

Building Single Molecules from Single Atoms

Yichao Yu

Lee Liu, Kenneth Wang, Lewis Picard, Jonathan Hood
Jessie T. Zhang, Eliot Fenton, Yen-Wei Lin

Ni Group/Harvard

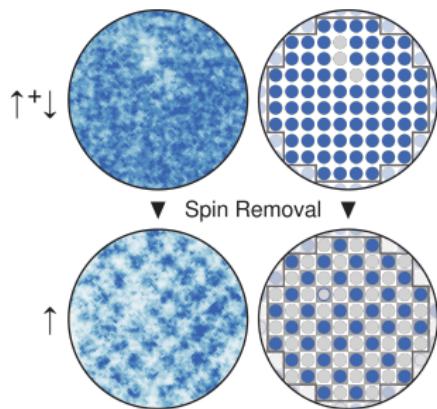
Sep 5, 2019

Atom

- Laser cooling/trapping
 - Internal state control
 - High fidelity imagining
- ⋮

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Nature 545, 462-466 (2017)

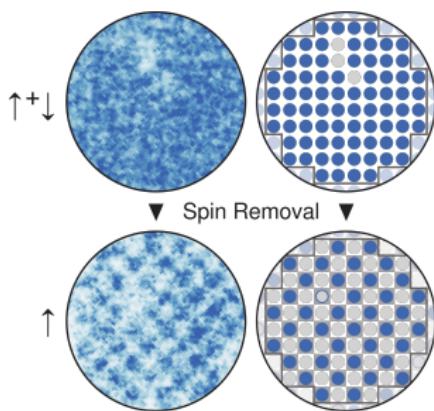
From Atom to Molecule

Atom

- Laser cooling/trapping
- Internal state control
- High fidelity imagining
- ⋮

Molecule

- Strong interaction
- Rich internal structure



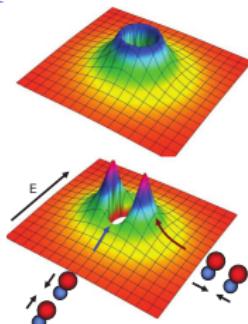
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From Atom to Molecule

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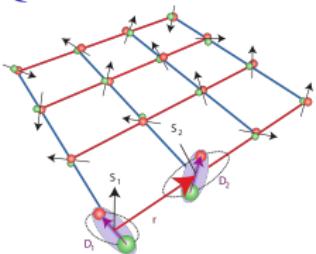
- Laser cooling/trapping
- Internal state control
- High fidelity imagining

Quantum Chemistry



Nature 464, 1324 (2010)

Quantum Simulation

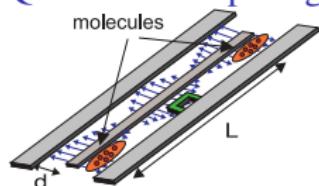


Nat. Phys. 2, 341 (2006)

Molecule

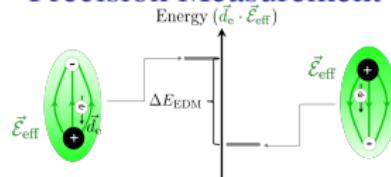
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Quantum Computing



Phys. Rev. Lett. 97, 33003 (2006)

Precision Measurement

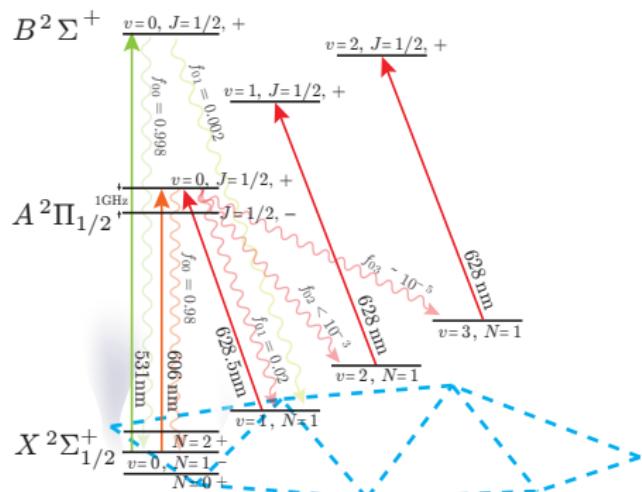


Science 343, p. 269-272 (2014)

Path to Ultracold Molecules

Direct molecule cooling

“Diagonal molecules”:
CaF, SrF, YO, . . .

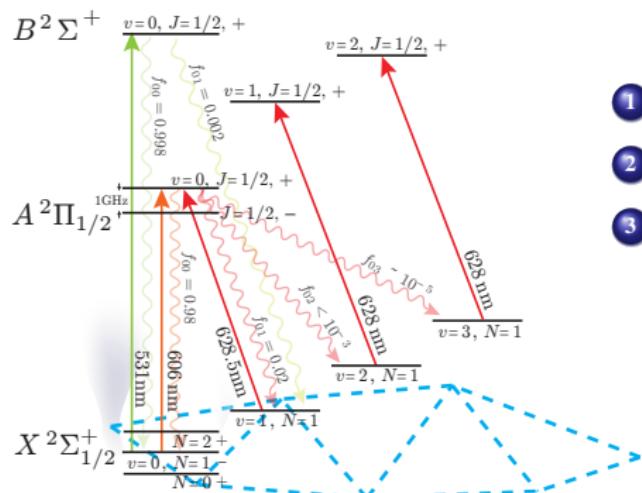


Phys. Rev. Lett. 119, 103201 (2017)

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Making molecule from atoms

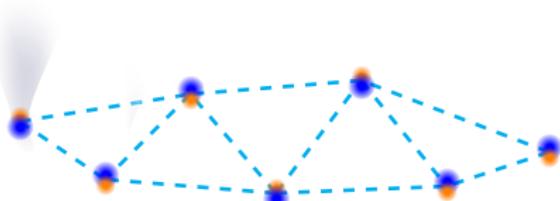
Bi-Alkali/Alkaline Earth:
KRb, RbCs, NaK, LiNa, . . .

- 1 Cold gas
- 2 Feshbach association
- 3 STIRAP

Path to Ultracold Molecules

Assemble molecule in tweezers

- Single site detection
- Single site addressing
- Control loading and interaction by rearranging.



Making molecule from atoms

Bi-Alkali/Alkaline Earth:
KRb, RbCs, NaK, LiNa, ...

- ① Cold gas
- ② Feshbach association
- ③ STIRAP

Outline

1 System Overview

2 Trapping and Cooling of Atoms

3 Atom-Atom Interaction and Molecule Formation

Steps



Loading



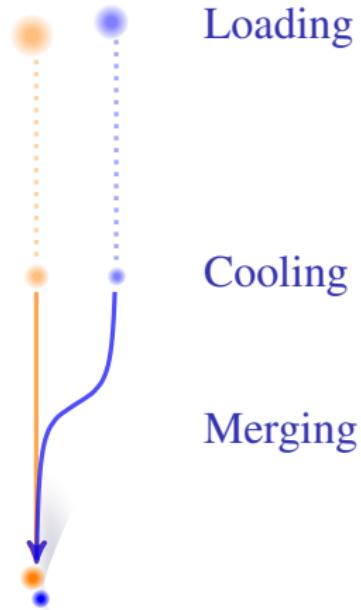
Steps



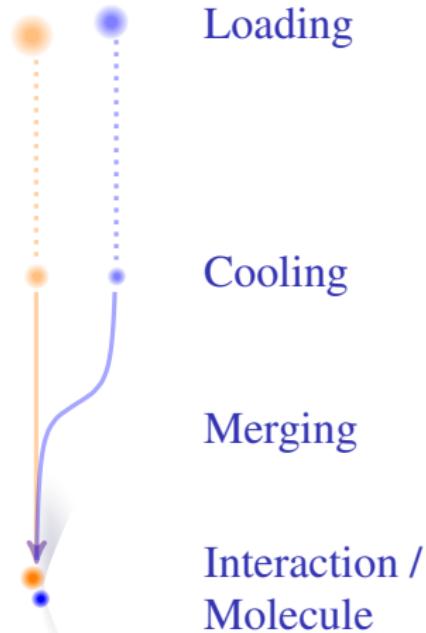
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Cooling

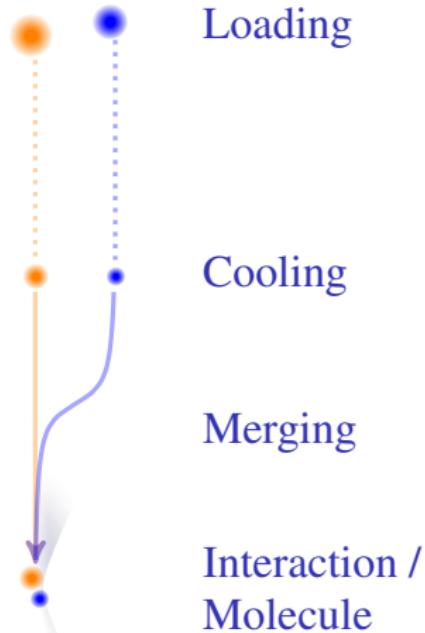
Steps



Steps



Steps



Loading

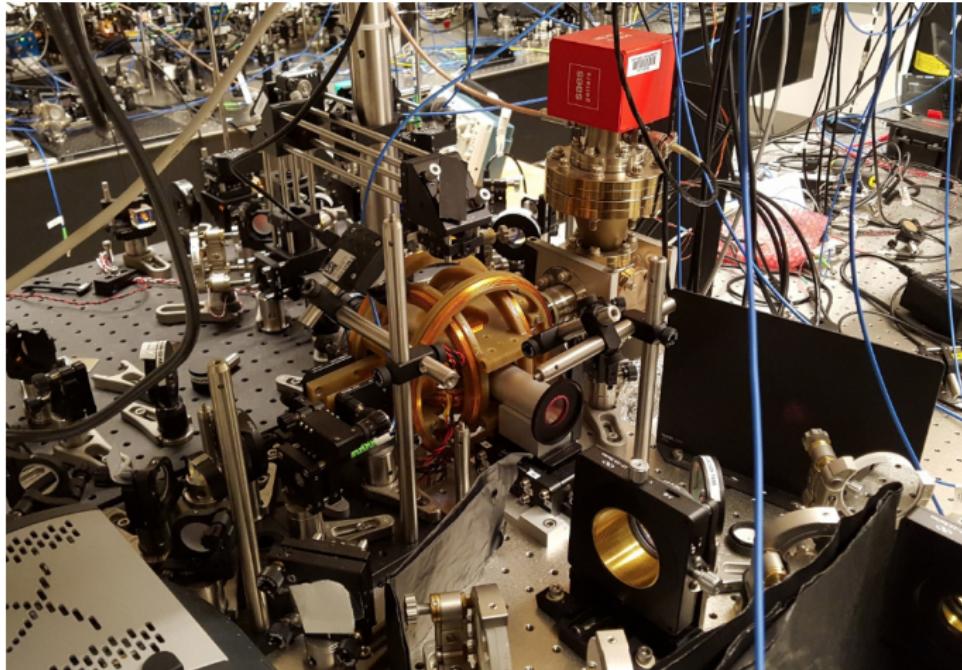
Cooling

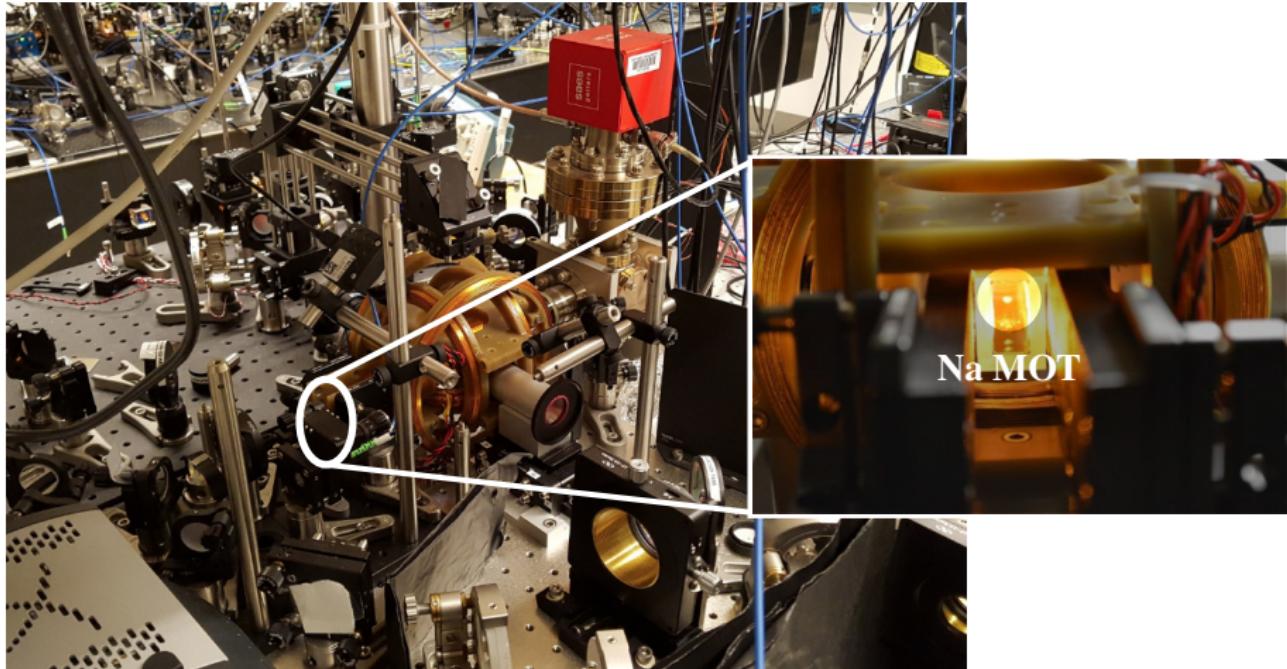
Merging

Interaction /
Molecule



Science 360 6391, 2018



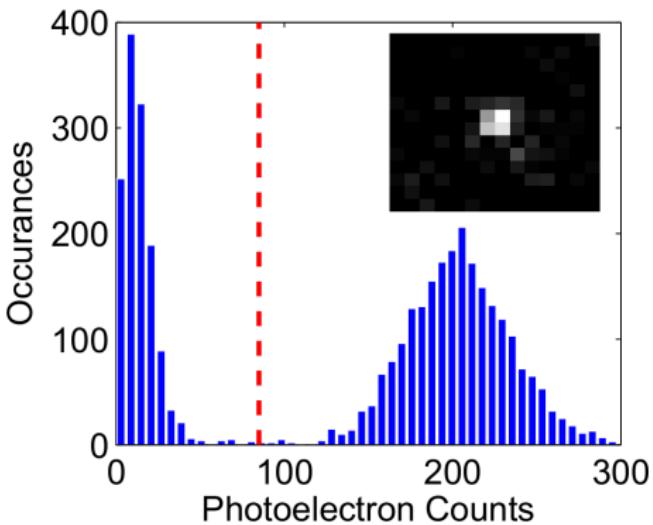


Single Atom in Tweezer

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

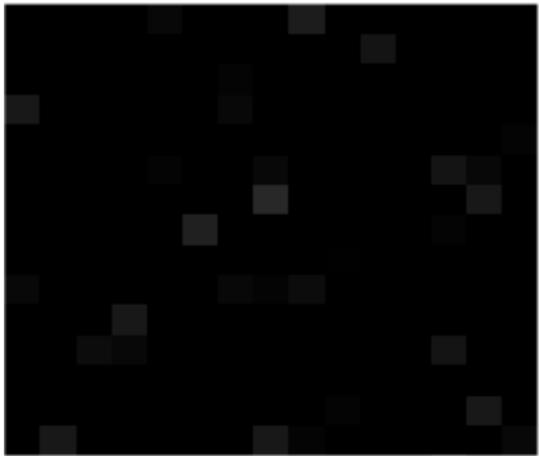
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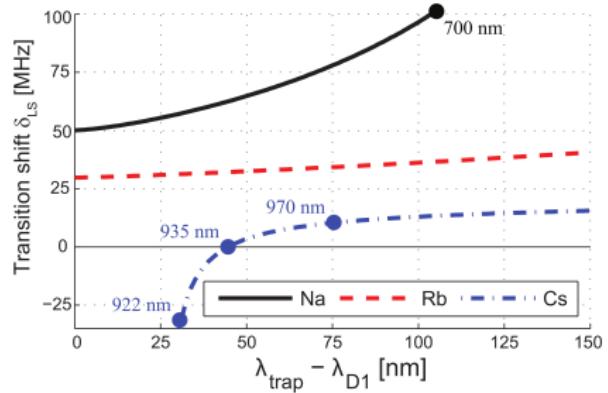
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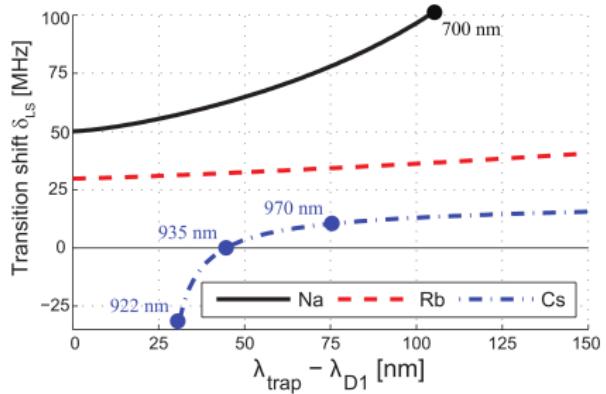
Issues with Na

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

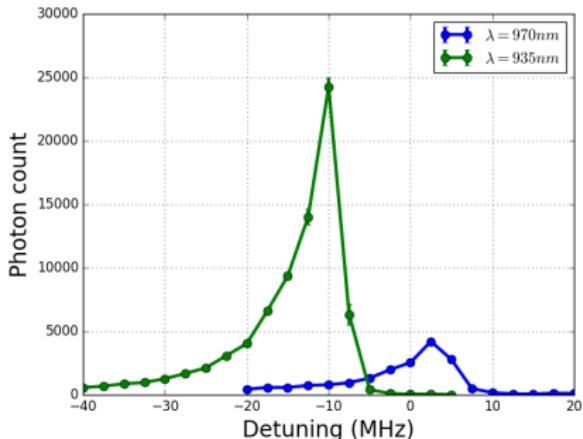
Real Issue with Na: Light Shift



Real Issue with Na: Light Shift



Cs single atom imaging



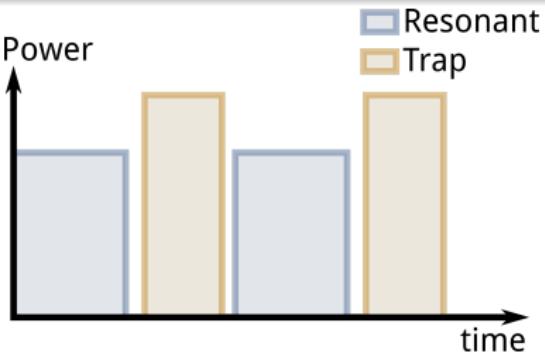
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Trap modulation

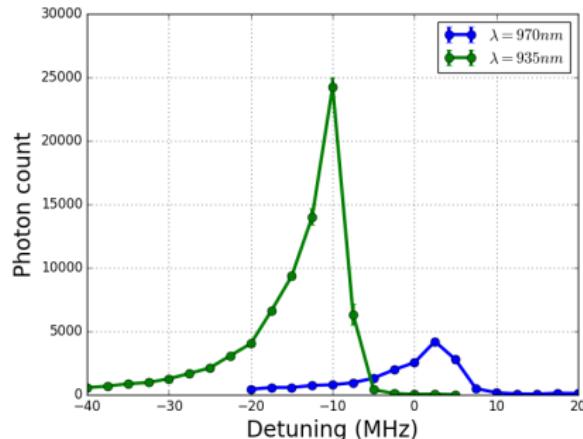
Alternate between trap and resonant (cooling and imaging) light at 2.5 MHz

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

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



Cs single atom imaging



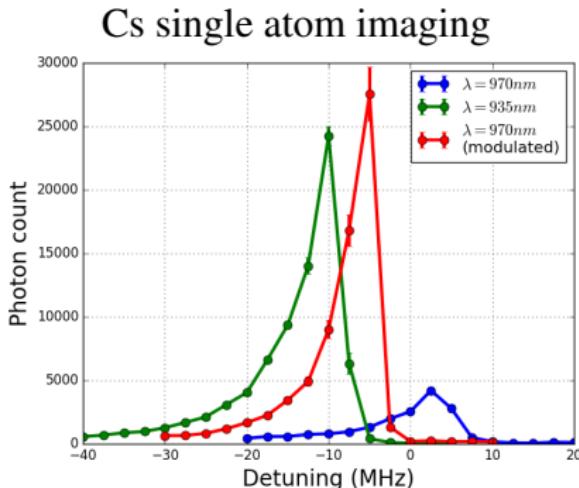
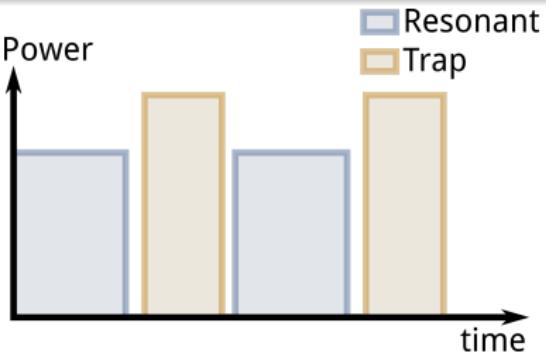
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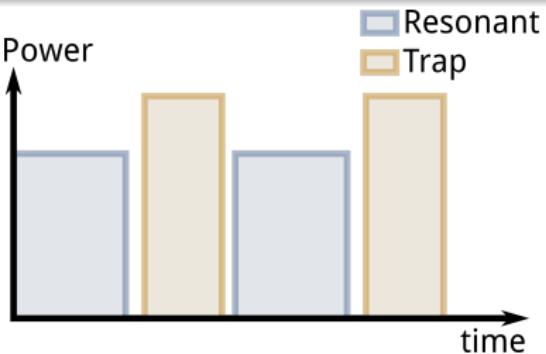
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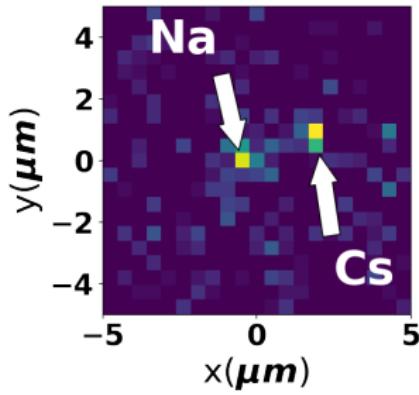
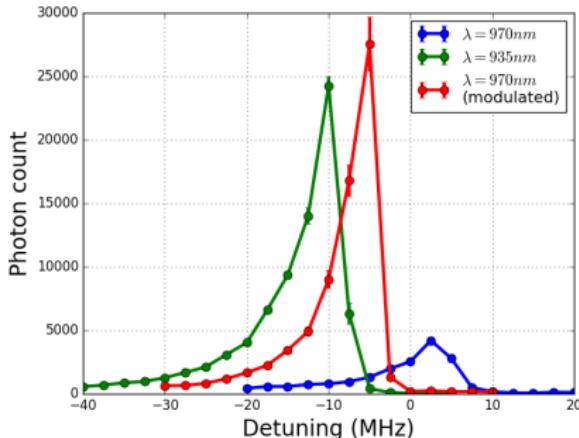
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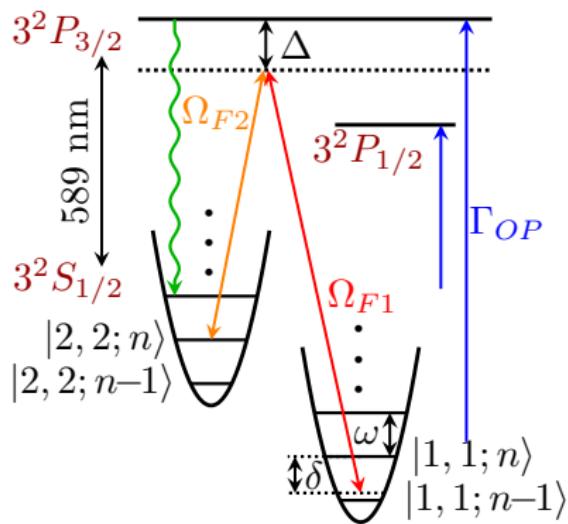
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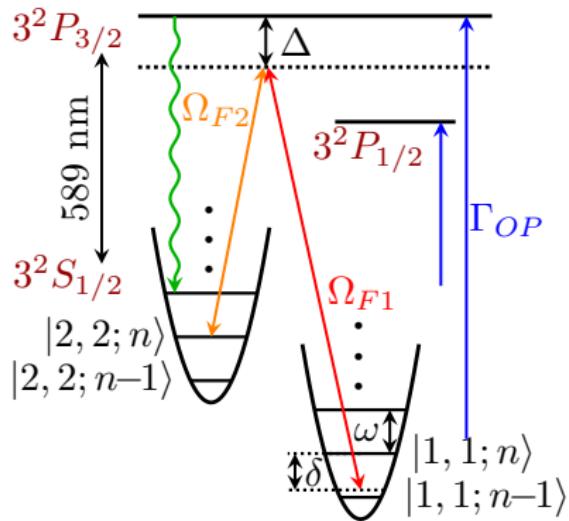
Cs single atom imaging



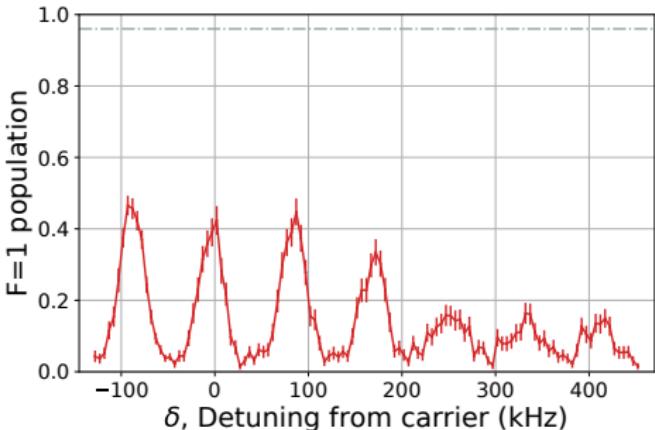
Raman Sideband Cooling



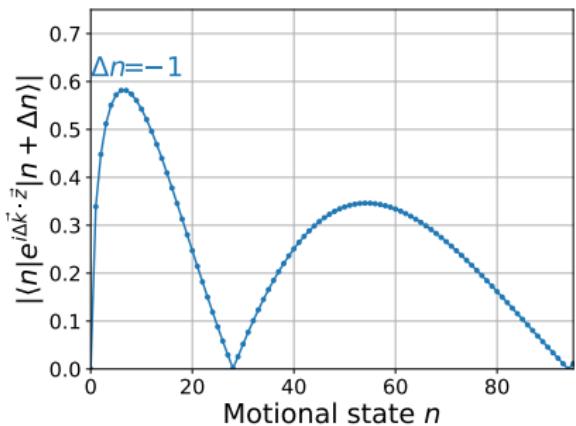
Raman Sideband Cooling



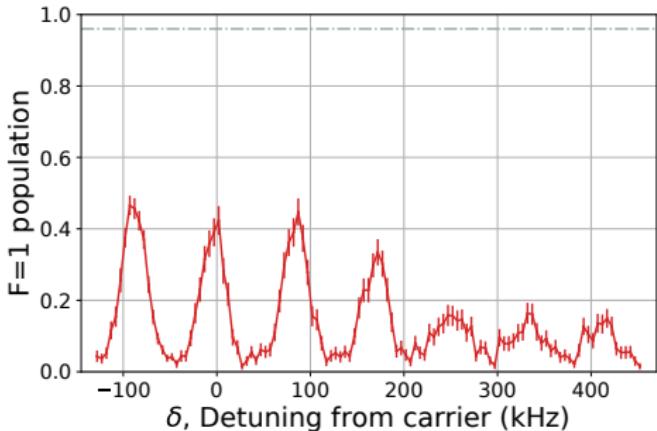
Axial sideband spectrum



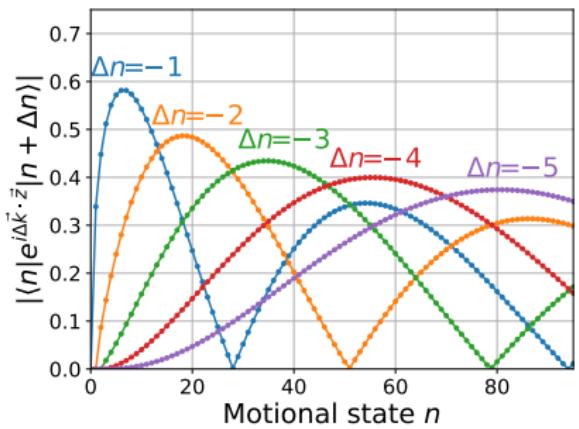
Raman Sideband Cooling



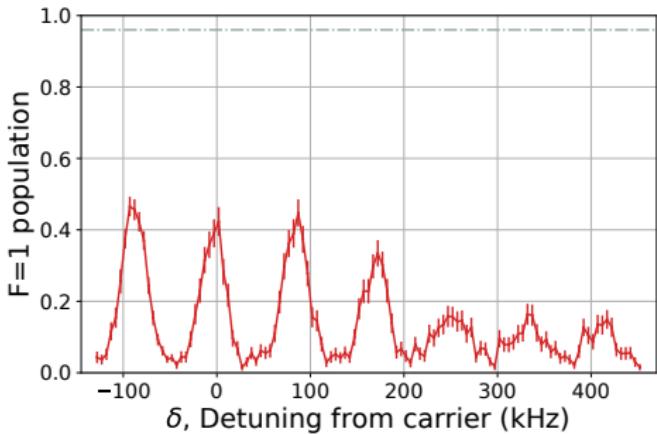
Axial sideband spectrum



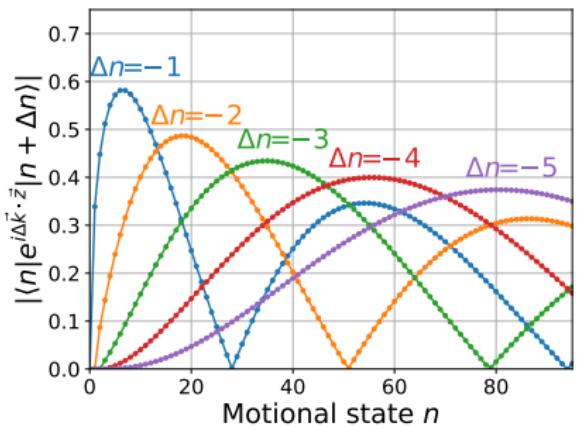
Raman Sideband Cooling



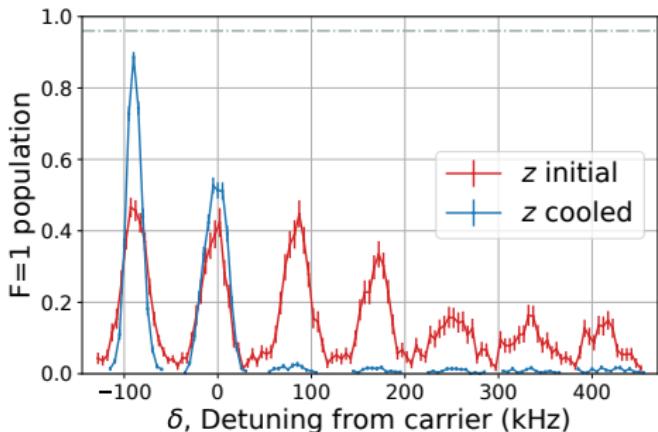
Axial sideband spectrum



Raman Sideband Cooling



Axial sideband spectrum



3D ground state: 93.5(7)%

Outline

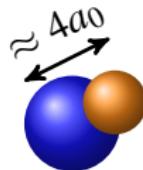
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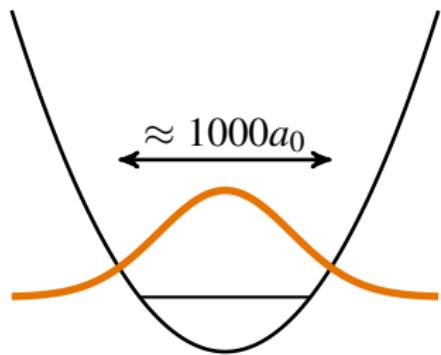
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Optical Transfer to Molecular State

Binding energy
 $\approx 150\text{THz}$



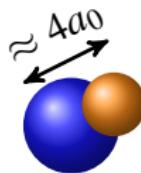
Molecule



Atoms

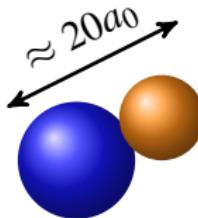
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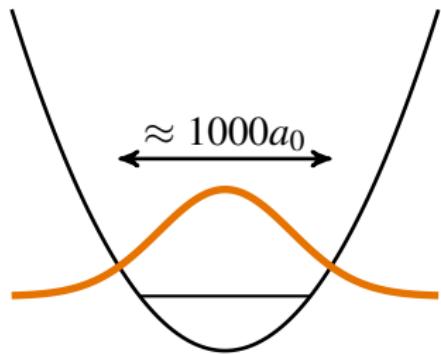


Molecule

Binding energy
 $\approx 300\text{MHz}$

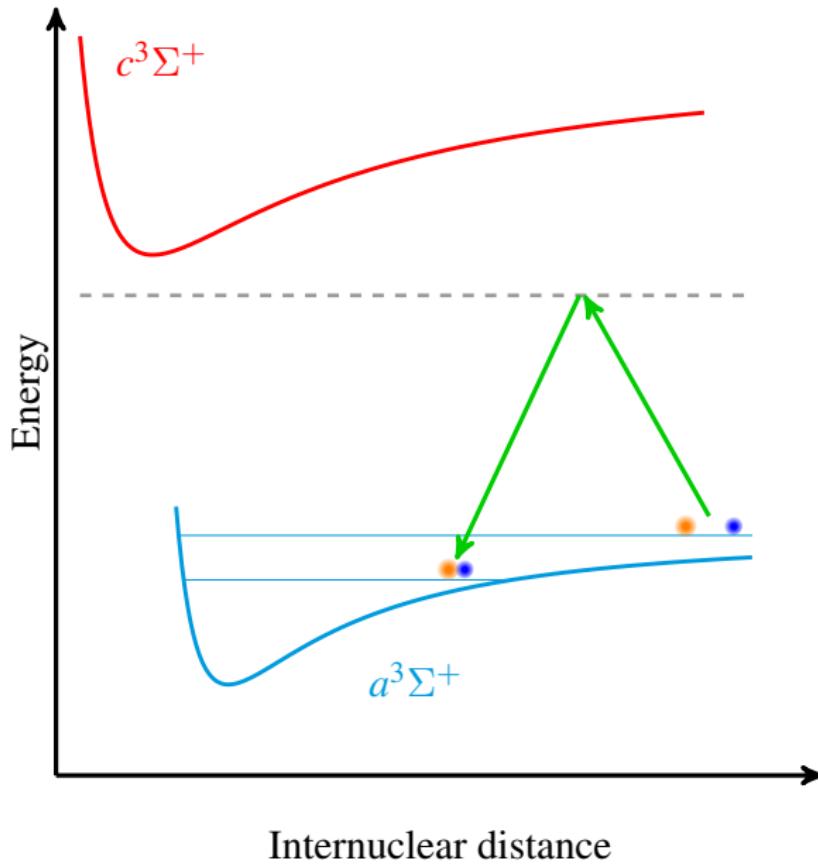


Weakly-Bound
Molecule

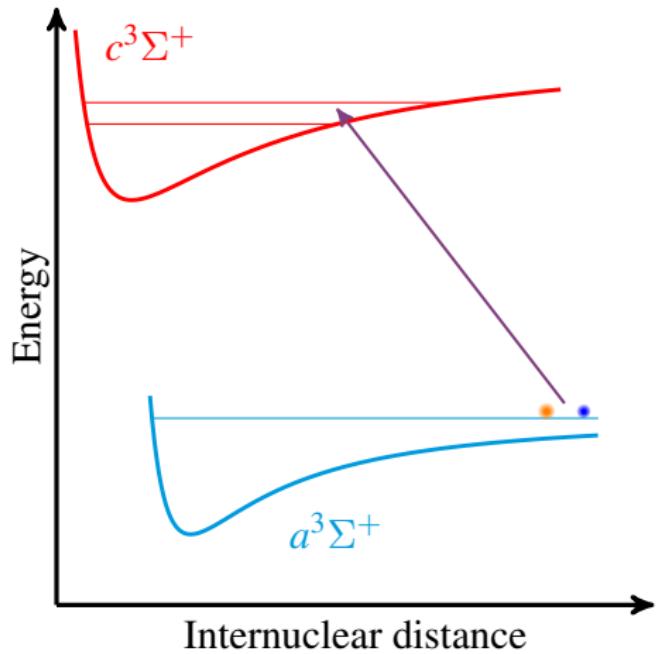


Atoms

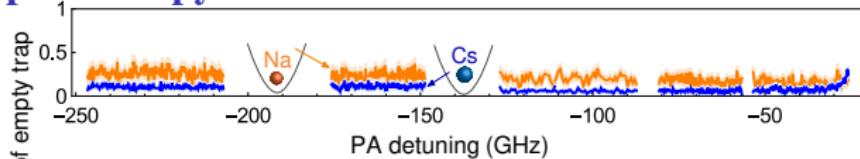
Optical Transfer to Molecular State



Photoassociation (PA) Spectroscopy

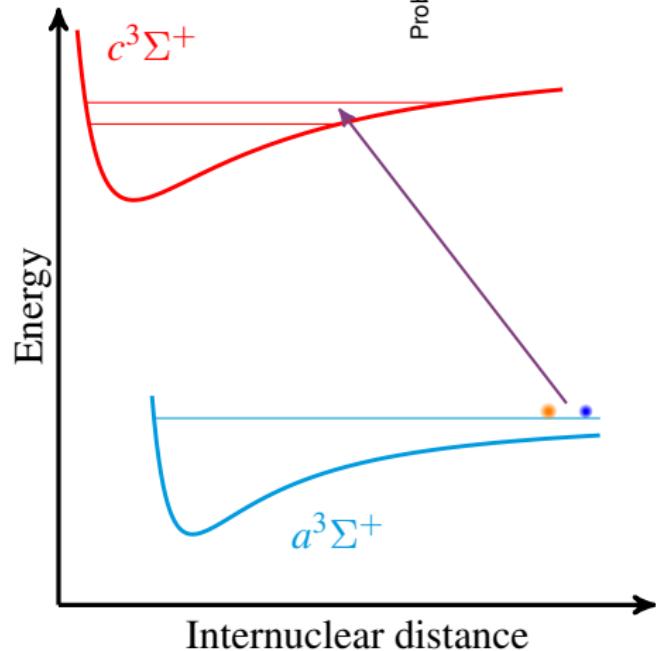


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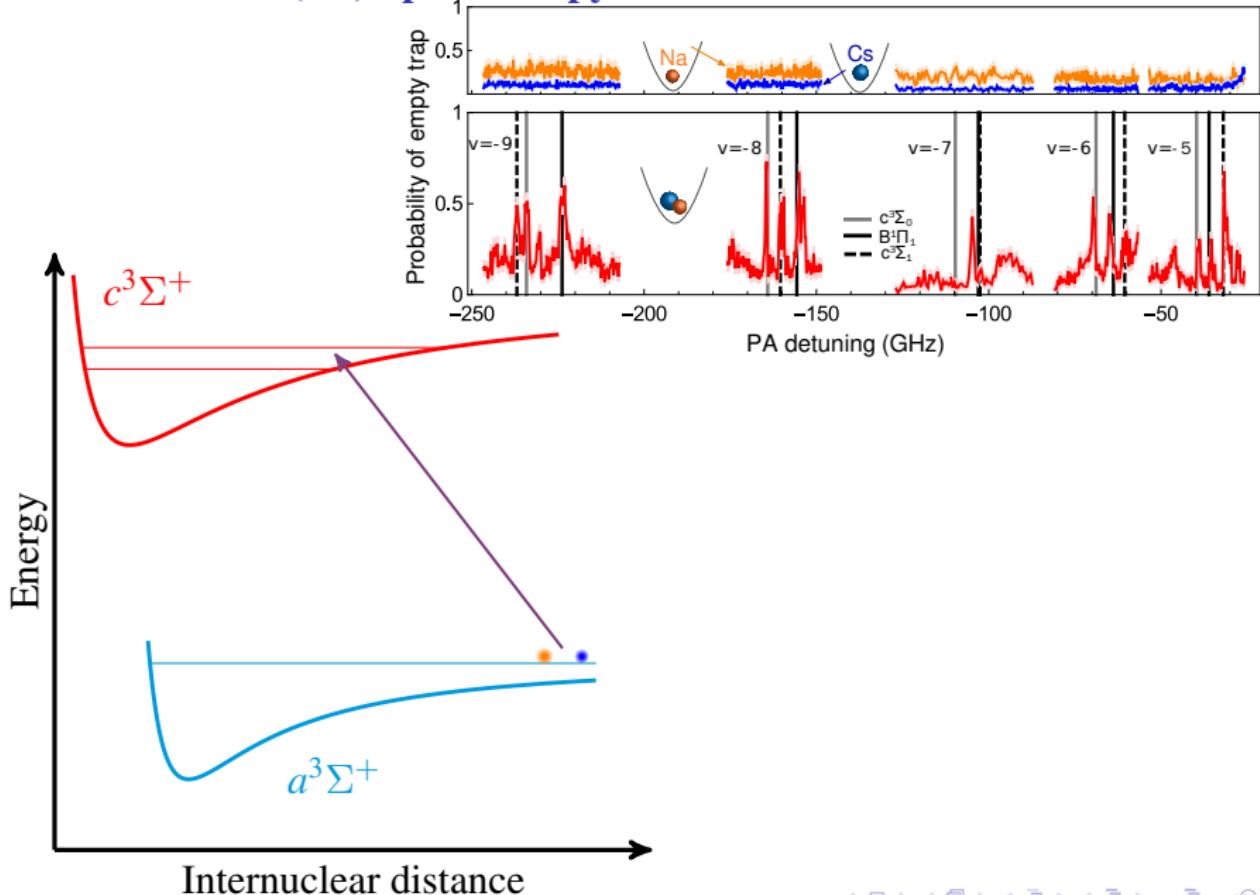


PA detuning (GHz)

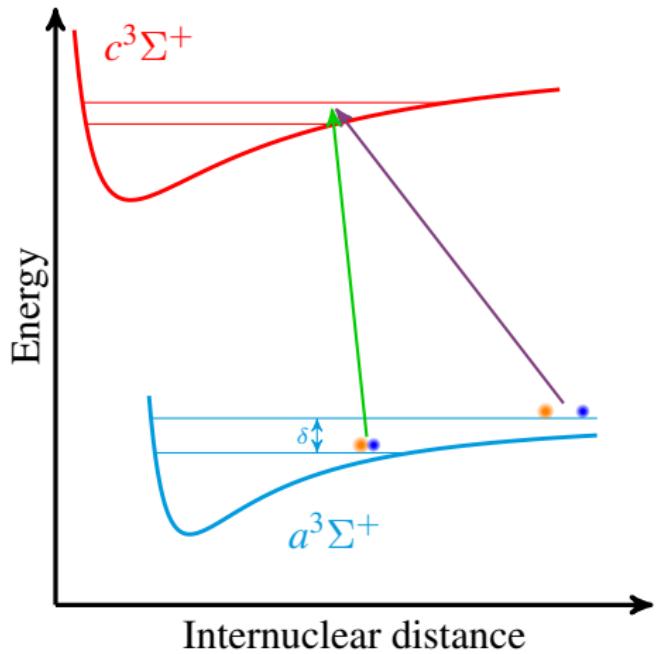
Probability of empty trap



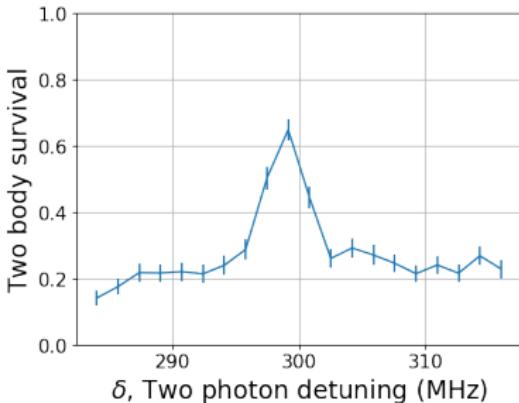
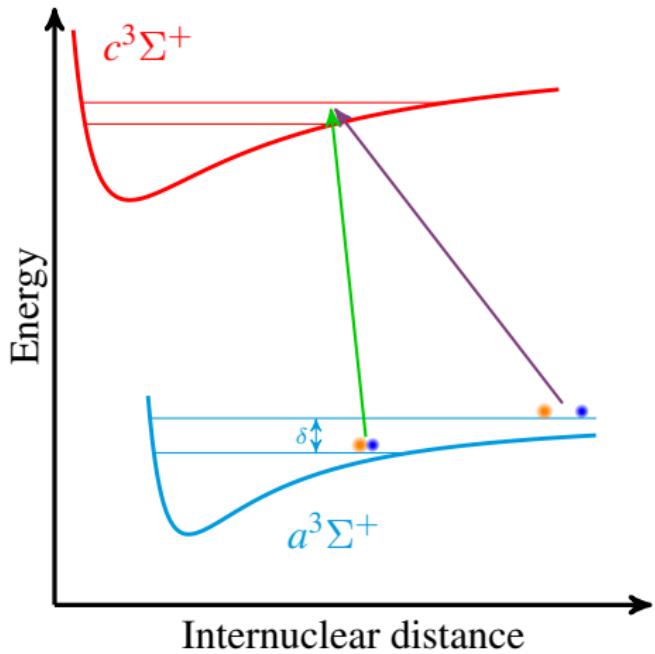
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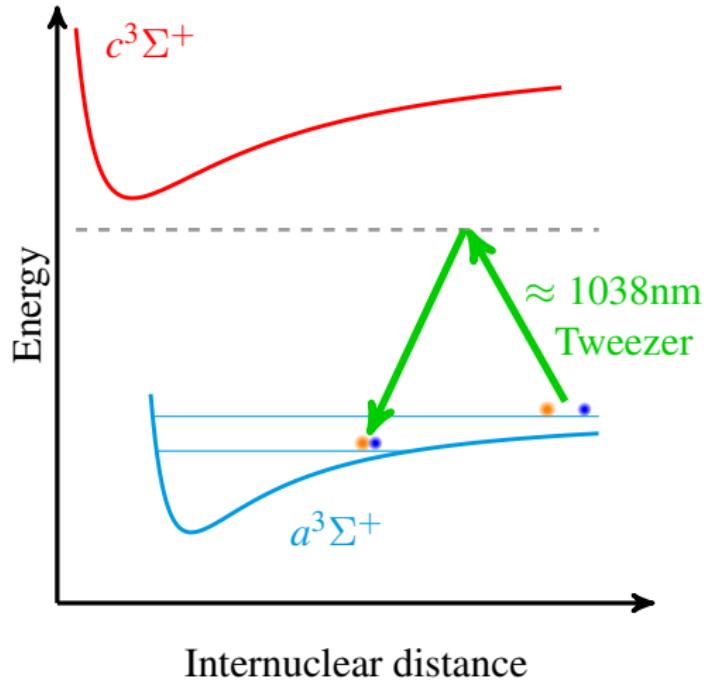
Electromagnetically Induced Transparency (EIT) Spectroscopy



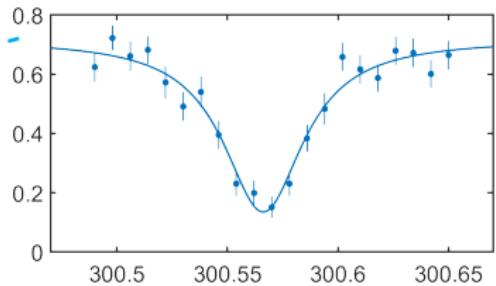
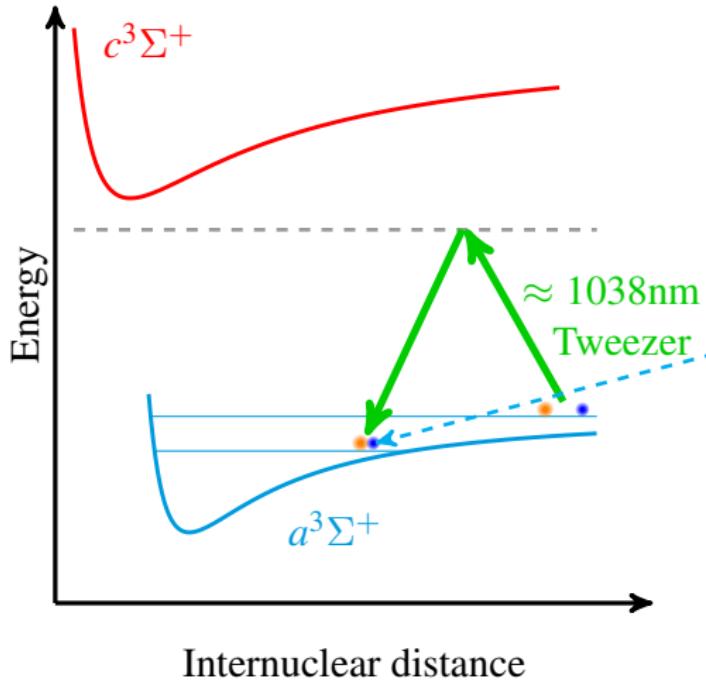
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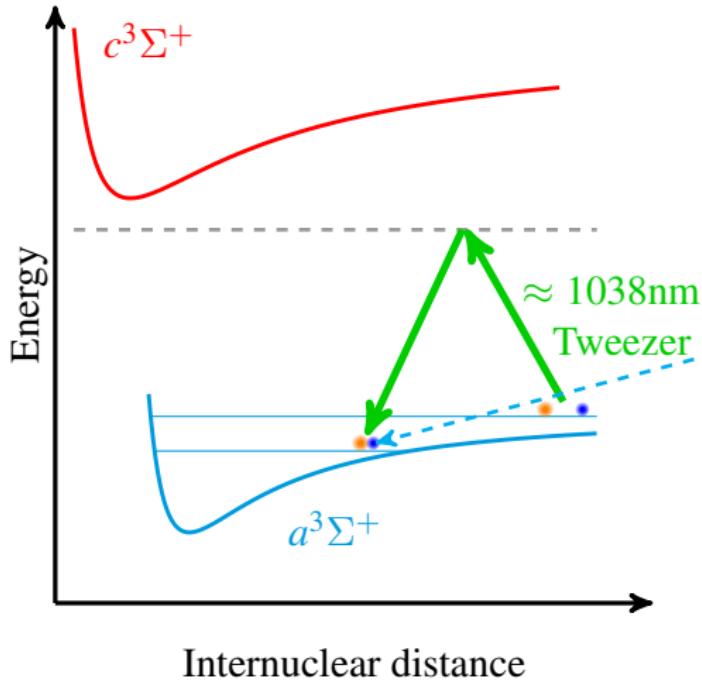
Optical Transfer to Weakly-Bound Molecular



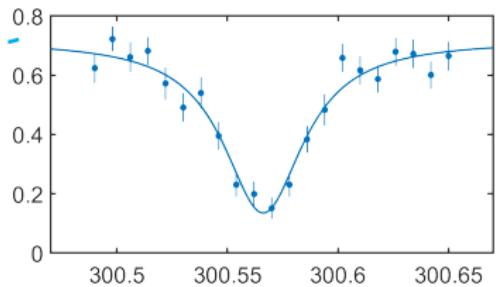
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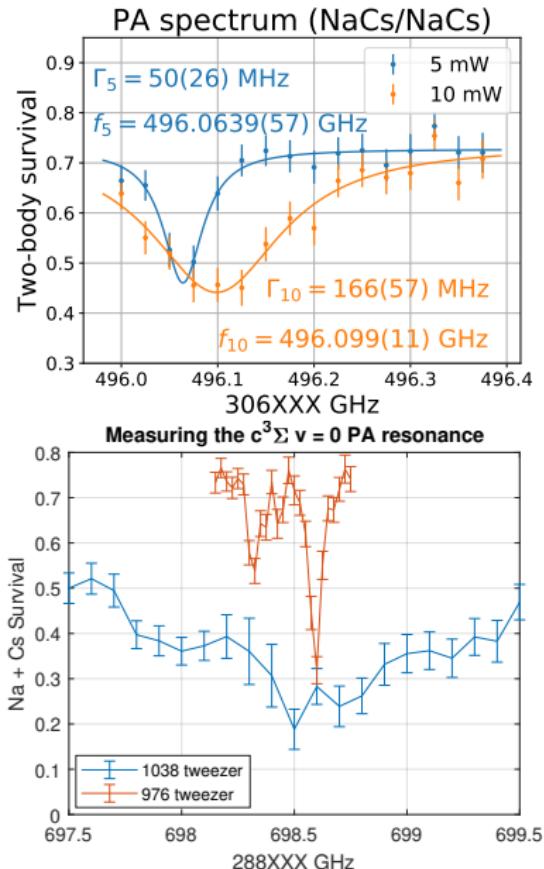
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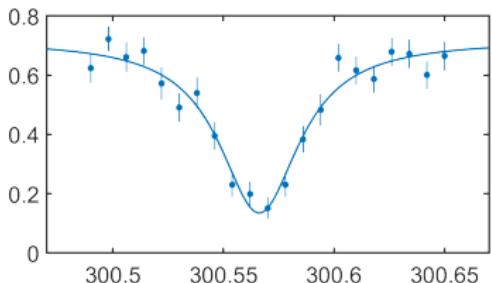
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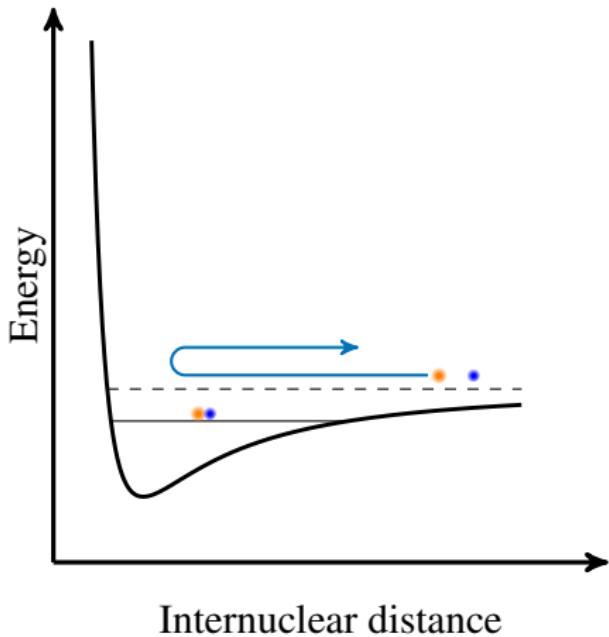


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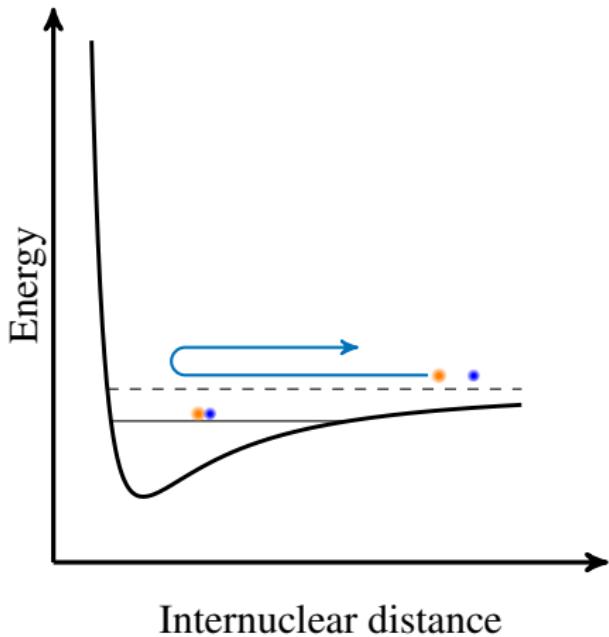
Scattering length a

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



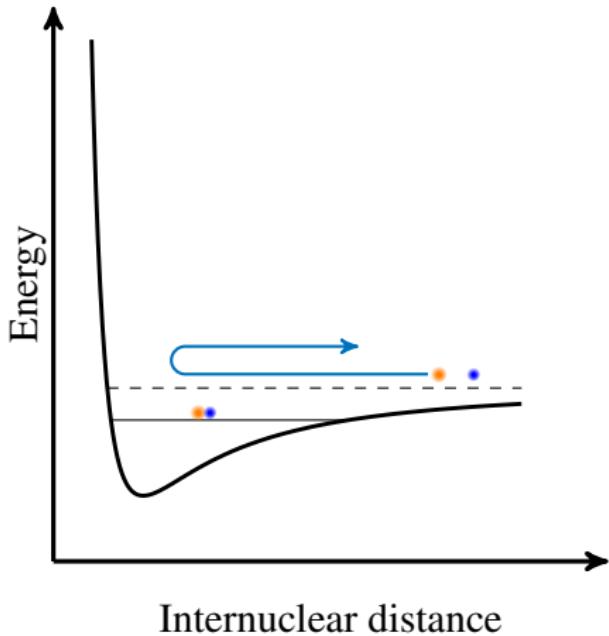
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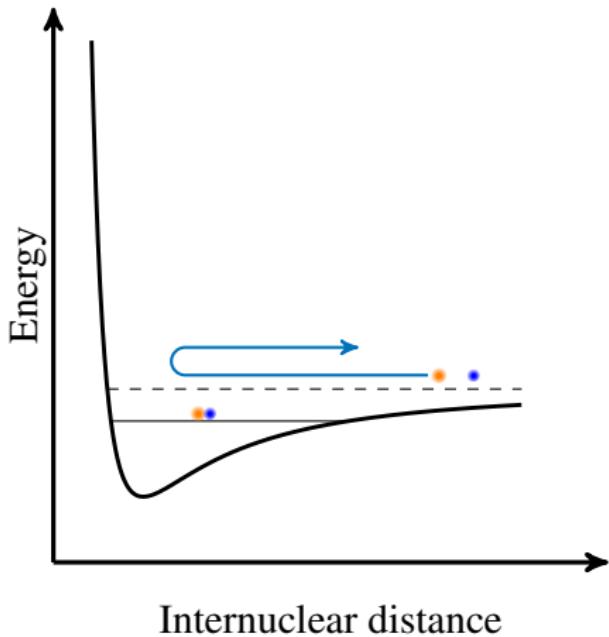
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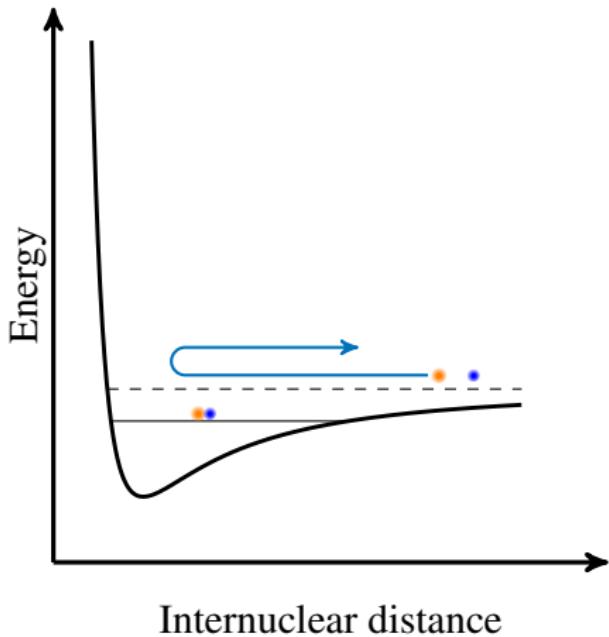
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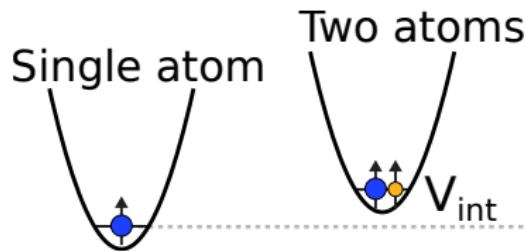


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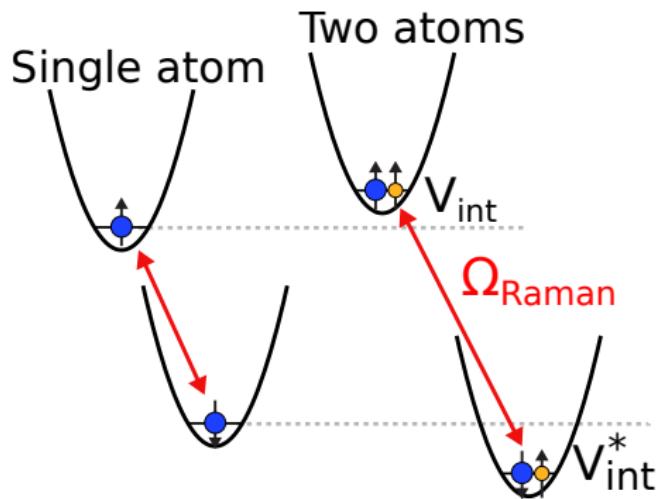
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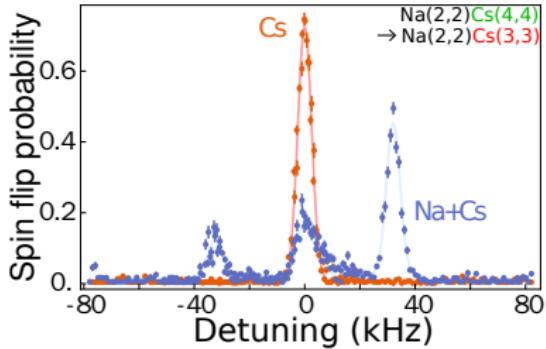
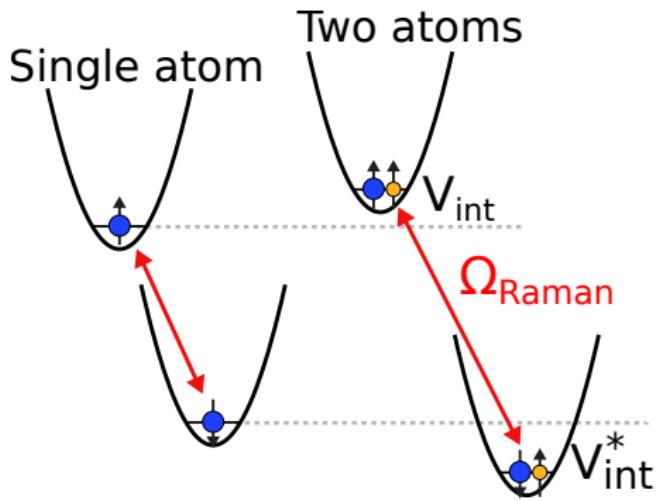
Interaction shift



Interaction shift



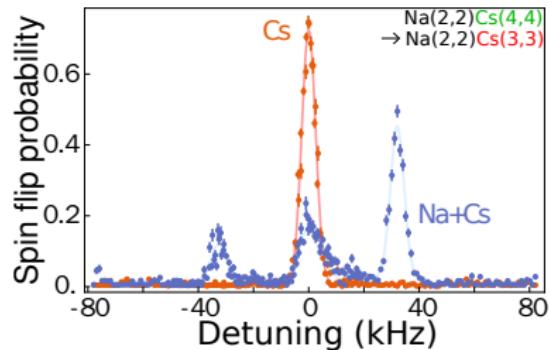
Interaction shift



Interaction shift

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

Interaction



Interaction shift

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To center of mass
and relative coordinates

$$M = m_1 + m_2$$

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

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

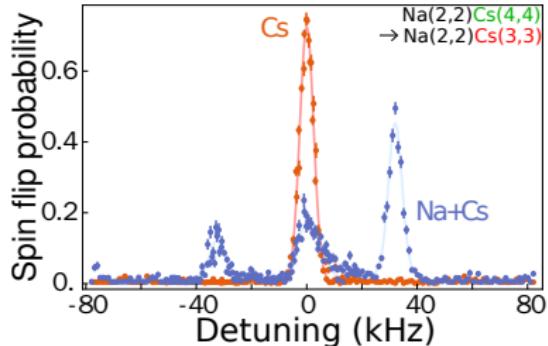
$$\omega_{R,i}^2 = \frac{m_2 \omega_{1,i}^2 + m_1 \omega_{2,i}^2}{m_1 + m_2}$$

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

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

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

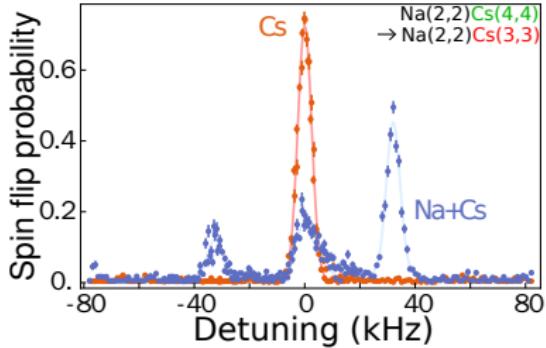
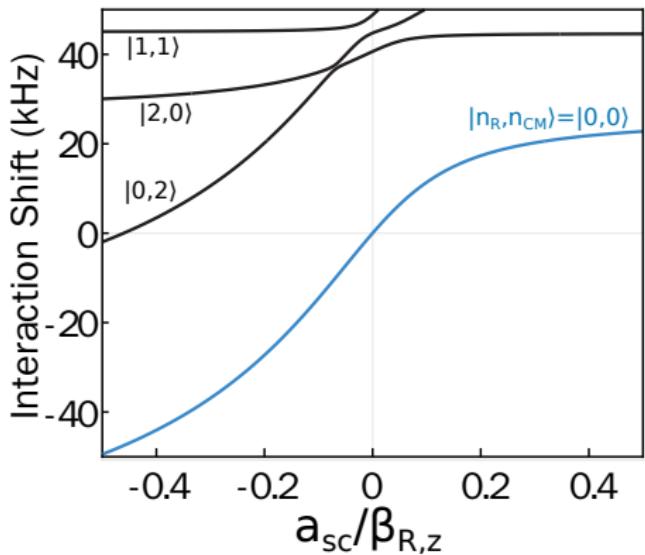
$$p_{R,i} = \frac{m_2 p_{1,i} - m_1 p_{2,i}}{m_1 + m_2}$$



Center of mass

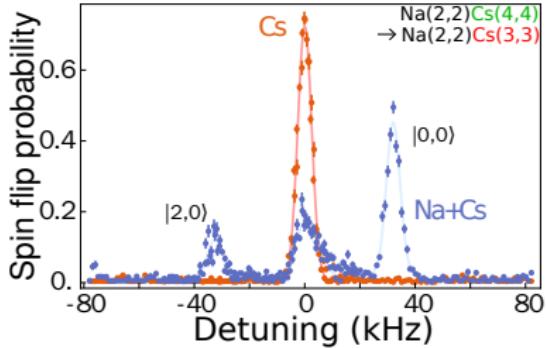
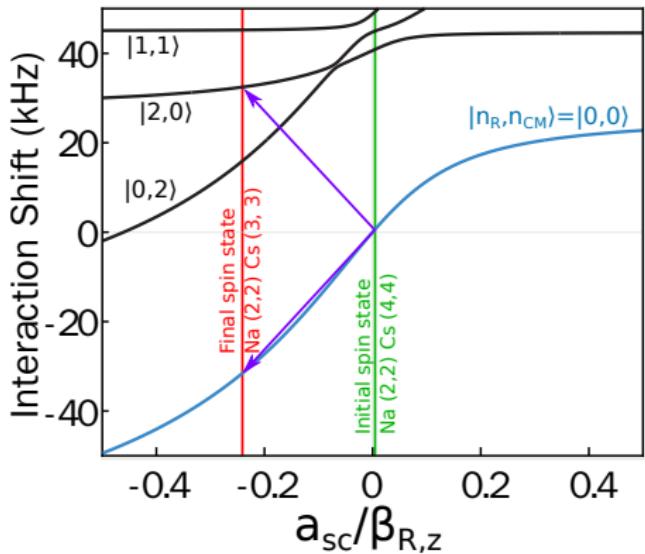
$$H = \underbrace{\sum_{i=x,y,z} \left(\frac{M \Omega_i^2 X_i^2}{2} + \frac{P_i^2}{2M} \right)}_{\text{Center of mass}} + \underbrace{\sum_{i=x,y,z} \left(\frac{\mu \omega_{R,i}^2 X_{R,i}^2}{2} + \frac{p_{R,i}^2}{2\mu} \right) + V_{int}(\vec{r}_R)}_{\text{Relative}} + \underbrace{\sum_{i=x,y,z} \mu (\omega_{1,i}^2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

Interaction shift



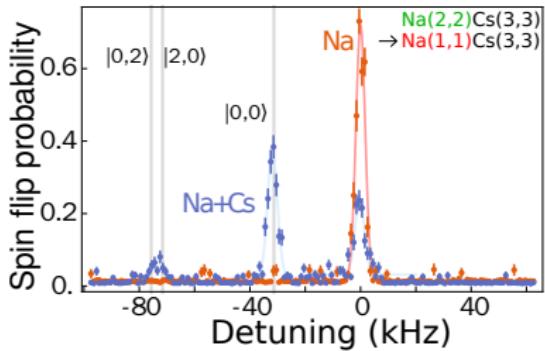
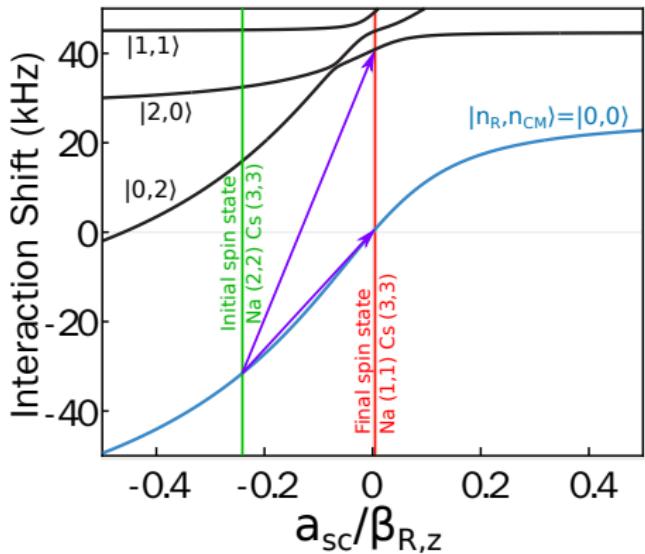
$$H = \underbrace{\sum_{i=x,y,z} \left(\frac{M\Omega_i^2 X_i^2}{2} + \frac{P_i^2}{2M} \right)}_{\text{Center of mass}} + \underbrace{\sum_{i=x,y,z} \left(\frac{\mu\omega_{R,i}^2 X_{R,i}^2}{2} + \frac{p_{R,i}^2}{2\mu} \right) + V_{int}(\vec{r}_R)}_{\text{Relative}} + \underbrace{\sum_{i=x,y,z} \mu(\omega_{1,i}^2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

Interaction shift



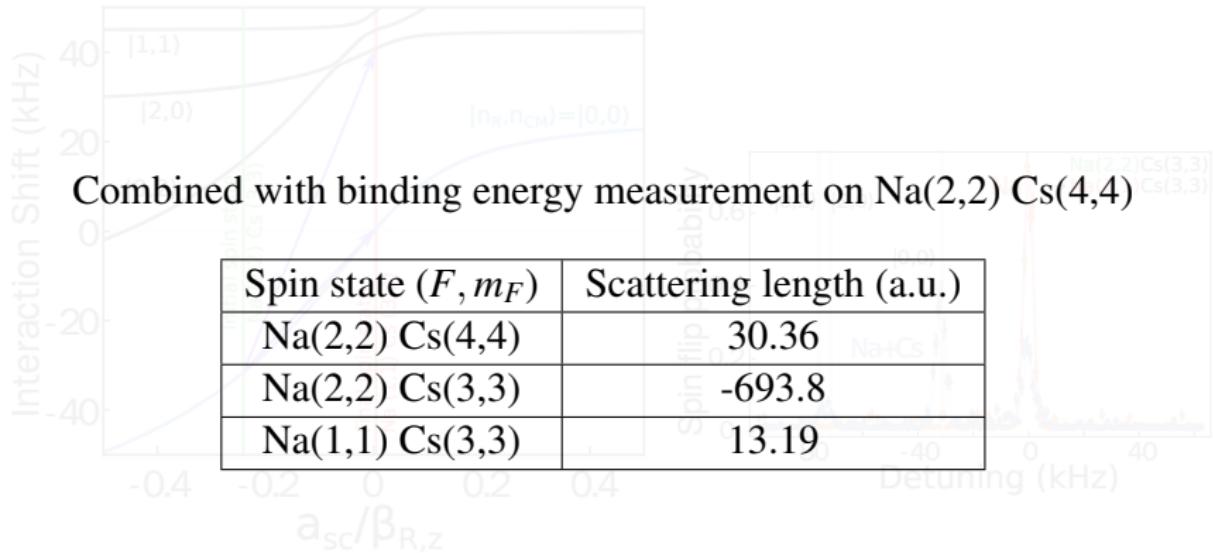
$$H = \underbrace{\sum_{i=x,y,z} \left(\frac{M\Omega_i^2 X_i^2}{2} + \frac{P_i^2}{2M} \right)}_{\text{Center of mass}} + \underbrace{\sum_{i=x,y,z} \left(\frac{\mu\omega_{R,i}^2 X_{R,i}^2}{2} + \frac{p_{R,i}^2}{2\mu} \right) + V_{int}(\vec{r}_R)}_{\text{Relative}} + \underbrace{\sum_{i=x,y,z} \mu(\omega_{1,i}^2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

Interaction shift



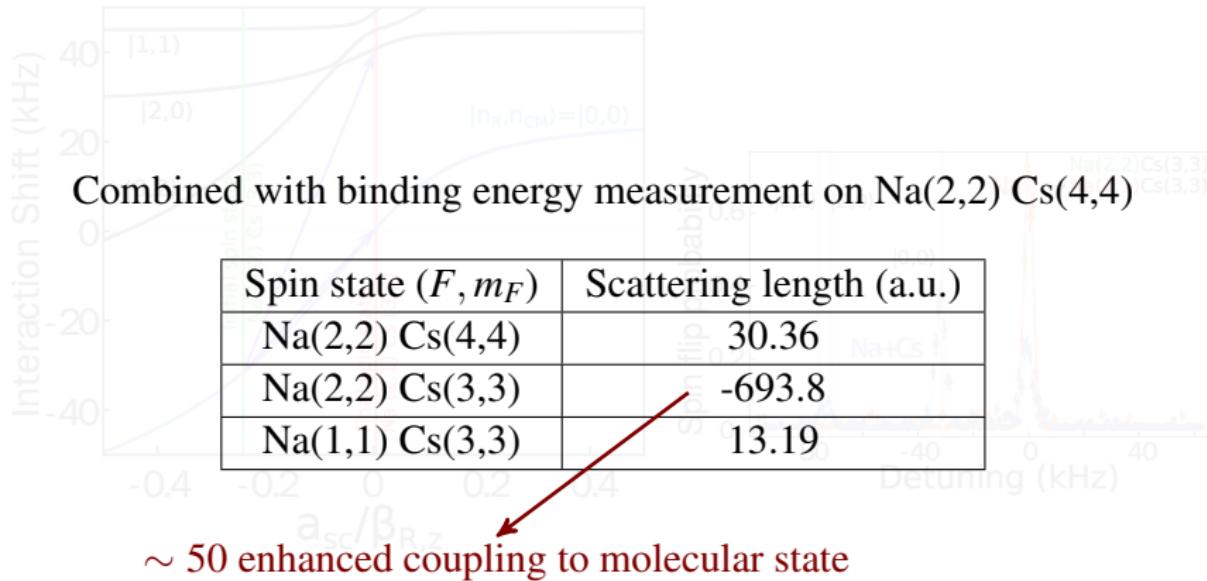
$$H = \underbrace{\sum_{i=x,y,z} \left(\frac{M\Omega_i^2 X_i^2}{2} + \frac{P_i^2}{2M} \right)}_{\text{Center of mass}} + \underbrace{\sum_{i=x,y,z} \left(\frac{\mu\omega_{R,i}^2 X_{R,i}^2}{2} + \frac{p_{R,i}^2}{2\mu} \right) + V_{int}(\vec{r}_R)}_{\text{Relative}} + \underbrace{\sum_{i=x,y,z} \mu(\omega_{1,i}^2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

Interaction shift



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

Interaction shift

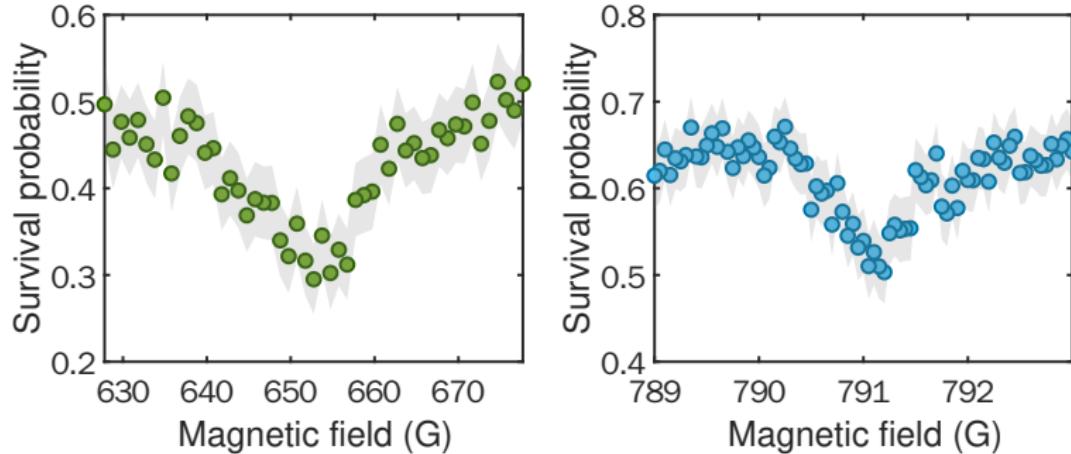


$$H = \underbrace{\sum_{i=x,y,z} \left(\frac{M\Omega_i^2 X_i^2}{2} + \frac{P_i^2}{2M} \right)}_{\text{Center of mass}} + \underbrace{\sum_{i=x,y,z} \left(\frac{\mu\omega_{R,i}^2 X_{R,i}^2}{2} + \frac{P_{R,i}^2}{2\mu} \right) + V_{int}(\vec{r}_R)}_{\text{Relative}} + \underbrace{\sum_{i=x,y,z} \mu(\omega_{1,i}^2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

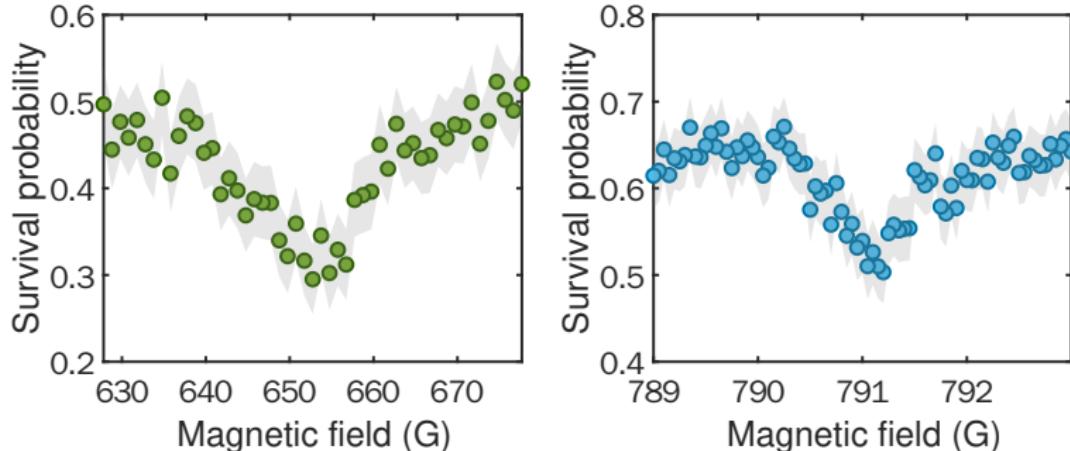
Na (1, -1) Cs (3, -3) Feshbach resonance



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



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

Summary

- A single Na and Cs atom prepared in the motional ground state of the same optical tweezer.
- Photoassociation and Raman transfer to weakly-bound state.
- Characterized Na-Cs scattering and observed first Feshbach resonances.

