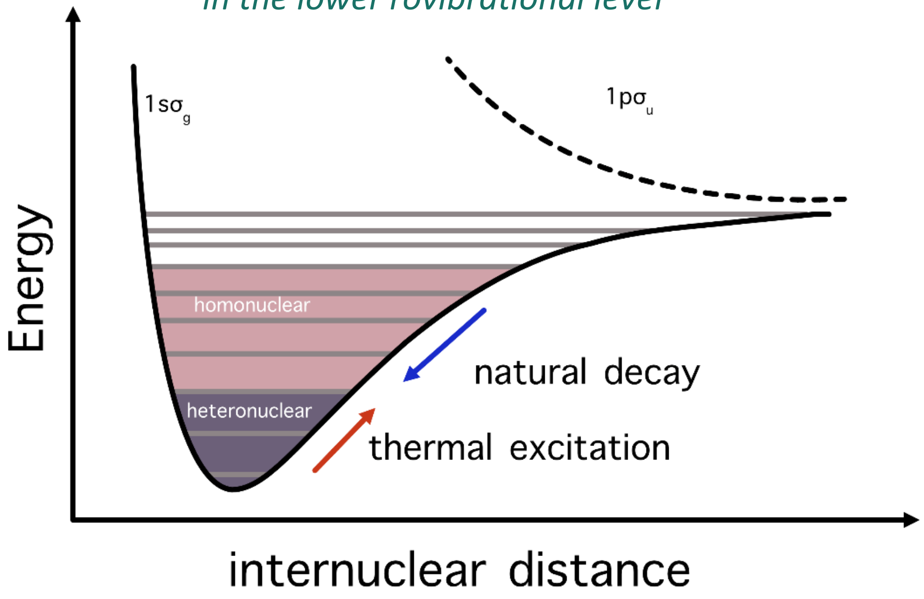


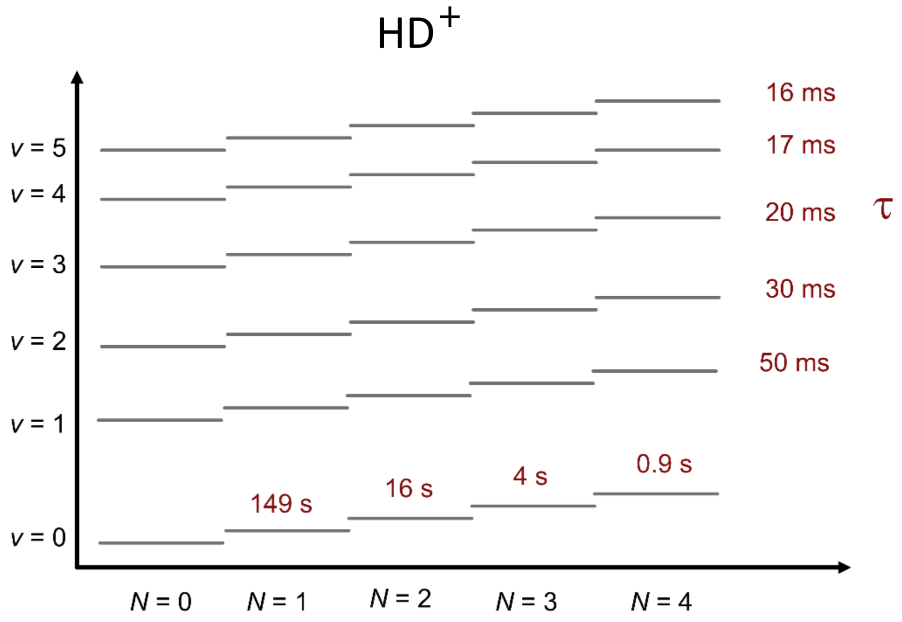
Science 2020

HD^+ vs. H_2^+

All lifetimes in H_2^+ are very long > 1 year

HD^+ *ensures population is concentrated in the lower rovibrational level*





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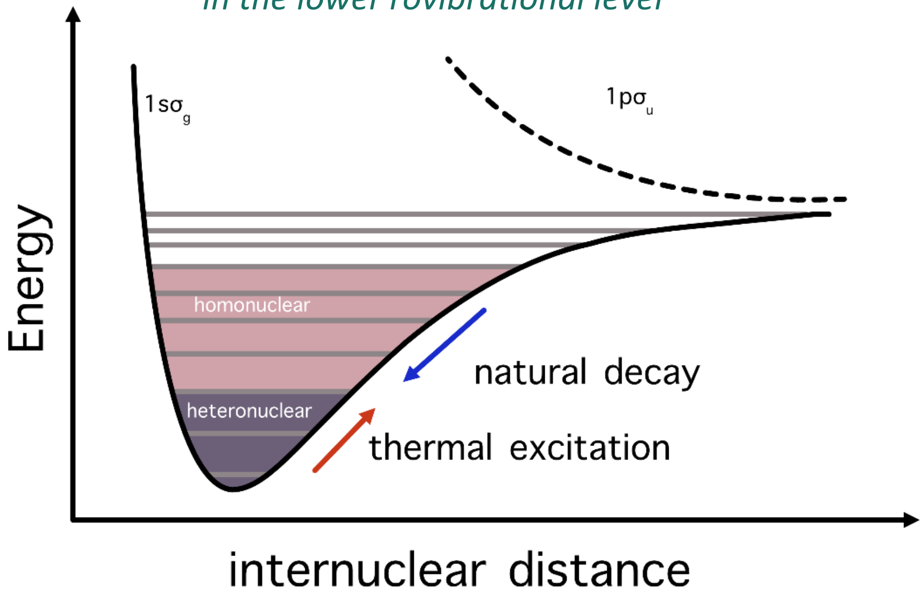

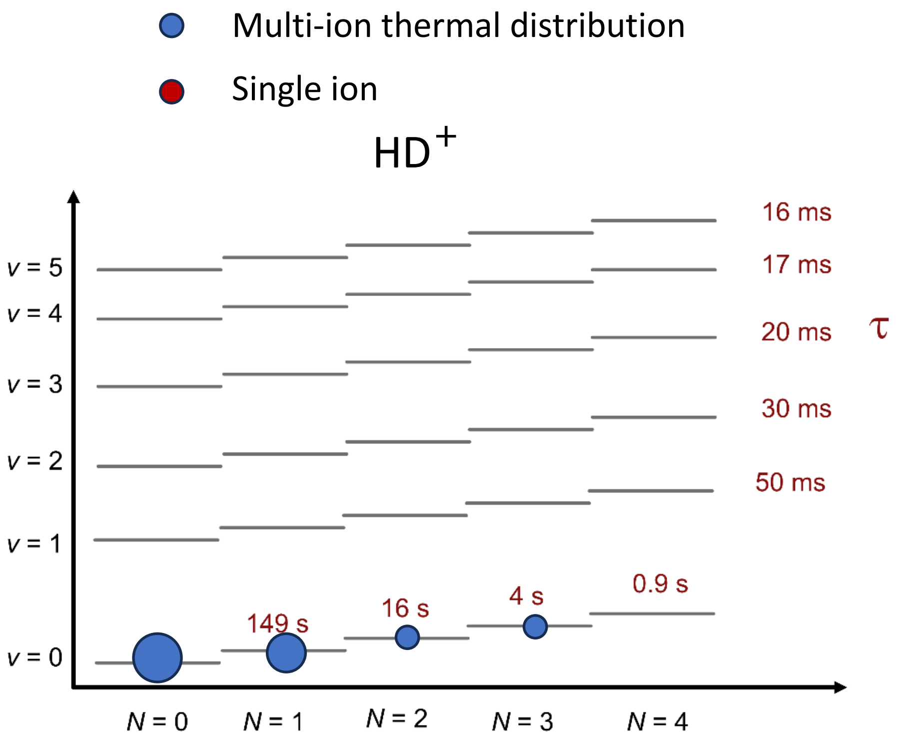

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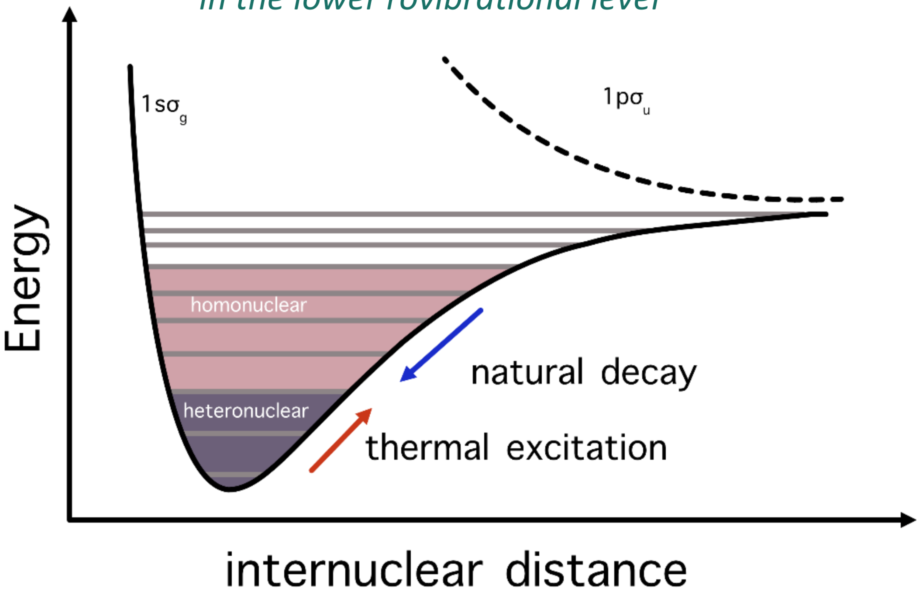
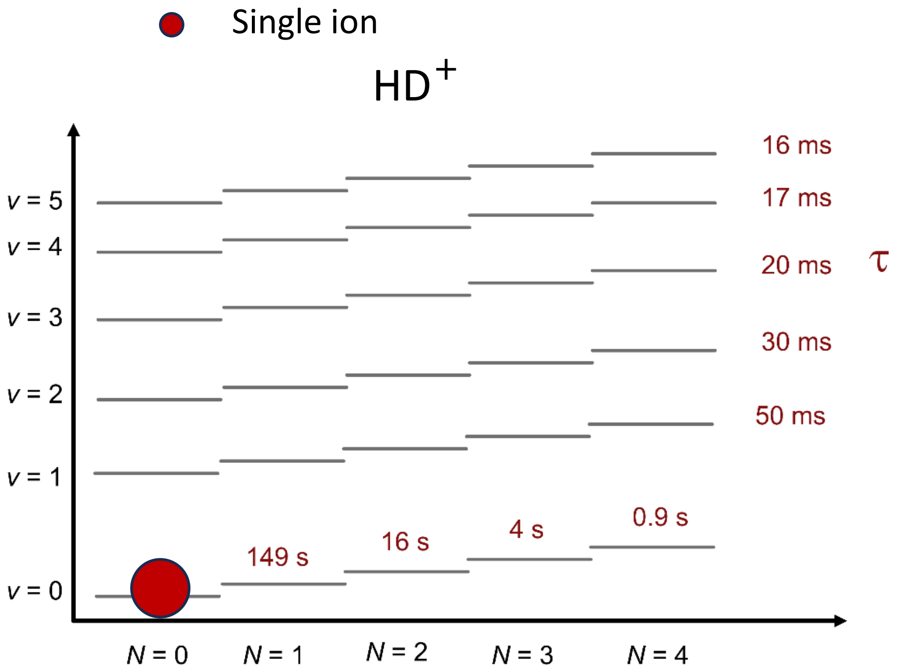




New approaches

Quantum state control dramatically changes the experimental landscape

and require new experimental approaches

Quantum logic spectroscopy

- Morning talk of Fabian Schmid
- Co-trapped MHI and Be^+
- Quantum control via ground state cooled motional modes

Penning traps

- MPIK in collaboration with HHU Düsseldorf
- “Exotic ion” approach using species independent state detection
- Extension in the future to antimatter $\overline{H}_2^-$

Penning trap approach

Techniques of precision Penning trap experiments, namely, g-factor measurements of highly charged ions or antimatter enable optical spectroscopy at the highest levels of precision.

MHI Campaign at ALPHATRAP

Goals

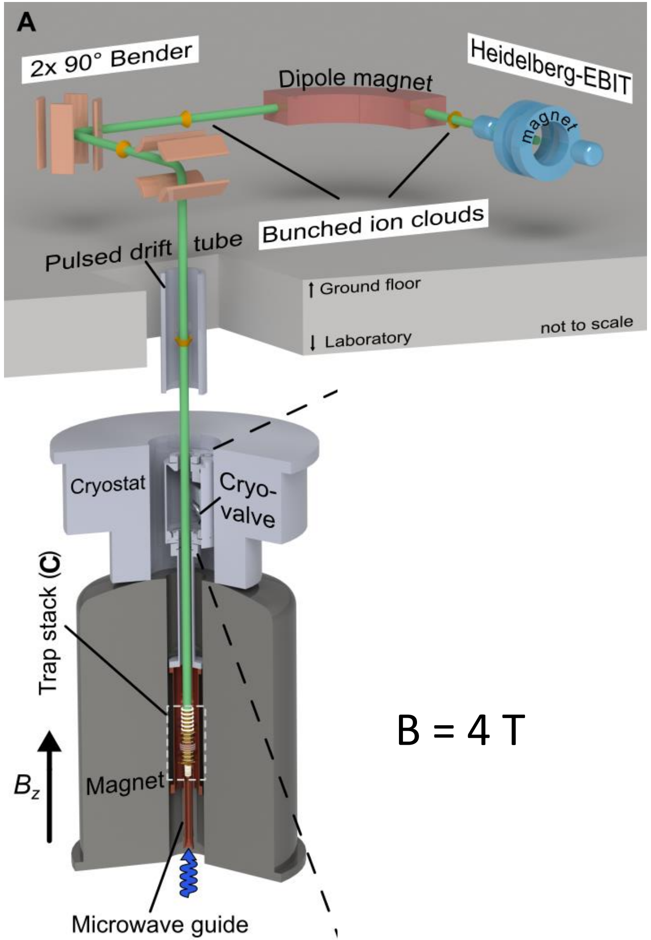
- External injection and capture of MHI, long-term ion storage (months+)
- Quantum control of single MHI
- Employ quantum control for precision measurement

Flagship measurement:
laser spectroscopy of the $(v, N) = (0, 0) \rightarrow (5, 1)$ transition with sub-kHz precision

ALPHATRAP Experiment

- Ions from electron beam ion traps (EBITs)
- Designed for precision measurements of highly-exotic heavy hydrogen-like ions
- Monday talk from Anton Gramberg

- Isolated, cryogenic environment for weeks-long storage of Sn^{49+}
- Optical access for millimeter wave (MW) electron spin-flip excitations
- 4 K image current detectors for species-independent cooling and detection

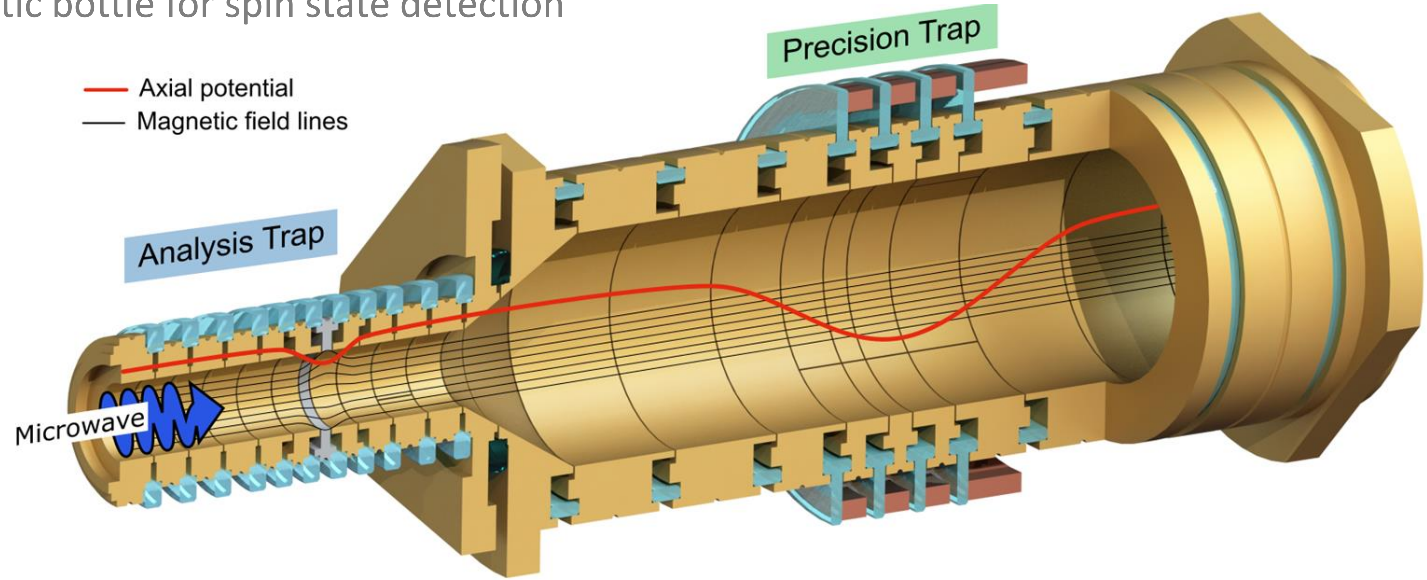


B = 4 T

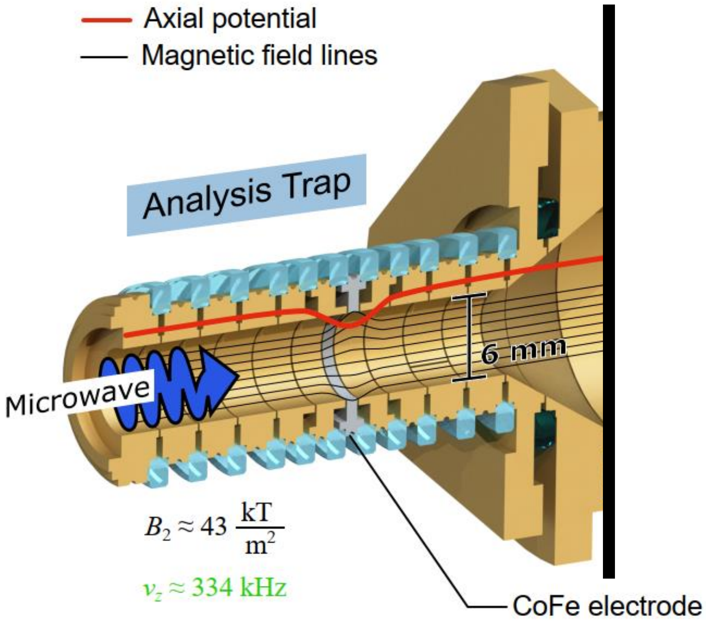
ALPHATRAP Penning trap

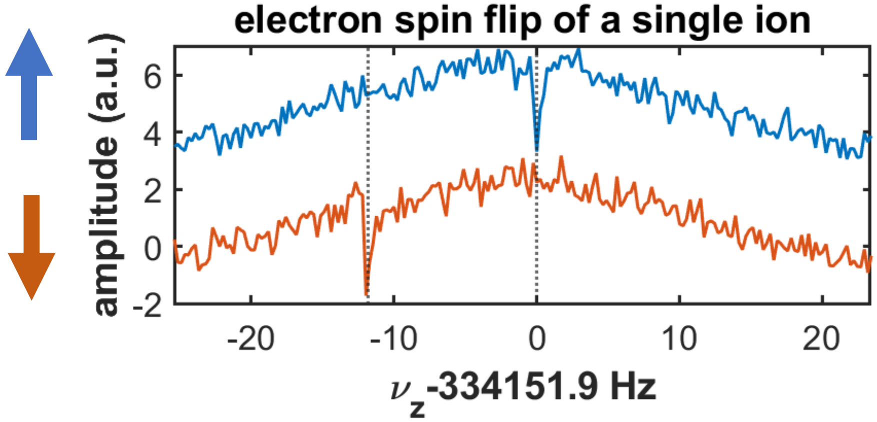
Precision Trap (PT)
Highly harmonic, homogeneous trap for precision spectroscopy

Analysis Trap (AT)
Magnetic bottle for spin state detection



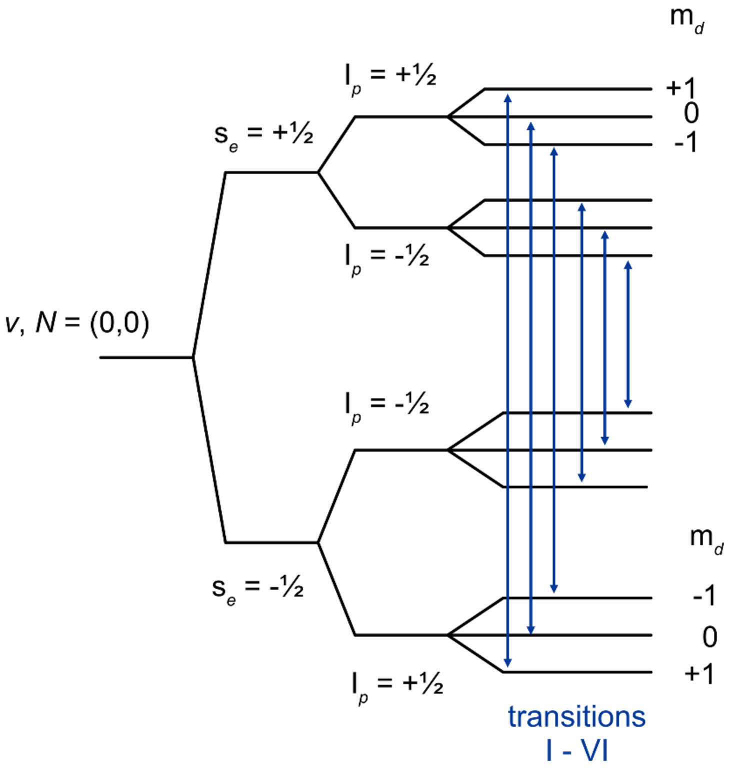
Quantum state detection





- Image current detection of axial motion
- Axial frequency ν_z in a magnetic bottle identifies the spin state

Ground state HFS of HD$^+$



Ability to drive electron spin flips uniquely, and non-destructively, determines the quantum state

$$H = h\,E_4\,(\mathbf{I}_\mathrm{p} \bullet \mathbf{s}_\mathrm{e}) + h\,\mathrm{E}_5\,(\mathbf{I}_\mathrm{d} \bullet \mathbf{s}_\mathrm{e})$$

$$- \mu_\mathrm{B}\, g_{e,\mathrm{bound}}\,(\mathbf{B} \bullet \mathrm{s}_\mathrm{e})$$

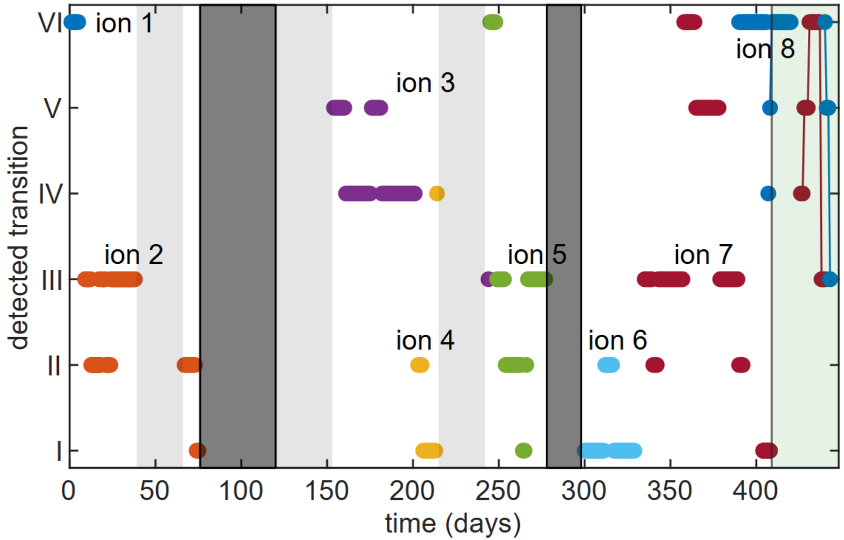
$$- \mu_\mathrm{B}\, g_p\,(\mathbf{B} \bullet \mathbf{I}_\mathrm{p})$$

$$- \mu_\mathrm{B}\, g_d\,(\mathbf{B} \bullet \mathbf{I}_\mathrm{d})$$

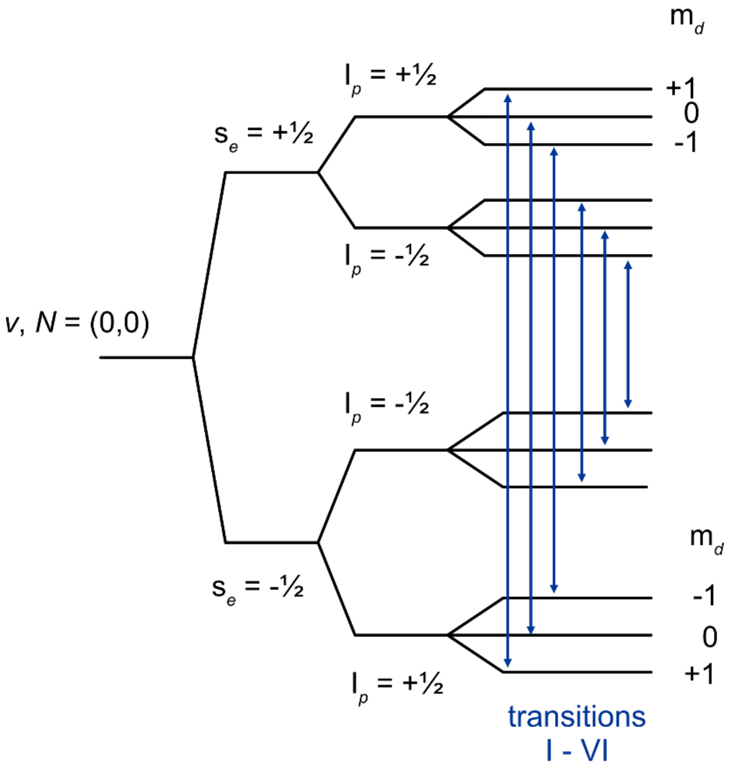
Trapping and quantum state preparation of single HD+ ions

- External injection and capture of HD+
- Months-long storage

König *et al.* PRL **134**, 163001



Ground state HFS of HD$^+$



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$$-\ \mu_\mathrm{B}\,g_{e,\mathrm{bound}}\,(\mathbf{B}\bullet\mathrm{s}_\mathrm{e})$$

$$-\ \mu_\mathrm{B}\,g_p\,(\mathbf{B}\bullet\mathbf{I}_\mathrm{p})$$

$$-\ \mu_\mathrm{B}\,g_d\,(\mathbf{B}\bullet\mathbf{I}_\mathrm{d})$$

Precision measurement of the ground state HFS

König *et al.* PRL **136**, 143002

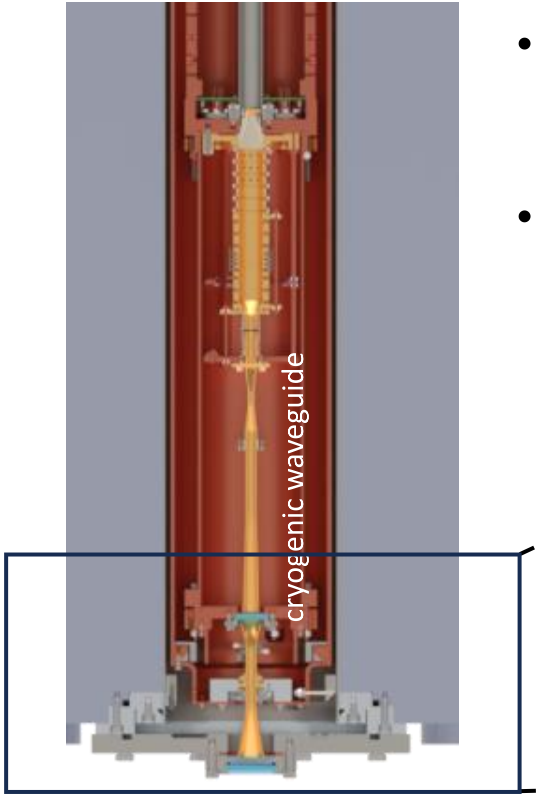
Precision measurement of the ground state HFS

- Bound electron *g*-factor measured to a precision of 2e-10, compared to new theory with excellent agreement
- E_4 and E_5 (proton-electron, deuteron-electron) terms measured to 44 ppb and 151 ppb are in slight tension to theory

(a)	$g_{e,\mathrm{bound}}(0,0)$
Hegstrom [27]	−2.002 278 46(20)
g_e [45]	−2.002 319 304 360 92(36)
$\Delta g^{(2)}_{\mathrm{nonrec-ad}}$	0.000 040 819 39
$\Delta g^{(2)}_{\mathrm{rec-na}}$	−0.000 000 006 99
$\Delta g^{(3)}$	−0.000 000 049 05(5)
$\Delta g^{(4+)}_{\mathrm{rel}}$	0.000 000 000 52
$\Delta g^{(5)}$	−0.000 000 000 20(9)
Total theory [36]	−2.002 278 540 70(10)
Experiment	$-2.002\,278\,540\,96(18)_{st}(35)_{sys}$
$\Delta(\sigma)$	0.6

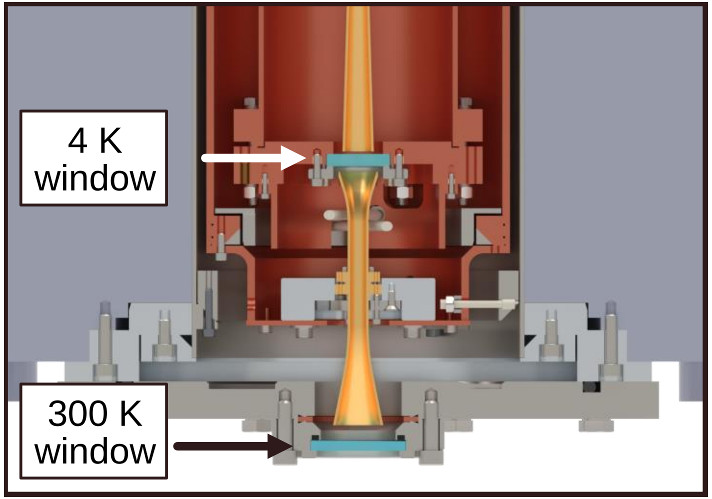
(b)	$E_4(0,0)$ (kHz)	$E_5(0,0)$ (kHz)
Theory [6,31]	925 394.16(86)	142 287.556(84)
Experiment	$925\,395.758(39)_{st}(11)_{sys}$	$142\,287.821(20)_{st}(8)_{sys}$
$\Delta(\sigma)$	1.9	3.1

Preparation for laser spectroscopy

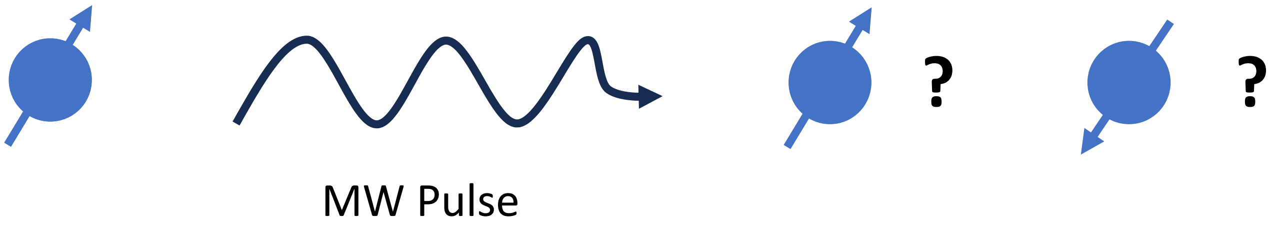


- Faster image current detection
  spin state readout time: 3 min → 15 s

- UV-FS window replaced with CaF for improved IR transmission



Checking spin flip probability



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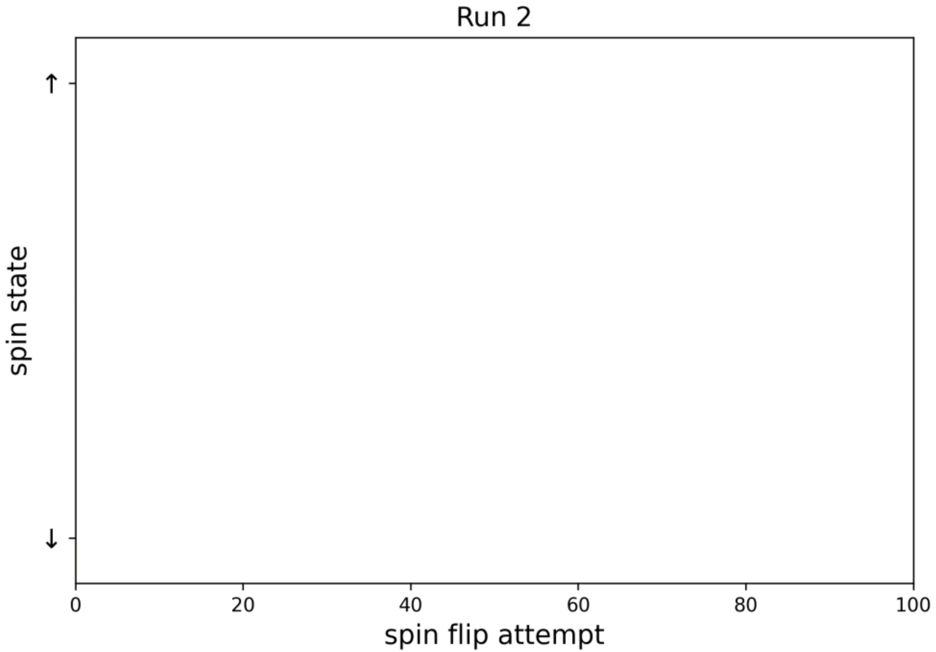
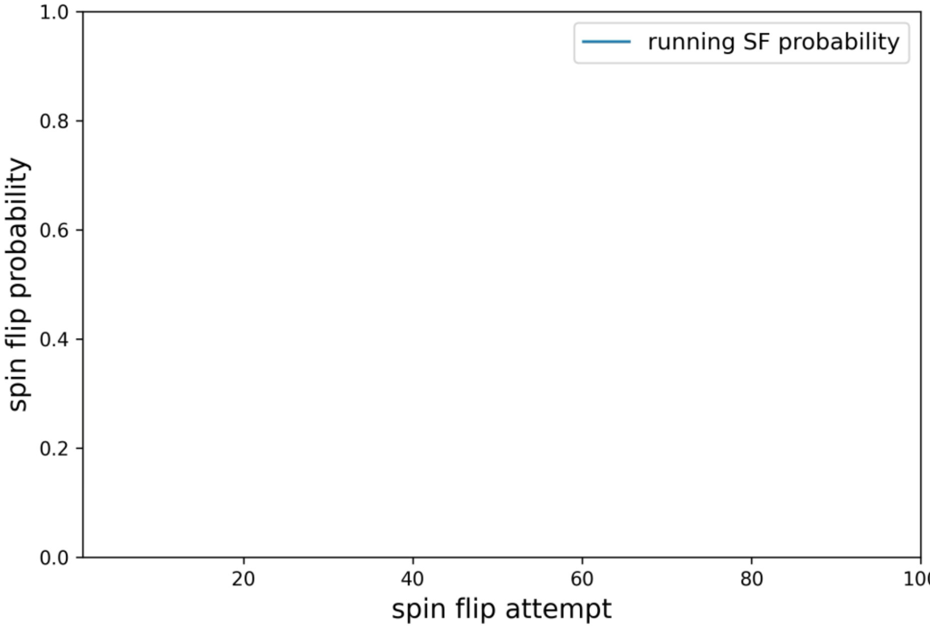
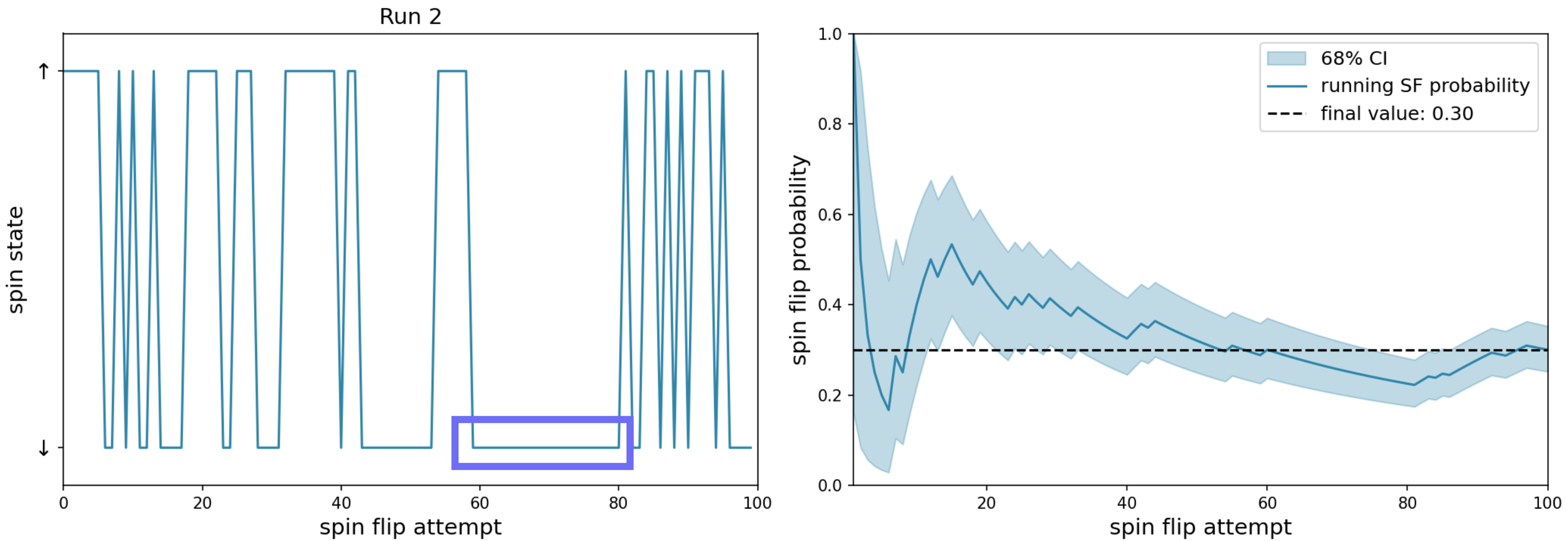




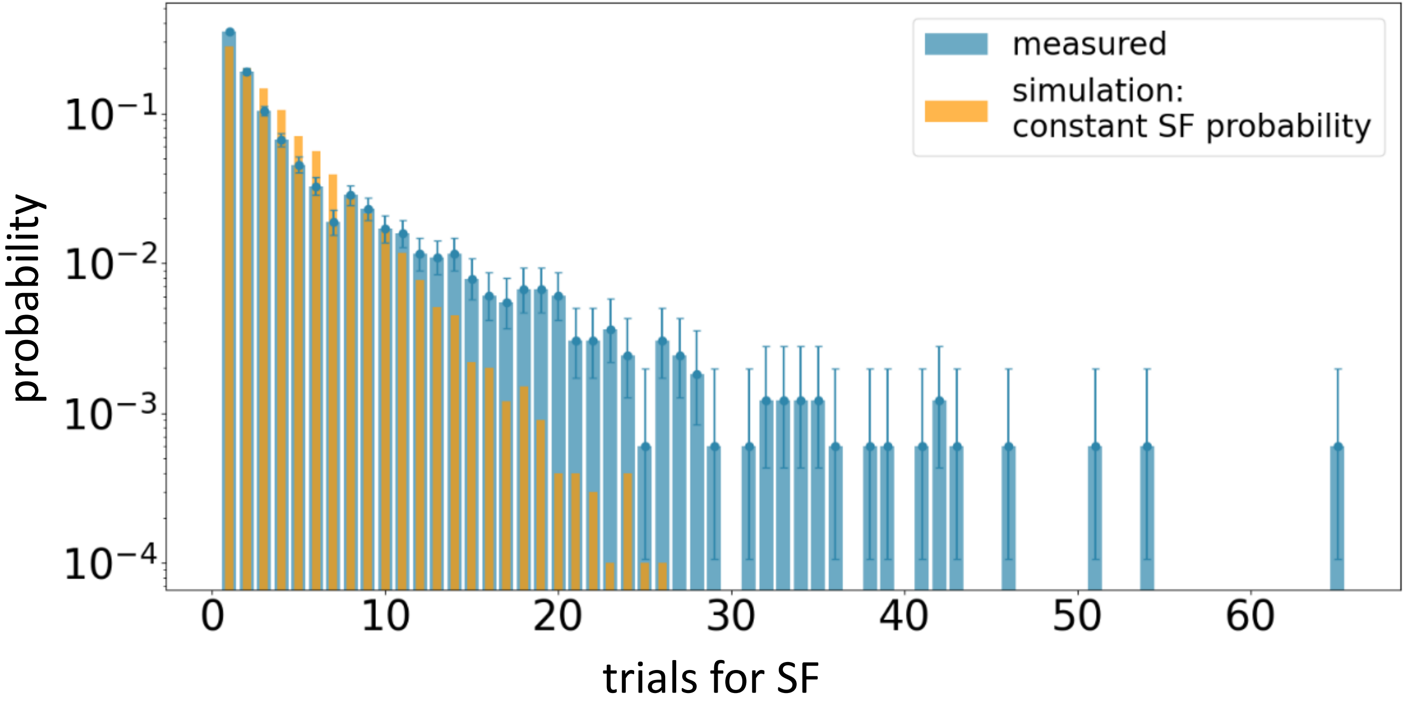
Checking spin flip probability



How likely is it that we measure 0 spin flips in 20 trials with 30% spin flip probability?

Not very!
0.08 %

Further analysis



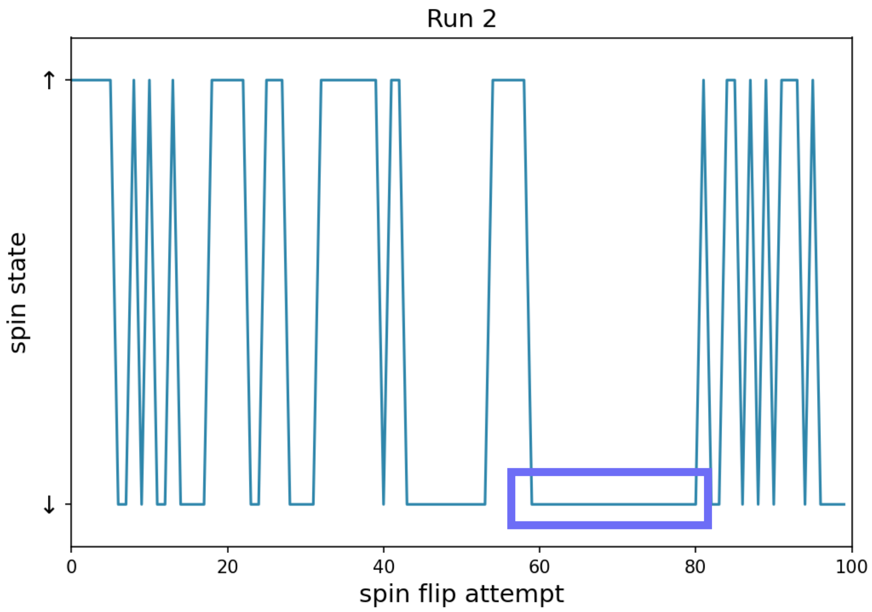
- Calculate average excitations required to drive a spin flip
- Compare to simulation

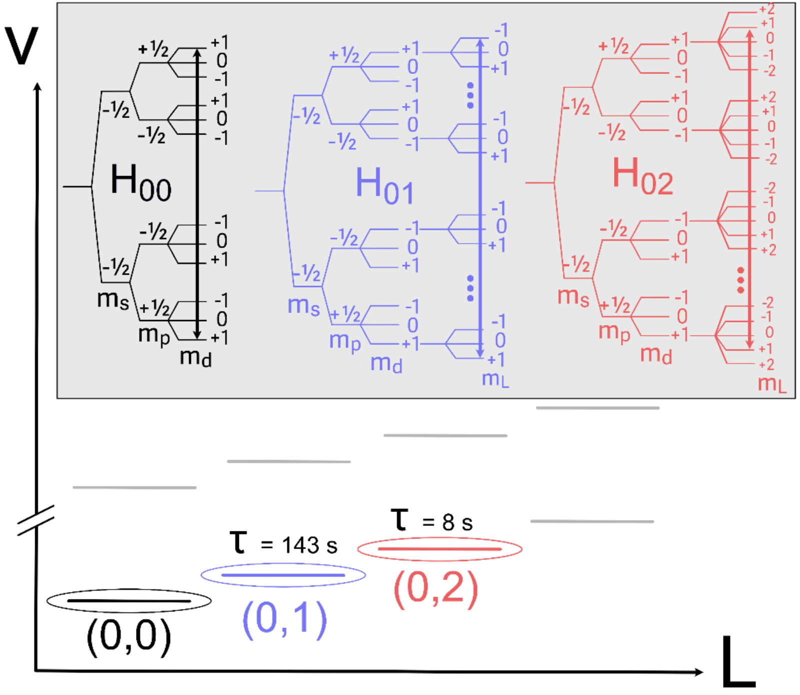
Conclusion:

A model of constant spin flip probability is not a good fit to the data!

Explanation

Hamiltonian for (0,1) also well known – we can drive ESR transitions there as well!

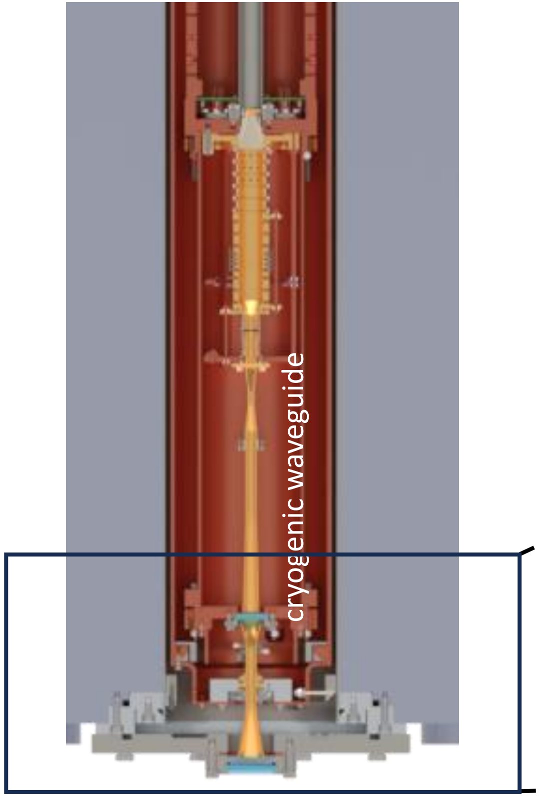




"dark" periods correspond to population in excited rotational states

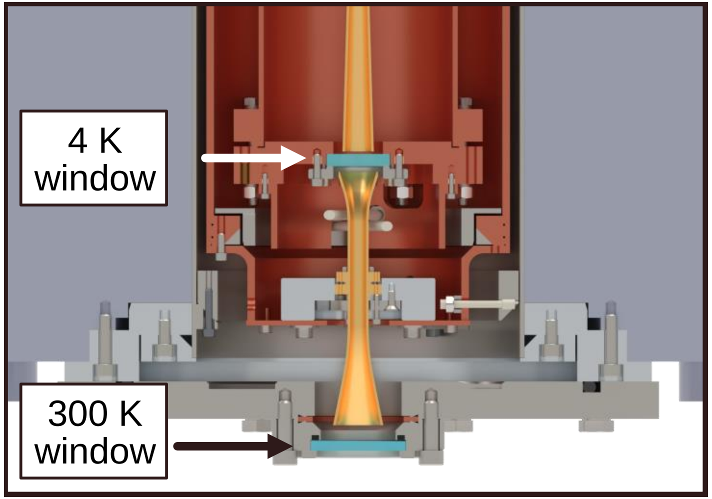
analogous to electron shelving

Preparation for laser spectroscopy



apparatus modifications

	300 K window	4 K window	State Detection
Run 1	UV-FS	CaF	slow
Run 2	CaF	CaF	fast
Run 3	UV-FS	UV-FS	fast



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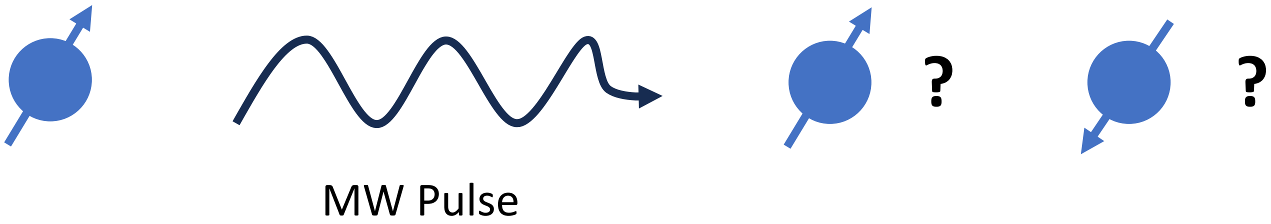
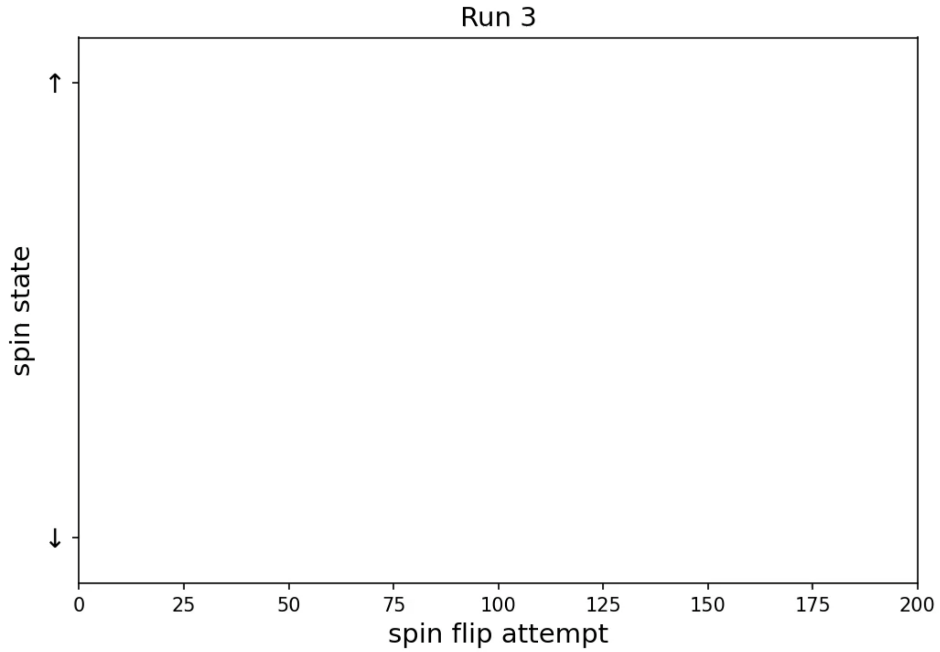
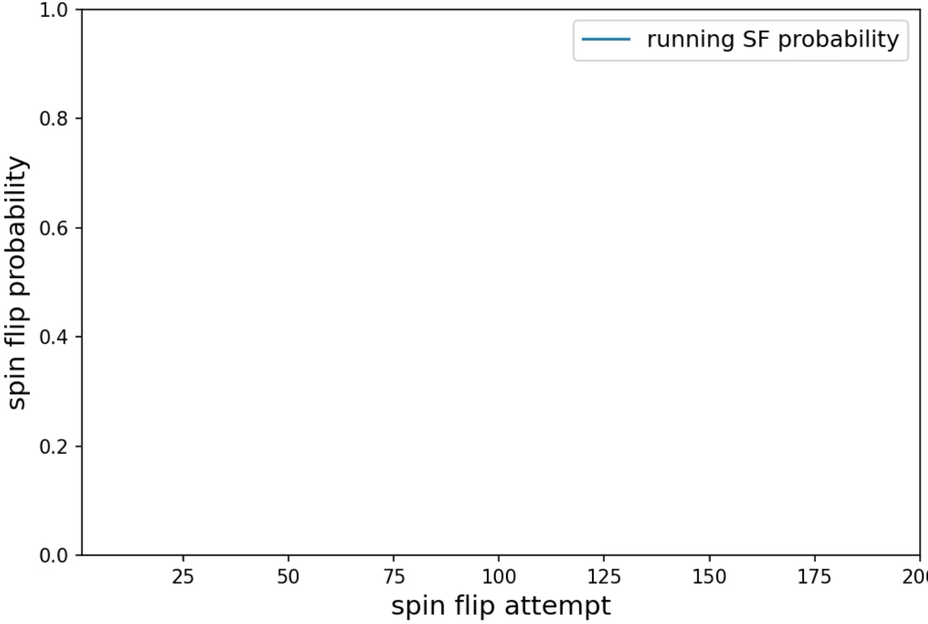


Revisiting spin flip probability





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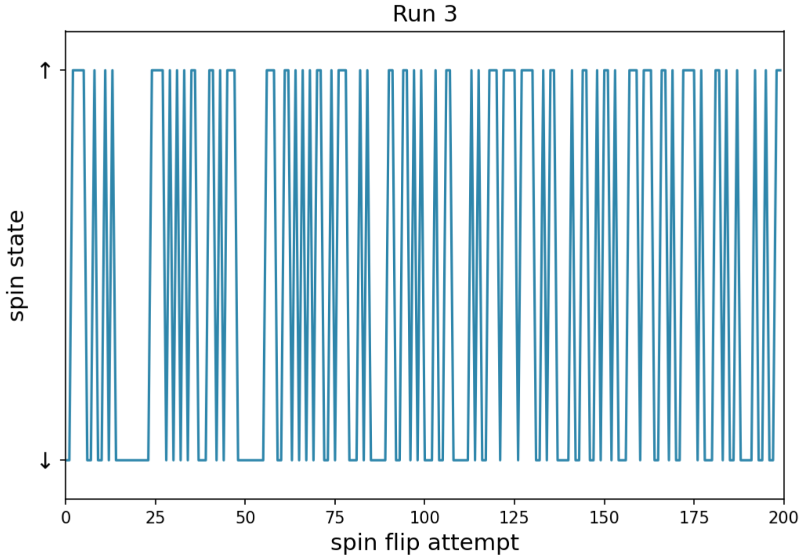

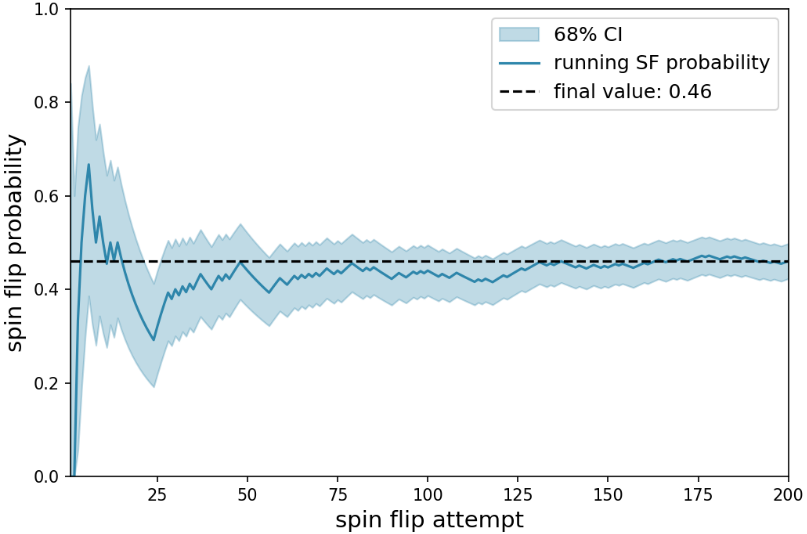

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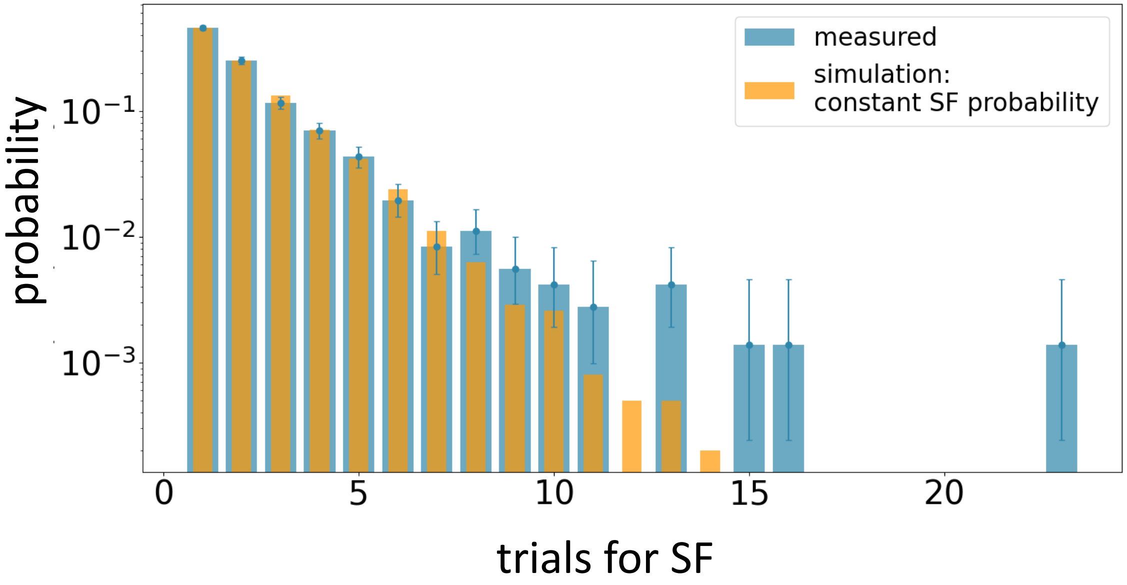
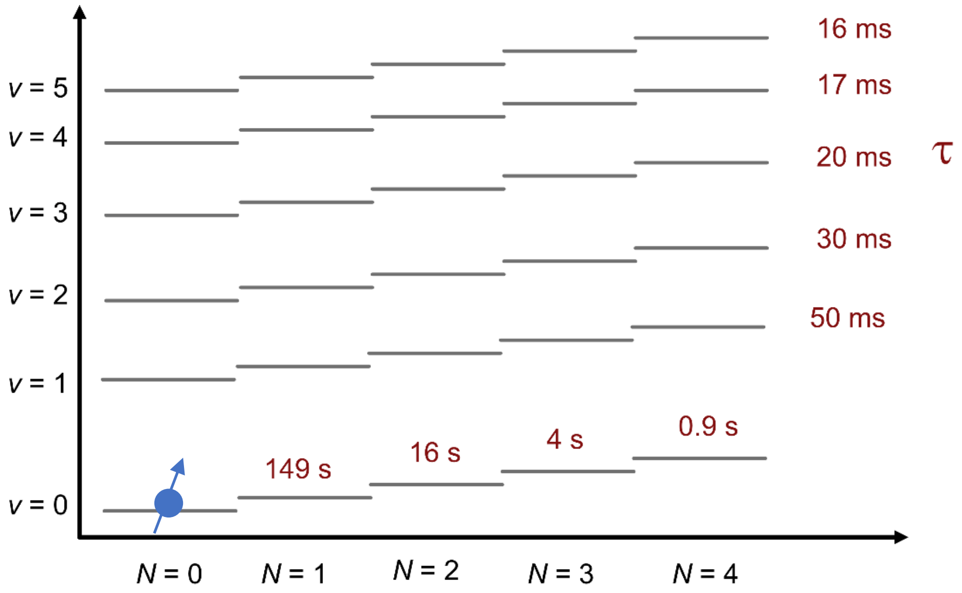


- Thermal radiation brings population into rotationally excited states
- Careful design of cryogenic environment is important
- Ingredients in place for laser spectroscopy

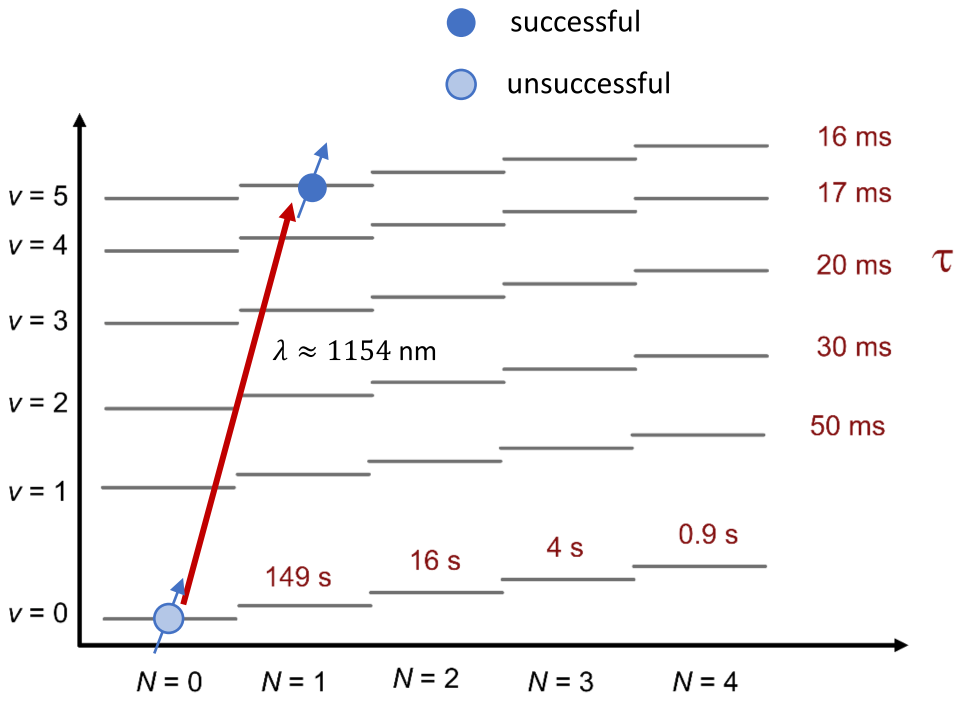
Laser Spectroscopy - scheme

1. Prepare ion in (0,0)



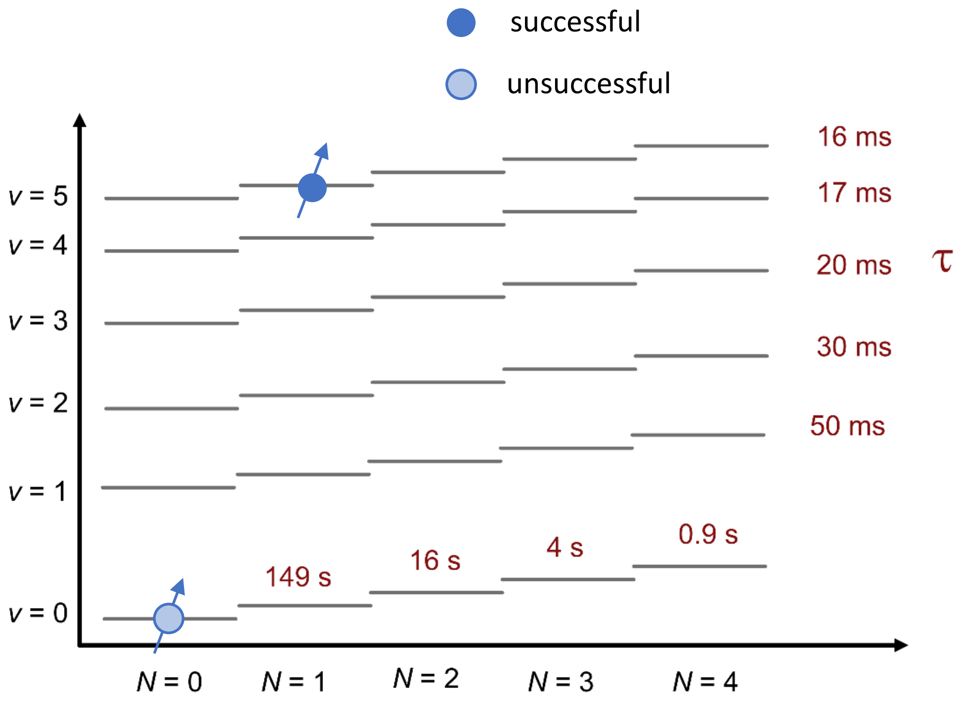
Laser Spectroscopy - scheme

1. Prepare ion in (0,0)
2. Probe the $(0,0) \rightarrow (5,1)$ rovibrational transition



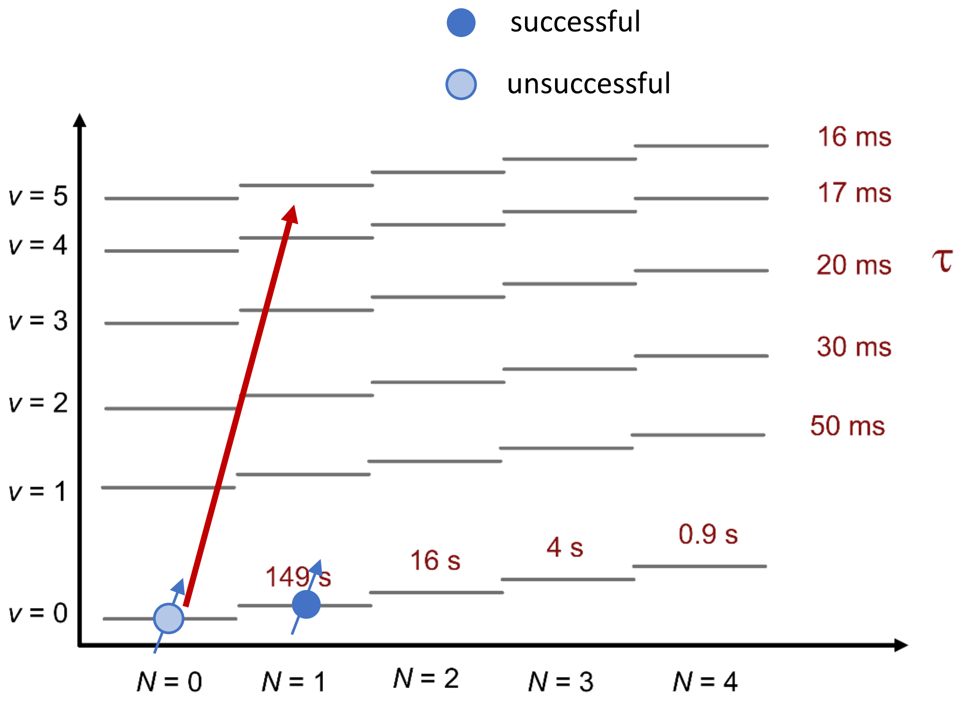
Laser Spectroscopy - scheme

1. Prepare ion in (0,0)
2. Probe the $(0,0) \rightarrow (5,1)$ rovibrational transition
3. Population decays down



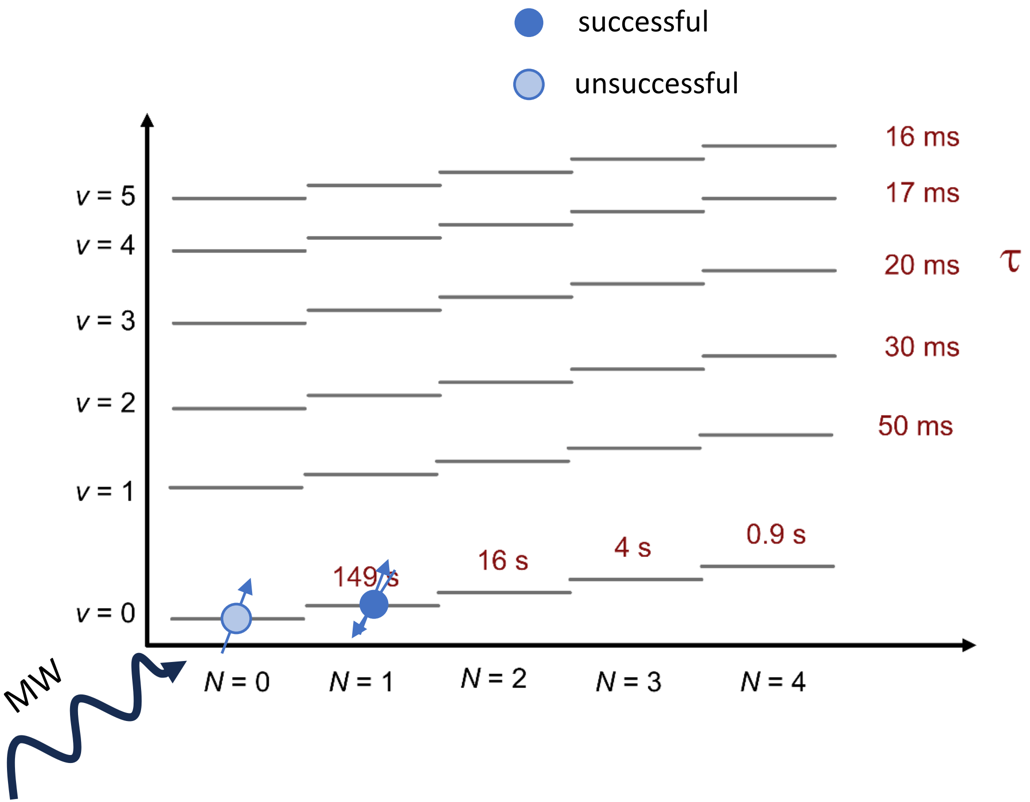
Laser Spectroscopy - scheme

1. Prepare ion in (0,0)
2. Probe the $(0,0) \rightarrow (5,1)$ rovibrational transition
3. Population decays down
4. Continuous pumping



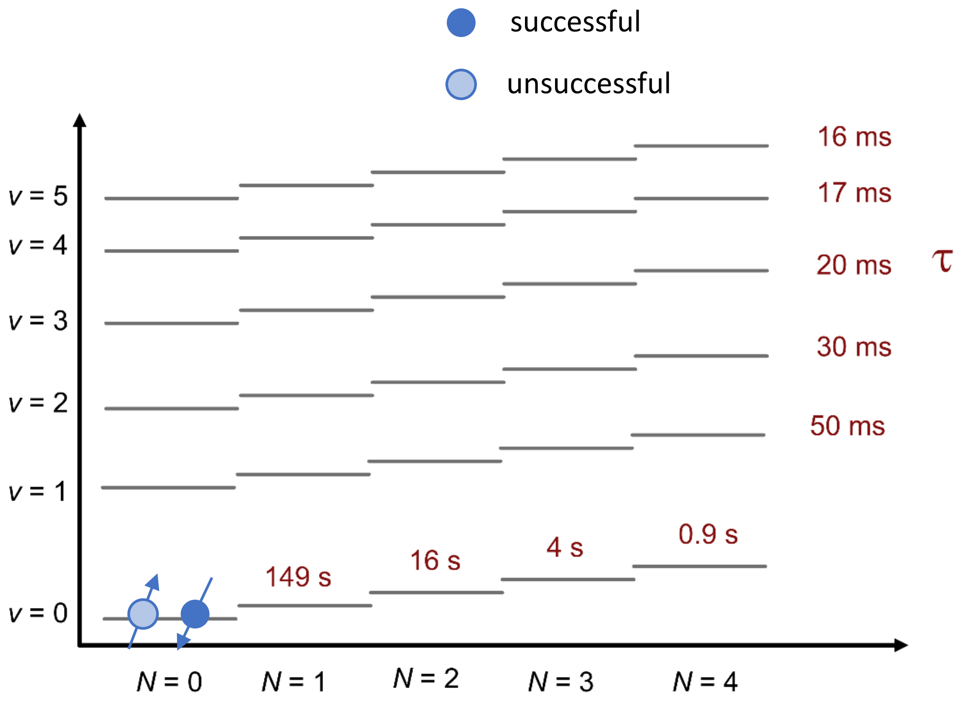
Laser Spectroscopy - scheme

1. Prepare ion in (0,0)
2. Probe the $(0,0) \rightarrow (5,1)$ rovibrational transition
3. Population decays down
4. Continuous pumping
5. MW Pulse



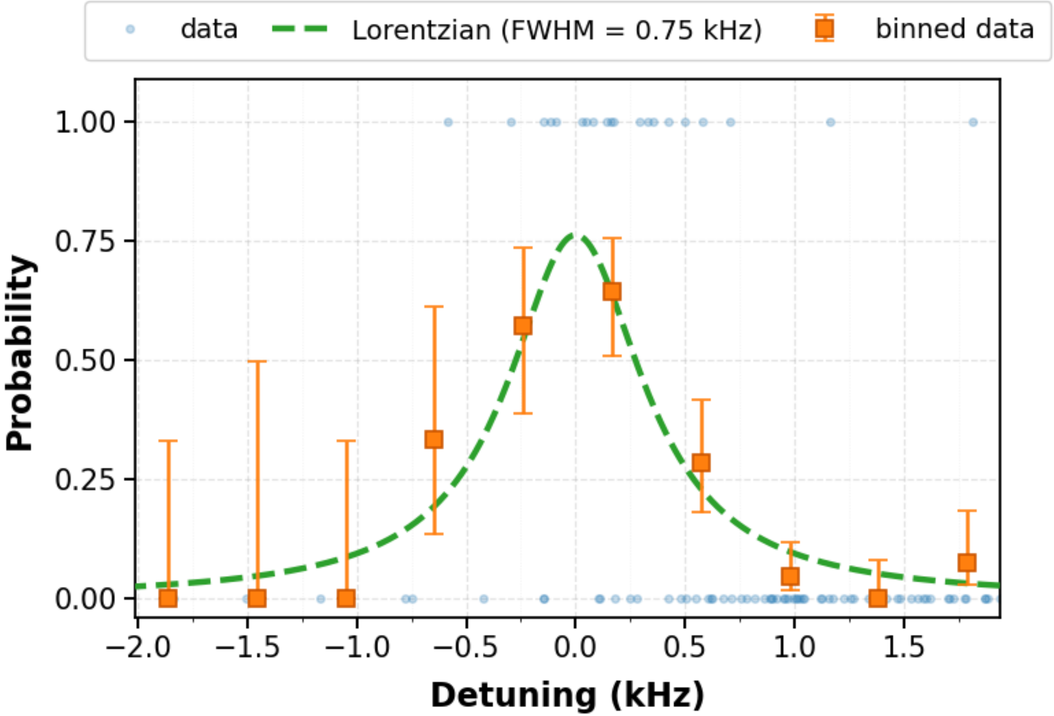
Laser Spectroscopy - scheme

1. Prepare ion in (0,0)
2. Probe the $(0,0) \rightarrow (5,1)$ rovibrational transition
3. Population decays down
4. Continuous pumping
5. MW Pulse
6. Decay and Detect



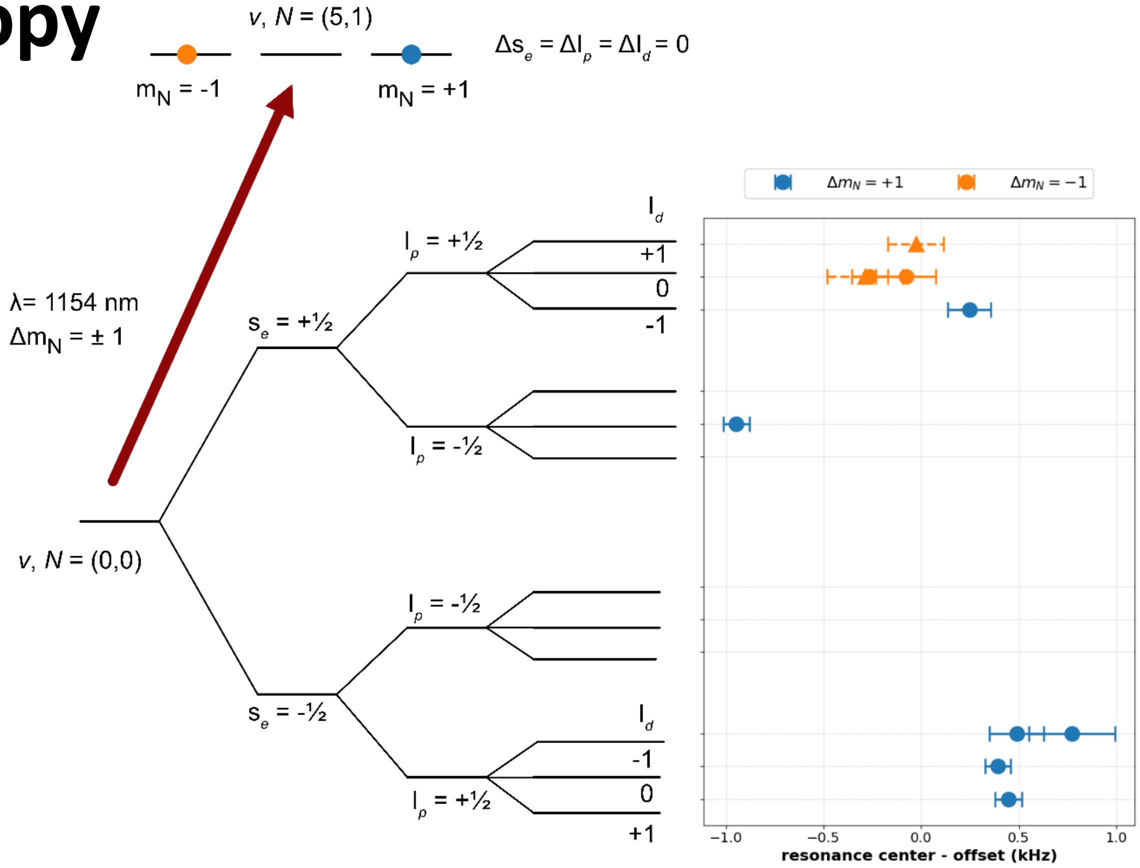
Laser Spectroscopy - results

- Achievable resonance linewidths < 1 kHz
- Statistical uncertainty < 100 Hz
- 10^{-13} level statistical precision – narrowest measured line in HD^+



Laser Spectroscopy - results

- Measured 8 out of 18 allowed transitions
- $3\ \Delta m_N = -1$
  $5\ \Delta m_N = +1$
- Extraction of $\frac{m_p}{m_e}$ limited by QED uncertainty and the emerging HFS puzzle in HD⁺



Acknowledgements

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