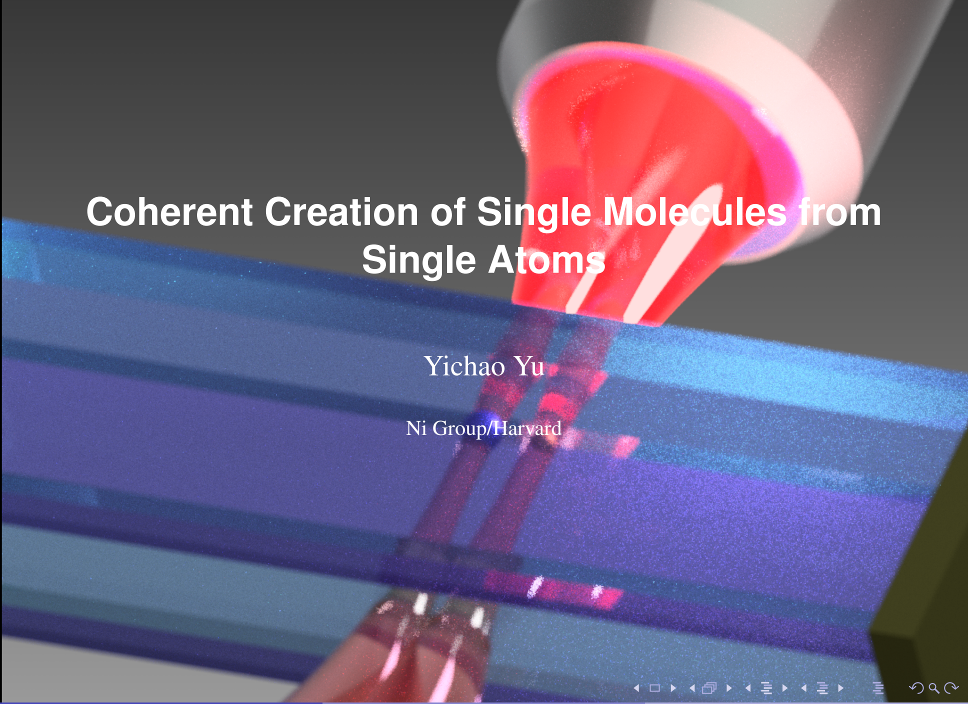
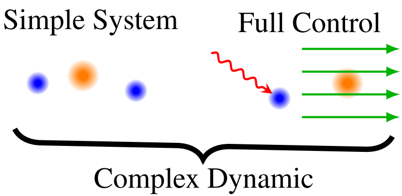


Coherent Creation of Single Molecules from Single Atoms

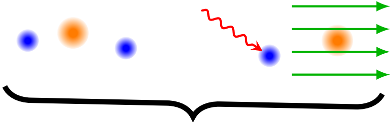
Yichao Yu

Ni Group/Harvard

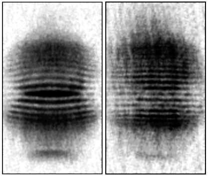

Simple System
Full Control
Complex Dynamic

Simple System

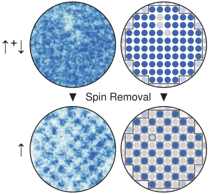
Full Control



Complex Dynamic



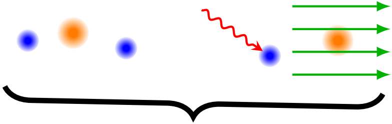
Ketterle et al.



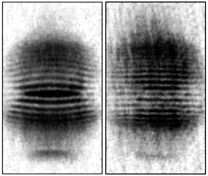
Greiner et al.

Simple System

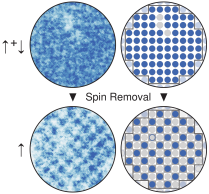
Full Control



Complex Dynamic

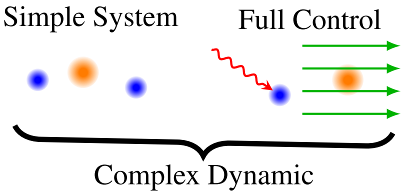


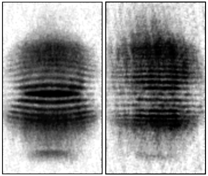
Ketterle et al.



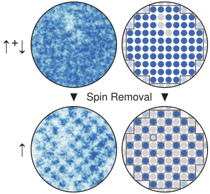
Greiner et al.

- × Simple internal structure
- × Weak interaction





Ketterle et al.



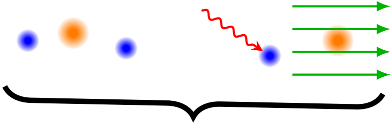
Greiner et al.

- ☐ Strong interaction
- ☐ Rich internal structure
- ☐ Long coherence time
- ☐ Fully controllable

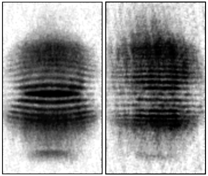
- × Simple internal structure
- × Weak interaction

Simple System

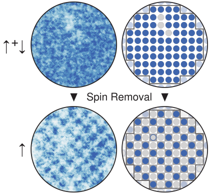
Full Control



Complex Dynamic



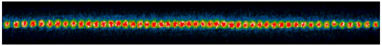
Ketterle et al.



Greiner et al.

- × Simple internal structure
- × Weak interaction

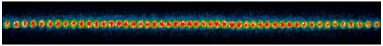
- ☐ Strong interaction
- ☐ Rich internal structure
- ☐ Long coherence time
- ☐ Fully controllable



Ions (Monroe et al.)

Rydberg Atoms (Lukin et al.)

- ☐ **Strong interaction**
- ☐ Rich internal structure
- ☐ Long coherence time
- ☐ **Fully controllable**



Ions (Monroe et al.)

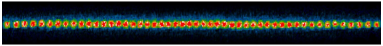
Rydberg Atoms (Lukin et al.)

✓ **Strong interaction** (kHz)

☐ Rich internal structure

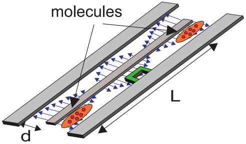
☐ Long coherence time

☐ **Fully controllable**



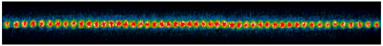
Ions (Monroe et al.)

Rydberg Atoms (Lukin et al.)



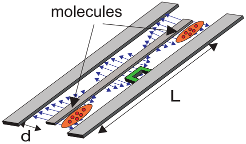
Dipolar Molecule (PRL. 97, 33003 (2006))

- ✓ **Strong interaction** (kHz)
- □ Rich internal structure
- ✓ Long coherence time
- □ **Fully controllable**



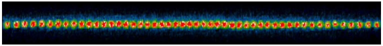
Ions (Monroe et al.)

Rydberg Atoms (Lukin et al.)



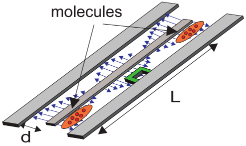
Dipolar Molecule (PRL. 97, 33003 (2006))

- ✓ **Strong interaction** (kHz)
- ✓ Rich internal structure
- ✓ Long coherence time
- ☐ **Fully controllable**



Ions (Monroe et al.)

Rydberg Atoms (Lukin et al.)



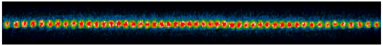
Dipolar Molecule (PRL. 97, 33003 (2006))

✓ **Strong interaction (kHz)**

✓ Rich internal structure

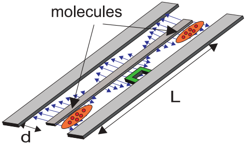
✓ Long coherence time

✓ **Fully controllable**



Ions (Monroe et al.)

Rydberg Atoms (Lukin et al.)



Dipolar Molecule (PRL. 97, 33003 (2006))

Optical tweezers

- Single site resolution
- ...

✓ **Strong interaction** (kHz)

✓ Rich internal structure

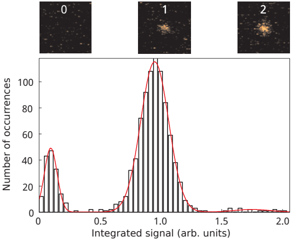
✓ Long coherence time

✓ **Fully controllable**

Optical tweezers

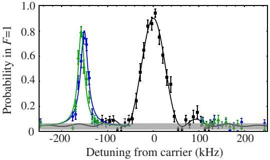
- Single site resolution
- . . .

Loading



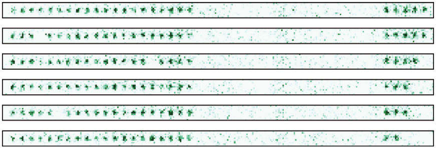
Nat. Phys. 6, 951 (2010)

Cooling



PRX. 2, 041014 (2012)

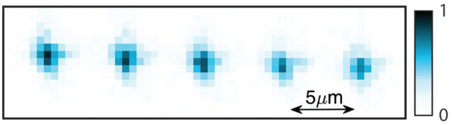
Rearranging



Science 354, 1024 (2016)

Ultracold molecules in tweezers

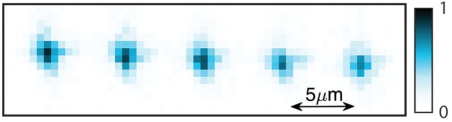
Direct cooling



Science 365, 1156 (2019)

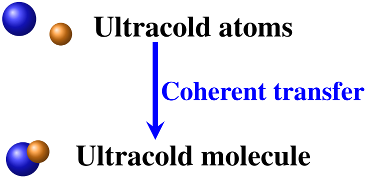
Ultracold molecules in tweezers

Direct cooling



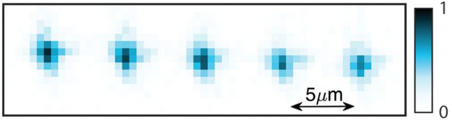
Science 365, 1156 (2019)

Assembly



Ultracold molecules in tweezers

Direct cooling



Science 365, 1156 (2019)

Assembly

Challenges

- Temperature in tweezer
- Quantum control

Ultracold molecules in tweezers

Direct cooling

Science 365, 1156 (2019)

Assembly

Ultracold atoms

Coherent transfer

Ultracold molecule

Challenges

- Temperature in tweezer
- 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**

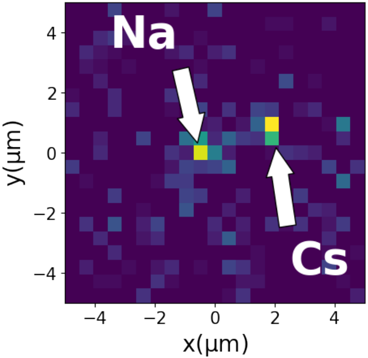
Experiment overview

NaCs molecule

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

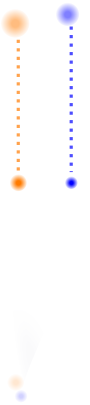
Experiment overview

Loading

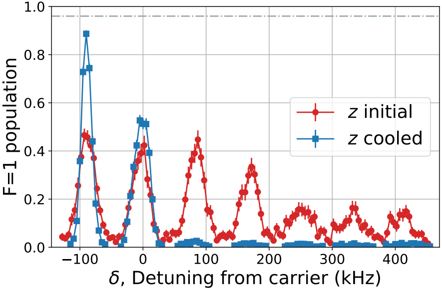


Loading probability per site: 60%
Post select on initial and final state.

Experiment overview



Cooling



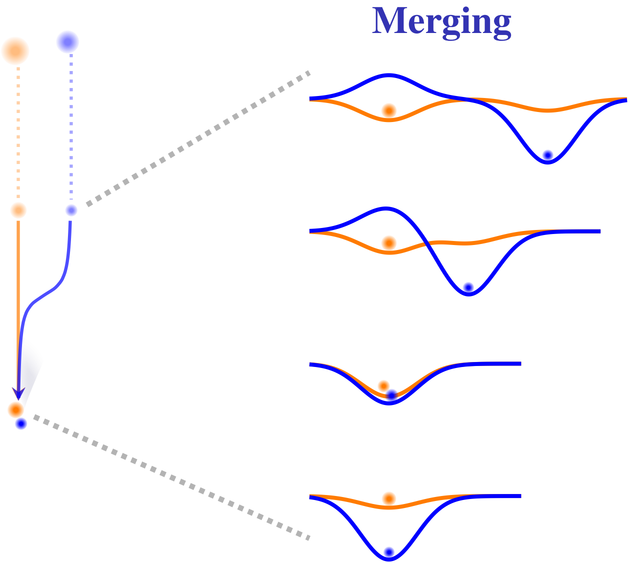
Cs: 96% ground state[1]

Na: 94% ground state[2]

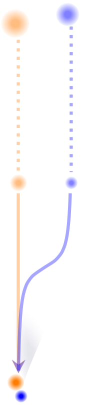
[1] **Y. Yu** et al. PRX 9, 021039 (2019)

[2] **Y. Yu** et al. PRA 97, 063423 (2018)

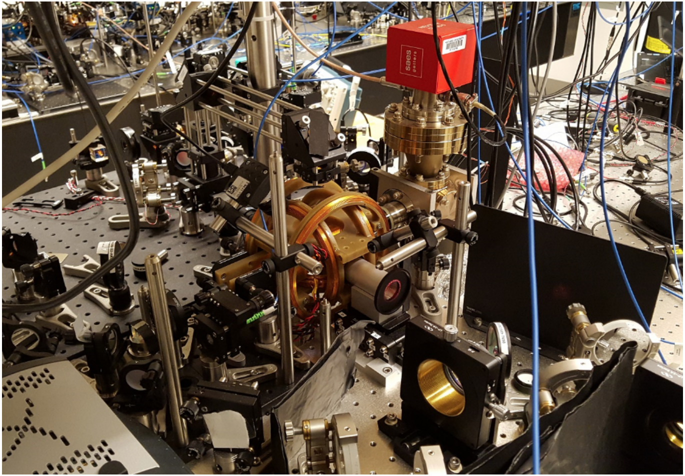
Experiment overview

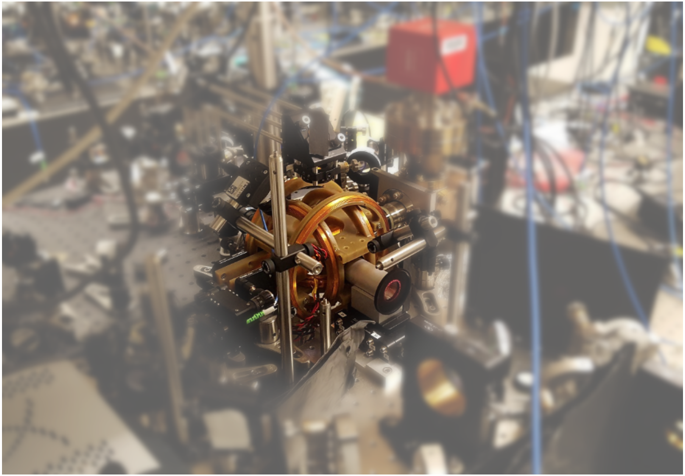


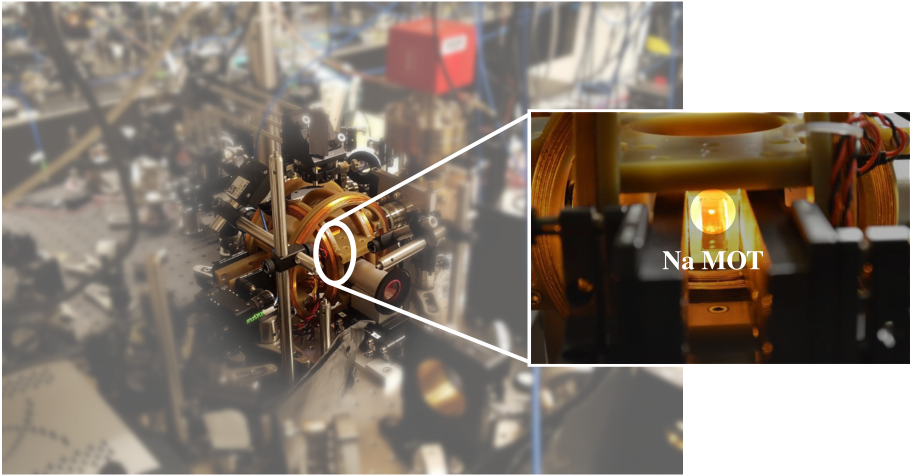
Experiment overview



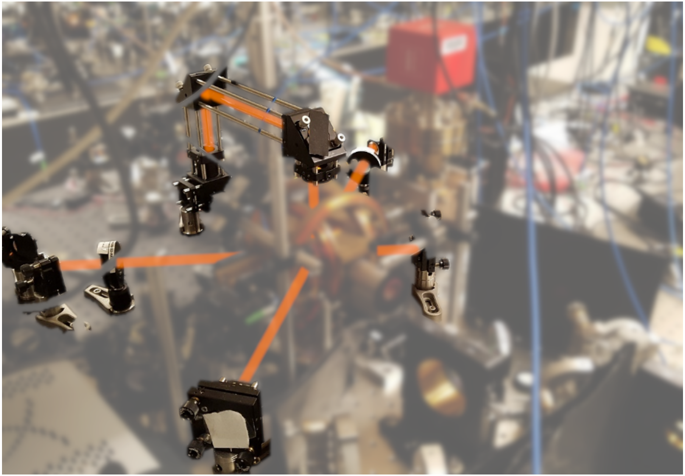
L. R. Liu, J. D. Hood, **Y. Yu** et al., Science 360, 6391 (2018)


saes
getters

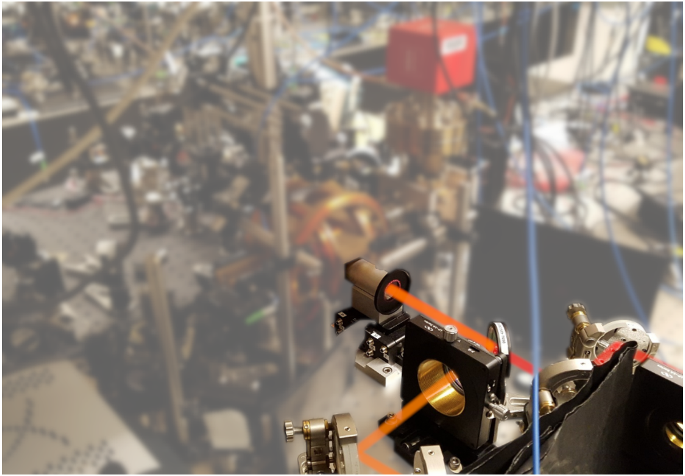



Na MOT

MOT beam path



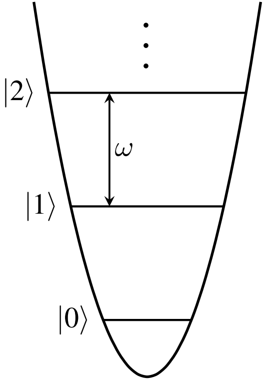
Tweezer and imaging beam path



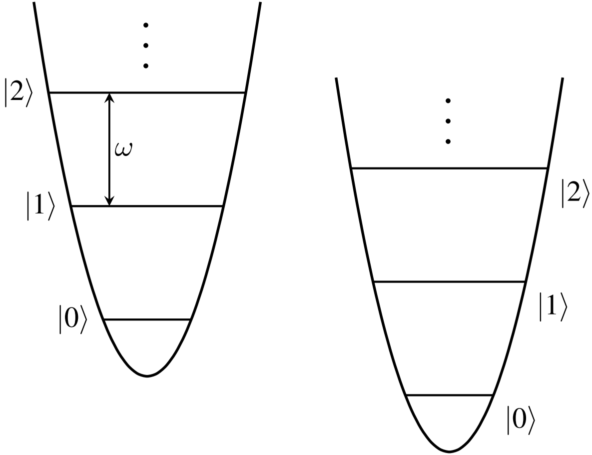
Outline

1. Experiment overview
2. **Atom state control**
   - Raman sideband cooling of Na atoms
3. Molecule creation
   - Atom-atom interaction
   - Coherent optical transfer
4. Conclusion

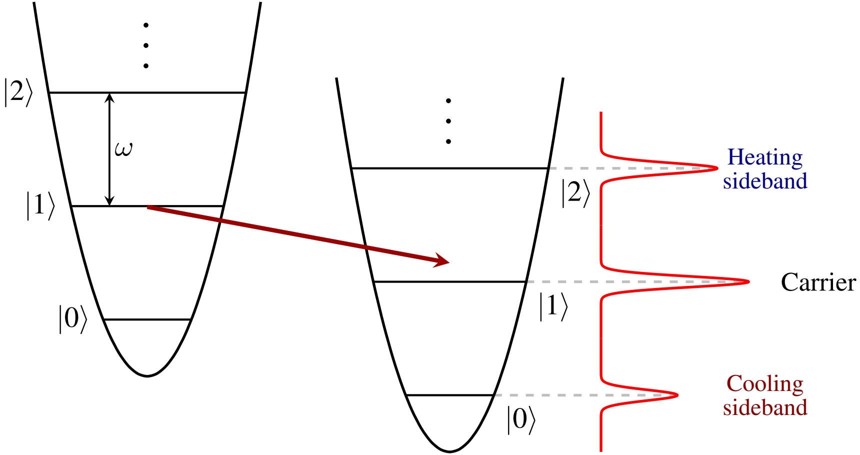
Raman sideband cooling



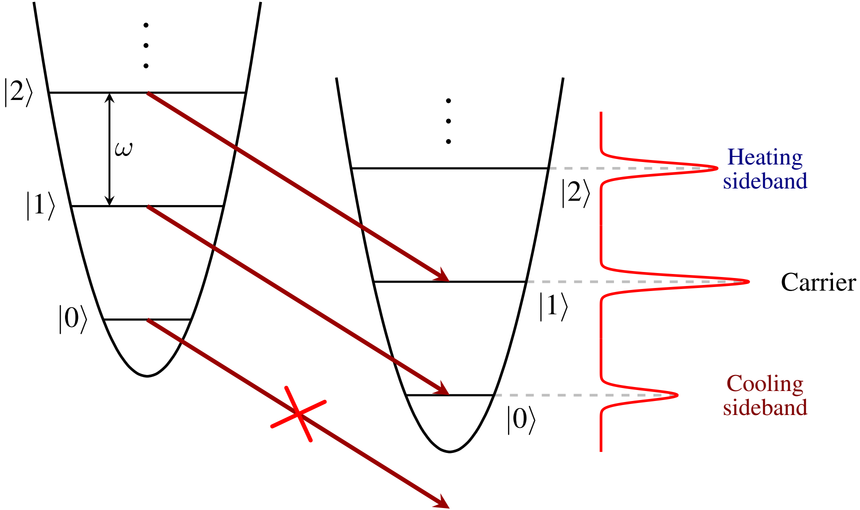
Raman sideband cooling



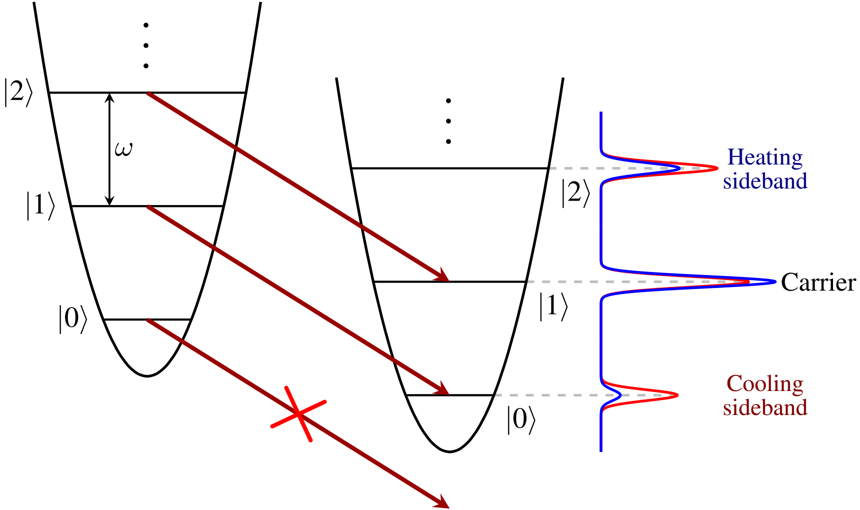
Raman sideband cooling



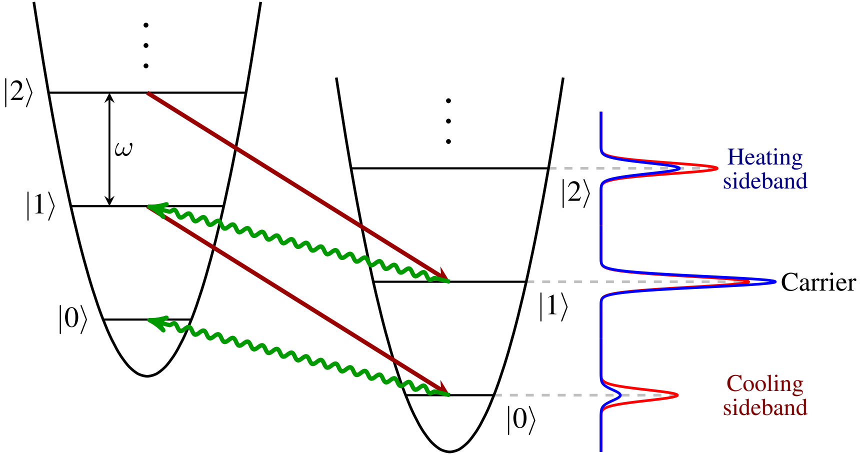
Raman sideband cooling



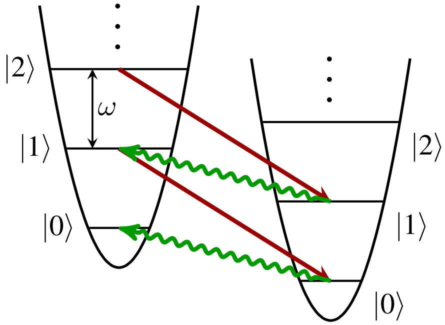
Raman sideband cooling



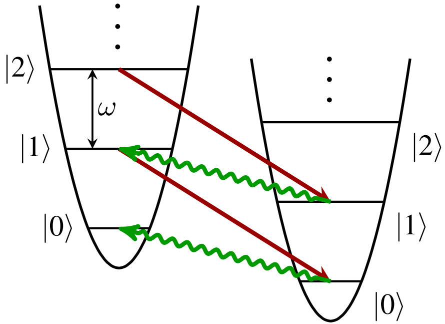
Raman sideband cooling



Raman sideband cooling



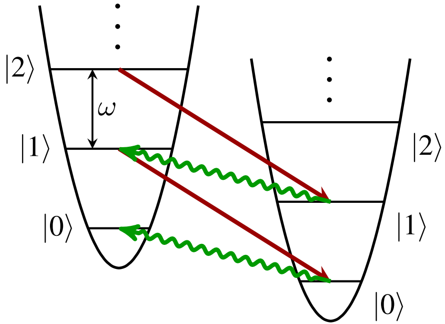
Raman sideband cooling



Lamb Dicke parameter

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

Raman sideband cooling



Lamb Dicke parameter

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

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

- Motional state branching
- Coupling "dead zone"

Raman sideband cooling

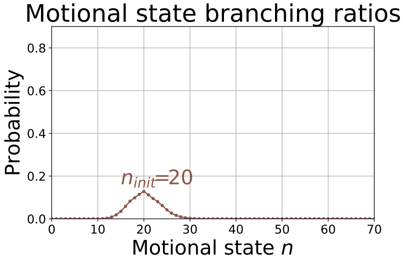
Lamb Dicke parameter

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

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

- Motional state branching
- Coupling "dead zone"

Raman sideband cooling



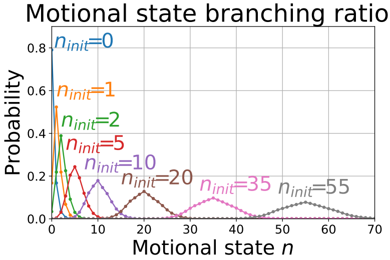
Lamb Dicke parameter

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

$$\eta^{OP}_{Na} = 0.55$$

- Motional state branching
- Coupling "dead zone"

Raman sideband cooling



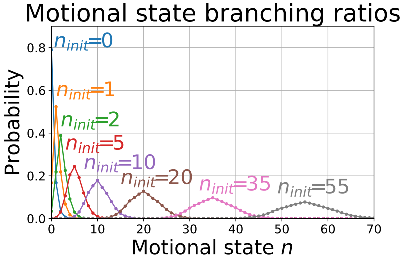
Lamb Dicke parameter

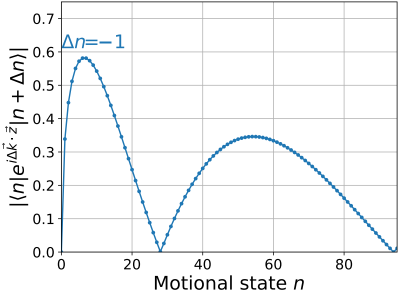
$$\eta \equiv k z_0 = \frac{2\pi z_0}{\lambda} = \sqrt{\frac{\omega_{\text{recoil}}}{\omega_{\text{trap}}}}$$

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

- Motional state branching
- Coupling “dead zone”

Raman sideband cooling





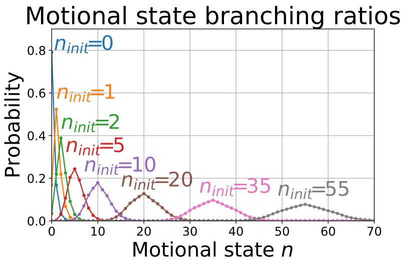
Lamb Dicke parameter

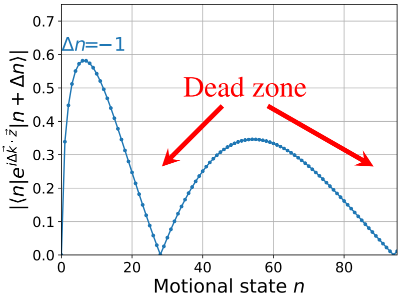
$$\eta \equiv kz_0 = \frac{2\pi z_0}{\lambda} = \sqrt{\frac{\omega_{\text{recoil}}}{\omega_{\text{trap}}}}$$

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

- Motional state branching
- Coupling "dead zone"

Raman sideband cooling





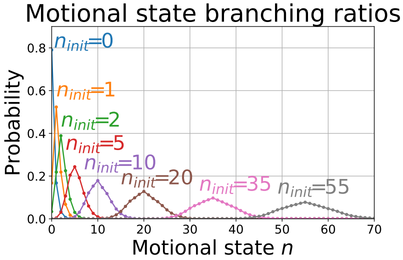
Lamb Dicke parameter

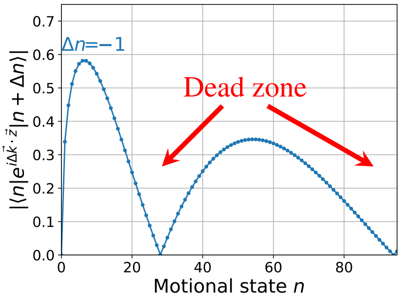
$$\eta \equiv kz_0 = \frac{2\pi z_0}{\lambda} = \sqrt{\frac{\omega_{\text{recoil}}}{\omega_{\text{trap}}}}$$

$$\eta^{OP}_{Na} = 0.55$$

- Motional state branching
- Coupling "dead zone"

Raman sideband cooling





Lamb Dicke parameter

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

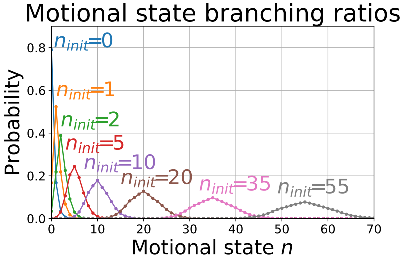
$$\eta^{OP}_{Na} = 0.55$$

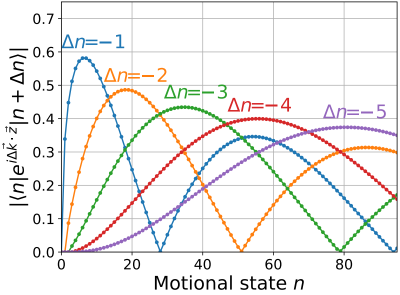
- Motional state branching
- Coupling “dead zone”

Solution

- Use higher order sidebands.
- Simulation-guided optimization.

Raman sideband cooling





Lamb Dicke parameter

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

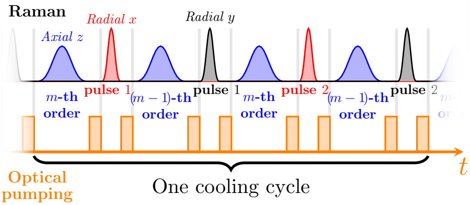
$$\eta^{OP}_{Na} = 0.55$$

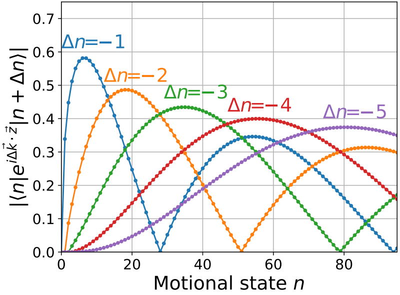
- Motional state branching
- Coupling “dead zone”

Solution

- Use higher order sidebands.
- Simulation-guided optimization.

Raman sideband cooling





Lamb Dicke parameter

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

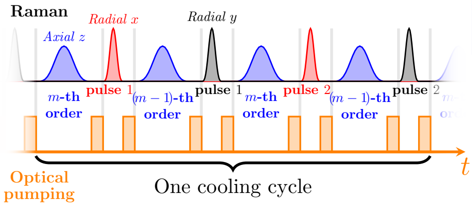
$$\eta_{Na}^{OP} = 0.55$$

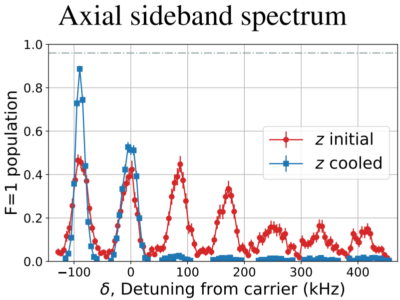
- Motional state branching
- Coupling "dead zone"

Solution

- Use higher order sidebands.
- Simulation-guided optimization.

Raman sideband cooling





Lamb Dicke parameter

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

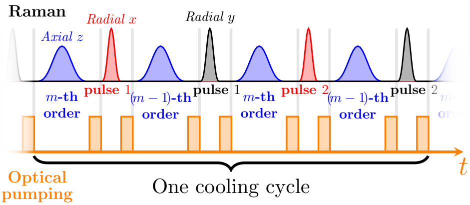
$$\eta_{Na}^{OP} = 0.55$$

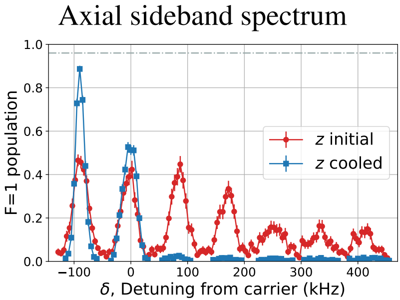
- Motional state branching
- Coupling "dead zone"

Solution

- Use higher order sidebands.
- Simulation-guided optimization.

Raman sideband cooling





Lamb Dicke parameter

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

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

- Motional state branching
- Coupling "dead zone"

Solution

- Use higher order sidebands.
- Simulation-guided optimization.

3D ground state: 93.5(7)%

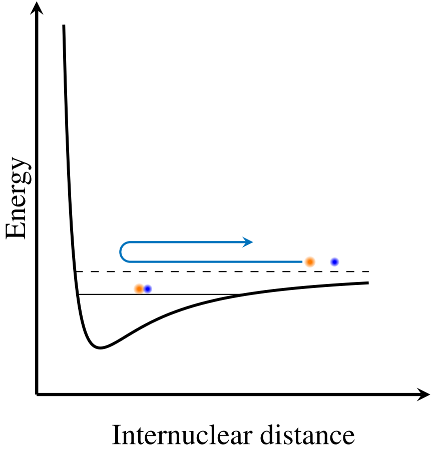
Outline

1. Experiment overview
2. Atom state control
   - Raman sideband cooling of Na atoms
3. **Molecule creation**
   - **Atom-atom interaction**
   - Coherent optical transfer
4. Conclusion

Scattering length a

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

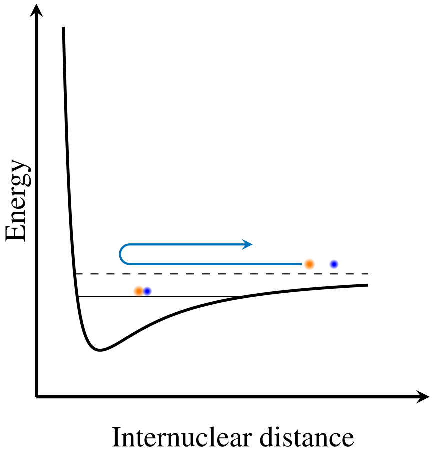
⋮



Scattering length a

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

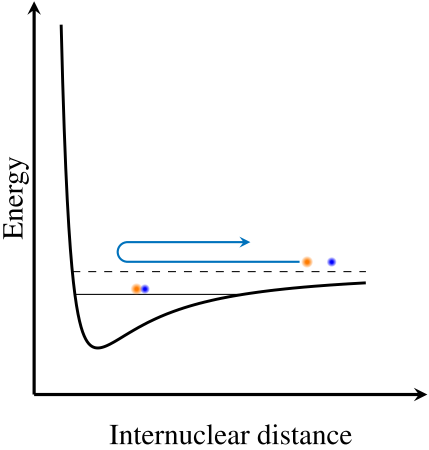
  ⋮



Scattering length a

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

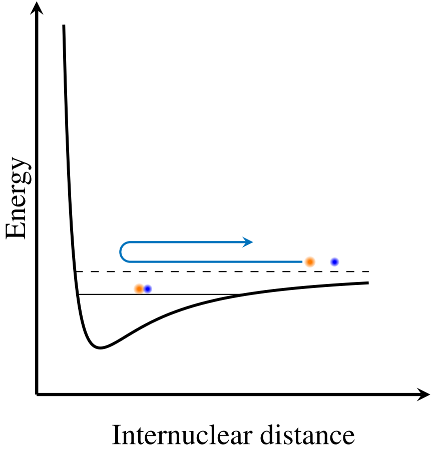
⋮



Scattering length a

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

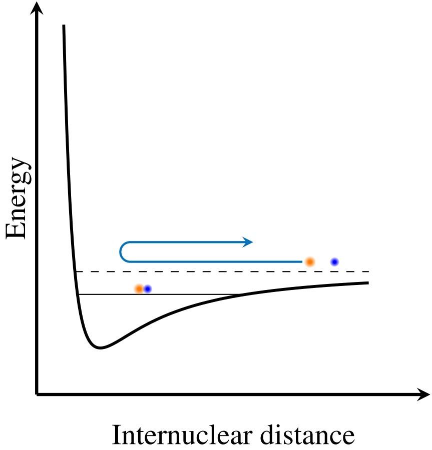
⋮



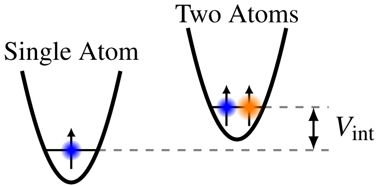
Scattering length a

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

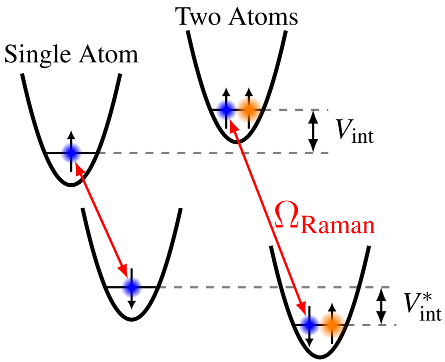
$\vdots$



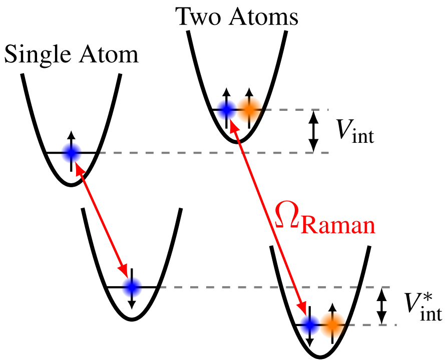
Interaction shift

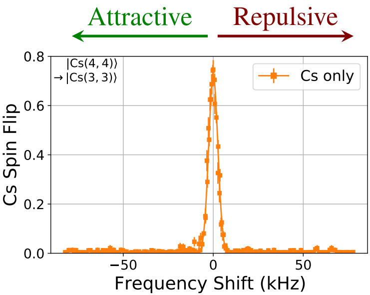


Interaction shift

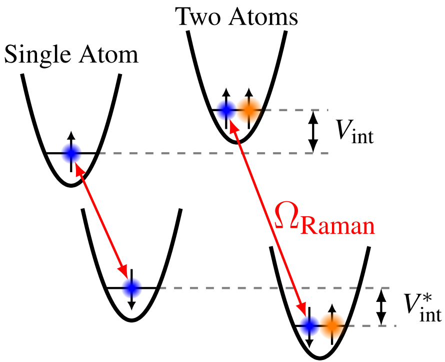


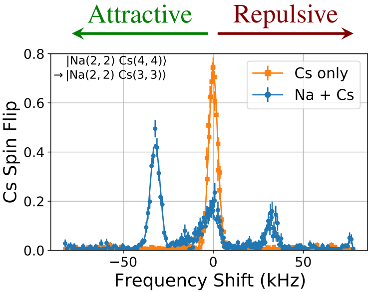
Interaction shift





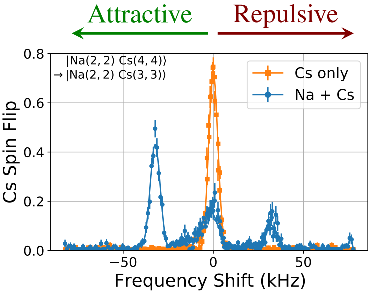
Interaction shift





Interaction shift

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



Interaction shift

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

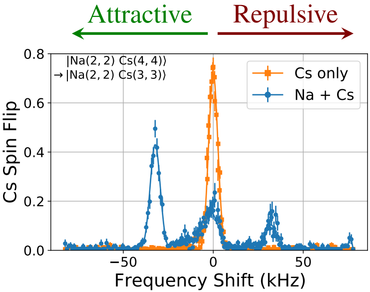
To center of mass
and relative coordinates

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

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

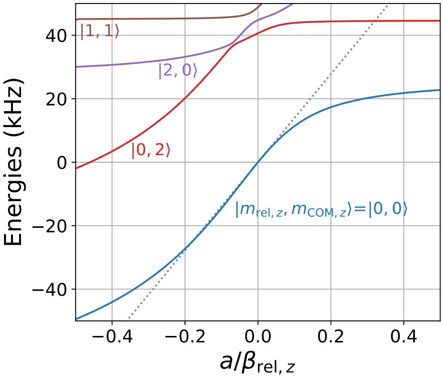
$$X_i = \frac{m_1 x_{1,i} + m_2 x_{2,i}}{m_1 + m_2} \qquad x_{R,i} = x_{1,i} - x_{2,i}$$

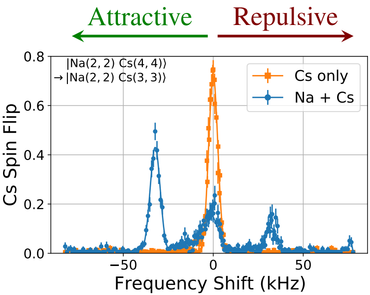
$$P_i = p_{1,i} + p_{2,i} \qquad p_{R,i} = \frac{m_2 p_{1,i} - m_1 p_{2,i}}{m_1 + m_2}$$



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

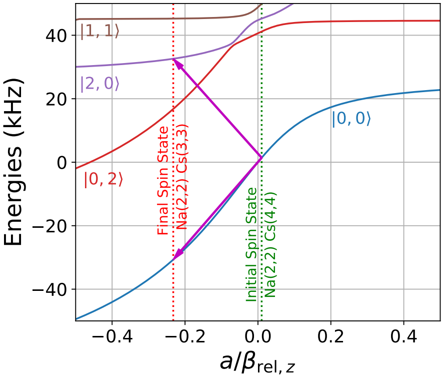
Interaction shift

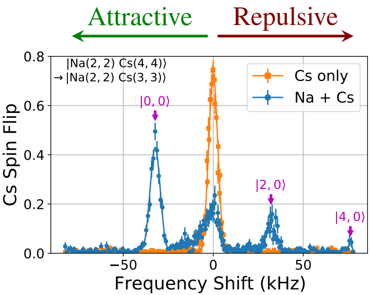




$$H = \overbrace{\sum_{i=x,y,z} \left(\frac{M\Omega_i^2 X_i^2}{2} + \frac{P_i^2}{2M}\right)}^{\text{Center of mass}} + \overbrace{\sum_{i=x,y,z} \left(\frac{\mu\omega_{R,i}^2 x_{R,i}^2}{2} + \frac{p_{R,i}^2}{2\mu}\right) + V_{int}(\vec{r}_R)}^{\text{Relative}} + \overbrace{\sum_{i=x,y,z} \mu(\omega_{1,i}^2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

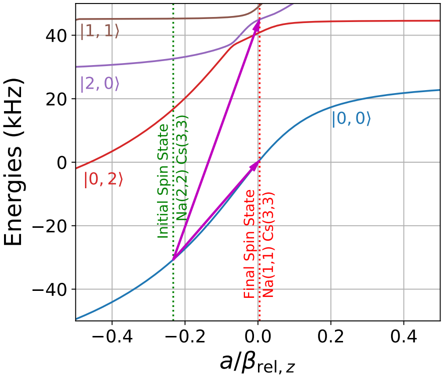
Interaction shift

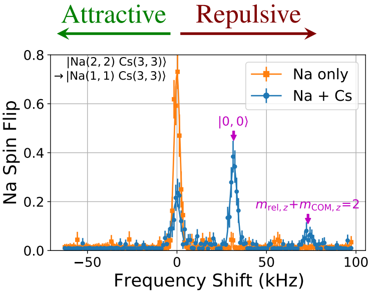




$$H = \overbrace{\sum_{i=x,y,z} \left(\frac{M\Omega_i^2 X_i^2}{2} + \frac{P_i^2}{2M}\right)}^{\text{Center of mass}} + \overbrace{\sum_{i=x,y,z} \left(\frac{\mu\omega_{R,i}^2 x_{R,i}^2}{2} + \frac{p_{R,i}^2}{2\mu}\right) + V_{int}(\vec{r}_R)}^{\text{Relative}} + \overbrace{\sum_{i=x,y,z} \mu(\omega_{1,i}^2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

Interaction shift



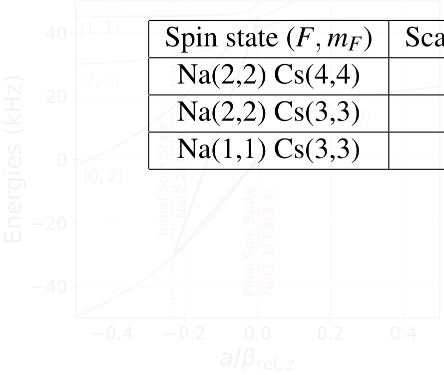


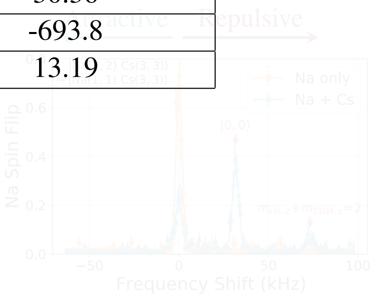
$$H = \overbrace{\sum_{i=x,y,z} \left(\frac{M\Omega_i^2 X_i^2}{2} + \frac{P_i^2}{2M}\right)}^{\text{Center of mass}} + \overbrace{\sum_{i=x,y,z} \left(\frac{\mu\omega_{R,i}^2 x_{R,i}^2}{2} + \frac{p_{R,i}^2}{2\mu}\right) + V_{int}(\vec{r}_R)}^{\text{Relative}} + \overbrace{\sum_{i=x,y,z} \mu(\omega_{1,i}^2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

Interaction shift

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

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





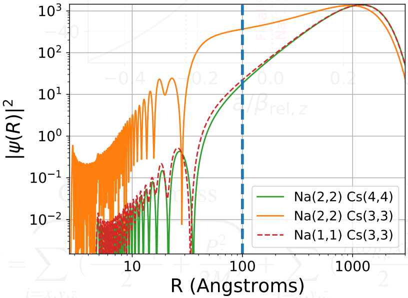
$$H = \underbrace{\sum_{i=x,y,z}\left(\frac{M\Omega_i^2X_i^2}{2} + \frac{P_i^2}{2M}\right)}_{\text{Center of mass}} + \underbrace{\sum_{i=x,y,z}\left(\frac{\mu\omega_{R,i}^2x_{R,i}^2}{2} + \frac{p_{R,i}^2}{2\mu}\right) + V_{int}(\vec{r}_R)}_{\text{Relative}} + \underbrace{\sum_{i=x,y,z}\mu(\omega_{1,i}^2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

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!

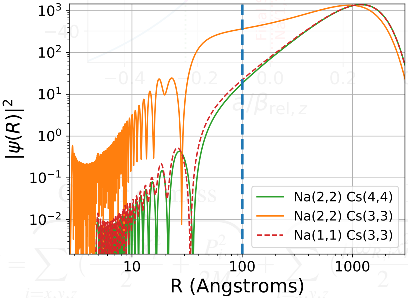


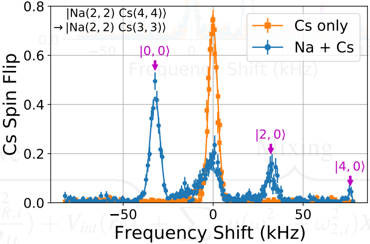
Interaction shift

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!



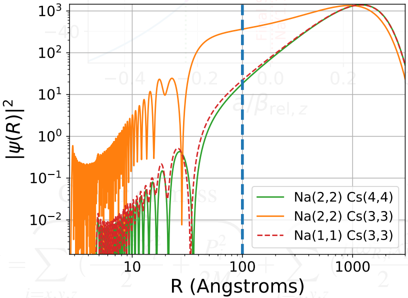


Interaction shift

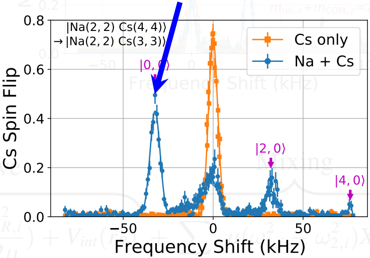
Combined with binding energy measurement on Na(2,2) Cs(4,4)

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!

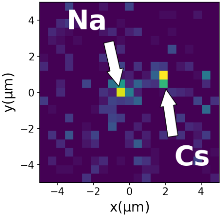


Ground State Only



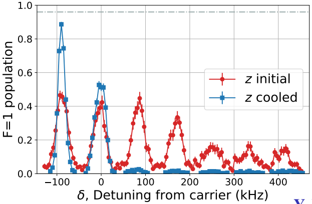
Outline

Loading



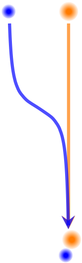
NJP. 19, 023007 (2017)

Cooling



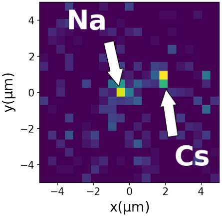
Y. Yu et al. PRA. 97, 063423 (2018)

Merging



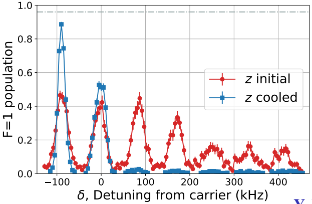
Y. Yu et al. PRX. 9, 021039 (2019)

Loading



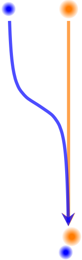
NJP. 19, 023007 (2017)

Cooling

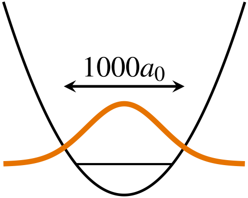


Y. Yu et al. PRA. 97, 063423 (2018)

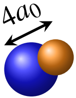
Merging



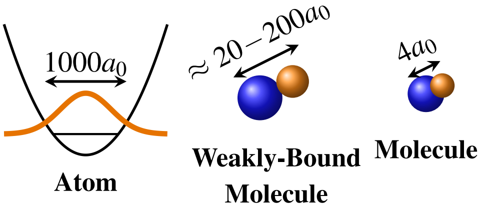
Y. Yu et al. PRX. 9, 021039 (2019)

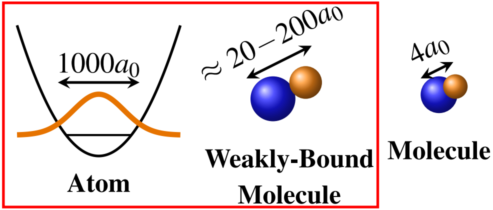


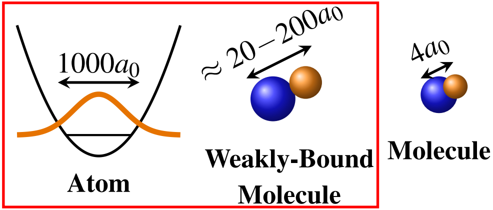
Atom



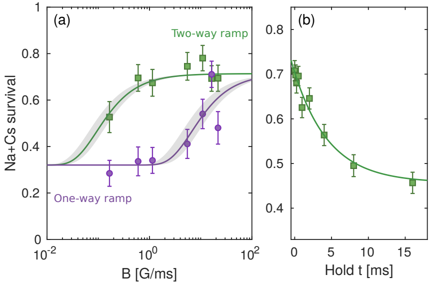
Molecule


$1000a_0$
Atom
$\approx 20-200a_0$
Weakly-Bound Molecule
$4a_0$
Molecule

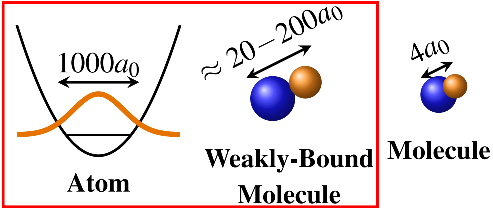

$1000a_0$
Atom
$\approx 20-200a_0$
Weakly-Bound Molecule
$4a_0$
Molecule



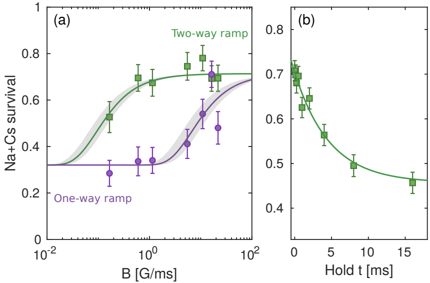
Feshbach molecule



PRL. 124, 253401 (2020)

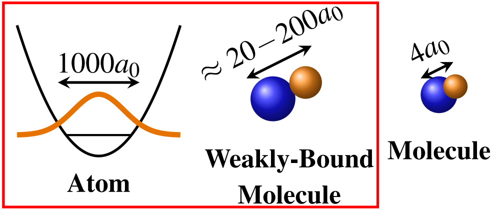


Feshbach molecule



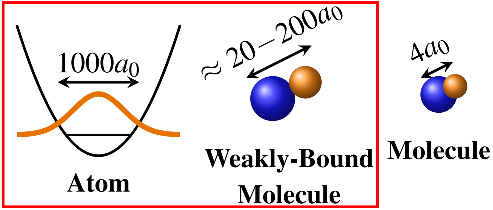
PRL. 124, 253401 (2020)

- Requires Feshbach resonance
- Usually large magnetic field



Optical transfer

- More general
- Faster



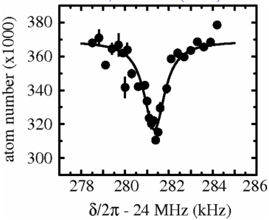
Optical transfer

- More general
- Faster

Previous results

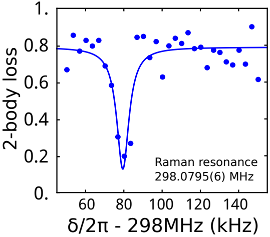
Rb_2 Science 287, 1016 (2000)

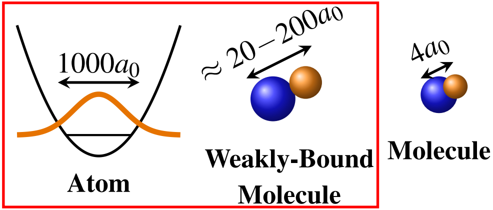
PRL. 93, 073002 (2004)



Sr_2 PRL. 109, 115302 (2012)

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





Optical transfer

- More general
- Faster

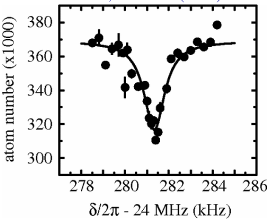
Limitations so far

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

Previous results

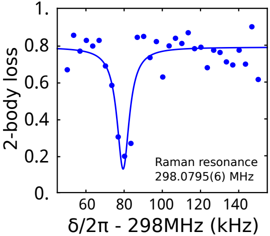
Rb_2 Science 287, 1016 (2000)

PRL. 93, 073002 (2004)

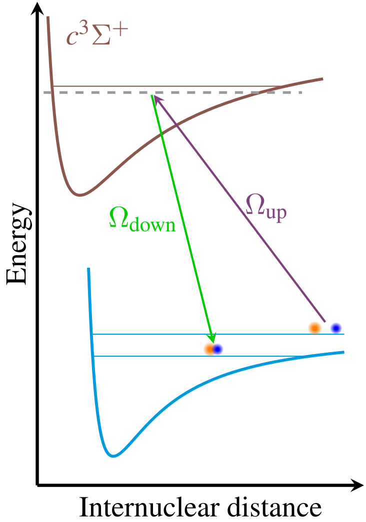


Sr_2 PRL. 109, 115302 (2012)

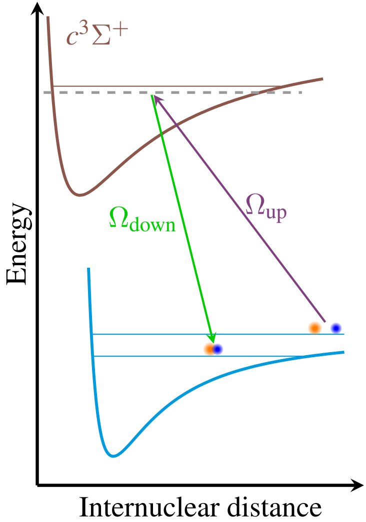
NaCs **Y. Yu** et al. PRX. 9, 021039 (2019)



Raman transfer



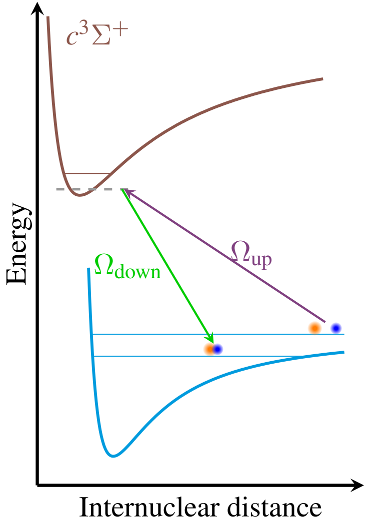
Raman transfer



Near threshold states

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

Raman transfer



Near threshold states

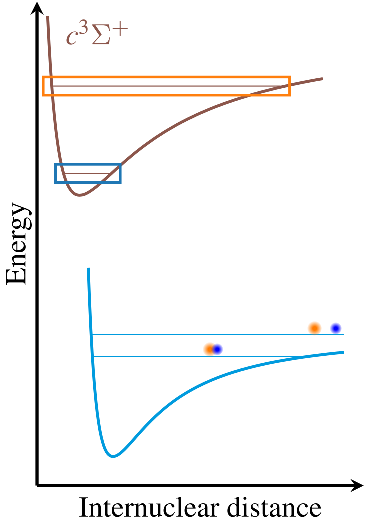
- Stronger coupling (Ω_{up} and Ω_{down})
- Closely spaced
- Fast scattering

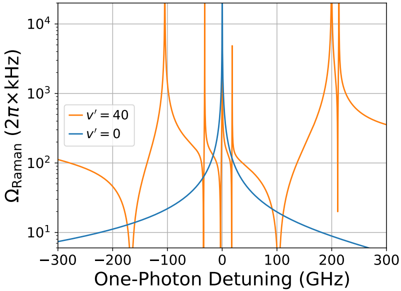
Deeply bound states

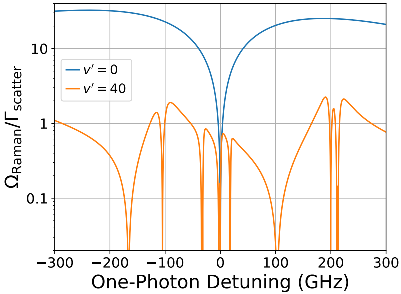
- Weaker coupling
- Sparsely spaced
- Allow larger detuning
- Slower scattering

arXiv:1701.03121(2017)

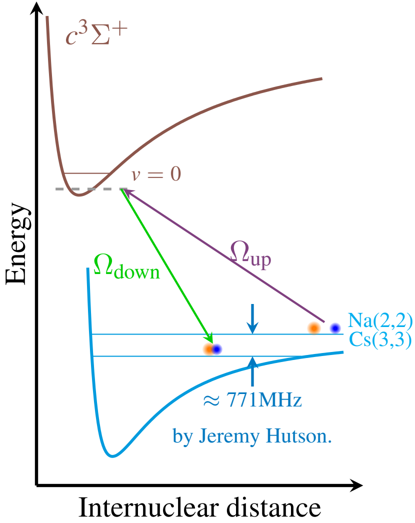
Raman transfer





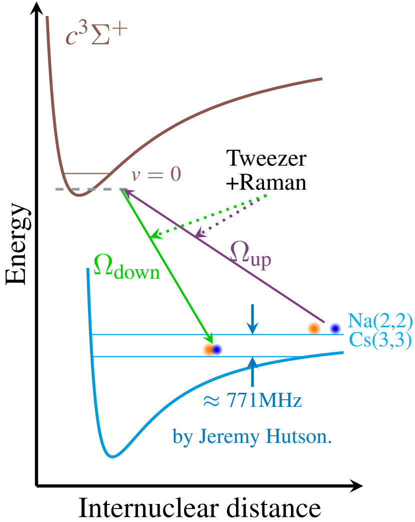


Experiment



$c^3\Sigma^+$
$v = 0$
Energy
Ω_{down}
Ω_{up}
Na(2,2)
Cs(3,3)
$\approx$ 771MHz
by Jeremy Hutson.
Internuclear distance

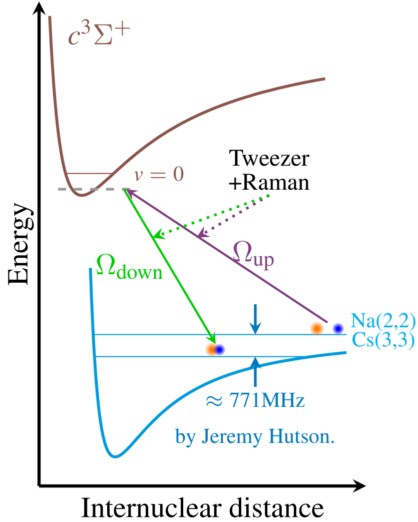
Experiment

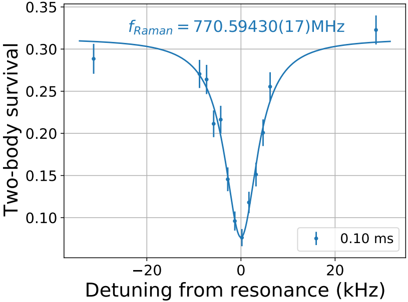


Tweezer as Raman beam

- Higher Raman Rabi frequency
- Lower scattering from other sources

Experiment

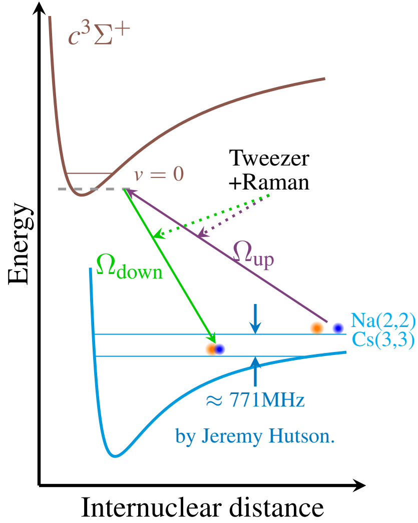


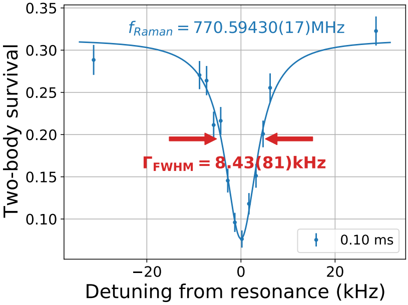


Tweezer as Raman beam

- Higher Raman Rabi frequency
- Lower scattering from other sources

Experiment

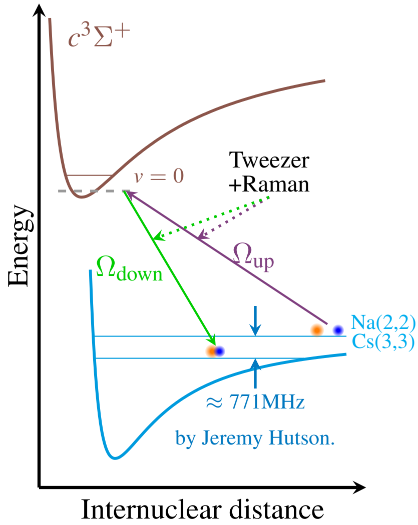




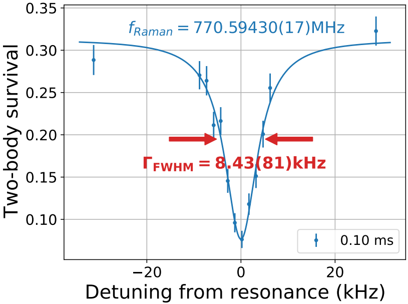
Tweezer as Raman beam

- Higher Raman Rabi frequency
- Lower scattering from other sources

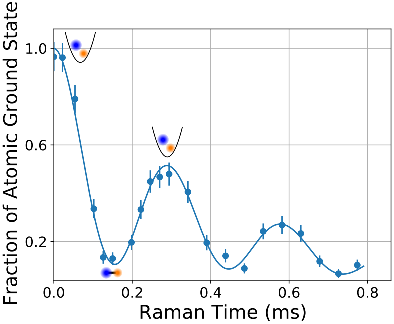
Experiment



Energy
$c^3\Sigma^+$
$v = 0$
Tweezer
+Raman
Ω_{down}
Ω_{up}
Na(2,2)
Cs(3,3)
≈ 771MHz
by Jeremy Hutson.
Internuclear distance



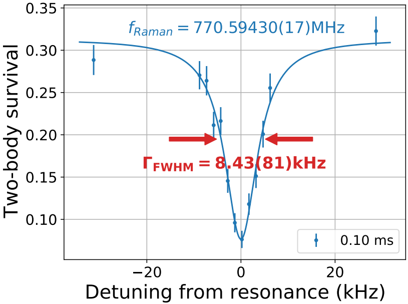
f_{Raman} = 770.59430(17)MHz
Γ_{FWHM} = 8.43(81)kHz
0.10 ms
Two-body survival
0.35
0.30
0.25
0.20
0.15
0.10
−20
0
20
Detuning from resonance (kHz)

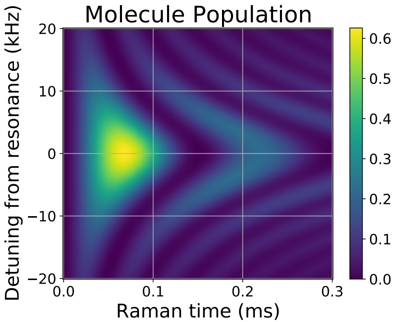


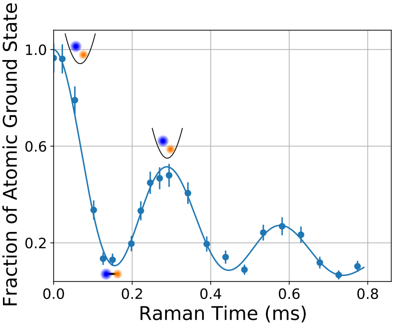
Fraction of Atomic Ground State
1.0
0.6
0.2
0.0
0.2
0.4
0.6
0.8
Raman Time (ms)

Experiment

- Transferred 63% of ground state atom to molecule.
- Single molecule spin state
- $>50\%$ of molecule in motional ground state.
- Limited by molecule lifetime

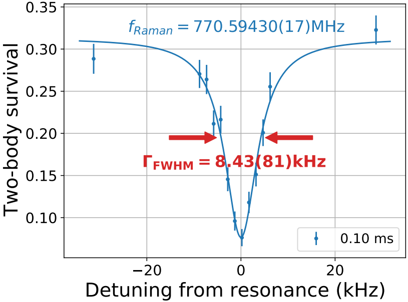


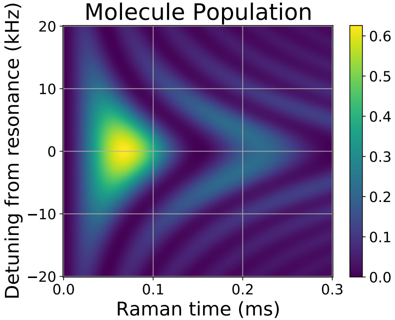


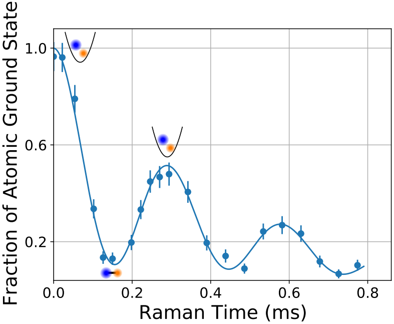


Experiment

- Transferred 63% of ground state atom to molecule.
- Single molecule spin state
- $>50\%$ of molecule in motional ground state.
- Limited by molecule lifetime

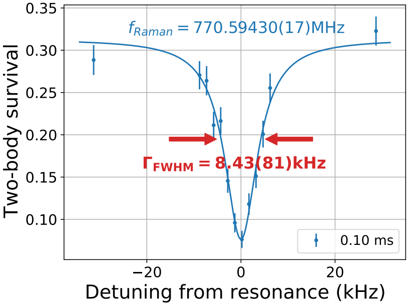


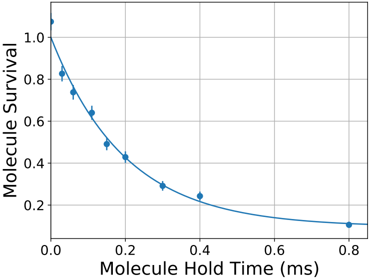


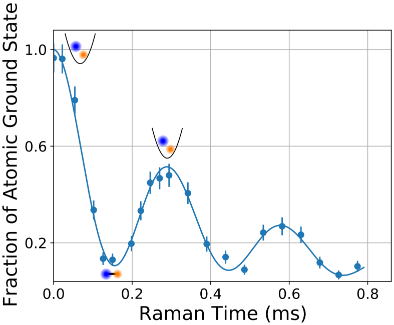


Experiment

- Transferred 63% of ground state atom to molecule.
- Single molecule spin state
- $>50\%$ of molecule in motional ground state.
- Limited by molecule lifetime







Conclusion and outlook

- New quatum 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 molecucle
- Rovibronic ground state

Conclusion and outlook

- New quatum 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 molecucle
- Rovibronic ground state

Conclusion and outlook

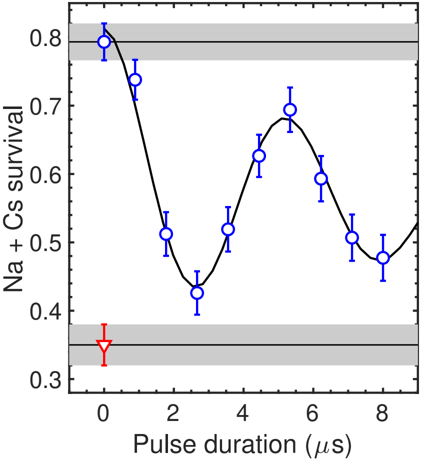
- New quatum platform based on ultracold molecules in tweezers
- Full quantum control of atoms in optical tweezers
- Measured interaction between single atoms
- Coherent all-optical creation of single molecucle
- Rovibronic ground state

Conclusion and outlook

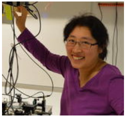
- New quatum platform based on ultracold molecules in tweezers
- Full quantum control of atoms in optical tweezers
- Measured interaction between single atoms
- Coherent all-optical creation of single molecucle
- Rovibronic ground state

Conclusion and outlook

- New quatum 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 molecucle
- Rovibronic ground state



PI



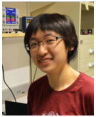
Kang-Kuen Ni

NaCs Team

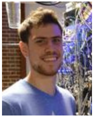
Kenneth Wang

Yu Wang

Fang Fang



Jessie Zhang



Lewis Picard

William Cairncross

KRb Team

Lingbang Zhu

Mingguang Hu

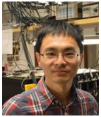
Matthew Nichols

Lee Liu
Postdoc @JILA

Jonathan Hood
AP @Purdue

Nick Hutzler
AP @Caltech

Eliot Fenton



Yen-Wei Lin
Intelon Optics

Yu Liu
Postdoc @NIST

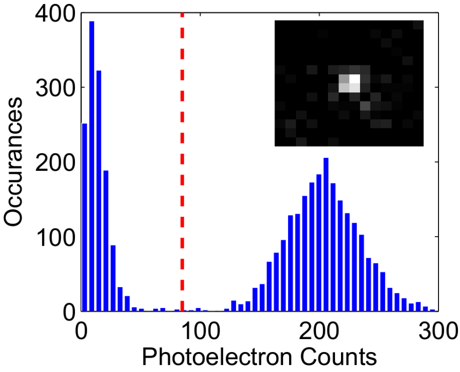
David Grimes
Instructor @MIT

Single Atom in Tweezer

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

Single Atom in Tweezer

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



Single Atom in Tweezer

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

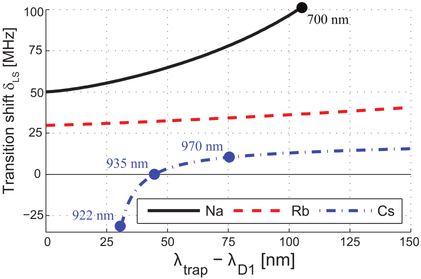
Single Atom in Tweezer

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

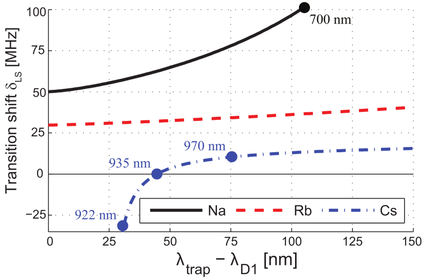
Issues with Na

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

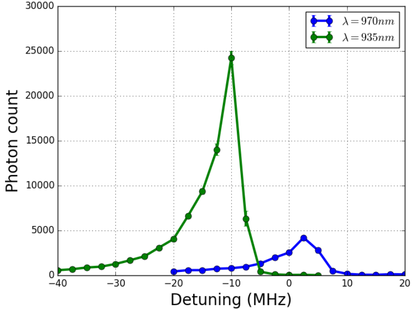
Real Issue with Na: Light Shift



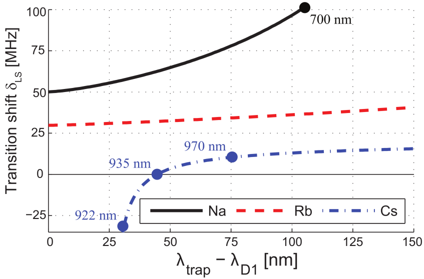
Real Issue with Na: Light Shift



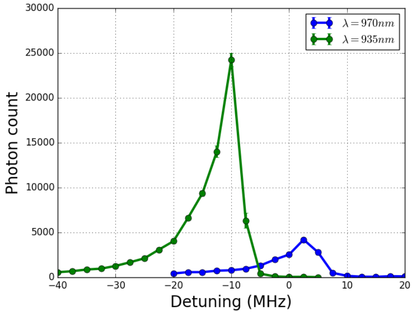
Cs single atom imaging



Real Issue with Na: Light Shift



Cs single atom imaging



- Low imaging signal
- No cooling in tweezer

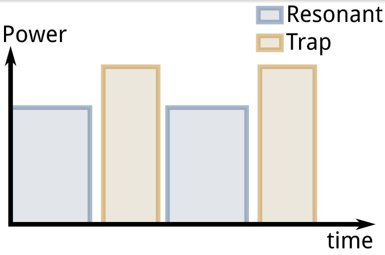
Real Issue with Na: Light Shift

Trap modulation

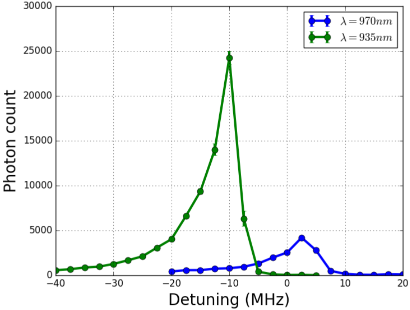
Alternate between trap and resonant (cooling and imaging) light at 2.5 MHz

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

$\Gamma = 2\pi \times 10$ MHz



Cs single atom imaging



- Low imaging signal
- No cooling in tweezer

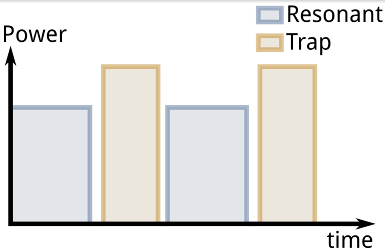
Real Issue with Na: Light Shift

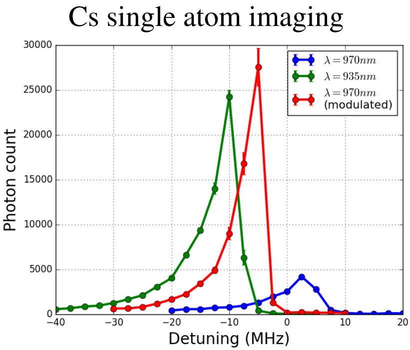
Trap modulation

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

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

$\Gamma = 2\pi \times 10$ MHz





- Low imaging signal
- No cooling in tweezer

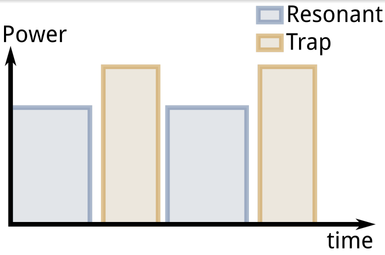
Real Issue with Na: Light Shift

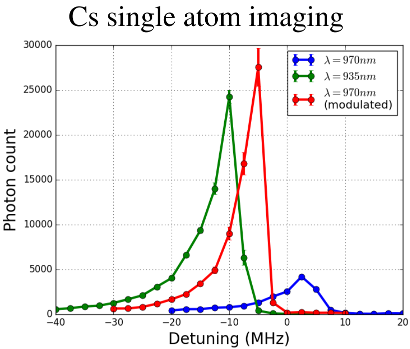
Trap modulation

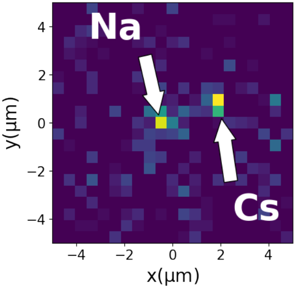
Alternate between trap and resonant (cooling and imaging) light at 2.5 MHz

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

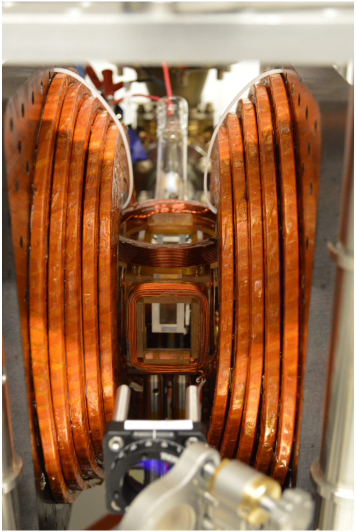
$\Gamma = 2\pi \times 10$ MHz



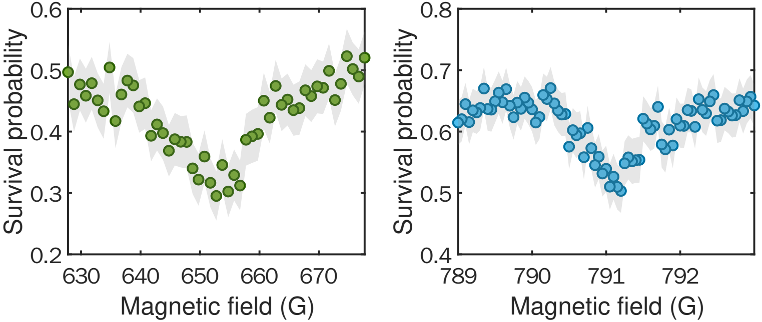




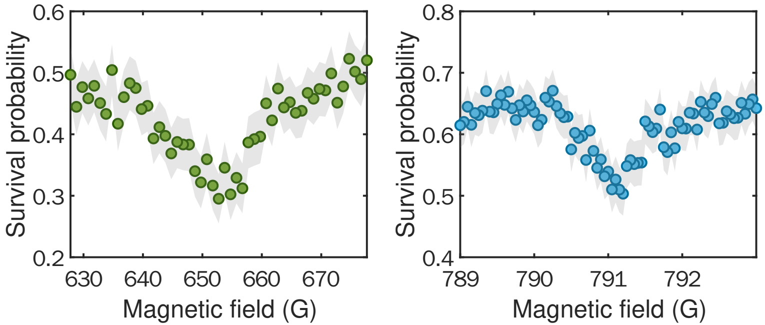
Na (1, -1) Cs (3, -3) Feshbach resonance



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



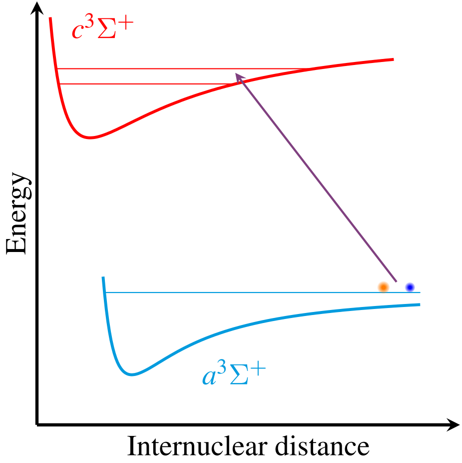
Na (1, -1) Cs (3, -3) Feshbach resonance



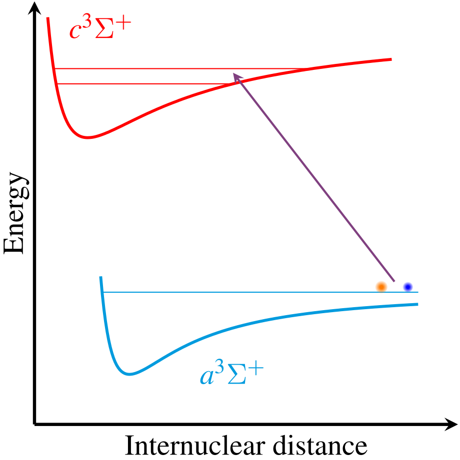
	s-wave	p-wave
Predicted (based on interaction shift)[1]	663 G	799 G
Measured	652(3) G	791.2(2) G

[1] In collaboration with Bo Gao

Photoassociation (PA) Spectroscopy



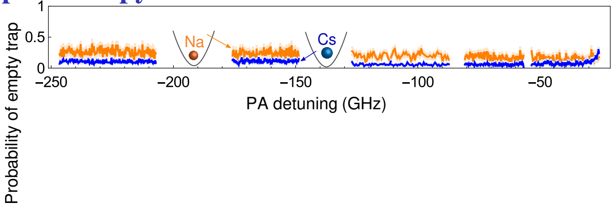
Photoassociation (PA) Spectroscopy

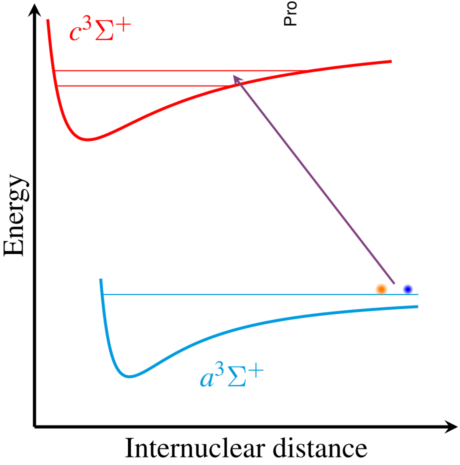


Single Atom PA

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

Photoassociation (PA) Spectroscopy

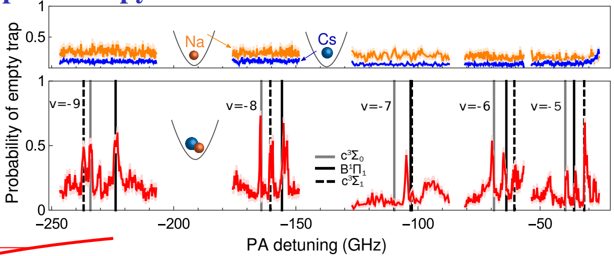


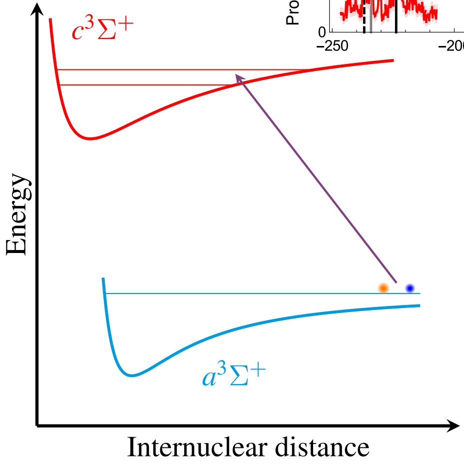


Single Atom PA

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

Photoassociation (PA) Spectroscopy

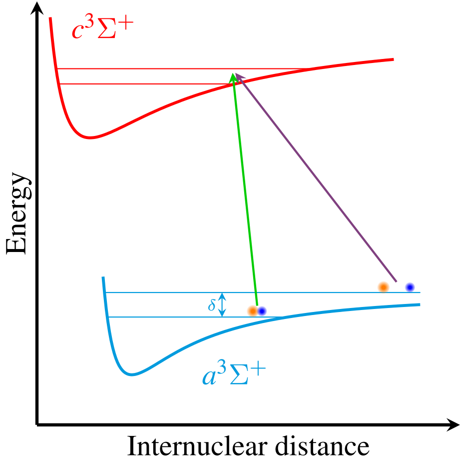




Single Atom PA

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

Electromagnetically Induced Transparency (EIT) Spectroscopy



Electromagnetically Induced Transparency (EIT) Spectroscopy