

# Building Single Molecules from Single Atoms

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Ni Group/Harvard

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# Atom

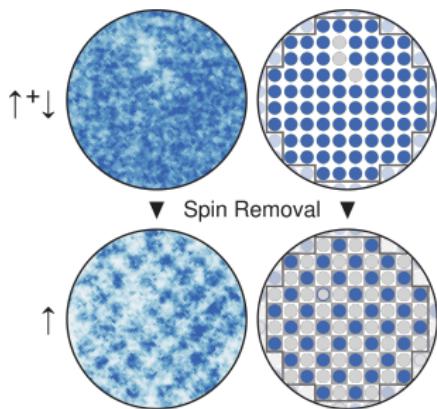
- Laser cooling/trapping
- Internal state control
- High fidelity imagining

⋮

## Atom

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

⋮

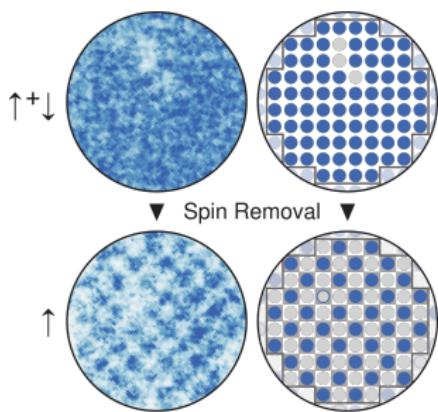


Nature 545, 462-466 (2017)

## Atom

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

⋮



## Molecule

- Strong interaction
- Rich internal structure

Nature 545, 462-466 (2017)

## Direct molecule cooling

# Path to Ultracold Molecules

**Direct molecule cooling**

**Making molecule from atoms**

# Path to Ultracold Molecules

**Assemble molecule in tweezers**

**Making molecule from atoms**

# Outline

1 System Overview

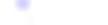
2 Trapping and Cooling of Atoms

3 Atom-Atom Interaction and Molecule Formation

# Steps



Loading



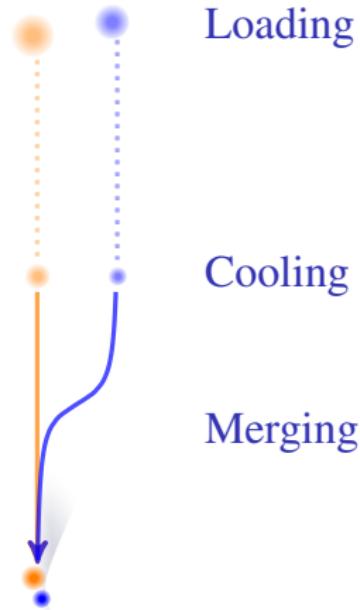
# Steps



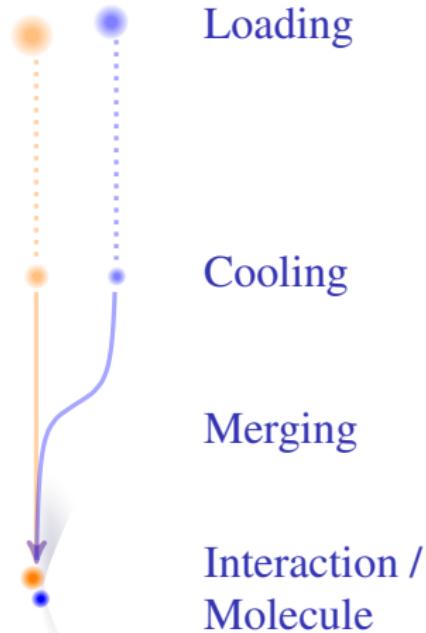
Loading

Cooling

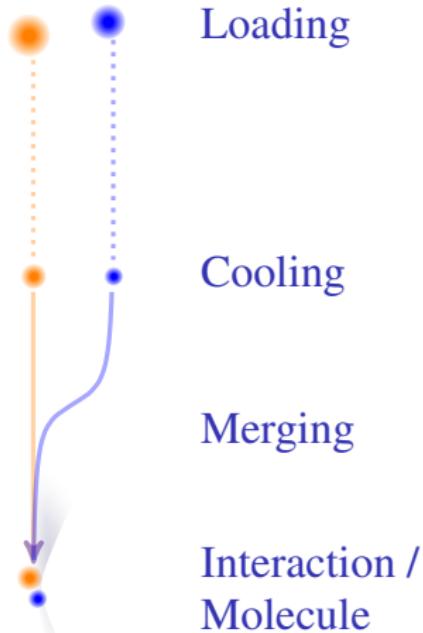
# Steps



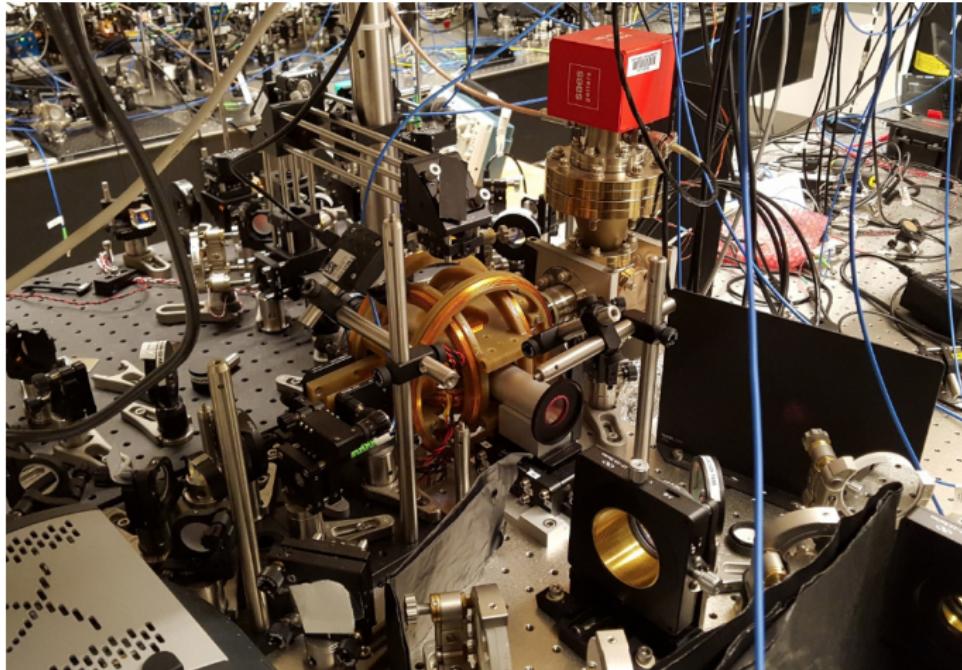
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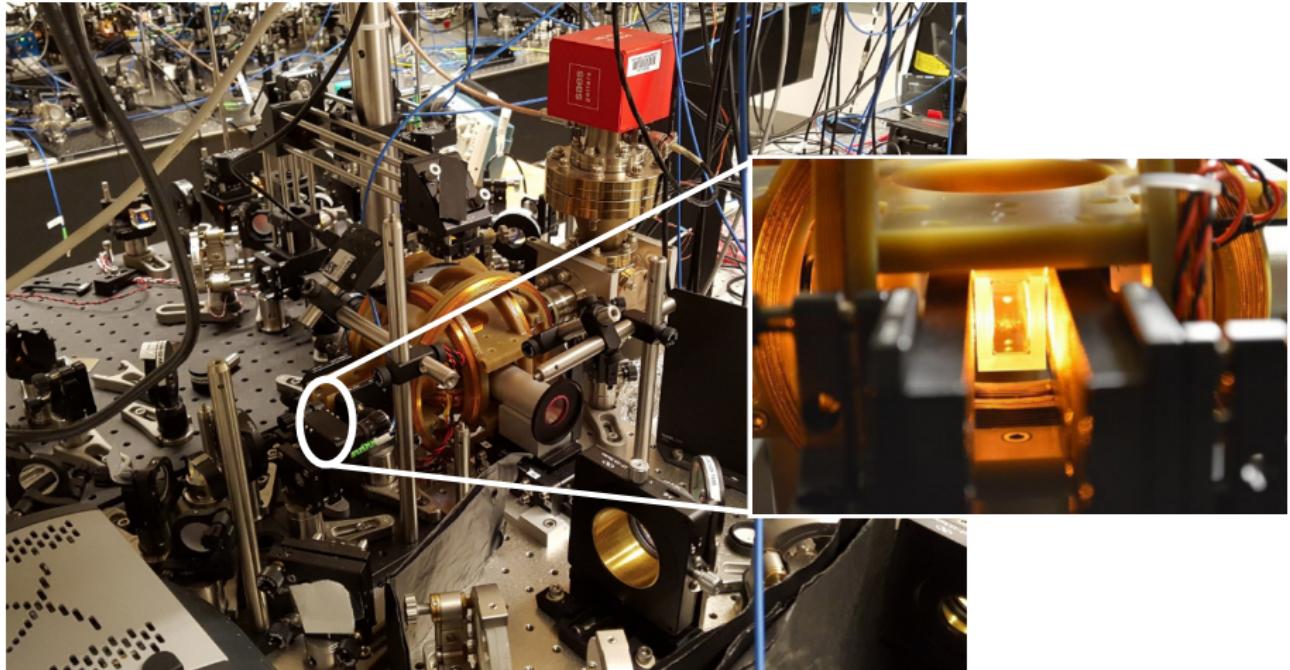


# Steps



Science 360 6391, 2018





# Single Atom in Tweezer

# Raman Sideband Cooling

# Outline

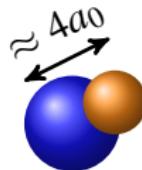
1 System Overview

2 Trapping and Cooling of Atoms

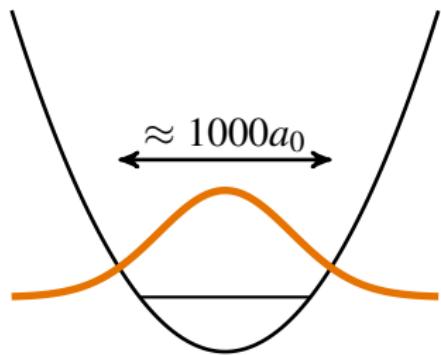
3 Atom-Atom Interaction and Molecule Formation

# Optical Transfer to Molecular State

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



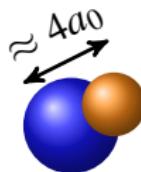
Molecule



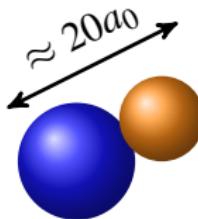
Atoms

# Optical Transfer to Molecular State

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

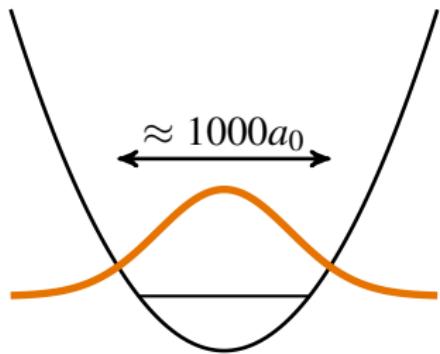


Binding energy  
 $\approx 300\text{MHz}$



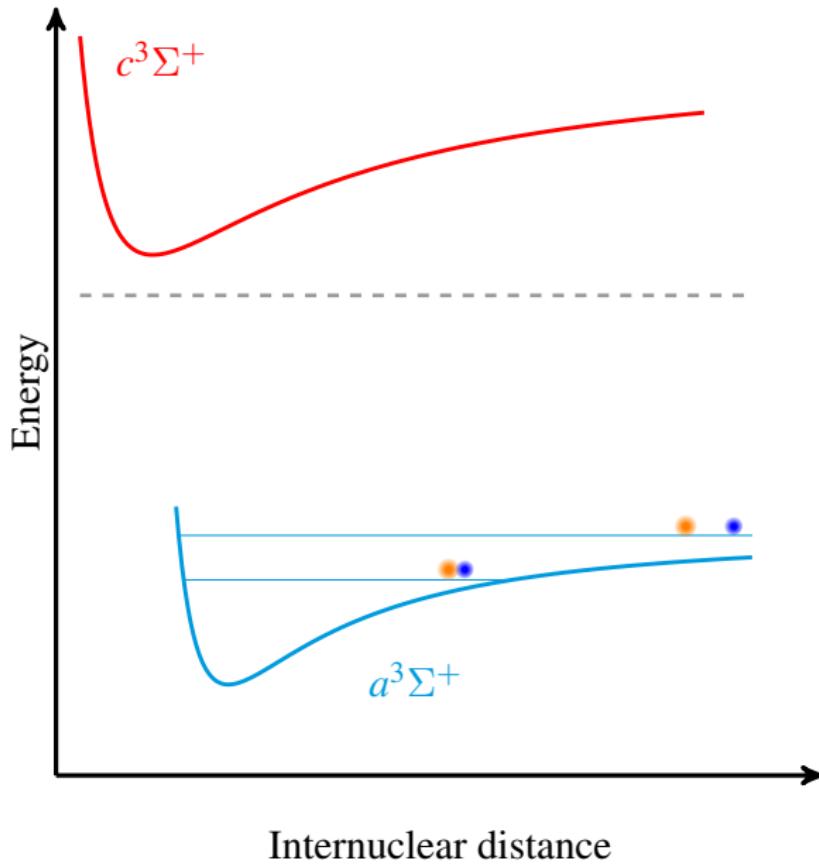
Molecule

Weakly-Bound  
Molecule



Atoms

# Optical Transfer to Molecular State

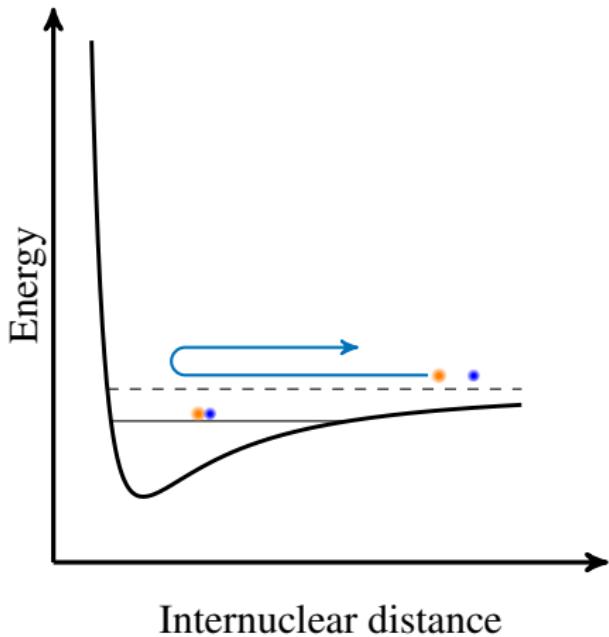


# Photoassociation (PA) Spectroscopy

# Optical Transfer to Weakly-Bound Molecular

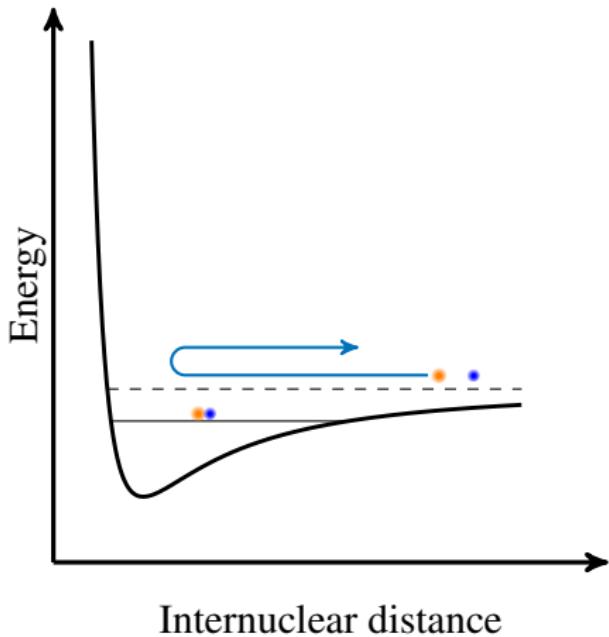
## Scattering length $a$

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



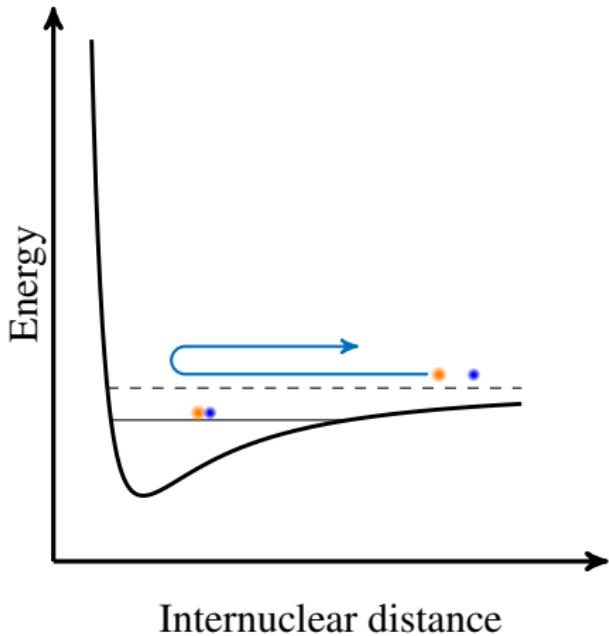
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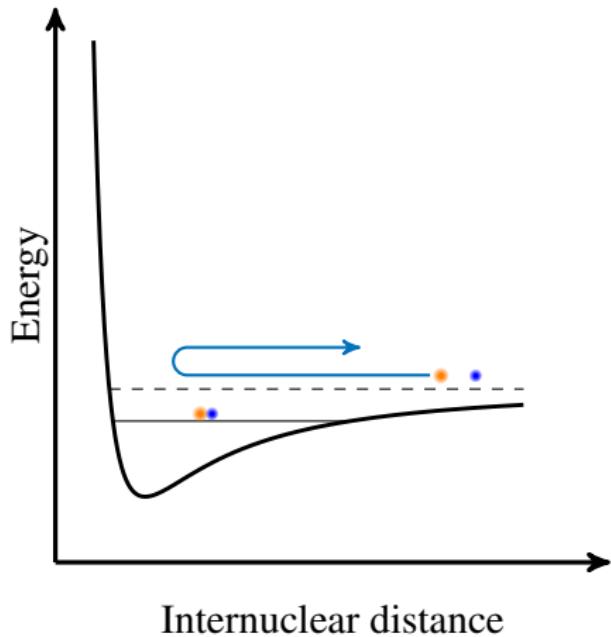
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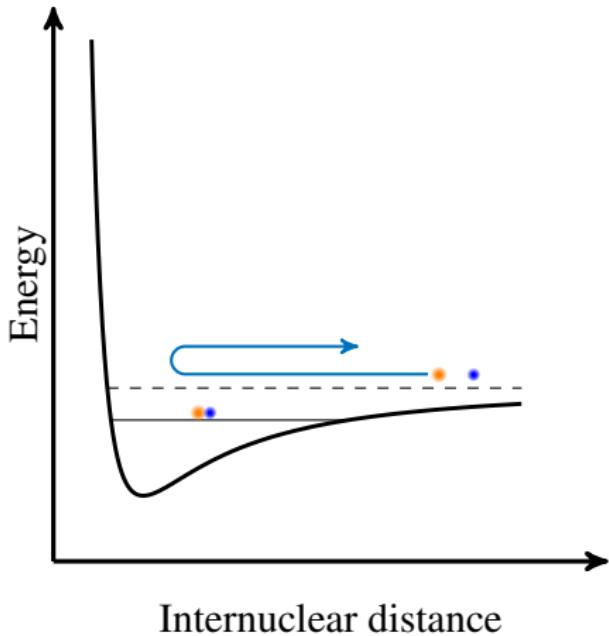
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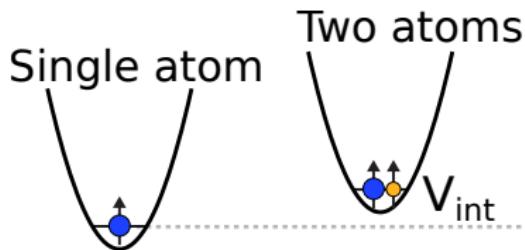


## Scattering length $a$

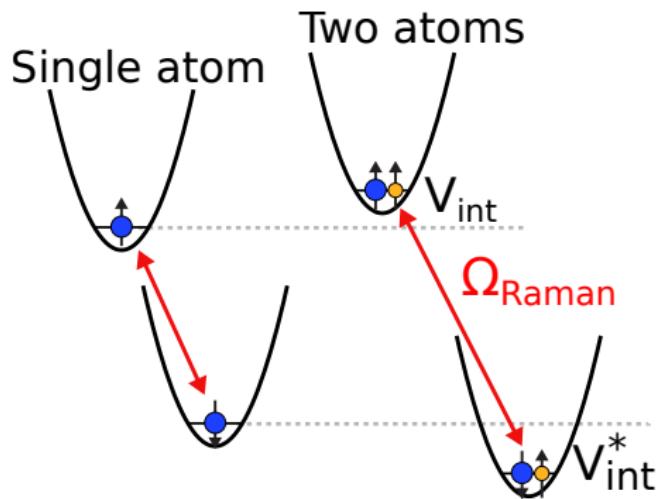
- Binding energy
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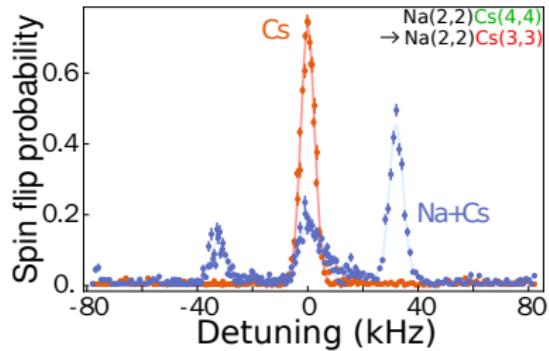
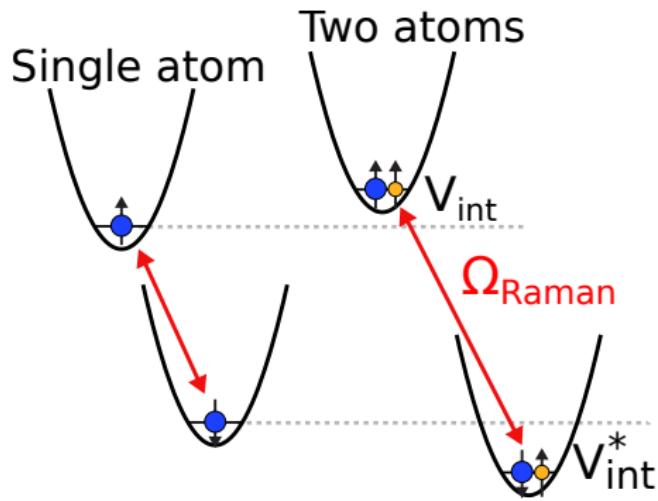
## Interaction shift



## Interaction shift



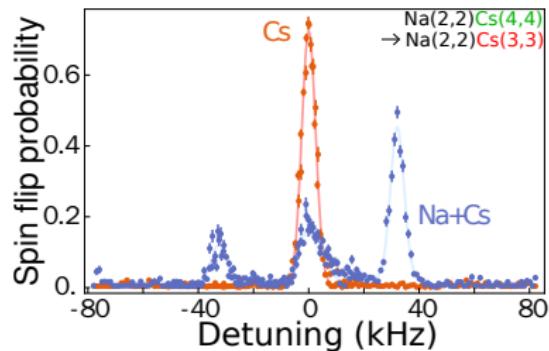
## Interaction shift



## 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

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

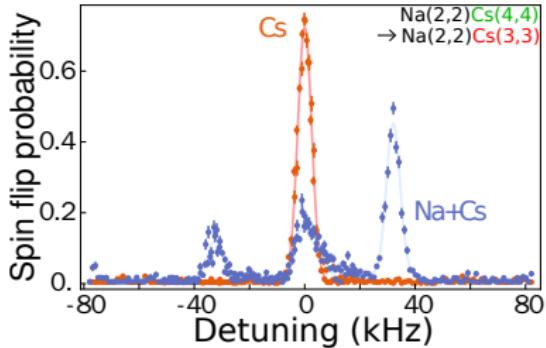
To center of mass  
and relative coordinates

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

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

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

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



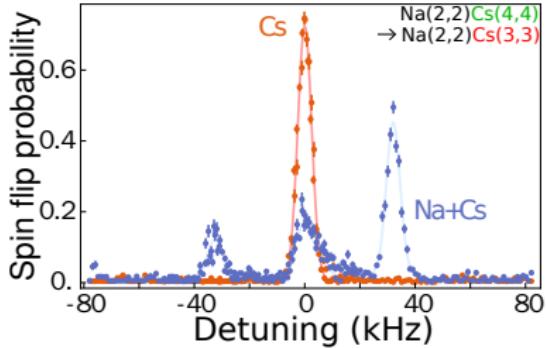
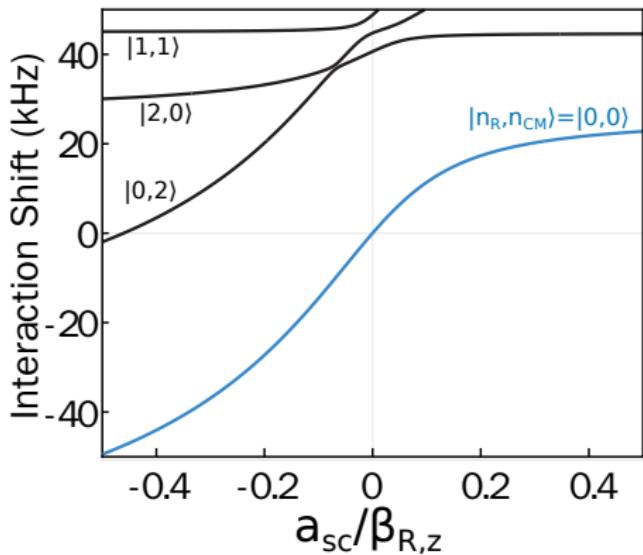
### Center of mass

## Relative

## Mixing

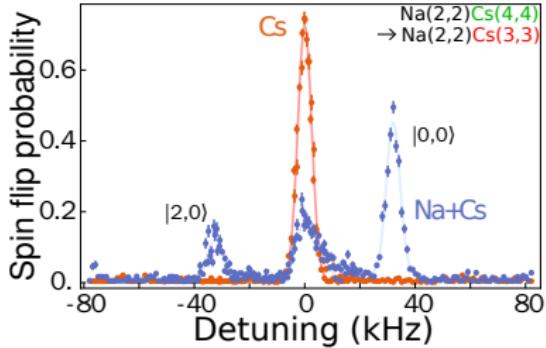
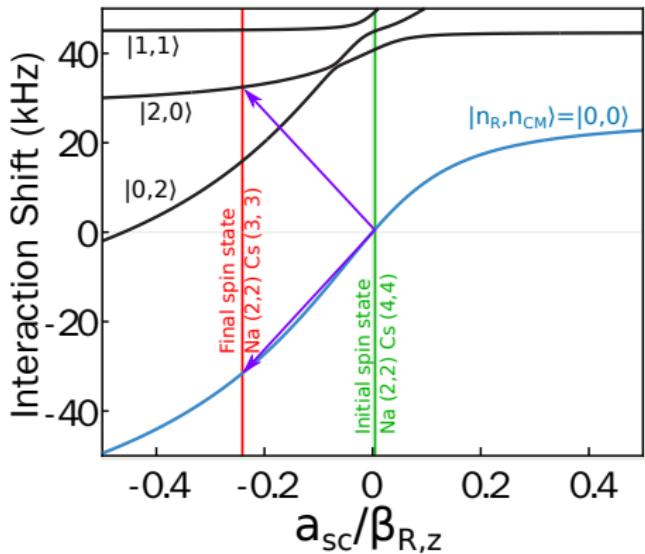
$$H = \underbrace{\sum_{i=x,y,z} \left( \frac{M\Omega_i^2 X_i^2}{2} + \frac{P_i^2}{2M} \right)}_{\text{kinetic energy}} + \underbrace{\sum_{i=x,y,z} \left( \frac{\mu\omega_{R,i}^2 X_{R,i}^2}{2} + \frac{p_{R,i}^2}{2\mu} \right) + V_{int}(\vec{r}_R)}_{\text{potential energy}} + \underbrace{\sum_{i=x,y,z}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

# Interaction shift



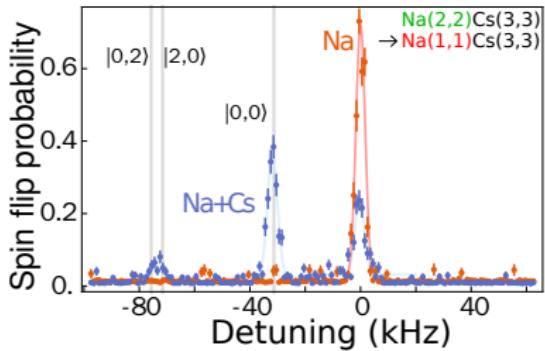
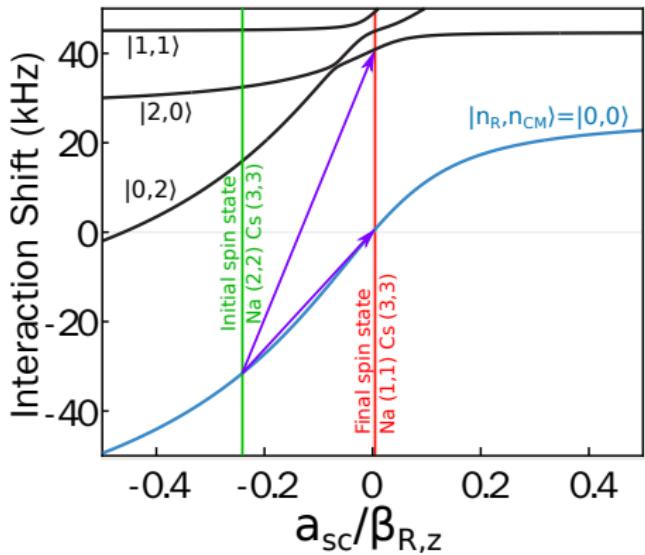
$$H = \underbrace{\sum_{i=x,y,z} \left( \frac{M\Omega_i^2 X_i^2}{2} + \frac{P_i^2}{2M} \right)}_{\text{Center of mass}} + \underbrace{\sum_{i=x,y,z} \left( \frac{\mu\omega_{R,i}^2 X_{R,i}^2}{2} + \frac{p_{R,i}^2}{2\mu} \right) + V_{int}(\vec{r}_R)}_{\text{Relative}} + \underbrace{\sum_{i=x,y,z} \mu(\omega_{1,i}^2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

# Interaction shift



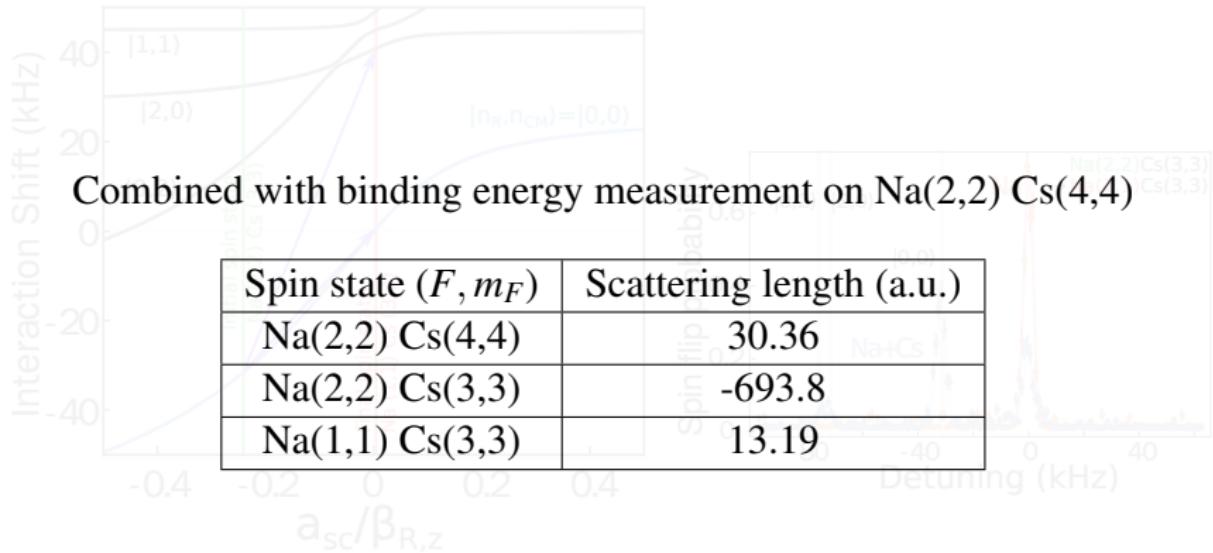
$$H = \underbrace{\sum_{i=x,y,z} \left( \frac{M\Omega_i^2 X_i^2}{2} + \frac{P_i^2}{2M} \right)}_{\text{Center of mass}} + \underbrace{\sum_{i=x,y,z} \left( \frac{\mu\omega_{R,i}^2 X_{R,i}^2}{2} + \frac{p_{R,i}^2}{2\mu} \right) + V_{int}(\vec{r}_R)}_{\text{Relative}} + \underbrace{\sum_{i=x,y,z} \mu(\omega_{1,i}^2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

# Interaction shift



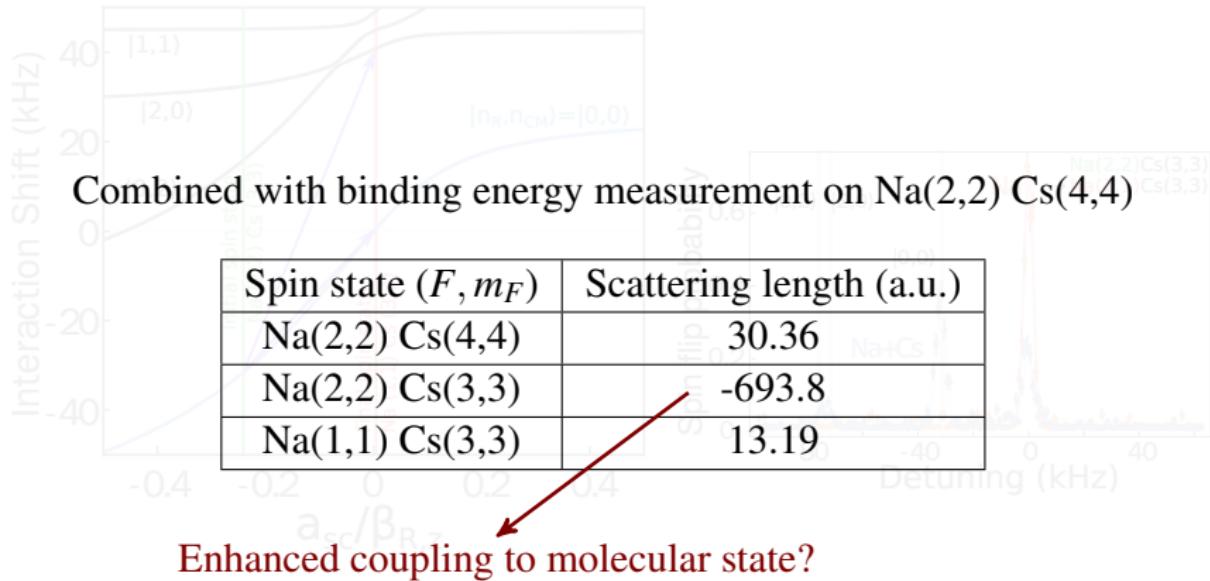
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# Interaction shift



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# Interaction shift

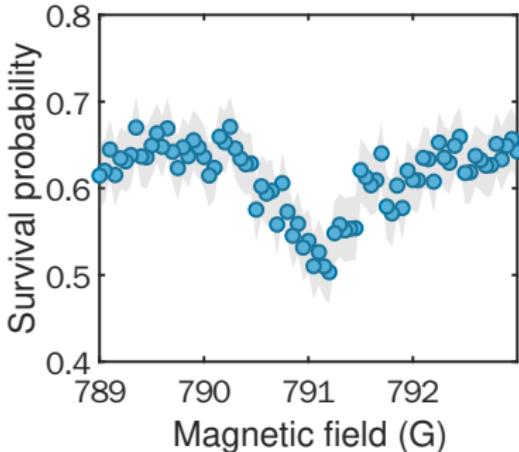
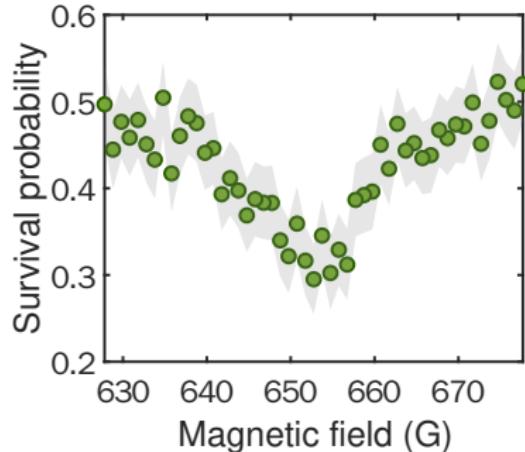


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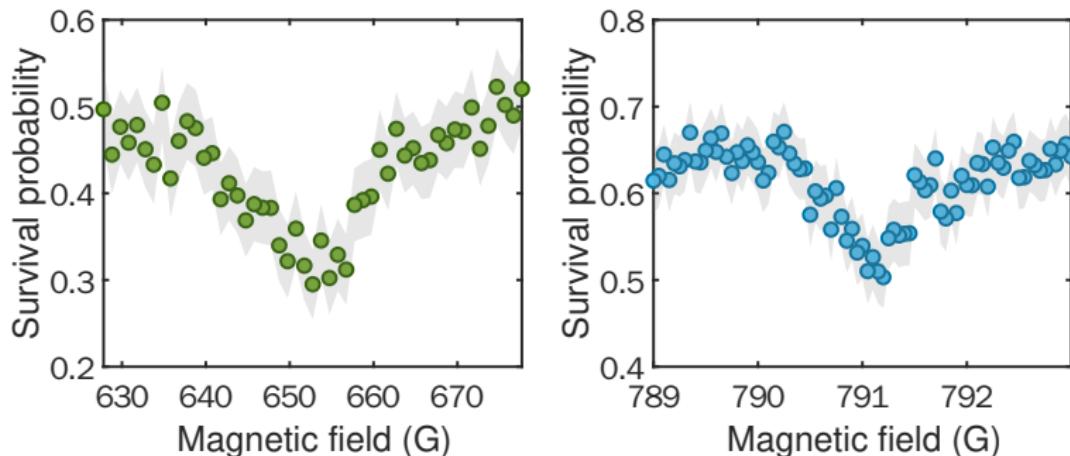
## Na (1, -1) Cs (3, -3) Feshbach resonance



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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) <sup>1</sup>	663 G	799 G
Measured	652(3) G	791.2(2) G

<sup>1</sup>In collaboration with Bo Gao



