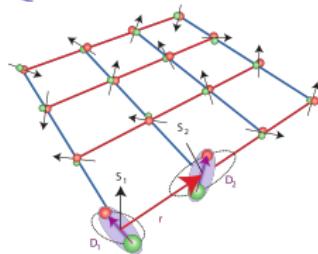


Coherent Creation of Single Molecules from Single Atoms

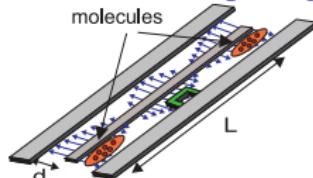
Yichao Yu

Ni Group/Harvard

Quantum Simulation



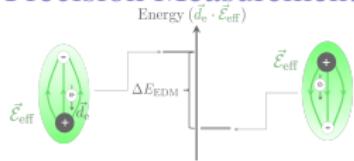
Quantum Computing



PRL. 97, 33003 (2006)

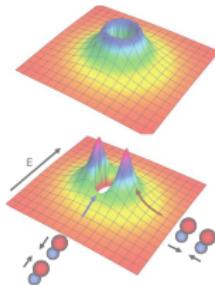
Nat. Phys. 2, 341 (2006)

Precision Measurement



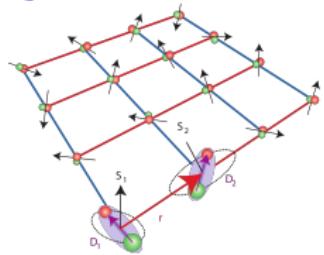
Science 343, 269 (2014)

Quantum Chemistry



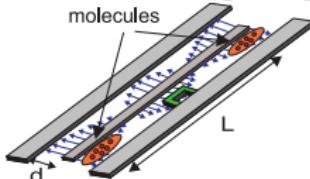
Nature 464, 1324 (2010)

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Nat. Phys. 2, 341 (2006)

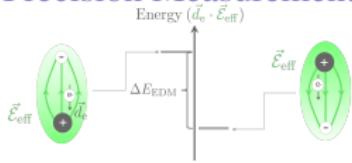
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PRL. 97, 33003 (2006)

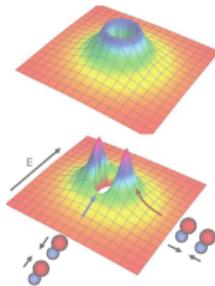
- Full quantum control
- Entanglement
- ...

Precision Measurement



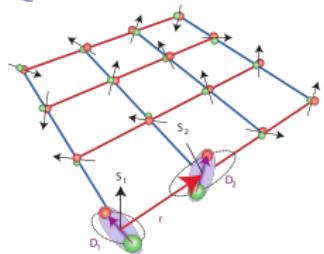
Science 343, 269 (2014)

Quantum Chemistry



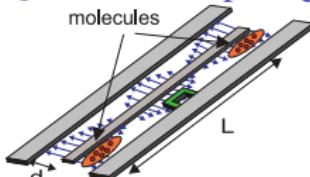
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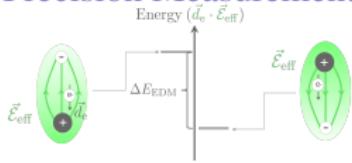
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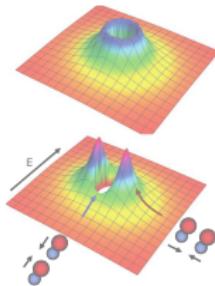
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Precision Measurement



Science 343, 269 (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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Optical tweezers

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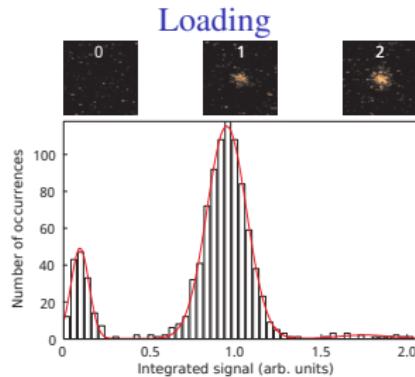
- Single site resolution



Entanglement

i.e. interaction

Dipolar molecules



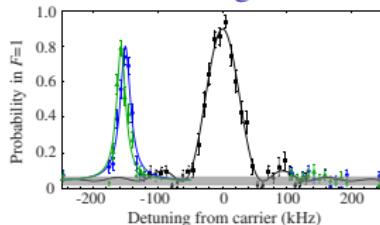
Single particle control

Optical tweezers

- Single site resolution

- ...

Cooling



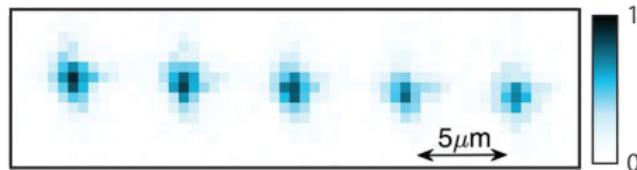
PRX. 2, 041014 (2012)

Rearranging



Ultracold molecule in tweezers

Direct cooling



Science 365, 1156 (2019)

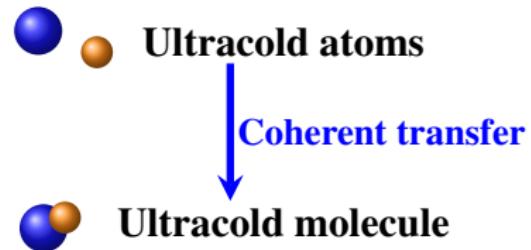
Ultracold molecule in tweezers

Direct cooling



Science 365, 1156 (2019)

Assembly



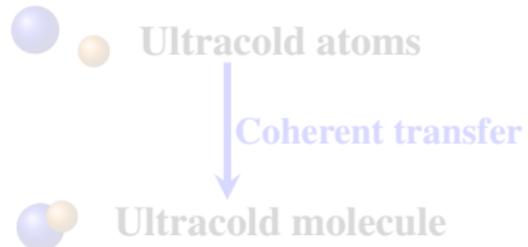
Ultracold molecule in tweezers

Direct cooling



Science 365, 1156 (2019)

Assembly



Challenges

- Temperature in tweezer
- Quantum control

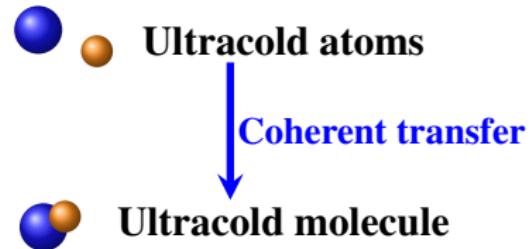
Ultracold molecule in tweezers

Direct cooling



Science 365, 1156 (2019)

Assembly



Challenges

- Temperature in tweezers
- Quantum control
- Control of atoms
- Coherent creation of molecules

Outline

1 Experiment overview

2 Atom state control

- Raman sideband cooling of Na atoms

3 Molecule creation

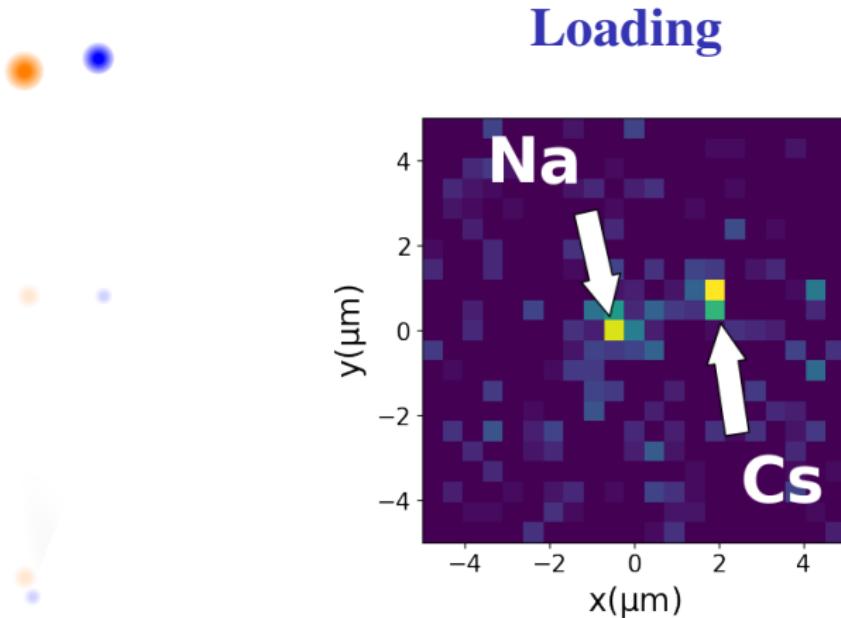
- Atom-atom interaction
- Coherent optical transfer

4 Conclusion

NaCs molecule

- Bi-alkali (easy to control)
- Large dipole moment: 4.6 D

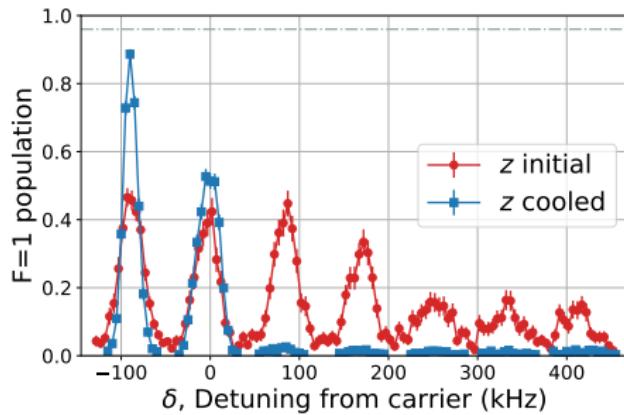
Experiment overview



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

Experiment overview

Cooling



Cs: 96% ground state¹

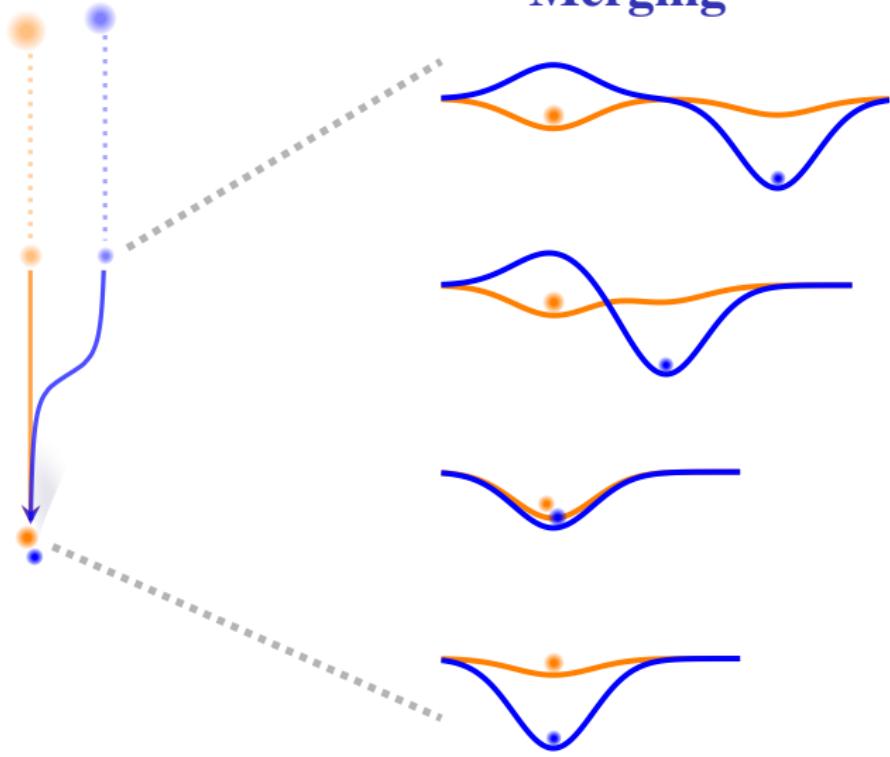
Na: 94% ground state²

¹Y. Yu et al. PRX 9, 021039 (2019)

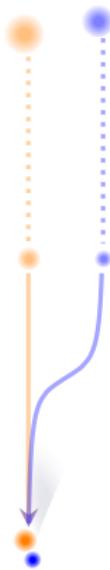
²Y. Yu et al. PRA 97, 063423 (2018)

Experiment overview

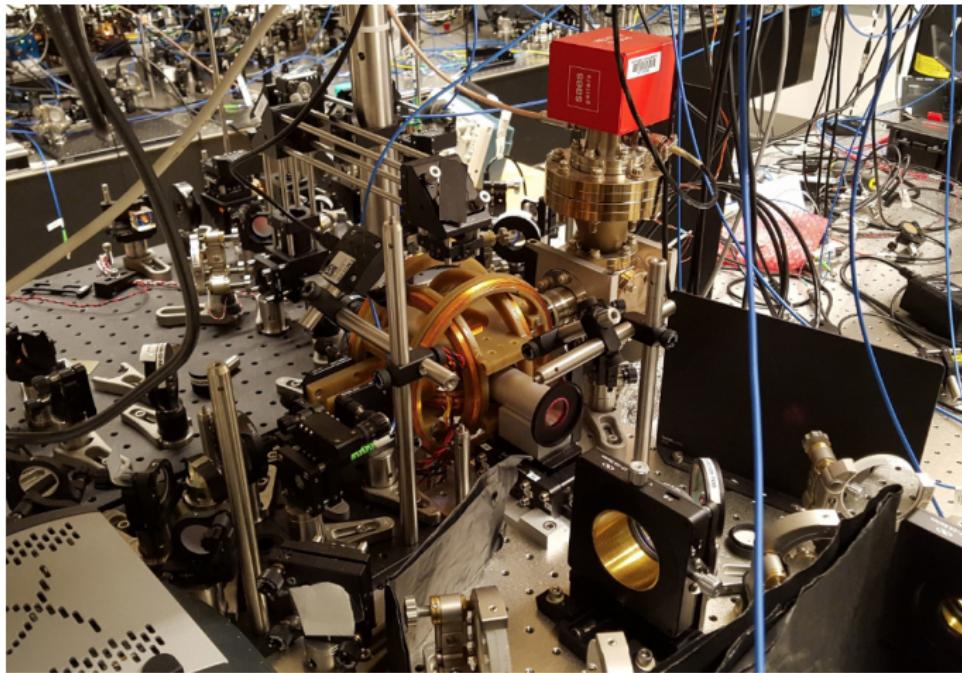
Merging

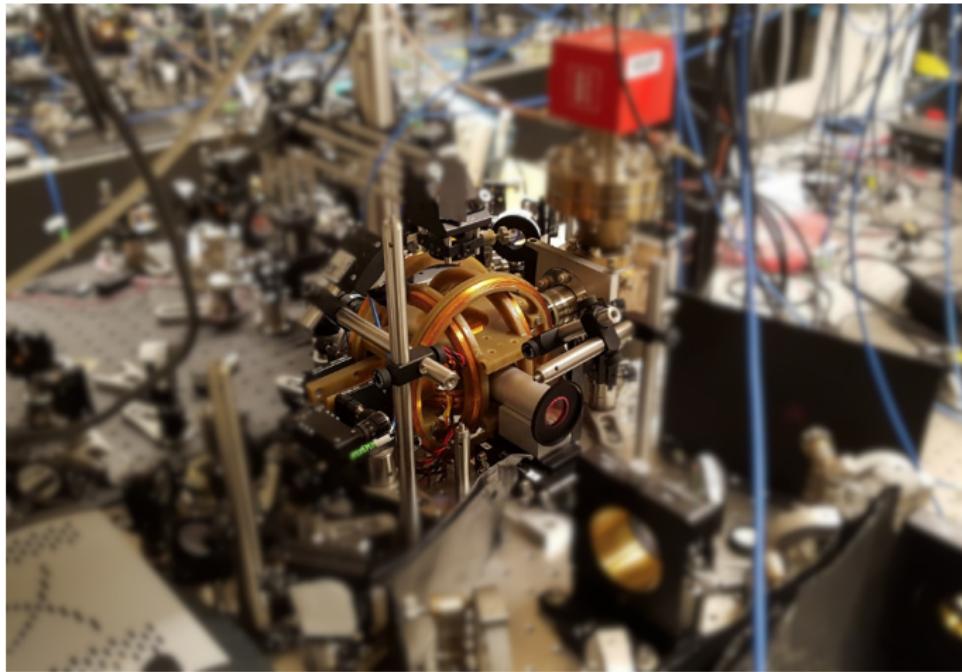


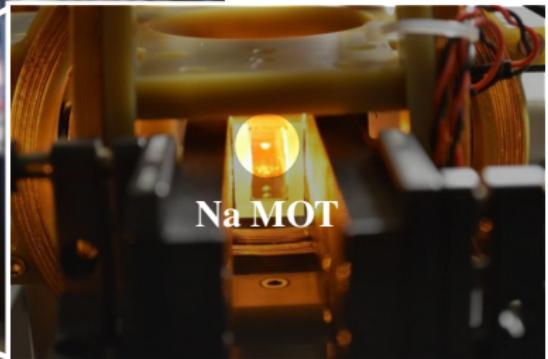
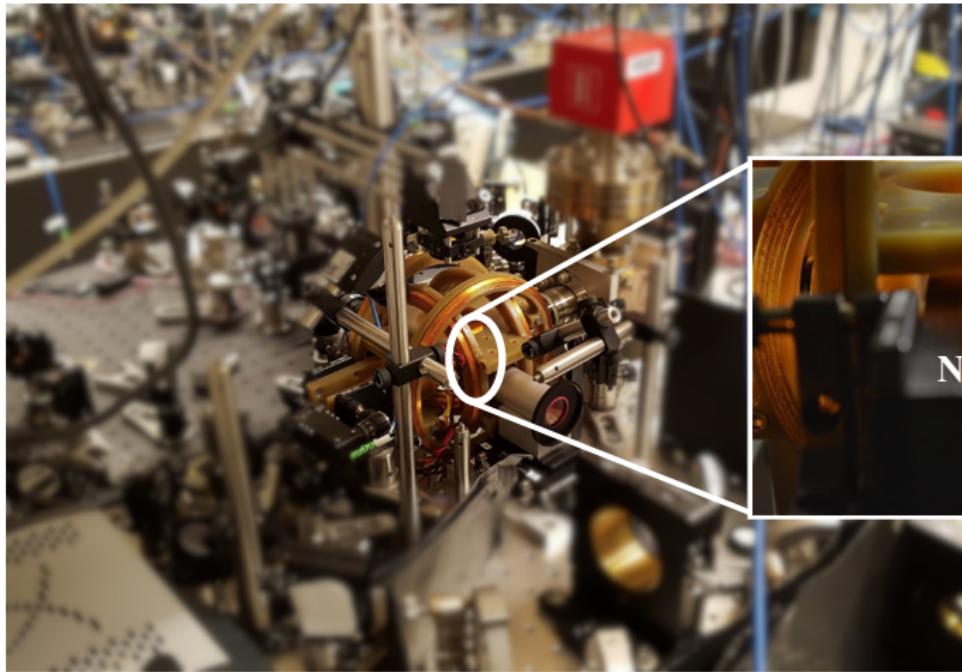
Experiment overview



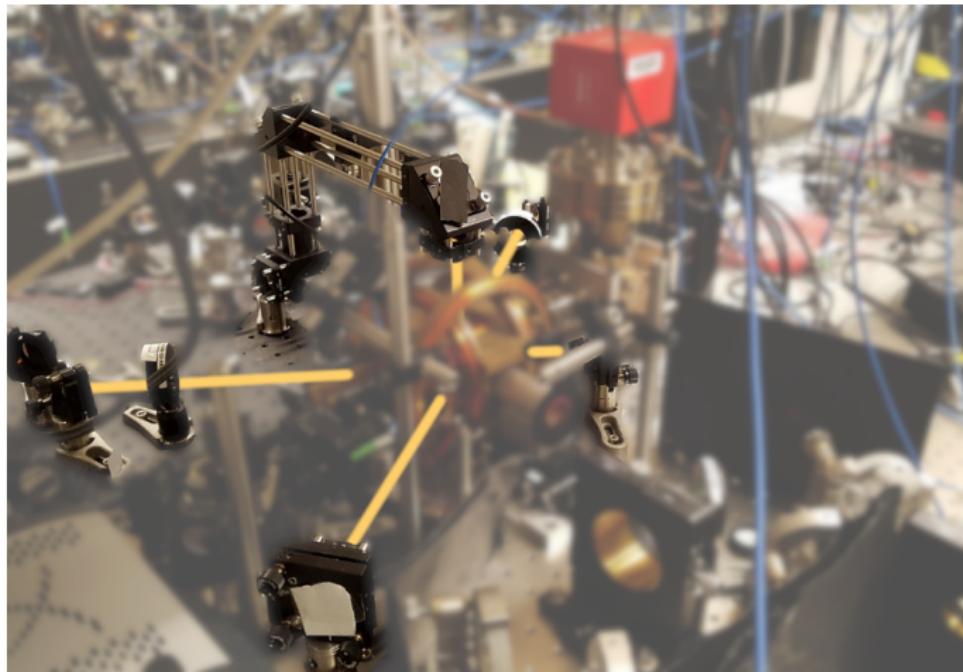
L. R. Liu, J. D. Hood, Y. Yu et al., *Science* 360, 6391 (2018)



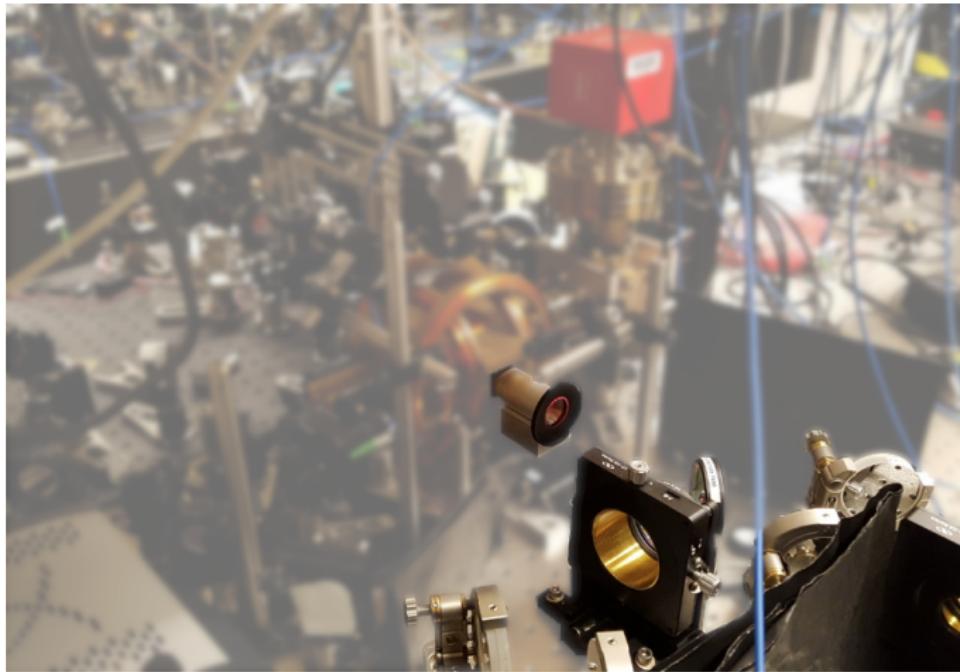




MOT beam path



Tweezer beam path



Outline

1 Experiment overview

2 Atom state control

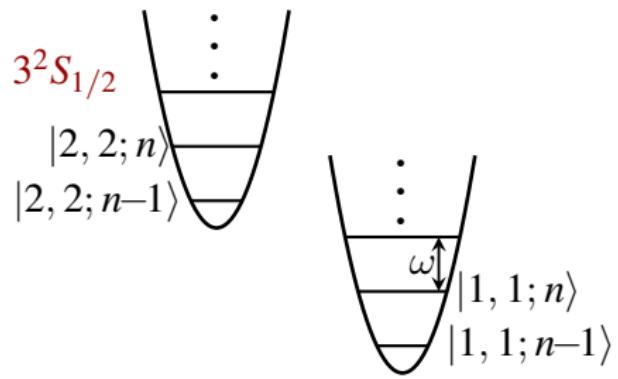
- Raman sideband cooling of Na atoms

3 Molecule creation

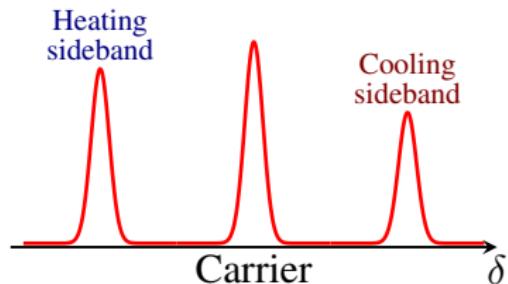
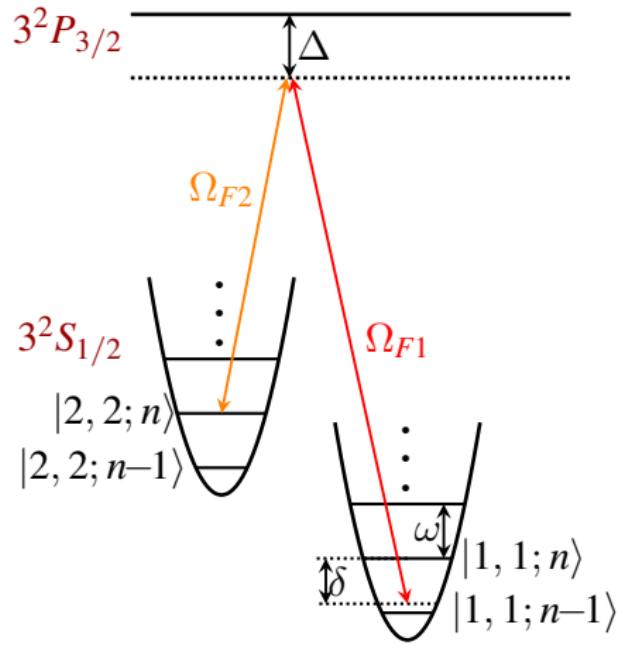
- Atom-atom interaction
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4 Conclusion

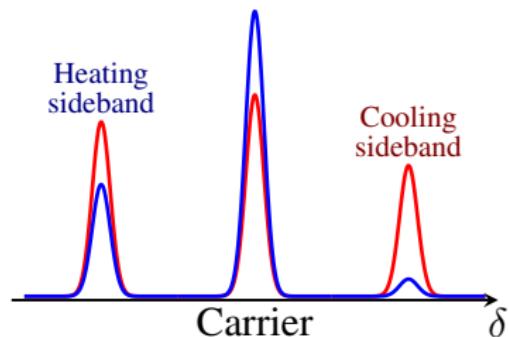
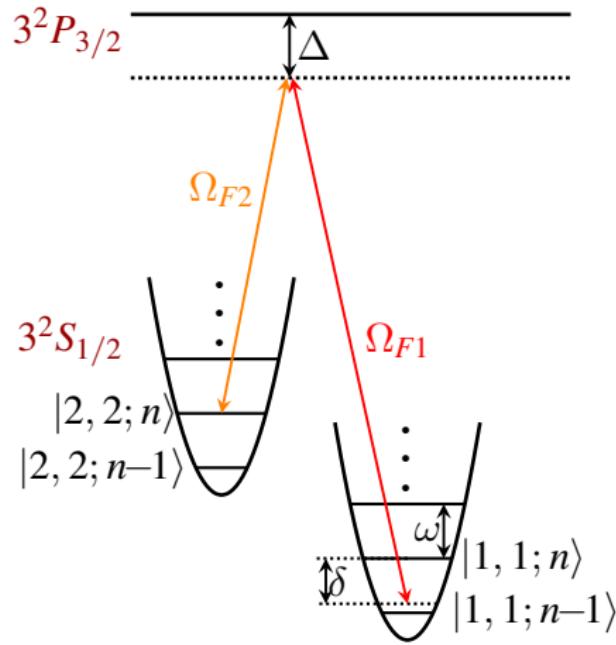
Raman sideband cooling



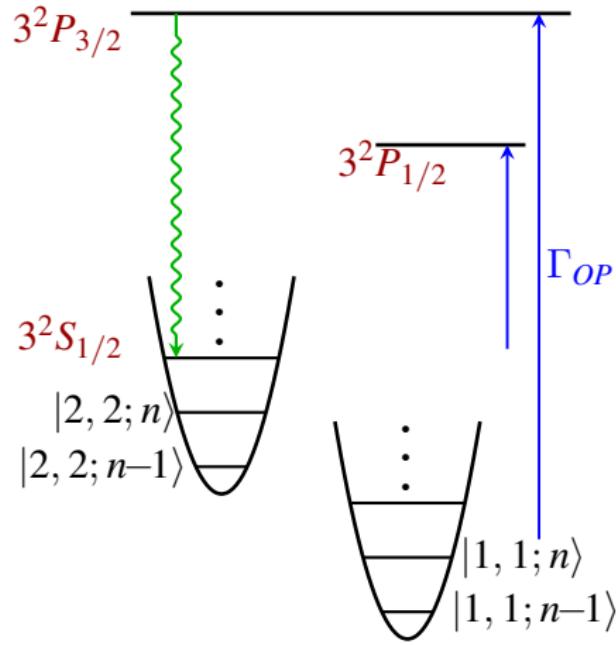
Raman sideband cooling



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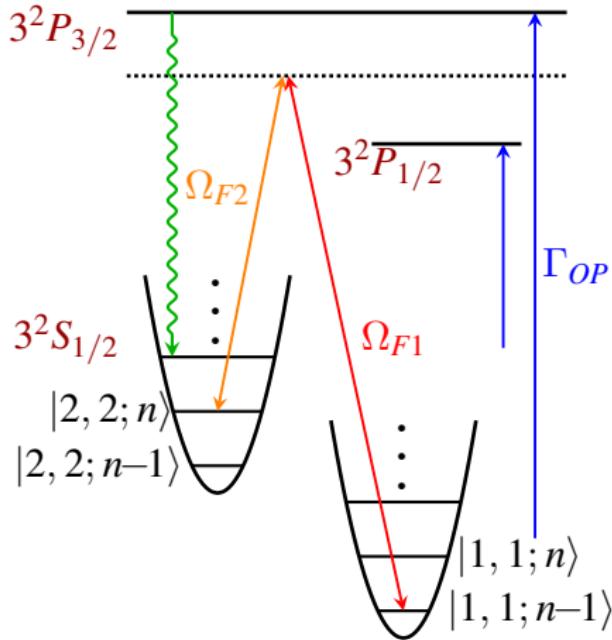
Raman sideband cooling



Raman sideband cooling

Lamb Dicke parameter

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

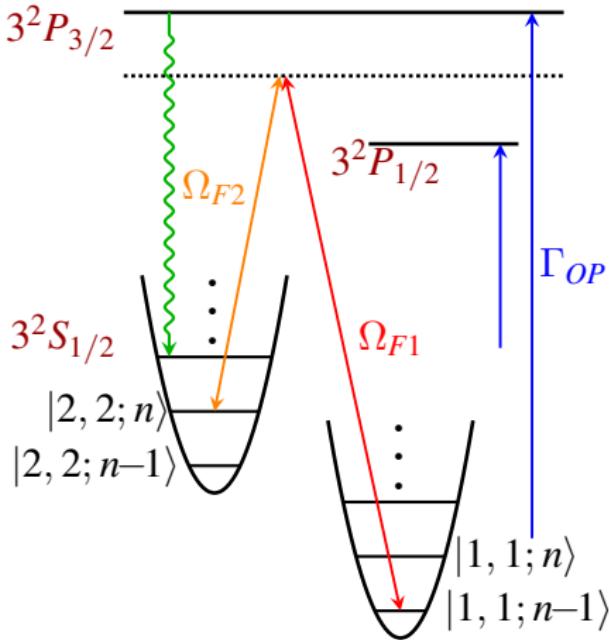


Raman sideband cooling

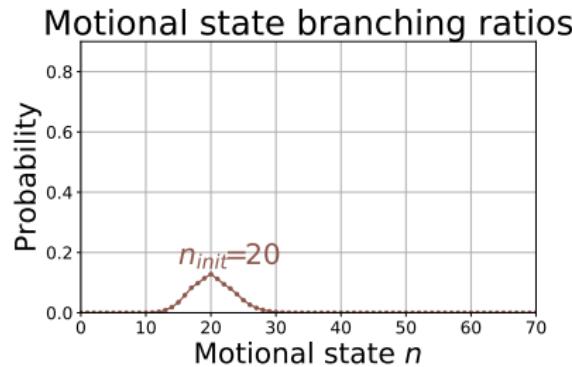
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$$\eta_{Na}^{OP} = 0.55$$



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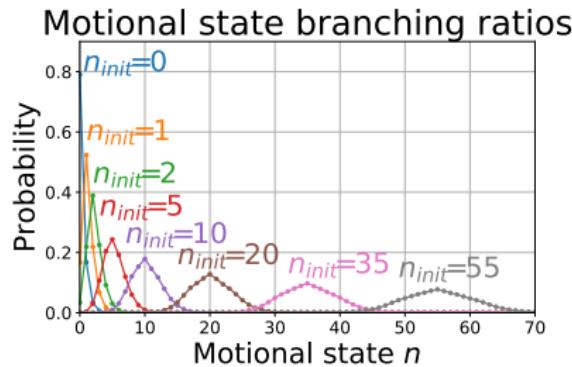
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- Motional state branching
- Coupling “dead zone”

Raman sideband cooling



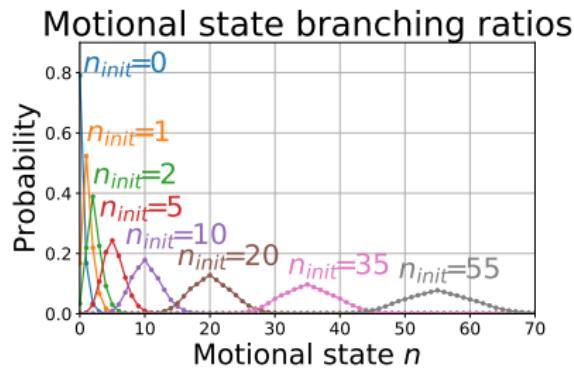
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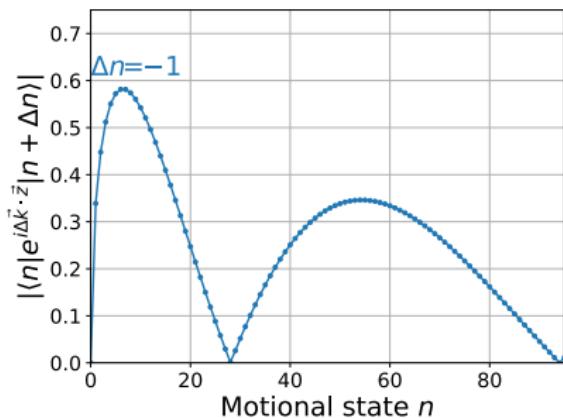


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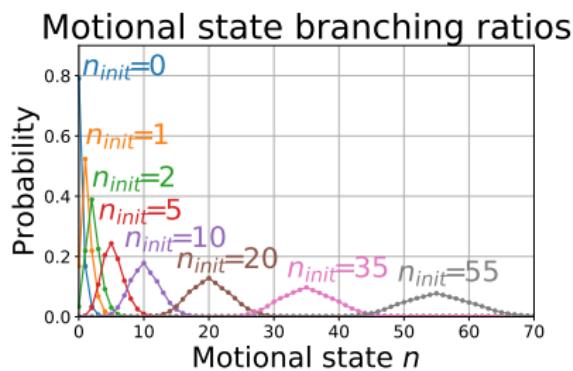
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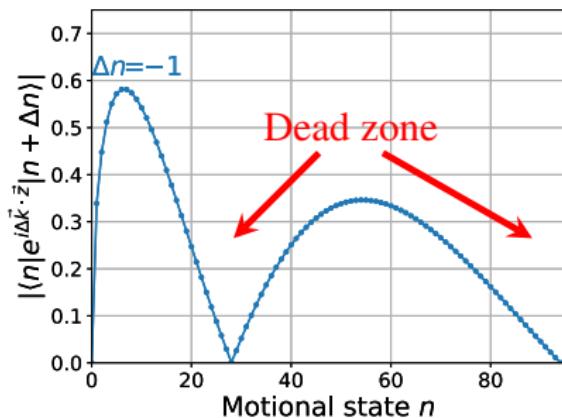


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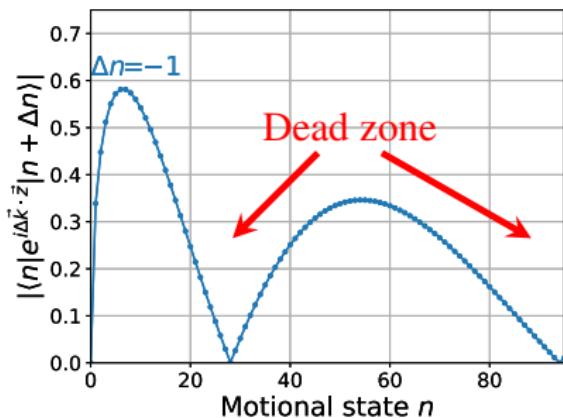
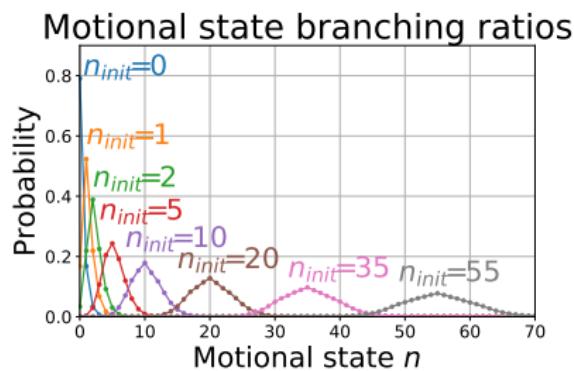
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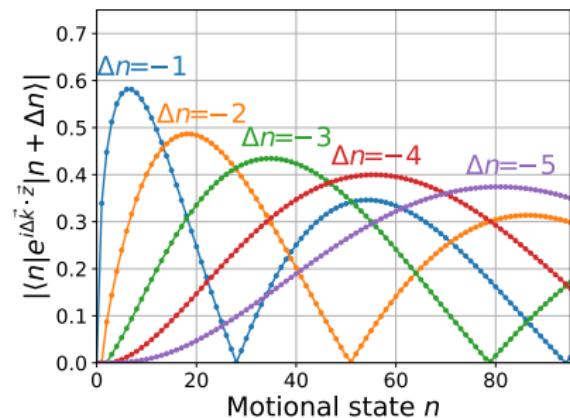
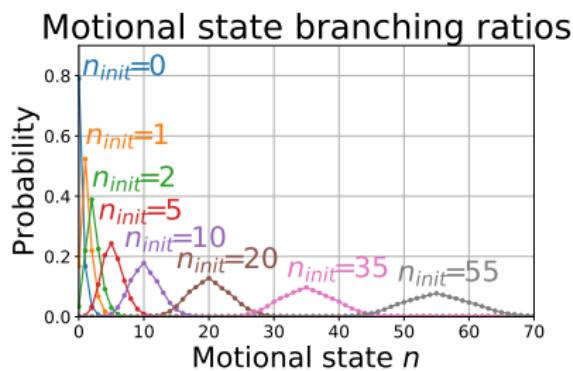
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- Use higher order sidebands.
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Raman sideband cooling



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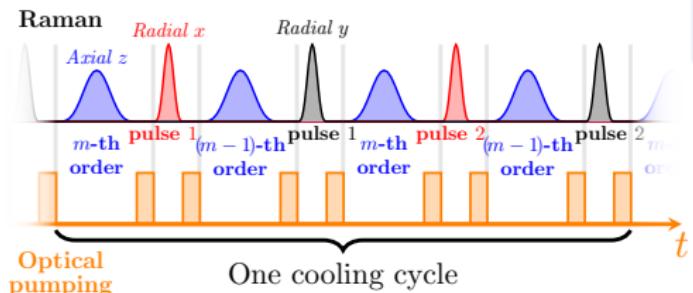
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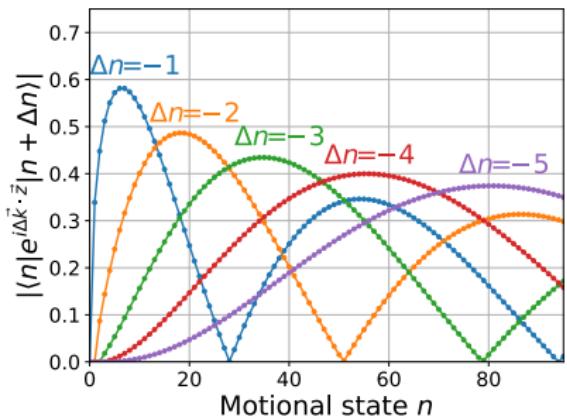
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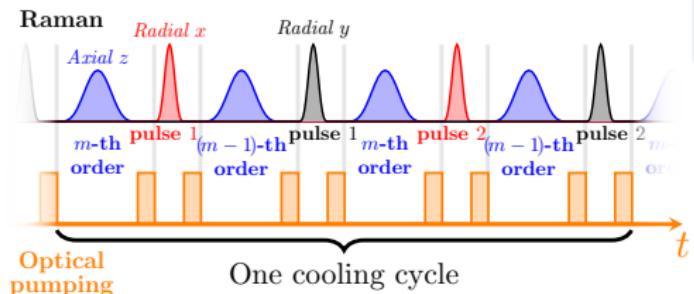
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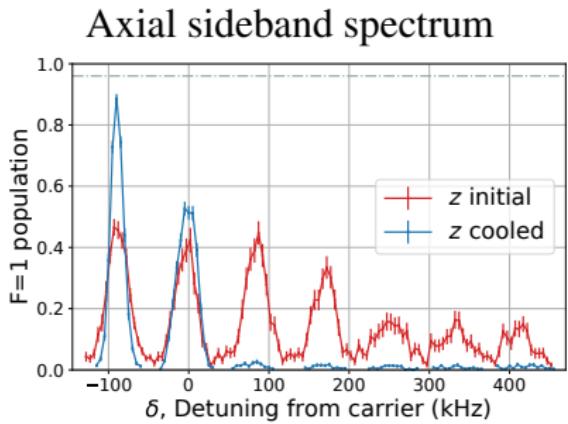
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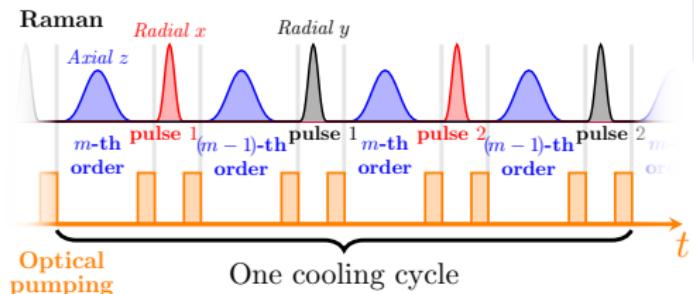
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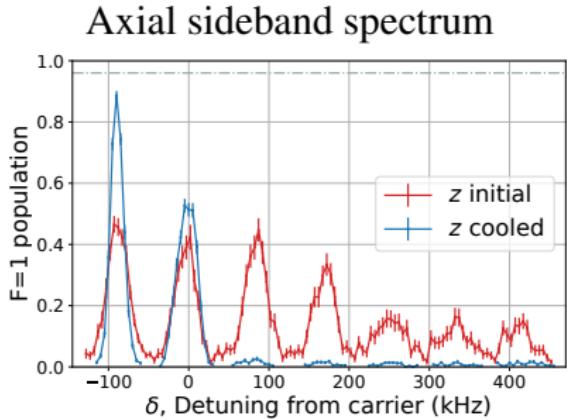
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3D ground state: 93.5(7)%

Outline

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- Raman sideband cooling of Na atoms

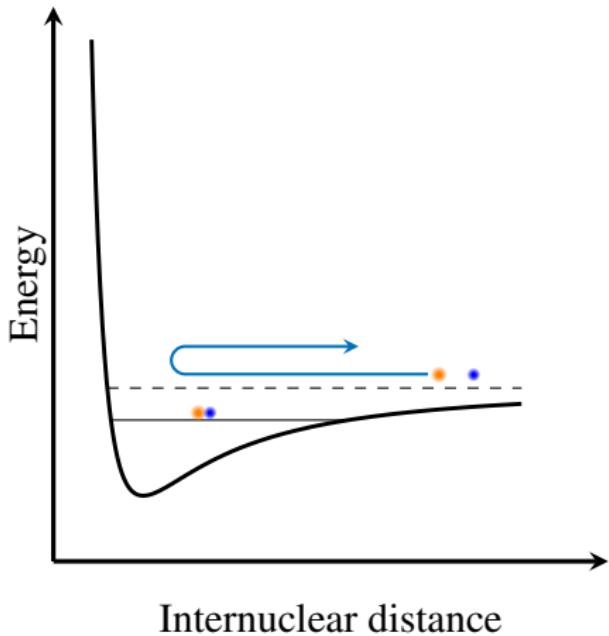
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- Coherent optical transfer

4 Conclusion

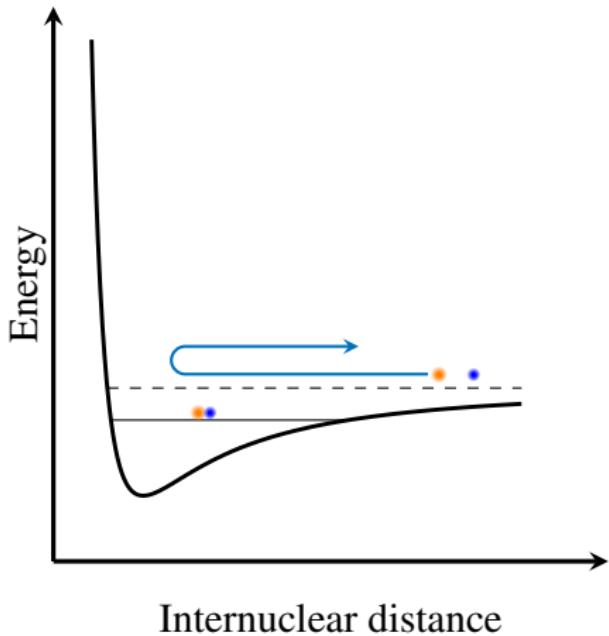
Scattering length a

- Binding energy
- Molecular potential
- Molecule formation
- Feshbach resonance
- ⋮



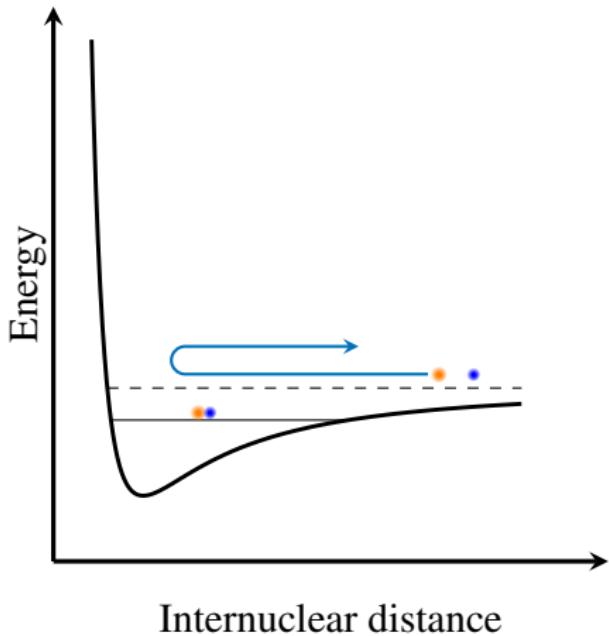
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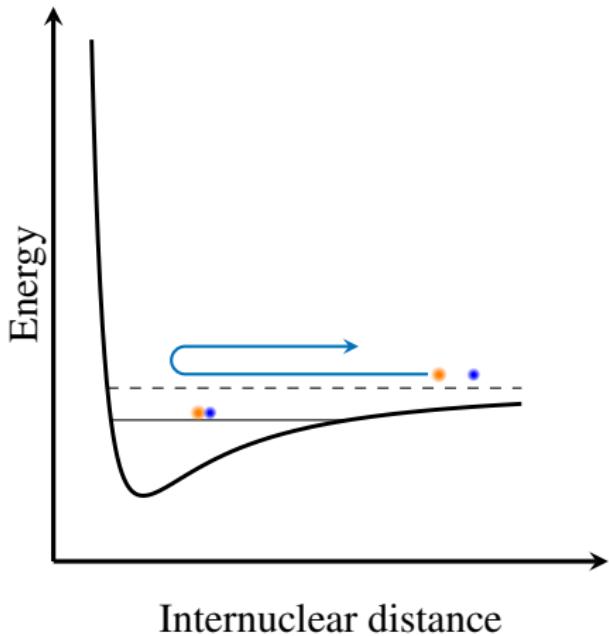
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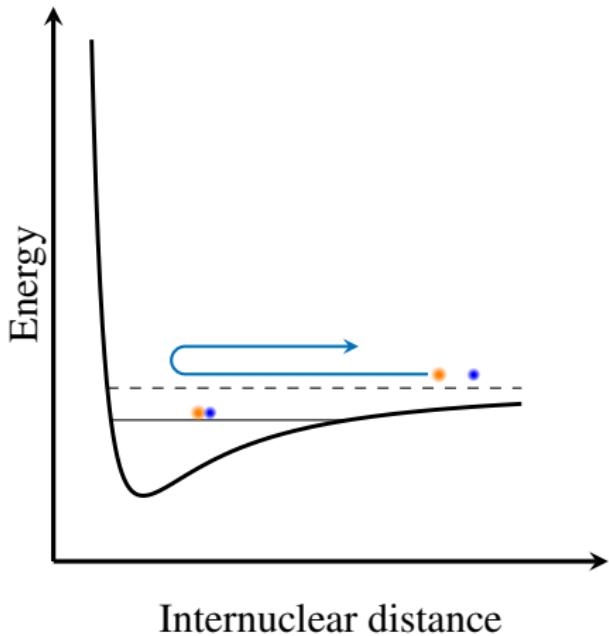
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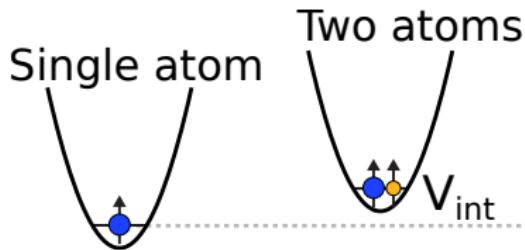


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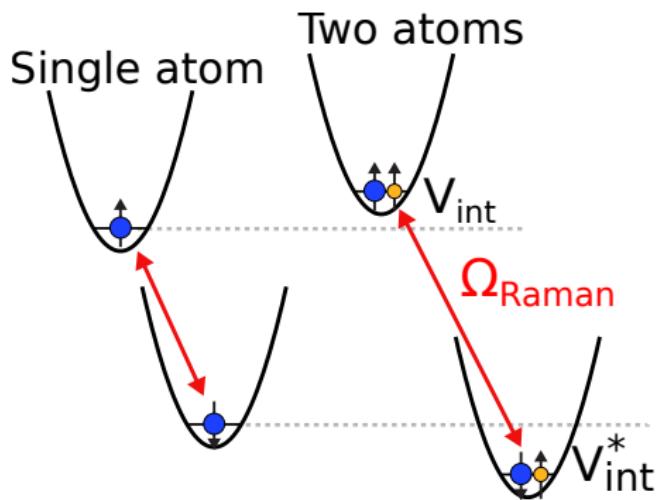
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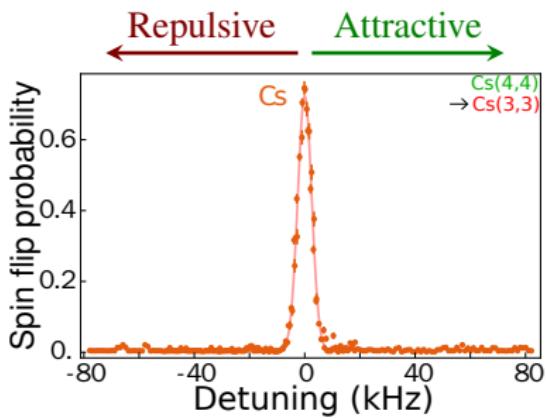
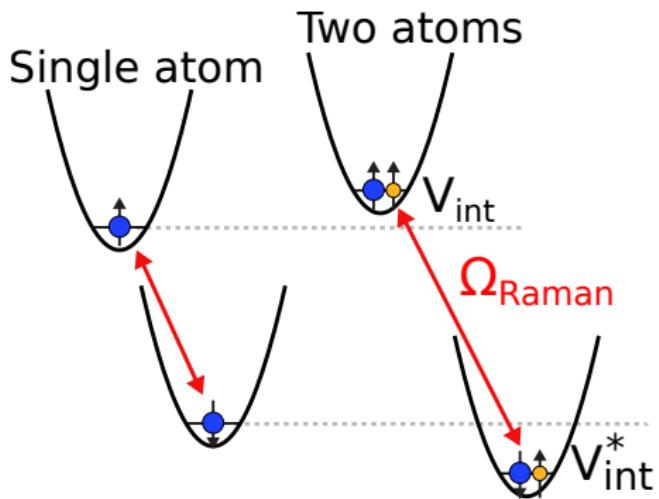
Interaction shift



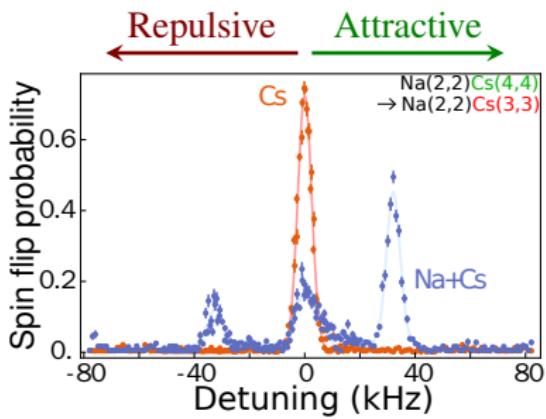
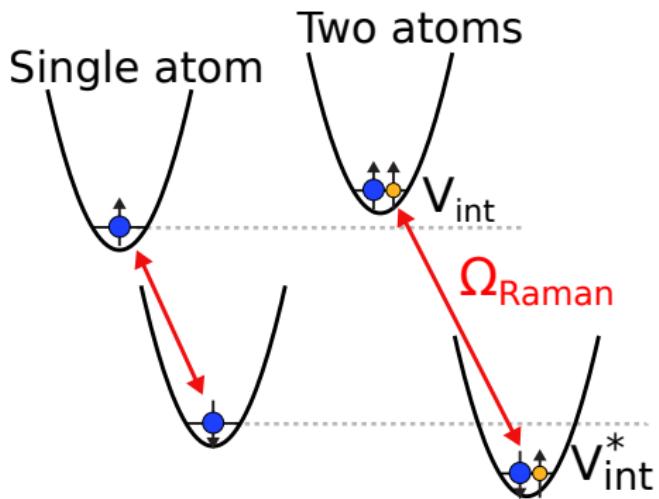
Interaction shift



Interaction shift



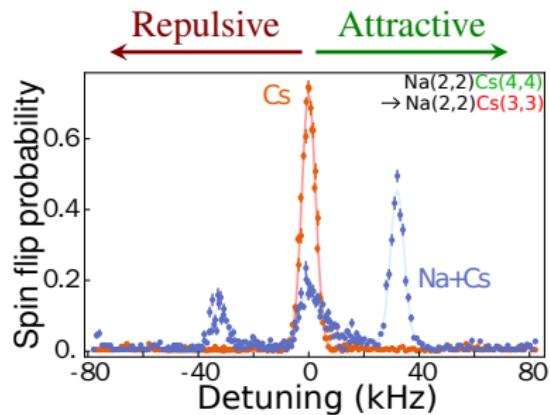
Interaction shift



Interaction shift

$$H = \underbrace{\sum_{i=x,y,z} \left(\frac{m_1 \omega_{1,i}^2 x_{1,i}^2}{2} + \frac{p_{1,i}^2}{2m_1} \right)}_{\text{Na}} + \underbrace{\sum_{i=x,y,z} \left(\frac{m_2 \omega_{2,i}^2 x_{2,i}^2}{2} + \frac{p_{2,i}^2}{2m_2} \right)}_{\text{Cs}} + V_{int}(\vec{r}_1 - \vec{r}_2)$$

Interaction



Interaction shift

$$H = \underbrace{\sum_{i=x,y,z} \left(\frac{m_1 \omega_{1,i}^2 X_{1,i}^2}{2} + \frac{p_{1,i}^2}{2m_1} \right)}_{\text{Na}} + \underbrace{\sum_{i=x,y,z} \left(\frac{m_2 \omega_{2,i}^2 X_{2,i}^2}{2} + \frac{p_{2,i}^2}{2m_2} \right)}_{\text{Cs}} + V_{int}(\vec{r}_1 - \vec{r}_2) \underbrace{\quad}_{\text{Interaction}}$$

To center of mass
and relative coordinates

$$M = m_1 + m_2$$

$$\mu = \frac{m_1 m_2}{m_1 + m_2}$$

$$\Omega_i^2 = \frac{m_1 \omega_{1,i}^2 + m_2 \omega_{2,i}^2}{m_1 + m_2}$$

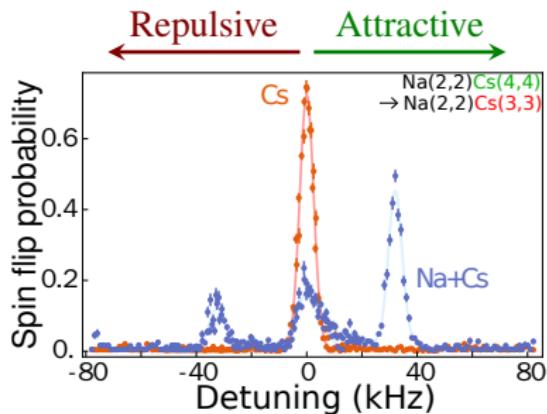
$$\omega_{R,i}^2 = \frac{m_2 \omega_{1,i}^2 + m_1 \omega_{2,i}^2}{m_1 + m_2}$$

$$X_i = \frac{m_1 x_{1,i} + m_2 x_{2,i}}{m_1 + m_2}$$

$$x_{R,i} = x_{1,i} - x_{2,i}$$

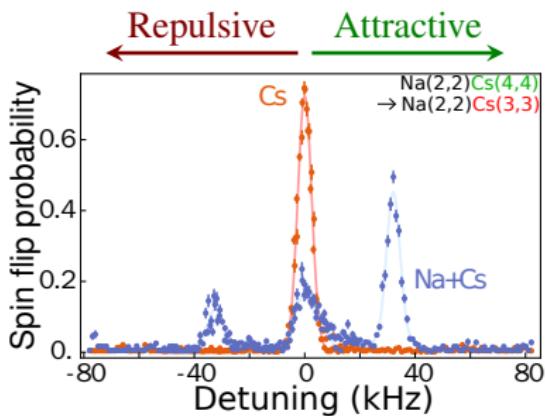
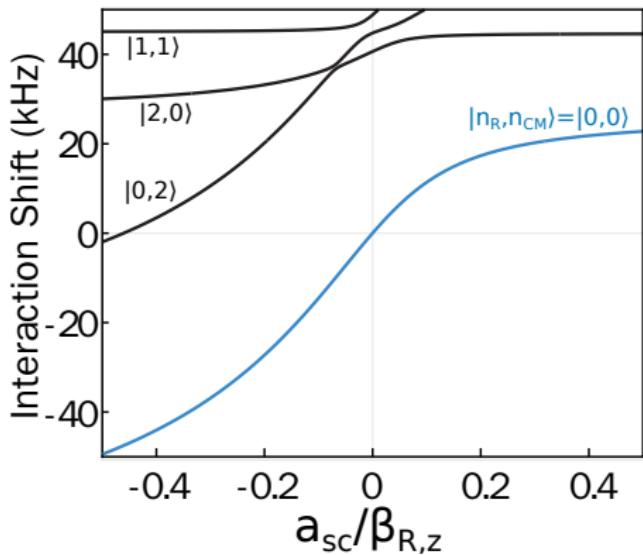
$$P_i = p_{1,i} + p_{2,i}$$

$$p_{R,i} = \frac{m_2 p_{1,i} - m_1 p_{2,i}}{m_1 + m_2}$$



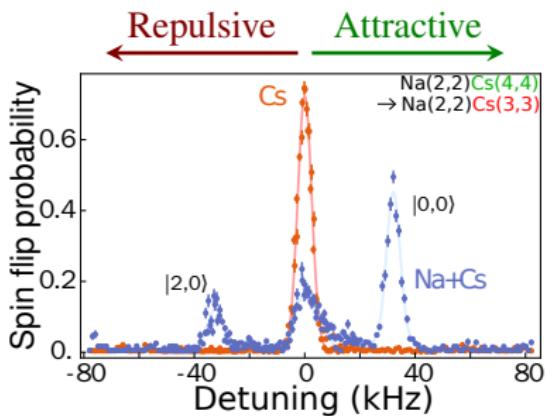
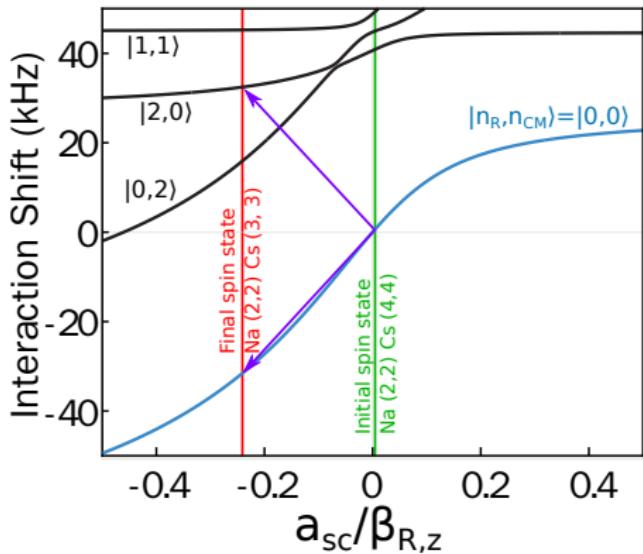
$$H = \underbrace{\sum_{i=x,y,z} \left(\frac{M \Omega_i^2 X_i^2}{2} + \frac{P_i^2}{2M} \right)}_{\text{Center of mass}} + \underbrace{\sum_{i=x,y,z} \left(\frac{\mu \omega_{R,i}^2 X_{R,i}^2}{2} + \frac{p_{R,i}^2}{2\mu} \right) + V_{int}(\vec{r}_R)}_{\text{Relative}} + \underbrace{\sum_{i=x,y,z} \mu (\omega_{1,i}^2 - \omega_{2,i}^2) X_i X_{R,i}}_{\text{Mixing}}$$

Interaction shift



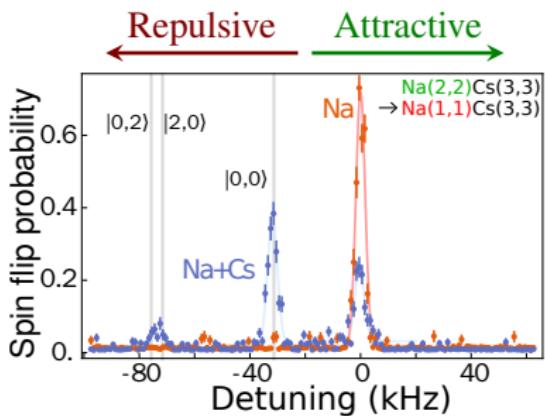
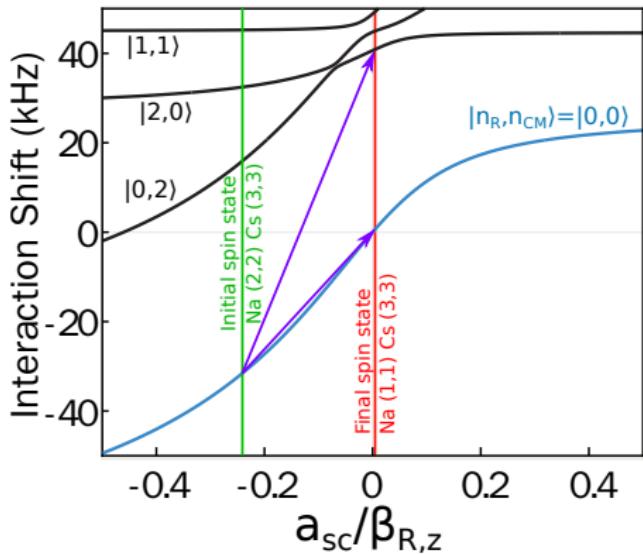
$$H = \underbrace{\sum_{i=x,y,z} \left(\frac{M\Omega_i^2 X_i^2}{2} + \frac{P_i^2}{2M} \right)}_{\text{Center of mass}} + \underbrace{\sum_{i=x,y,z} \left(\frac{\mu\omega_{R,i}^2 X_{R,i}^2}{2} + \frac{p_{R,i}^2}{2\mu} \right) + V_{int}(\vec{r}_R)}_{\text{Relative}} + \underbrace{\sum_{i=x,y,z} \mu(\omega_{1,i}^2 - \omega_{2,i}^2) X_i X_{R,i}}_{\text{Mixing}}$$

Interaction shift



$$H = \underbrace{\sum_{i=x,y,z} \left(\frac{M\Omega_i^2 X_i^2}{2} + \frac{P_i^2}{2M} \right)}_{\text{Center of mass}} + \underbrace{\sum_{i=x,y,z} \left(\frac{\mu\omega_{R,i}^2 X_{R,i}^2}{2} + \frac{p_{R,i}^2}{2\mu} \right) + V_{int}(\vec{r}_R)}_{\text{Relative}} + \underbrace{\sum_{i=x,y,z} \mu(\omega_{1,i}^2 - \omega_{2,i}^2) X_i X_{R,i}}_{\text{Mixing}}$$

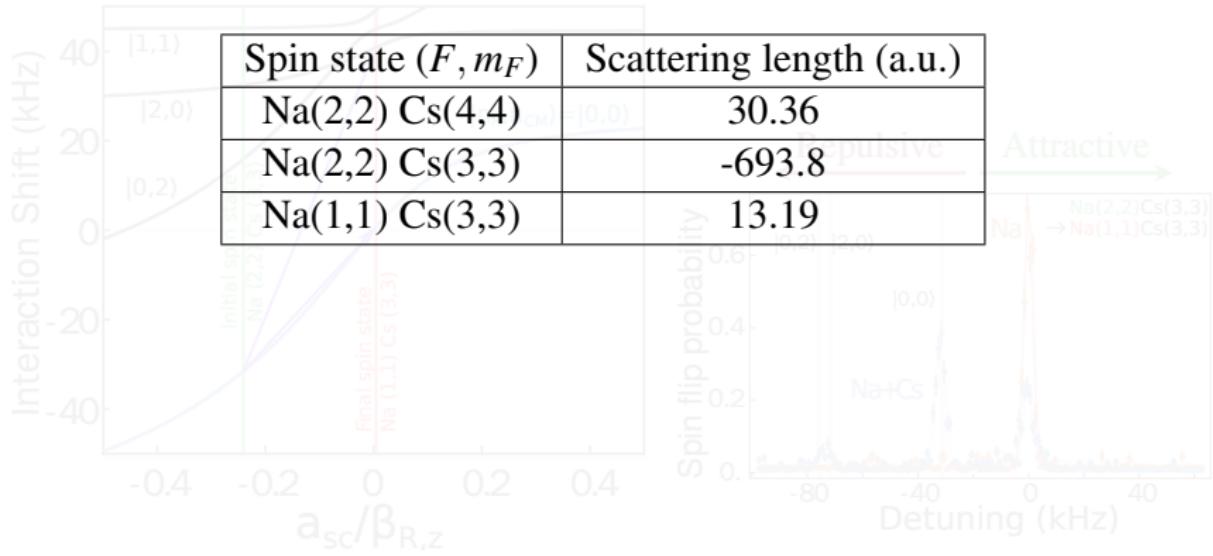
Interaction shift



$$H = \underbrace{\sum_{i=x,y,z} \left(\frac{M\Omega_i^2 X_i^2}{2} + \frac{P_i^2}{2M} \right)}_{\text{Center of mass}} + \underbrace{\sum_{i=x,y,z} \left(\frac{\mu\omega_{R,i}^2 X_{R,i}^2}{2} + \frac{p_{R,i}^2}{2\mu} \right) + V_{int}(\vec{r}_R)}_{\text{Relative}} + \underbrace{\sum_{i=x,y,z} \mu(\omega_{1,i}^2 - \omega_{2,i}^2) X_i X_{R,i}}_{\text{Mixing}}$$

Interaction shift

Combined with binding energy measurement on Na(2,2) Cs(4,4)



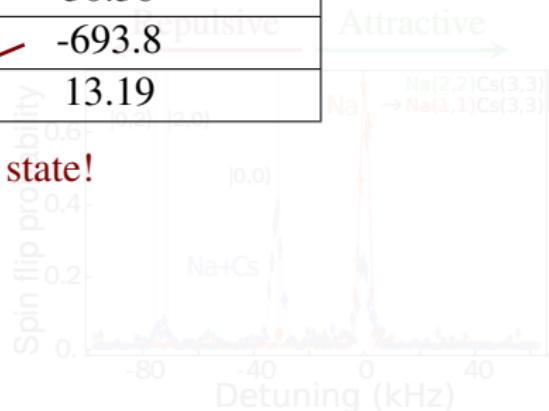
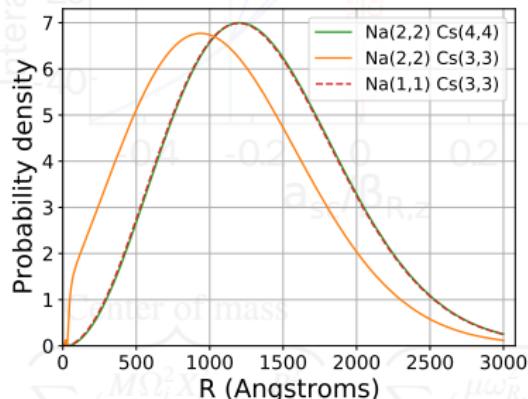
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Interaction shift

Combined with binding energy measurement on Na(2,2) Cs(4,4)

Spin state (F, m_F)	Scattering length (a.u.)
Na(2,2) Cs(4,4)	30.36
Na(2,2) Cs(3,3)	-693.8
Na(1,1) Cs(3,3)	13.19

Enhanced coupling to molecular state!



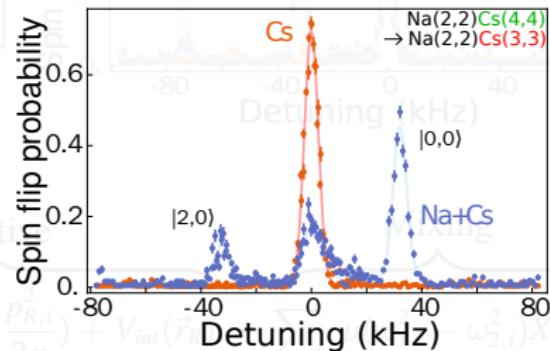
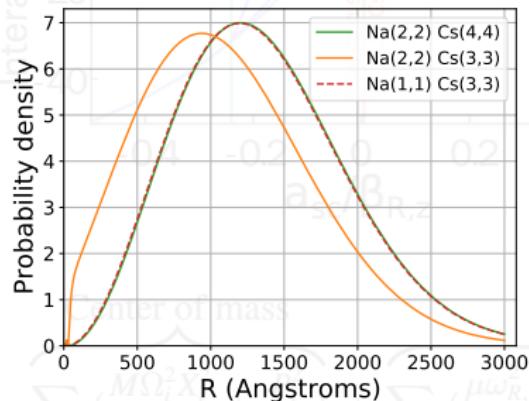
$$H = \sum_{i=x,y,z} \left(\frac{\mu \omega_{R,i} X_{R,i}}{2M} + \frac{p_{R,i}^2}{2\mu} \right) + V_{int}(\vec{r}_R) + \sum_{i=x,y,z} \mu (\omega_{1,i}^2 - \omega_{2,i}^2) X_i x_{R,i}$$

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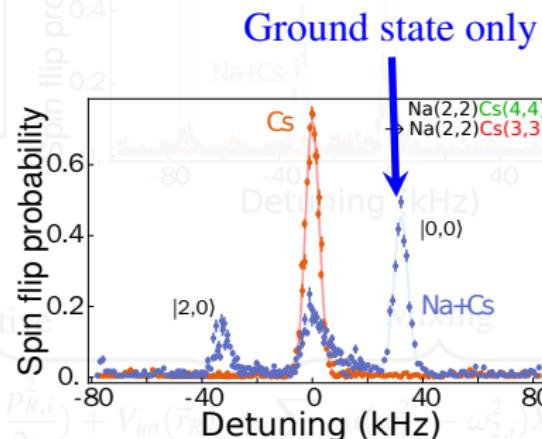
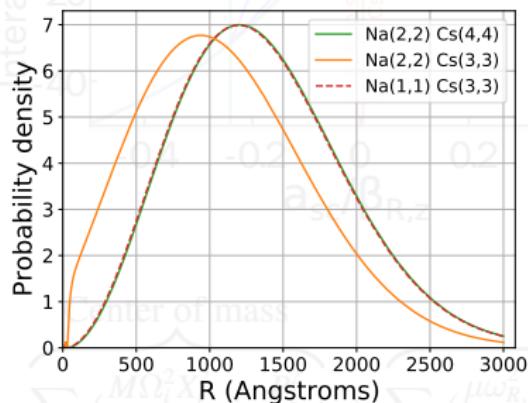


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Enhanced coupling to molecular state!



Outline

1 Experiment overview

2 Atom state control

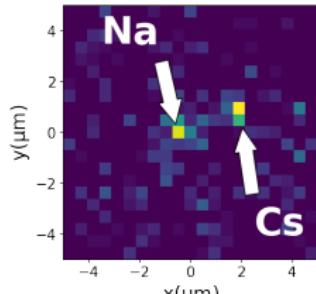
- Raman sideband cooling of Na atoms

3 Molecule creation

- Atom-atom interaction
- Coherent optical transfer

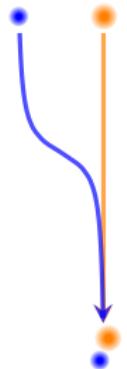
4 Conclusion

Loading

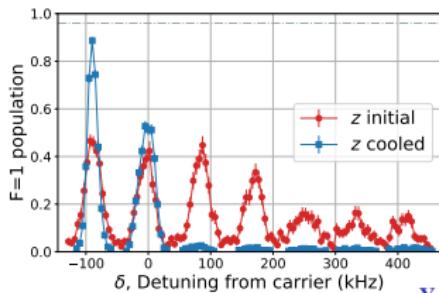


NJP. 19, 023007 (2017)

Merging



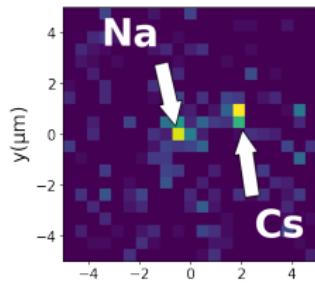
Cooling



Y. Yu et al. PRX. 9, 021039 (2019)

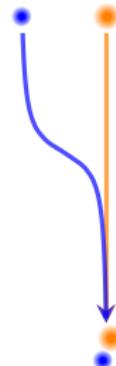
Y. Yu et al. PRA. 97, 063423 (2018)

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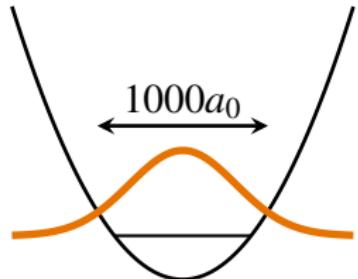


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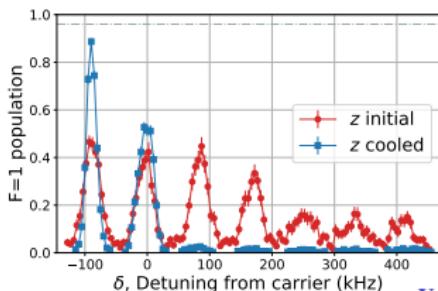
Merging



Atom



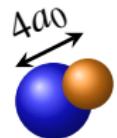
Cooling

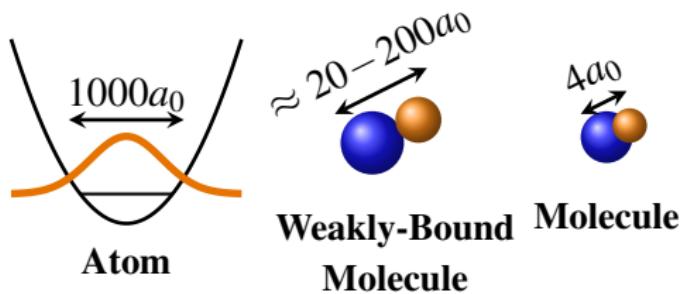


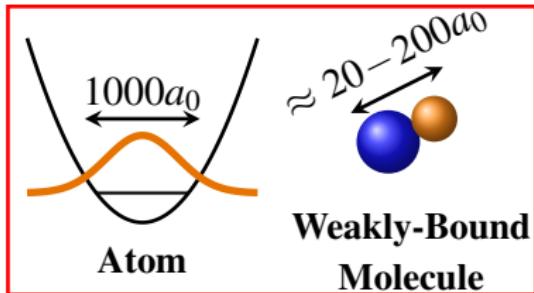
Y. Yu et al. PRA. 97, 063423 (2018)

Y. Yu et al. PRX. 9, 021039 (2019)

Molecule

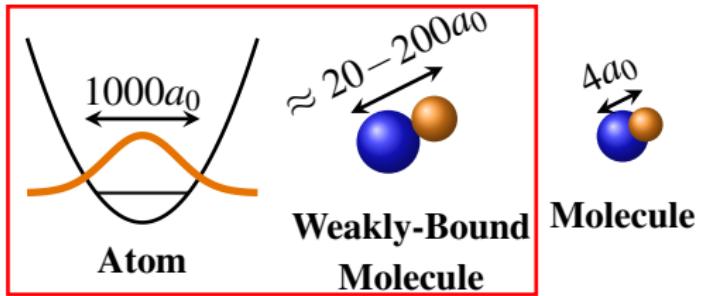




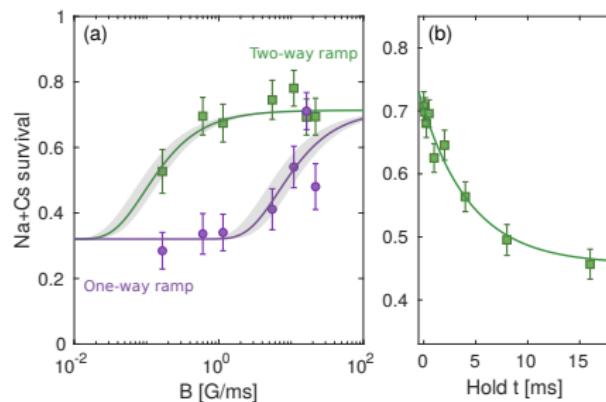


Weakly-Bound
Molecule

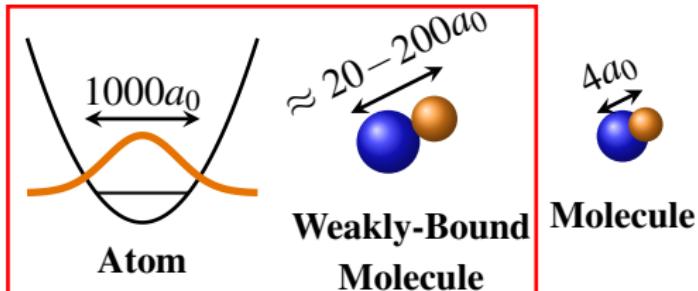
Molecule



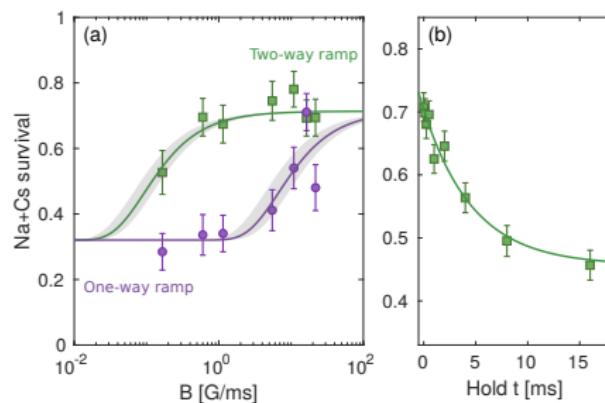
Feshbach molecule



PRL. 124, 253401 (2020)

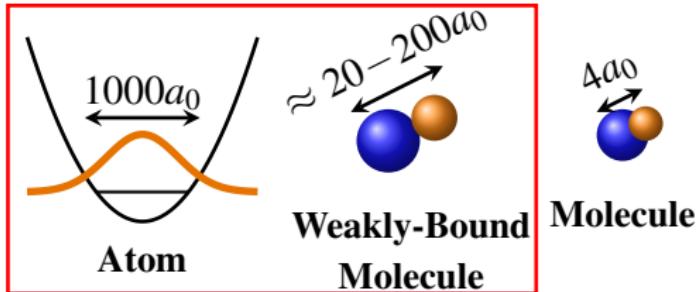


Feshbach molecule



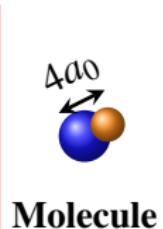
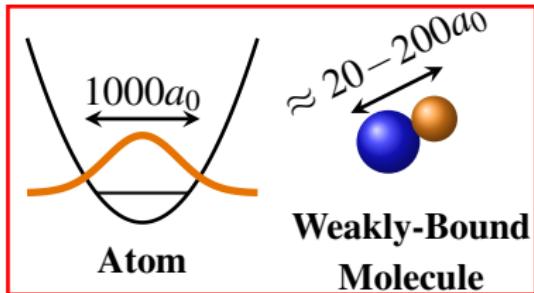
- Requires Feshbach resonance
- Usually large magnetic field

PRL. 124, 253401 (2020)



Optical transfer

- More general
- Faster

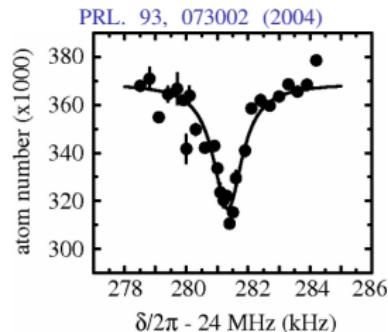


Optical transfer

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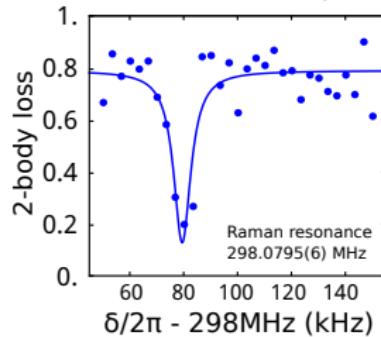
Previous results

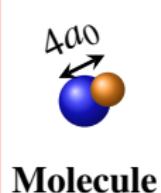
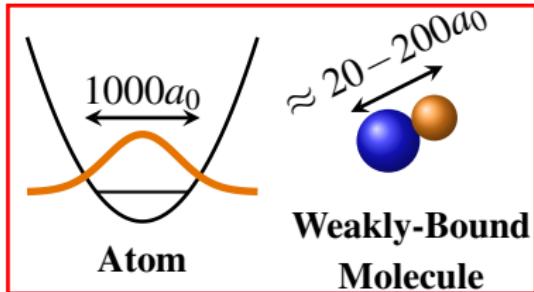
Rb₂ Science 287, 1016 (2000)



Sr₂ PRL. 109, 115302 (2012)

NaCs Y. Yu et al. PRX. 9, 021039 (2019)





Optical transfer

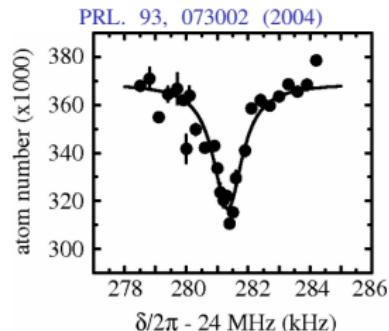
- More general
- Faster

Limitations so far

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

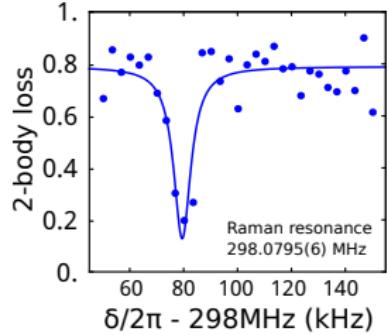
Previous results

Rb_2 Science 287, 1016 (2000)

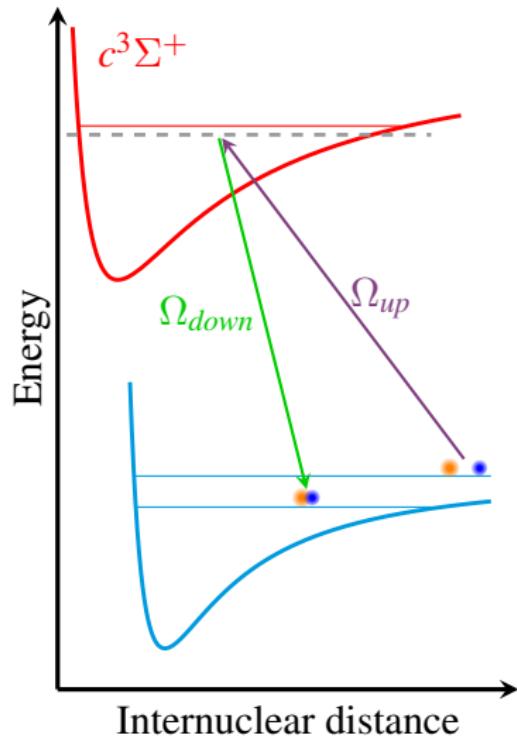


Sr_2 PRL. 109, 115302 (2012)

NaCs Y. Yu et al. PRX. 9, 021039 (2019)



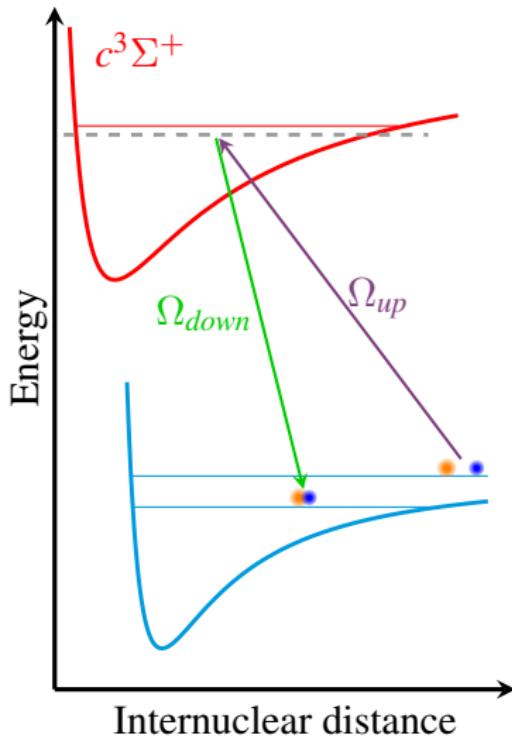
Raman transfer



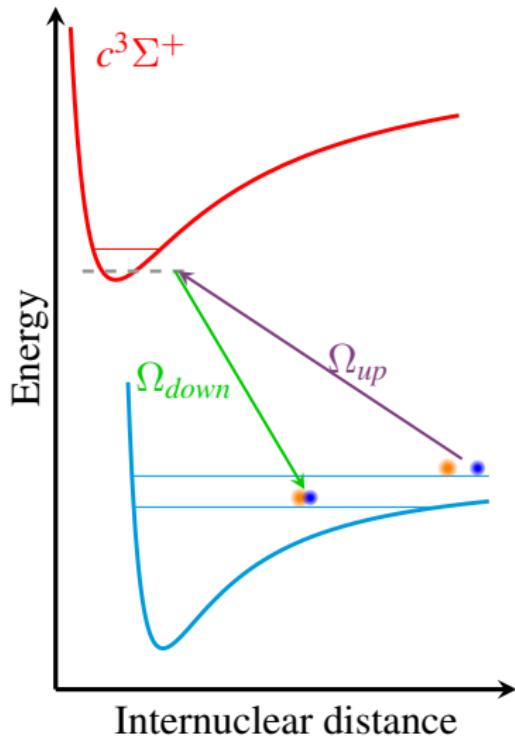
Raman transfer

Near threshold states

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



Raman transfer



Near threshold states

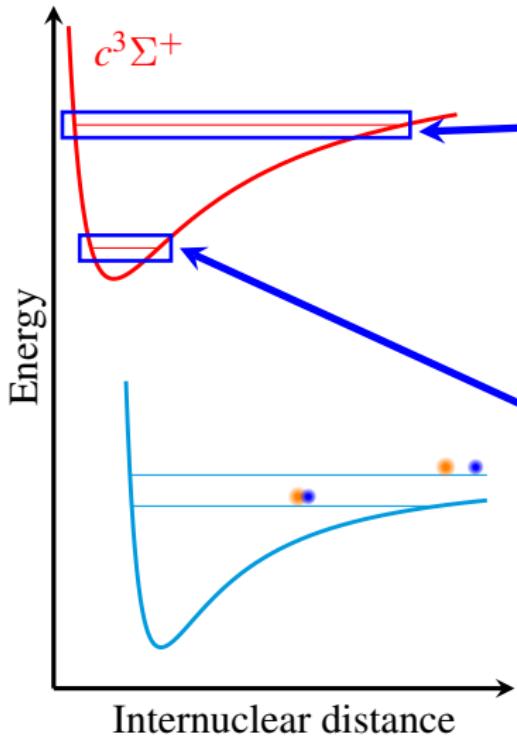
- Stronger coupling (Ω_{up} and Ω_{down})
- Closely spaced
- Fast scattering

Deeply bound states

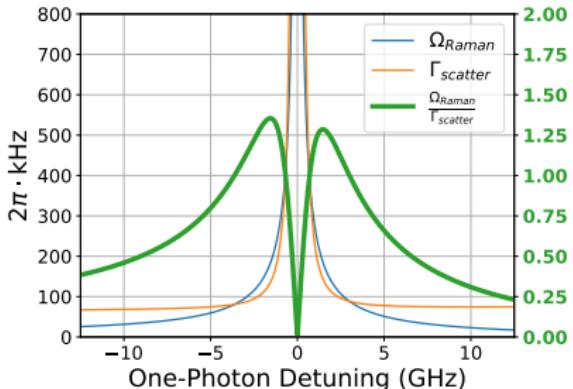
- Weaker coupling
- Sparsely spaced
- Allow larger detuning
- Slower scattering

arXiv:1701.03121(2017)

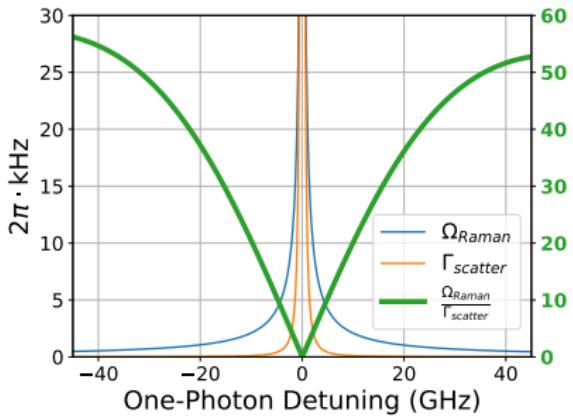
Raman transfer



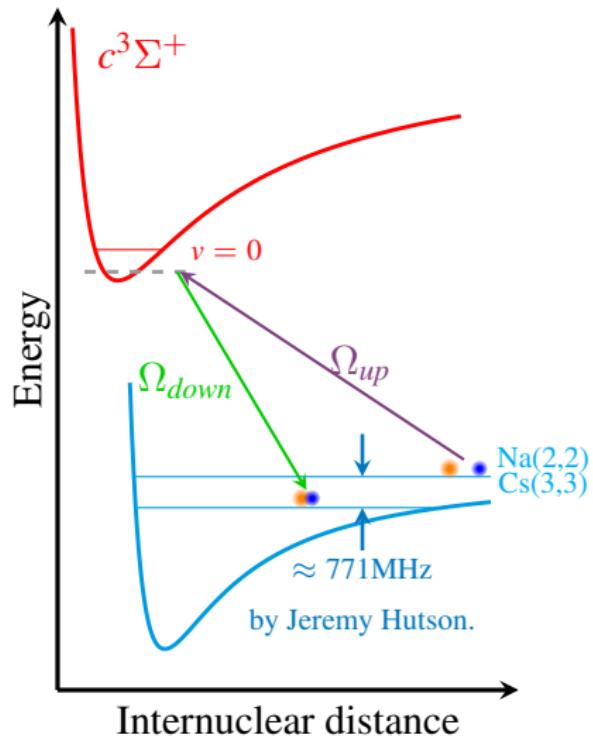
Near threshold states



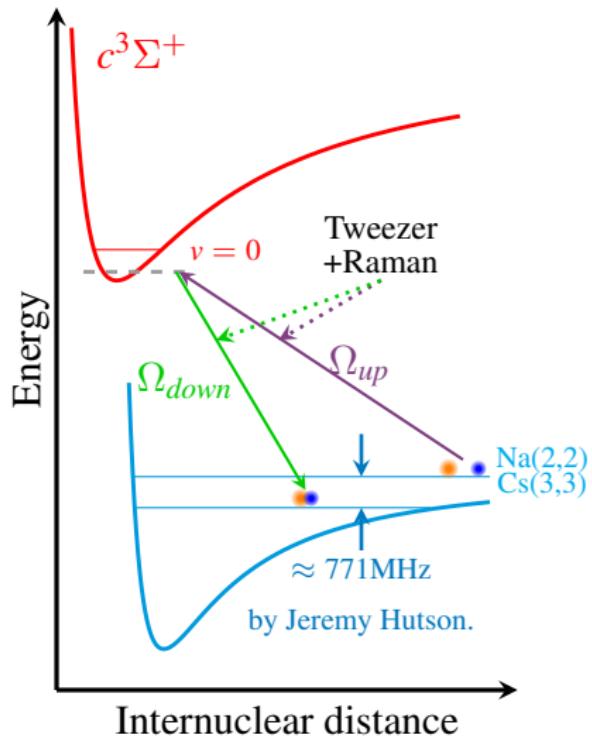
Deeply bound states



Experiment



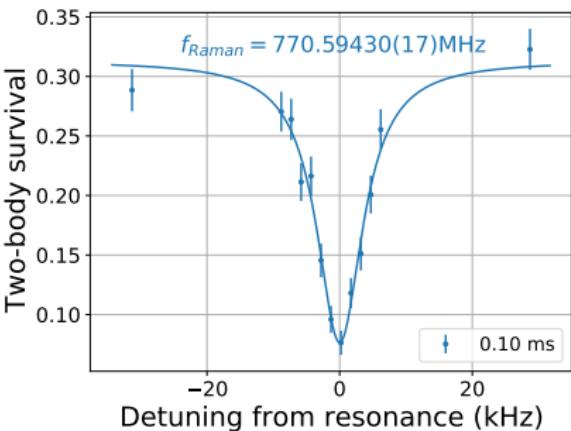
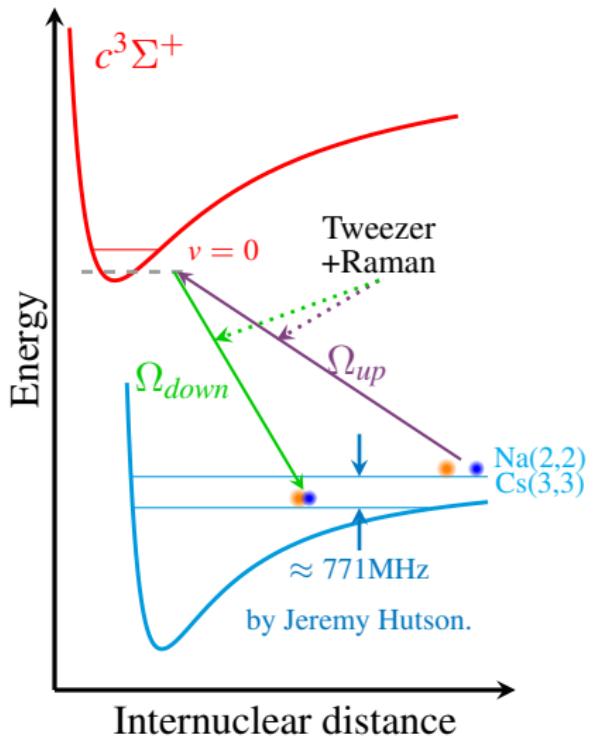
Experiment



Tweezer as Raman beam

- Higher Raman Rabi frequency
- Lower scattering from other sources

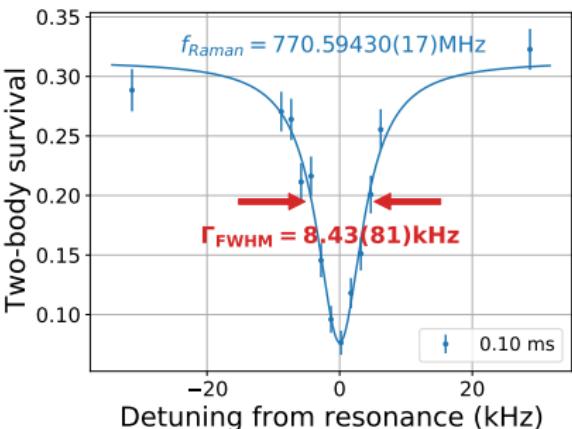
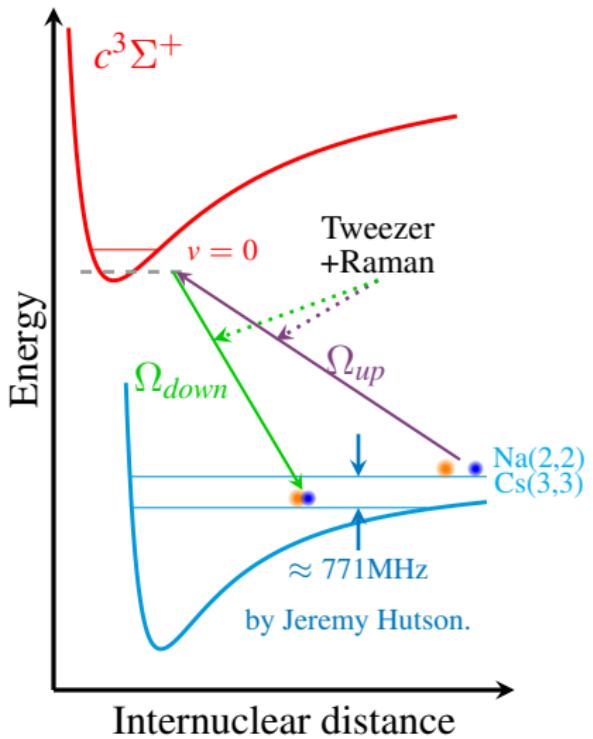
Experiment



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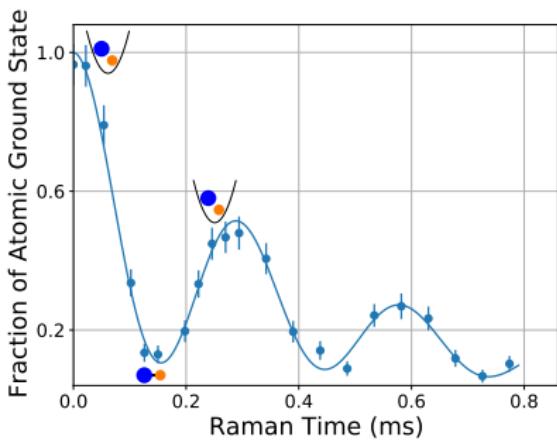
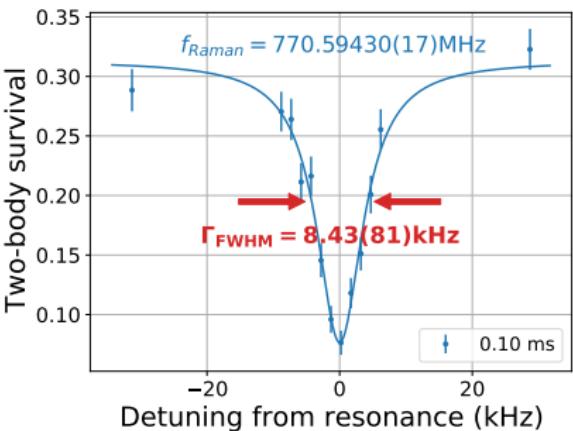
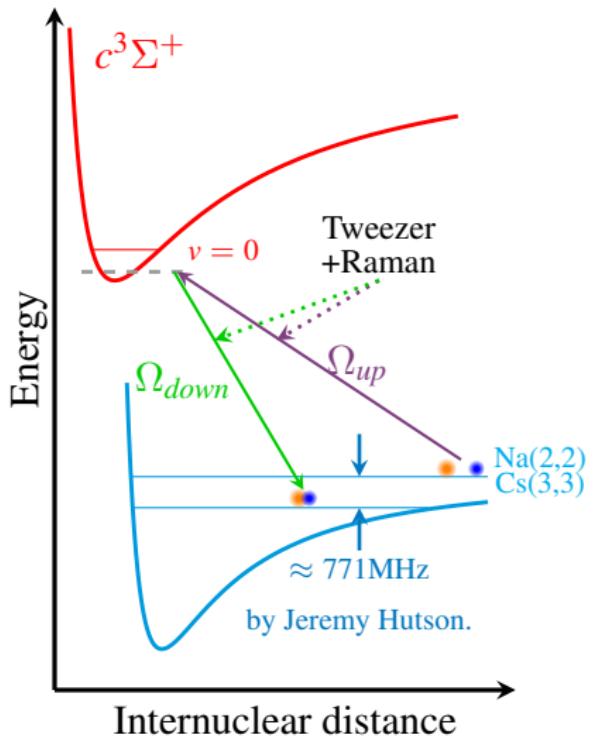
Experiment



Tweezer as Raman beam

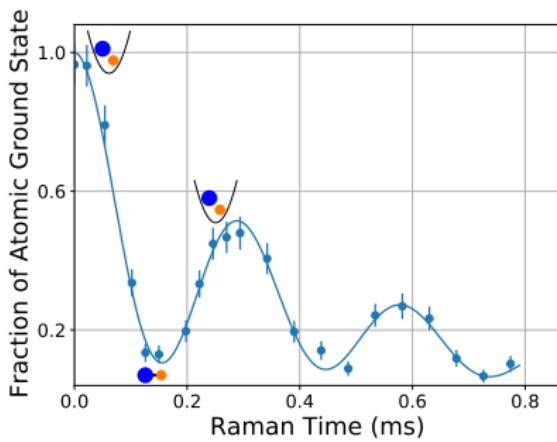
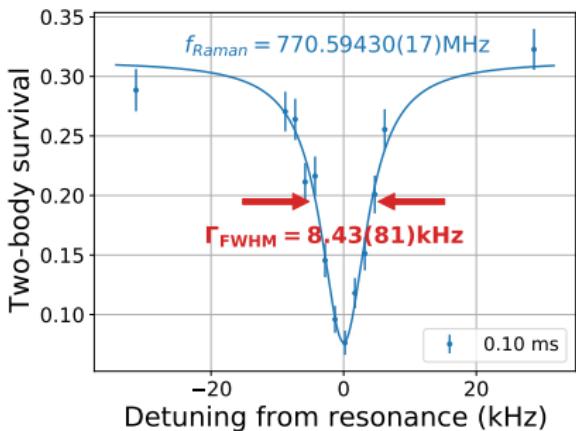
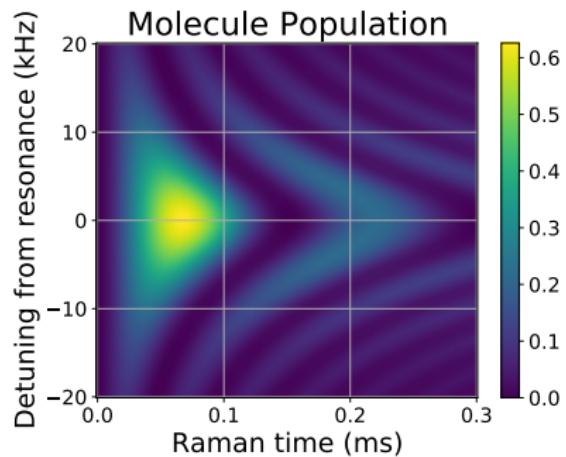
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Experiment



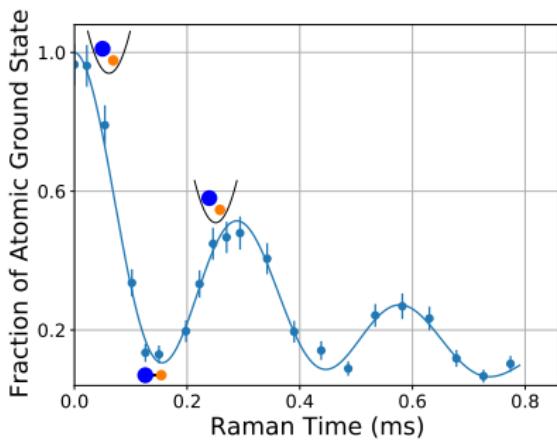
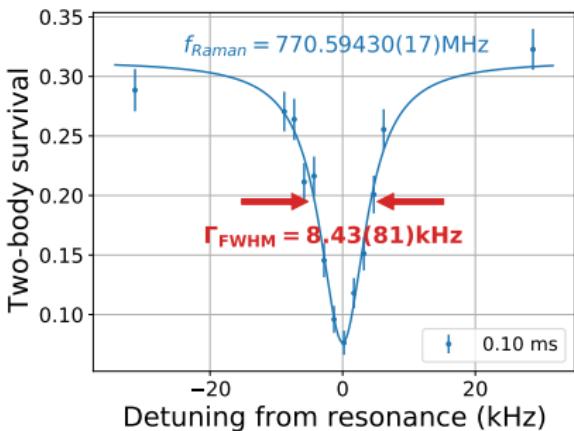
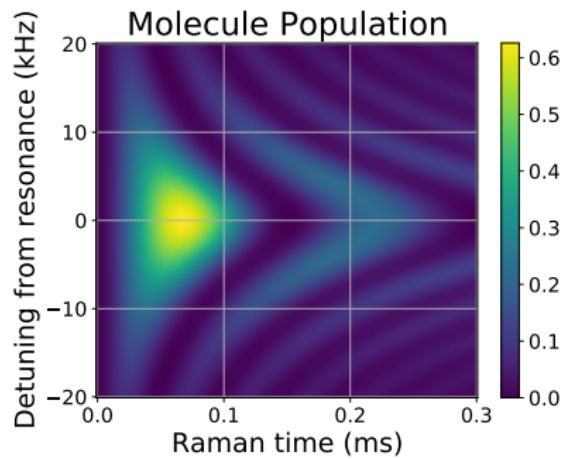
Experiment

- Transferred 63% of ground state atom to molecule.
- Single molecule spin state
- > 50% of molecule in motional ground state.
- Improving signal



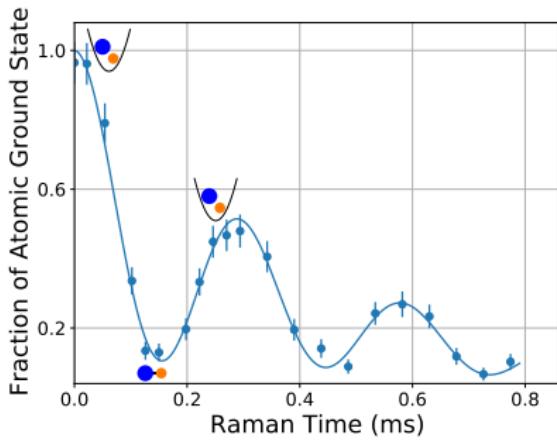
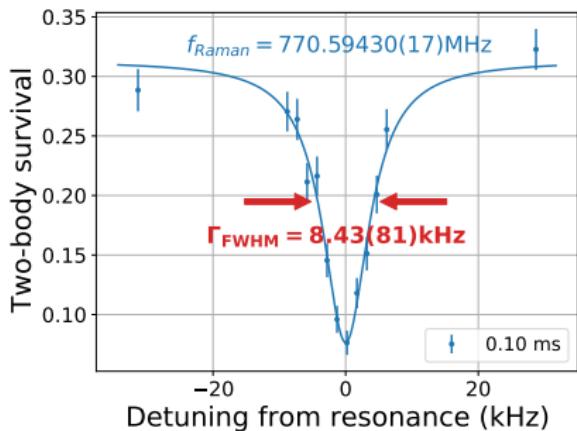
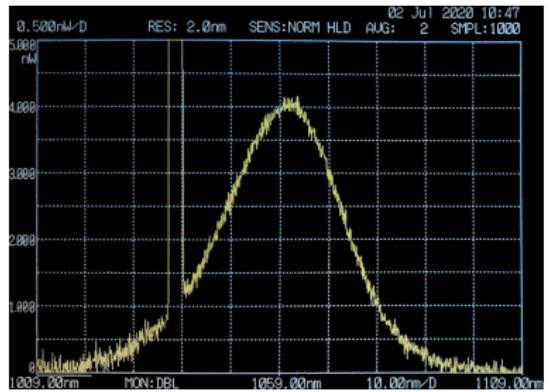
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Conclusion and outlook

- New quantum platform based on ultracold molecules in tweezers
- Full quantum control of atoms in optical tweezers
- Measured interaction between single atoms
- Coherent all-optical creation of single molecule
- Working towards fully controlled, strongly interacting tweezer array

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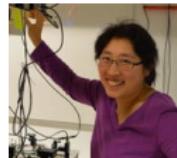
Conclusion and outlook

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- Coherent all-optical creation of single molecule
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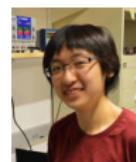
Experiment



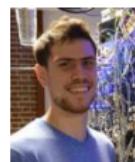
Kang-Kuen Ni



Kenneth
Wang



Jessie
Zhang



Lewis
Picard



William
Cairncross



Lee Liu
Postdoc @JILA



Jonathan Hood
Asstn Prof @Purdue



Nick Hutzler
Asstn Prof @Caltech

Theory



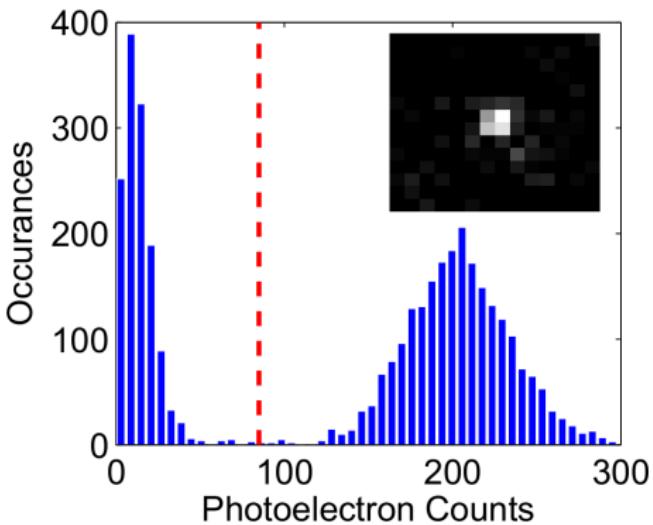
Jeremy Hutson

Single Atom in Tweezer

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

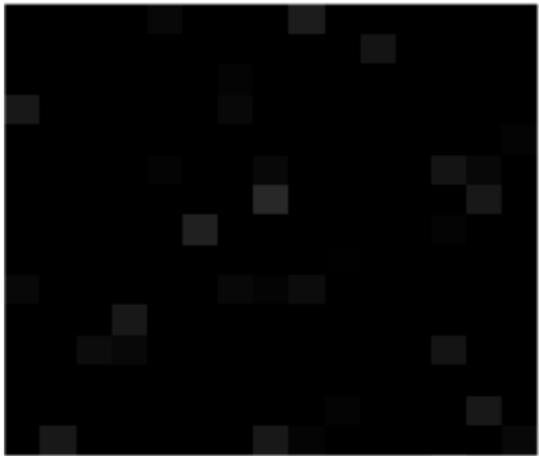
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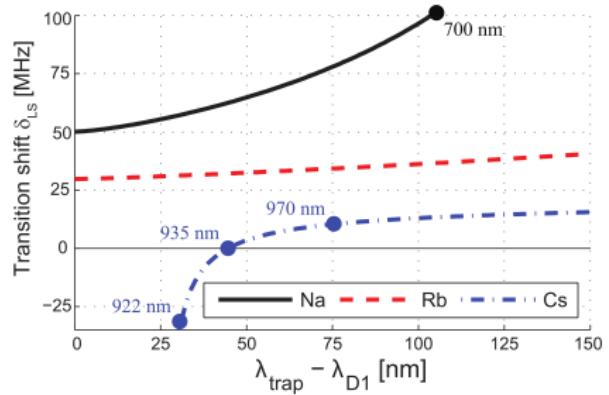
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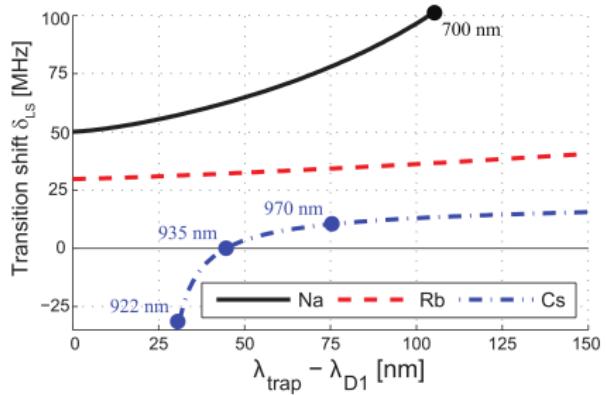
Issues with Na

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

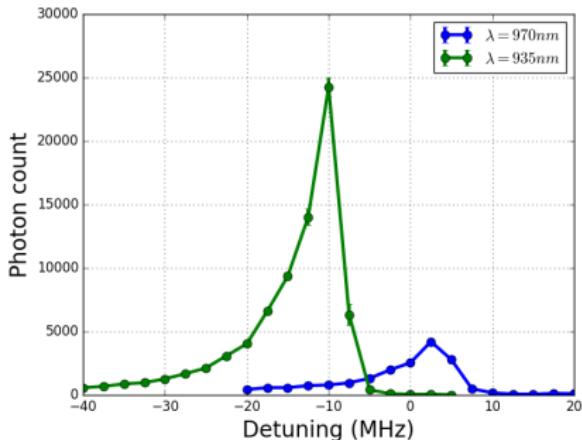
Real Issue with Na: Light Shift



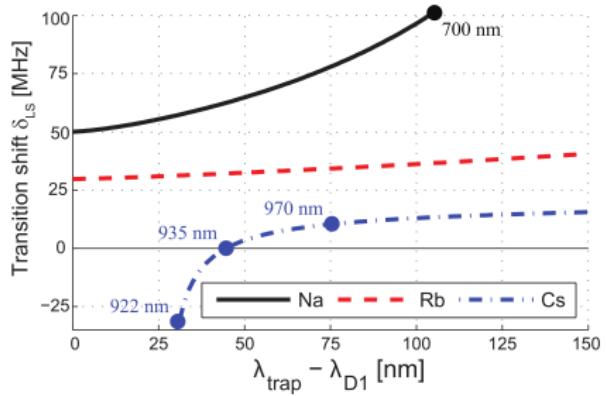
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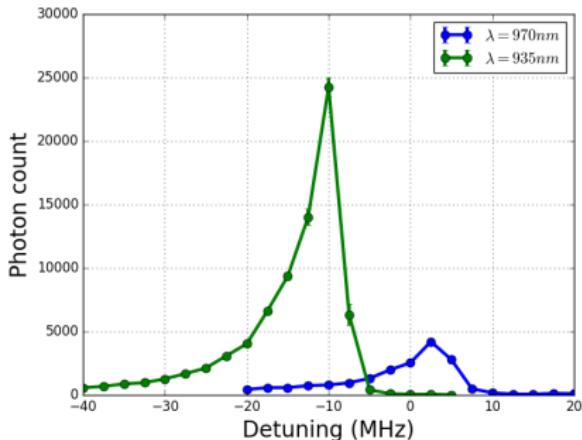
Cs single atom imaging



Real Issue with Na: Light Shift



Cs single atom imaging



- Low imaging signal
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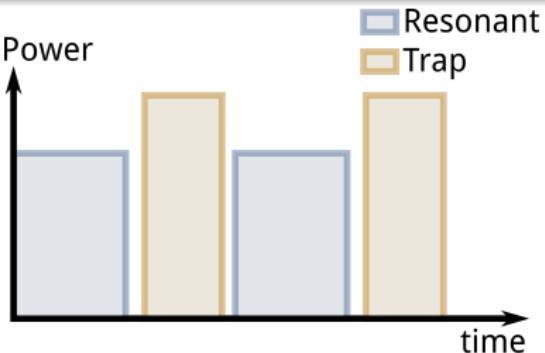
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Trap modulation

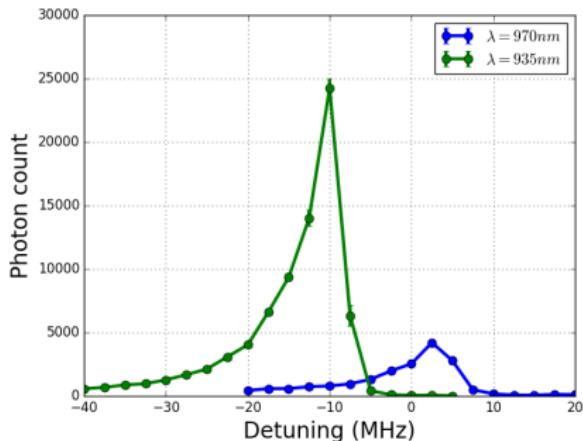
Alternate between trap and resonant (cooling and imaging) light at 2.5 MHz

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

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



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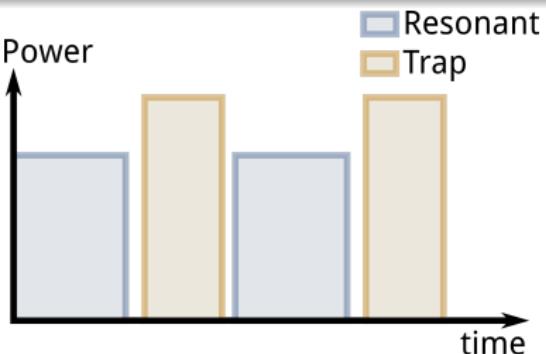
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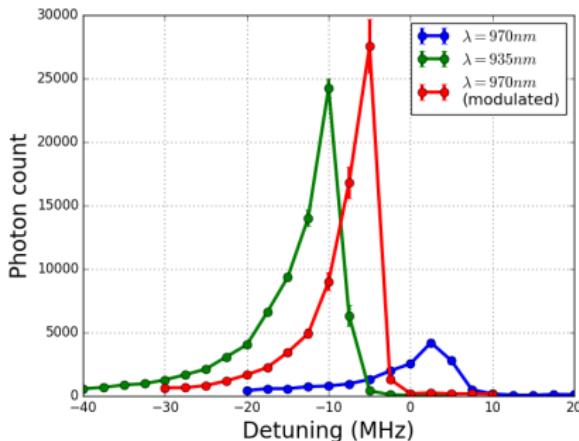
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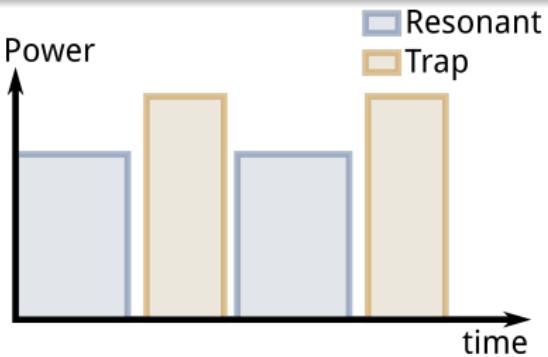
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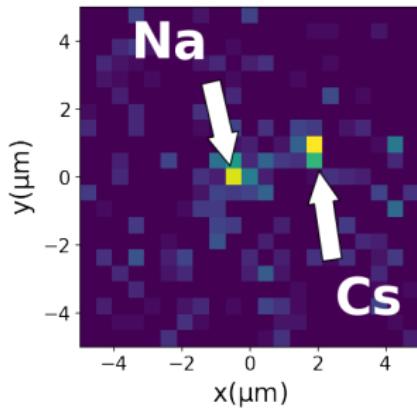
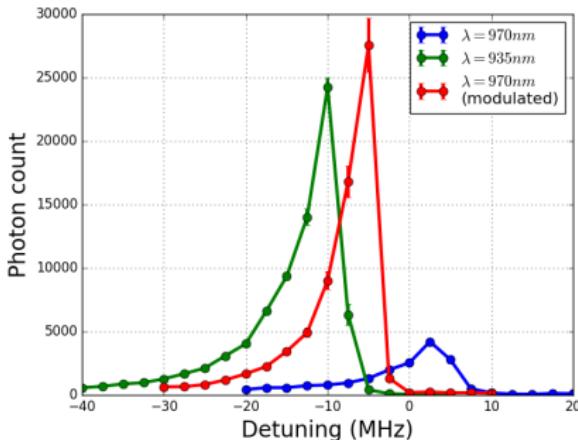
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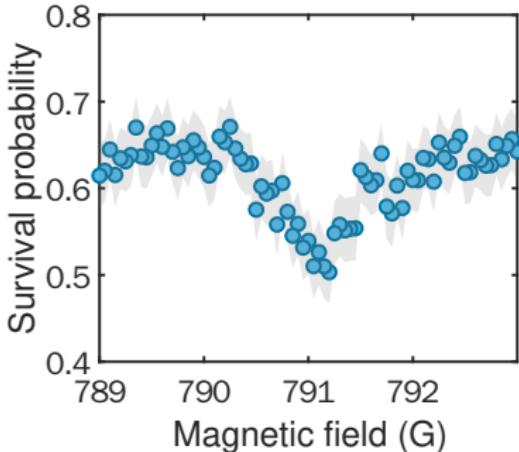
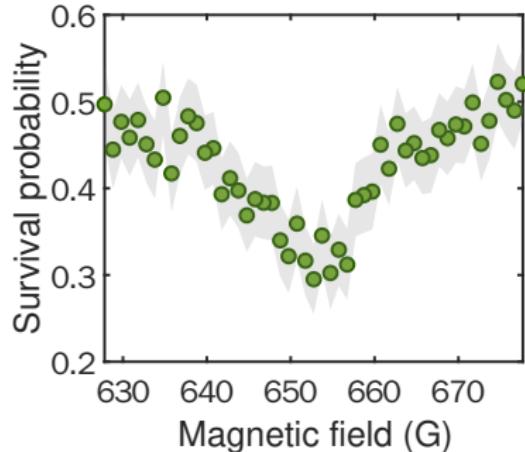
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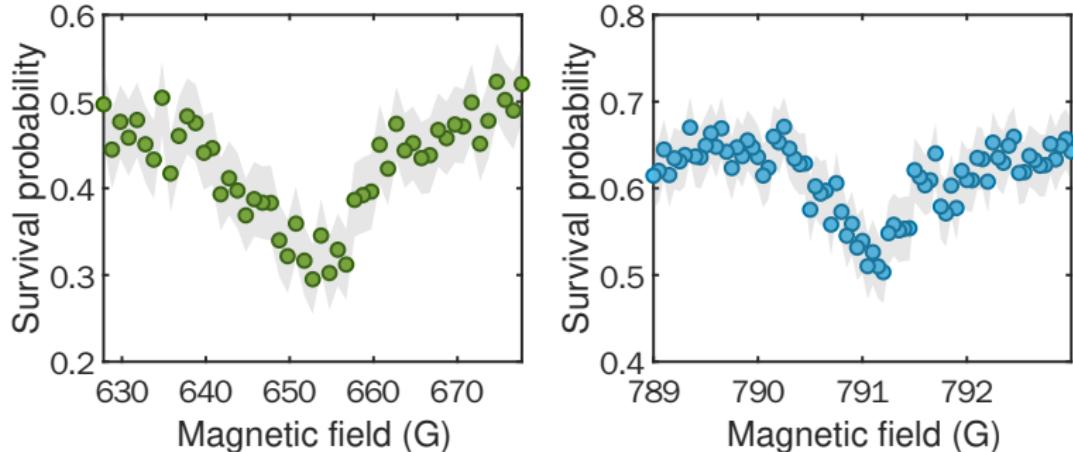
Na (1, -1) Cs (3, -3) Feshbach resonance



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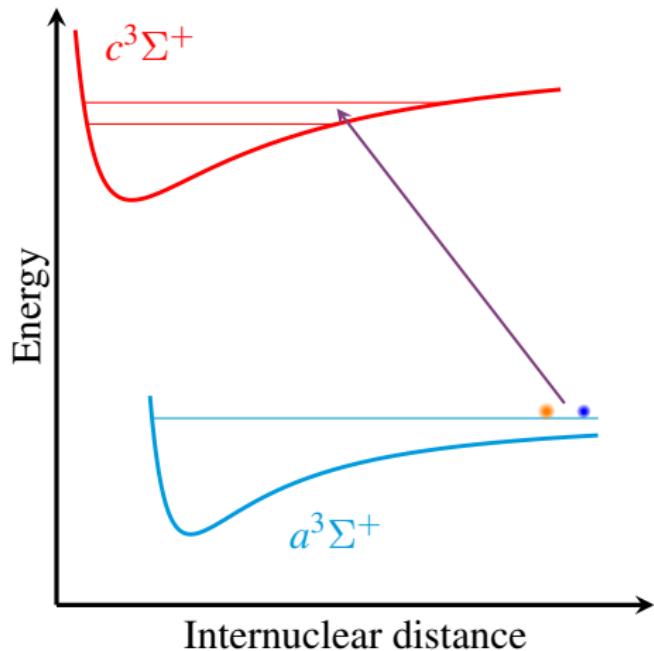
Na (1, -1) Cs (3, -3) Feshbach resonance



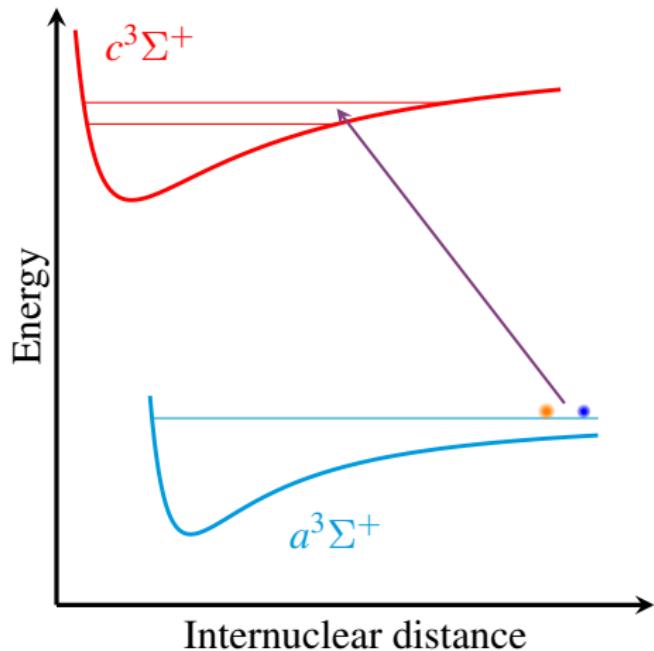
	<i>s</i> -wave	<i>p</i> -wave
Predicted (based on interaction shift) ¹	663 G	799 G
Measured	652(3) G	791.2(2) G

¹In collaboration with Bo Gao

Photoassociation (PA) Spectroscopy



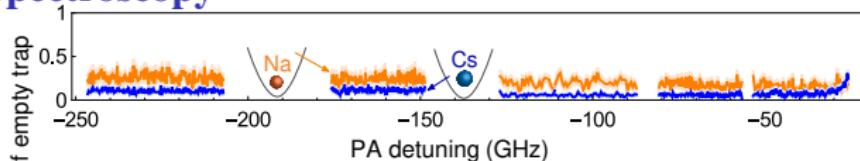
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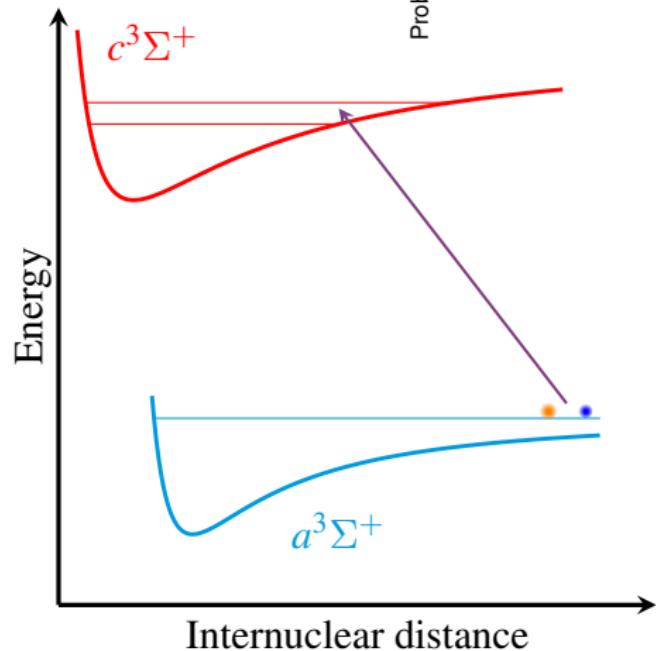
Single Atom PA

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

Photoassociation (PA) Spectroscopy



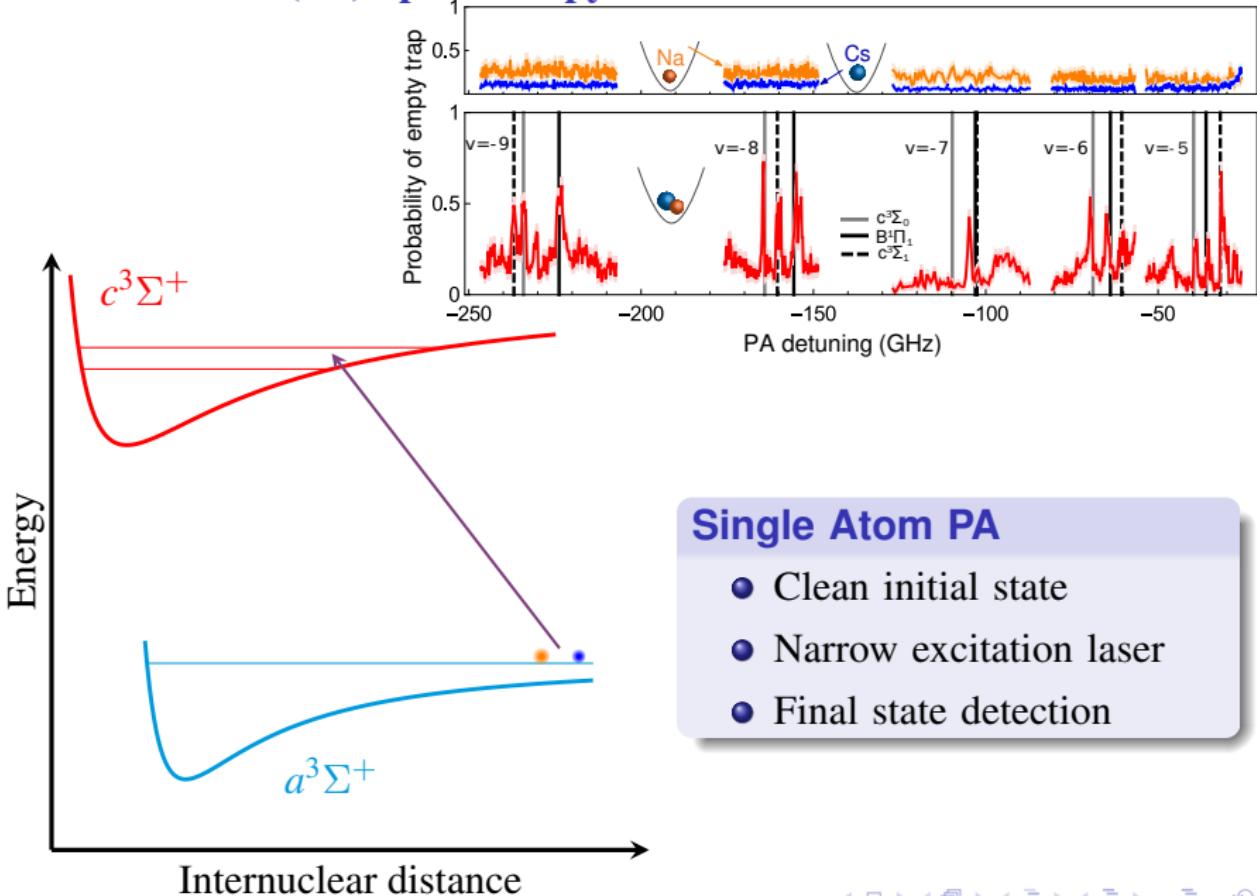
Probability of empty trap



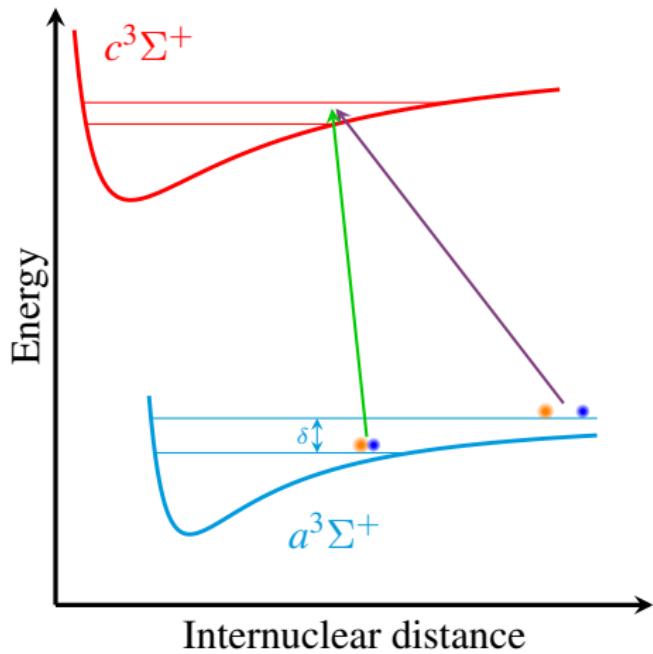
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Photoassociation (PA) Spectroscopy



Electromagnetically Induced Transparency (EIT) Spectroscopy



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