

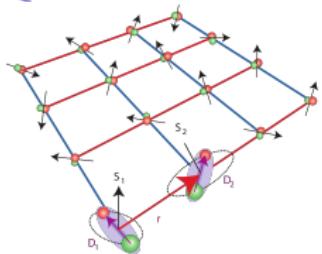
Building Single Molecules from Single Atoms

Yichao Yu

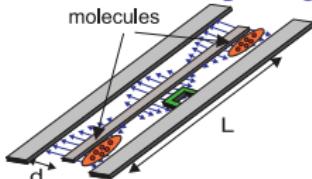
Ni Group/Harvard

Jul. 2020

Quantum Simulation



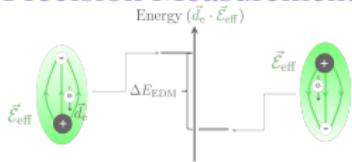
Quantum Computing



PRL. 97, 33003 (2006)

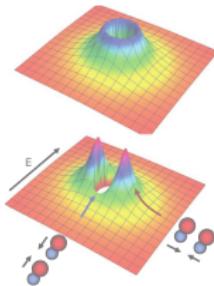
Nat. Phys. 2, 341 (2006)

Precision Measurement



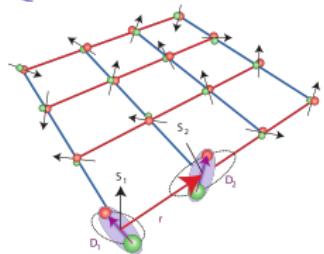
Science 343, p. 269-272 (2014)

Quantum Chemistry



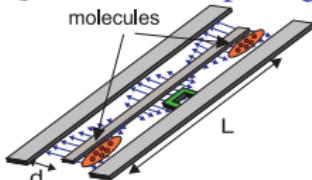
Nature 464, 1324 (2010)

Quantum Simulation



Nat. Phys. 2, 341 (2006)

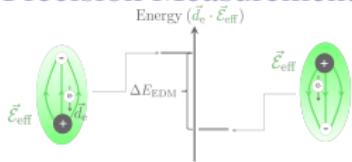
Quantum Computing



PRL. 97, 33003 (2006)

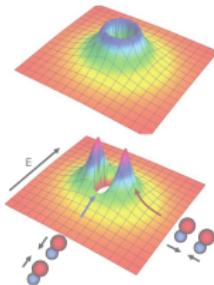
- Full quantum control
- Entanglement
- ...

Precision Measurement



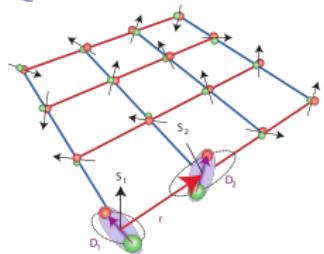
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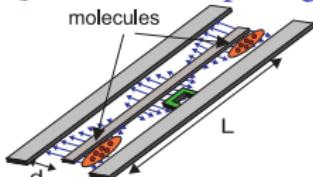
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Nat. Phys. 2, 341 (2006)

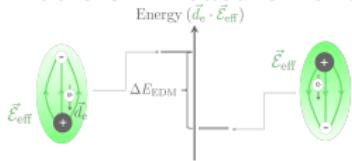
Quantum Computing



PRL. 97, 33003 (2006)

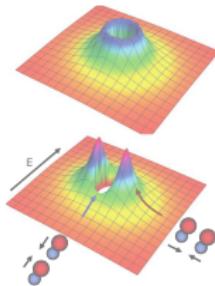
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Science 343, p. 269-272 (2014)

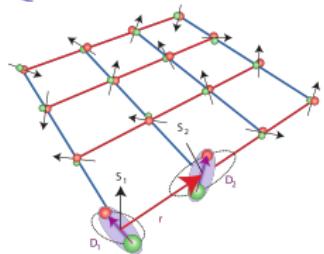
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Nature 464, 1324 (2010)

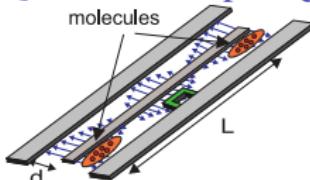
New Approach?

Quantum Simulation



Nat. Phys. 2, 341 (2006)

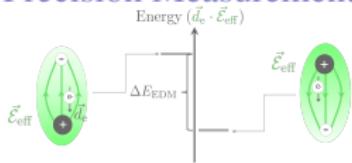
Quantum Computing



PRL. 97, 33003 (2006)

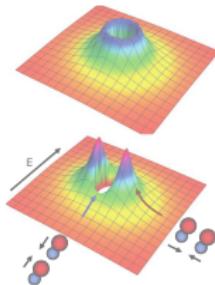
- Full quantum control
- Entanglement
- ...

Precision Measurement



Science 343, p. 269-272 (2014)

Quantum Chemistry



Nature 464, 1324 (2010)

New Approach!

Entanglement

Single particle control

Entanglement

i.e. interaction

Single particle control

Entanglement

i.e. interaction

Single particle control

Dipolar molecules

Dipolar molecules

- Strong and tunable interaction
($\approx k\text{Hz}$ at $\approx \mu\text{m}$ distance)
 - ▶ Fast gate operations
 - ▶ Long coherence time
- Rich internal structure
(Electronic, vibrational,
rotational, hyperfine, etc.)

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Single particle control

Optical tweezers

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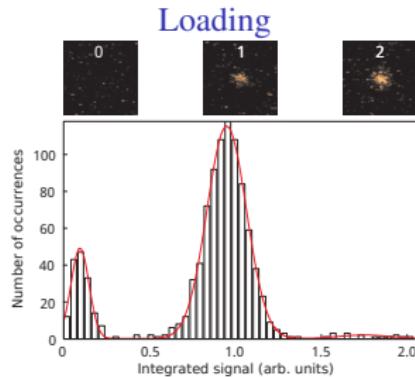
- Single site resolution



Entanglement

i.e. interaction

Dipolar molecules



Nat. Phys. 6, 951 (2010)

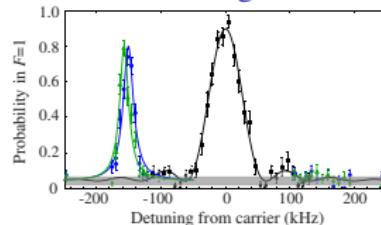
Single particle control

Optical tweezers

- Single site resolution

- ...

Cooling



PRX. 2, 041014 (2012)

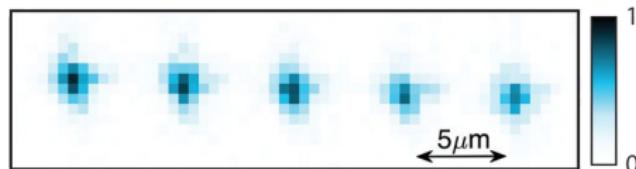
Rearranging



Science 354, 1024 (2016)

Ultracold molecule in tweezers

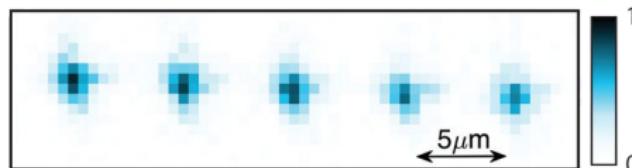
Direct cooling



Science 365, 1156 (2019)

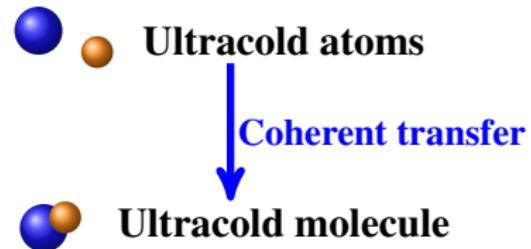
Ultracold molecule in tweezers

Direct cooling



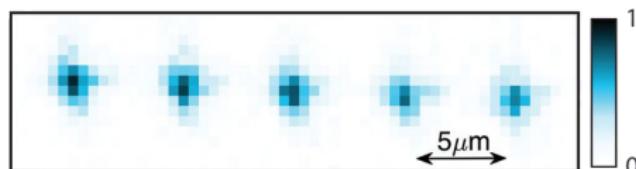
Science 365, 1156 (2019)

Assembly



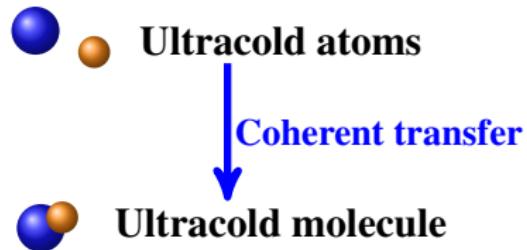
Ultracold molecule in tweezers

Direct cooling



Science 365, 1156 (2019)

Assembly

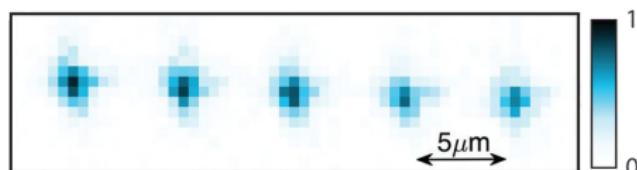


Challenges

- Temperature in tweezers
- Quantum control

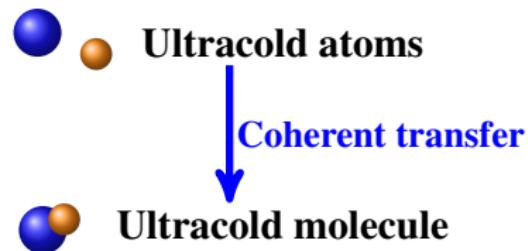
Ultracold molecule in tweezers

Direct cooling



Science 365, 1156 (2019)

Assembly



Challenges

- Temperature in tweezer
- Quantum control
- Creating molecules
- Maintain coherence

Outline

1 Experiment overview

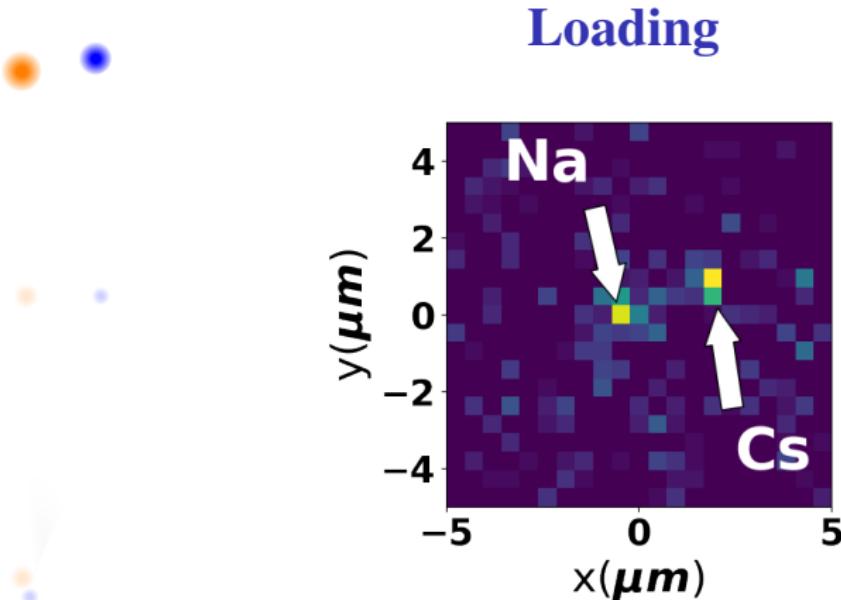
2 Atom state control

- Raman sideband cooling of Na atoms

3 Optical molecule creation

4 Conclusion

Experiment overview

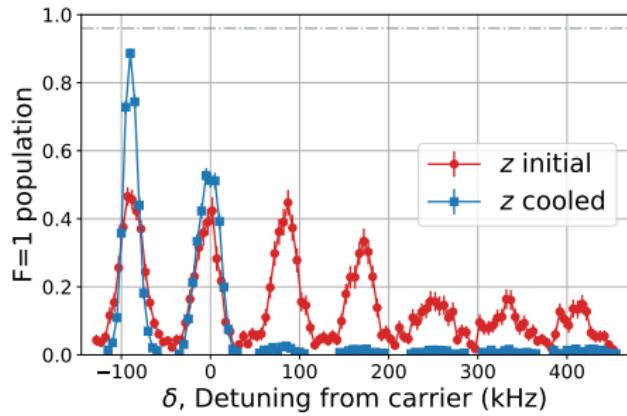


Loading probability per site: 60%
Post select on initial and final state.

Experiment overview



Cooling

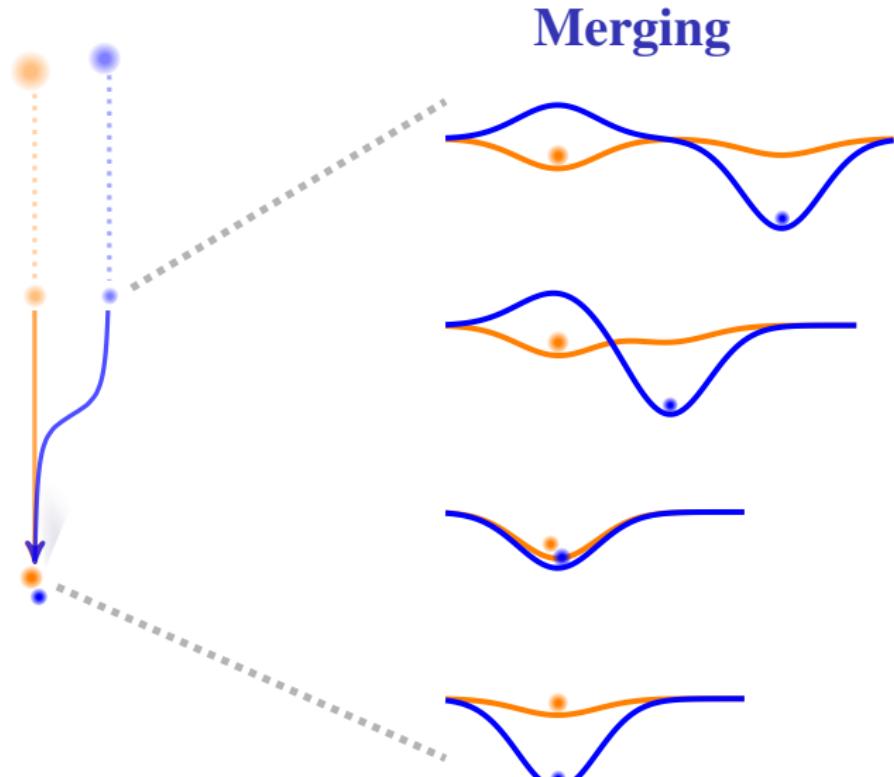


Cs: 96% ground state¹
Na: 94% ground state²

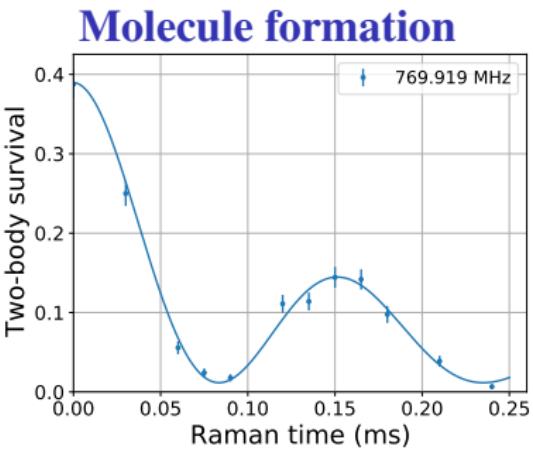
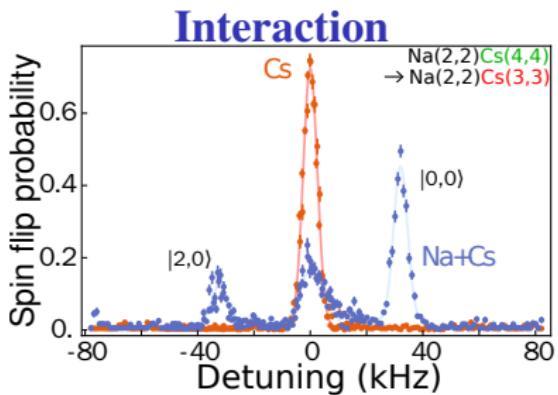
¹Phys. Rev. X 9, 021039

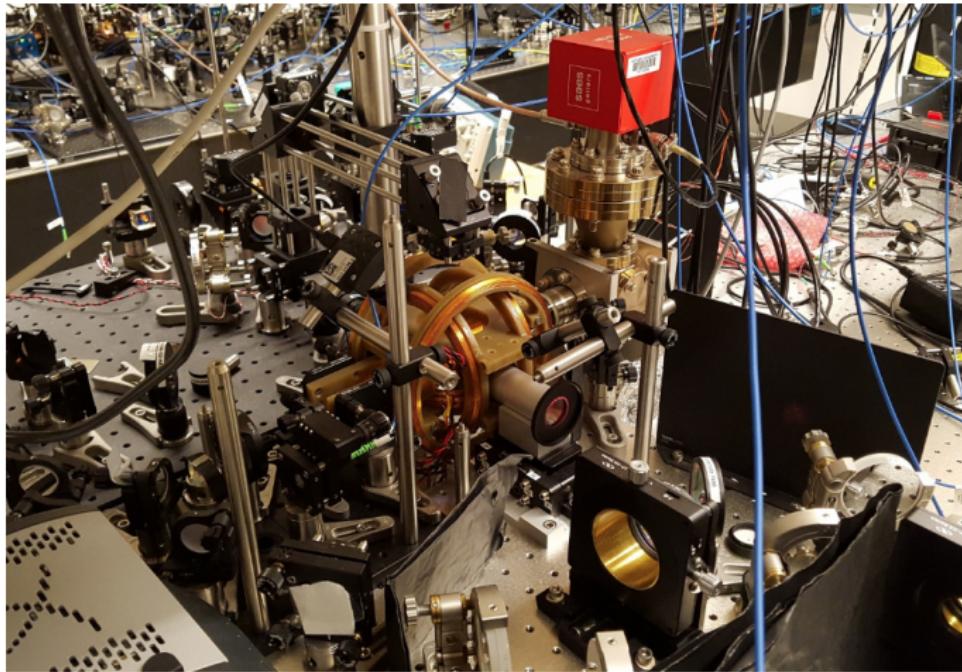
²Phys. Rev. A 97, 063423

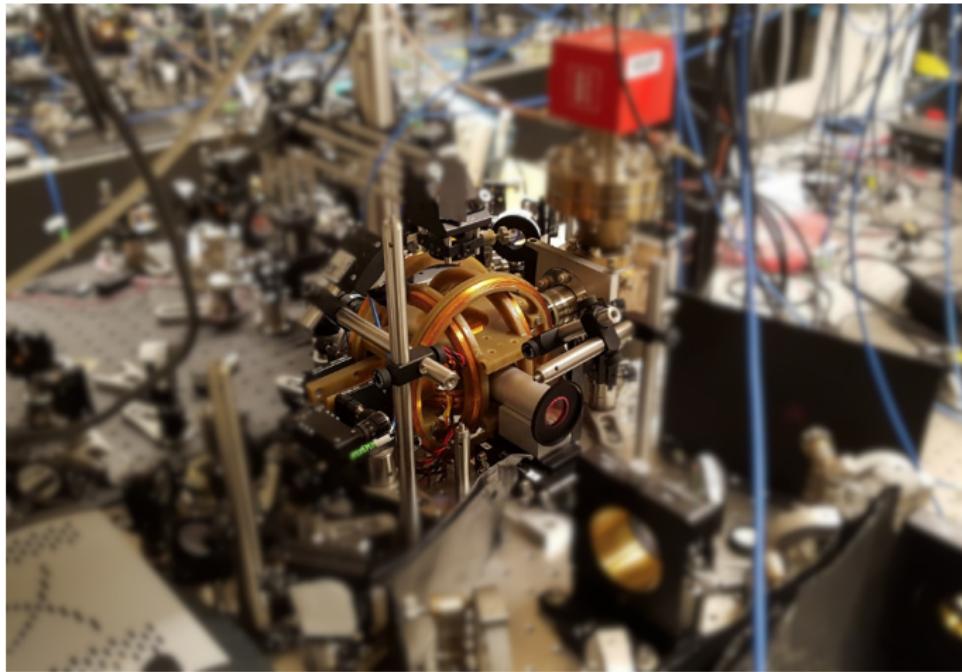
Experiment overview

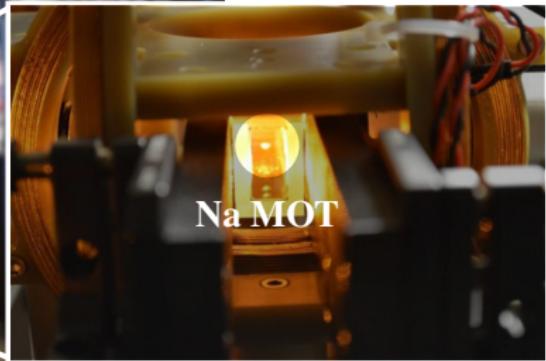
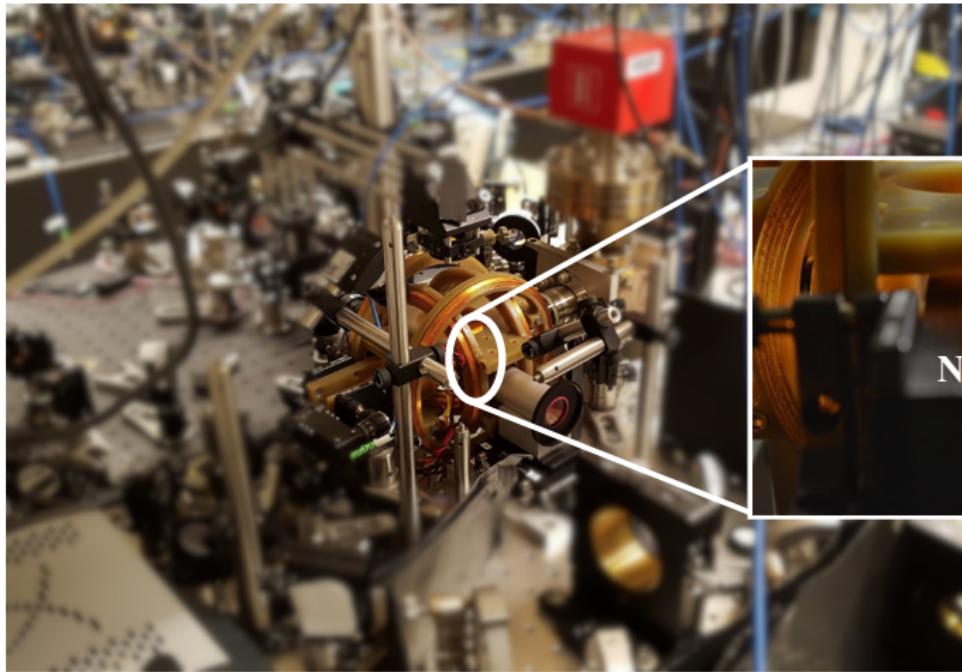


Experiment overview

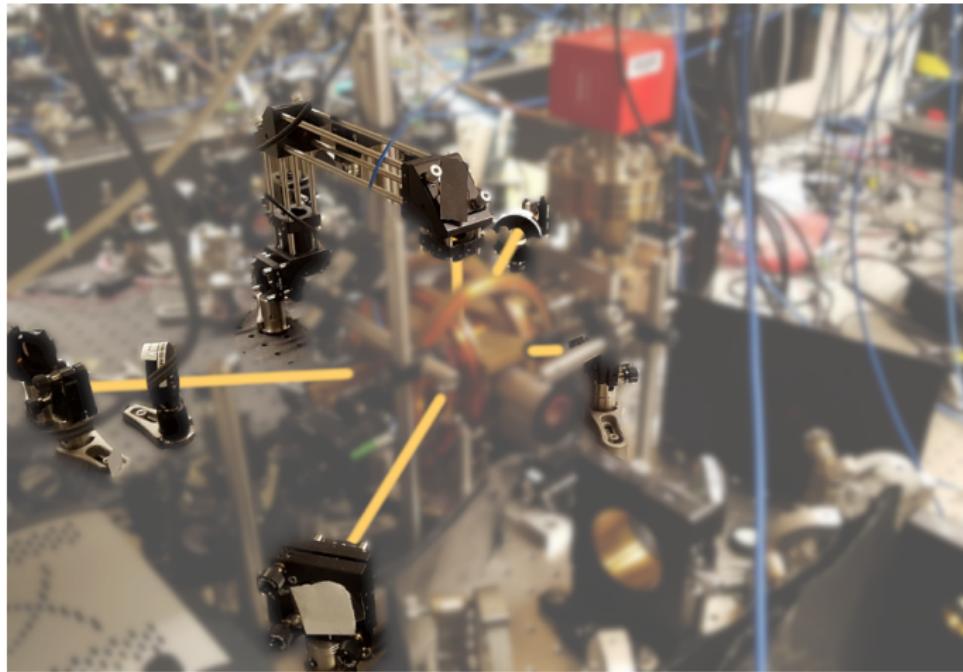




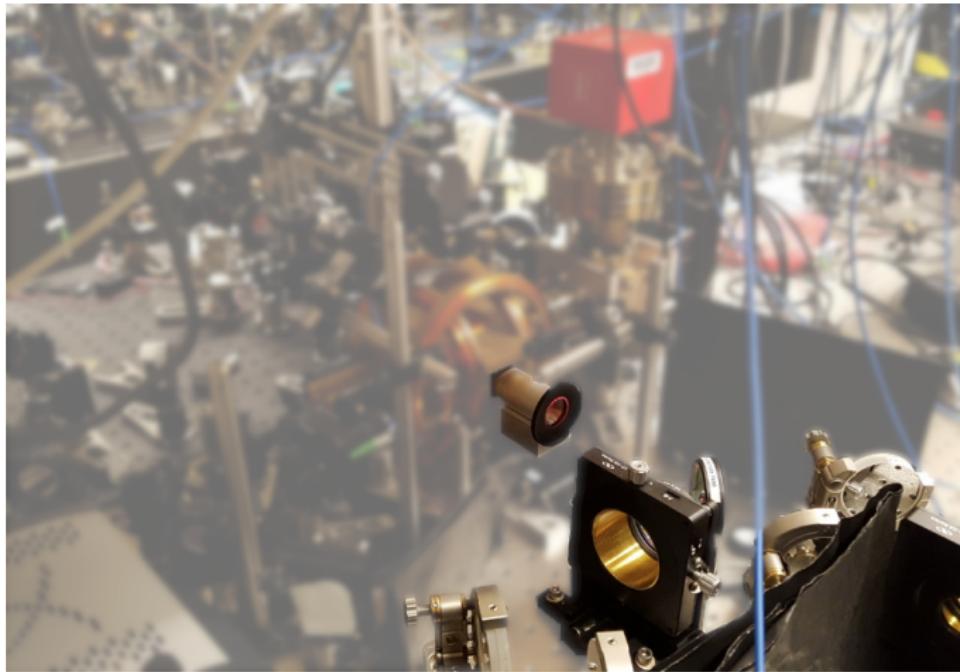




MOT beam path



Tweezer beam path



Outline

1 Experiment overview

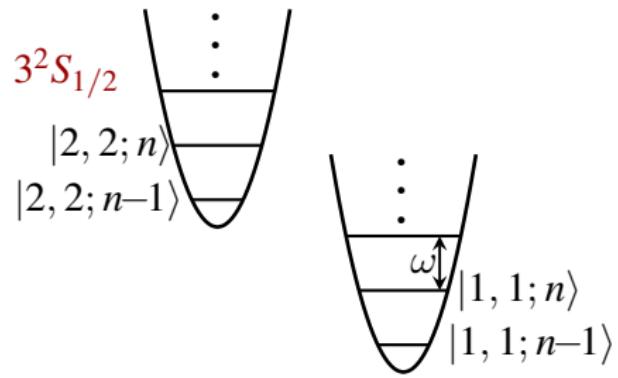
2 Atom state control

- Raman sideband cooling of Na atoms

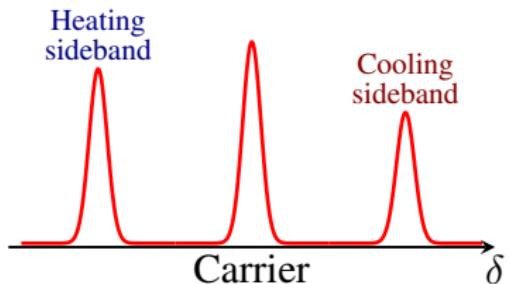
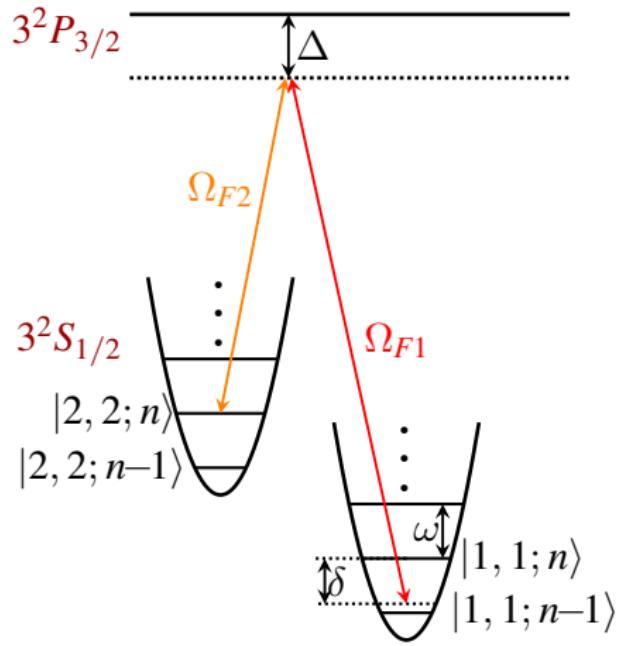
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4 Conclusion

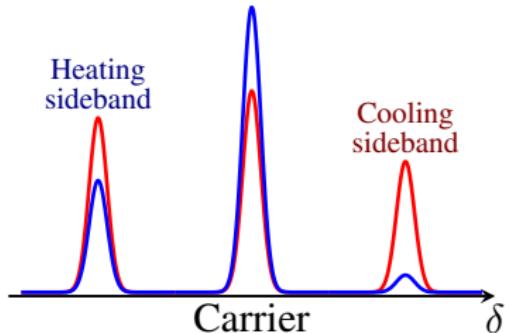
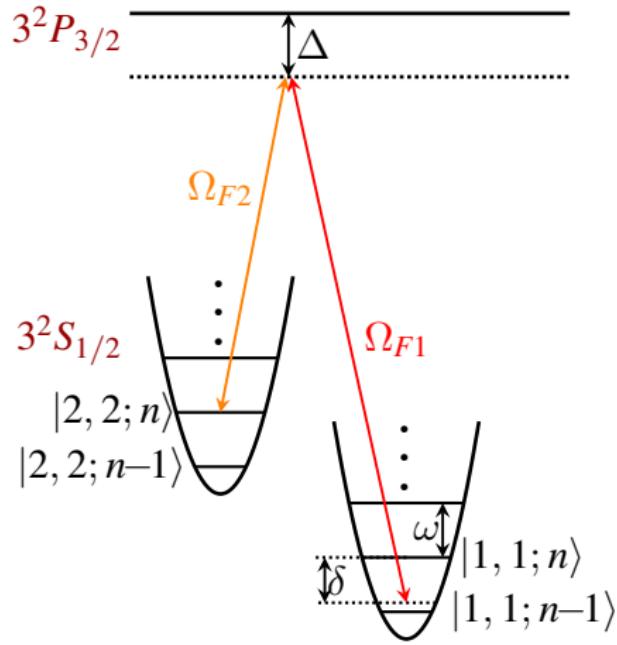
Raman sideband cooling



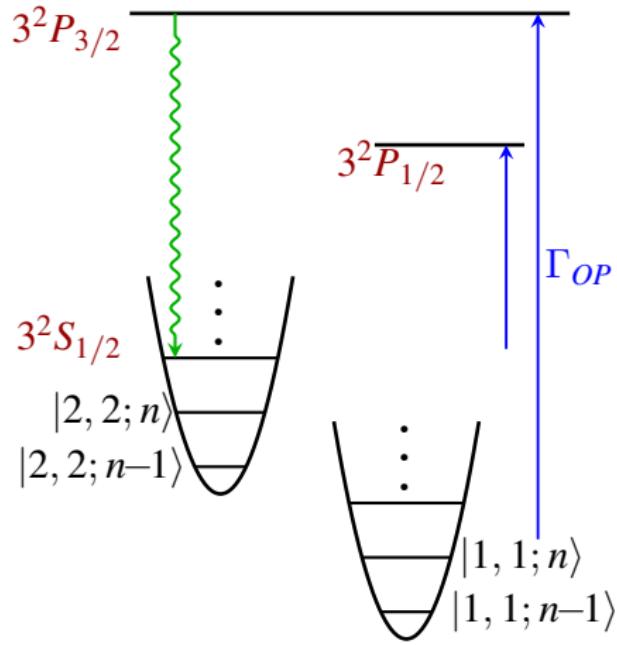
Raman sideband cooling



Raman sideband cooling



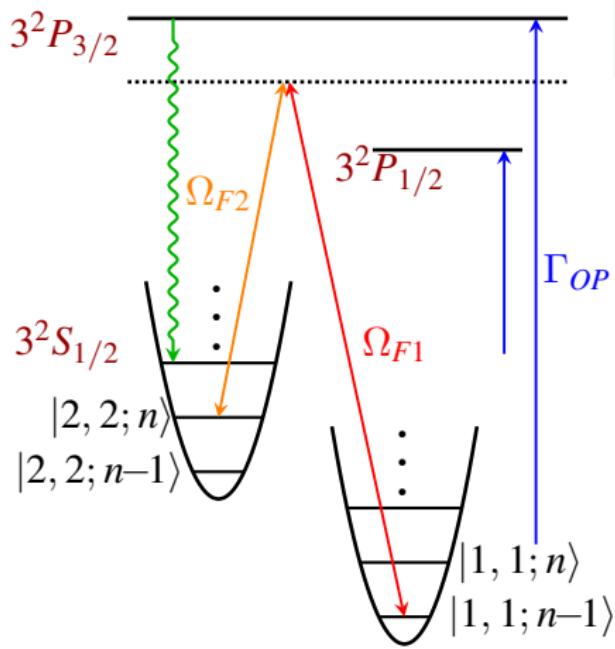
Raman sideband cooling



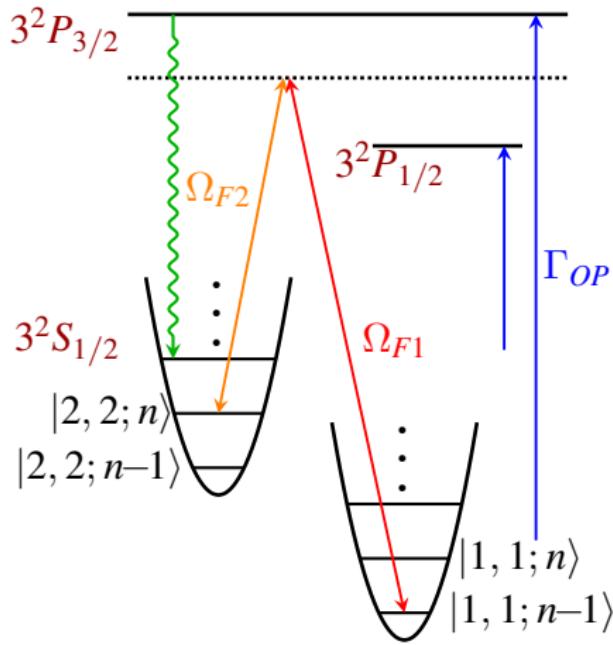
Raman sideband cooling

Lamb Dicke parameter

$$\eta \equiv kz_0 = \frac{2\pi z_0}{\lambda} = \sqrt{\frac{\omega_{recoil}}{\omega_{trap}}}$$



Raman sideband cooling

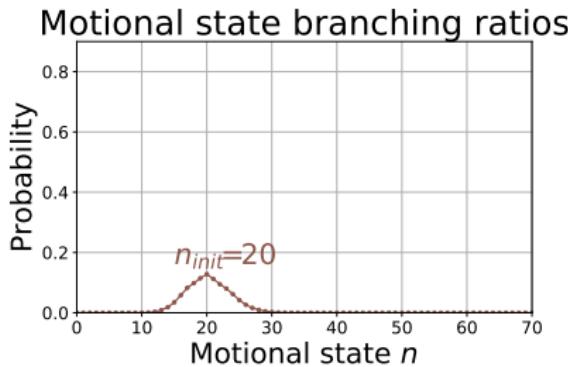


Lamb Dicke parameter

$$\eta \equiv kz_0 = \frac{2\pi z_0}{\lambda} = \sqrt{\frac{\omega_{recoil}}{\omega_{trap}}}$$

$$\eta_{Na}^{OP} = 0.55$$

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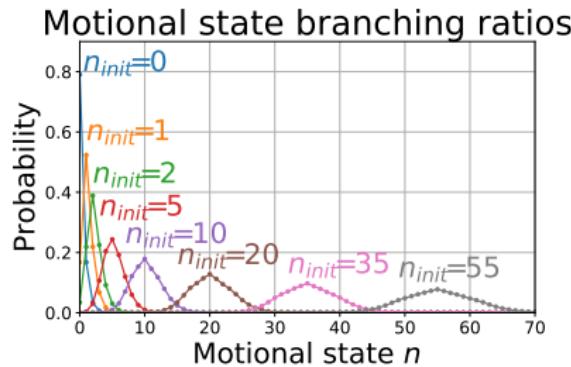
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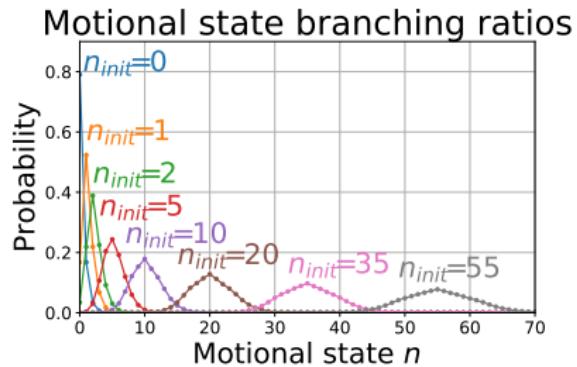
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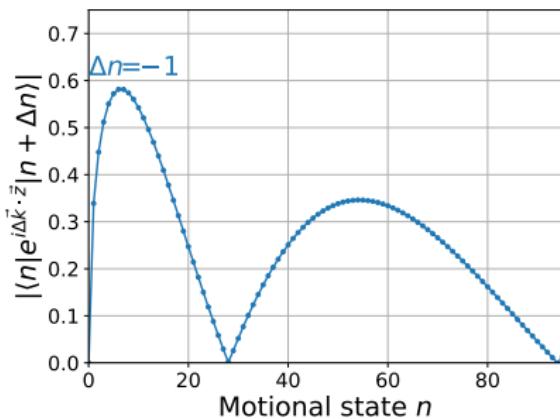


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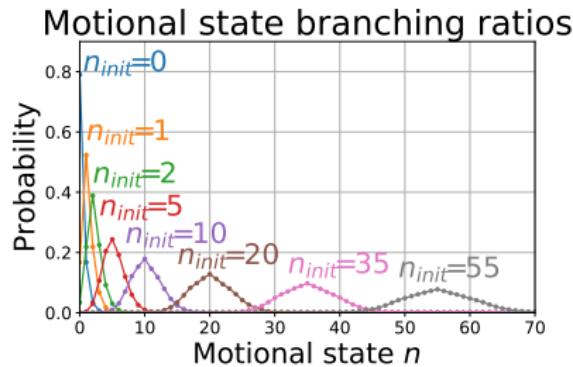
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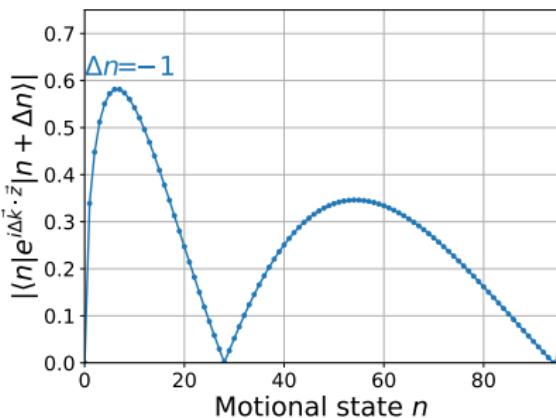


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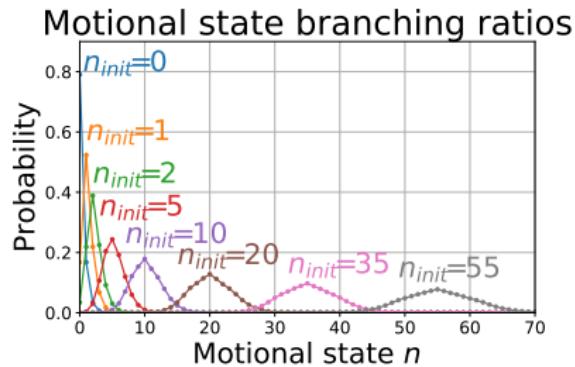
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Solution

Use higher order sidebands.

Raman sideband cooling

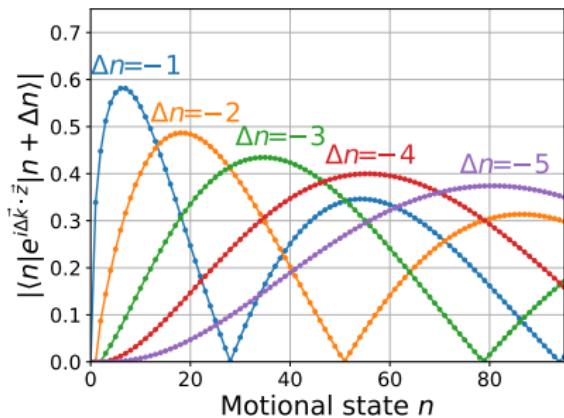


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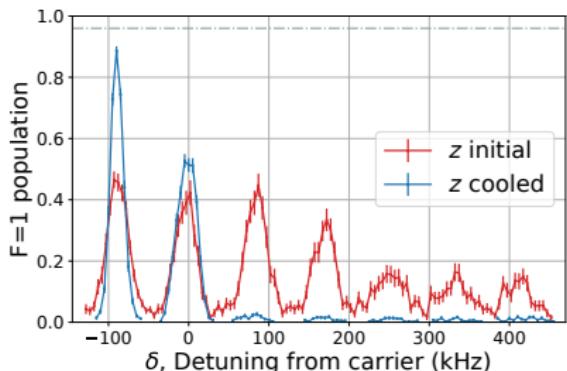


Solution

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Raman sideband cooling

Axial sideband spectrum

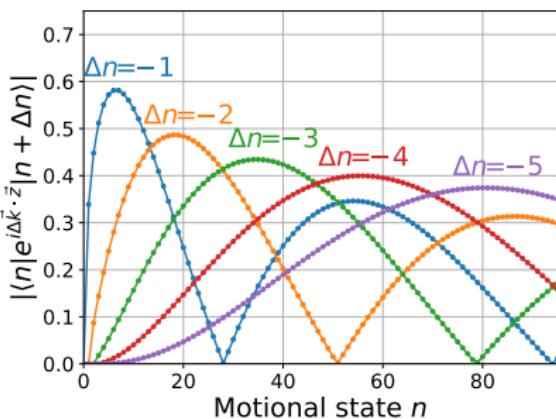


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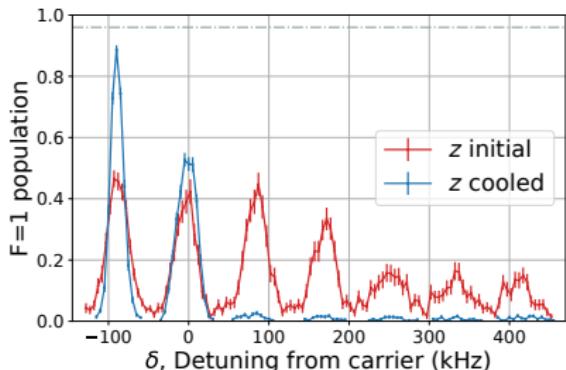


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Axial sideband spectrum

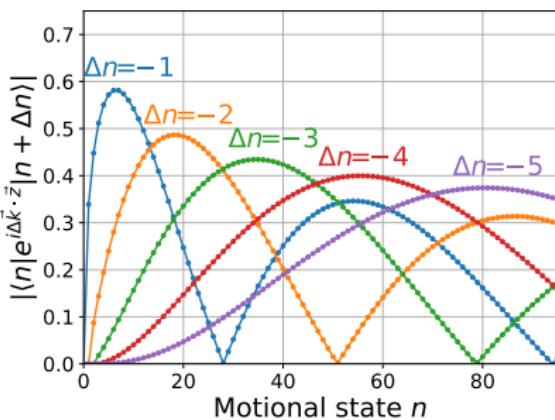


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3D ground state: 93.5(7)%

Outline

1 Experiment overview

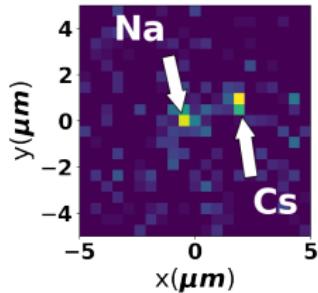
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Loading

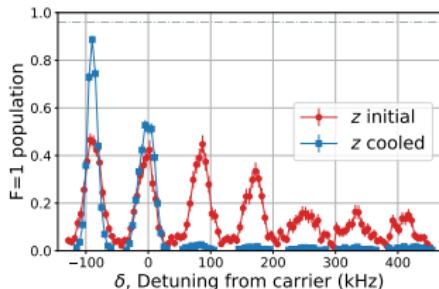


NJP. 19, 023007 (2017)

Merging

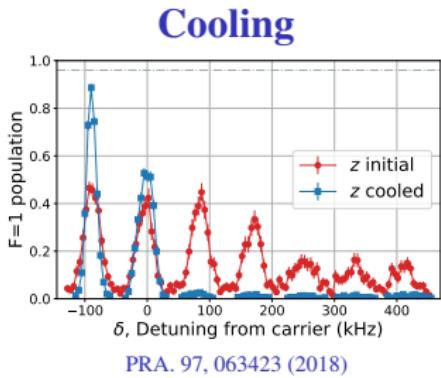
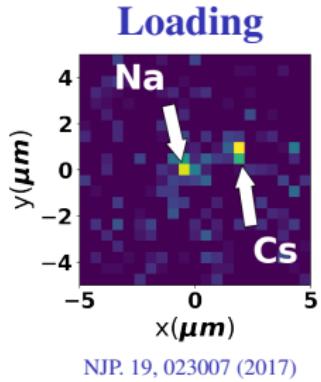


Cooling

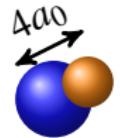
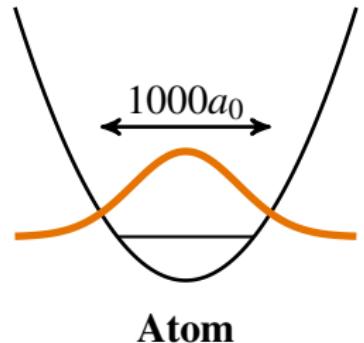
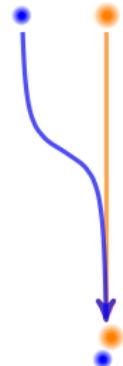


PRA. 97, 063423 (2018)

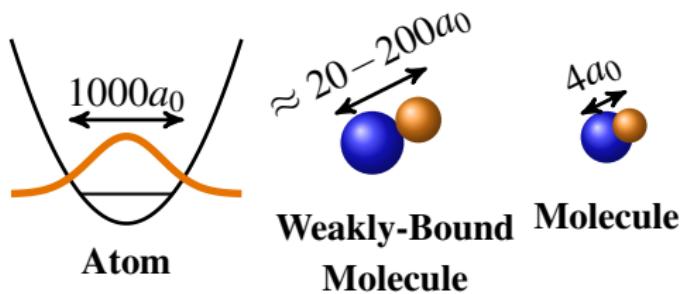
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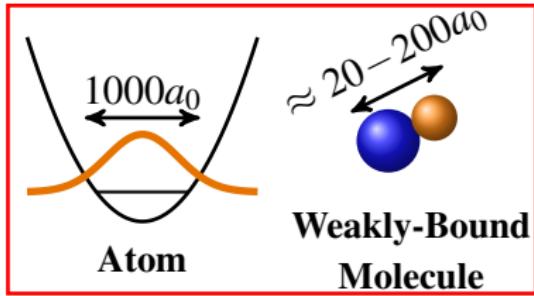


Merging



Molecule





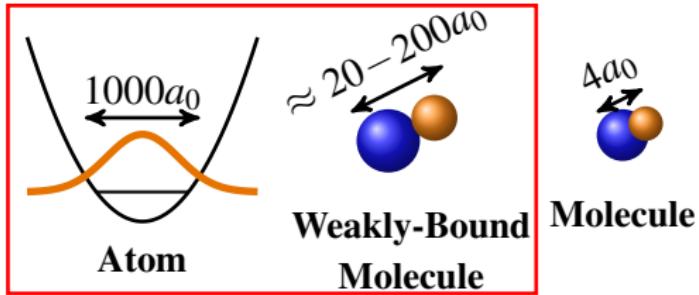
Atom

Weakly-Bound Molecule

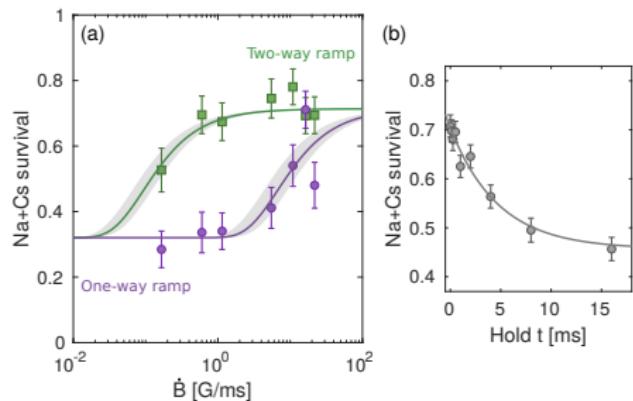
Molecule



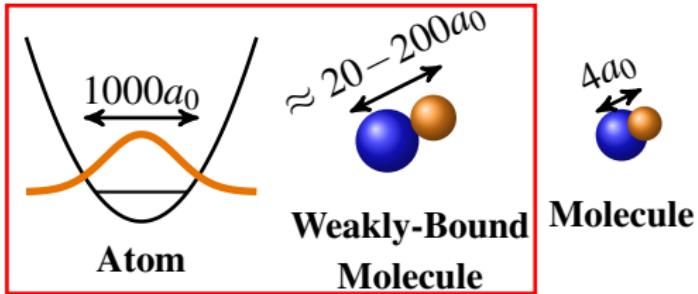
Molecule



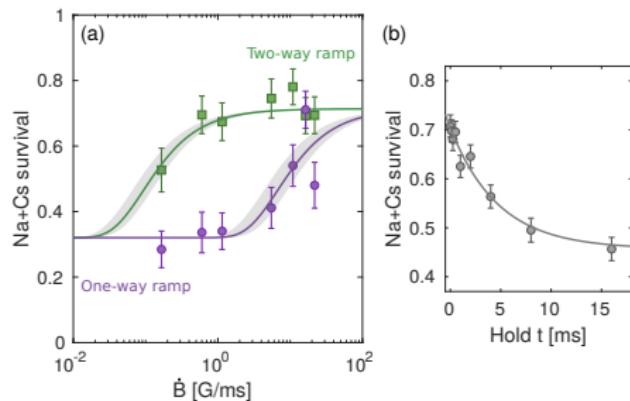
Feshbach molecule



PRL. 124, 253401 (2020)

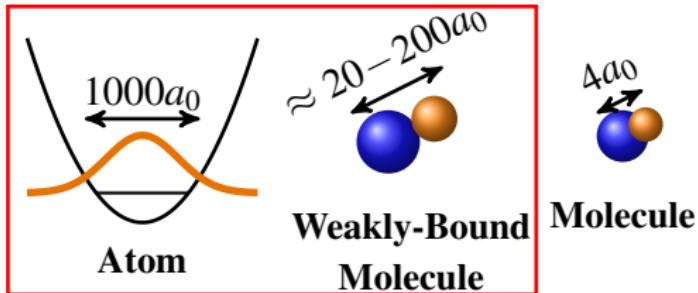


Feshbach molecule



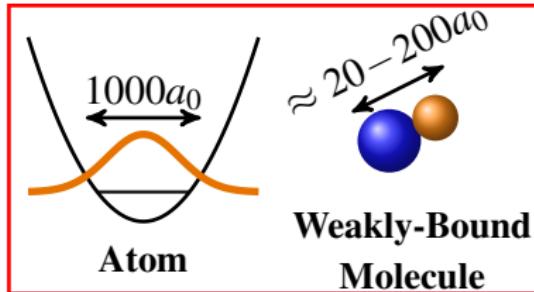
- Requires Feshbach resonance
- Usually large magnetic field

PRL. 124, 253401 (2020)



Optical transfer

- More general
- Faster

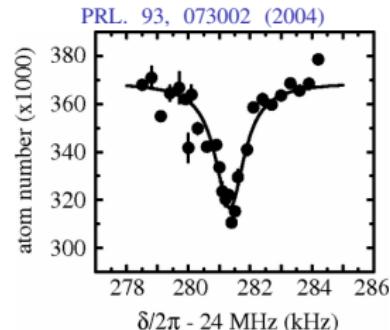


Optical transfer

- More general
 - Faster

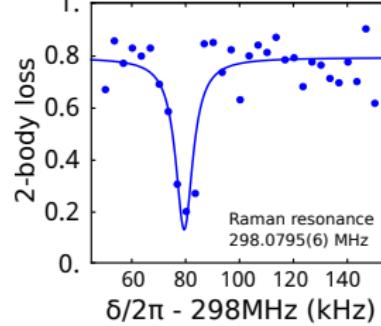
Previous results

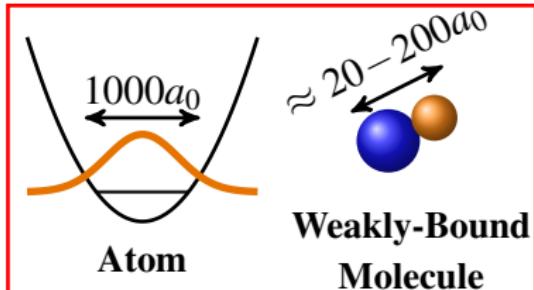
Rb₂ Science 287, p. 1016-1019 (2000)



Sr₂ PRL. 109, 115302 (2012)

NaCs PRX. 9, 021039 (2019)





Optical transfer

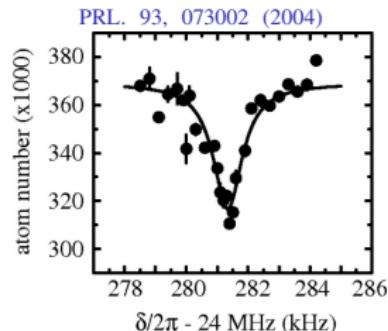
- More general
- Faster

Limitations so far

- Incoherent due to scattering
- Rely on narrow line optical transition

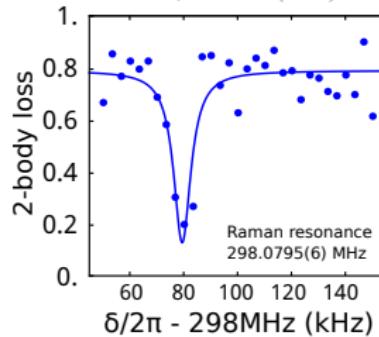
Previous results

Rb_2 Science 287, p. 1016-1019 (2000)

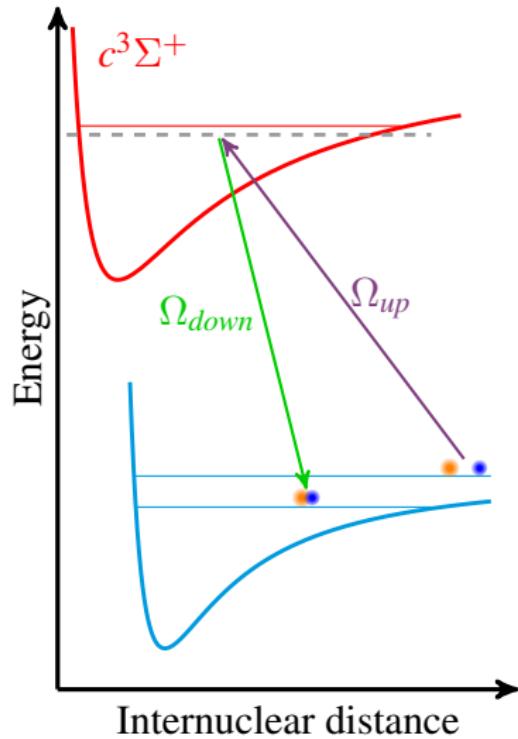


Sr_2 PRL. 109, 115302 (2012)

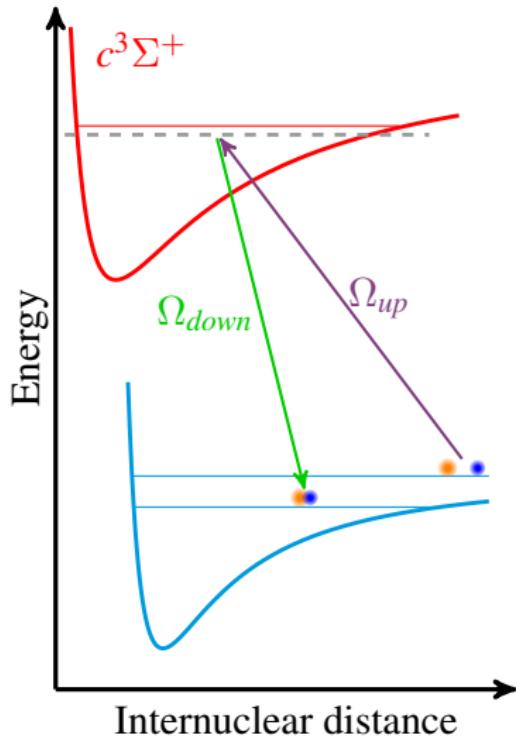
NaCs PRX. 9, 021039 (2019)



Raman transfer



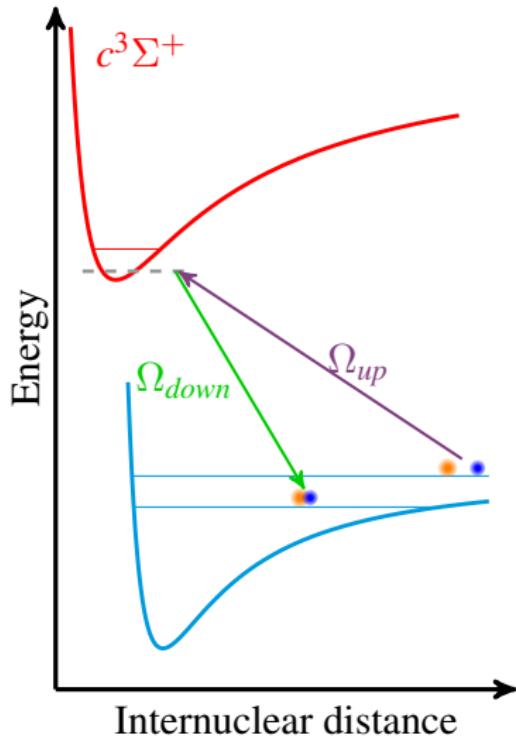
Raman transfer



Near threshold states

- Stronger coupling (Ω_{up} and Ω_{down})
- Closely spaced
- Fast scattering

Raman transfer



Near threshold states

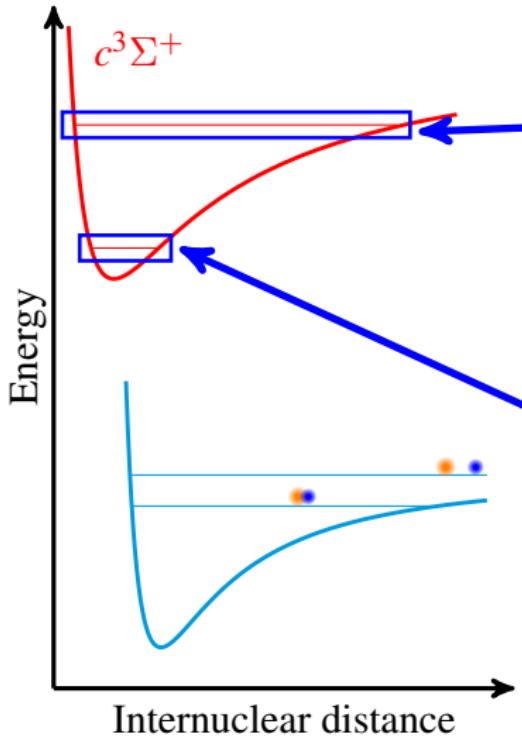
- Stronger coupling (Ω_{up} and Ω_{down})
- Closely spaced
- Fast scattering

Deeply bound states

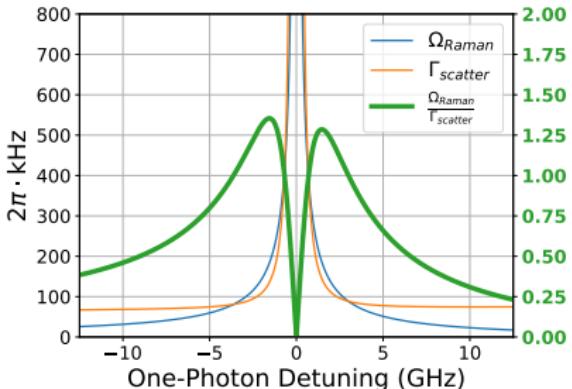
- Weaker coupling
- Sparsely spaced
- Allow larger detuning
- Slower scattering

arXiv:1701.03121(2017)

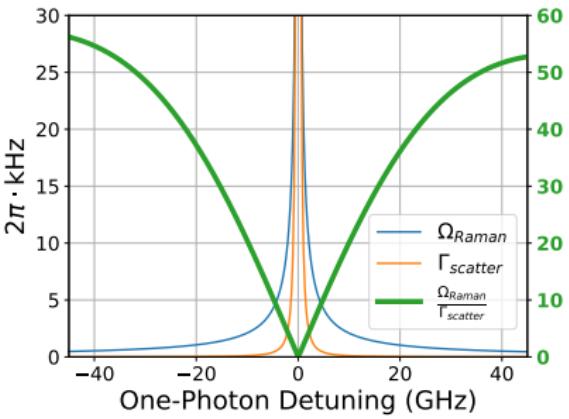
Raman transfer



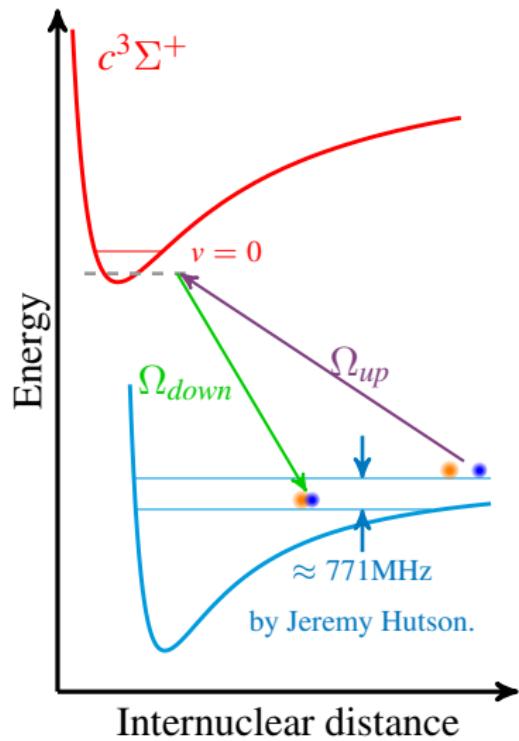
Near threshold states



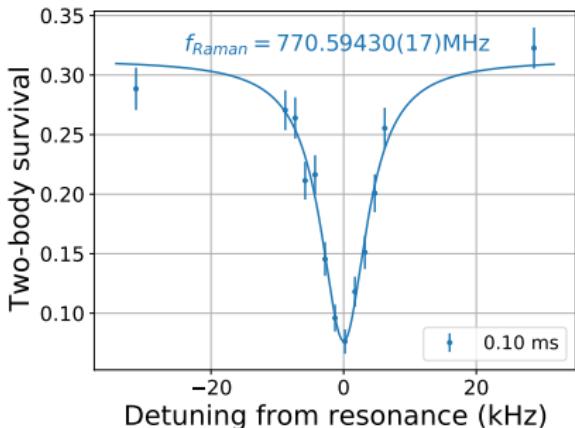
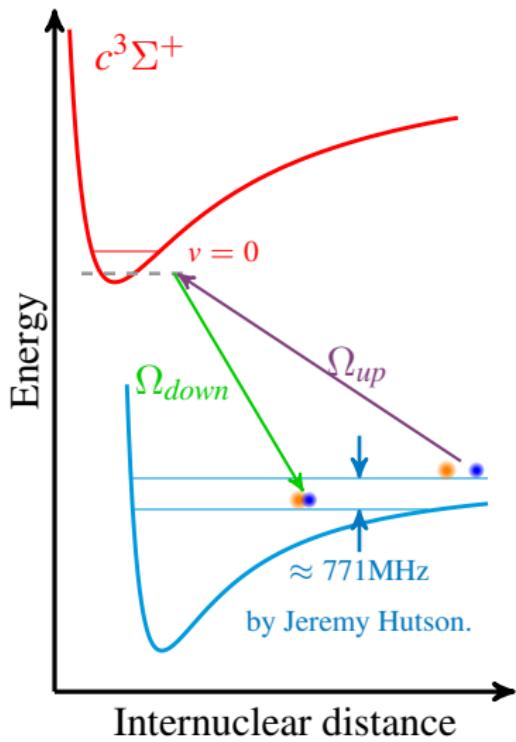
Deeply bound states



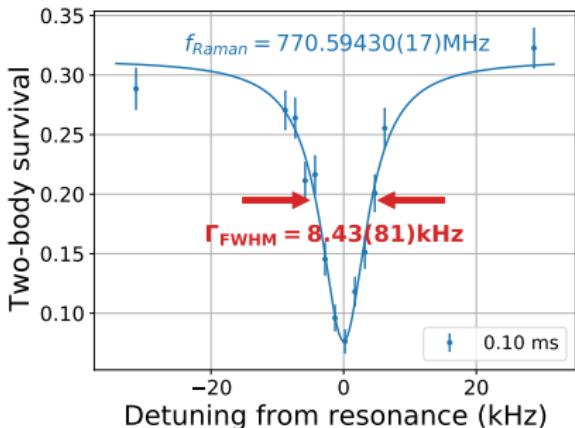
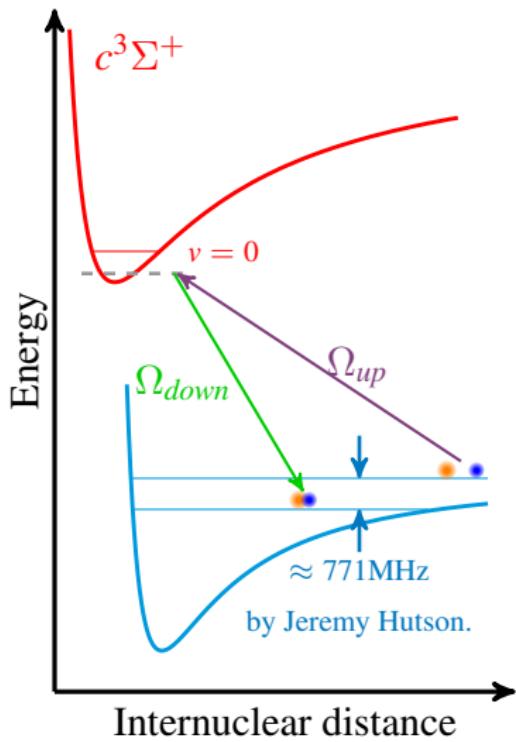
Experiment



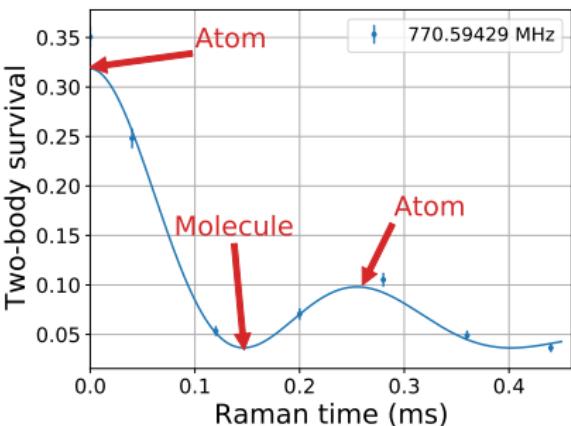
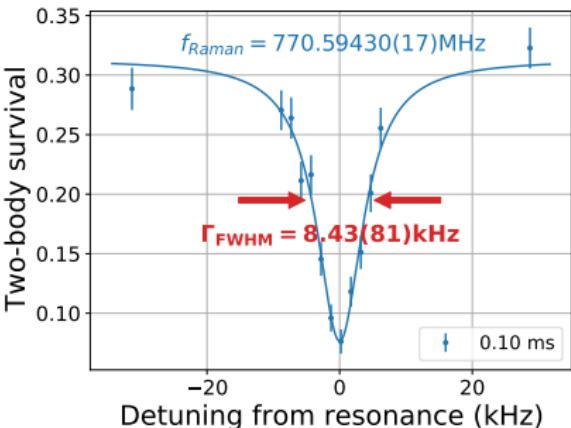
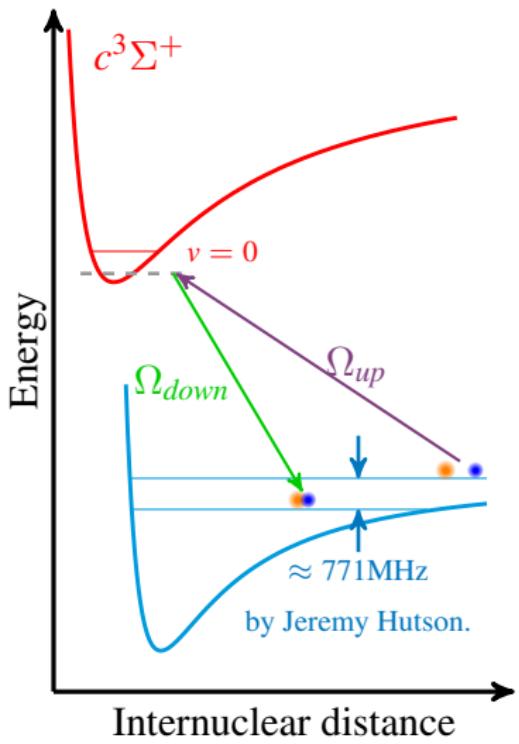
Experiment



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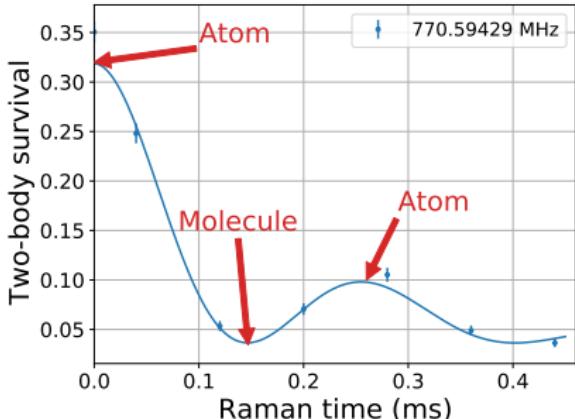
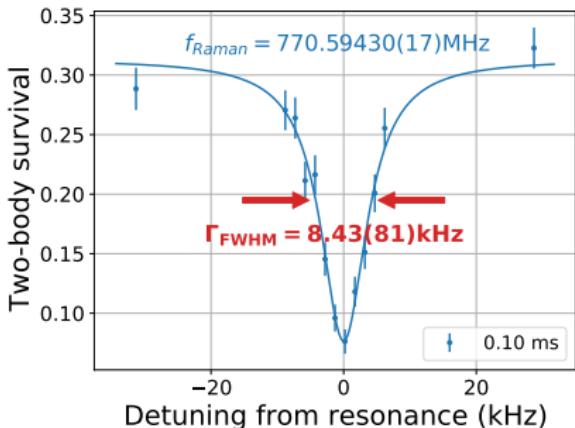
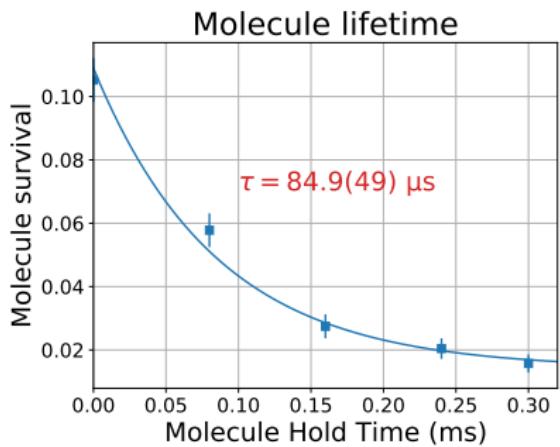


Experiment



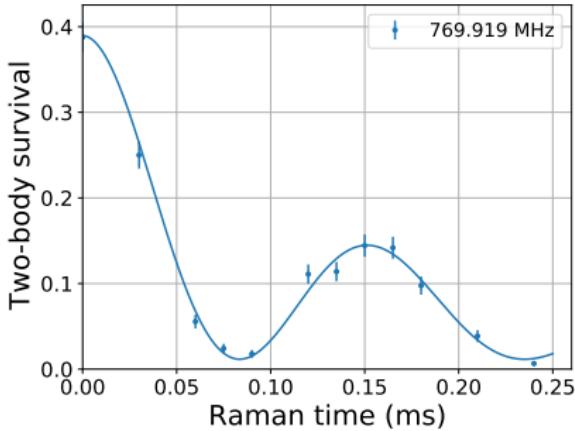
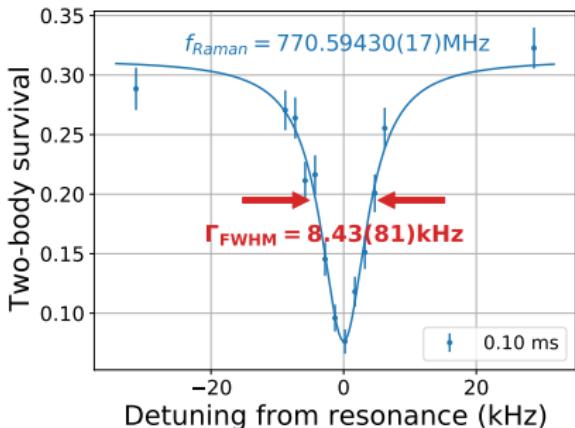
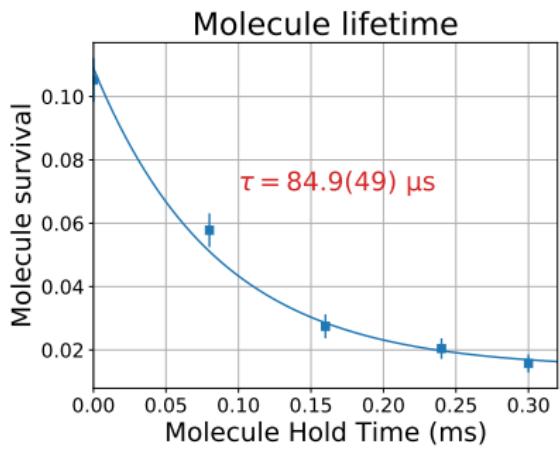
Experiment

- Transferred 50% of ground state atom to molecule.
- Improving signal
- Single molecule spin state
- > 50% of molecule in motional ground state.



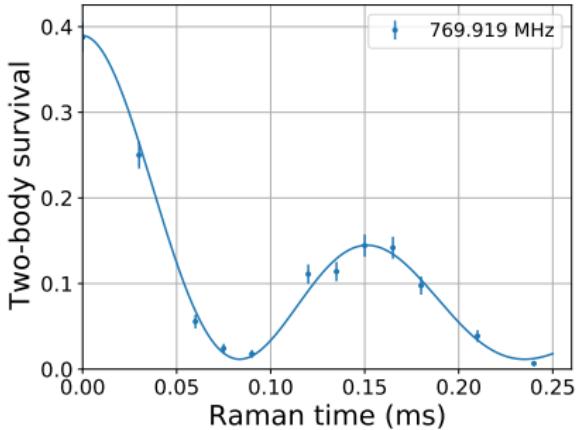
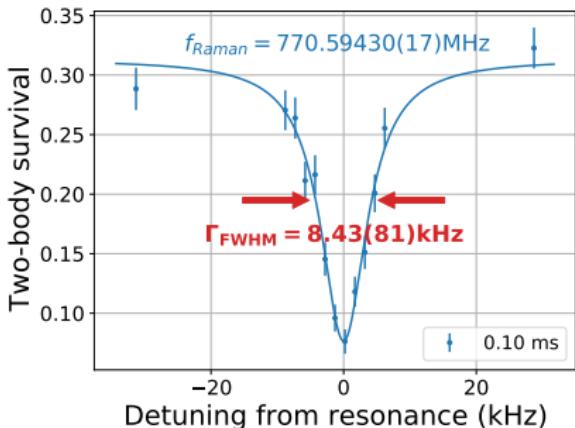
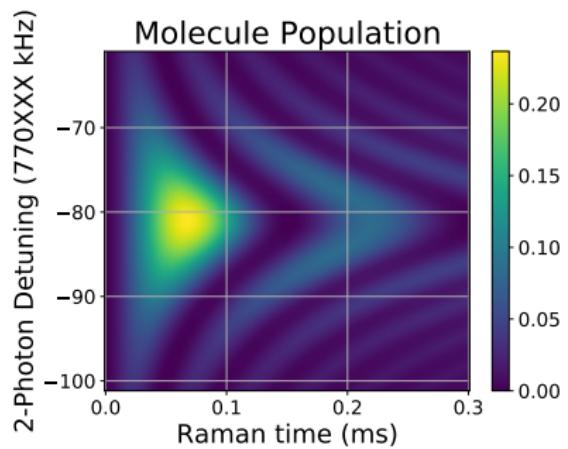
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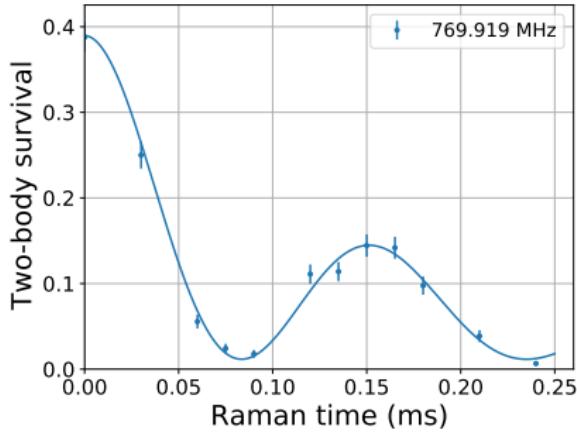
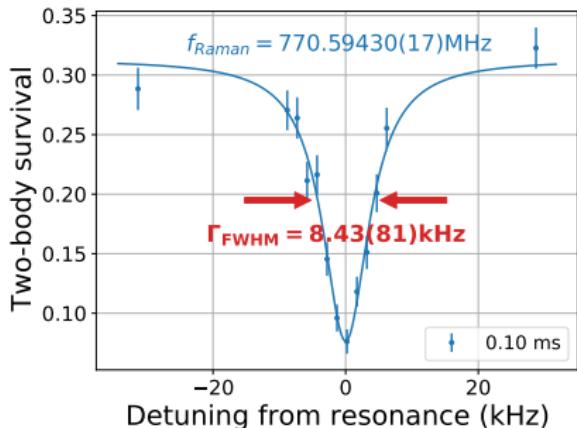
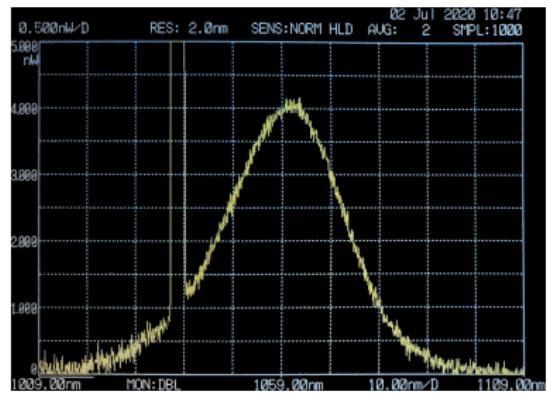
Experiment

- Transferred 65% of ground state atom to molecule.
- Improving signal
- Single molecule spin state
- > 50% of molecule in motional ground state.



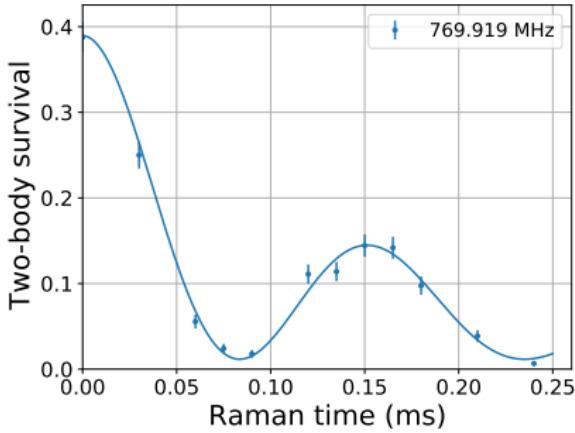
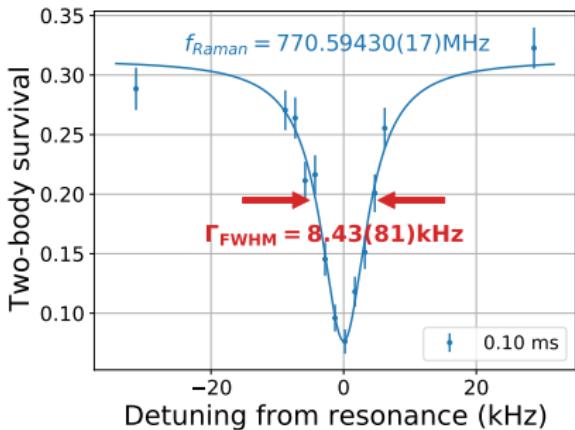
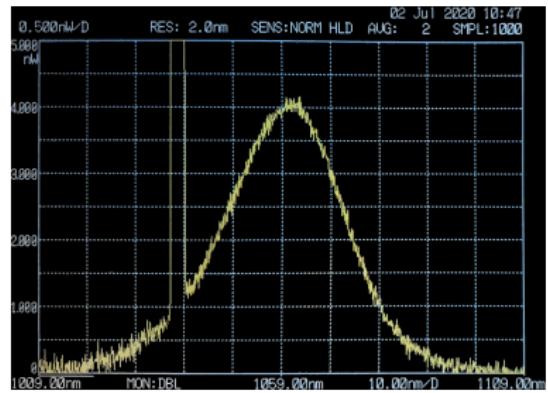
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Conclusion and outlook

- Full quantum control of atoms in optical tweezers
- Coherent all-optical creation of single molecule
- Improve molecule lifetime and signal contrast
- Feshbach molecule ($\tau = 4.7(7)$ ms)

Conclusion and outlook

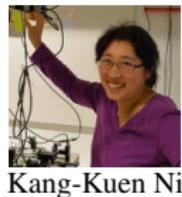
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Conclusion and outlook

Experiment

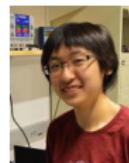


Kang-Kuen Ni

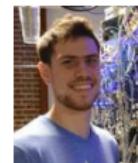
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Kenneth
Wang



Jessie
Zhang



Lewis
Picard



William
Cairncross



Lee Liu
Postdoc @JILA



Jonathan Hood
Asstn Prof @Purdue



Nick Hutzler
Asstn Prof @Caltech

Theory



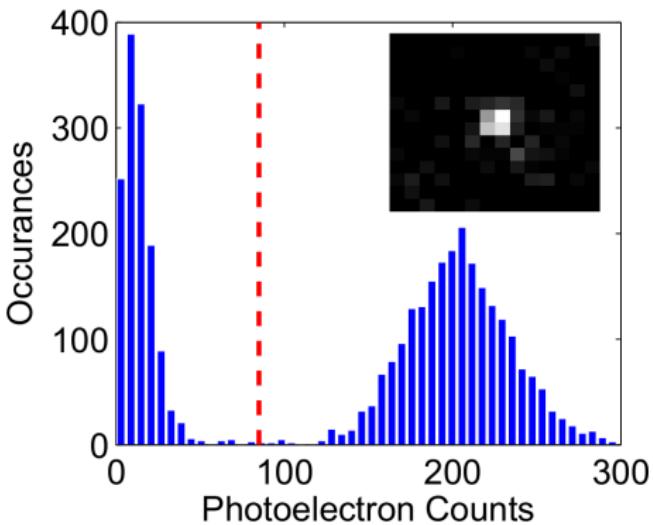
Jeremy Hutson

Single Atom in Tweezer

- Previously done with Rb
- Works for Cs
- Doesn't work for Na

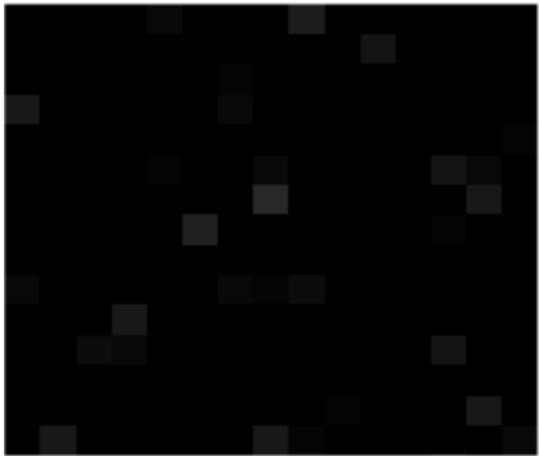
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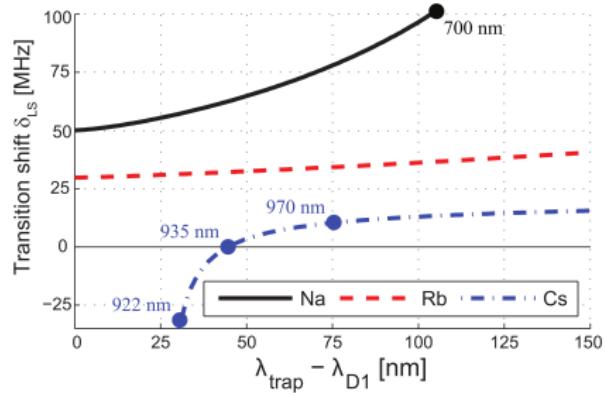
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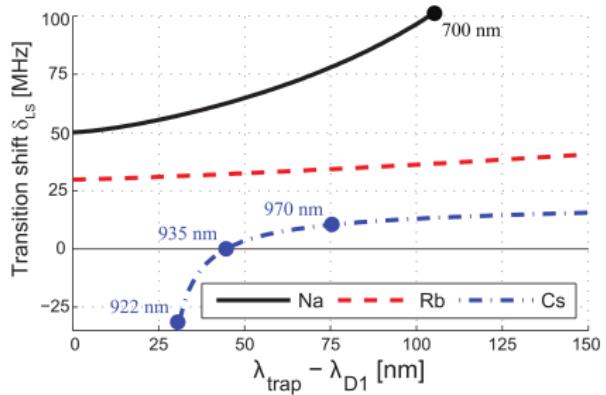
Issues with Na

- Low vapor pressure
- Broad linewidth
- Low mass
- Small hyperfine structure

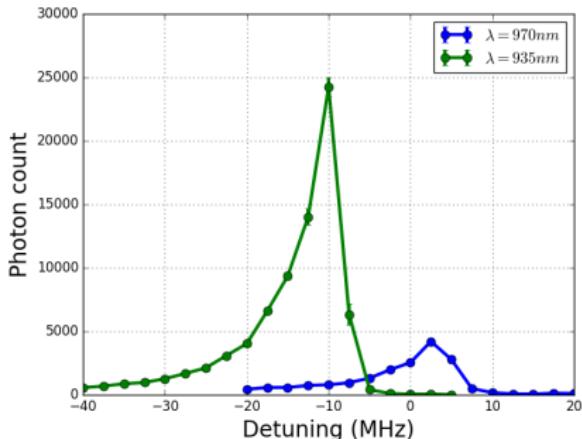
Real Issue with Na: Light Shift



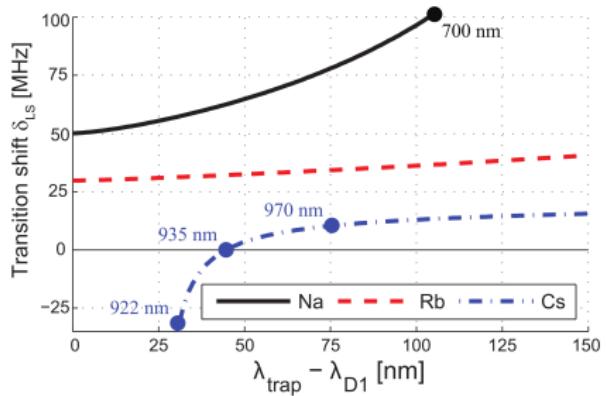
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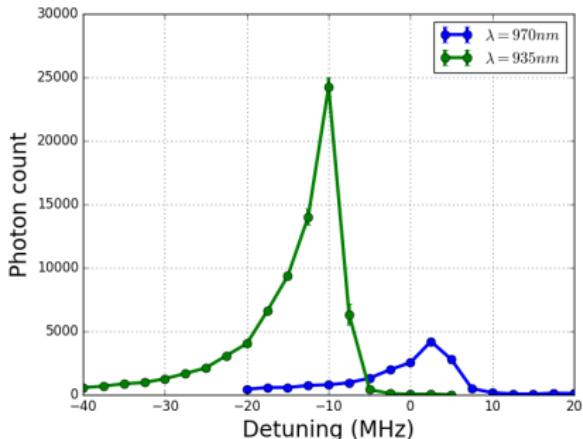
Cs single atom imaging



Real Issue with Na: Light Shift



Cs single atom imaging



- Low imaging signal
- No cooling in tweezer

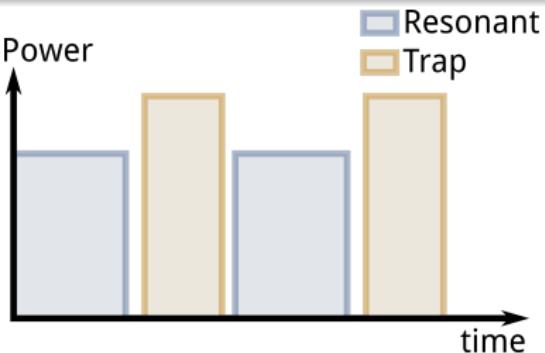
Real Issue with Na: Light Shift

Trap modulation

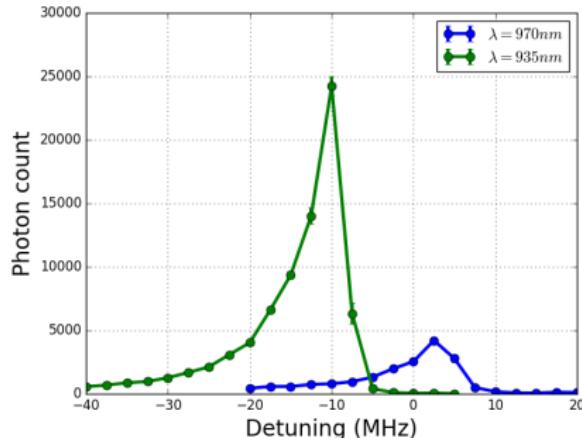
Alternate between trap and resonant (cooling and imaging) light at 2.5 MHz

$$f_{trap} = 100 \sim 500 \text{ kHz}$$

$$\Gamma = 2\pi \times 10 \text{ MHz}$$



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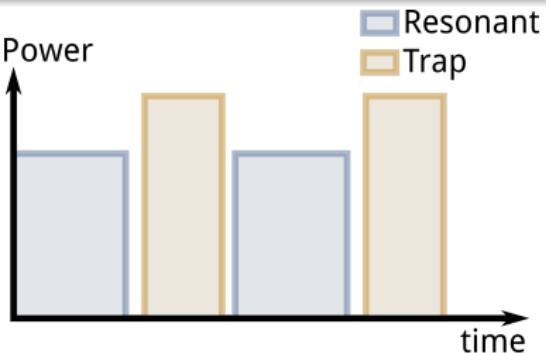
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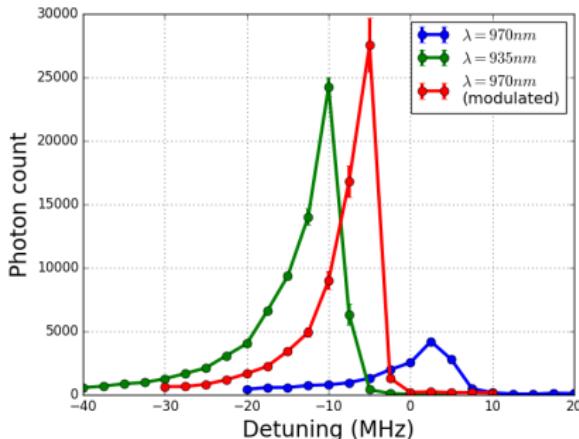
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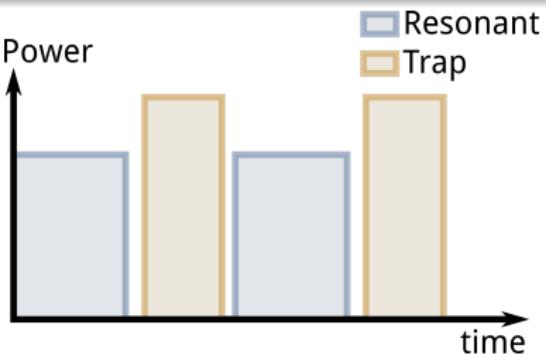
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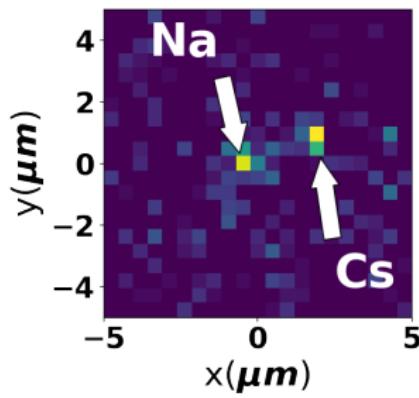
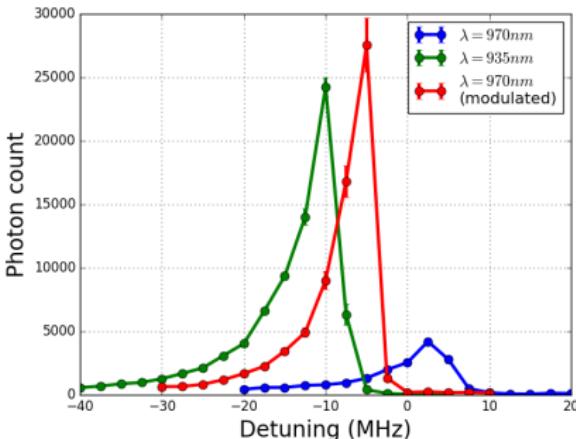
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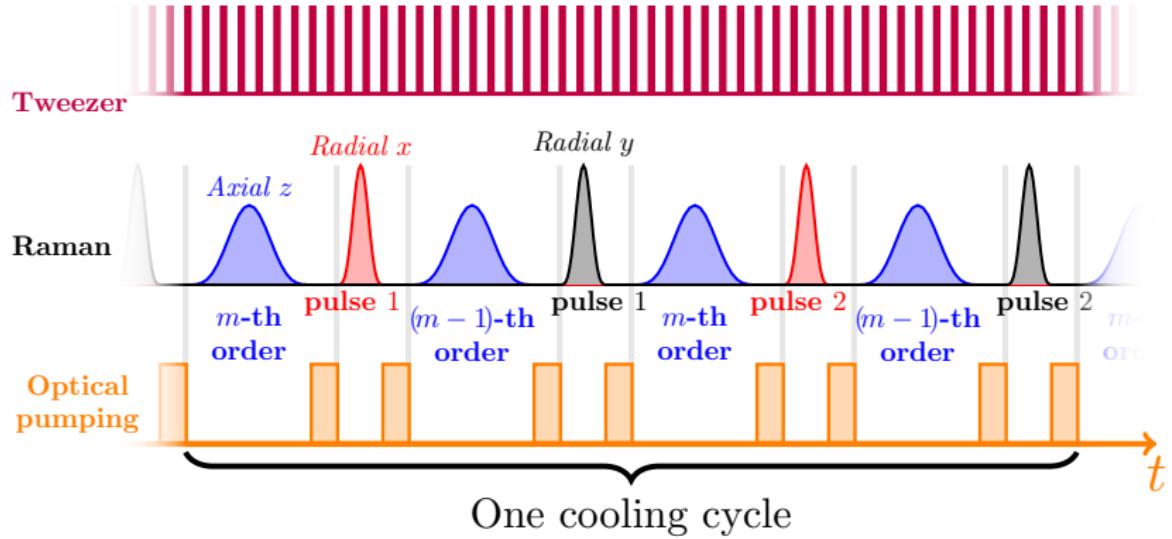
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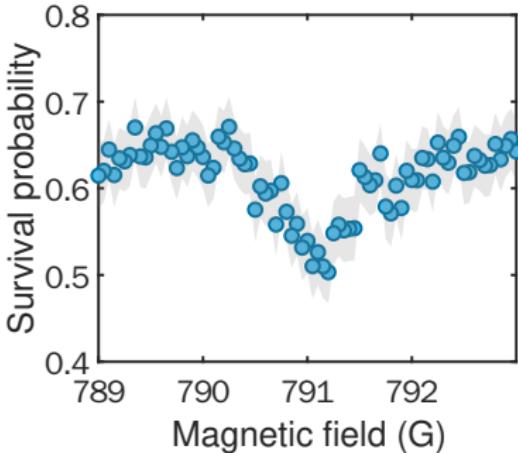
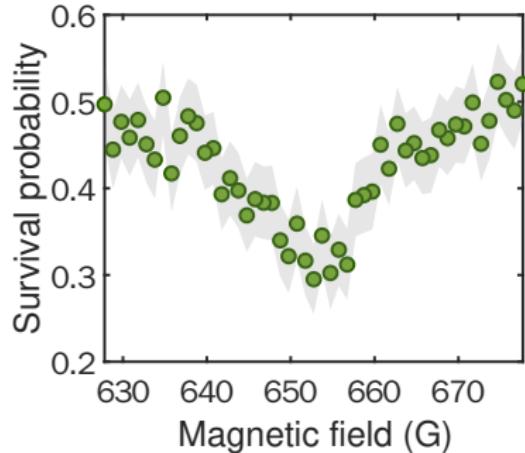
Na Raman sideband cooling sequence



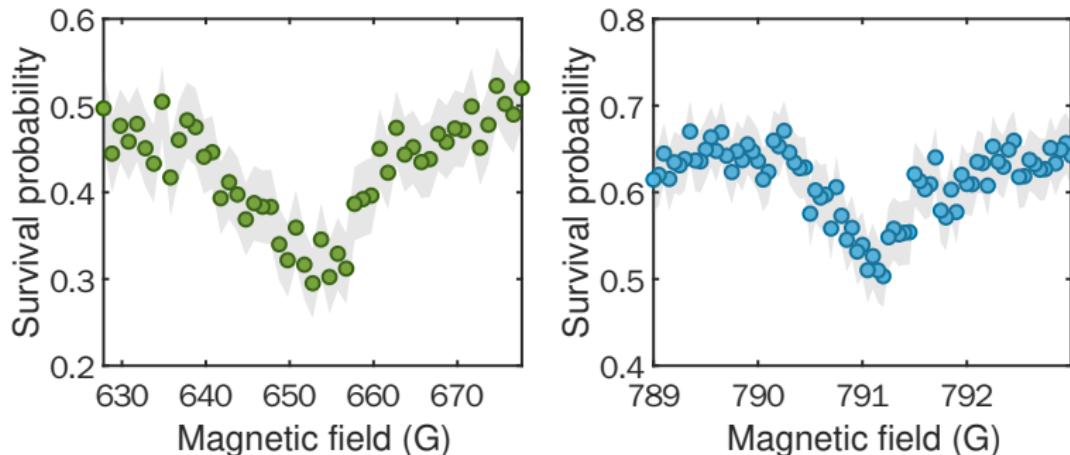
Na (1, -1) Cs (3, -3) Feshbach resonance



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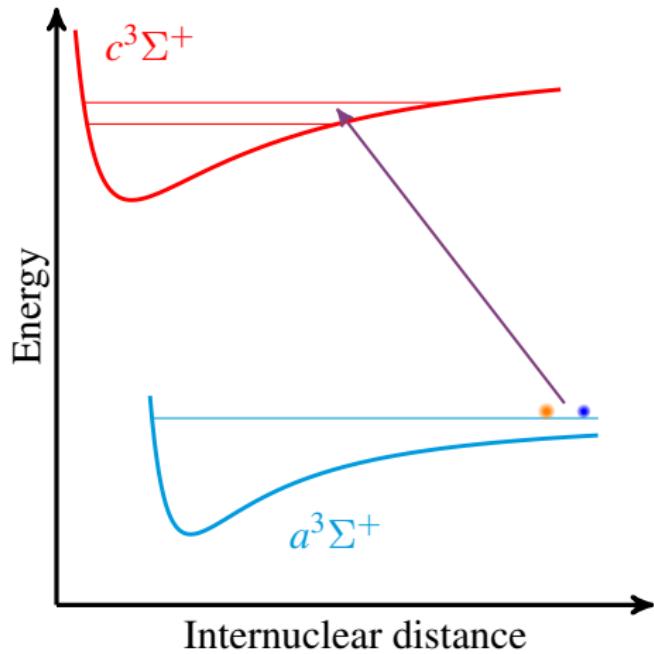
Na (1, -1) Cs (3, -3) Feshbach resonance



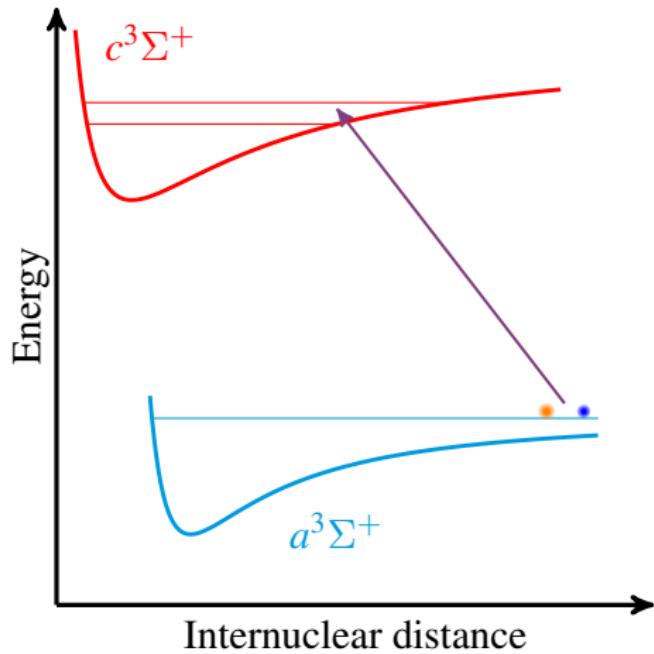
	<i>s</i> -wave	<i>p</i> -wave
Predicted (based on interaction shift) ¹	663 G	799 G
Measured	652(3) G	791.2(2) G

¹In collaboration with Bo Gao

Photoassociation (PA) Spectroscopy



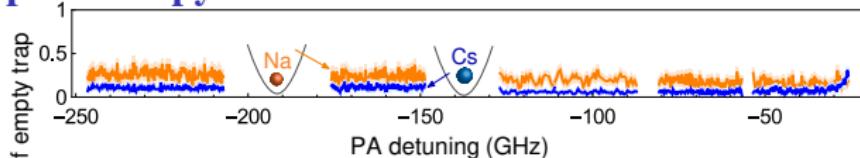
Photoassociation (PA) Spectroscopy



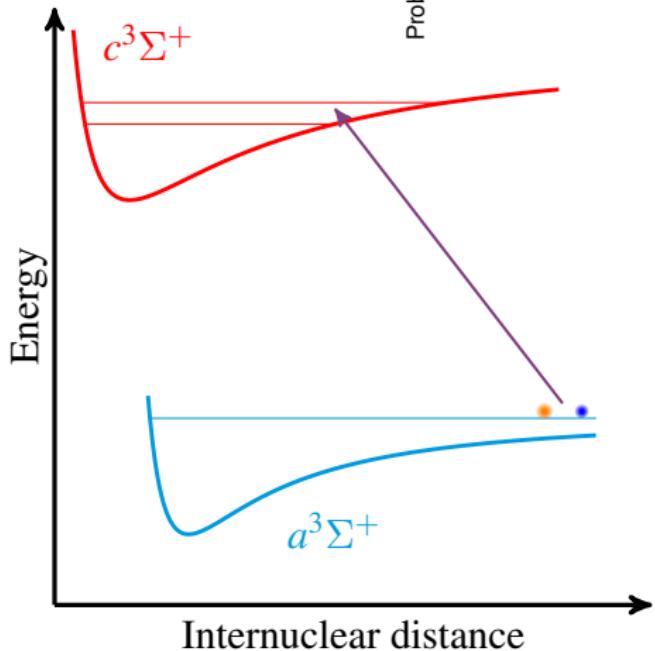
Single Atom PA

- Clean initial state
- Narrow excitation laser
- Final state detection

Photoassociation (PA) Spectroscopy



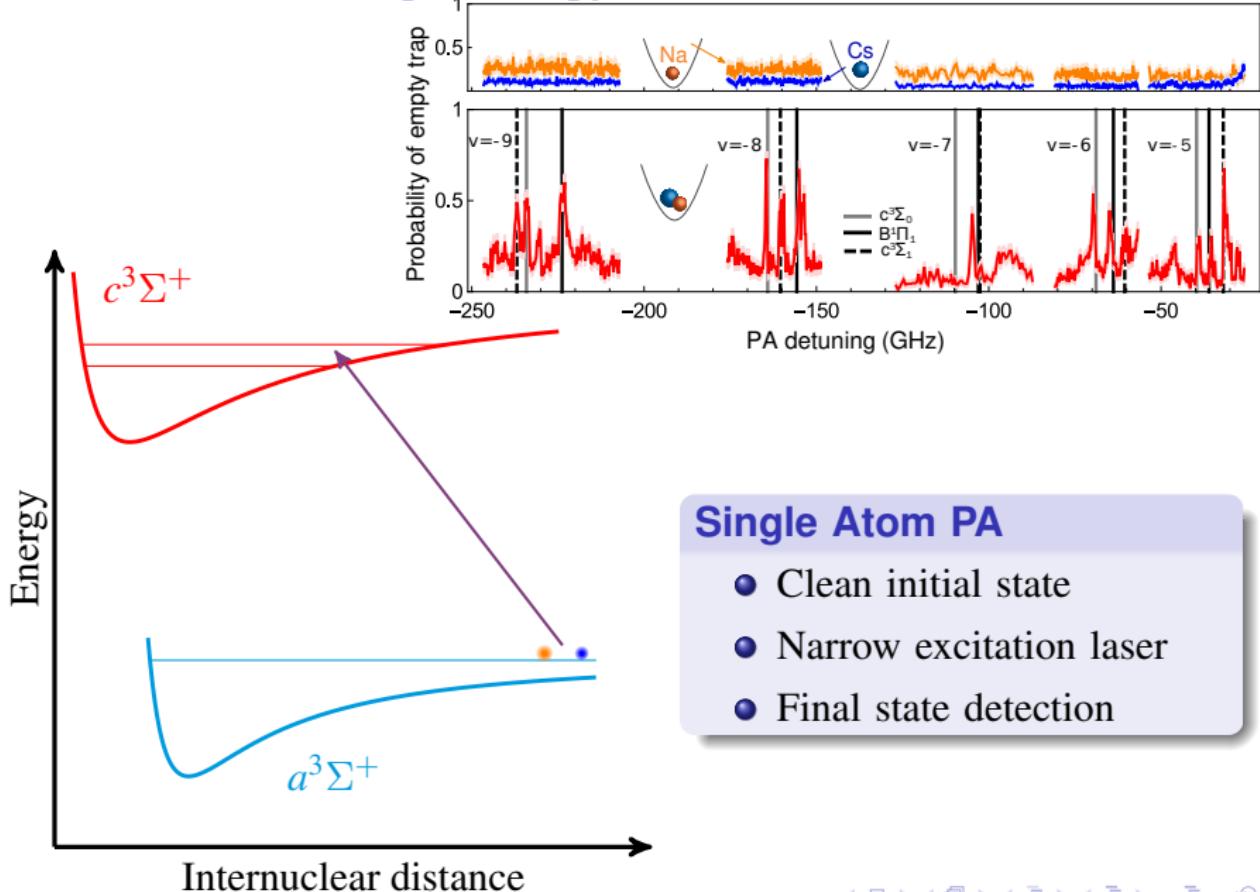
Probability of empty trap



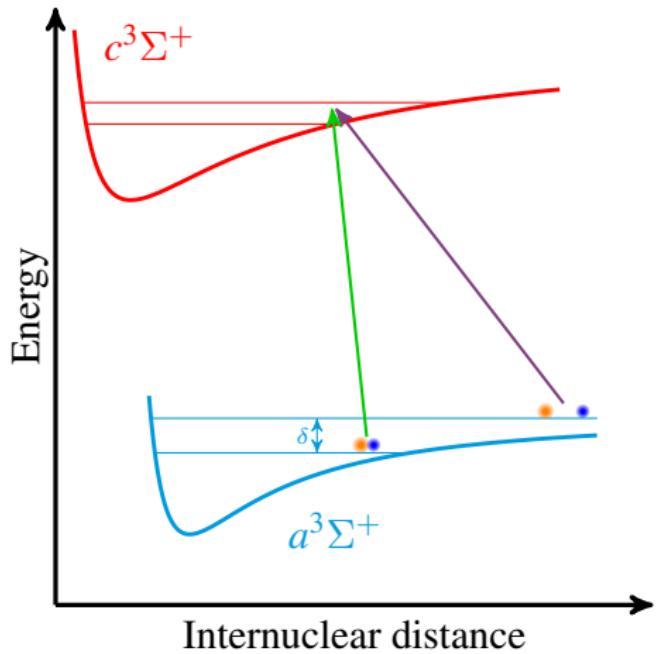
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Photoassociation (PA) Spectroscopy



Electromagnetically Induced Transparency (EIT) Spectroscopy



Electromagnetically Induced Transparency (EIT) Spectroscopy

