Durham
University

Introduction to ultracold molecules

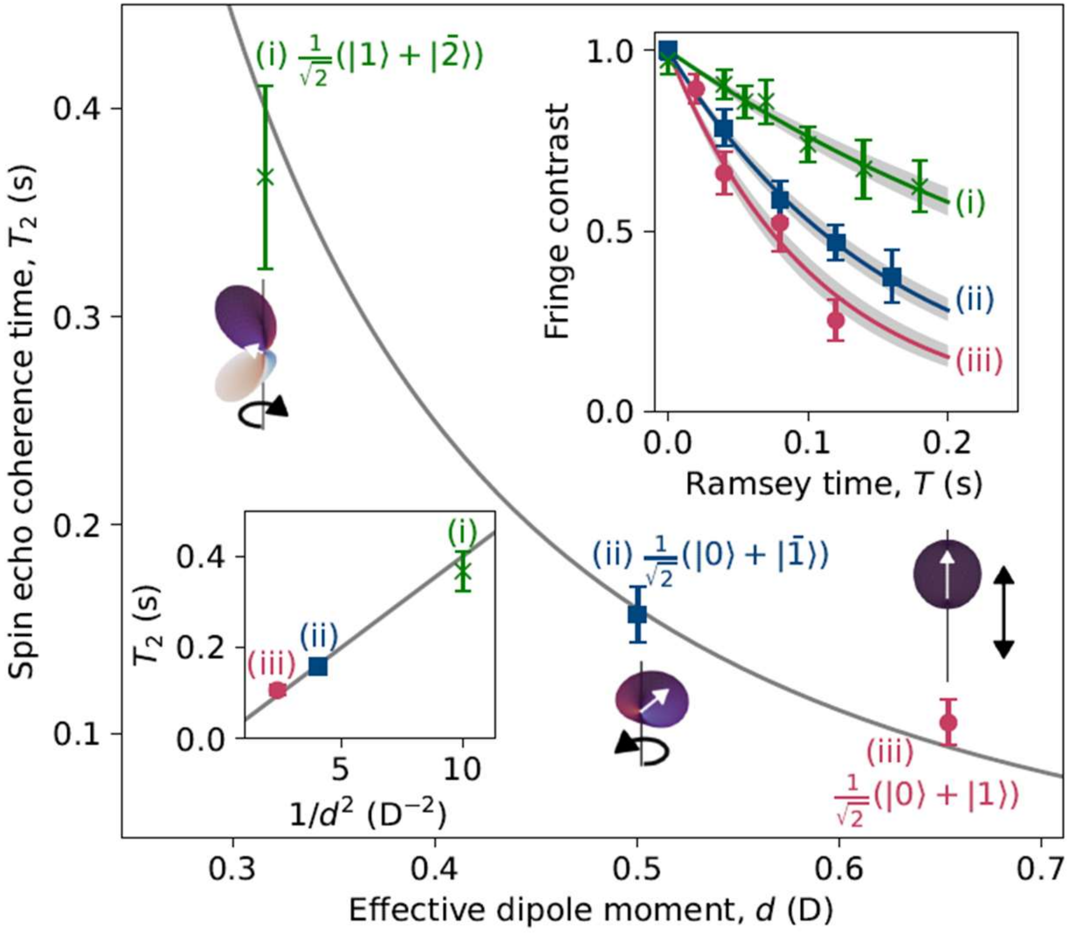
3. Controlling molecular motion and collisions

Simon L. Cornish

Quantum Light and Matter Group
Department of Physics
Durham University

www.cornishlabs.uk

Controllable dipole-dipole interactions



Change superposition
to control size of dipole

$$T_2 \propto 1/V_{\mathrm{DDI}}$$

Next step:
Arrays of molecules

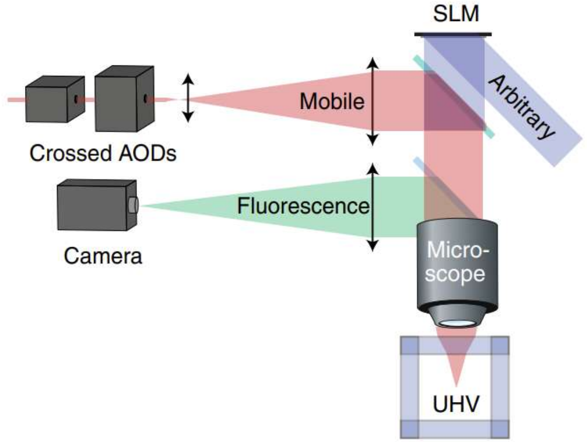
Dephasing due to random thermal distribution of molecules

Gregory *et al.*, Nature Physics 20, 415 (2024)

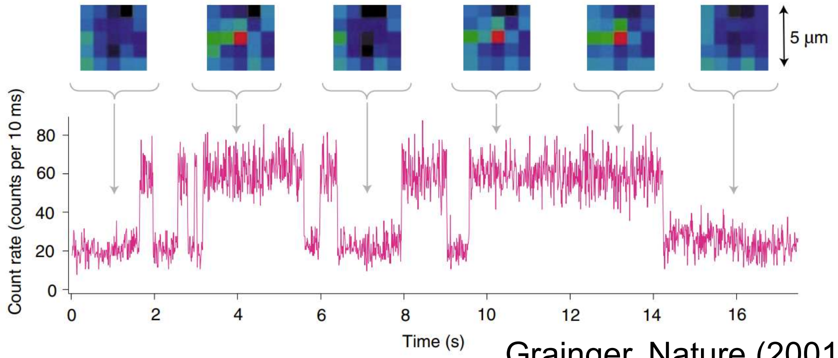
Controlling the motional state
Assembly of molecules in tweezers
Controlling interactions & entanglement
Lattices & quantum gas microscopy

Atoms in optical tweezers

Kaufman & Ni, Nature Physics Review (2019)

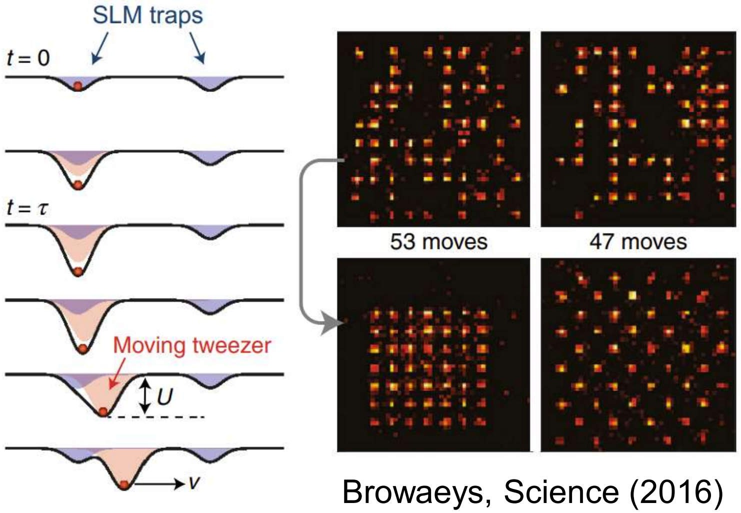


Single atom loading & detection:



Grainger, Nature (2001)

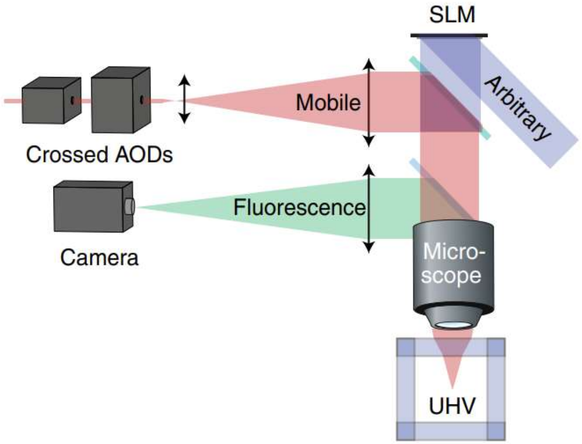
Dynamic rearrangement:



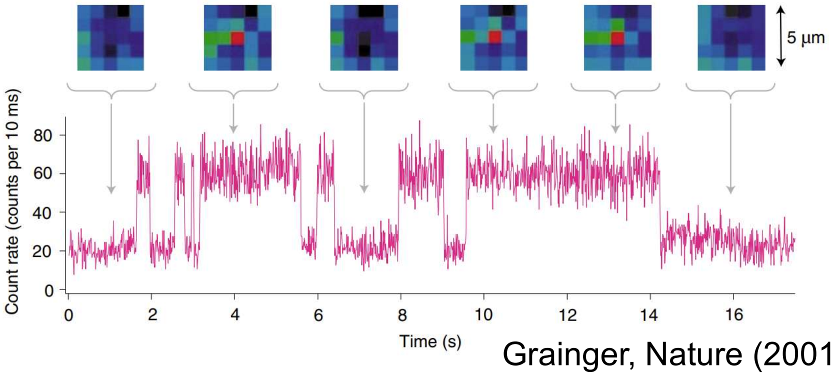
Browaeys, Science (2016)

Atoms in optical tweezers

Kaufman & Ni, Nature Physics Review (2019)

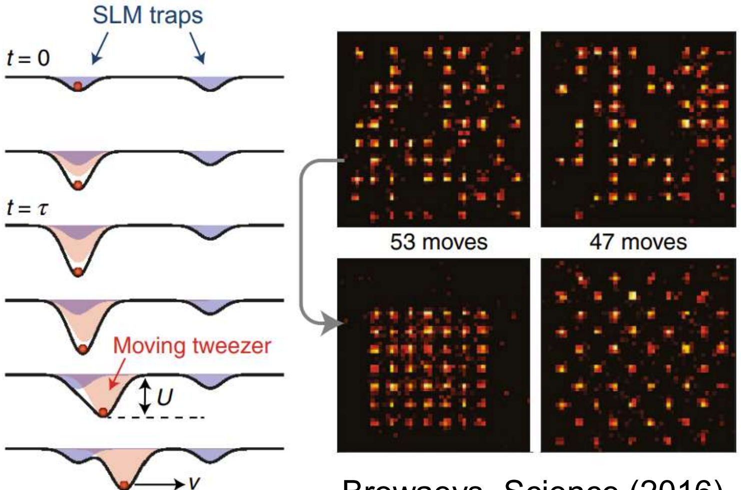


Single atom loading & detection:



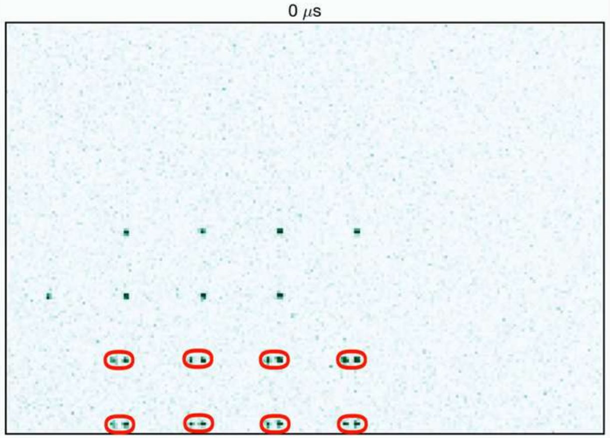
Grainger, Nature (2001)

Dynamic rearrangement:



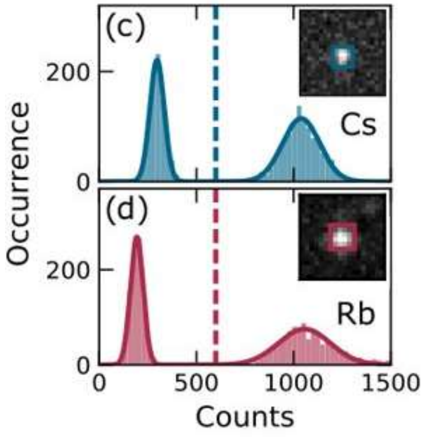
Browaeys, Science (2016)

A beautiful example:

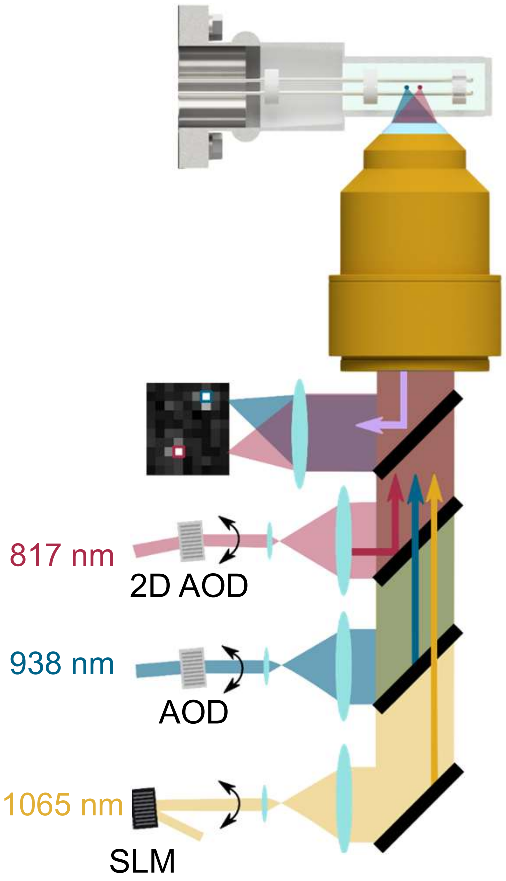


Lukin, Nature (2022)

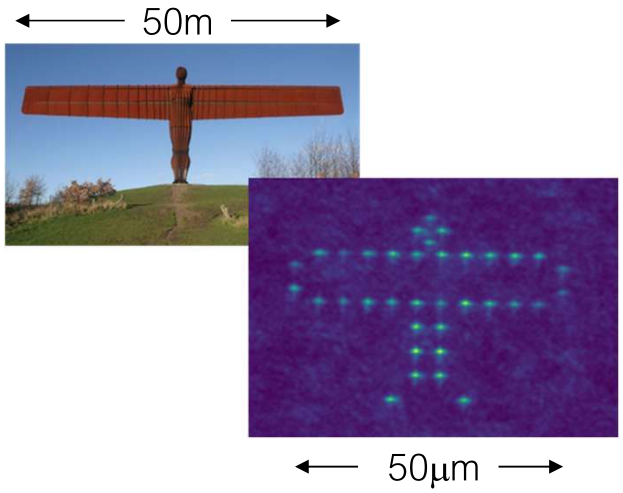
Single molecules in optical tweezers



Fluorescence imaging to
detect tweezer occupation
(fidelity >> 99.9%)

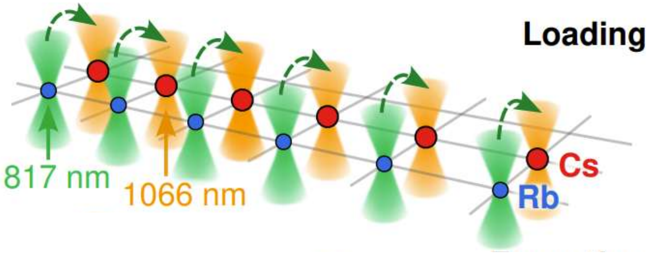


Inspired by experiments
in the Ni group at Harvard

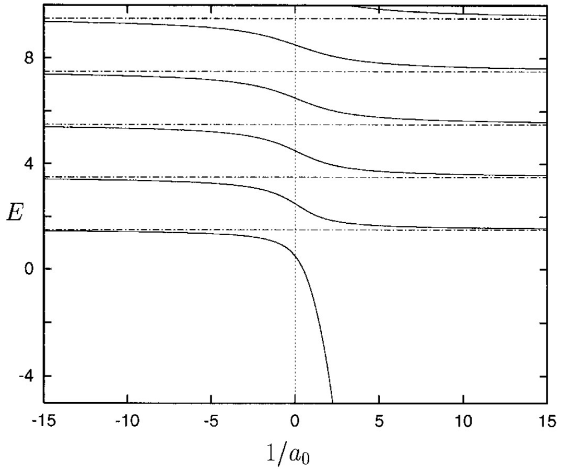


Brooks *et al.*, *NJP* **23** 065002 (2021)
Spence *et al.*, *NJP* **24** 103022 (2022)

Molecular assembly in optical tweezers

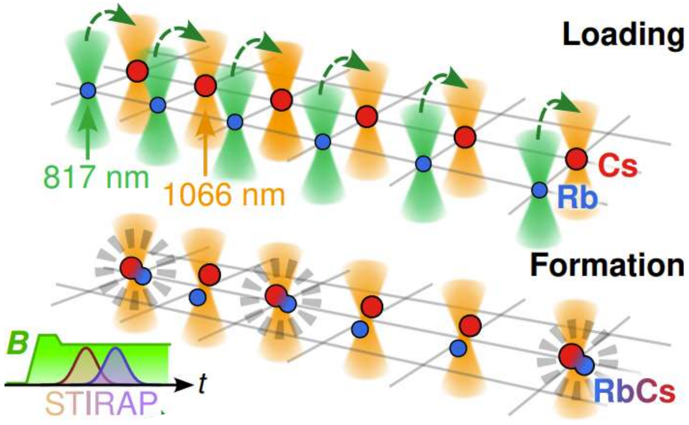


- Load, image, rearrange Rb & Cs
- Raman sideband cooling to 3D ground state
- Merge traps



Busch et al.,
Foundations of Physics
28, 549 (1998)

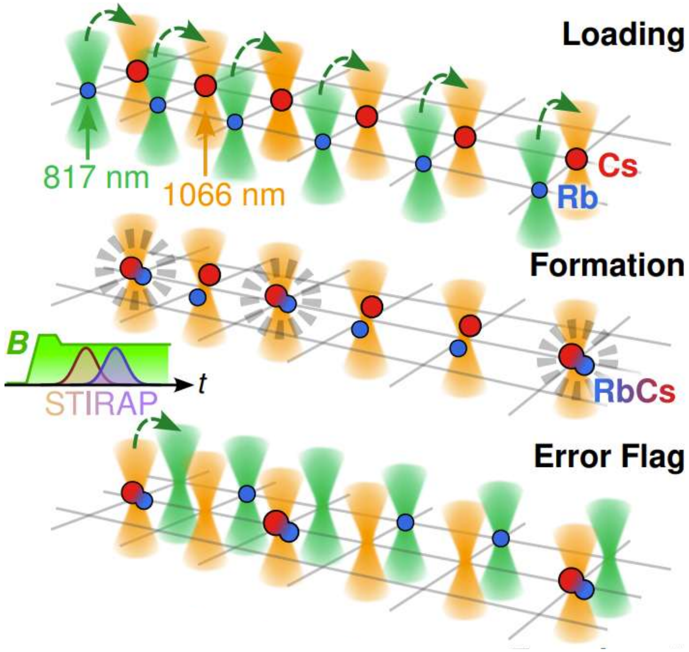
Molecular assembly in optical tweezers



- Load, image, rearrange Rb & Cs
- Raman sideband cooling
- Merge traps

- Magnetoassociation & STIRAP
- Atom pairs remain on sites where formation failed

Molecular assembly in optical tweezers

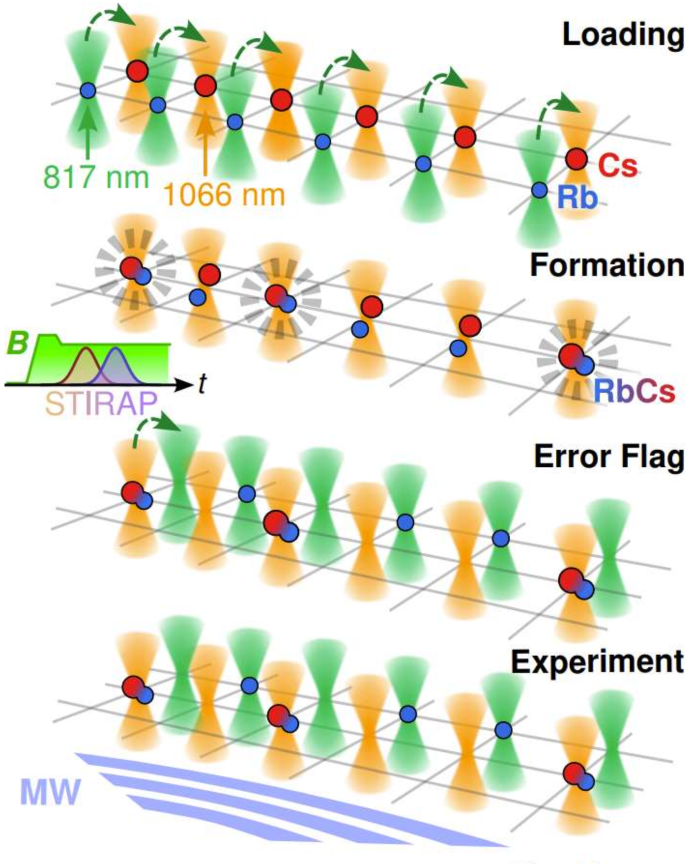


- Load, image, rearrange Rb & Cs
- Raman sideband cooling
- Merge traps

- Magnetoassociation & STIRAP
- Atom pairs remain on sites where formation failed

- Pullout Rb using 817nm tweezer
- Blow away Cs

Molecular assembly in optical tweezers



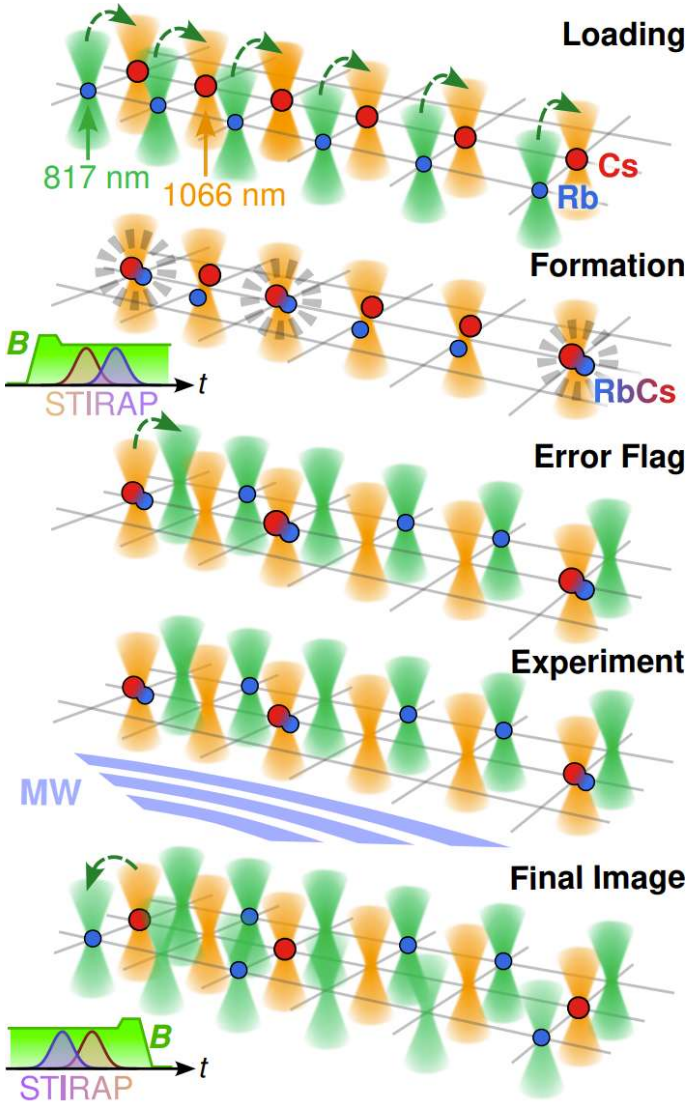
- Load, image, rearrange Rb & Cs
- Raman sideband cooling
- Merge traps

- Magnetoassociation & STIRAP
- Atom pairs remain on sites where formation failed

- Pullout Rb using 817nm tweezer
- Blow away Cs

- Perform experiment

Molecular assembly in optical tweezers



- Load, image, rearrange Rb & Cs
- Raman sideband cooling
- Merge traps

- Magnetoassociation & STIRAP
- Atom pairs remain on sites where formation failed

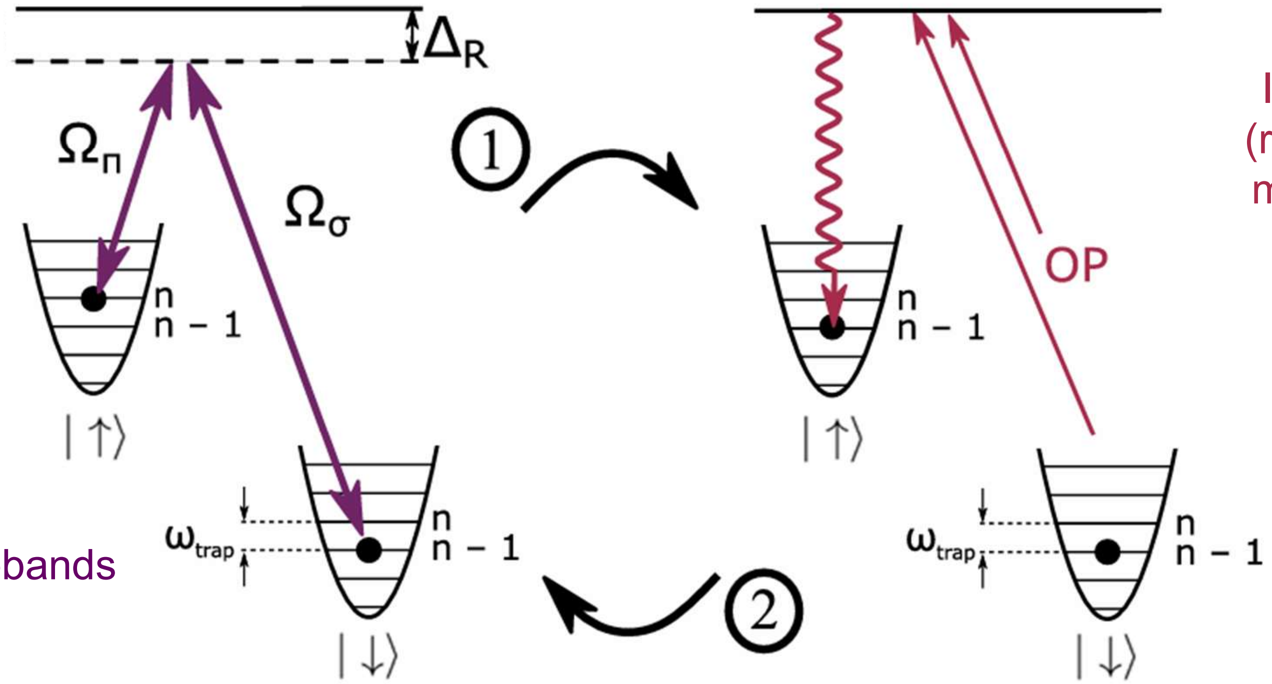
- Pullout Rb using 817nm tweezer
- Blow away Cs

- Perform experiment

- Recover & image atoms
- Post select on recovery of Rb and Cs
- Ignore sites with an error flag

Simultaneous Raman sideband cooling

Raman transition → Optical pumping → Repeat



In Lamb-Dicke regime
(recoil energy less than
motional state spacing)
n does not change

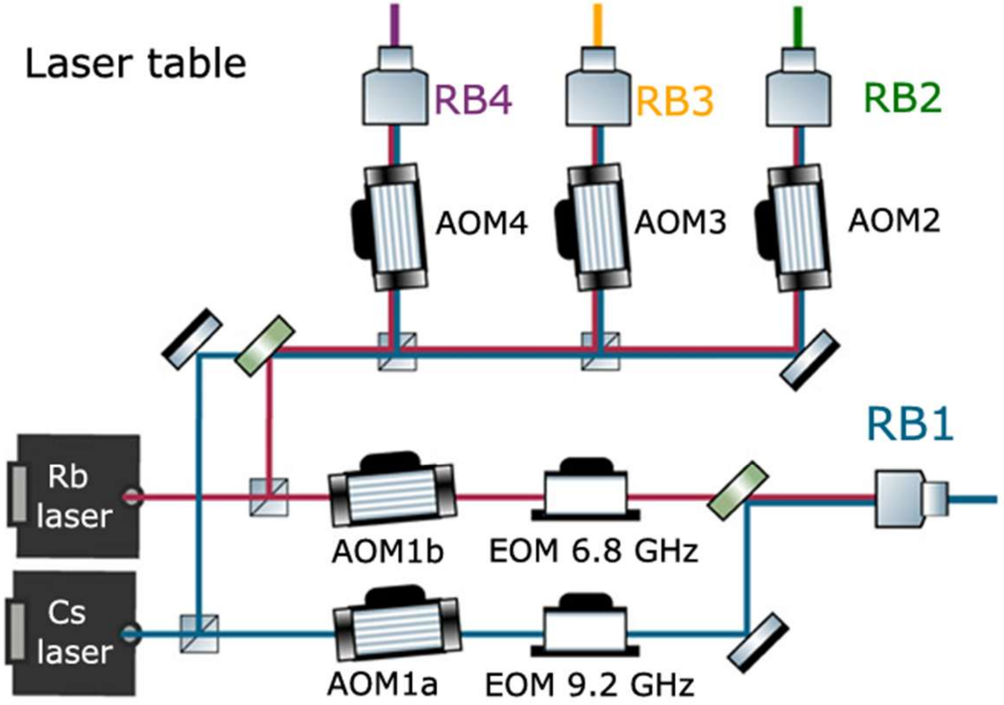
Narrow linewidth
Resolves motional sidebands

Spence *et al.*, *NJP* **24** 103022 (2022)

Each cycle removes one quanta of motional energy

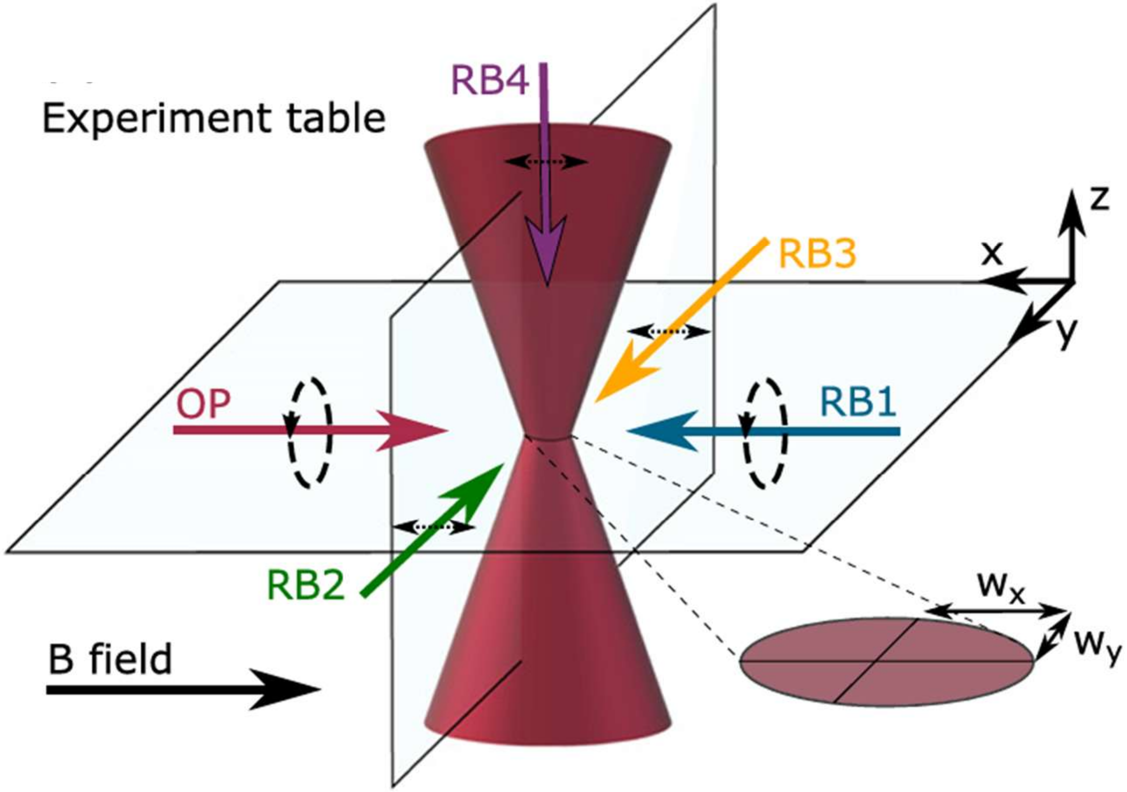
Simultaneous Raman sideband cooling

Common AOMs:
pulse durations same



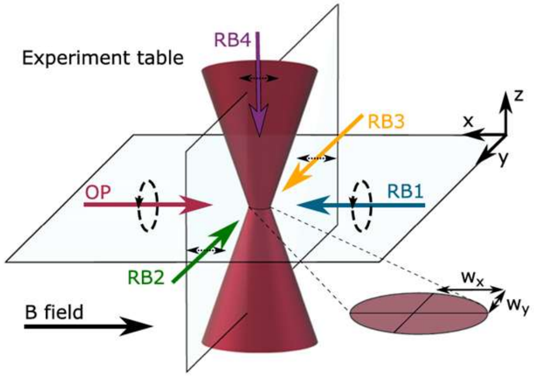
Independent AOMs:
detuning and Rabi frequency control

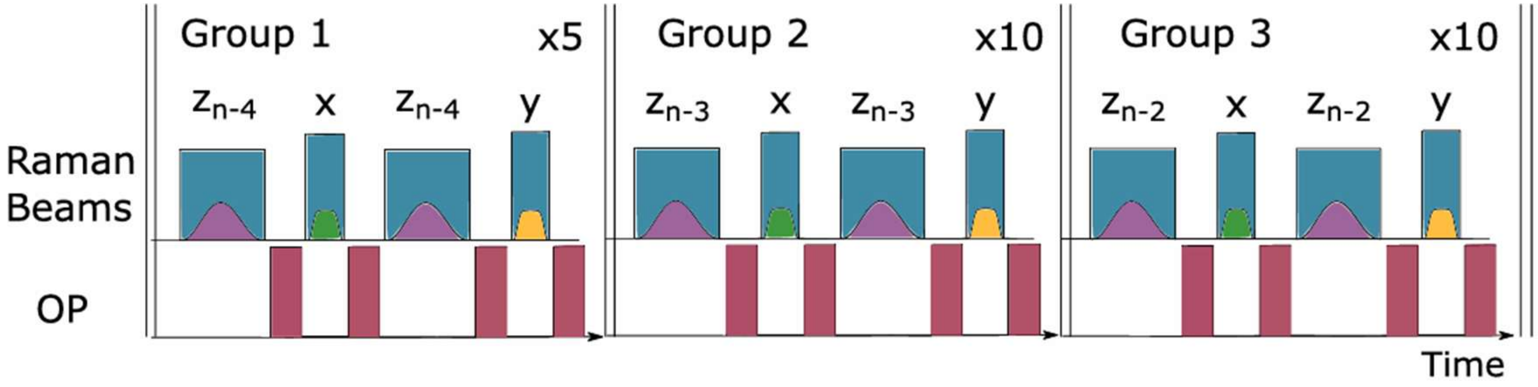
Three pairs of Raman beams – one for each axis
(RB1 is common to all)

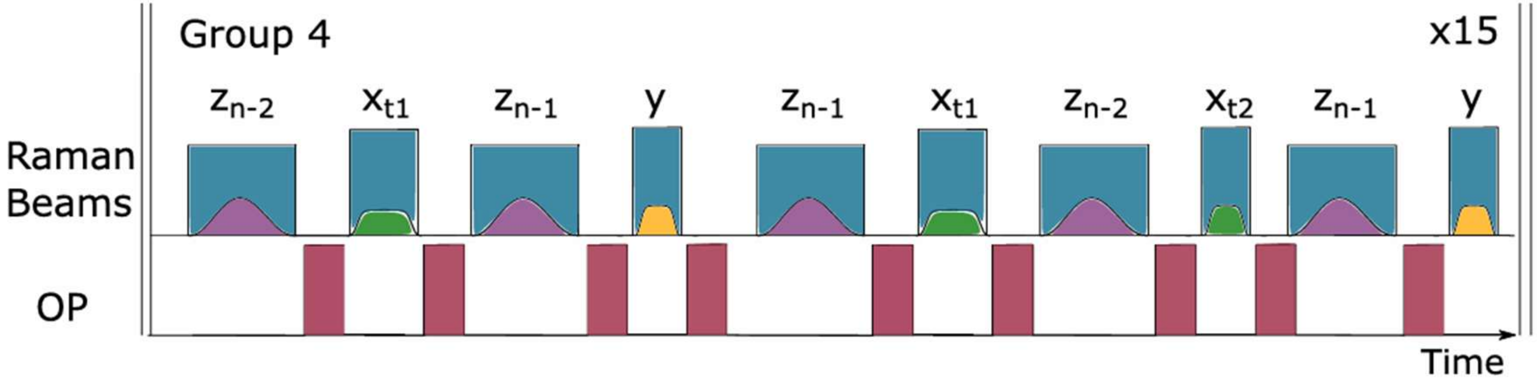


Trap is a little elliptic due to clipping before objective

Simultaneous Raman sideband cooling



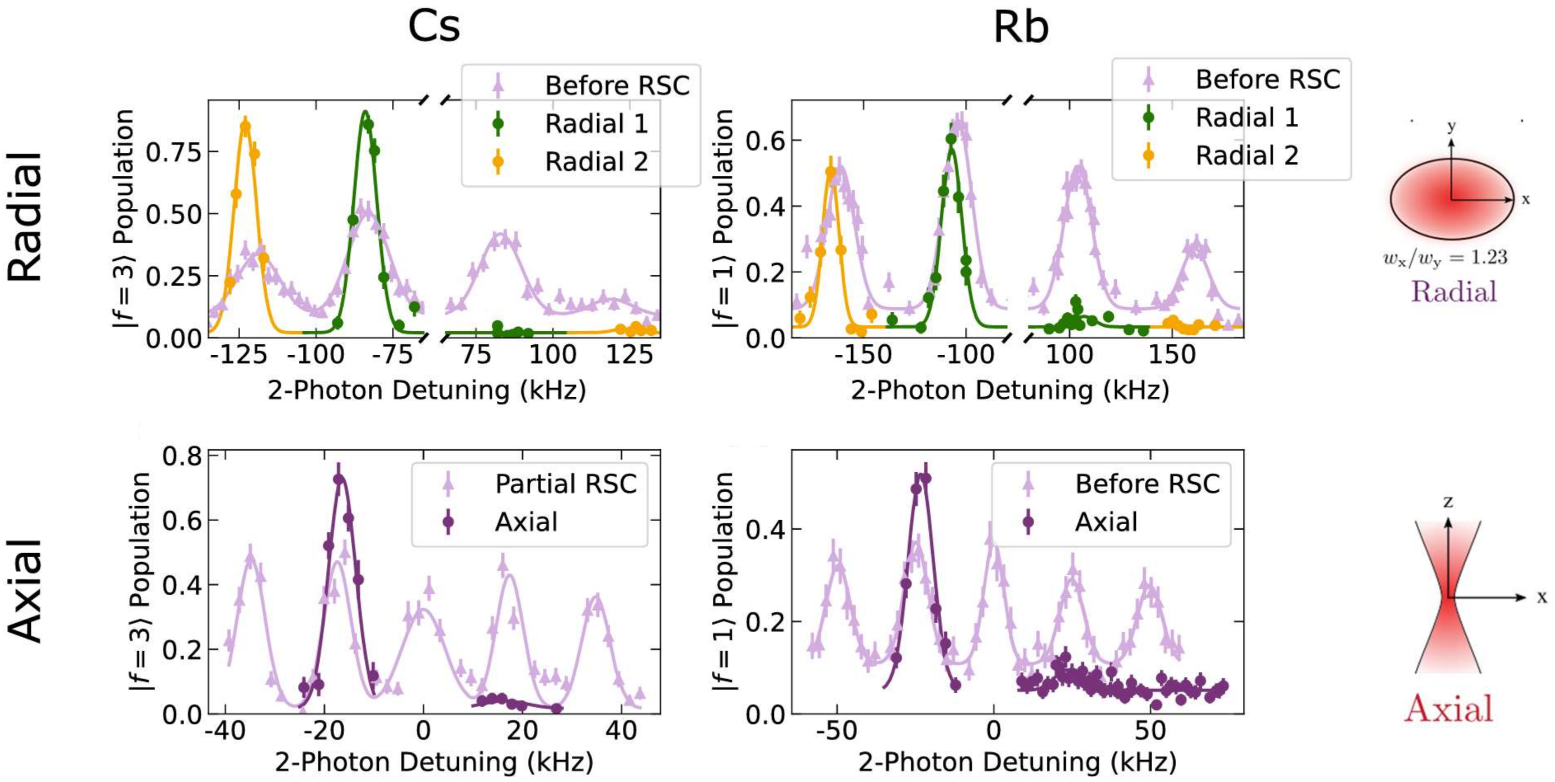




Start outside LD regime in axial direction – use higher order sidebands
Shaped pulses suppress off-resonant excitation of wrong sideband transition
Apply to Cs and Rb at same time. Each Raman pulse approximately a pi-pulse.
Rabi frequencies ~ 5 kHz (axially) and ~20 kHz (radially)

Simultaneous Raman sideband cooling

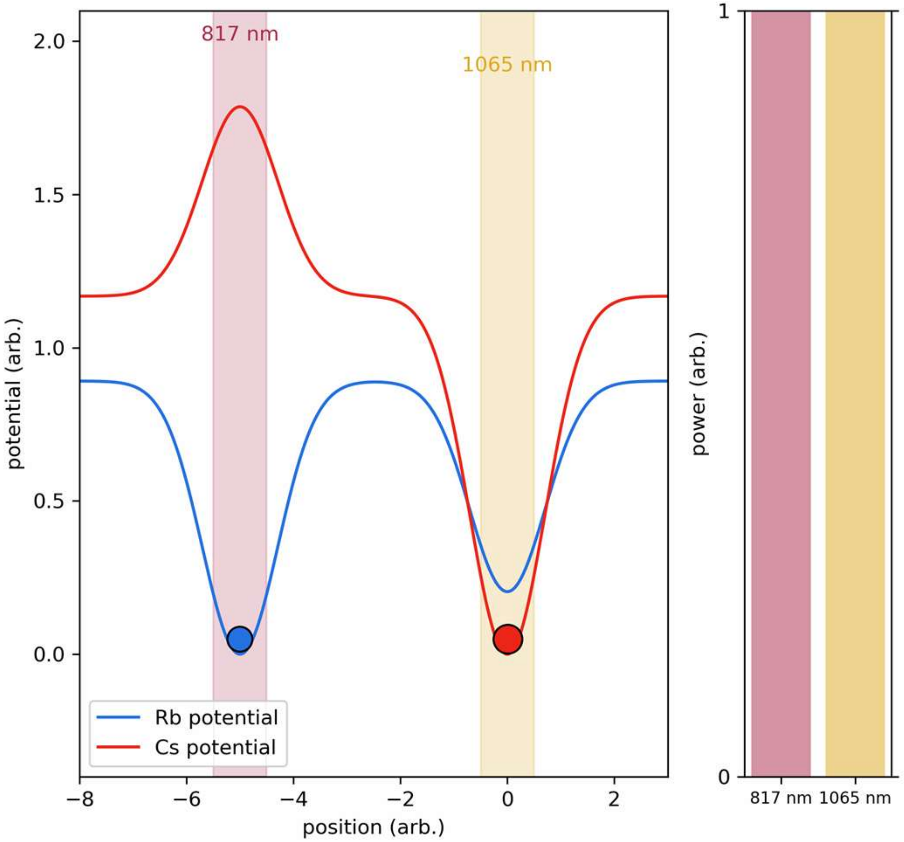
After 45 ms of cooling, the probabilities to occupy 3D motional ground state are
86(4)% for Rb and 95(3)% for Cs



Final temperature balance of cooling and heating

Spence *et al., NJP* **24** 103022 (2022)

Merging Tweezers



Merging optimised to maintain high population in ground state of relative motion

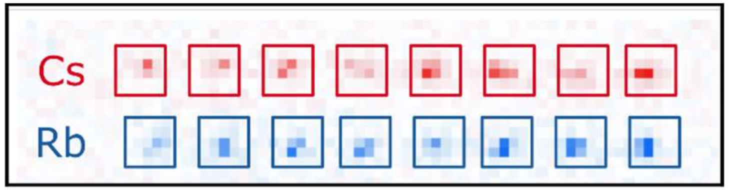
Estimate >60% of atom pairs are in (1,1)(3,3) and n_{rel}=0

New method of forming molecules
Ruttley & Guttridge *et al.*,
PRL **130**, 223401 (2023).

“Mergoassociation”

Formation of arrays of molecules

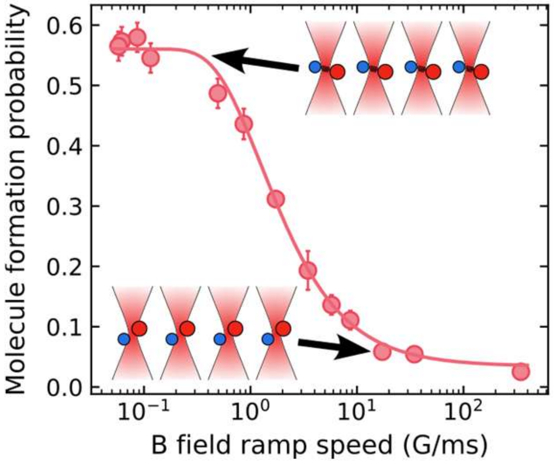
Typically load 8-12 tweezers



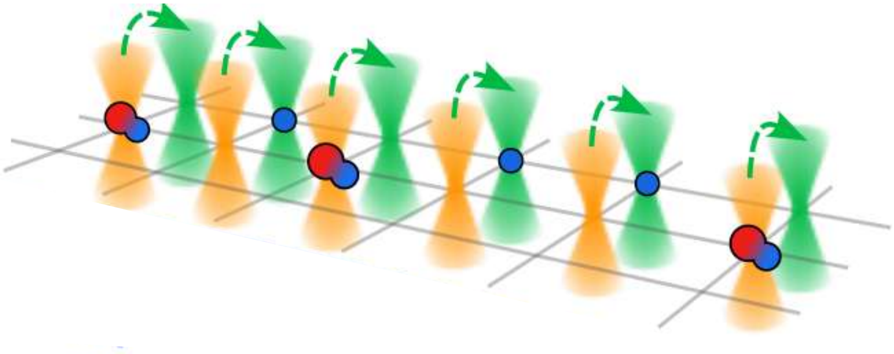
Use 1D rearrangement of Rb and Cs

Molecule formation budget

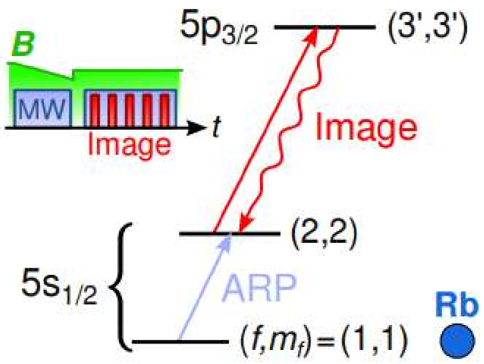
Atom pair state preparation	0.93(3)
Relative motional ground state occupancy after merging	0.56(5)
Magnetoassociation	>0.99

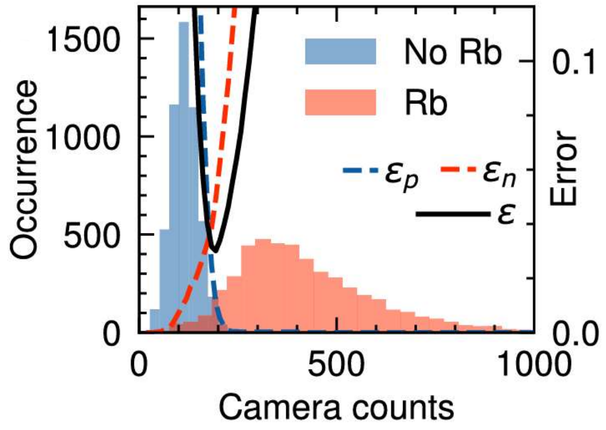


Aside: rearrangement

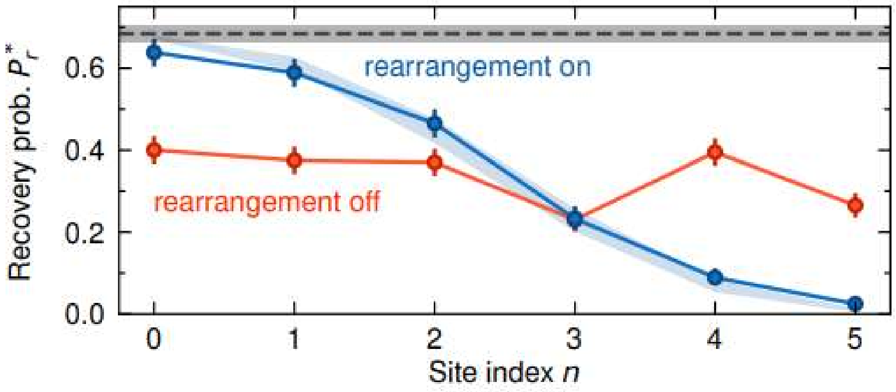


Detect errors mid-sequence with high-field imaging





No longer post-selecting on molecule formation!



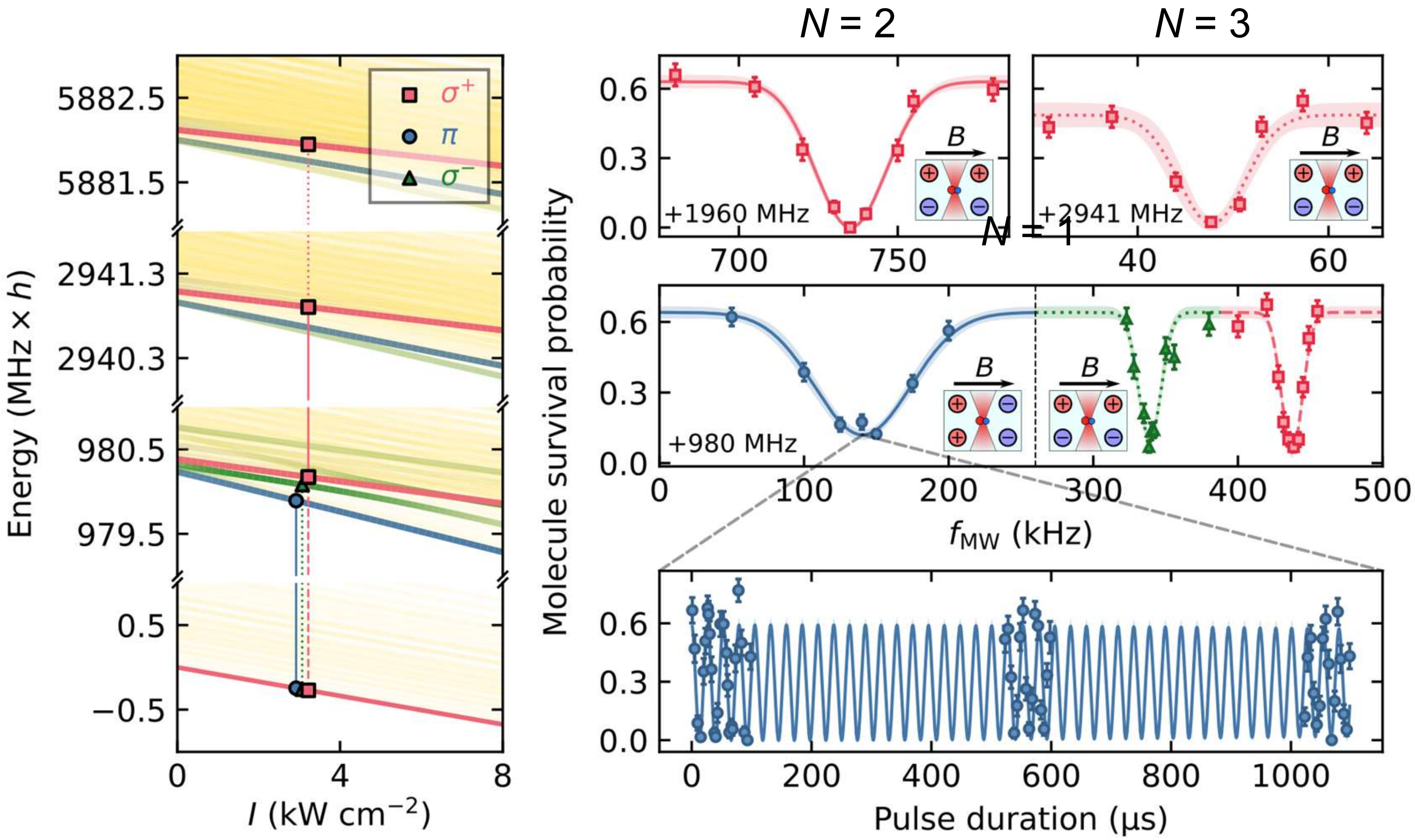
← Recovery limit set by Feshbach loss, return STIRAP and loss of atoms due to imperfect state preparation

Next steps

- Scaling to more traps
- Direct detection of molecule

Ruttley et al., PRX Quantum 5, 020333 (2024)
see also Picard et al., PRX Quantum 5, 020344 (2024)

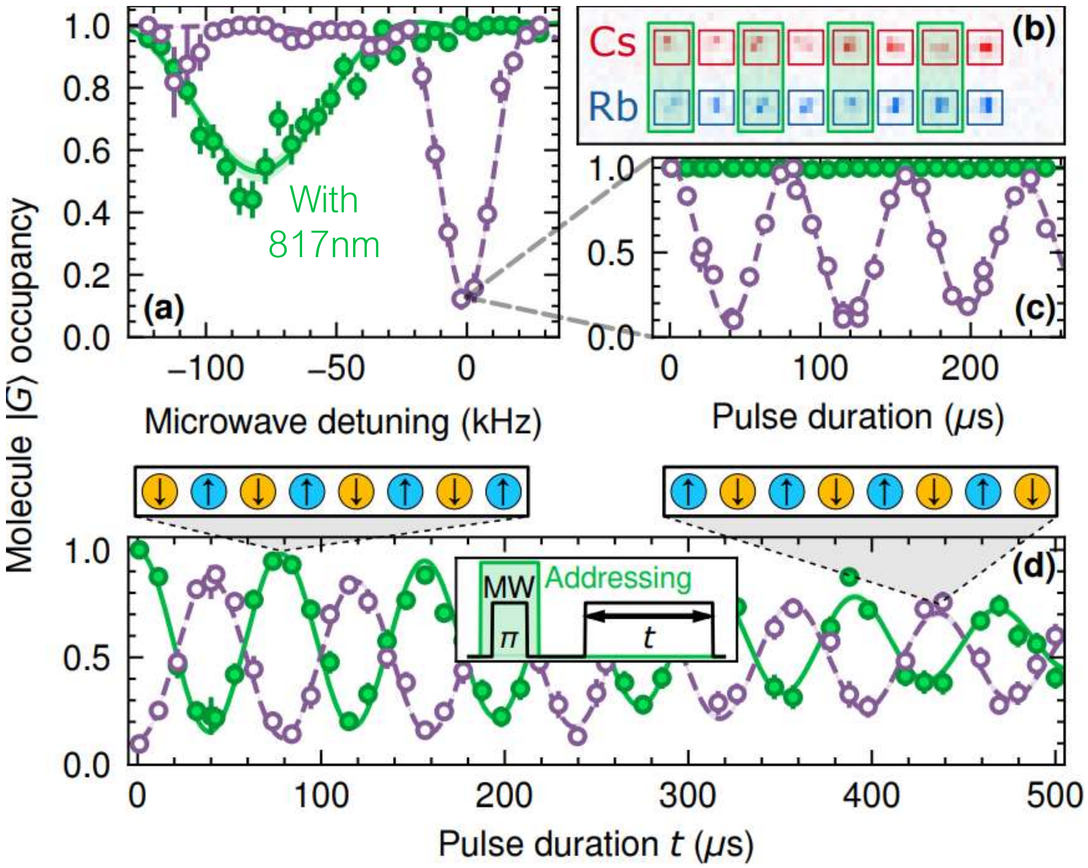
MW Spectroscopy



Builds upon spectroscopy in bulk gases: Gregory et al. Phys. Rev. A 94, 041403(R) (2016)

Microwave transitions & single-site addressing

Add 817nm tweezer to AC Stark shift sites off resonance, global microwave pulse addresses remaining sites

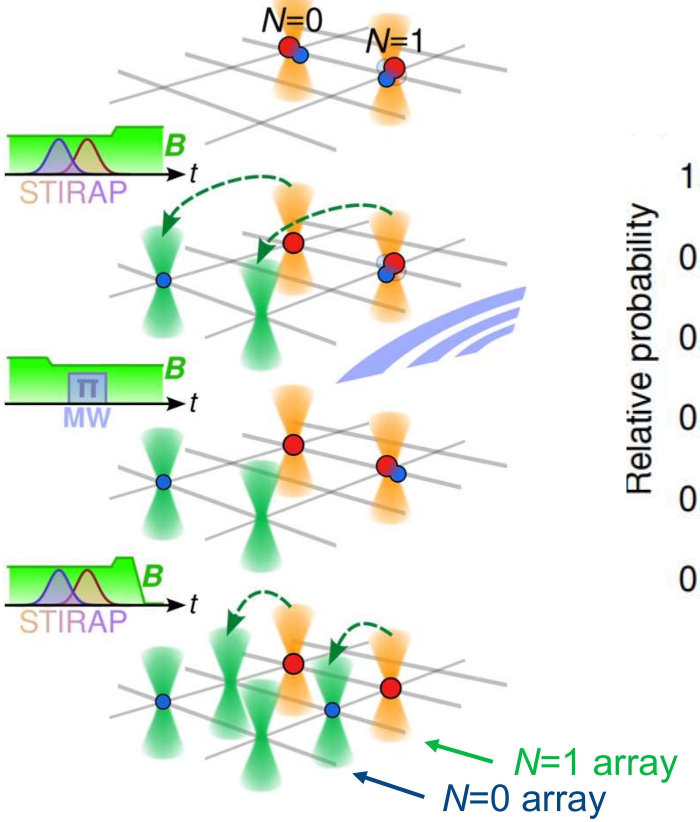


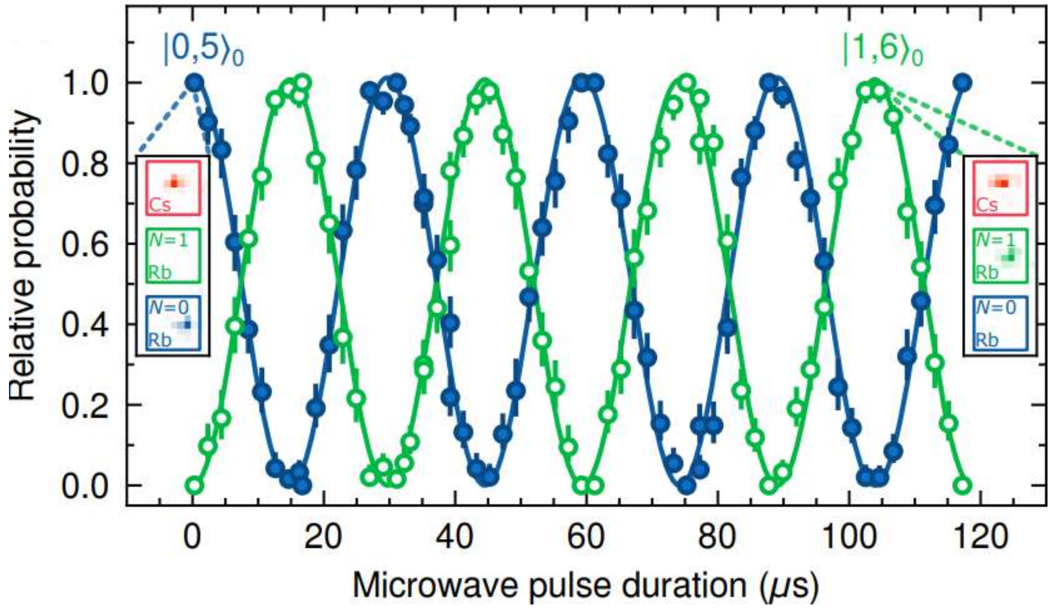
Ruttley et al., PRX Quantum 5, 020333 (2024)
see also Picard et al., PRX Quantum 5, 020344 (2024)

Microwave transition with multi-state readout

Multistate readout key to microwave measurements

Mitigates leakage errors and loss/formation errors that would otherwise look like excitation to $N = 1$

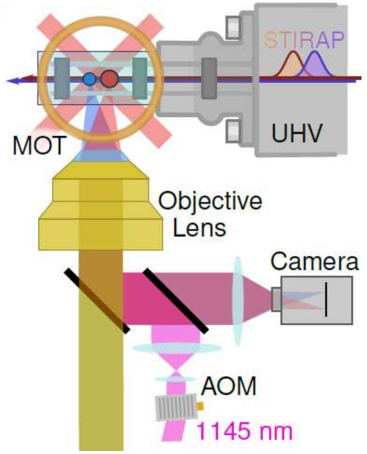


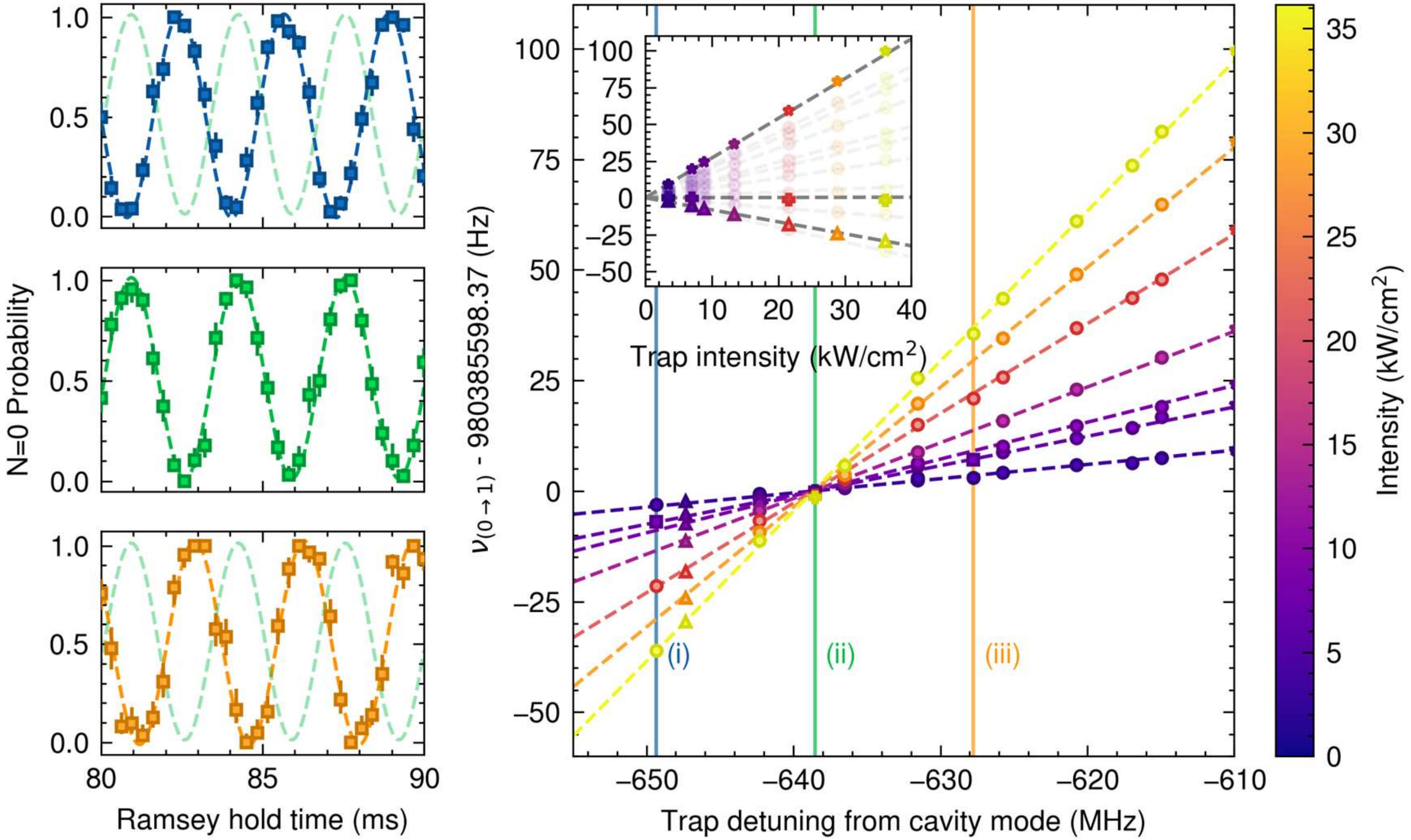


Ruttley et al., PRX Quantum 5, 020333 (2024)
see also Picard et al., PRX Quantum 5, 020344 (2024)

Magic-wavelength tweezers

Added magic tweezer into imaging path – waist 1.87(5) μm. Laser now locked to ULE cavity.
Find magic detuning on $(N=0, M_N=0) \rightarrow (1,1)$ transition using Ramsey spectroscopy.



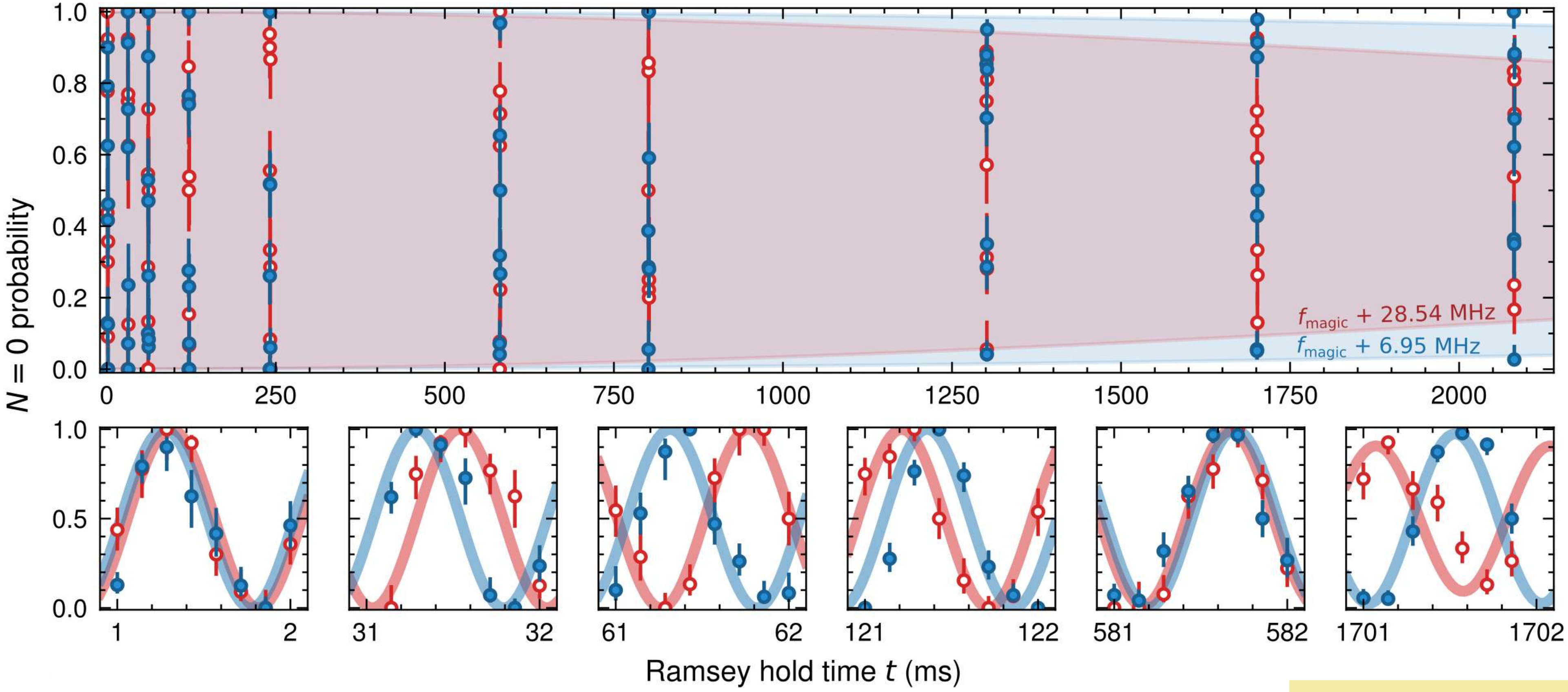


Sensitivity
93.9(3) mHz / $\underbrace{\text{MHz/(kW/cm}^2\text{)}}_{\text{Trap detuning and intensity}}$

Typical coherence assuming 1 MHz detuning, 4 kW/cm^2 and 4% intensity variation:
~66 seconds!

What about rotational coherence?

Two tweezers 8 μm apart so no interactions. Depth = 4 μK (3.6kW/cm^2). Lifetime ~ 10(2) s.
(Blue f_{magic}+6.95 MHz, Red f_{magic} +28.4 MHz) → **~6 Hz difference in transition frequencies**



No spin echo. No dynamic decoupling. Just magic!

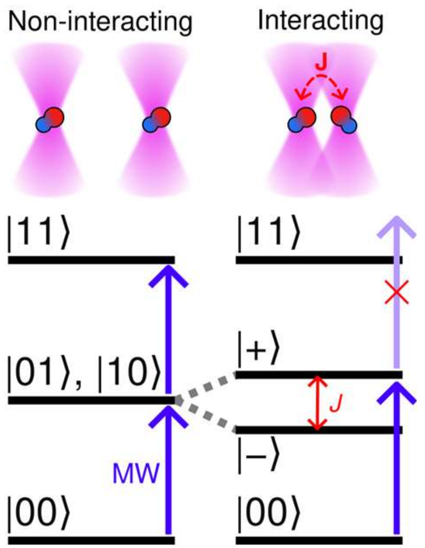
**Measurement time
> 2 seconds!**

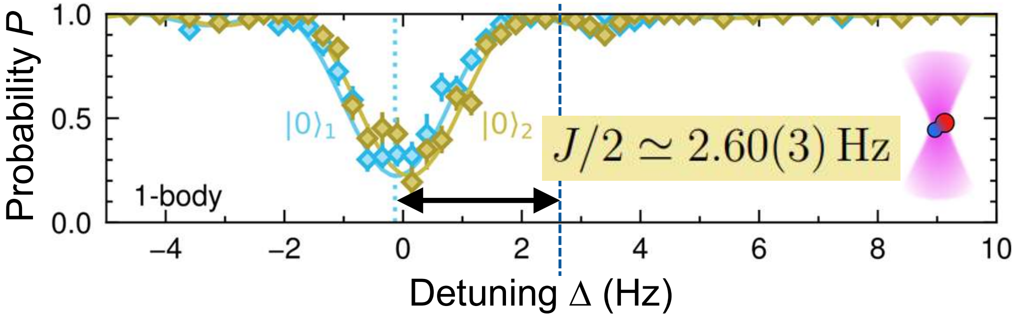
What about interactions?

$$H_{\mathrm{DDI}} = \frac{J}{2}\left(\hat{s}_1^{+}\hat{s}_2^{-} + \hat{s}_1^{-}\hat{s}_2^{+}\right)$$

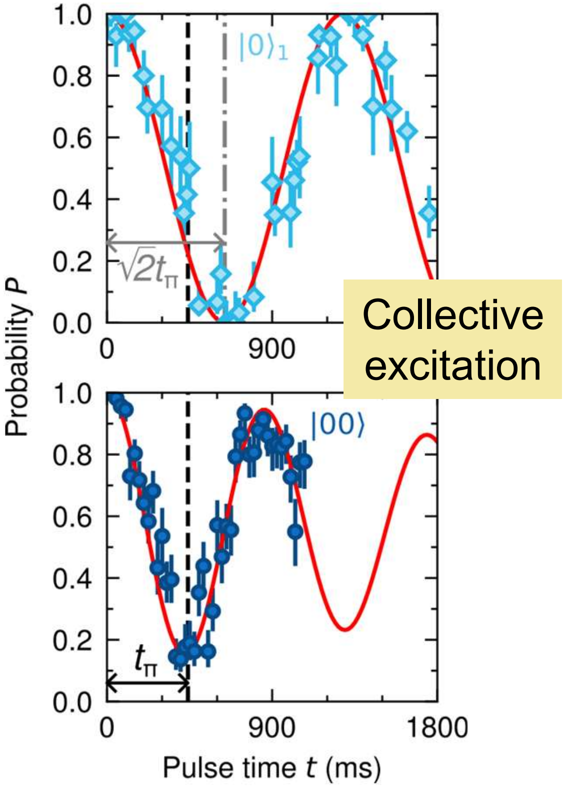
But for ~3 μm separation and $(0,0) \rightarrow (1,1)$ transition, expect $J \simeq 5.6\,\mathrm{Hz}$

Need to make both tweezers magic! Requires some trickery…





$J/2 \simeq 2.60(3)\,\mathrm{Hz}$



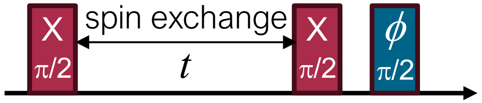
Collective excitation

Ruttley et al., Nature **637**, 821 (2025)

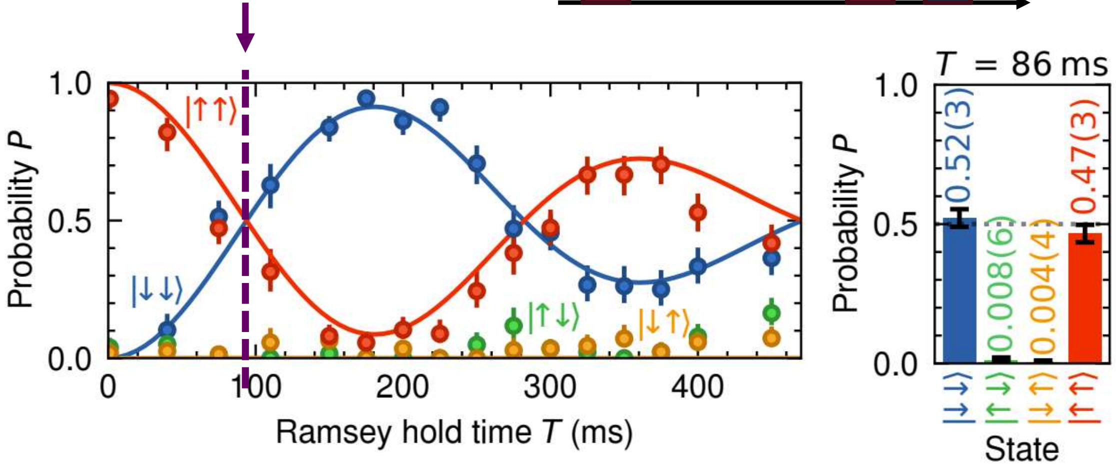
Entanglement via spin-exchange interactions

Spin-exchange interaction in Ramsey sequence $|\Psi(t)\rangle = -e^{-2\pi i \frac{Jt}{4}} \left[\cos\left(2\pi \frac{Jt}{4}\right) |\downarrow\downarrow\rangle - i \sin\left(2\pi \frac{Jt}{4}\right) |\uparrow\uparrow\rangle\right]$

Evolve for $\dfrac{1}{2J}$ to produce maximally entangled state $\frac{1}{\sqrt{2}}(|\downarrow\downarrow\rangle - i\,|\uparrow\uparrow\rangle)$ (- equivalent to Bell state $|\Phi^{\pm}\rangle$)

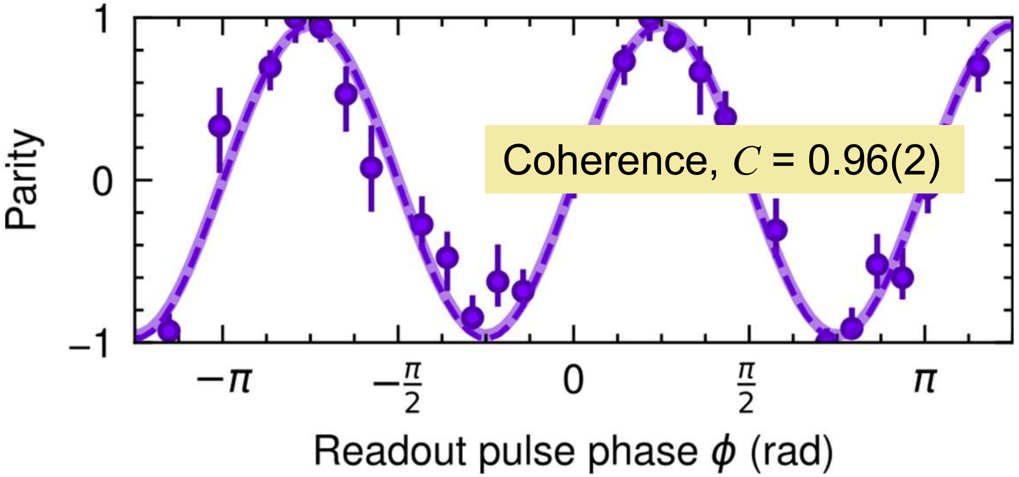


~86 ms



Measure coherence with parity oscillations

Parity $= P_{00} + P_{11} - P_{01} - P_{10}$



Coherence, C = 0.96(2)

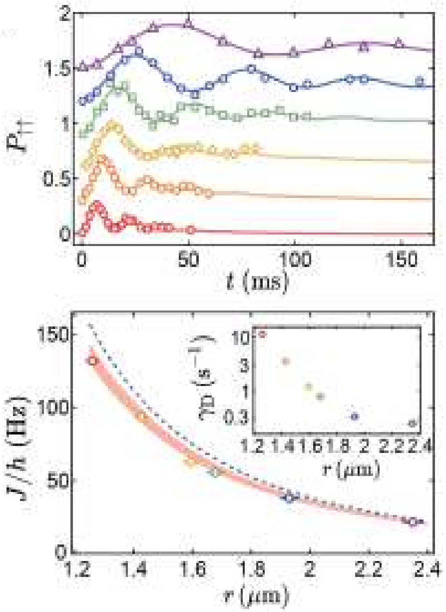
$$\text{Fidelity} = \frac{1}{2}(C + P_{|\downarrow\downarrow\rangle} + P_{|\uparrow\uparrow\rangle}) = 0.976^{+0.014}_{-0.016}$$

Ruttley et al., Nature **637**, 821 (2025)

(Automatically corrected for loss; otherwise $0.924^{+0.013}_{-0.016}$)

Competitive with state of the art

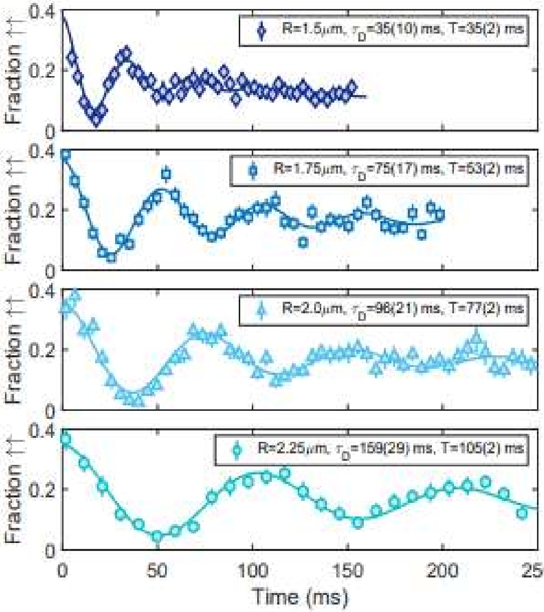
CaF



Cheuk Group
(Princeton)
Science **382**, 1143 (2023)

Fidelity, F_{SPAM} = 0.80(2)

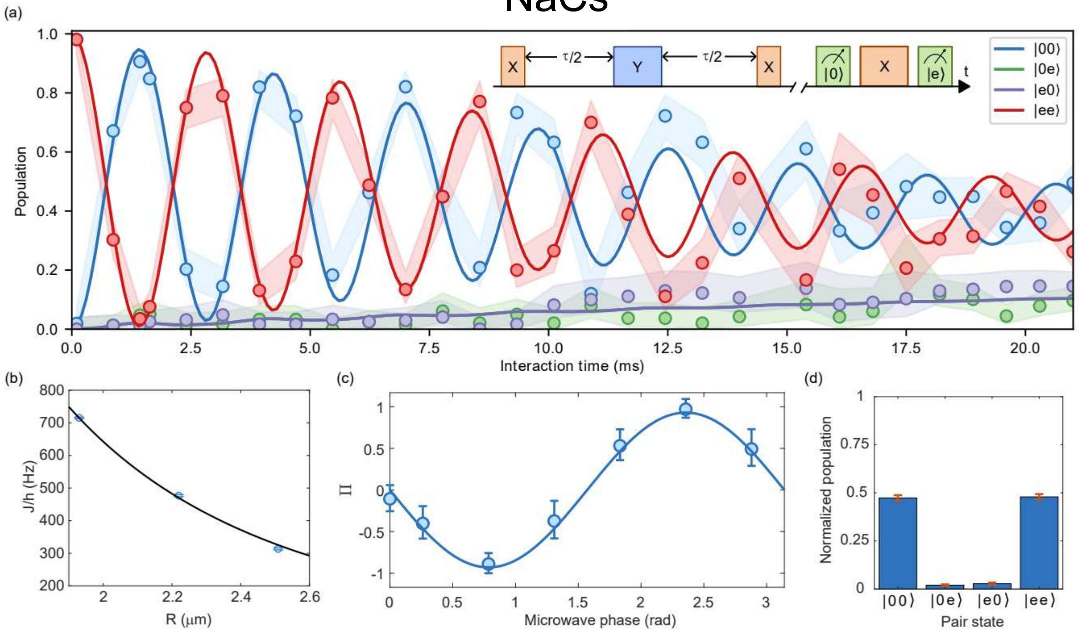
CaF



Doyle group
(Harvard)
Science **382**, 1138 (2023)

Fidelity, F_{SPAM} = 0.89(7)

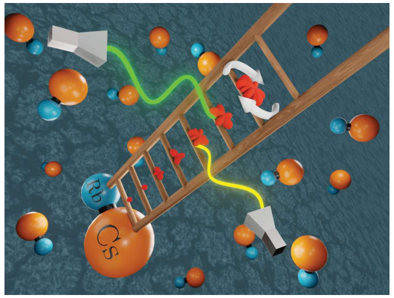
NaCs



Ni group
(Harvard)
Nature **637**, 821 (2025)

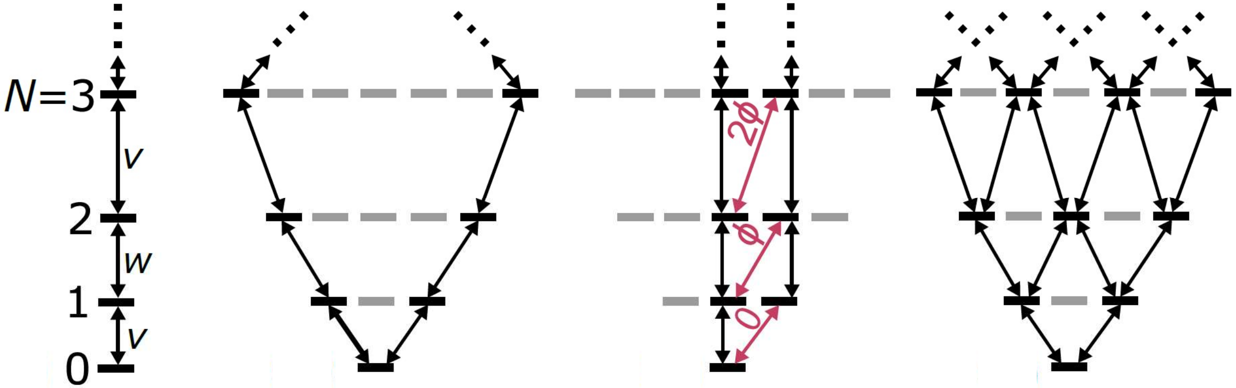
Fidelity = 0.94(3)

Exploiting the richness of rotation – synthetic dimensions



Advantages of synthetic dimensions:

- Increase dimensionality of the system
- Site specific tunnelling controlled with microwave fields
- Geometry easily reconfigured
- Single site detection trivial



Su-Schrieffer-Heeger model

1D chain with periodic boundary conditions

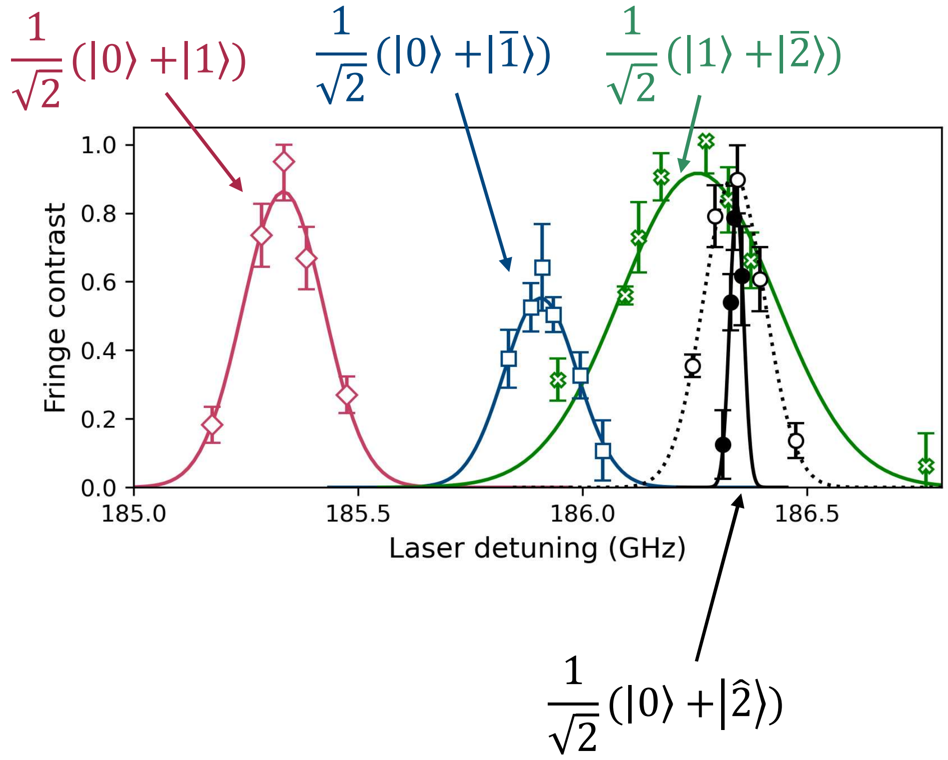
Simulating gauge fields

2D square lattice

“Synthetic dimensions in ultracold polar molecules”
Sundar, Gadway, Hazzard, Scientific Reports **8**, 3422 (2018)

Extending to multiple rotational levels

But – the magic detuning depends on the rotational-state superposition

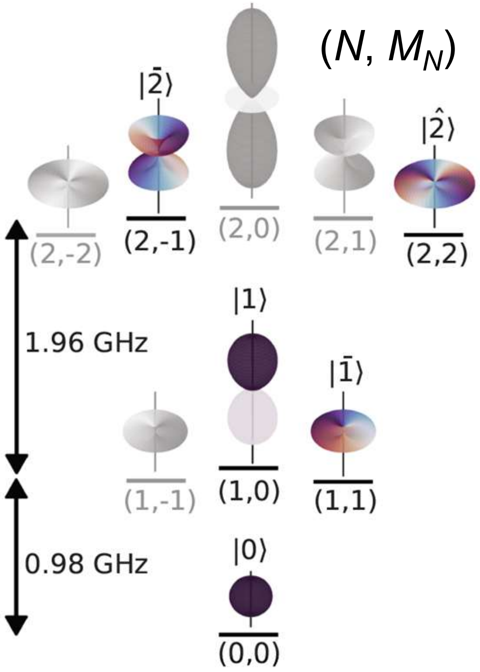


$\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$

$\frac{1}{\sqrt{2}}(|0\rangle + |\bar{1}\rangle)$

$\frac{1}{\sqrt{2}}(|1\rangle + |\bar{2}\rangle)$

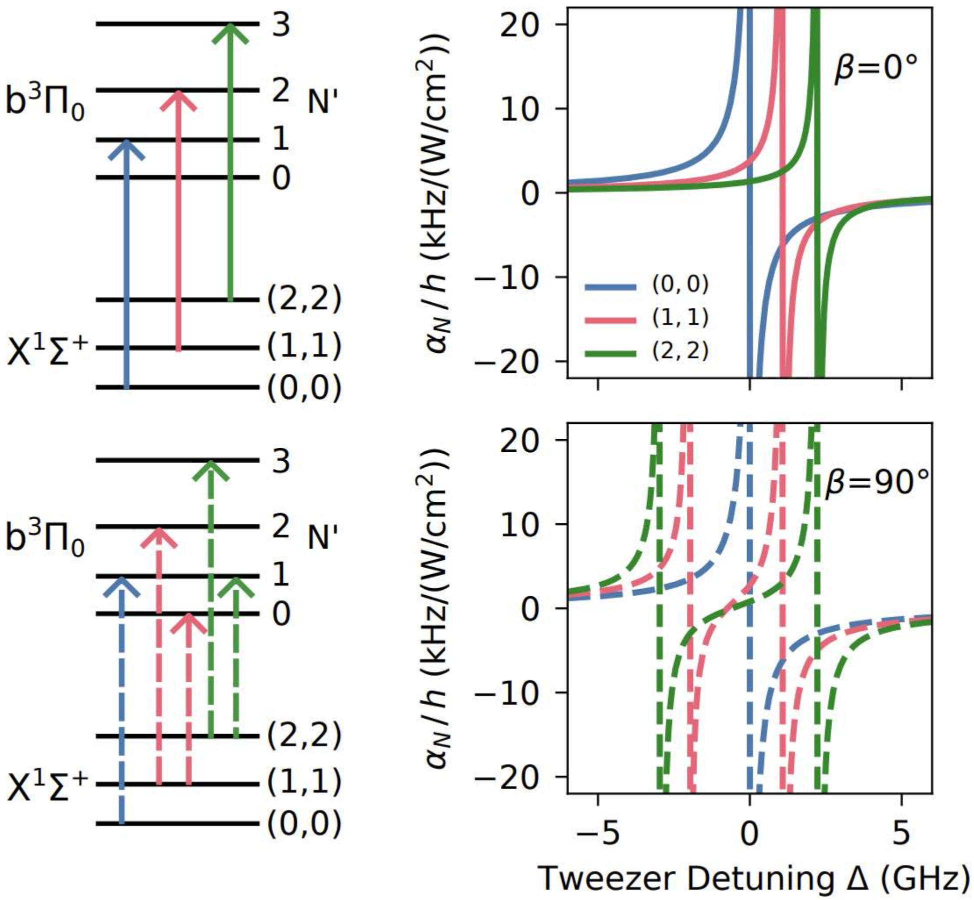
$\frac{1}{\sqrt{2}}(|0\rangle + |\hat{2}\rangle)$



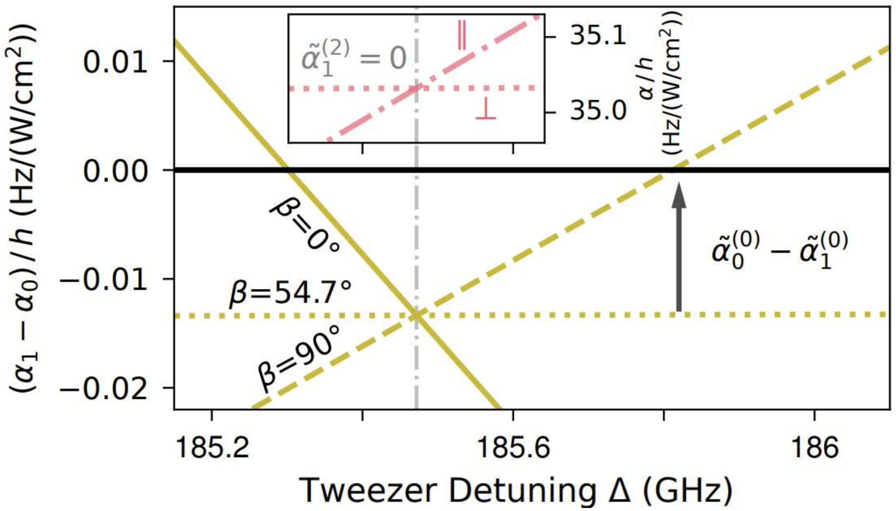
Gregory *et al.*, Nature Physics 20, 415 (2024)

Origin of rotational dependence

Transitions controlling the polarizability shift due to rotational structure & selection rules



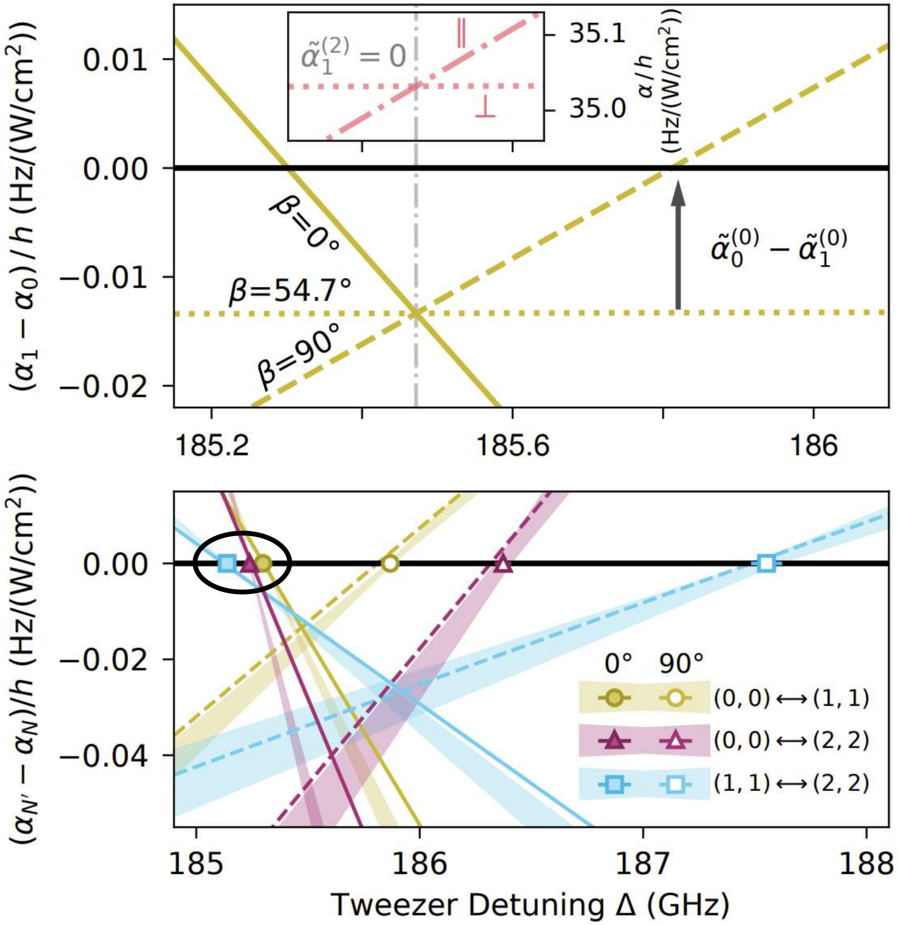
At 185 GHz – isotropic polarizability is *slightly* *N* dependent
Compensate with *small* anisotropic polarizability



We can measure this in tweezers!

Extending to three rotational states

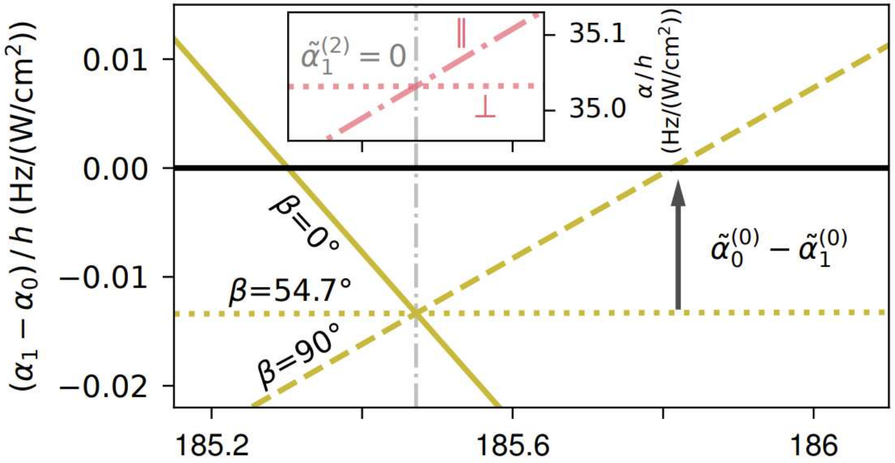
Measure magic detuning for different superpositions.

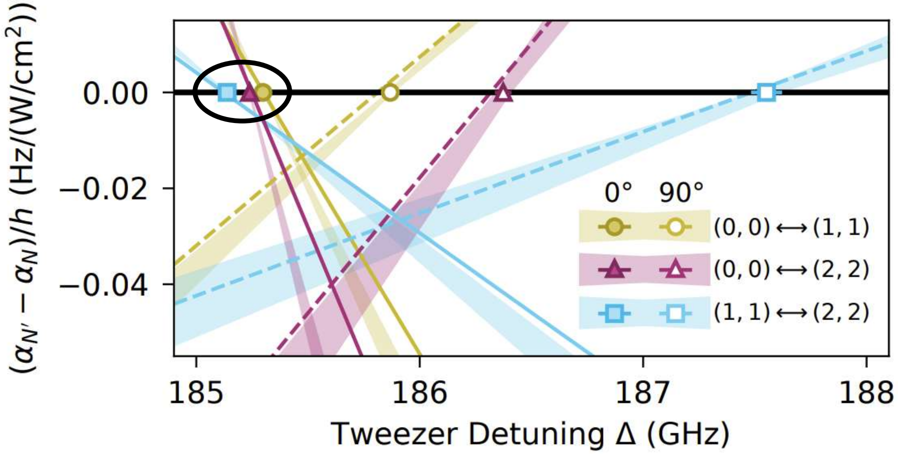


Parallel polarisation is better!

Extending to three rotational states

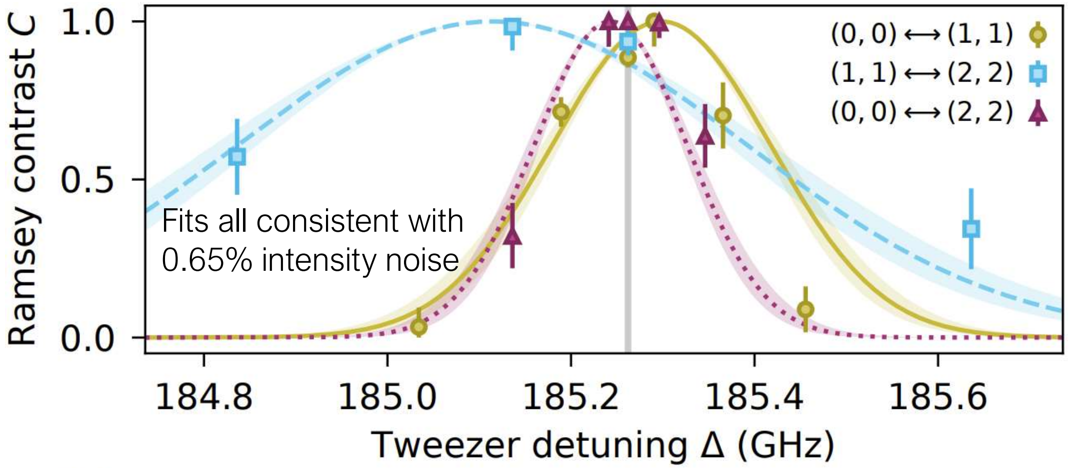
Measure magic detuning for different superpositions



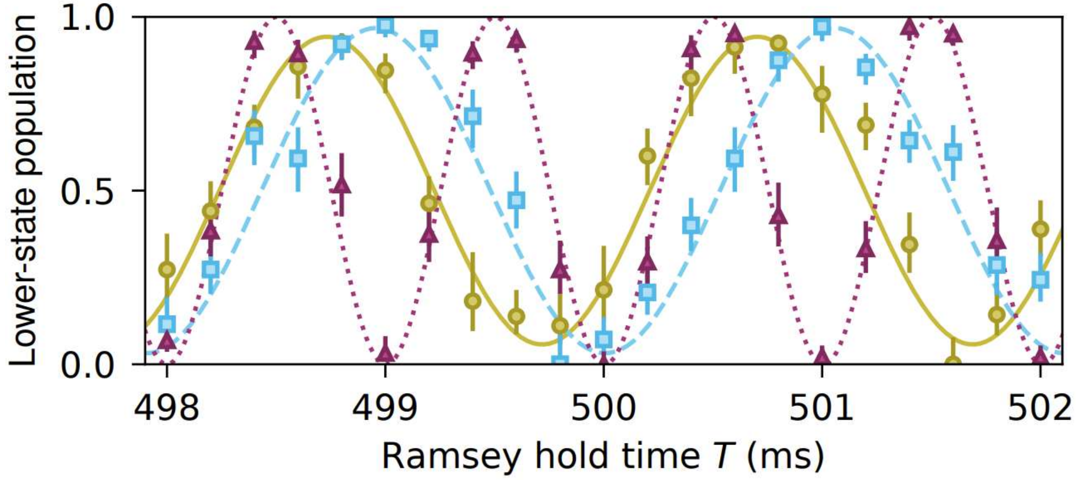


Parallel polarisation is better!

Map out fringe contrast for 0.5s Ramsey time



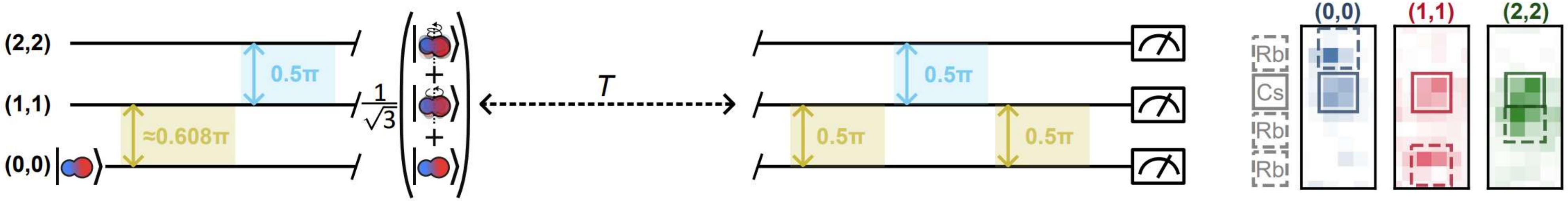
Fits all consistent with 0.65% intensity noise



High contrast for all three superpositions

Three level generalised Ramsey sequence

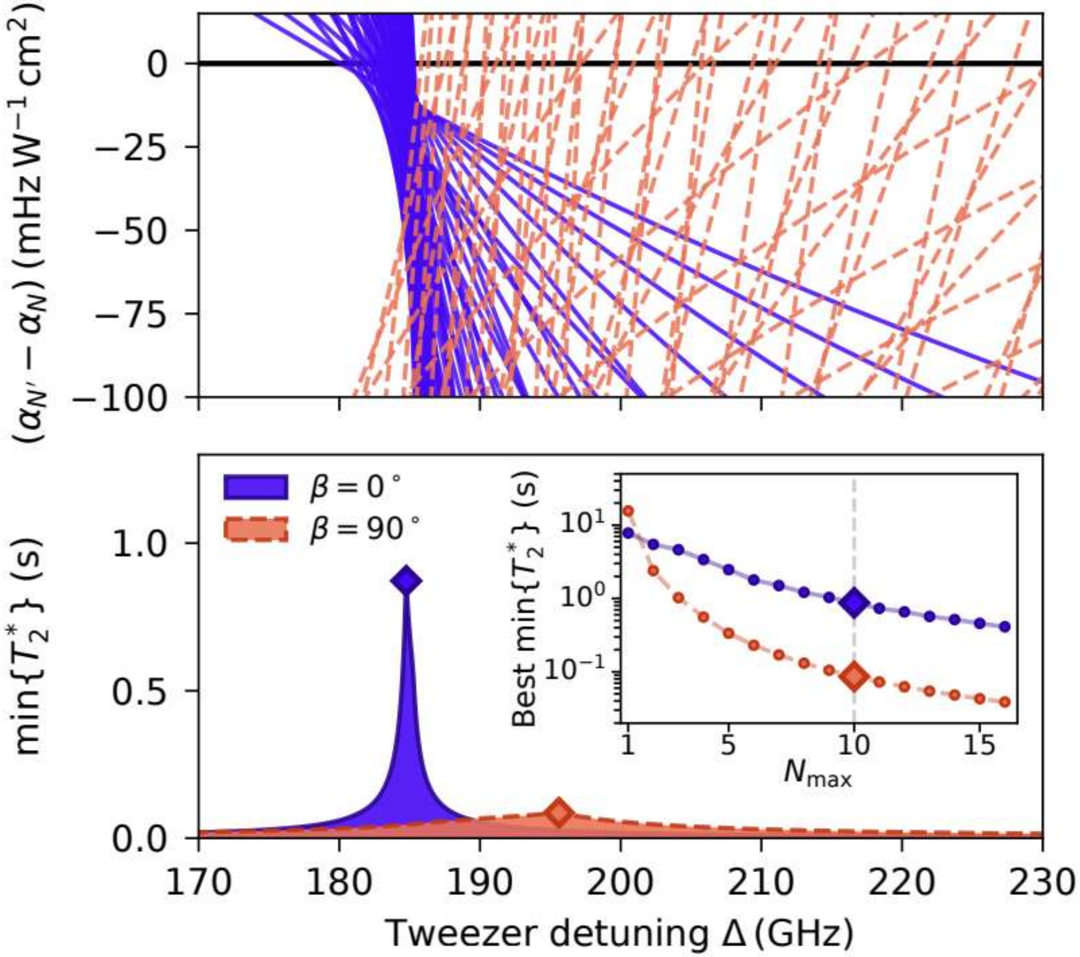
Prepare coherent superposition of 3 **rotational states**, evolve, close Ramsey interferometer. Multistate readout.



Next: interacting spin-1 system OR mapping to spin ½ hard-core bosons / t-J models:
Homeier et al., PRL **132**, 230401 (2024); Wellnitz et al., arXiv:2409.05109; Qiao et al., arXiv:2501.08233

Extending the magic trap to more levels

Prediction assuming I = 4.6(3) kW/cm^2 and intensity noise of 0.1%

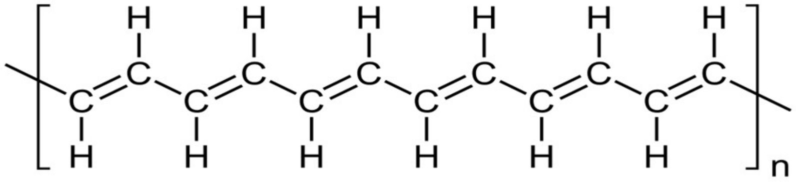


Crossings indicate predicted magic detuning for different rotational superpositions

Estimated coherence time for all superpositions involving N = 0 to 10

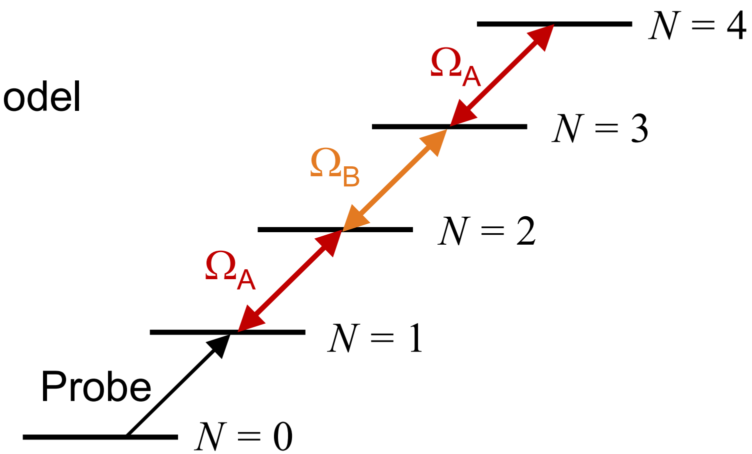
Example: Su-Shreiffer-Heeger (SSH) model

- 1D lattice model with topological features
- Developed to describe conductivity of polyacetylene
- Chain with two alternating tunnelling rates



Map onto rotational levels with tunnelling controlled by microwave Rabi frequencies

E.g. minimal 4-level model



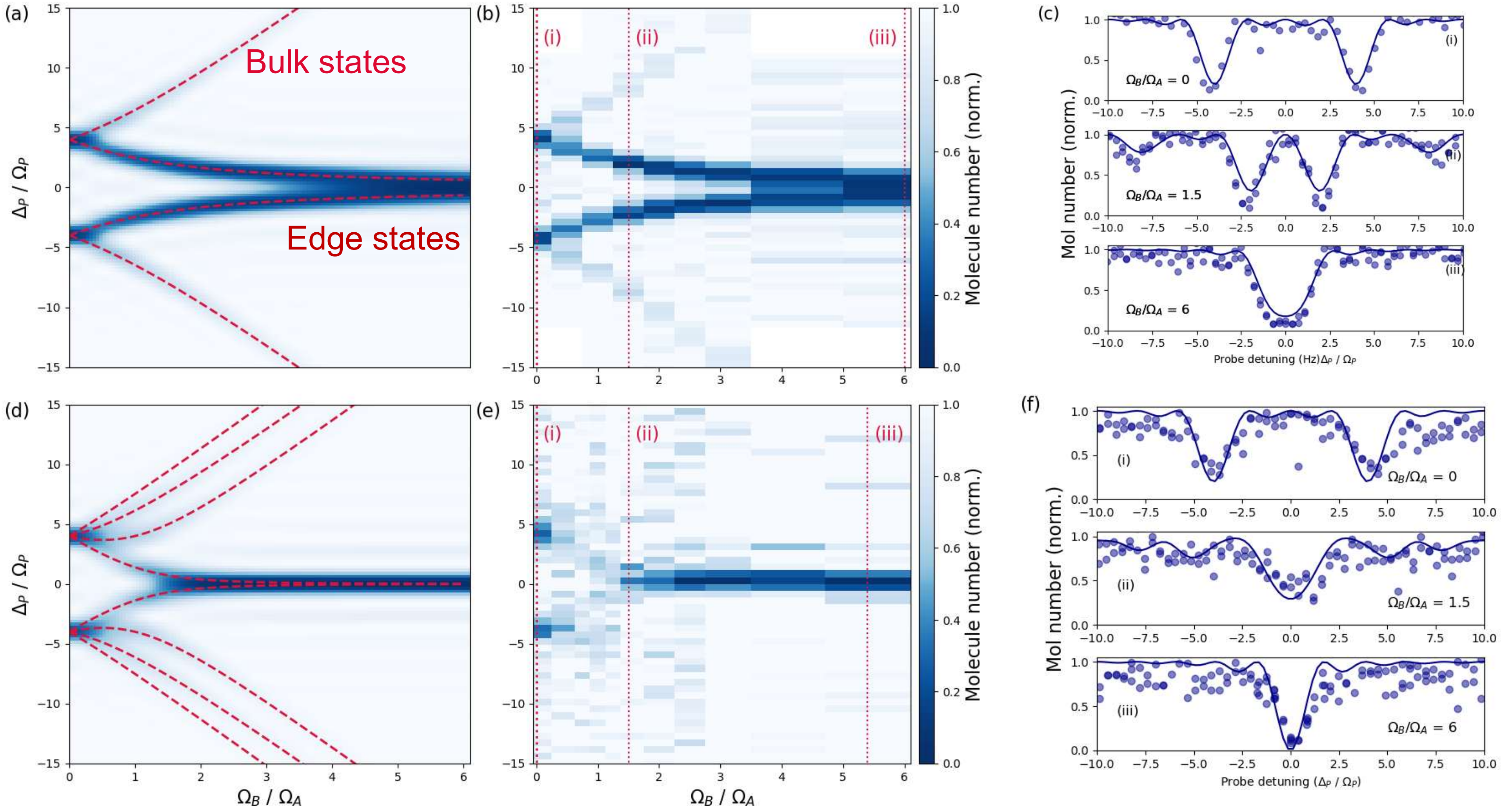
Perform spectroscopy on
N = 0 → 1 transition

See similar work in Rydberg atoms:
Browaeys, Killian, Gadway, Deiglmayr…

Example: Su-Shreiffer-Heeger (SSH) model

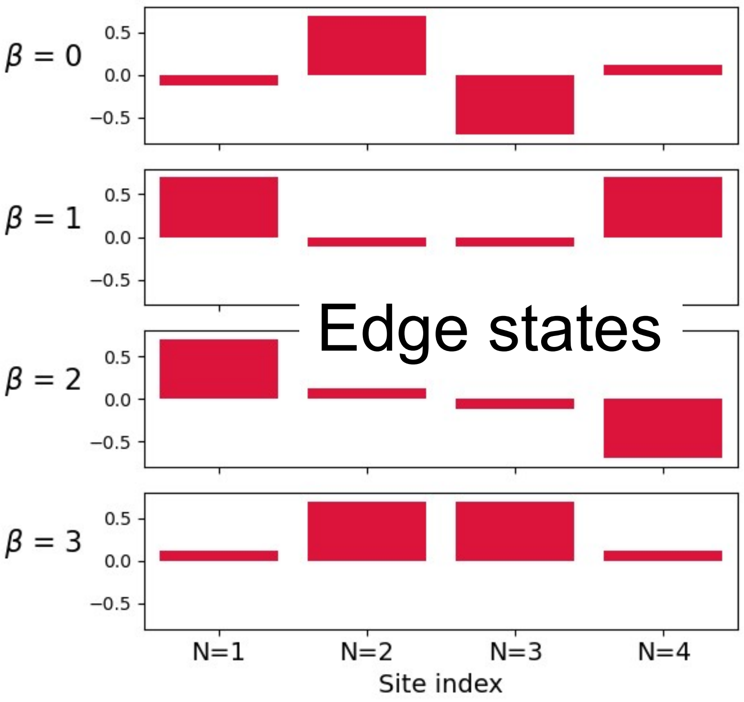
4 levels

8 levels

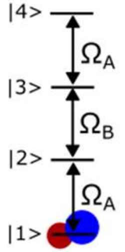


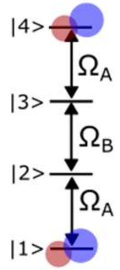
Example: SSH time dynamics

Eigenstate composition
(4-levels Ω_A = 2.3 kHz, Ω_B = 13 kHz)

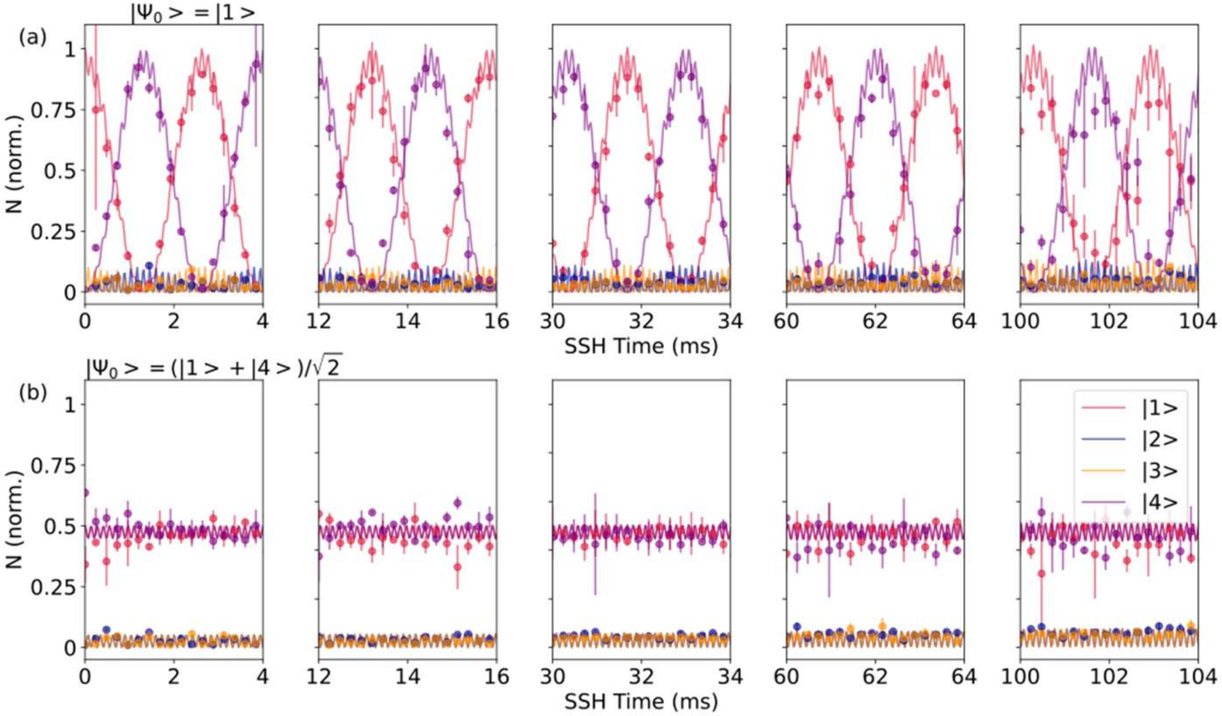


Edge states



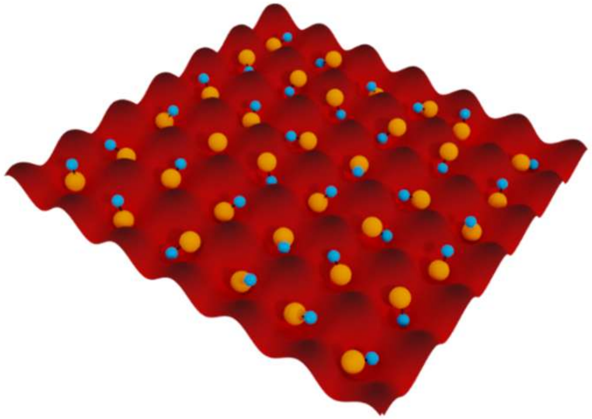


Prepare in N = 1 (≈ superposition of eigenstates)



Prepare in superposition of N = 1 and 4 (≈ an eigenstate)

What about lattices?



First observation of spin-exchange interactions

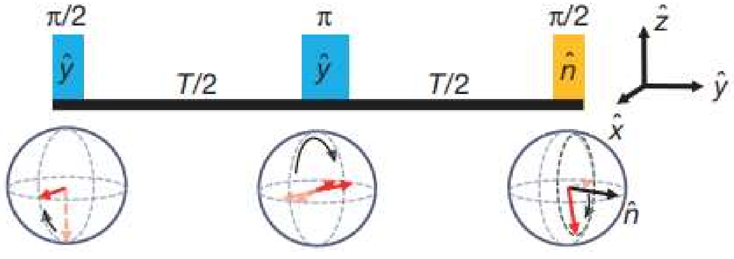
Letter | Published: 18 September 2013

Observation of dipolar spin-exchange interactions with lattice-confined polar molecules

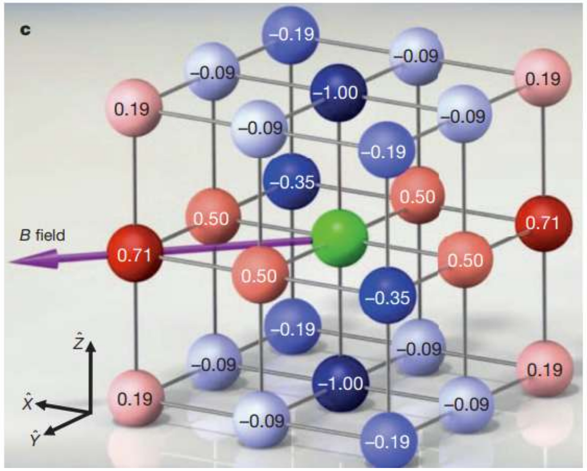
Bo Yan, Steven A. Moses, Bryce Gadway, Jacob P. Covey, Kaden R. A. Hazzard, Ana Maria Rey, Deborah S. Jin & Jun Ye

Nature **501**, 521–525 (2013) | Cite this article

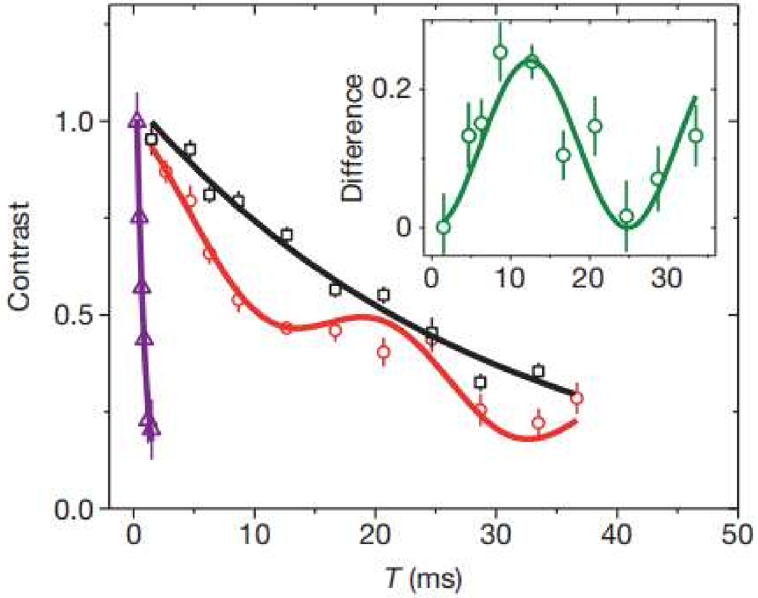
Perform Ramsey interferometry



3D lattice with ~10% filling



Using KRb molecules
(0,0) & (1,1)

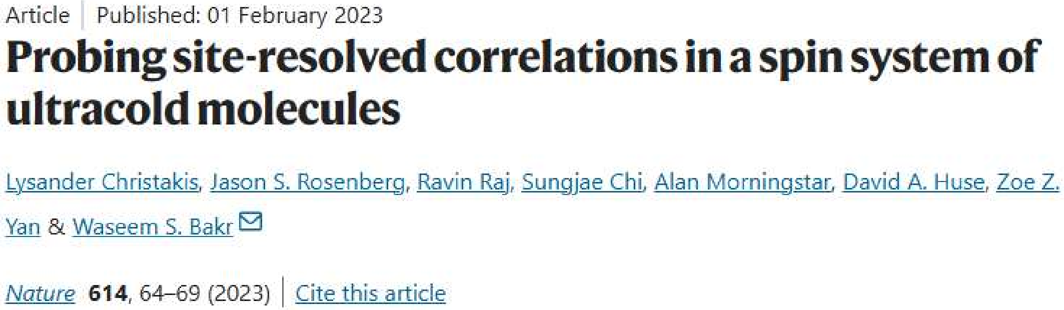


Pulse sequence to suppress pair-wise dipolar interactions
(contrast decay now due to interactions of multiple molecules)

Spin echo - oscillation due to spin-exchange interactions
(removes single particle dephasing)

No spin echo
(single particle dephasing)

Quantum gas microscopy



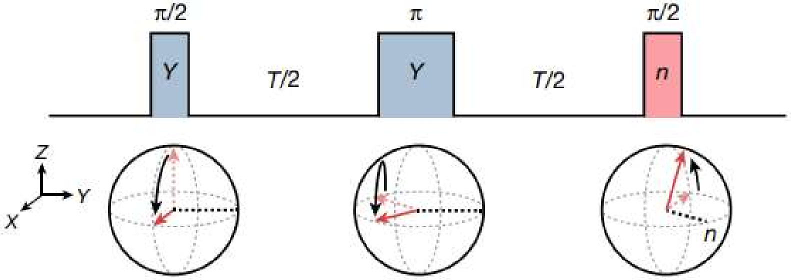
Article | Published: 01 February 2023

Probing site-resolved correlations in a spin system of ultracold molecules

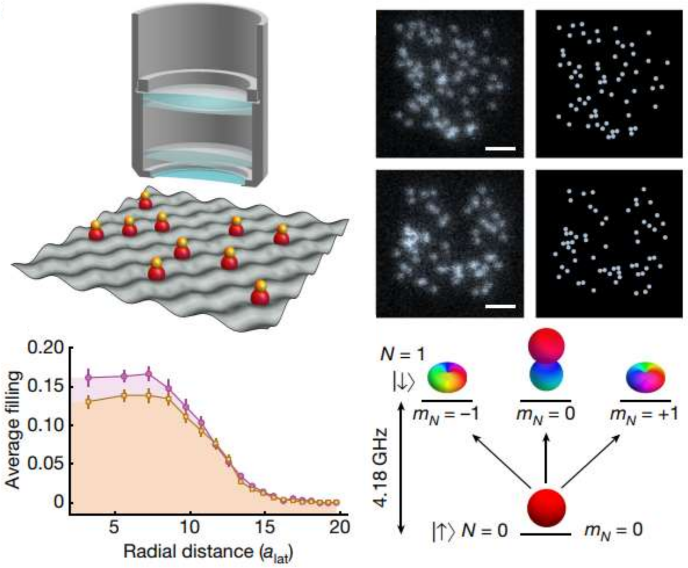
Lysander Christakis, Jason S. Rosenberg, Ravin Raj, Sungjae Chi, Alan Morningstar, David A. Huse, Zoe Z. Yan & Waseem S. Bakr

Nature **614**, 64–69 (2023) | Cite this article

Perform Ramsey interferometry

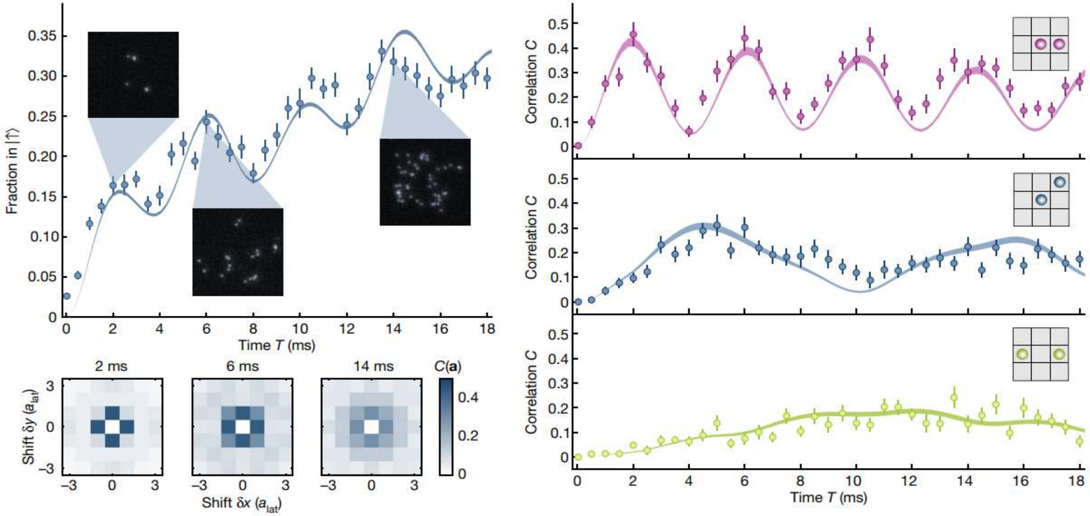


2D lattice with ~10% filling



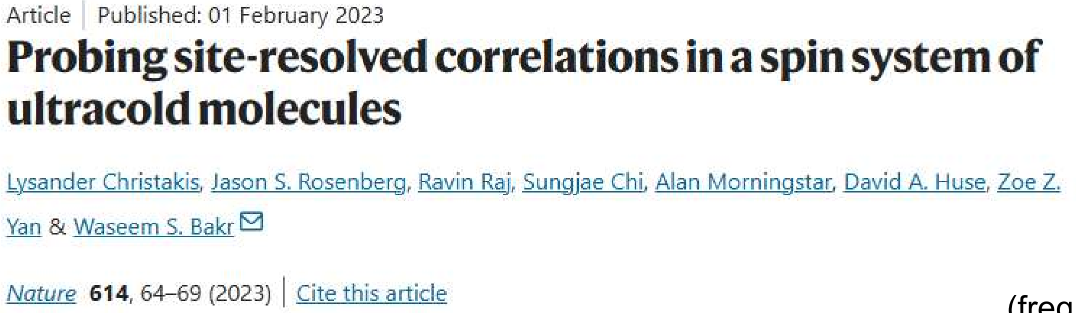
Using NaRb molecules

Observe correlated XY spin dynamics



Ramsey phase set to leave molecules in $|\downarrow\rangle$ which is dark to detection
Interactions entangle pairs producing oscillations between $|\downarrow\downarrow\rangle$ & $|\uparrow\uparrow\rangle$ c.f. tweezers

Quantum gas microscopy



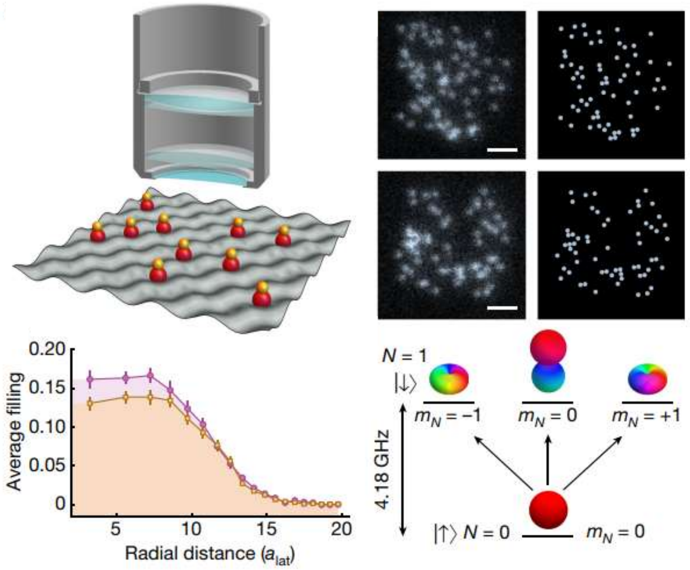
Article | Published: 01 February 2023

Probing site-resolved correlations in a spin system of ultracold molecules

Lysander Christakis, Jason S. Rosenberg, Ravin Raj, Sungjae Chi, Alan Morningstar, David A. Huse, Zoe Z. Yan & Waseem S. Bakr

Nature **614**, 64–69 (2023) | Cite this article

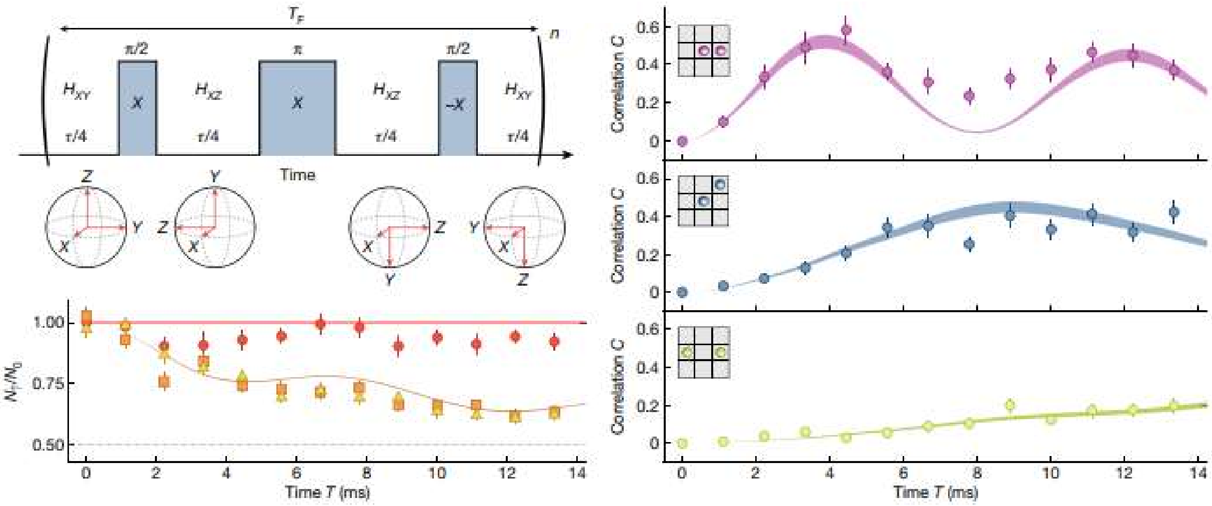
2D lattice with ~10% filling



Using NaRb molecules

Floquet engineering of XXZ model

(frequent rotations around the Bloch sphere such that the molecules evolve for an equal time under H_{XY} and H_{XZ} time-averaging to H_{XXZ})



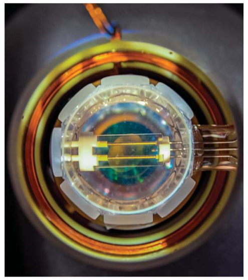
Recent advances

Article | Published: 11 September 2024

Two-axis twisting using Floquet-engineered XYZ spin models with polar molecules

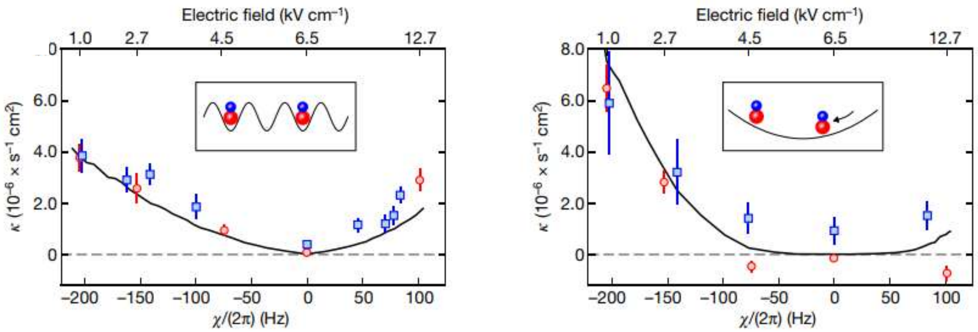
Calder Miller, Annette N. Carroll, Junyu Lin, Henrik Hirzler, Haoyang Gao, Hengyun Zhou, Mikhail D. Lukin & Jun Ye

Nature **633**, 332–337 (2024) | Cite this article

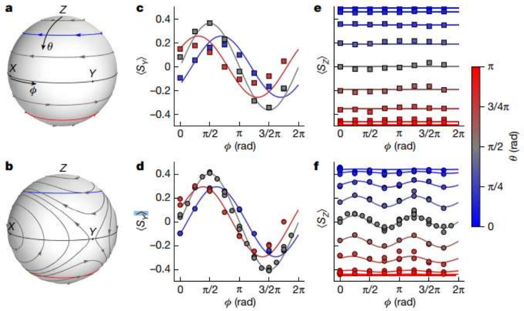


Benchmarking XXZ spin dynamics

Electric field vs. Floquet engineering



Then use Floquet engineering to realise TAT Hamiltonian



Observation of generalized *t*-*J* spin dynamics with tunable dipolar interactions

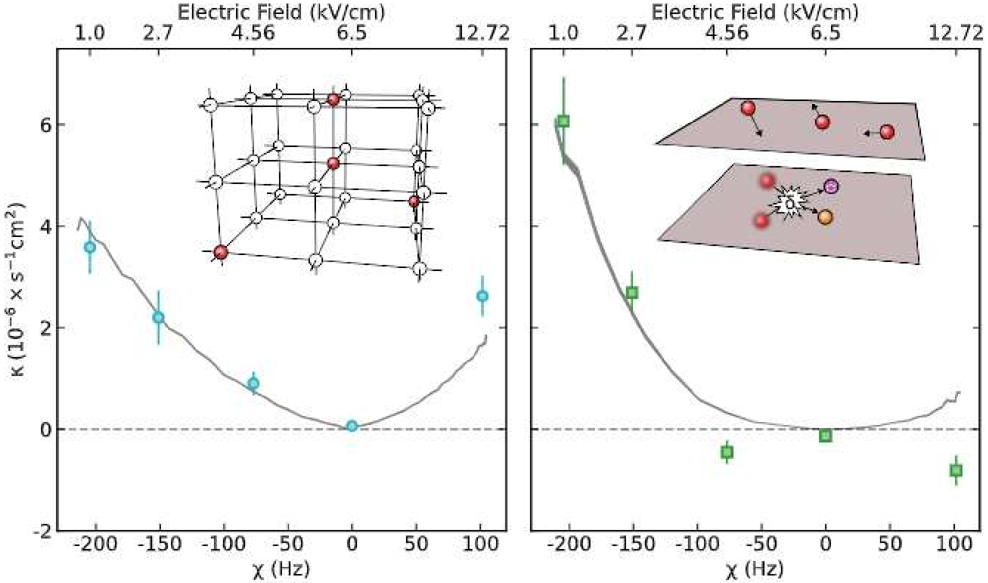
ANNETTE N. CARROLL, HENRIK HIRZLER, CALDER MILLER, DAVID WELLNITZ, SEAN R. MULEADY, JUNYU LIN, KRZYSZTOF P. ZAMARSKI, REUBEN R. W. WANG, JOHN L. BOHN, ANA MARIA REY, AND JUN YE

fewer

Authors Info & Affiliations

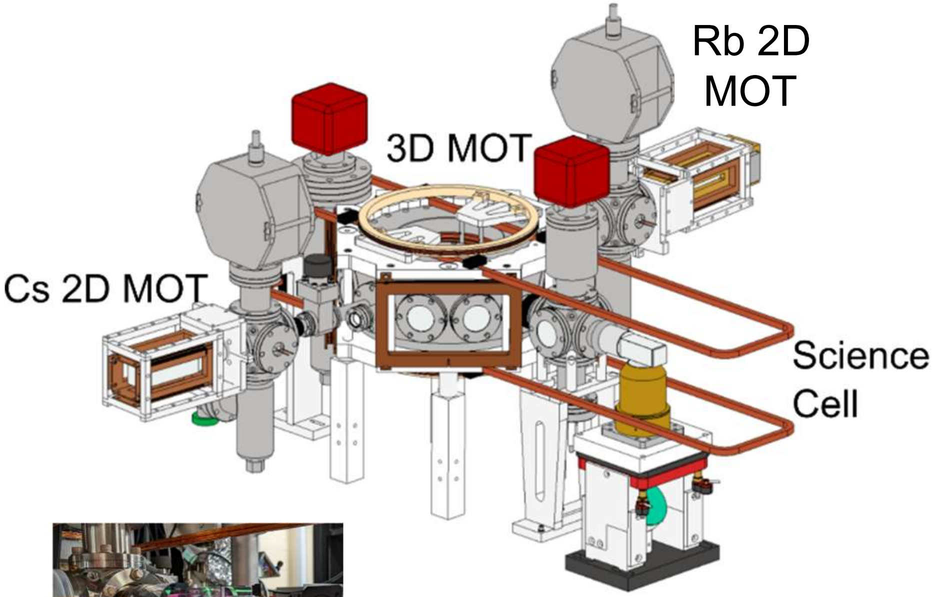
SCIENCE · 24 Apr 2025 · Vol 388, Issue 6745 · pp. 381-386 · DOI: 10.1126/science.adq0911

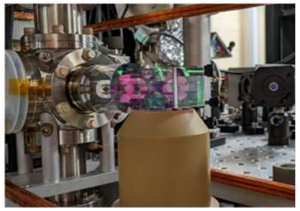
Study Ramsey contrast decay rate κ as a function of interaction anisotropy $\chi = J_z - J_\perp$ & motion in lattices



Our work on lattices

Quantum gas microscope:



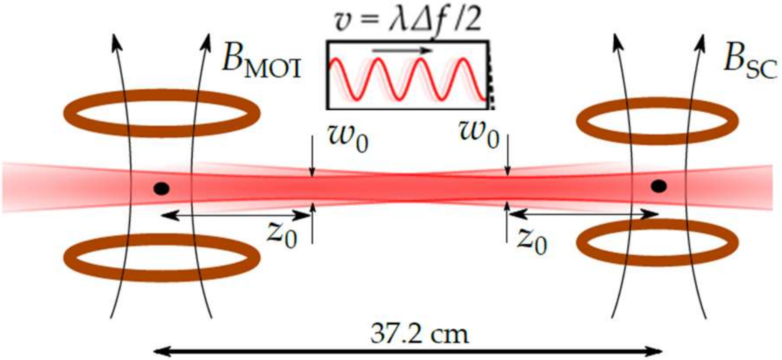


NA = 0.7

$$\lambda/\sqrt{2} = 810\,\mathrm{nm},\ J \simeq 280\,\mathrm{Hz}$$

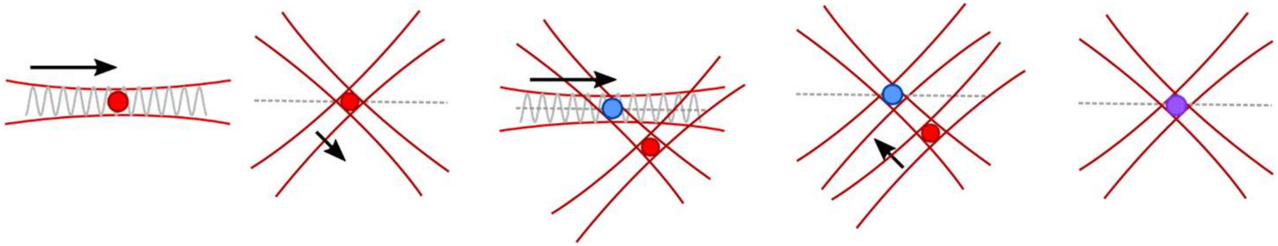
See also:
Bakr group: Nature **614**, 64-69 (2023)

- DRSC of both species in 3D MOT chamber
- Fast moving-lattice transport to cell (~30 ms)
- Duty cycle < 30s



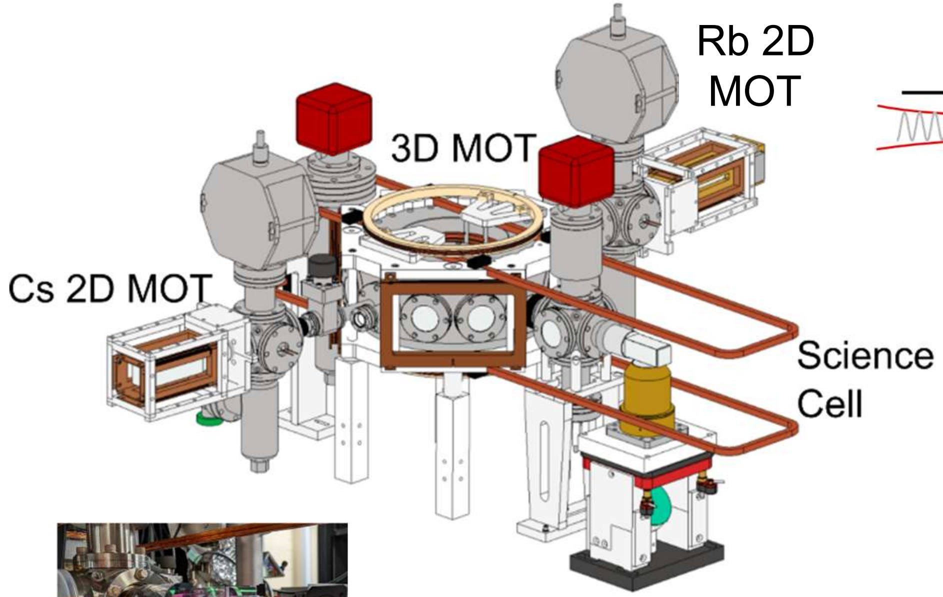
Matthies *et al.* PRA **109**, 023321 (2024)

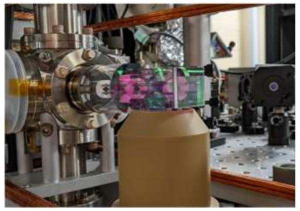
- Sequential transfer and separate cooling



Dual-species BEC

Quantum gas microscope:



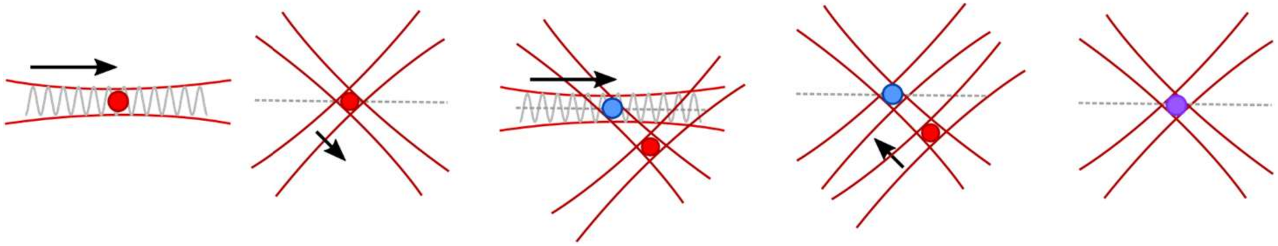


NA = 0.7

$$\lambda/\sqrt{2} = 810\,\mathrm{nm},\ J \simeq 280\,\mathrm{Hz}$$

See also:
Bakr group: Nature **614**, 64-69 (2023)

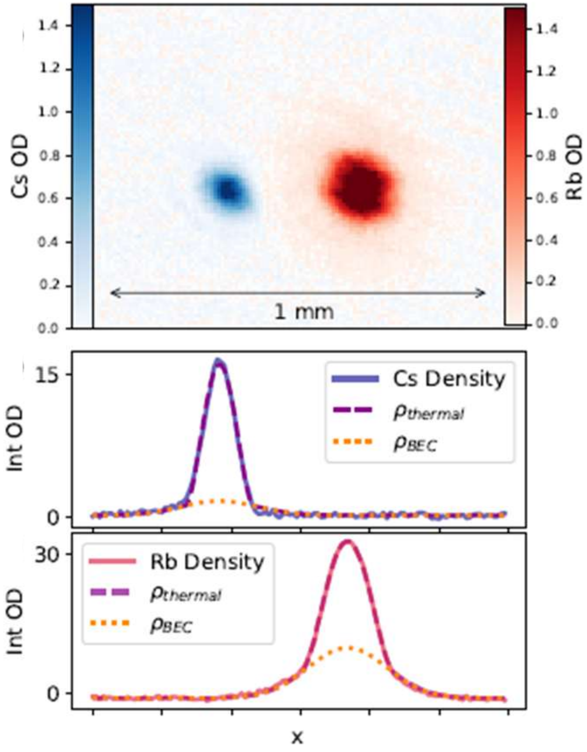
- Sequential transfer and separate cooling



Produce separated dual species BECs (ready for lattice loading)

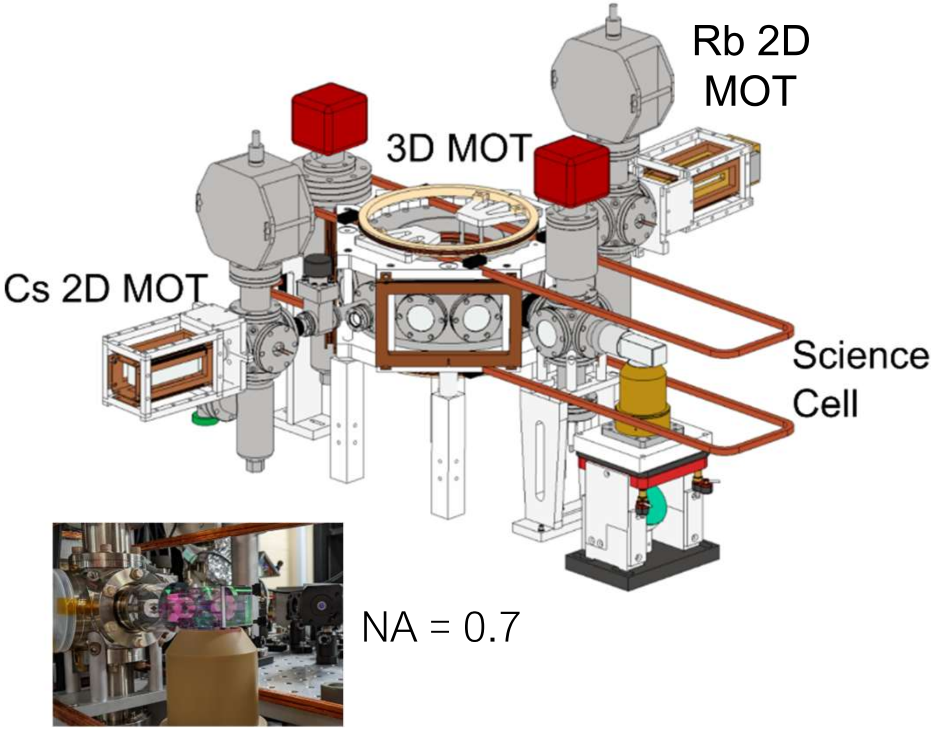
OR

Merge thermal clouds and make ~3000 RbCs molecules



Lattices: put the molecules closer together!

Quantum gas microscope:

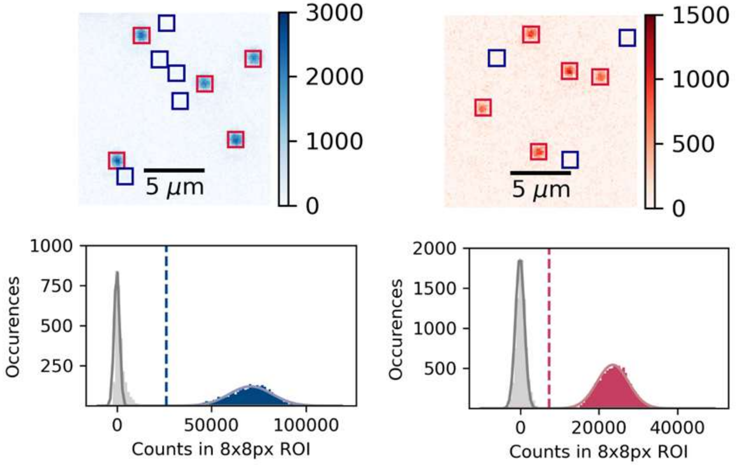


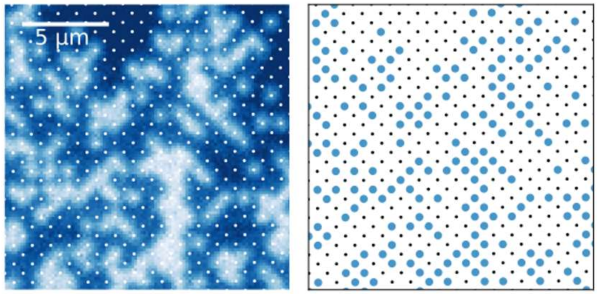
NA = 0.7

$$\lambda/\sqrt{2} = 810\,\mathrm{nm},\ J \simeq 280\,\mathrm{Hz}$$

See also:
Bakr group: Nature **614**, 64-69 (2023)

Imaging in 2D lattice + light sheet

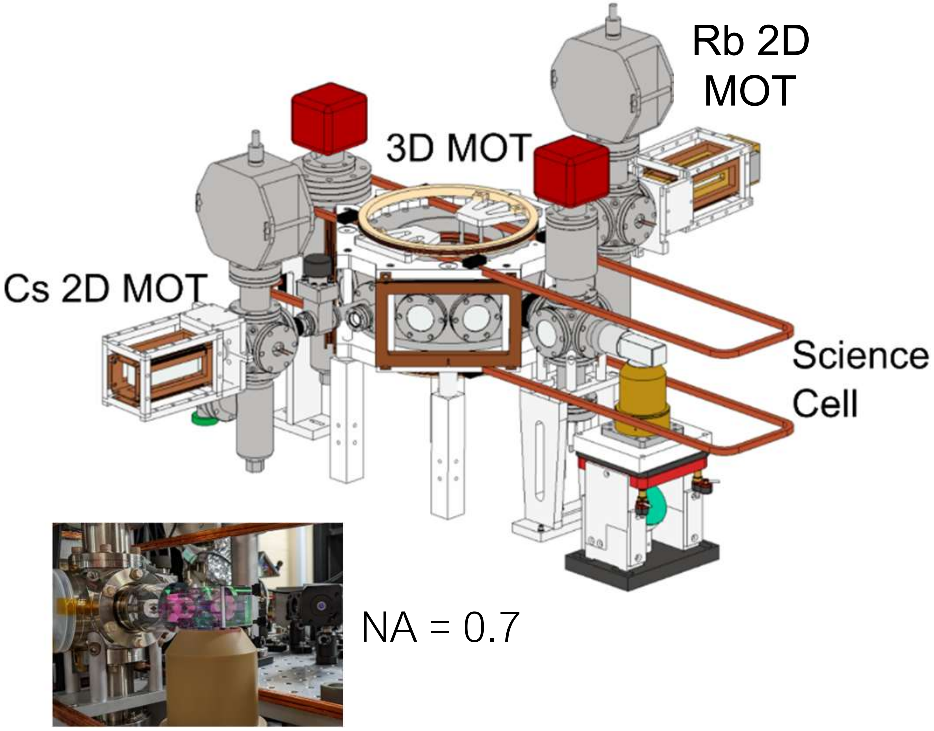




Parity projected Cs cloud

Lattices: put the molecules closer together!

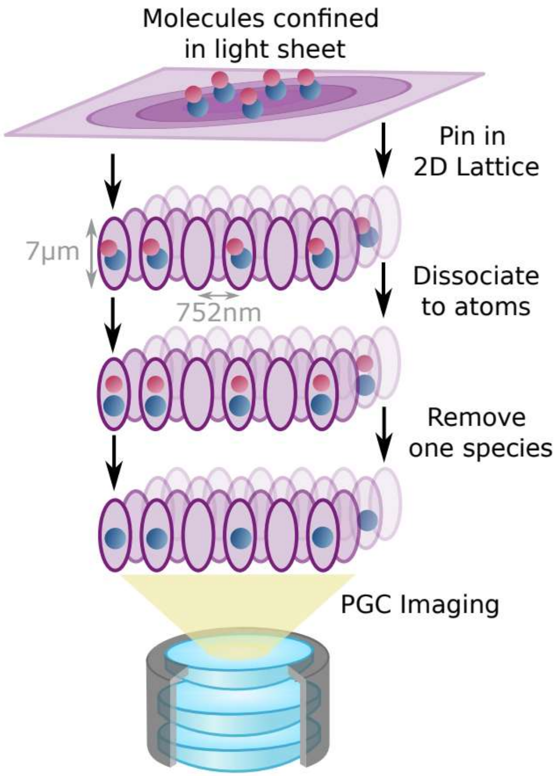
Quantum gas microscope:

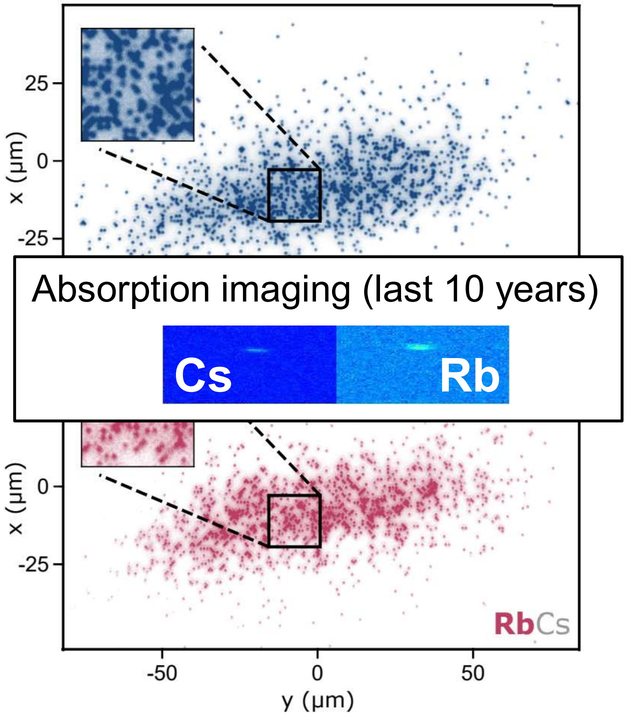


NA = 0.7

$$\lambda/\sqrt{2} = 810\,\mathrm{nm},\ J \simeq 280\,\mathrm{Hz}$$

Detecting single molecules in a bulk gas:



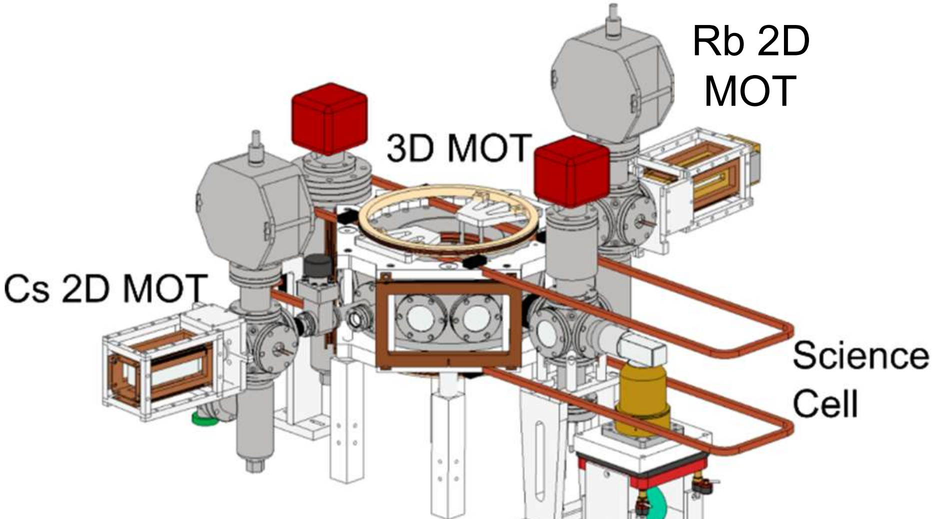


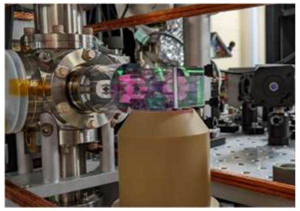
See also:
Bakr group: Nature **614**, 64-69 (2023)

See also "Continuum microscopes"
T. de Jongh *et al*. PRL **134**, 183403 (2025).
R. Yao *et al* PRL **134**, 183402 (2025).
J. Xiang, *et al.* PRL **134**, 183401 (2025).

Lattices: put the molecules closer together!

Quantum gas microscope:

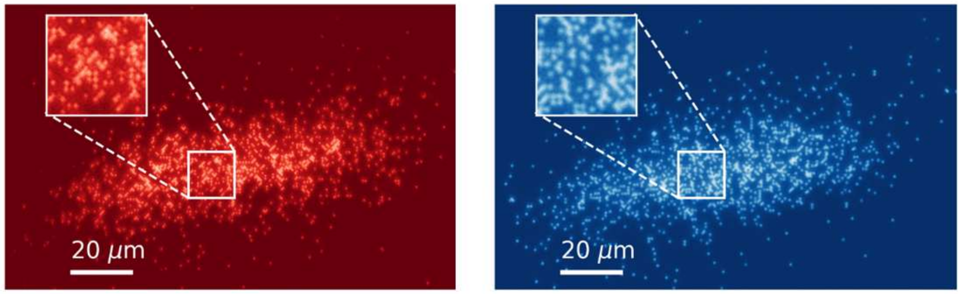




NA = 0.7

$$\lambda/\sqrt{2} = 810\,\mathrm{nm},\ J \simeq 280\,\mathrm{Hz}$$

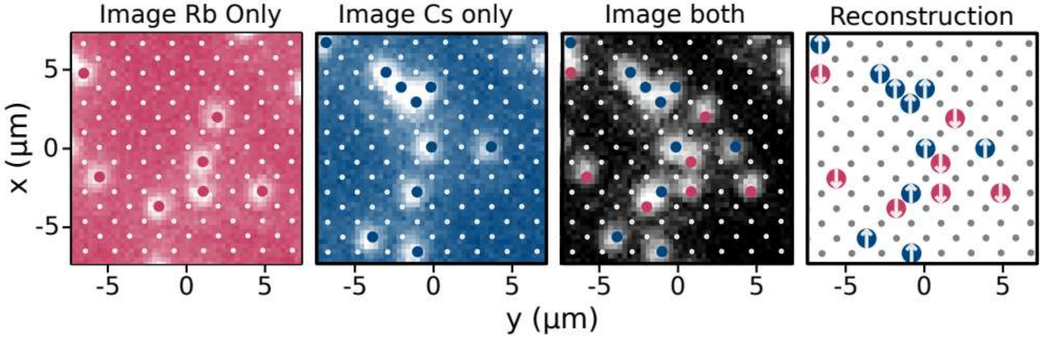
Multistate readout of molecules



RbCs N=0 → Rb

RbCs N=1 → Cs

Take 3 images in each experimental run

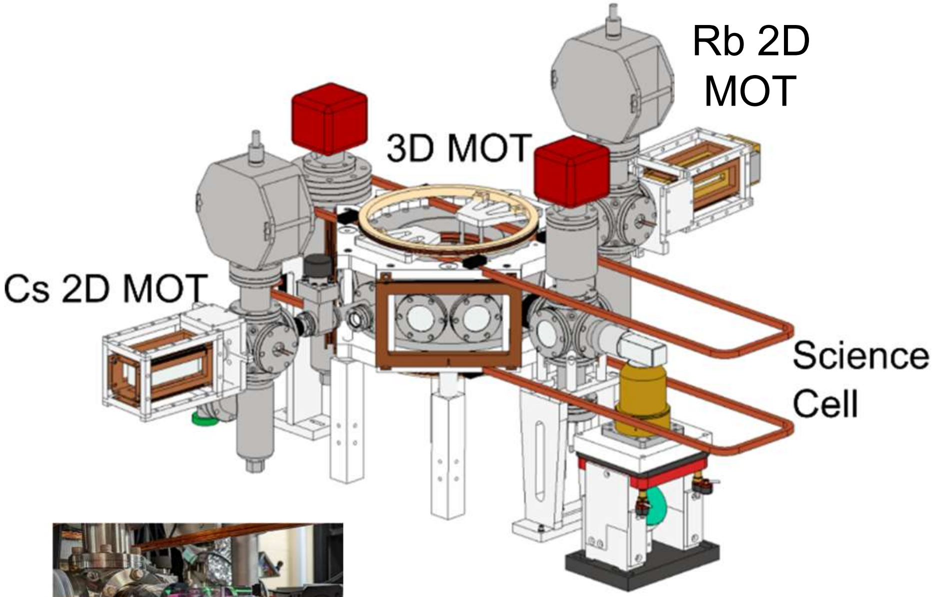


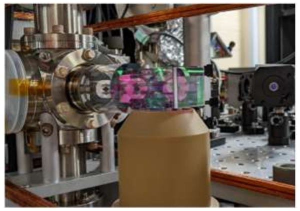
c.f. Covey et al., New J. Phys. **20**, 043031 (2018)

See also:
Bakr group: Nature **614**, 64-69 (2023)

Lattices: put the molecules closer together!

Quantum gas microscope:

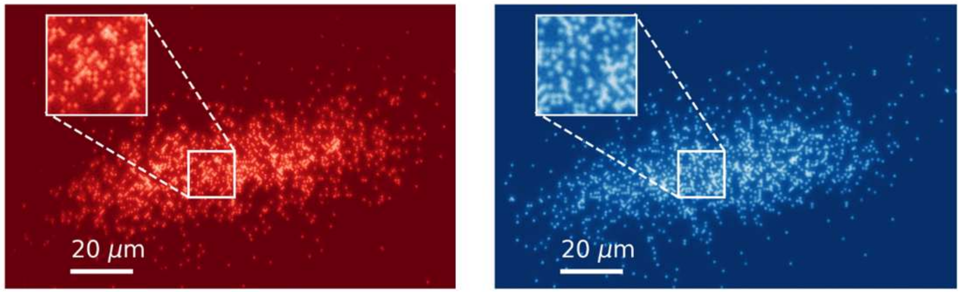




NA = 0.7

$$\lambda/\sqrt{2} = 810\,\mathrm{nm},\ J \simeq 280\,\mathrm{Hz}$$

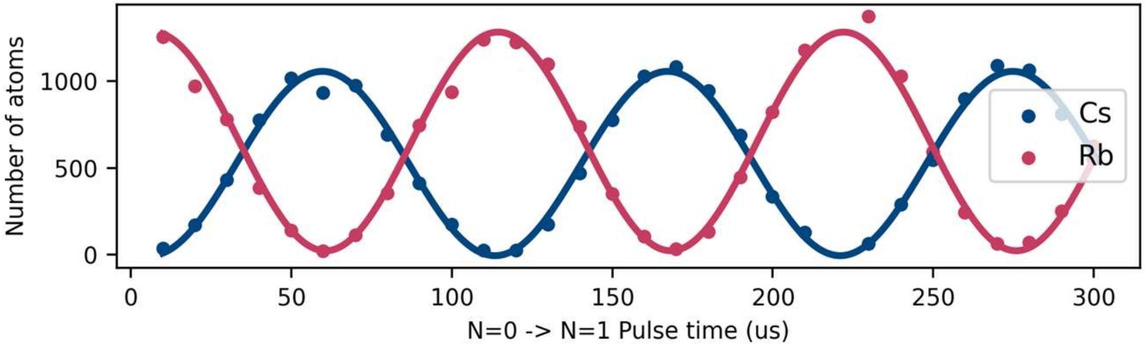
Multistate readout of molecules



RbCs N=0 → Rb

RbCs N=1 → Cs

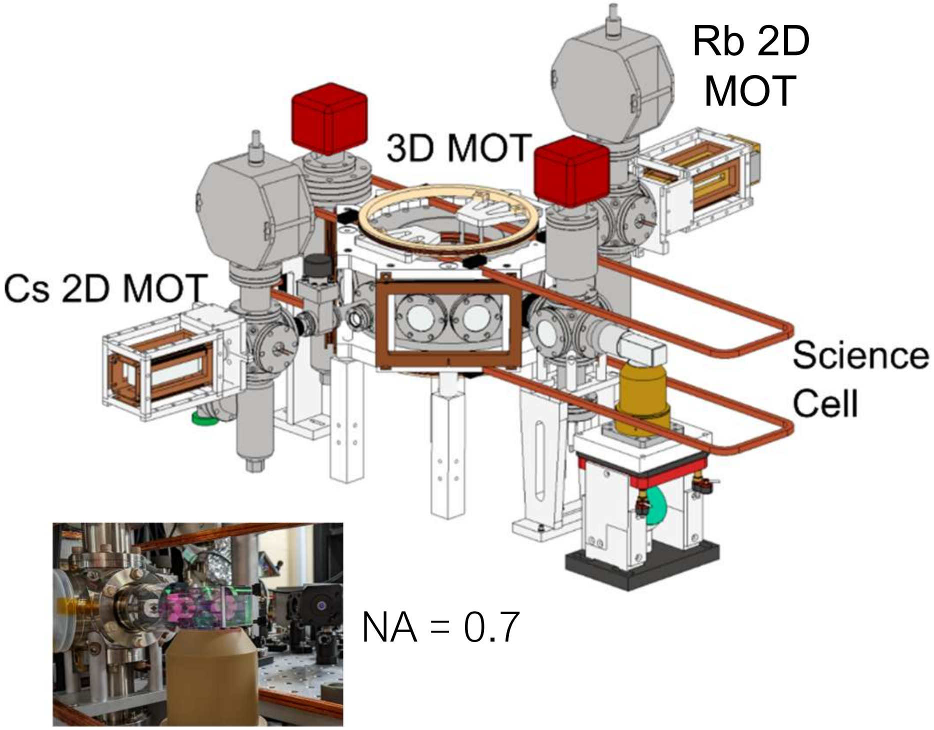
Rabi oscillations with multistate readout



See also:
Bakr group: Nature **614**, 64-69 (2023)

Lattices: put the molecules closer together!

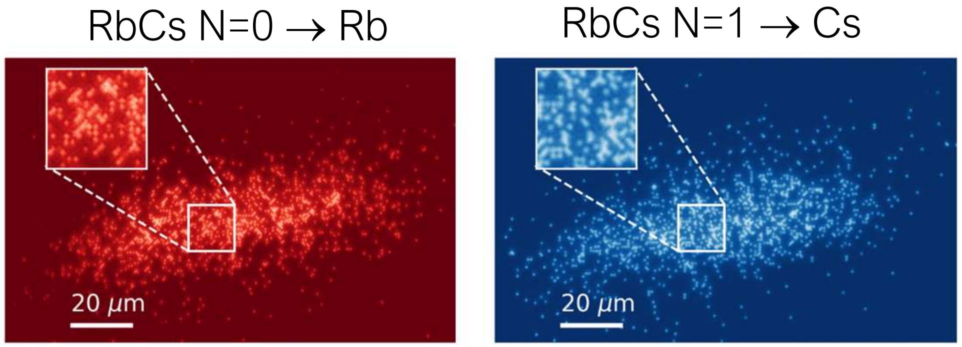
Quantum gas microscope:



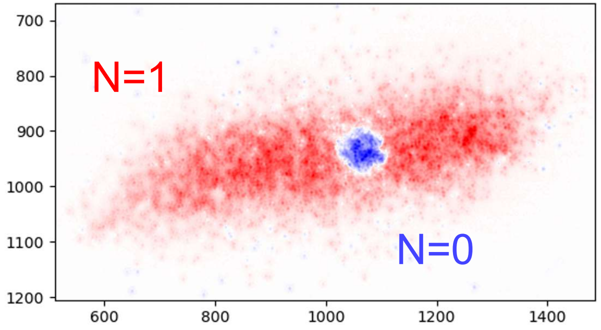
NA = 0.7

$$\lambda/\sqrt{2} = 810\,\mathrm{nm},\ J \simeq 280\,\mathrm{Hz}$$

Multistate readout of molecules


RbCs N=0 → Rb

RbCs N=1 → Cs

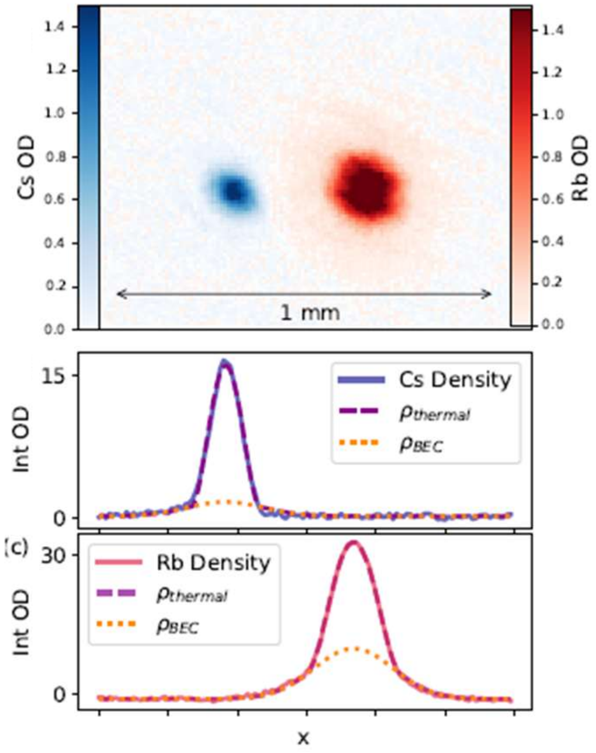


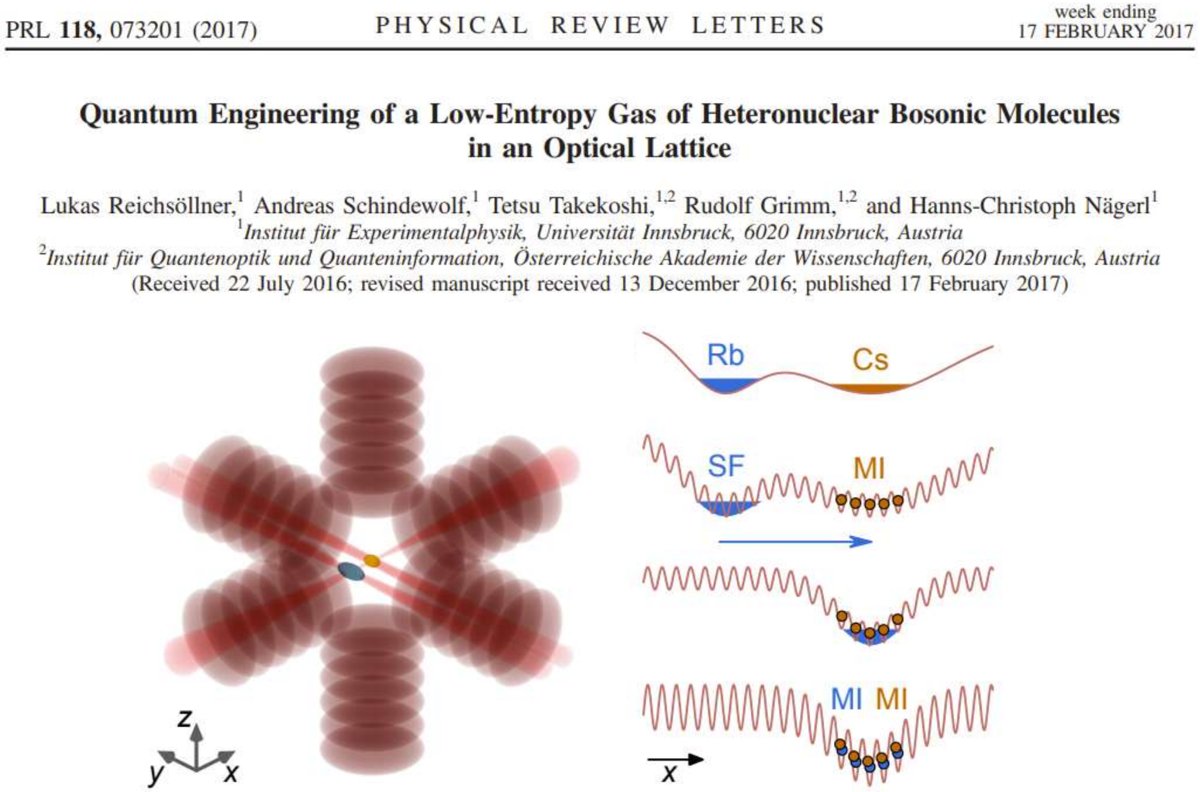
+ Local addressing

See also:
Bakr group: Nature **614**, 64-69 (2023)

Still a lot to do, but moving towards many-body physics in lattices with single molecule and single site detection

Future: prepare molecules in lowest band of magic lattice





PRL **118,** 073201 (2017) PHYSICAL REVIEW LETTERS week ending 17 FEBRUARY 2017

Quantum Engineering of a Low-Entropy Gas of Heteronuclear Bosonic Molecules in an Optical Lattice

Lukas Reichsöllner,[1] Andreas Schindewolf,[1] Tetsu Takekoshi,[1,2] Rudolf Grimm,[1,2] and Hanns-Christoph Nägerl[1]

[1]*Institut für Experimentalphysik, Universität Innsbruck, 6020 Innsbruck, Austria*

[2]*Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, 6020 Innsbruck, Austria*

(Received 22 July 2016; revised manuscript received 13 December 2016; published 17 February 2017)

Achieved 30% filling of Feshbach molecules

New STIRAP route: Das et al., SciPost Phys. 15, 220 (2023)

XY Quantum magnetism and t-J-V-W models (Gorshkov et al., PRL 107, 115301 (2011))

Questions?

Controlling collisions
Loss of molecules
Shielding
BEC

Early KRb experiments showed loss

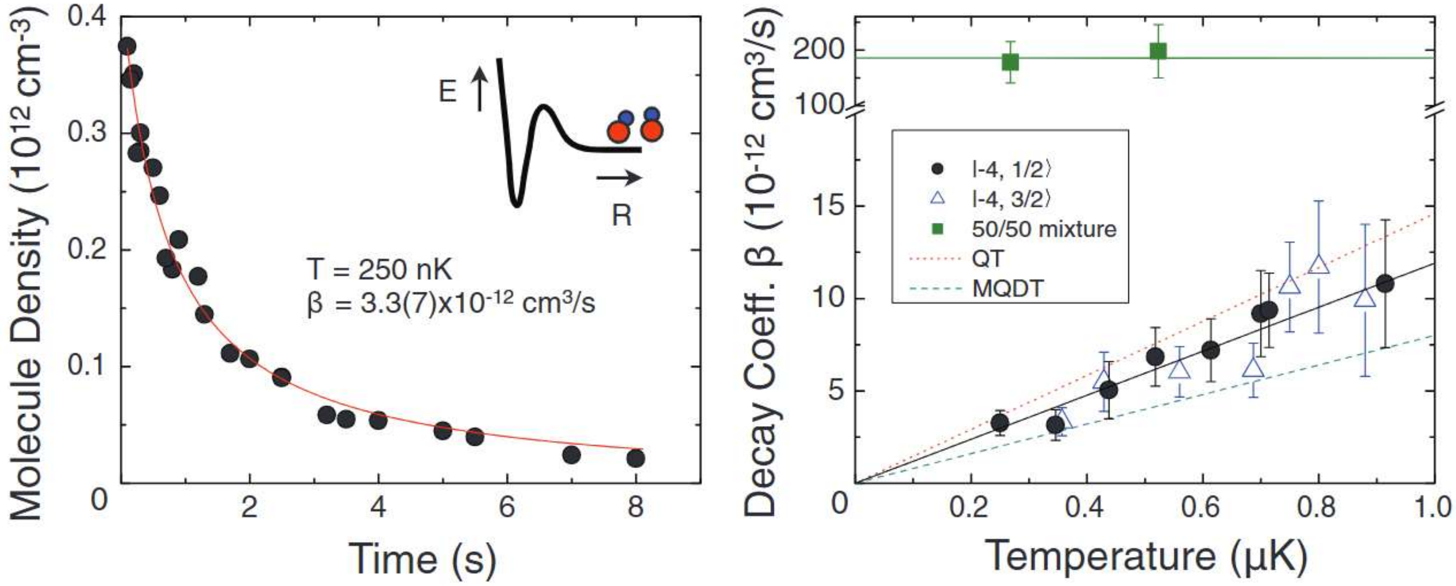
Quantum-State Controlled Chemical Reactions of Ultracold Potassium-Rubidium Molecules

S. Ospelkaus,[1]* K.-K. Ni,[1]* D. Wang,[1] M. H. G. de Miranda,[1] B. Neyenhuis,[1] G. Quéméner,[1]
P. S. Julienne,[2] J. L. Bohn,[1] D. S. Jin,[1]† J. Ye[1]†

Science **327**, 853 – 857 (2010)

Chemistry!

$\mathrm{KRb} + \mathrm{KRb} \rightarrow \mathrm{K_2} + \mathrm{Rb_2}$



s-wave

p-wave

Where do our molecules go?

Stable against reactive collisions

$$\mathrm{RbCs}+\mathrm{RbCs}\not\rightarrow\mathrm{Rb}_2+\mathrm{Cs}_2$$

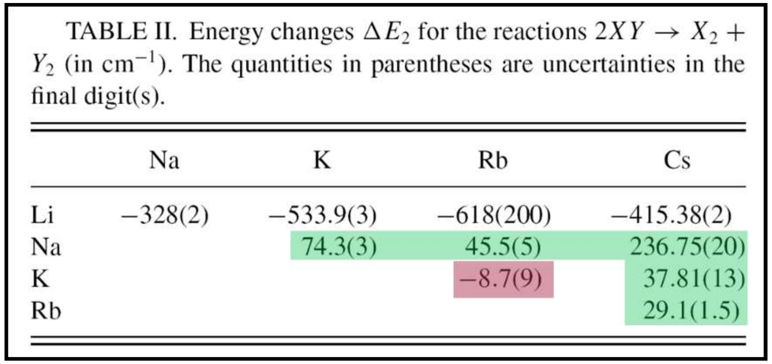
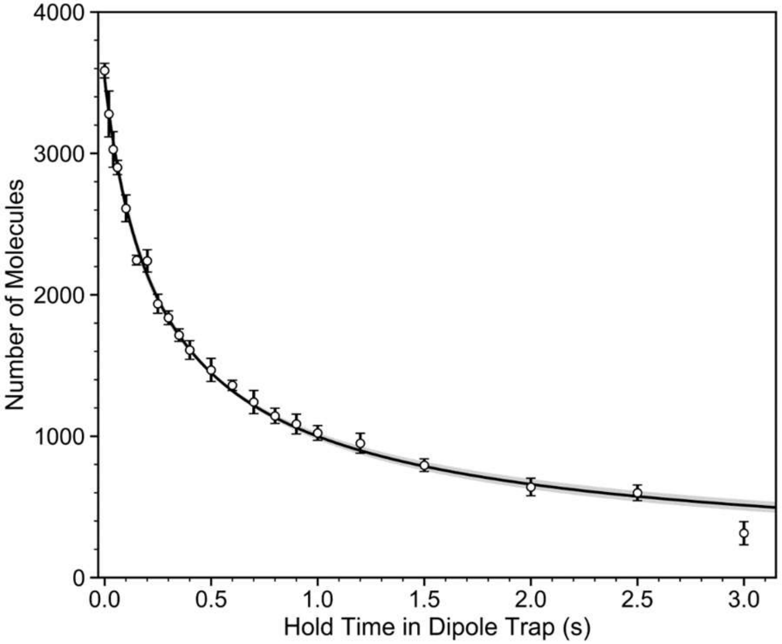


TABLE II. Energy changes ΔE_2 for the reactions $2XY \rightarrow X_2 + Y_2$ (in cm^{-1}). The quantities in parentheses are uncertainties in the final digit(s).

	Na	K	Rb	Cs
Li	−328(2)	−533.9(3)	−618(200)	−415.38(2)
Na		74.3(3)	45.5(5)	236.75(20)
K			−8.7(9)	37.81(13)
Rb				29.1(1.5)

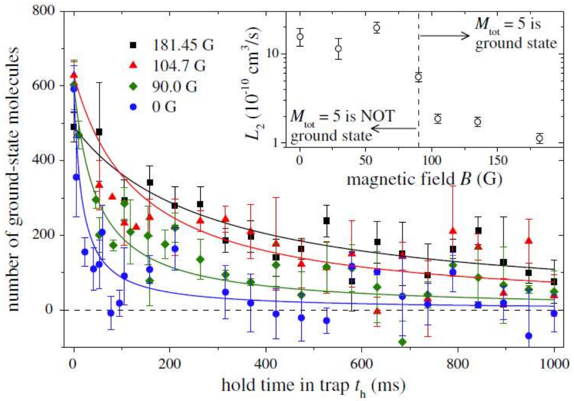
Zuchowski & Hutson PRA **81**, 060703(R) (2010)

But…



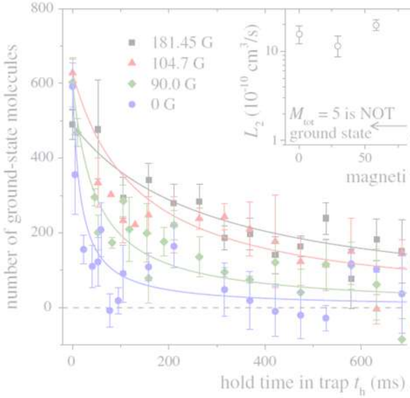
Experiments on NaK and NaRb show similar behaviour

Not all bialkali molecules are reactive!

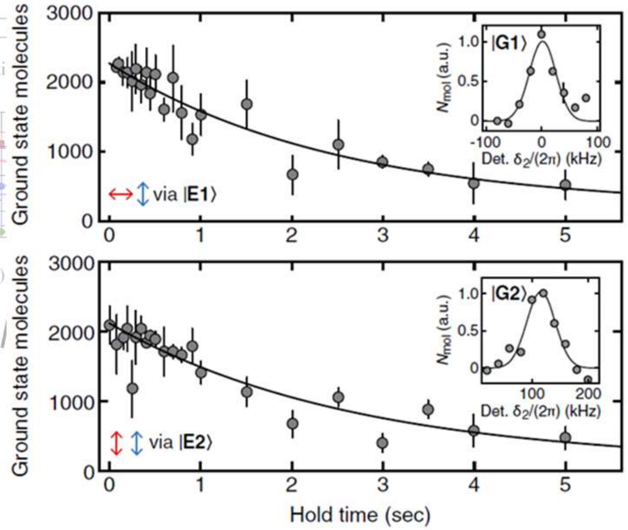


RbCs - Takekoshi *et al*., PRL 2014

Not all bialkali molecules are reactive!



RbCs - Takekoshi *et al*



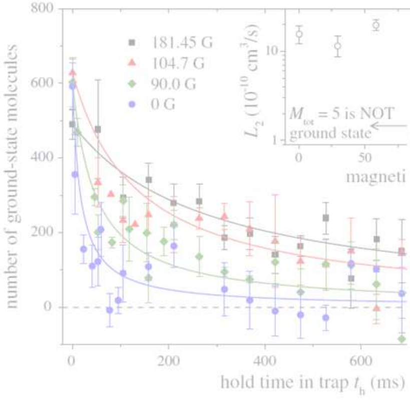
NaK – Park *et al.*, PRL 2015

Not all bialkali molecules are reactive!

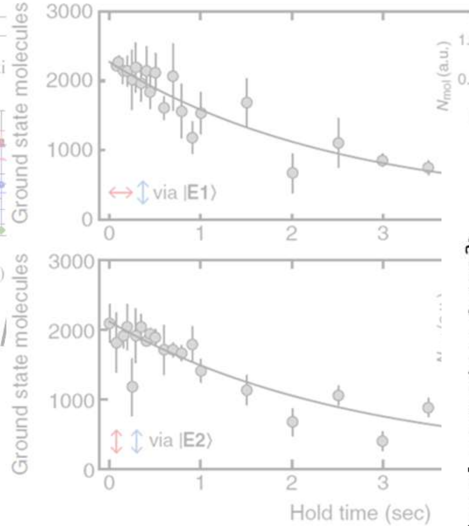
What is the mechanism for the observed loss?

“Sticky Collisions”?

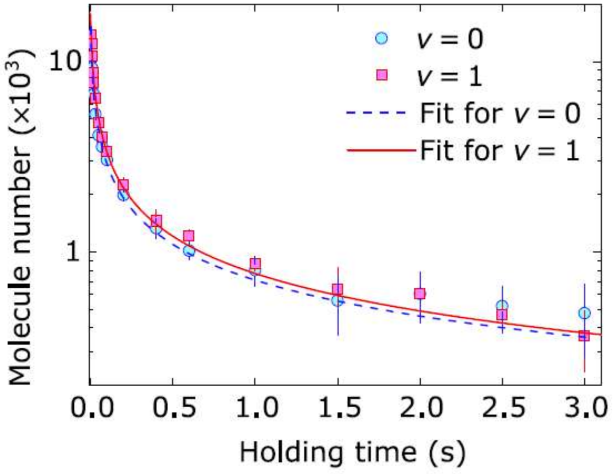
Mayle *et al*., PRA **87**, 012709 (2013)



RbCs - Takekoshi *et al*



NaK – Park *et al*., F

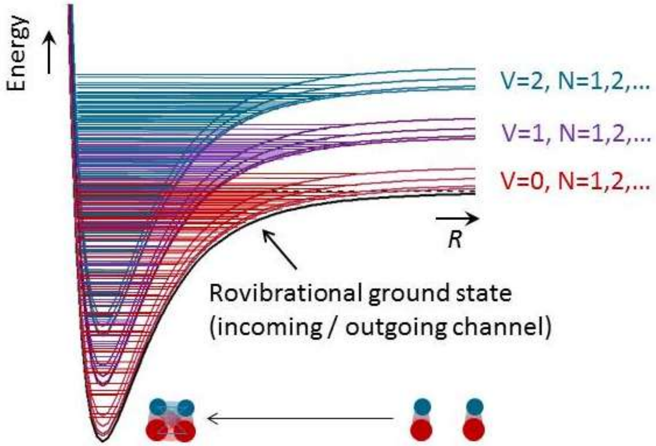


NaRb - Ye *et al*., Sci. Adv. 2018

Molecular scattering is highly resonant

Even simple diatomic molecules collide on **anisotropic** 4-body potential energy surfaces!

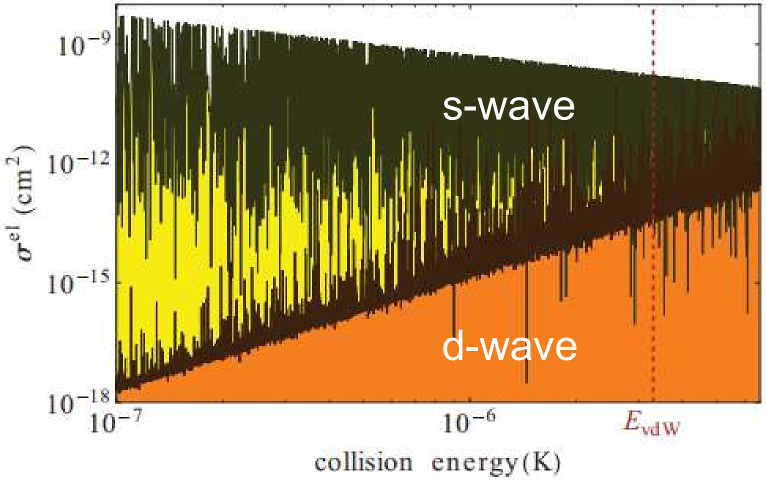
4-body collision complexes can have fairly deep wells (1000 to 2000 cm^{-1})



High density of states near top of well associated with vibrational and rotation

Scattering is highly resonant!
Observables averaged over many resonances

RbCs + RbCs elastic cross section



From a statistical treatment with model potentials to estimate DOS

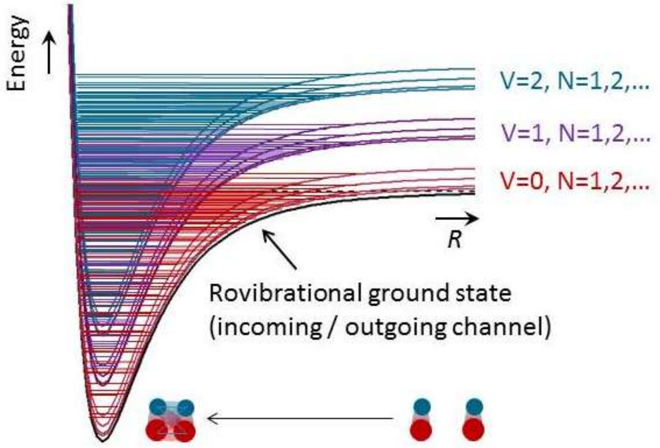
Mayle *et al.*, PRA **87**, 012709 (2013)

Molecular scattering is highly resonant

Durham University

Even simple diatomic molecules collide on **anisotropic** 4-body potential energy surfaces!

4-body collision complexes can have fairly deep wells (1000 to 2000 cm^{-1})



High density of states near top of well associated with vibrational and rotation

Scattering is highly resonant!
Observables averaged over many resonances

Can lead to "**sticky collisions**"
= The formation of long-lived
4-body collision complexes

$$\tau_{\mathrm{c}} = 2\pi\hbar\underset{\nwarrow}{\rho}$$

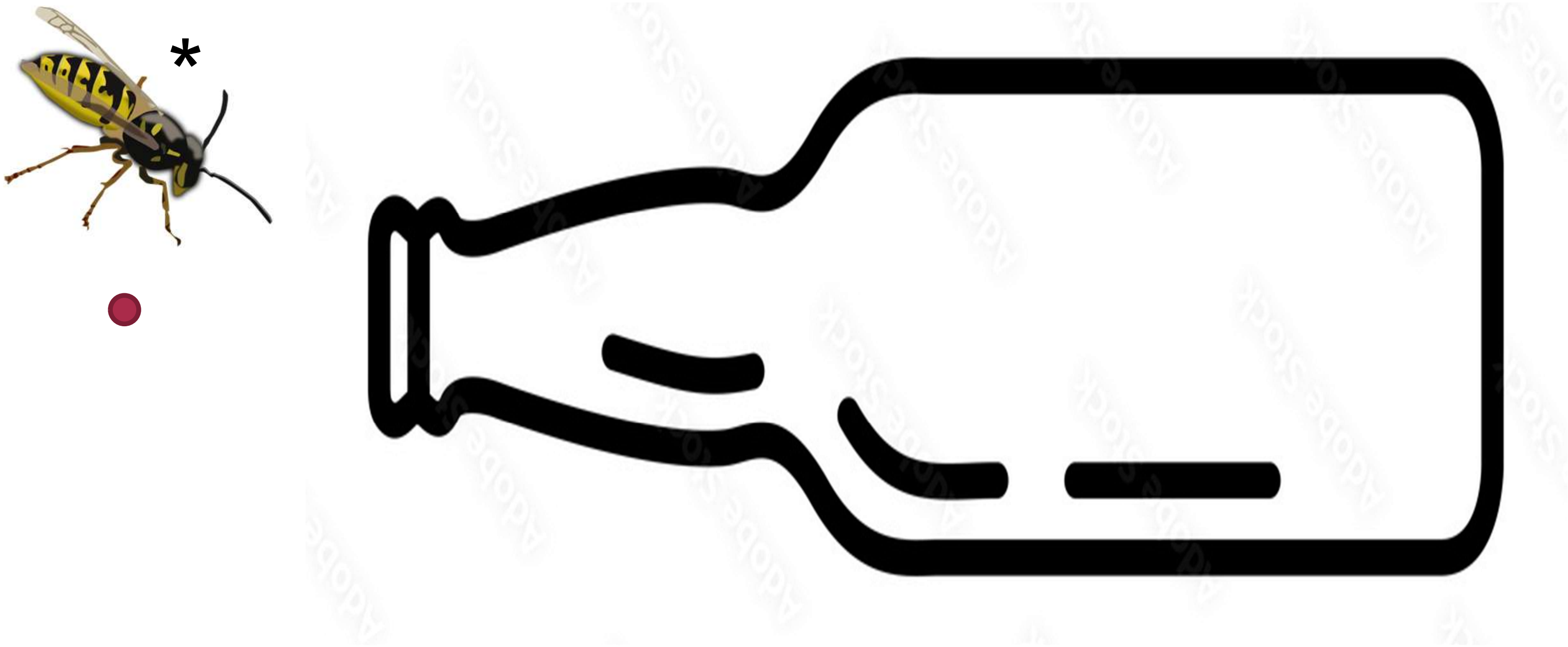
Density of states

(Estimated from model potentials)

Mayle *et al.*, PRA **87**, 012709 (2013)

Sticky collisions

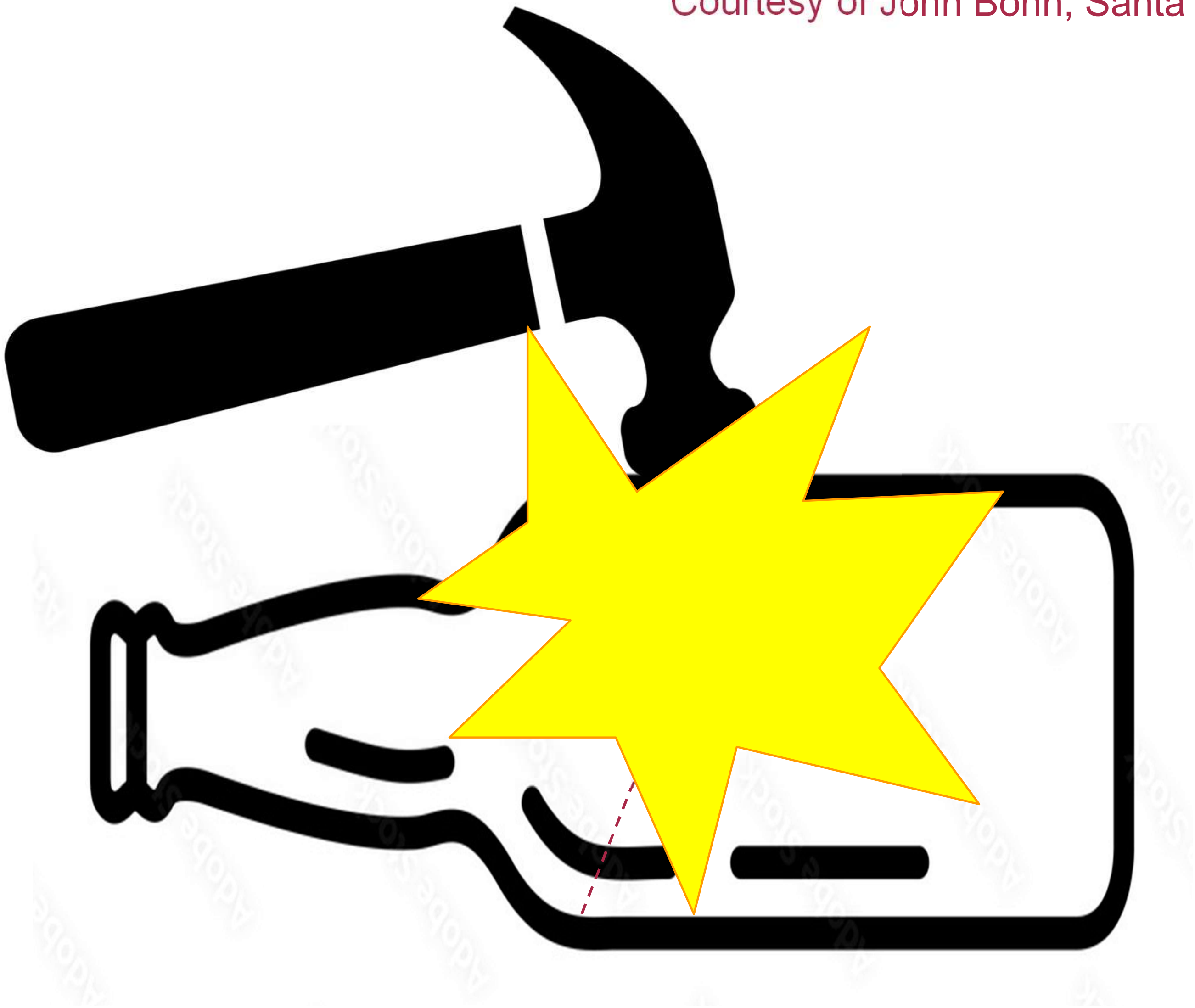
Courtesy of John Bohn, Santa Barbara



* EDI note: other insects are available

The problem with sticky collisions

Courtesy of John Bohn, Santa Barbara



Complex formation and loss

"Sticky Collisions"

Mayle *et al.*, PRA **87**, 012709 (2013)

If long-lived collision complexes collide with a molecule → **LOSS!**

Requires 'long' Complex lifetime

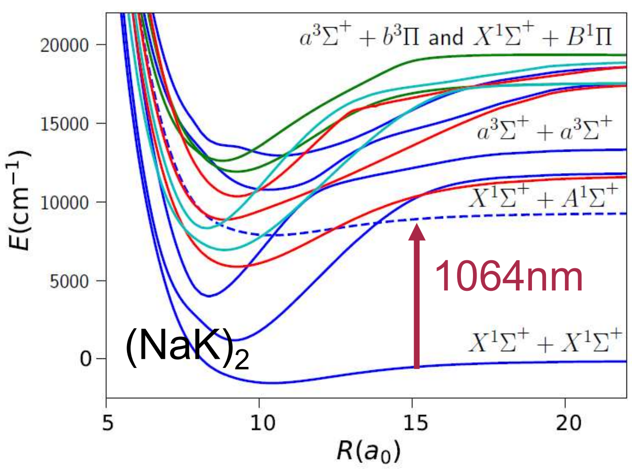
Trap laser limits lifetime

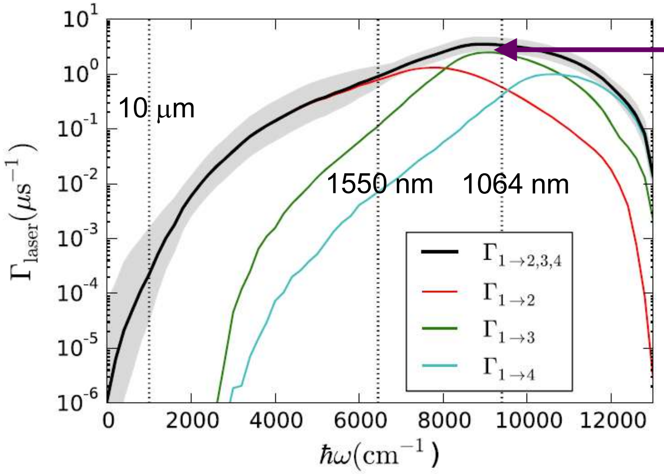
Karman *et al.*, PRL **123**, 123402 (2019)

New DOS calculation shows complex lifetimes too short for collisional loss

For $(RbCs)_2$ 0.25 ms

But laser excitation very fast !!





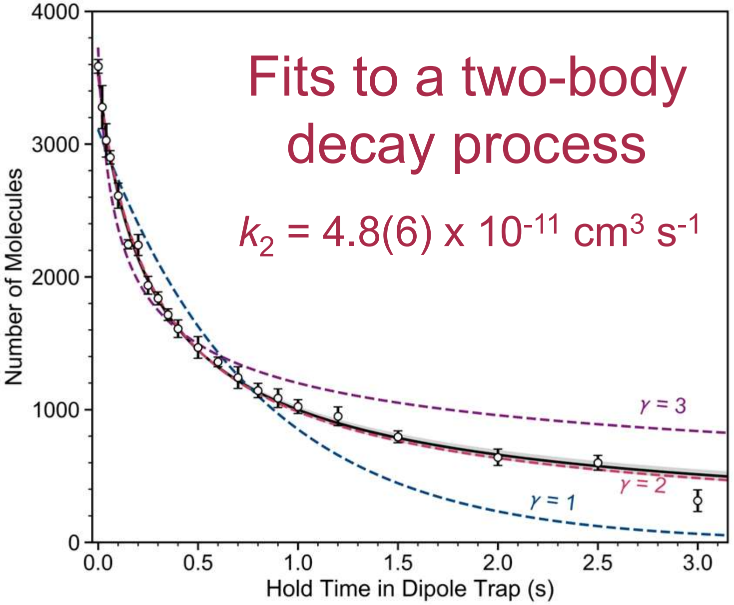
$$\Gamma_{\mathrm{laser}} \gg \frac{1}{\tau_c}$$

In both cases, if complex formation is rate-limiting step expect 2nd order kinetics

Confirmation of optical excitation 1

Final Molecule Sample

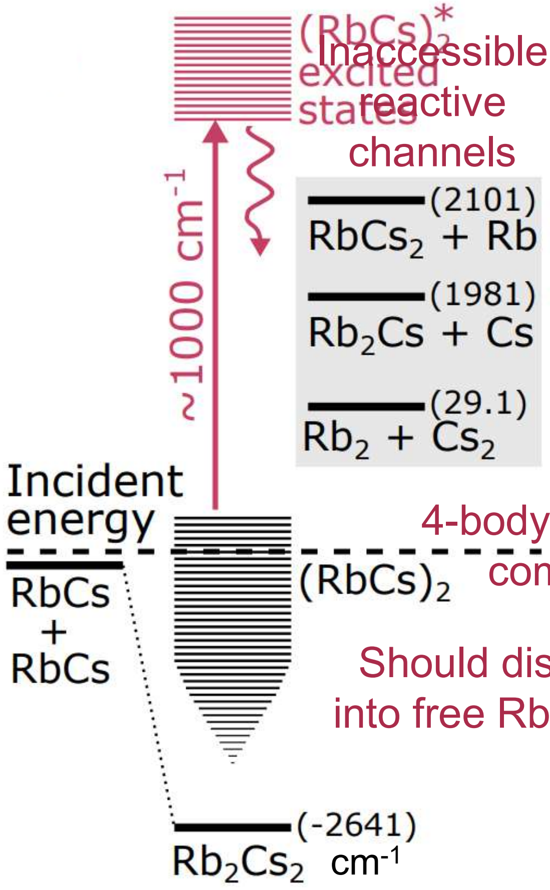
N = 4000, T = 1.5 μK, $n_{pk} \approx 10^{11}$ cm^{-3}



Fits to a two-body decay process

k_2 = 4.8(6) x 10^{-11} cm^3 s^{-1}

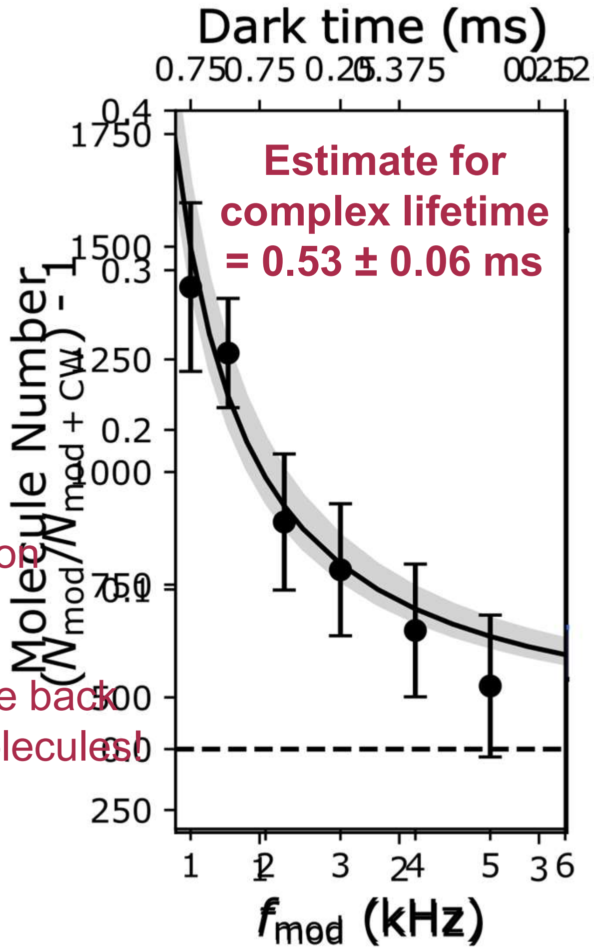
$$\mathrm{RbCs} + \mathrm{RbCs} \cancel{\rightarrow} \mathrm{Rb}_2 + \mathrm{Cs}_2$$



Inaccessible reactive channels

4-body collision complex

Should dissociate back into free RbCs molecules!



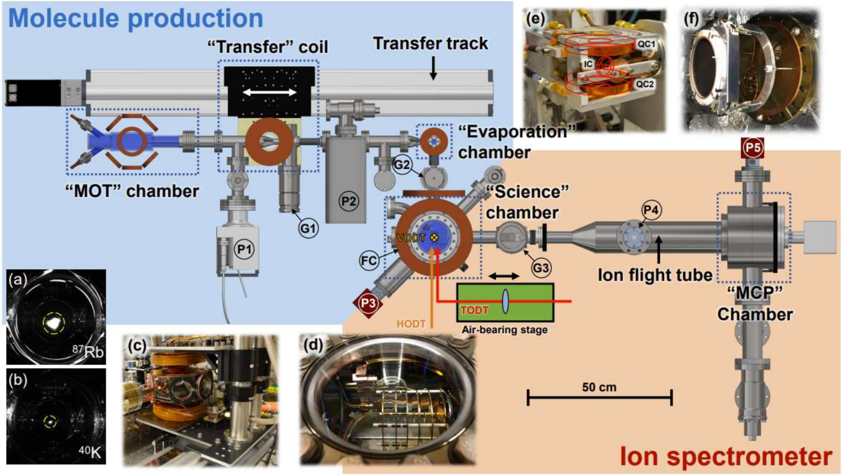
Estimate for complex lifetime = 0.53 ± 0.06 ms

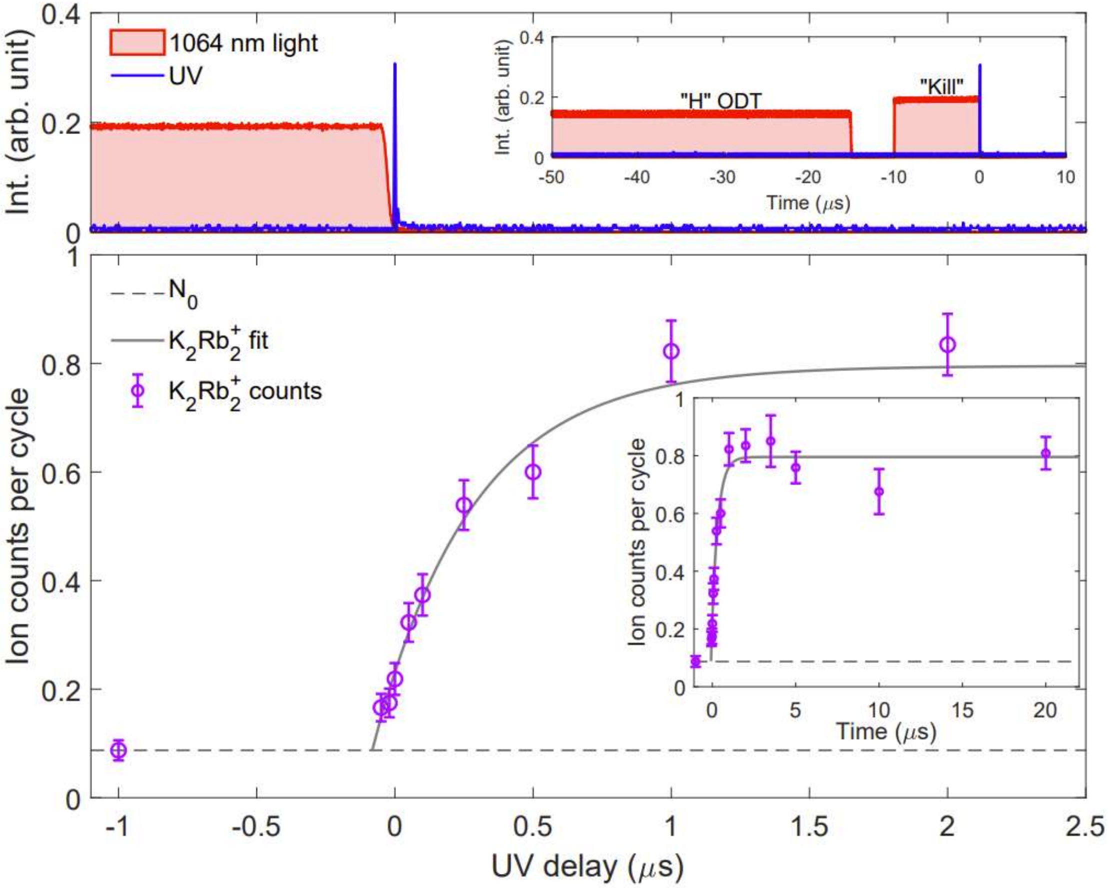
Gregory *et al.* Nat. Comms. **10**, 3104 (2019)

Gregory *et al.* PRL **124**, 263402 (2020)

Confirmation of optical excitation 2

Ni group – direct detection of the collision complex allows measurement of lifetime



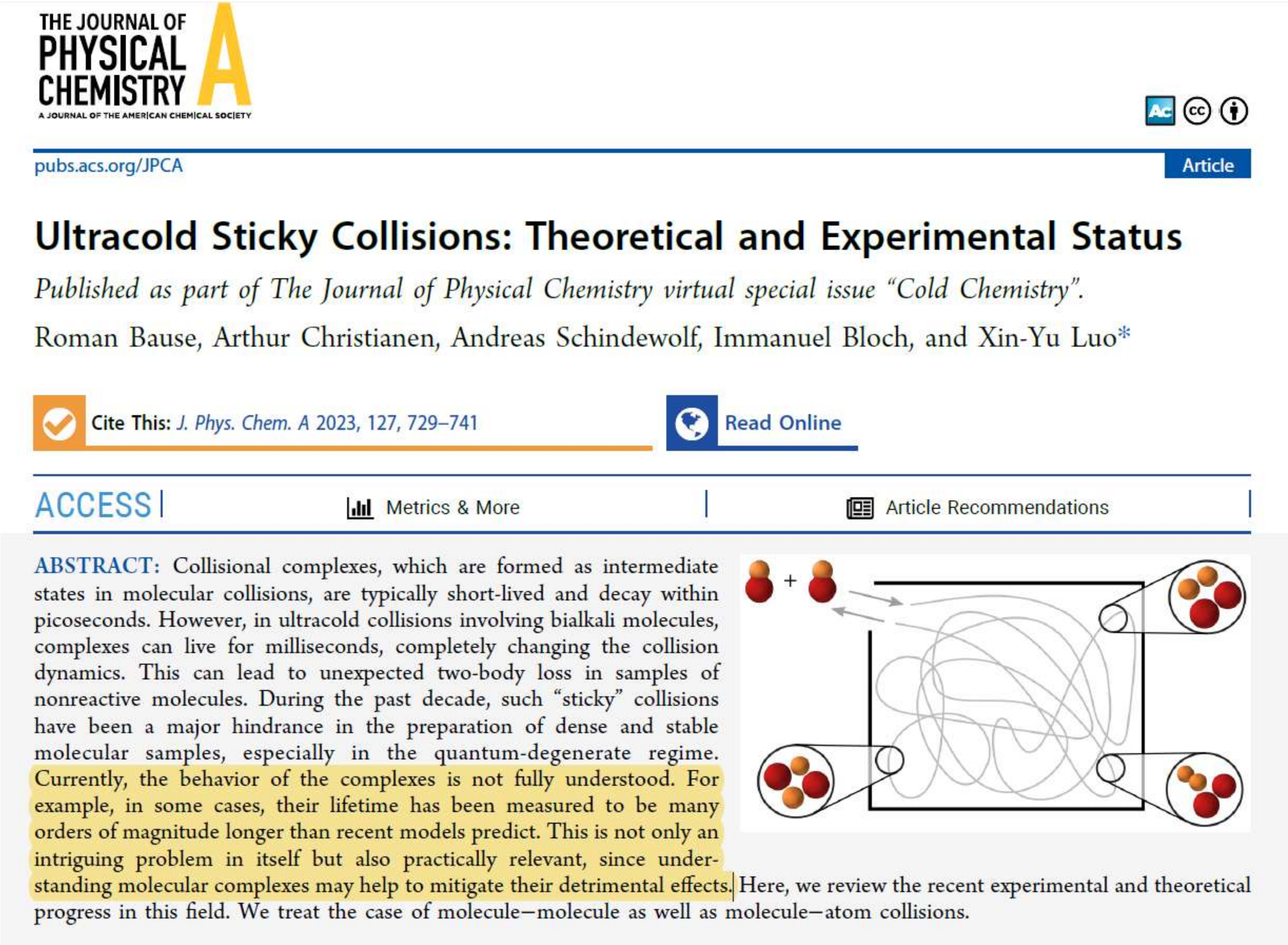


Experimental lifetime 360 ± 30 ns

Theory prediction 170 ± 60 ns

Liu et al., Nature Physics **16**, 1132–1136 (2020)

Despite the apparent understanding…



THE JOURNAL OF PHYSICAL CHEMISTRY A
A JOURNAL OF THE AMERICAN CHEMICAL SOCIETY

pubs.acs.org/JPCA

Article

Ultracold Sticky Collisions: Theoretical and Experimental Status

Published as part of The Journal of Physical Chemistry virtual special issue "Cold Chemistry".

Roman Bause, Arthur Christianen, Andreas Schindewolf, Immanuel Bloch, and Xin-Yu Luo*

Cite This: *J. Phys. Chem. A* 2023, 127, 729–741

Read Online

ACCESS | Metrics & More | Article Recommendations |

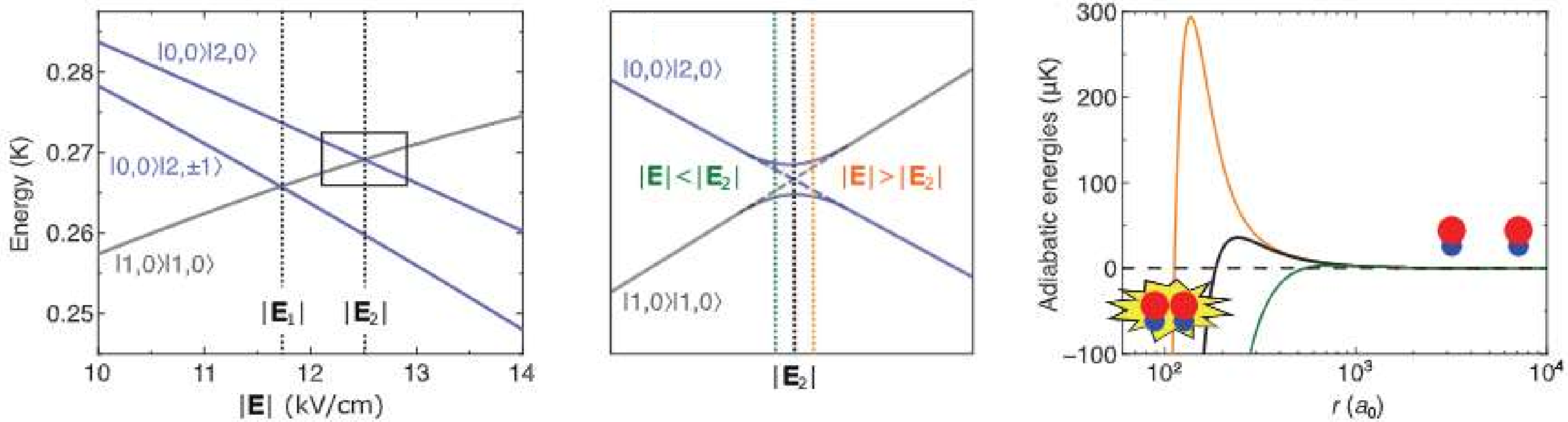
ABSTRACT: Collisional complexes, which are formed as intermediate states in molecular collisions, are typically short-lived and decay within picoseconds. However, in ultracold collisions involving bialkali molecules, complexes can live for milliseconds, completely changing the collision dynamics. This can lead to unexpected two-body loss in samples of nonreactive molecules. During the past decade, such "sticky" collisions have been a major hindrance in the preparation of dense and stable molecular samples, especially in the quantum-degenerate regime. Currently, the behavior of the complexes is not fully understood. For example, in some cases, their lifetime has been measured to be many orders of magnitude longer than recent models predict. This is not only an intriguing problem in itself but also practically relevant, since understanding molecular complexes may help to mitigate their detrimental effects. Here, we review the recent experimental and theoretical progress in this field. We treat the case of molecule–molecule as well as molecule–atom collisions.

How do we overcome this problem?

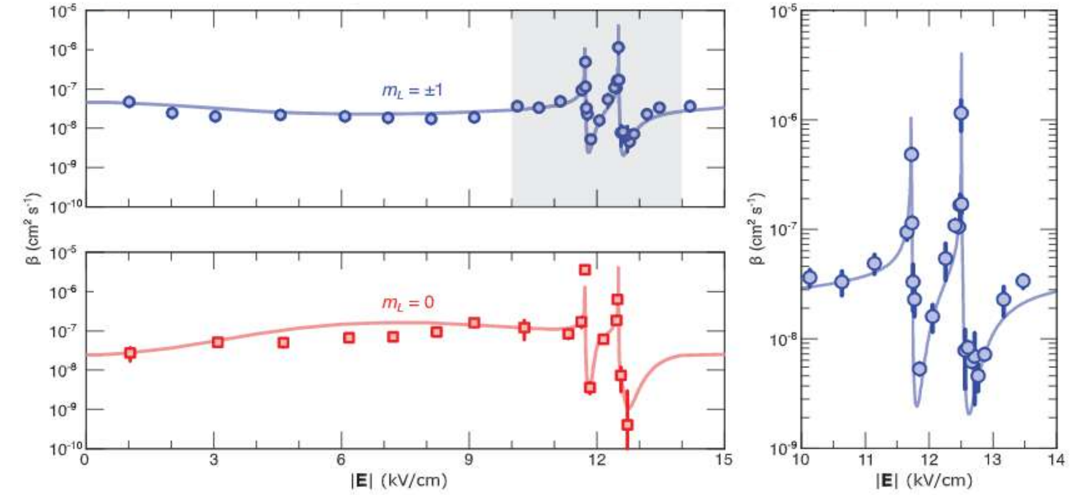
Use dipolar interactions to shield collisions!

Resonant collisional shielding using electric fields

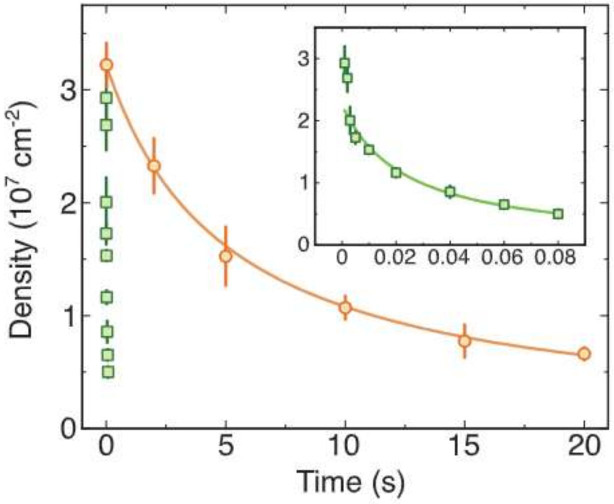
Barrier prevents molecules from reaching short range where the chemistry happens



Controlling 2-body loss rate



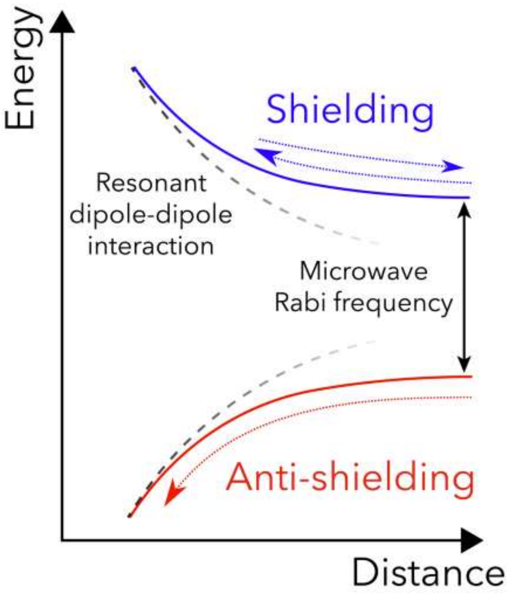
Suppressing/enhancing loss

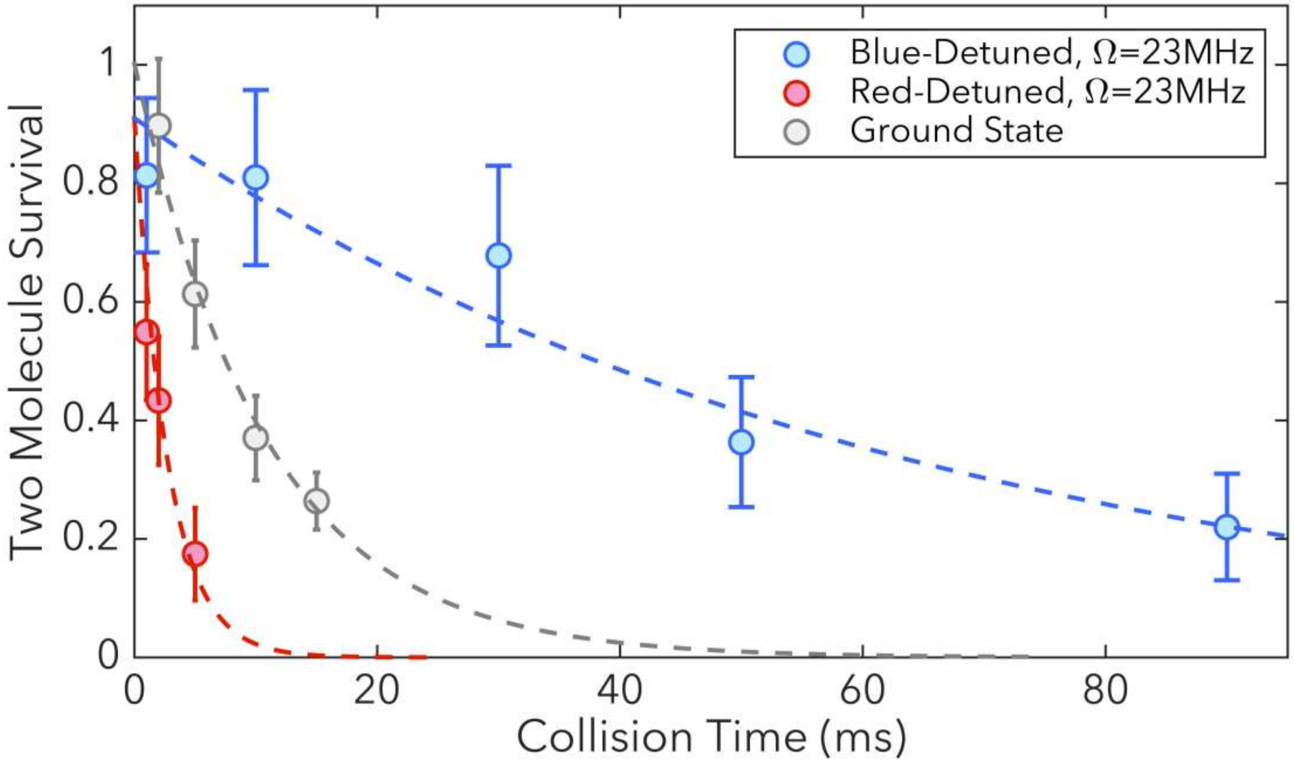


Matsuda *et al*., Science **370**, 1324-27 (2020)

Microwave shielding

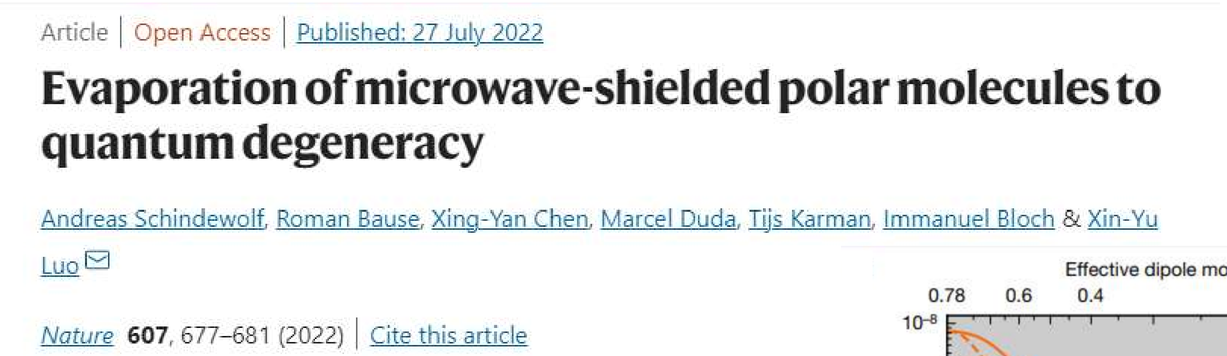
Two CaF molecules in an optical tweezer:





Anderegg et al., Science **373**, 779 (2021)

Microwave shielding



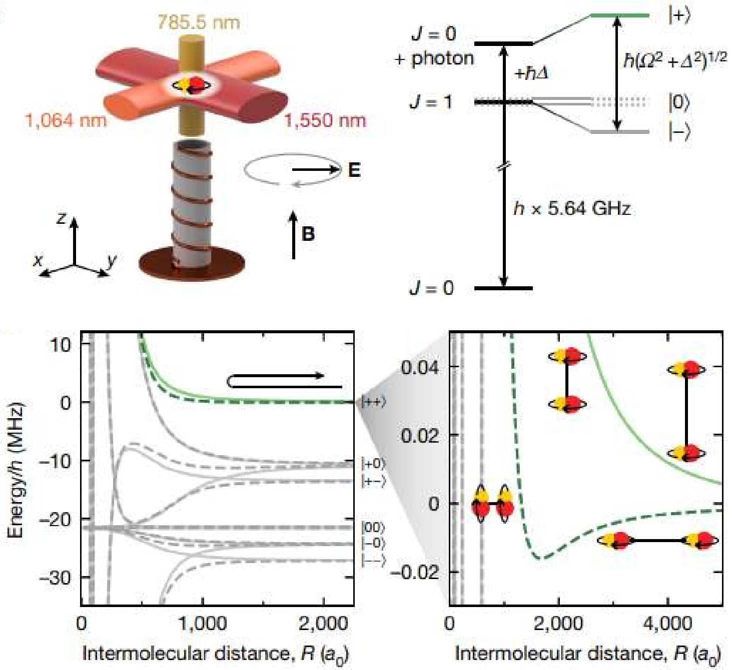
Article | Open Access | Published: 27 July 2022

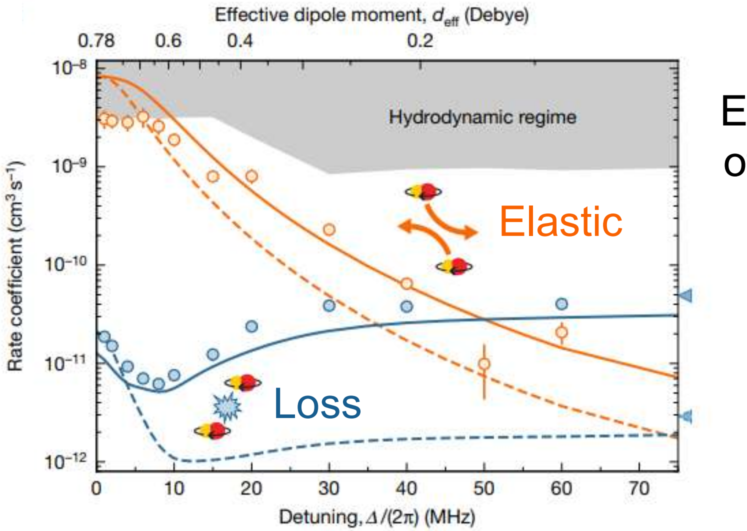
Evaporation of microwave-shielded polar molecules to quantum degeneracy

Andreas Schindewolf, Roman Bause, Xing-Yan Chen, Marcel Duda, Tijs Karman, Immanuel Bloch & Xin-Yu Luo ✉

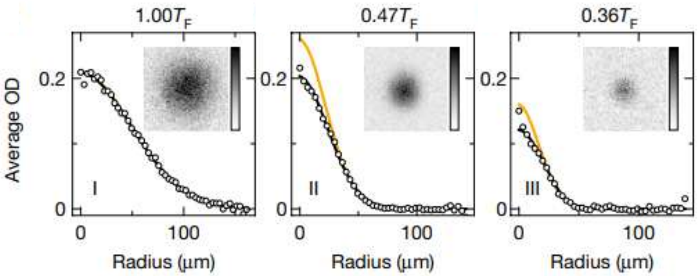
Nature **607**, 677–681 (2022) | Cite this article

Requires circularly polarized microwaves





Enhances ratio of good-to-bad collisions



Quantum degenerate Fermi gas of molecules

BEC of dipolar molecules

Article

Observation of Bose–Einstein condensation of dipolar molecules

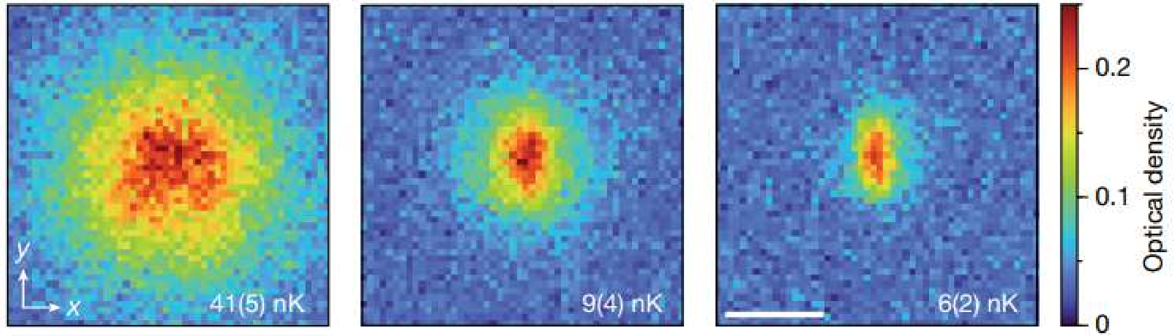
https://doi.org/10.1038/s41586-024-07492-z

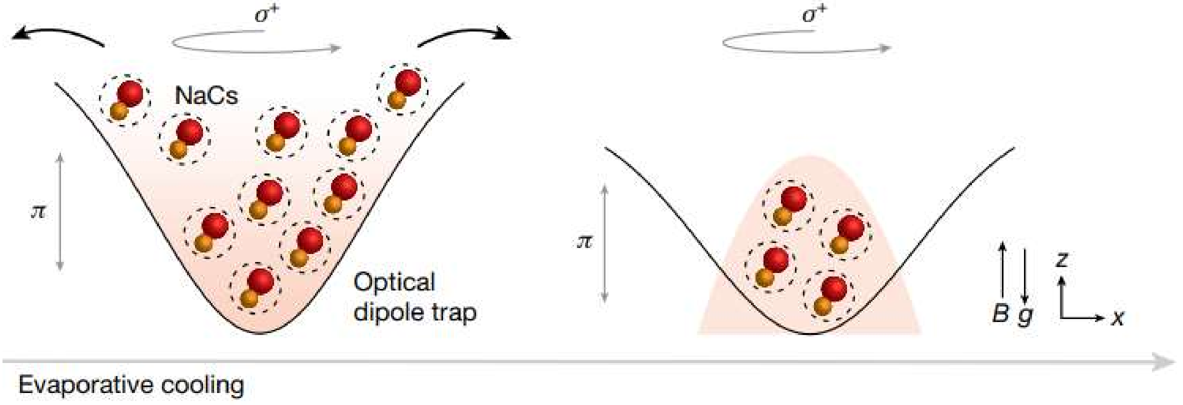
Received: 18 December 2023

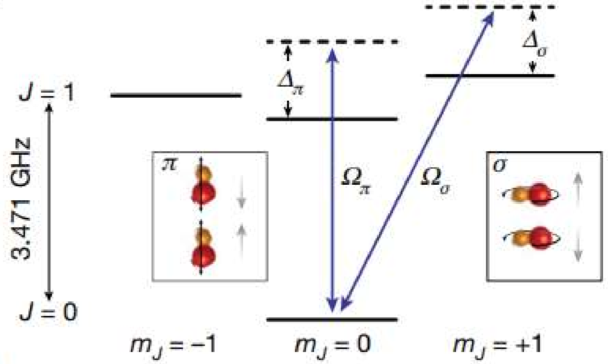
Niccolò Bigagli[1,3], Weijun Yuan[1,3], Siwei Zhang[1,3], Boris Bulatovic[1], Tijs Karman[2], Ian Stevenson[1] & Sebastian Will[1]✉

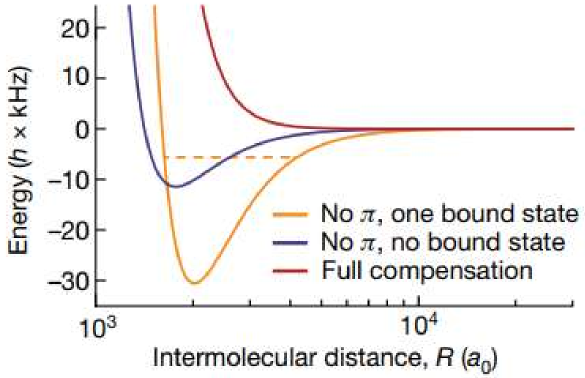
Nature **631**, 289 – 293 (2024)

Add a second microwave field
to eliminate bound states and
hence suppress 3-body loss





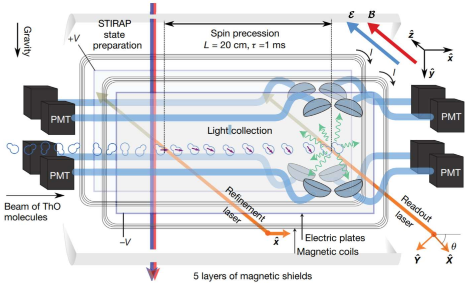




Conclusion

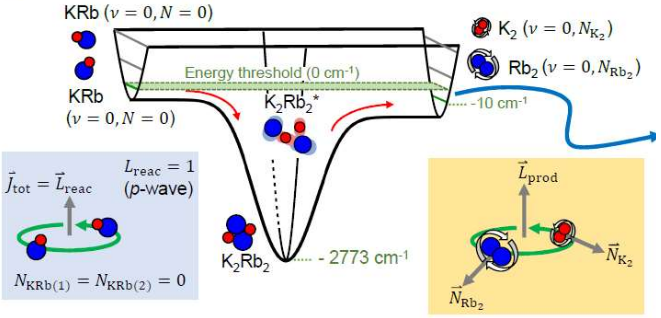
Why ultracold polar molecules?

Precision measurement



The ACME collaboration, Nature **562**, 355 (2018)

Ultracold Chemistry

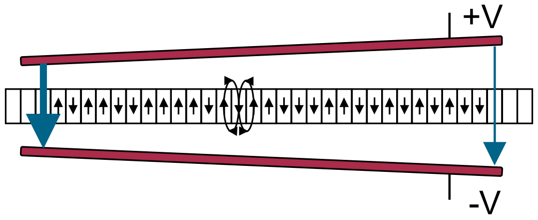


Liu, Nat. Phys. **16**, 1132 (2020)

Novel quantum fluids

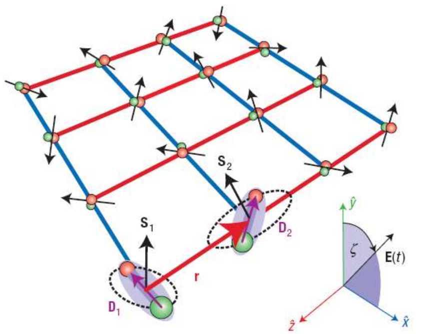
Schmidt, PRR **4**, 013235 (2022)

Quantum computation



DeMille, PRL **88**, 067901 (2002)

Quantum simulation



Micheli, Nat. Phys. **2**, 341 (2006)

Acknowledgements

These experiments are a big team effort:

Philip Gregory

Alex Guttridge

Royal Society University
Research Fellows

Theory Collaborators:
Jeremy Hutson (everything molecule related)
Svetlana Kotochigova (magic trapping)
Rosario Gonzalez-Ferez (Rydberg molecules)
Hossein Sadeghpour (Rydberg molecules)
Kaden Hazzard (DDI & synthetic dimensions)

erc European Research Council

Advanced Grant
Selected by ERC
funded by:

UKRI Engineering and Physical Sciences Research Council

Thank you