Long-lived entanglement of molecules in magic-wavelength optical tweezers

Daniel Ruttley

PhD $\longrightarrow$ PDRA
Cornish Group

25 November 2025

3 Long-lived entanglement of molecules 1
in magic-wavelength optical tweezers
2

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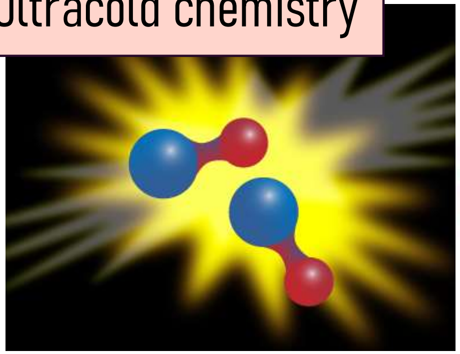
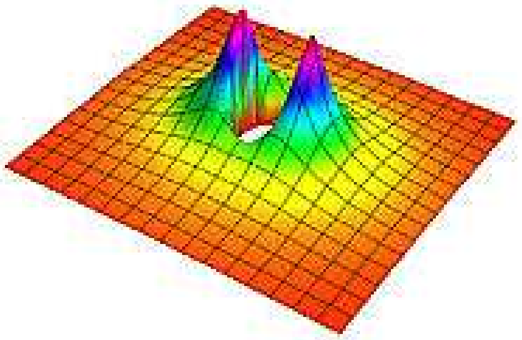
Quantum science with ultracold molecules

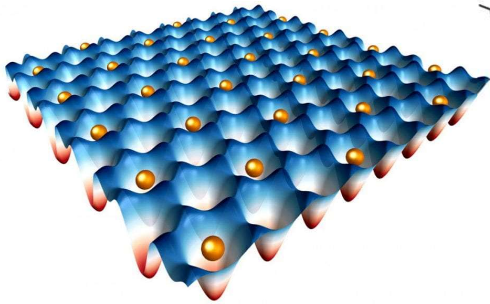
Ultracold chemistry

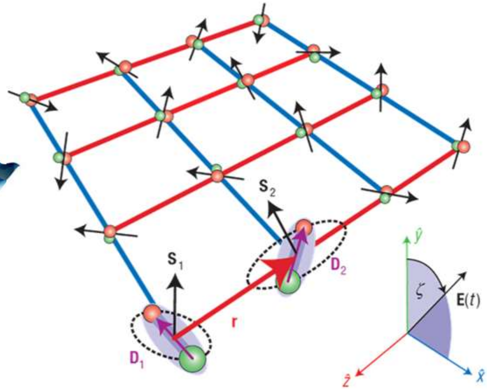




Ni et al, Nature, **464**, 1324 (2010)

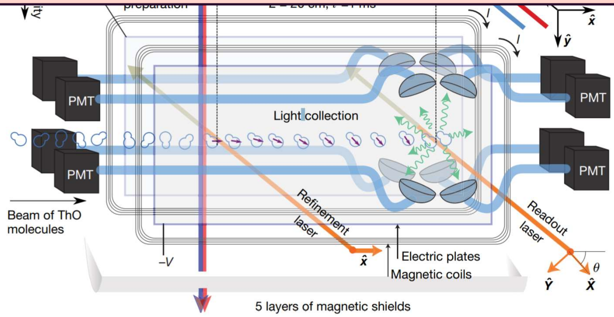
Quantum simulation

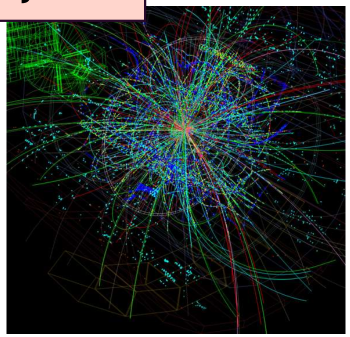




Micheli et al., Nature Physics, **2**, 341 (2006)

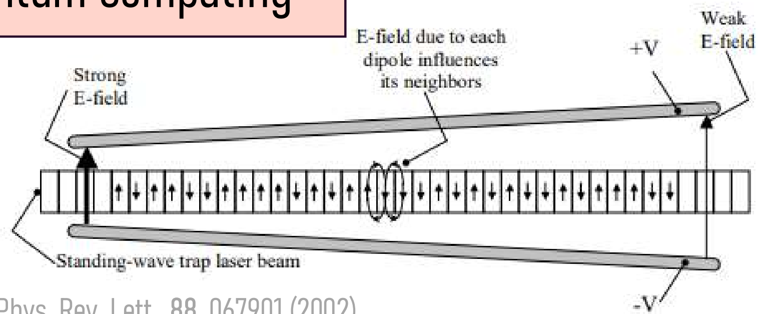
Precision measurement for new physics





ACME Collaboration., Nature, **562**, 355 (2018)

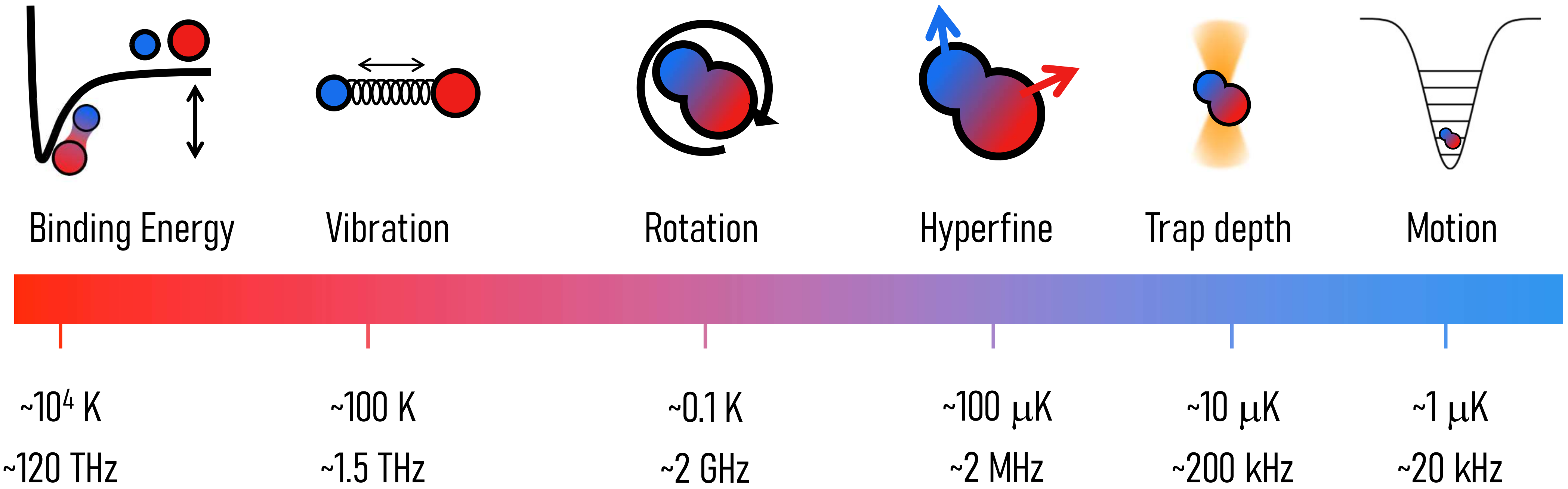
Quantum computing

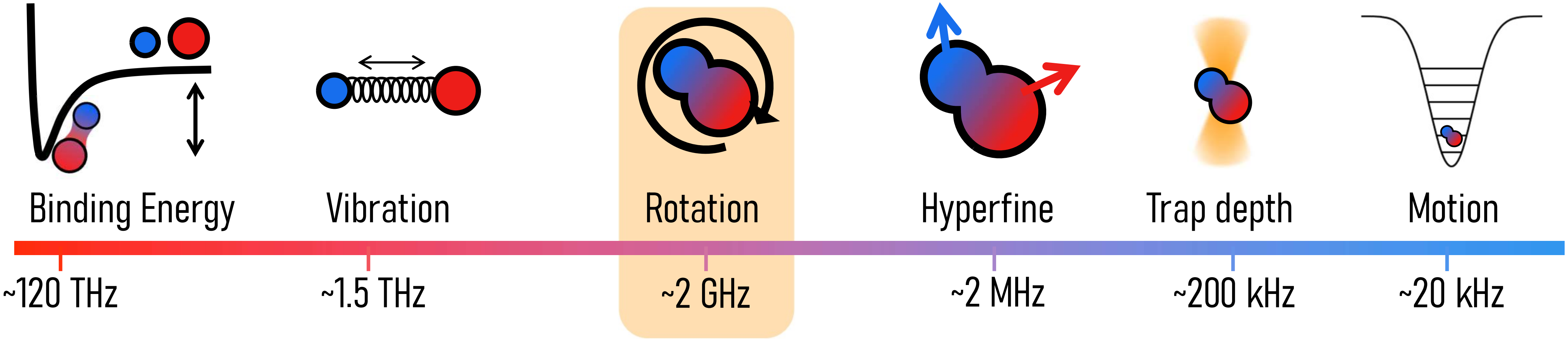


DeMille, Phys. Rev. Lett., **88**, 067901 (2002)

Images: Cornell University, ACME collaboration, Forbes, Physics, NIST

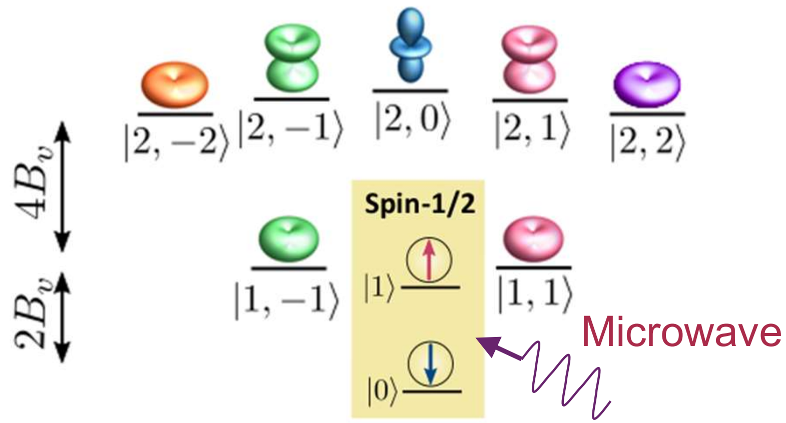
Rich internal structure





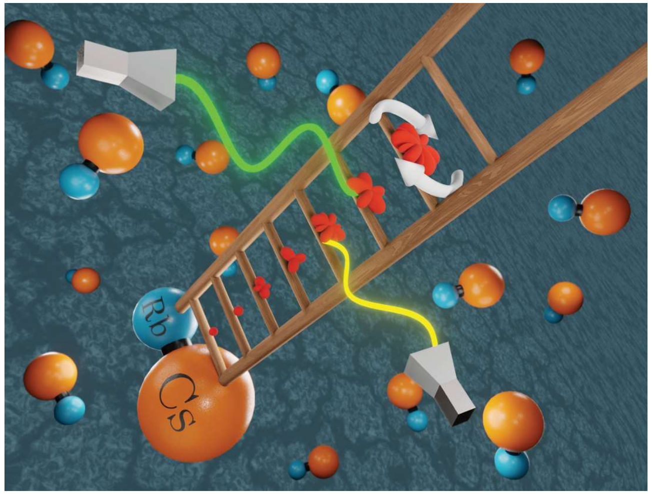
Ladder of long-lived rotational states

$$E_N = B_v N(N+1)$$



Encode and manipulate spins

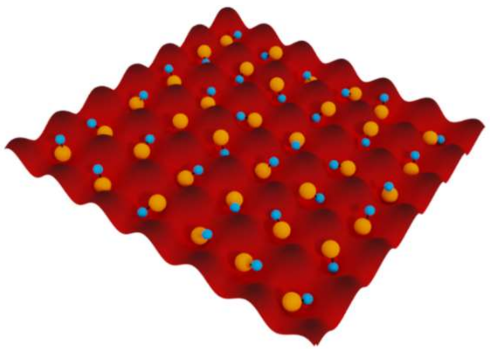
Blackmore et al., Phys. Chem. Chem. Phys. 22, 27529 (2020)

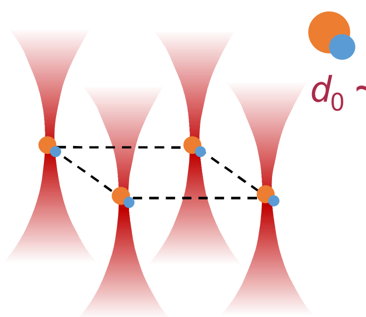


Engineering synthetic dimensions

Sundar et al., Scientific Reports 8, 3422 (2022)

Dipole-dipole interactions





$$H_{\mathrm{XXZ}} = \sum_{i \neq j} \left[\frac{J_\perp}{2} (S_i^+ S_j^- + S_i^- S_j^+) + J_z S_i^z S_j^z \right]$$

$$J_\perp \propto |\langle \uparrow | d_0 | \downarrow \rangle|^2$$

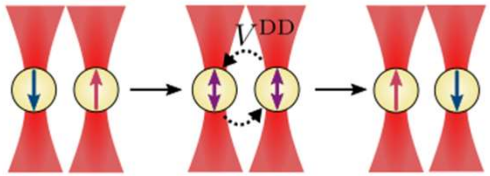
Spin exchange

$$J_z \propto (\langle \uparrow | d_0 | \uparrow \rangle - \langle \downarrow | d_0 | \downarrow \rangle)^2$$

"Ising" interaction

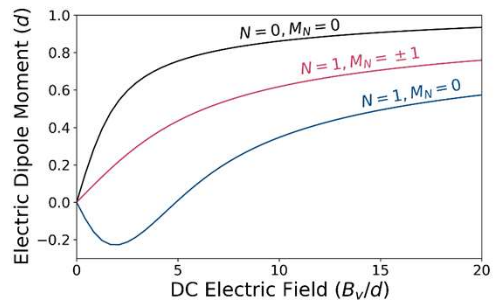
Controllable

Via transition dipole moment between rotational states



Spin-exchange interactions

External fields (electric, MW)



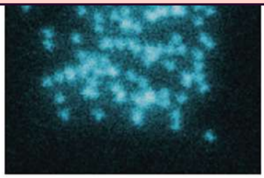
Details:
Wall, Hazzard, Rey, *Quantum magnetism with ultracold molecules* (2015)
Cornish, Tarbutt, Hazzard, Nat. Phys. 20, 730 (2024)

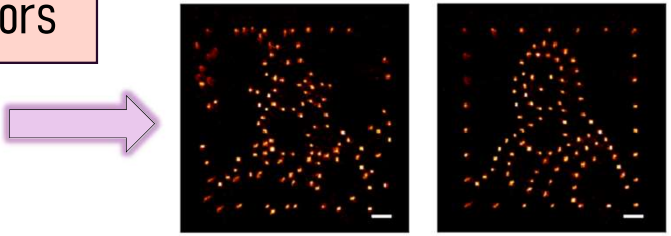
Why tweezed and assembled molecules?

Durham University

Individual particle control

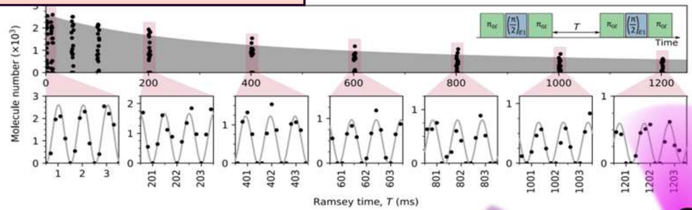
Low filling factors

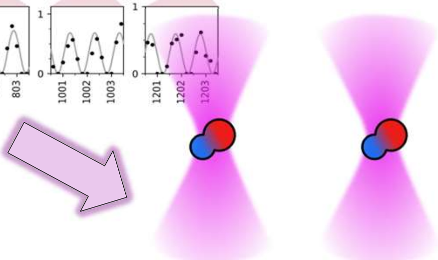




Rosenberg, …, Bakr, Nat. Phys. 18, 1062 (2022)
Schymik, …, Lahaye, Phys. Rev. A 102, 063107 (2020)

Collisional loss

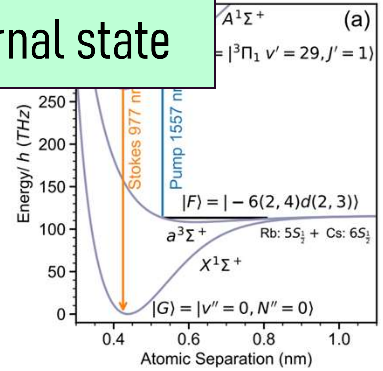




Gregory, …, Cornish,
Nat. Phys. 17, 1149 (2021)

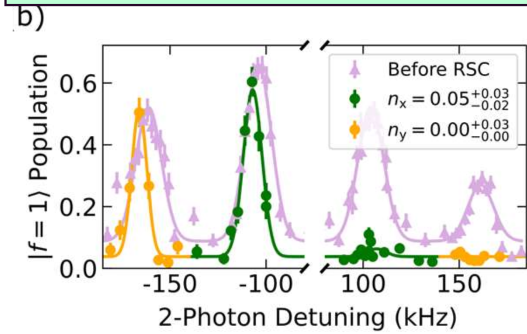
Molecular assembly

Single internal state



J. Blackmore,
PhD thesis (2020)

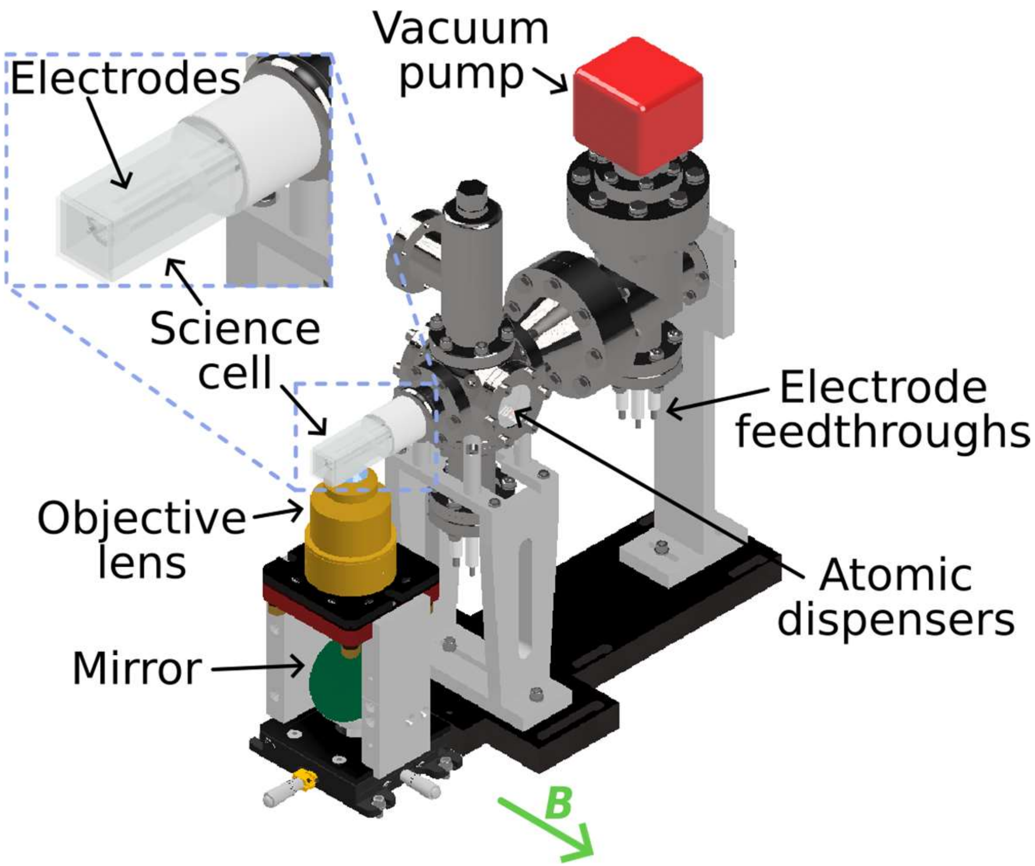
Ultracold (from atomic cooling)

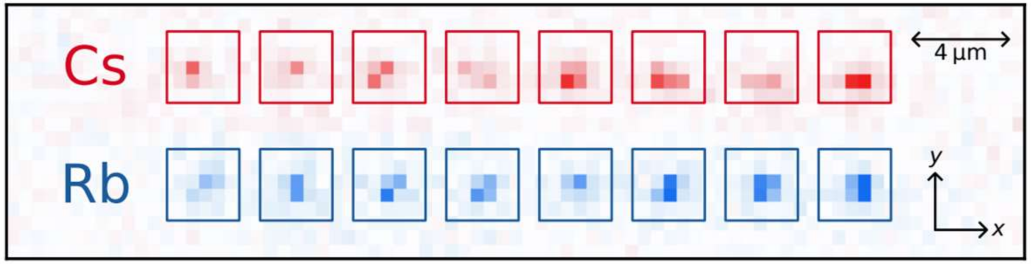


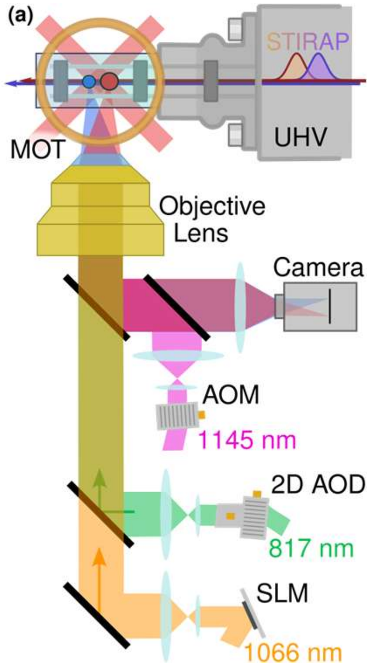
Spence, …, Cornish, New J.
Phys. 24, 103022 (2022)

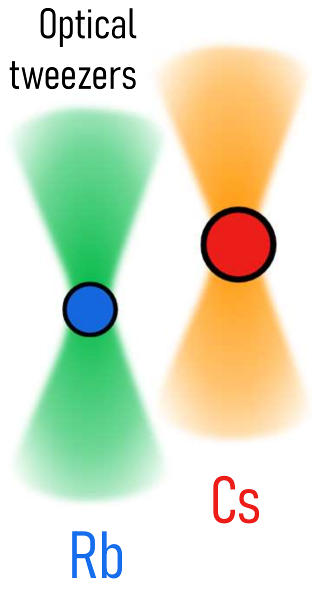
The Durham apparatus

Experiments take place in ultra-high vacuum





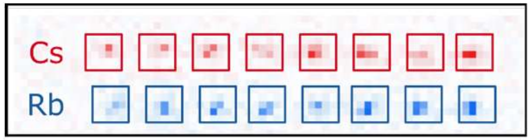




The Durham apparatus

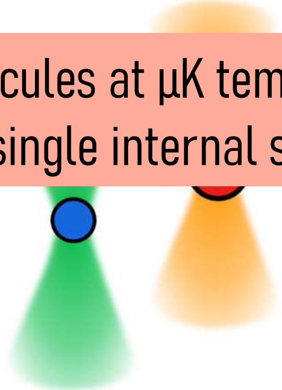
Durham University

Load and image tweezers



Merge tweezers

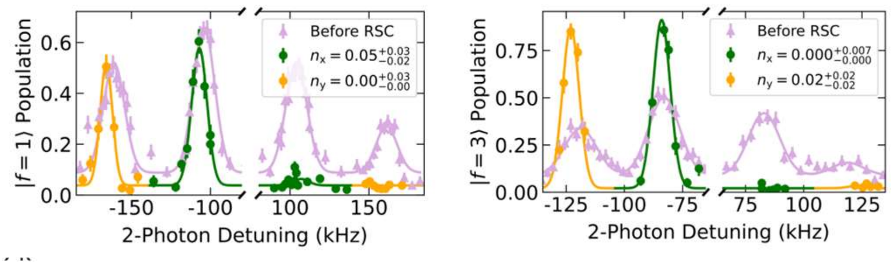
Form molecules at μK temperatures in a single internal state



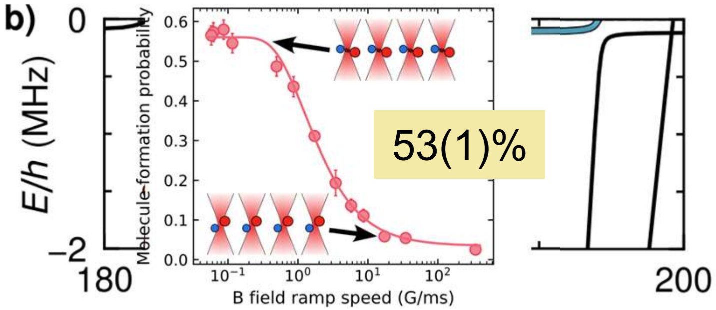
Rb

Cs

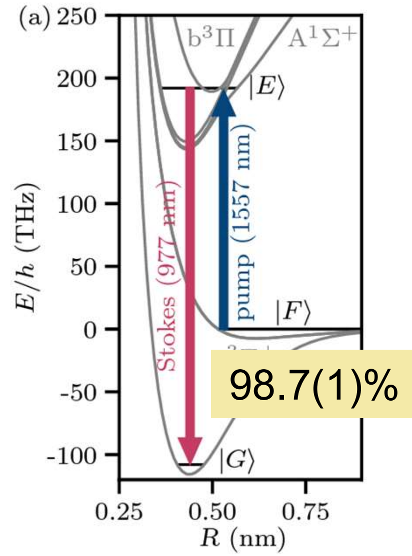
Raman sideband cooling



Associate into weakly bound molecule

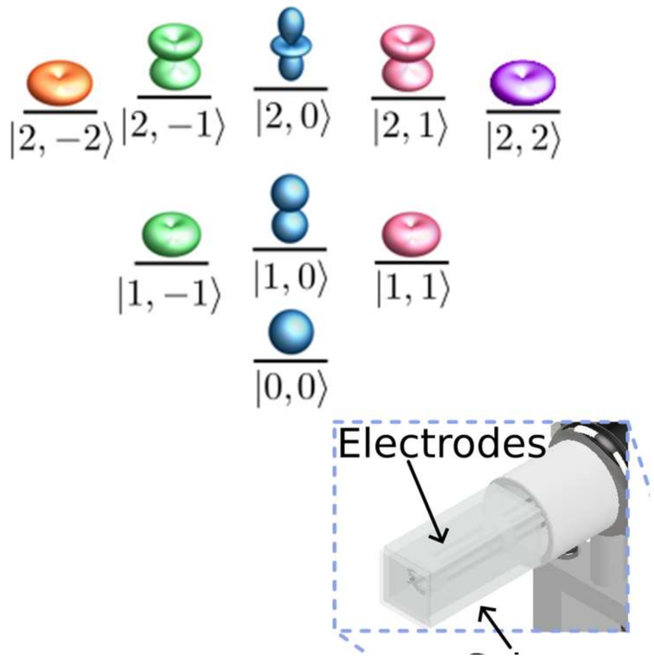


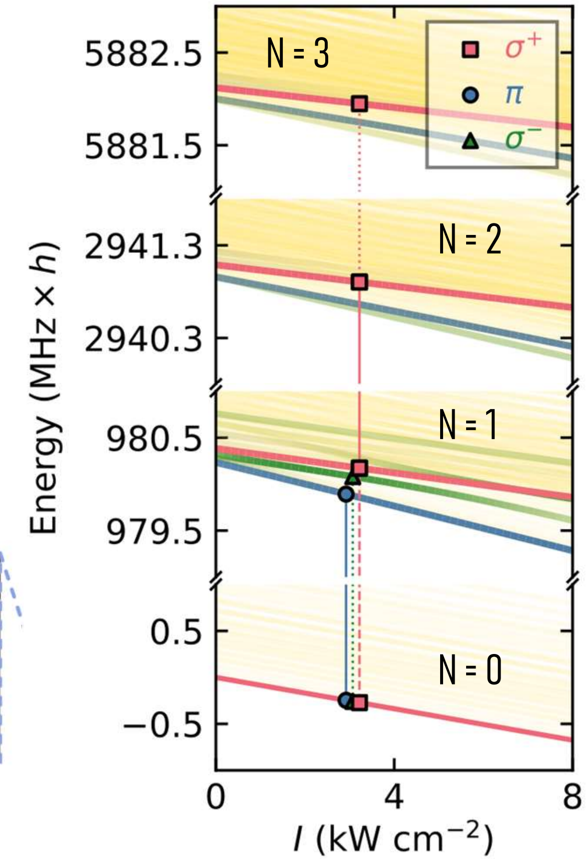
Transfer molecule to rovibrational ground state

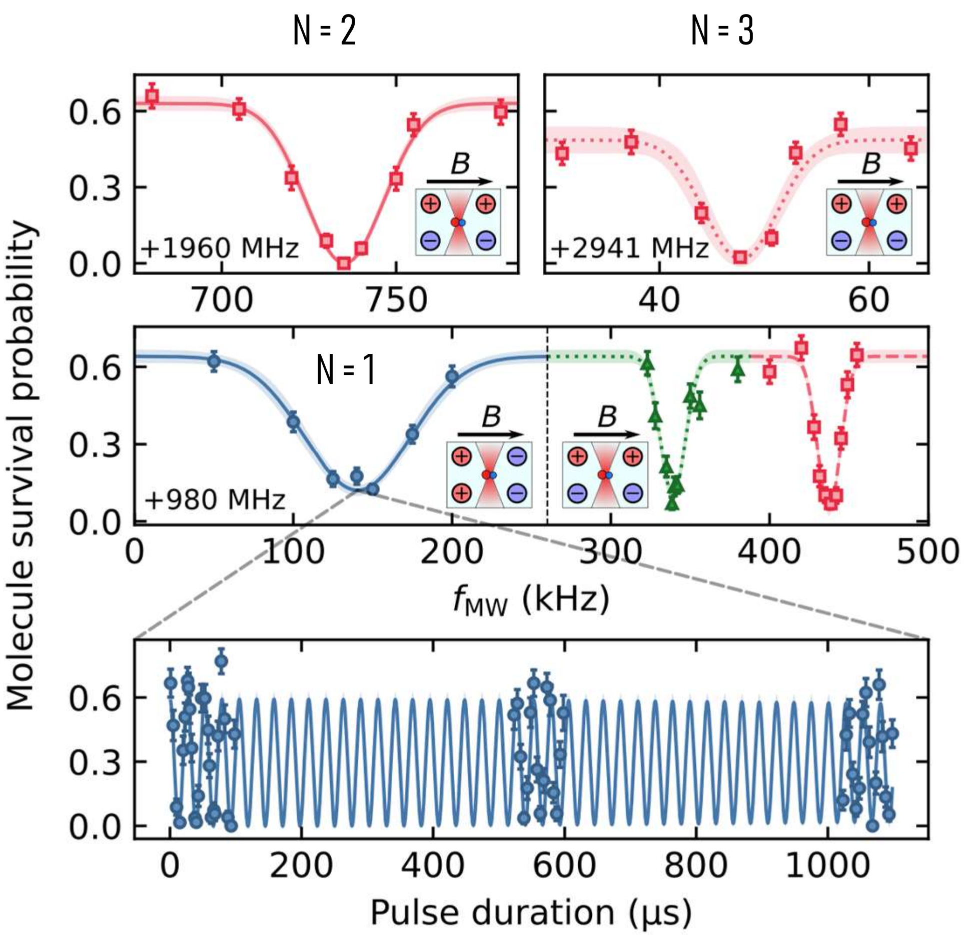


Maddox, …, Cornish, PRL133, 253202 (2024)

State control and readout

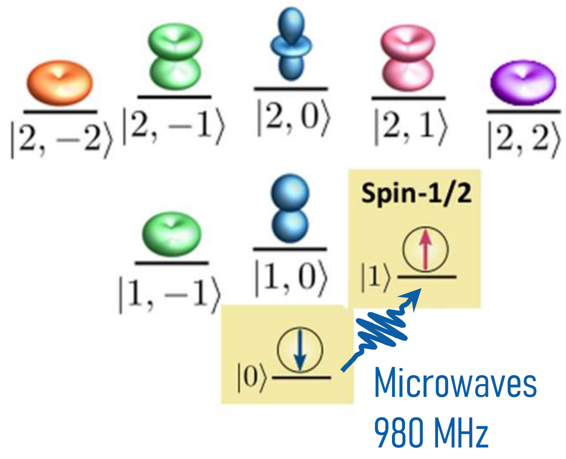


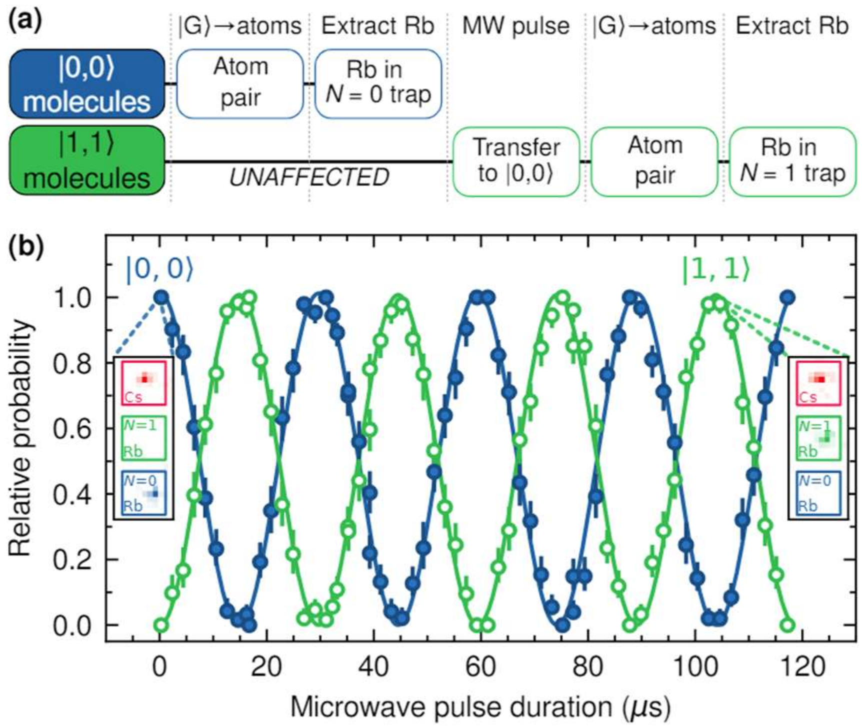


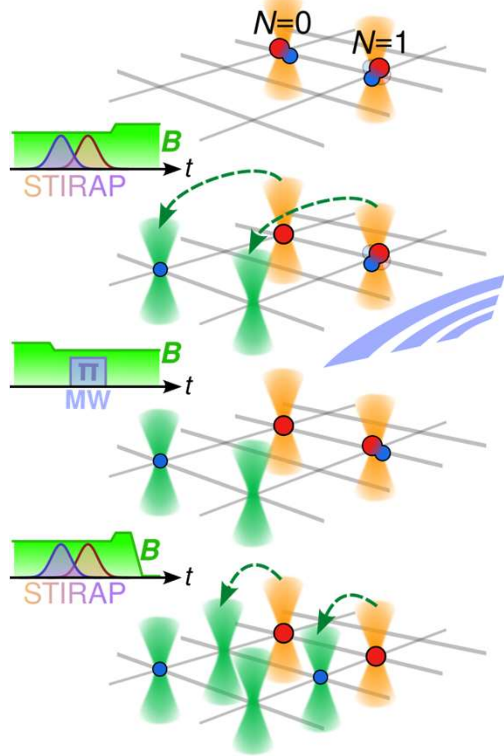


Ruttley, …, Cornish, PRX Quantum 5, 020333
See also: Picard, …, Ni, PRX Quantum 5, 020344 (2024)

State control and readout







Ruttley, …, Cornish, PRX Quantum 5, 020333 (2024)
See also: Picard, …, Ni, PRX Quantum 5, 020344 (2024)

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Interactions in a molecular quantum computer

VOLUME 88, NUMBER 6 PHYSICAL REVIEW LETTERS 11 FEBRUARY 2002

Quantum Computation with Trapped Polar Molecules

D. DeMille
Department of Physics, P.O. Box 208120, Yale University, New Haven, Connecticut 06520
(Received 27 October 2001; published 24 January 2002)

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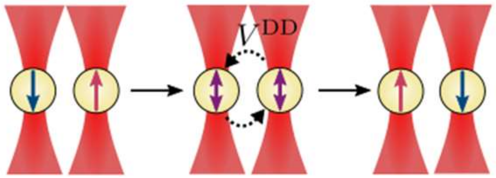
Cite this: Chem. Sci., 2018, 9, 6830
All publication charges for this article have been paid for by the Royal Society

Dipolar exchange quantum logic gate with polar molecules

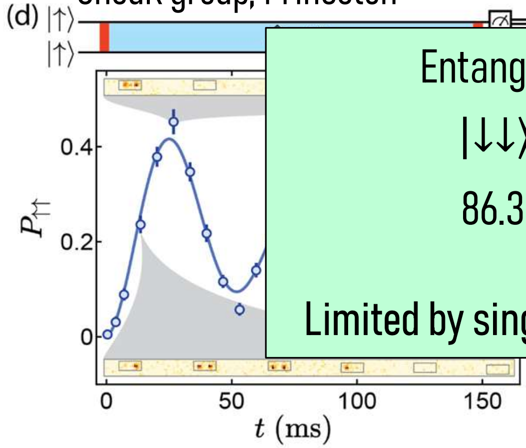
Kang-Kuen Ni,[*abc] Till Rosenband[b] and David D. Grimes[abc]



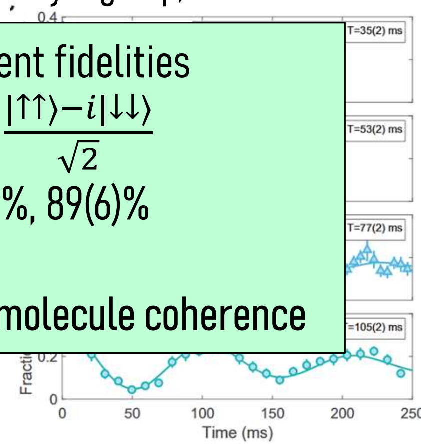
Exploit spin-exchange interactions to entangle molecules for two-qubit gates

2023: Demonstrated with CaF molecules with interaction strengths ~50 Hz and many rephasing pulses

Cheuk group, Princeton



Doyle group, Harvard



Entanglement fidelities

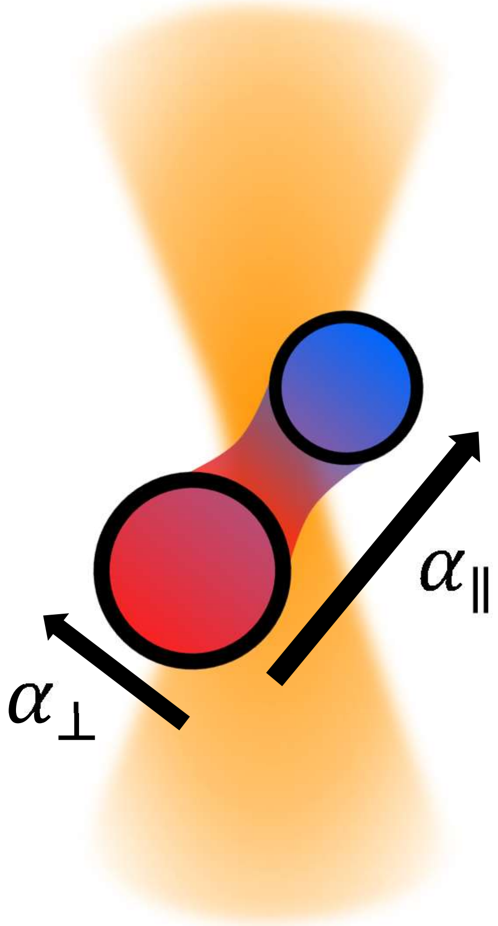
$$|\downarrow\downarrow\rangle \rightarrow \frac{|\uparrow\uparrow\rangle - i|\downarrow\downarrow\rangle}{\sqrt{2}}$$

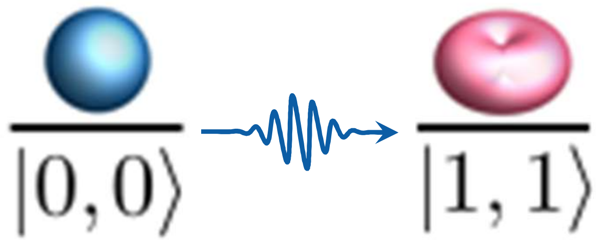
86.3(2.5)%, 89(6)%

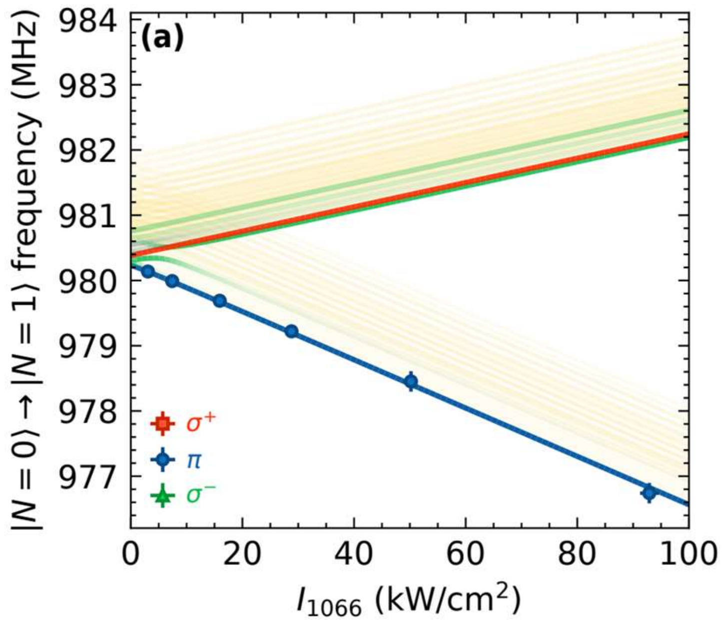
Limited by single-molecule coherence

DeMille, PRL **88**, 067901 (2002)
Ni, Rosenband, & Grimes, Chem. Sci. **9**, 6830 (2018)
Holland, …, Cheuk, Science **382**, 1143 (2023)
Bao, …, Doyle, Science **382**, 1138 (2023)

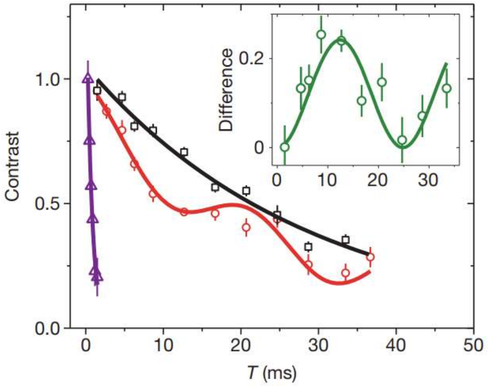
ac Stark shifts of molecules







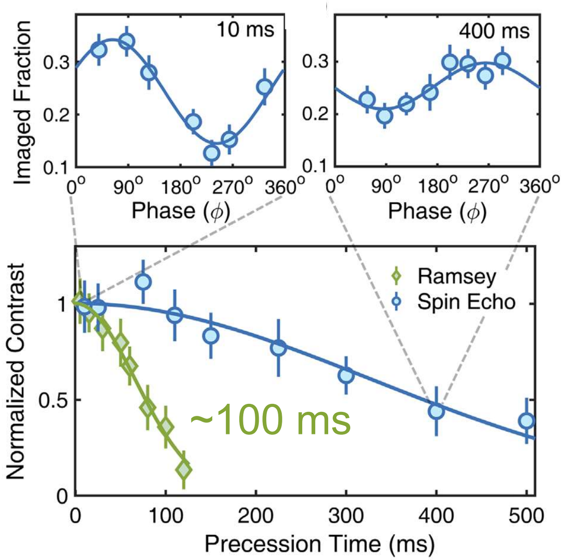
KRb in optical lattice



Single particle dephasing ~ 1 ms

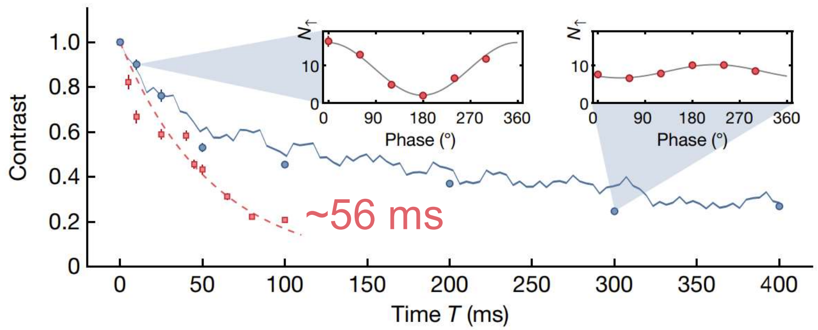
Yan *et al.*, Nature 501, 521-525 (2013)

Single CaF molecule in magic angle tweezer



Burchesky *et al.*, PRL 127,123202 (2021)

NaRb molecules low filling in near-magic lattice



Christakis *et al.*, Nature 614, 64-69 (2023)

NaCs in magic ellipticity tweezer

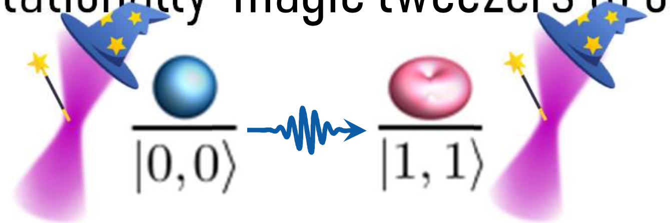
Park *et al.*, PRL 131,183401 (2023)

62(3) ms with single spin-echo pulse

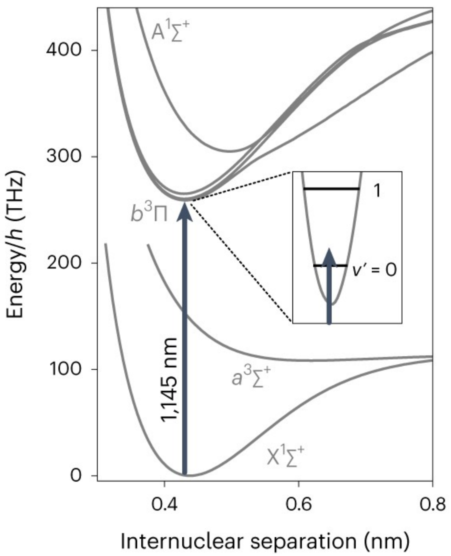
Magic wavelength to the rescue

Durham University

Utilise rotationally-magic tweezers to overcome rotational decoherence



b



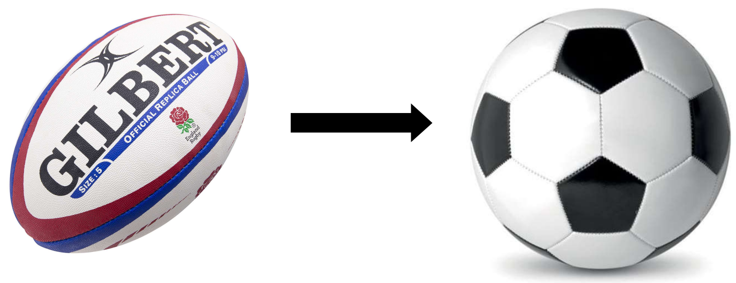
$X^1\Sigma^+ \rightarrow b^3\Pi$

(Nominally) Forbidden

$X^1\Sigma^+ \rightarrow A^1\Sigma^+$

Tunes $\alpha_{\parallel}$

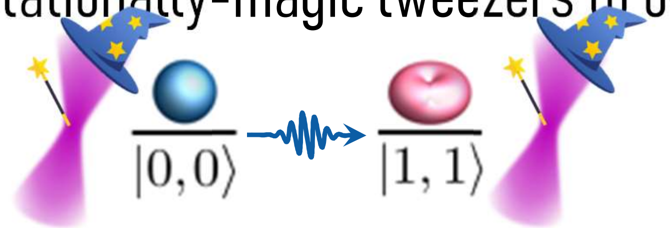
Set $\alpha_{\parallel} = \alpha_{\perp}$

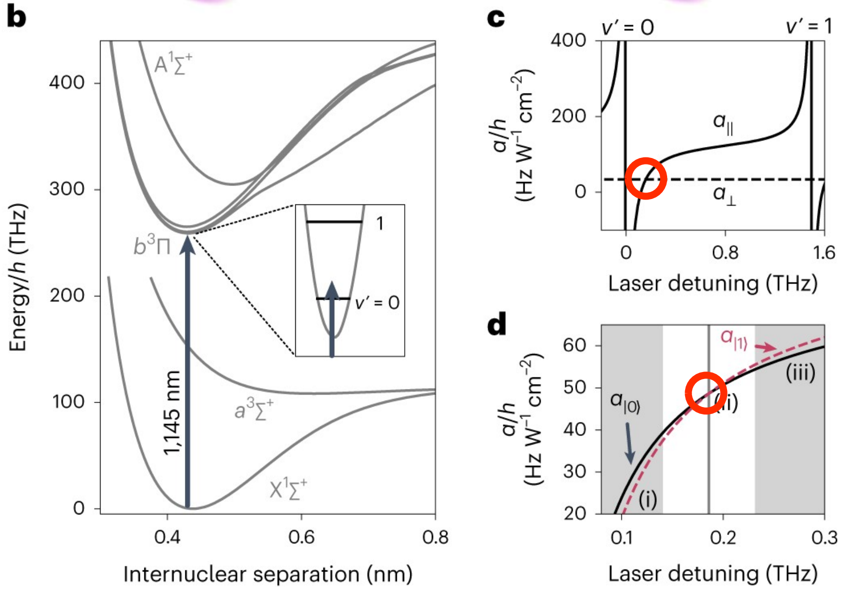


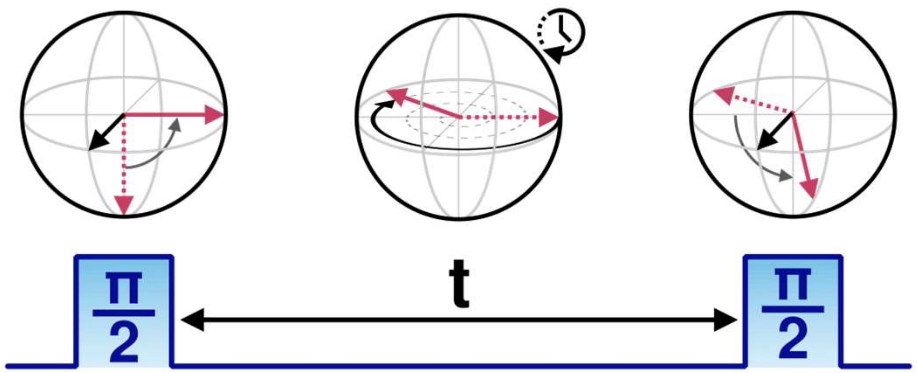
Bause, …, Luo, PRL **125**, 023201 (2020)
Gregory, …, Cornish, Nat. Phys. **20**, 415 (2024)
Theory proposal: Guan, …, Kotochigova, Phys. Rev. A **103**, 043311 (2021)

Magic wavelength to the rescue

Utilise rotationally-magic tweezers to overcome rotational decoherence





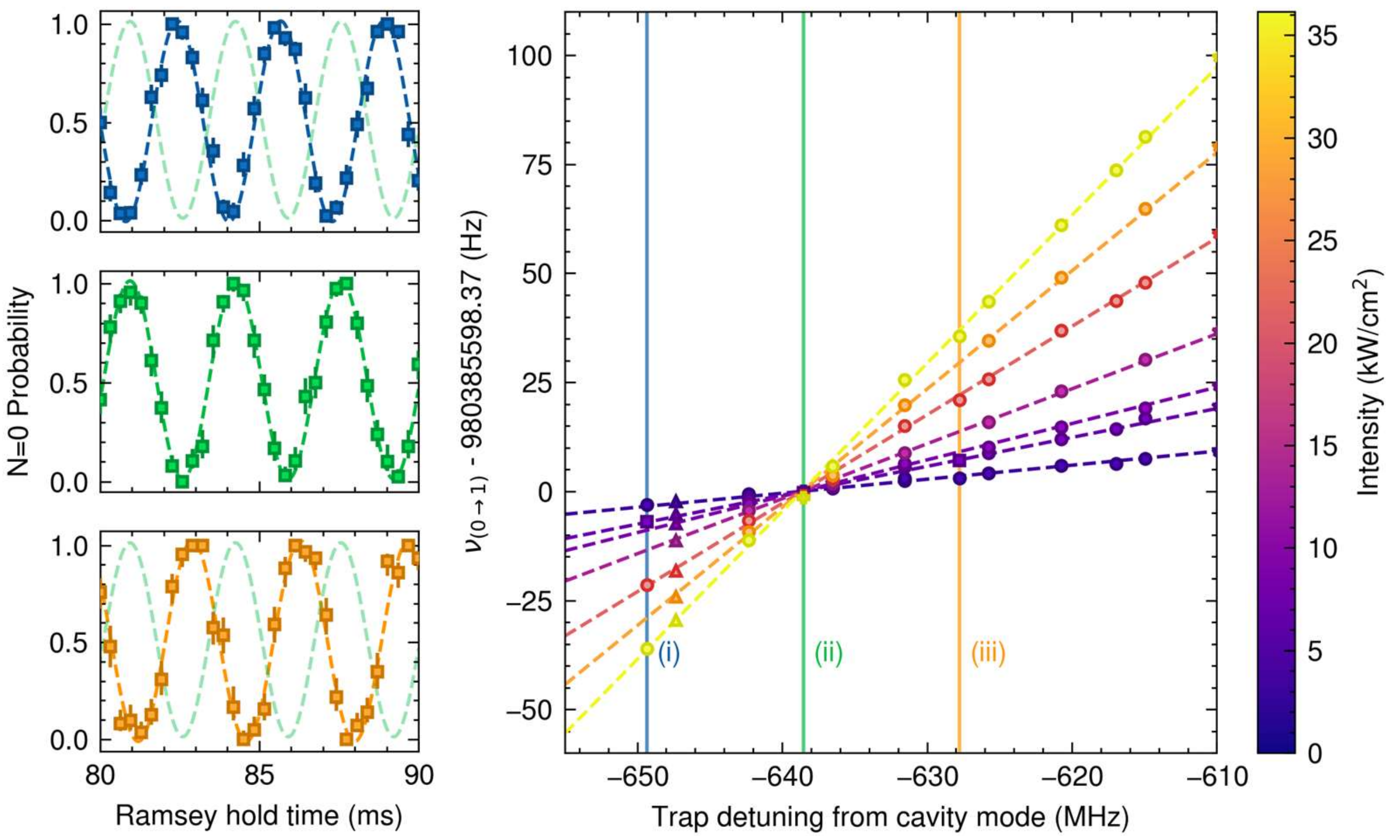


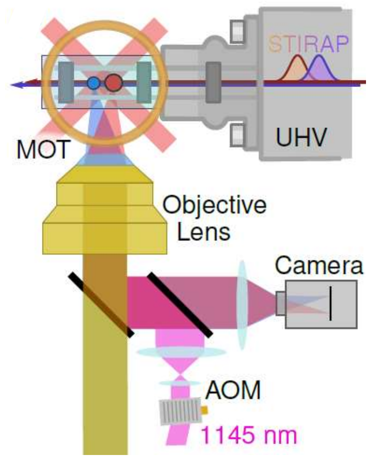
Bause, …, Luo, PRL **125**, 023201 (2020)
Gregory, …, Cornish, Nat. Phys. **20**, 415 (2024)
Theory proposal: Guan, …, Kotochigova, Phys. Rev. A **103**, 043311 (2021)

Magic wavelength to the rescue

Added magic tweezer, 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 / MHz/(kW/cm^2)

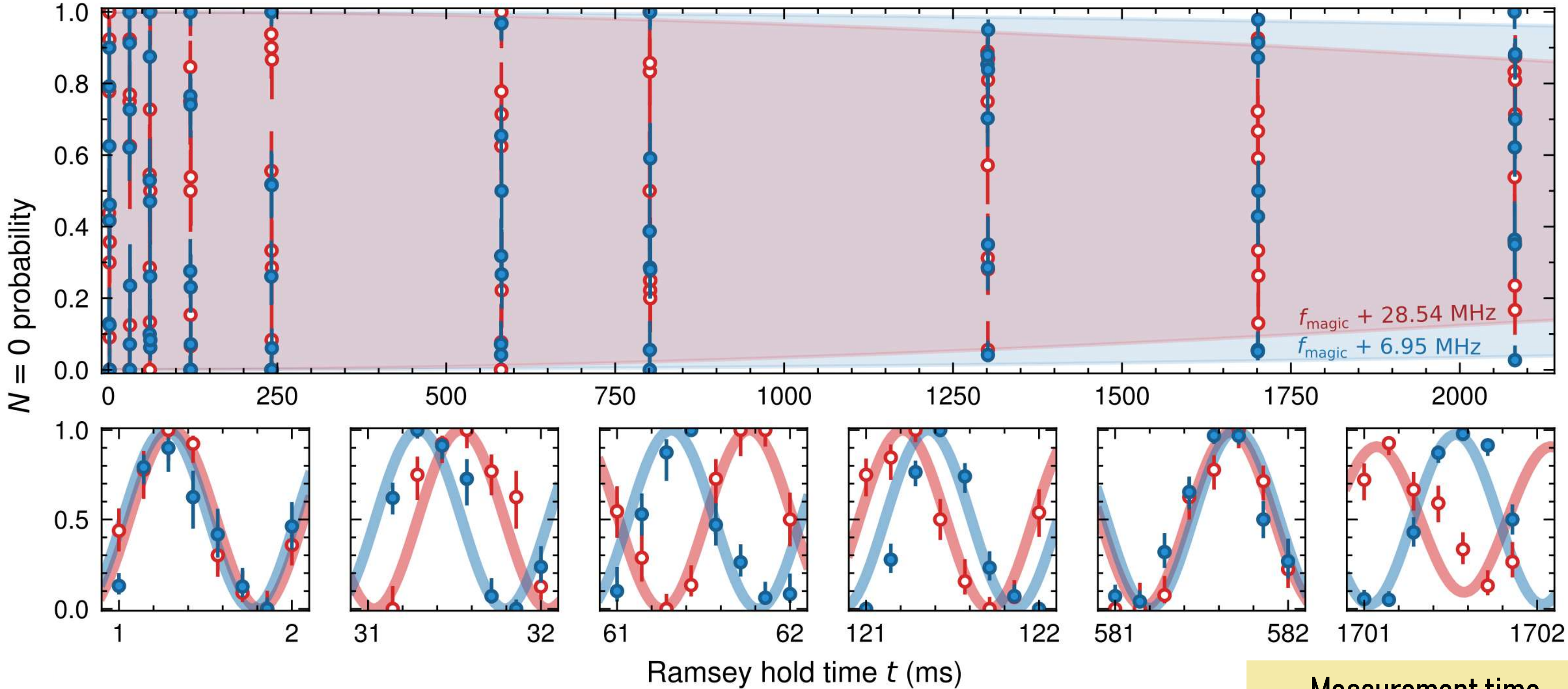
Trap detuning and intensity

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

Magic wavelength to the rescue

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**



15(6) s coherence. No spin echo. No dynamical decoupling. Just magic!

Measurement time > 2 seconds!

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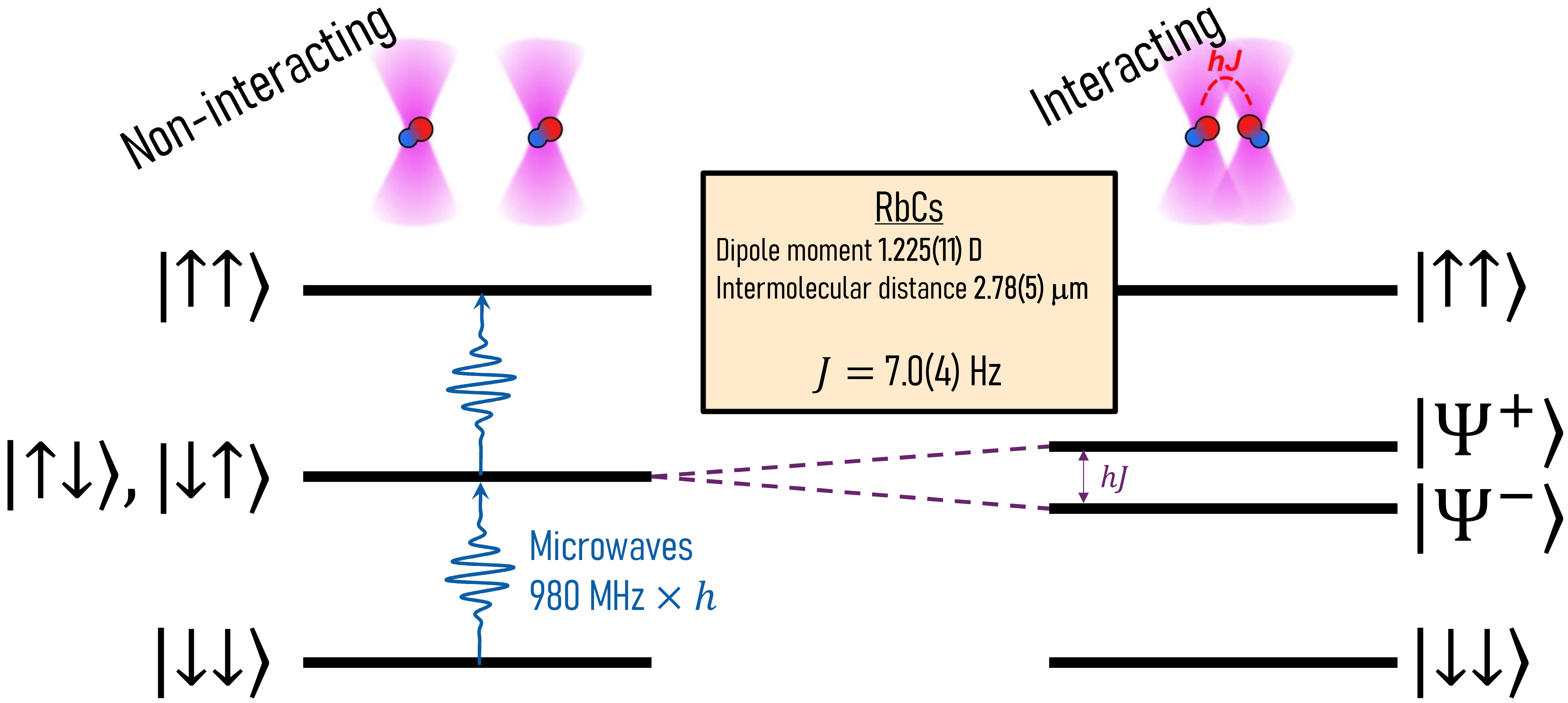
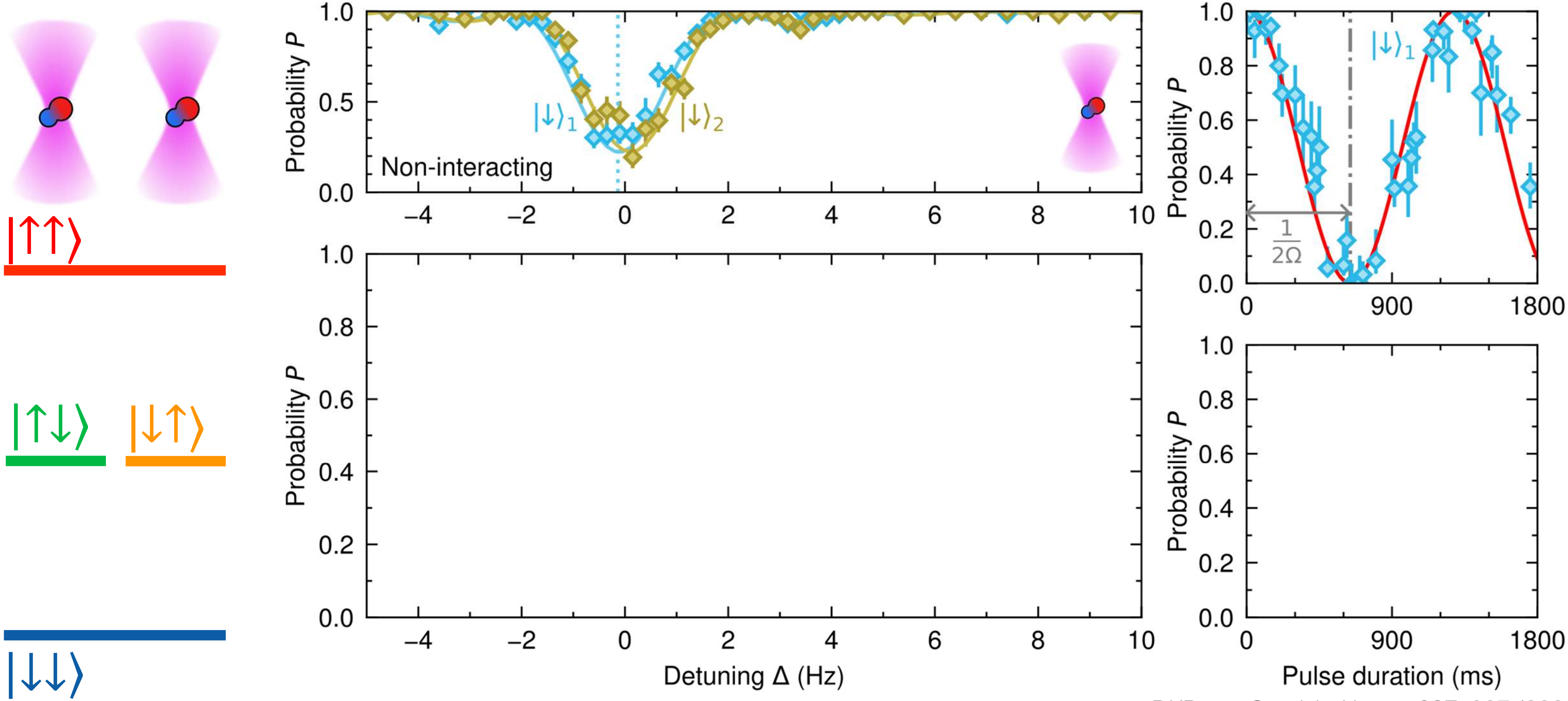
Dipolar interactions

Durham University



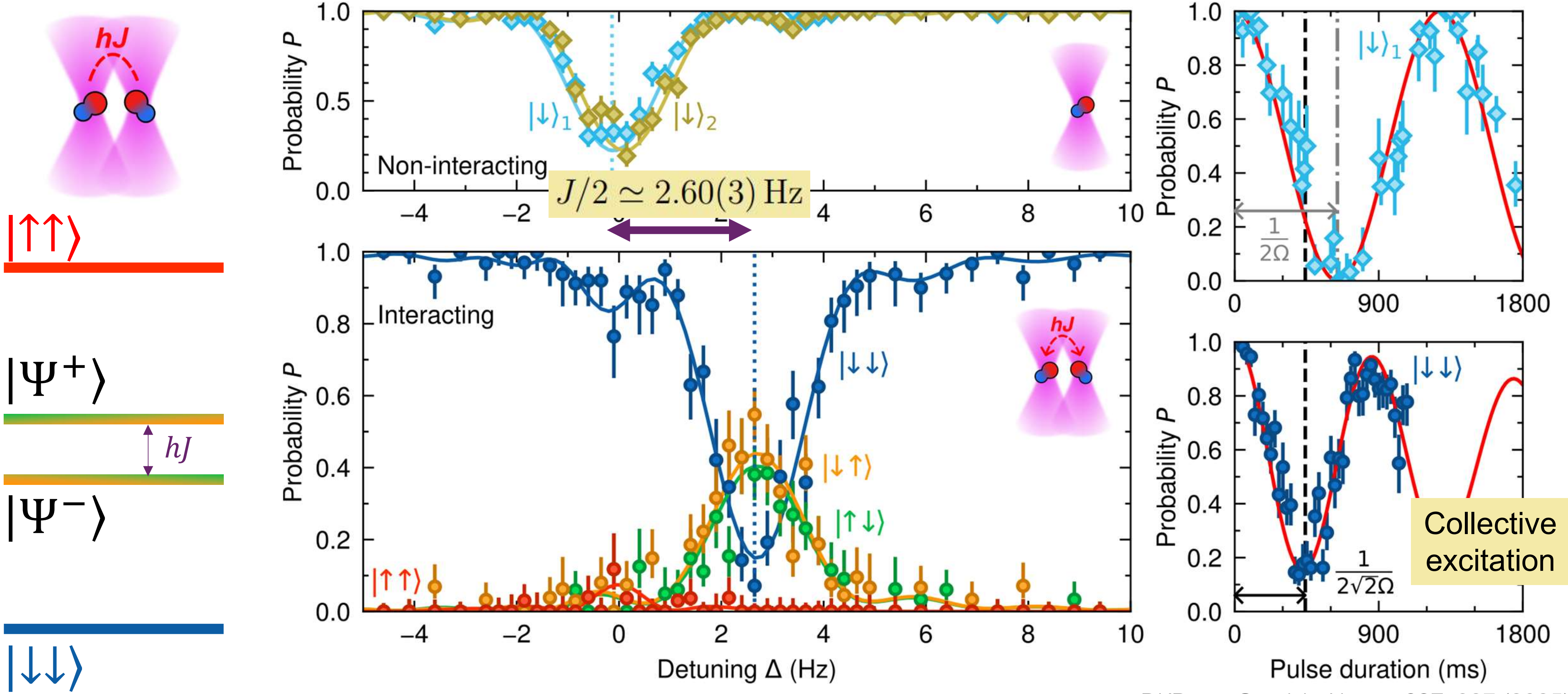
Resolvable Hz-level interactions



DKR, …, Cornish, Nature 637, 827 (2025)

Resolvable Hz-level interactions

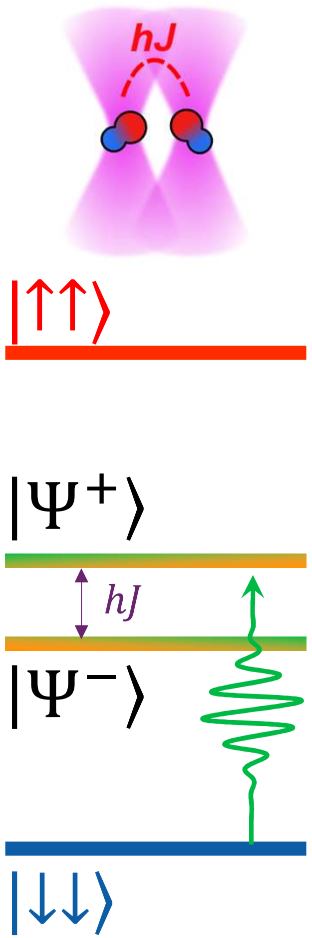
Durham University



DKR, …, Cornish, Nature 637, 827 (2025)

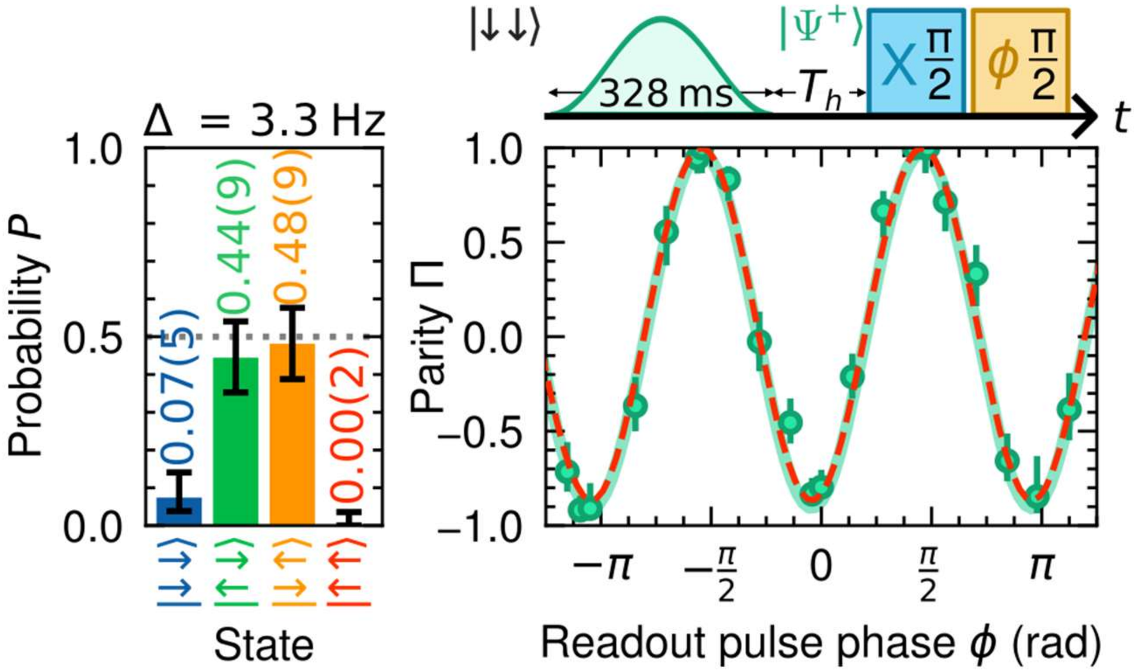
Direct microwave entanglement: characterisation

Durham University



Find the entanglement fidelity $\mathcal{F}$ by measuring entanglement coherence

$$\mathcal{F} = (P_{\downarrow\uparrow} + P_{\uparrow\downarrow} + C)/2$$



$$\mathcal{F} = 0.76^{+0.03}_{-0.04}$$

Limited by <u>detectable</u> leakage/erasure errors

Correct for these errors

$$\mathcal{F} = 0.93^{+0.03}_{-0.05}$$

Limited by molecule temperature

DKR, …, Cornish, Nature **637**, 827 (2025)
Turchette, …, Wineland, Phys. Rev. Lett. **81**, 3631 (1998)

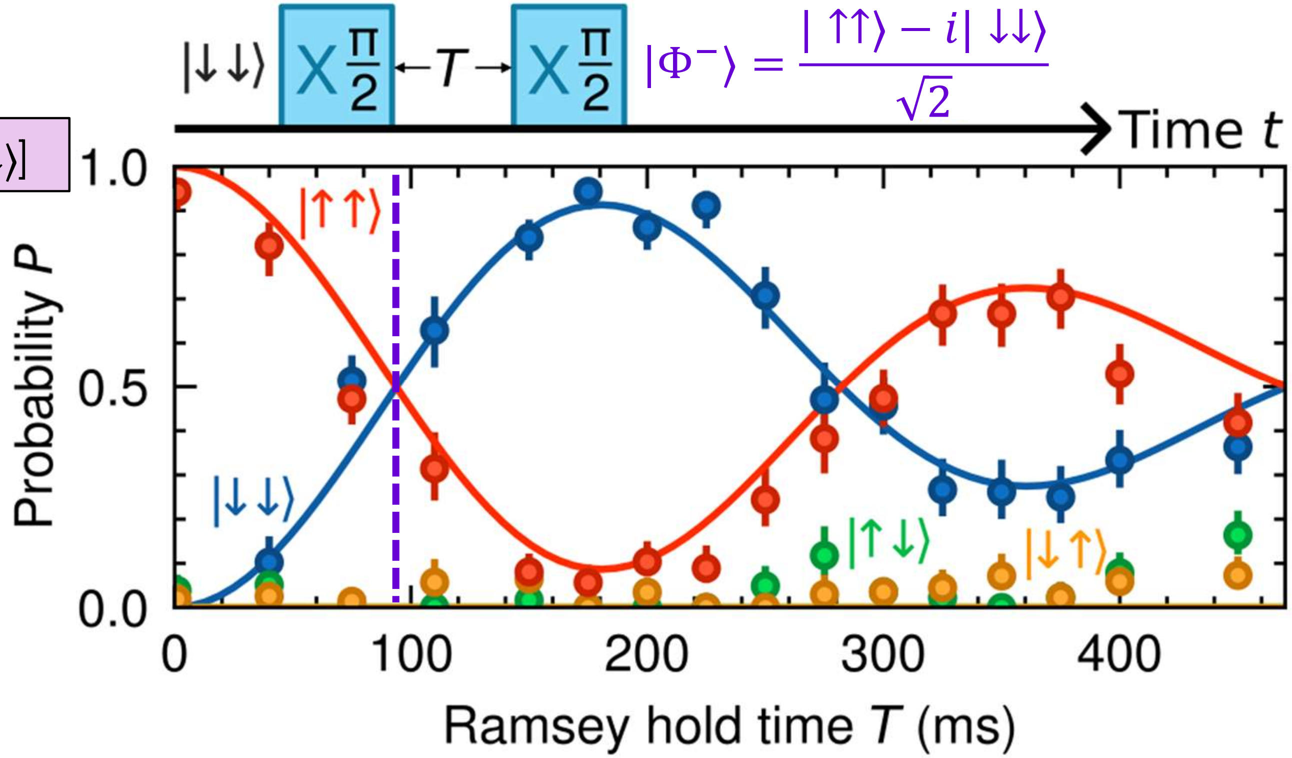
Spin-exchange entanglement

Use a Ramsey sequence which prepares each molecule in a rotational superposition

After evolution time T:

$$\Psi(T) = -e^{-2\pi i\bar{T}}[\cos(2\pi\bar{T})\,|\uparrow\uparrow\rangle - i\sin(2\pi\bar{T})\,|\downarrow\downarrow\rangle]$$

$$\boxed{\bar{T} = \frac{JT}{4}}$$



See also:
Holland, …, Cheuk, Science **382**, 1143 (2023)
Bao, …, Doyle, Science **382**, 1138 (2023)
Picard, …, Ni, Nature **637**, 821 (2025)

DKR, …, Cornish, Nature **637**, 827 (2025)

Spin-exchange entanglement: characterisation

As before, find the entanglement fidelity $\mathcal{F}$

$$\mathcal{F} = (P_{\downarrow\downarrow} + P_{\uparrow\uparrow} + C)/2$$

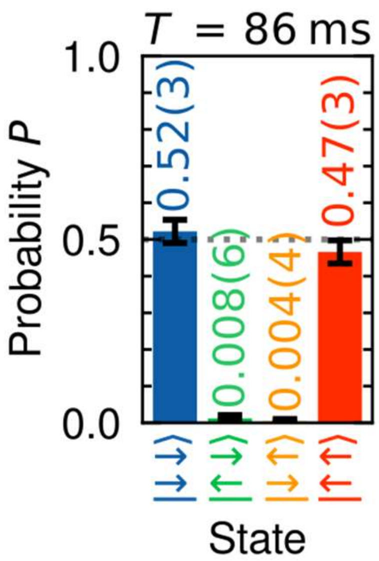
$$\mathcal{F} = 0.924^{+0.013}_{-0.016}$$

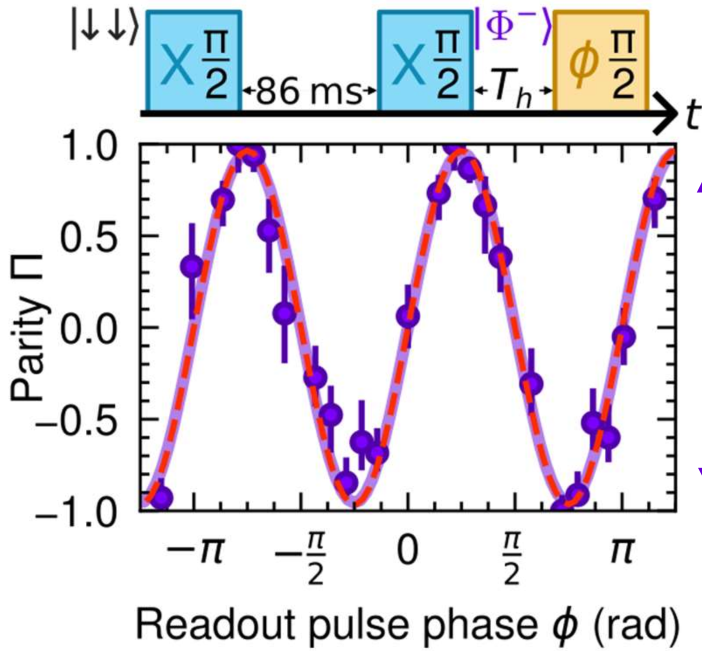
Limited by detectable leakage/erasure errors

Correct for these errors

$$\mathcal{F} = 0.976^{+0.014}_{-0.016}$$

Limited by molecule temperature





$2C$

See also:
Holland, …, Cheuk, Science **382**, 1143 (2023)
Bao, …, Doyle, Science **382**, 1138 (2023)
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Long-lived entanglement ⟶ quantum-enhanced sensors

Durham University

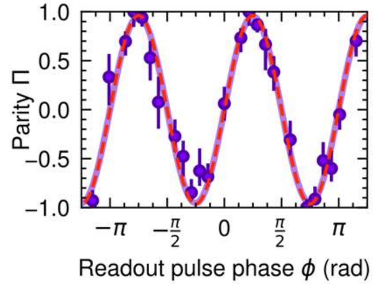
Different entangled states =
different physical probes

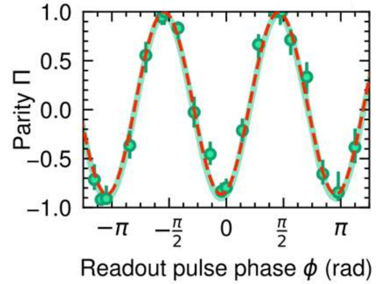
$$|\Phi^{-}\rangle = \frac{|\uparrow\uparrow\rangle - i|\downarrow\downarrow\rangle}{\sqrt{2}}$$

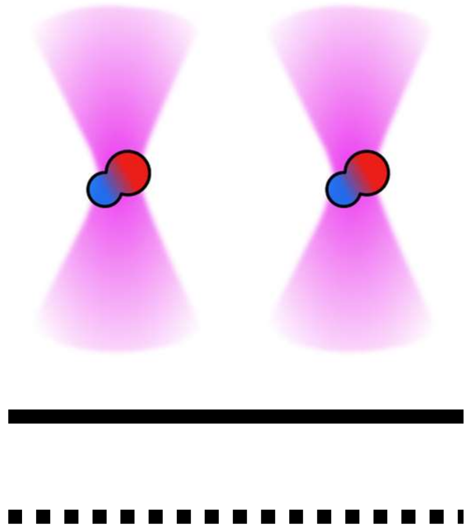
Sensitive to <u>global</u> perturbations

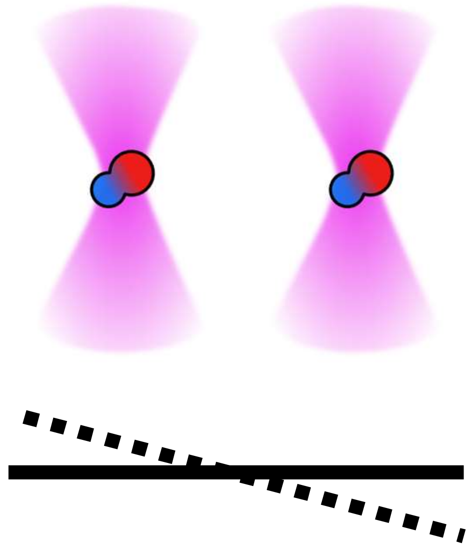
$$|\Psi^{+}\rangle = \frac{|\downarrow\uparrow\rangle + |\uparrow\downarrow\rangle}{\sqrt{2}}$$

Sensitive to <u>local</u> perturbations









DKR, …, Cornish, Nature **637**, 827 (2025)

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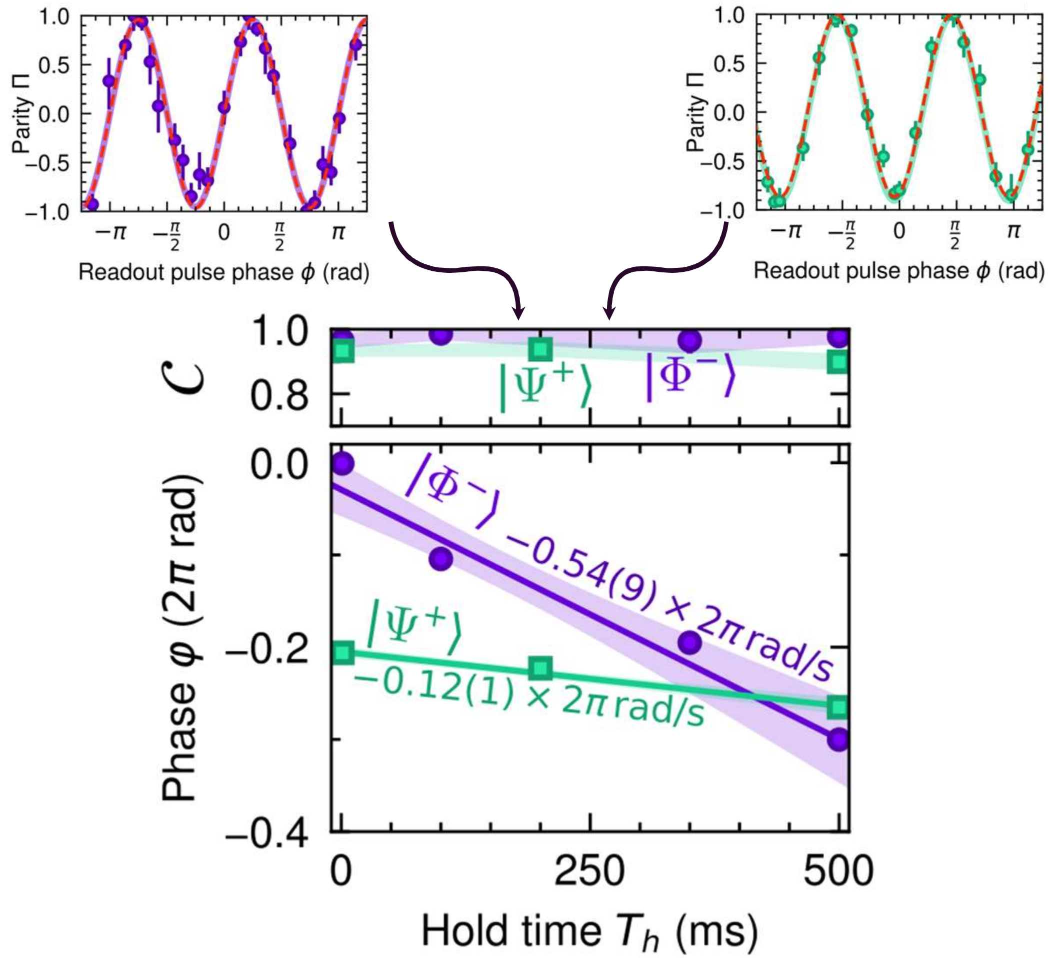
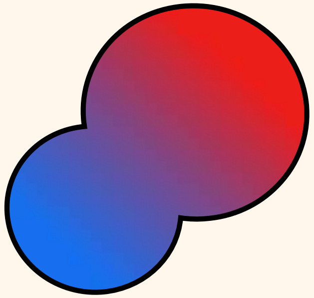


DKR, …, Cornish, Nature **637**, 827 (2025)

Summary

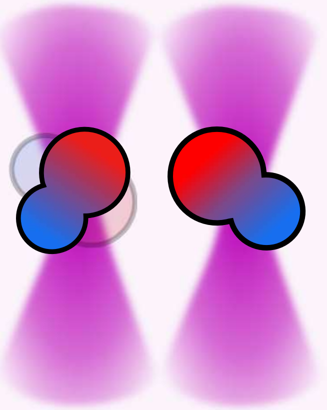
Durham University

1. Molecules



2. Magic tweezers

3. Entanglement



What's next?

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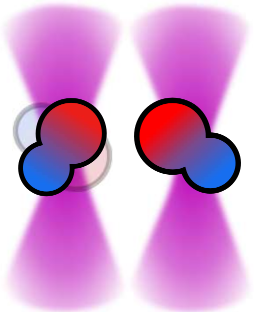
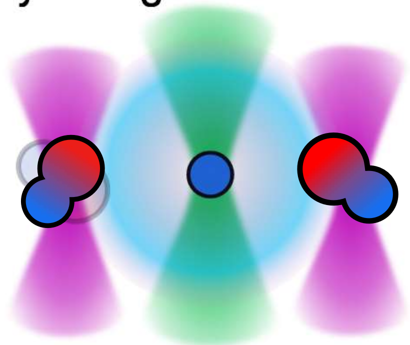
Stronger interactions

Lattice ⟶ Closer molecules



d = 570 nm
J ~ 800 Hz

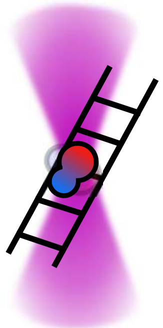
Rydberg-mediated interactions



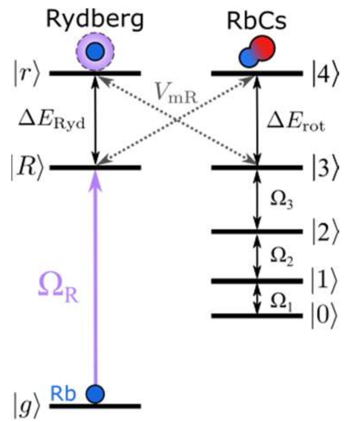
J_{eff} ~ kHz - MHz

1.2 D **~ 1 kD** 1.2 D

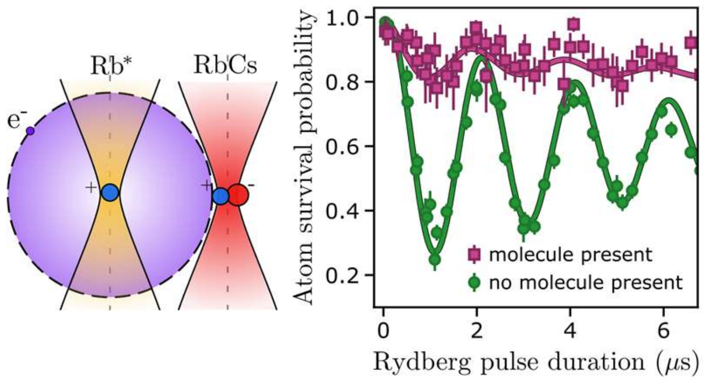
High-spin systems



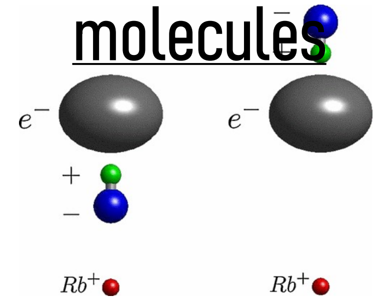
Synthetic dimensions
Qudits
Dense quantum memories



Non-destructive detection



Giant Rydberg molecules



Rittenhouse & Sadeghpour, PRL 104, 243002 (2010)

Simon Cornish

Alex Guttridge

Phil Gregory

Tom Hepworth

Fritz von Gierke
(⟶ Hannover)

Mol. control

PRX Quantum 5, 020333 (2024)

Entanglement

Nature 637, 827 (2025)

Spin-1 dynamics

Nat. Commun. 16 7131 (2025)

Durham University

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UKRI Engineering and Physical Sciences Research Council

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Adarsh Raghuram
Caleb Rich
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Albert Tao
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Svetlana Kotochigova (Temple)

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Hossein Sadeghpour (ITAMP)