

Building Single Molecules from Single Atoms

Yichao Yu

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Jessie T. Zhang, Eliot Fenton, Yen-Wei Lin

Ni Group/Harvard

Sep 5, 2019

Atom

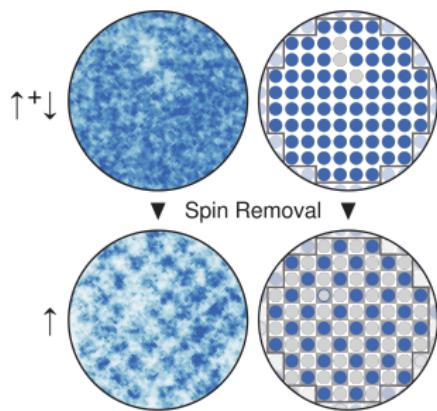
- Laser cooling/trapping
 - Internal state control
 - High fidelity imagining
- ⋮

From Atom to Molecule

Atom

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

⋮



Nature 545, 462-466 (2017)

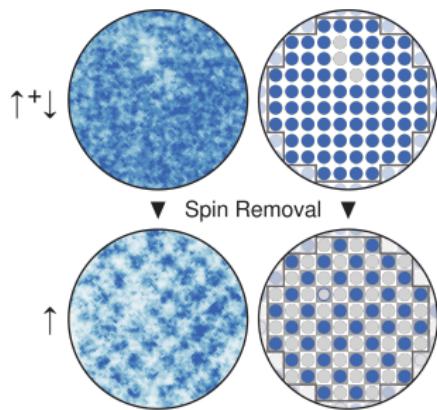
From Atom to Molecule

Atom

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

Molecule

- Strong interaction
- Rich internal structure



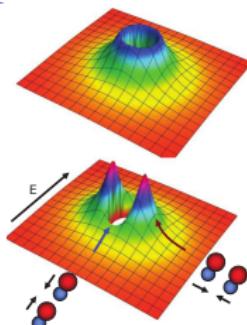
Nature 545, 462-466 (2017)

From Atom to Molecule

Atom

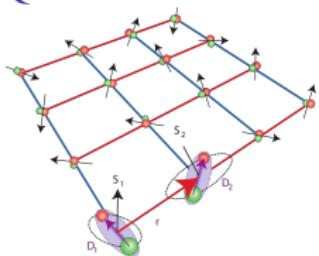
- Laser cooling/trapping
- Internal state control
- High fidelity imaging

Quantum Chemistry



Nature 464, 1324 (2010)

Quantum Simulation

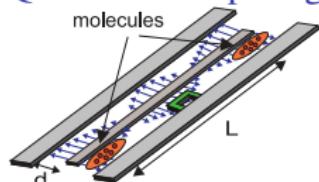


Nat. Phys. 2, 341 (2006)

Molecule

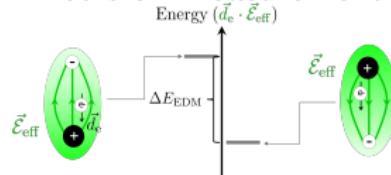
- Strong interaction
- Rich internal structure

Quantum Computing



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

Precision Measurement



Science 343, p. 269-272 (2014)

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



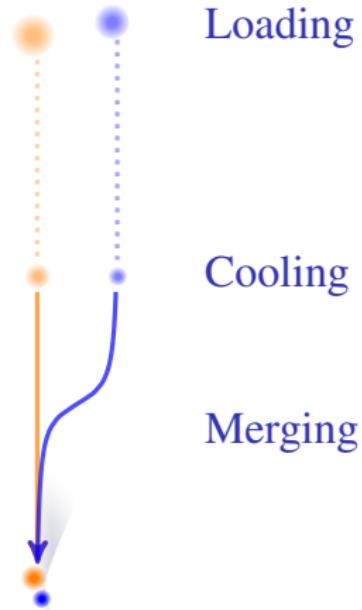
Steps



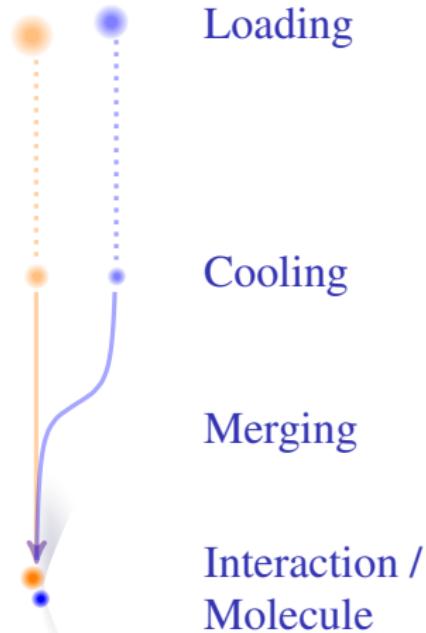
Loading

Cooling

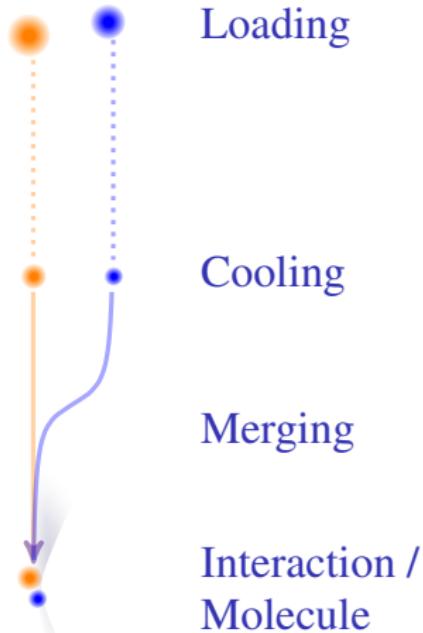
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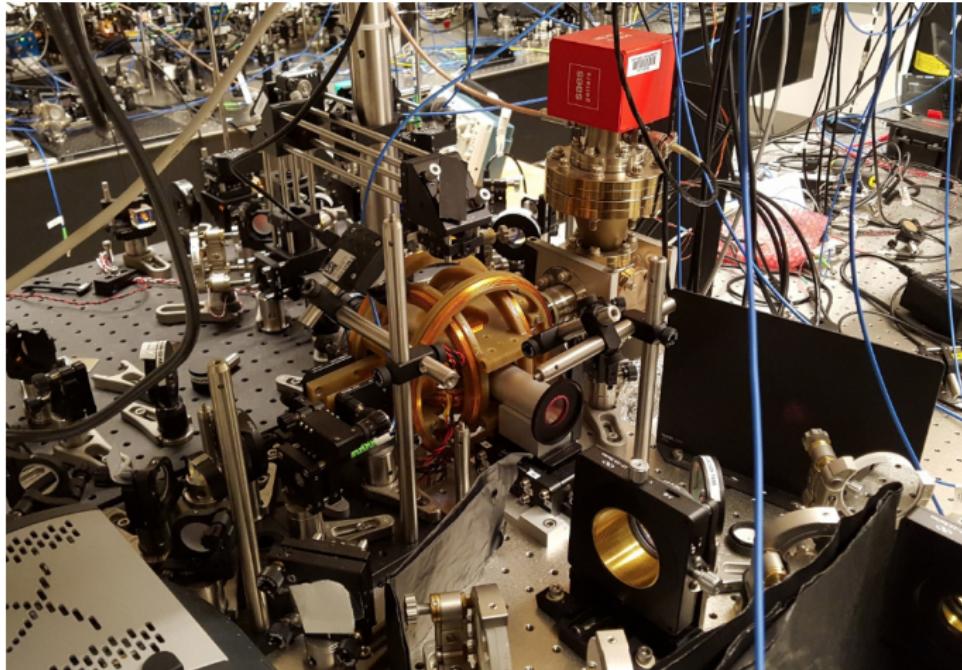
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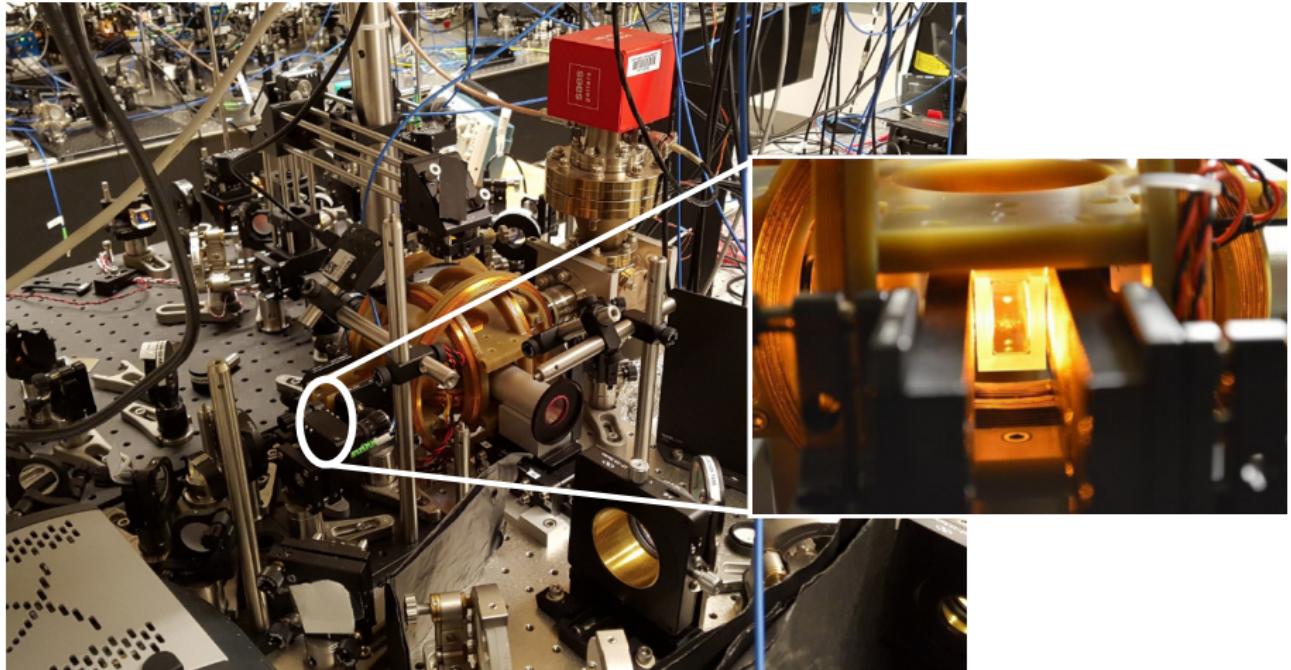


Steps



Science 360 6391, 2018





Single Atom in Tweezer

Raman Sideband Cooling

Outline

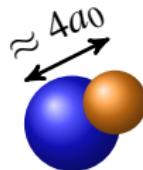
1 System Overview

2 Trapping and Cooling of Atoms

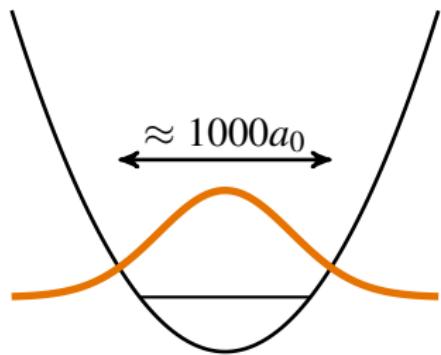
3 Atom-Atom Interaction and Molecule Formation

Optical Transfer to Molecular State

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



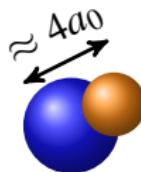
Molecule



Atoms

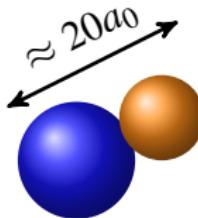
Optical Transfer to Molecular State

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

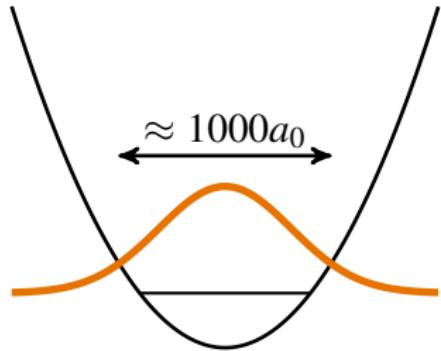


Molecule

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

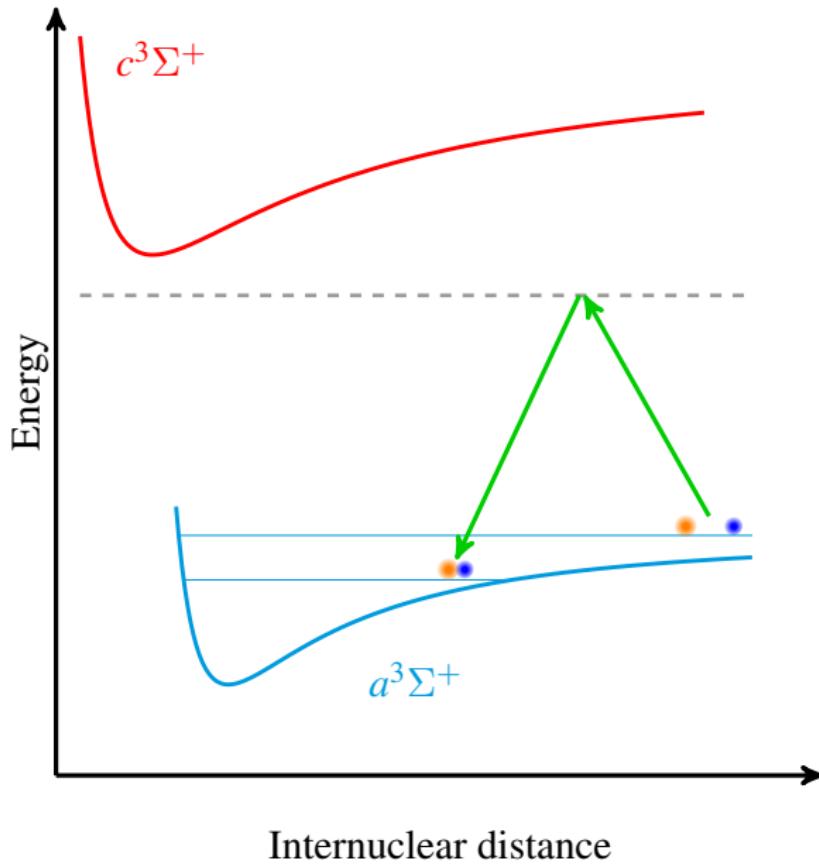


Weakly-Bound
Molecule

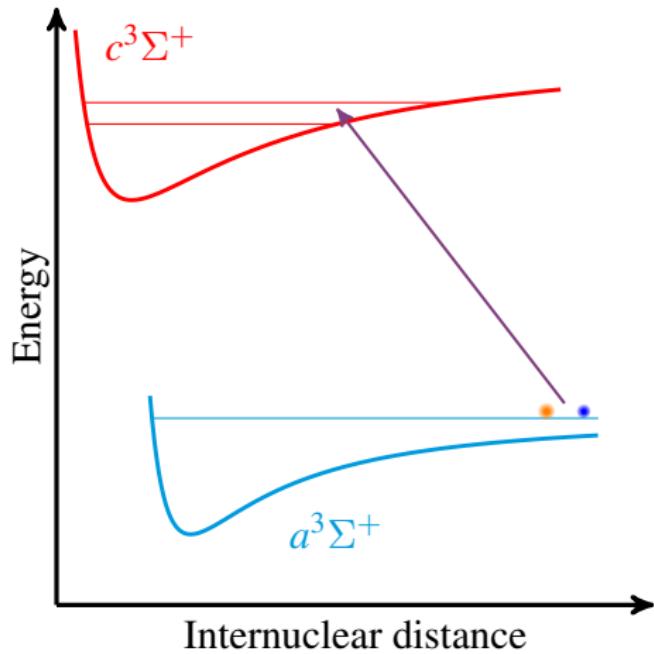


Atoms

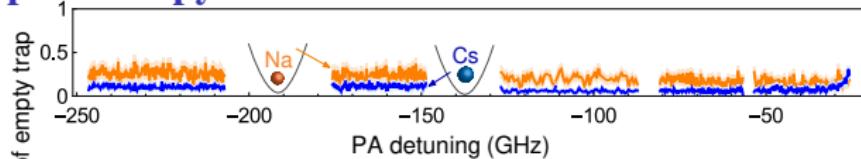
Optical Transfer to Molecular State



Photoassociation (PA) Spectroscopy

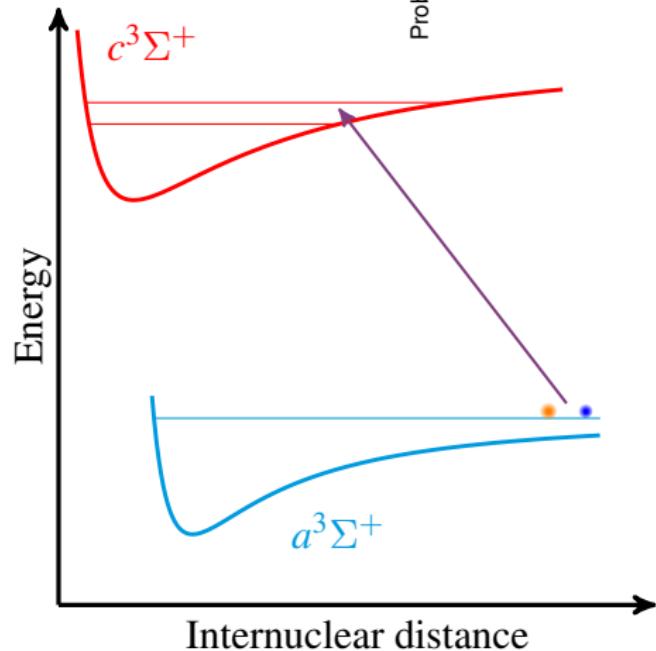


Photoassociation (PA) Spectroscopy

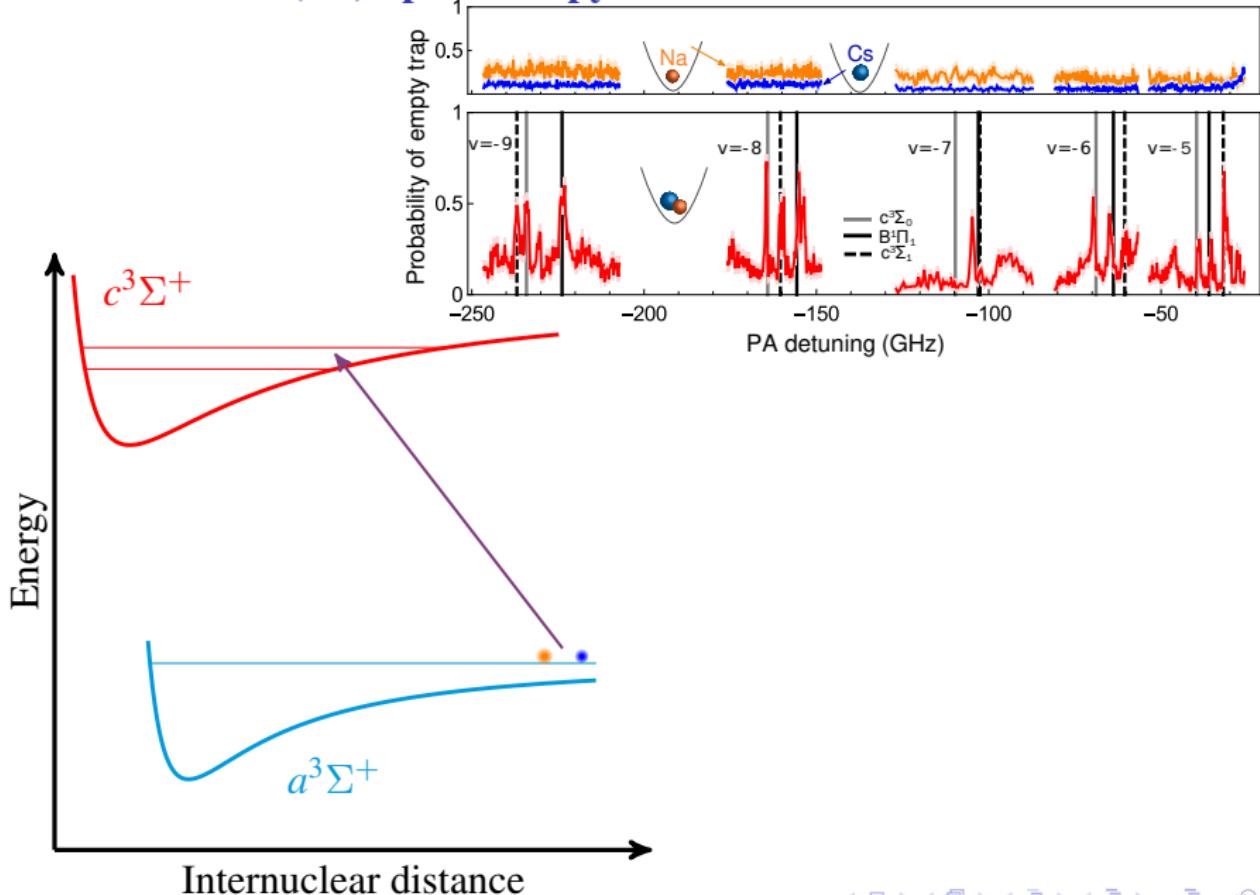


PA detuning (GHz)

Probability of empty trap



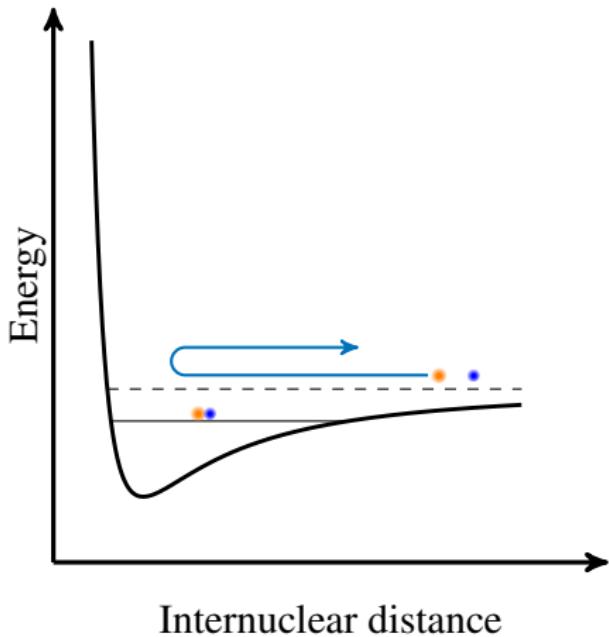
Photoassociation (PA) Spectroscopy



Optical Transfer to Weakly-Bound Molecular

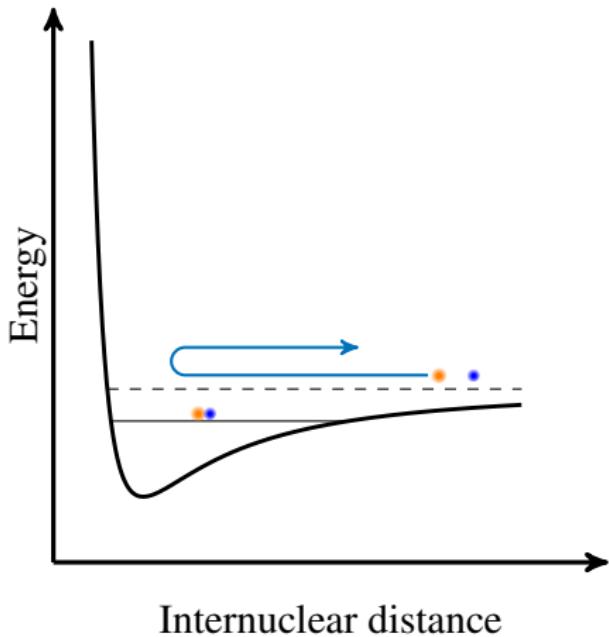
Scattering length a

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



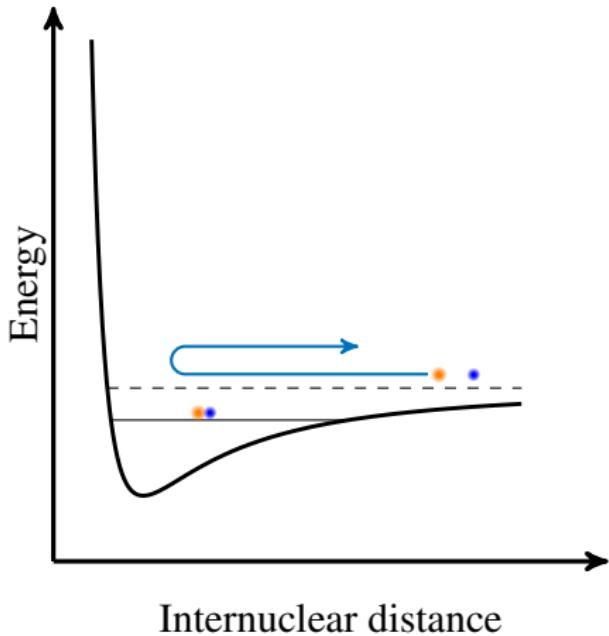
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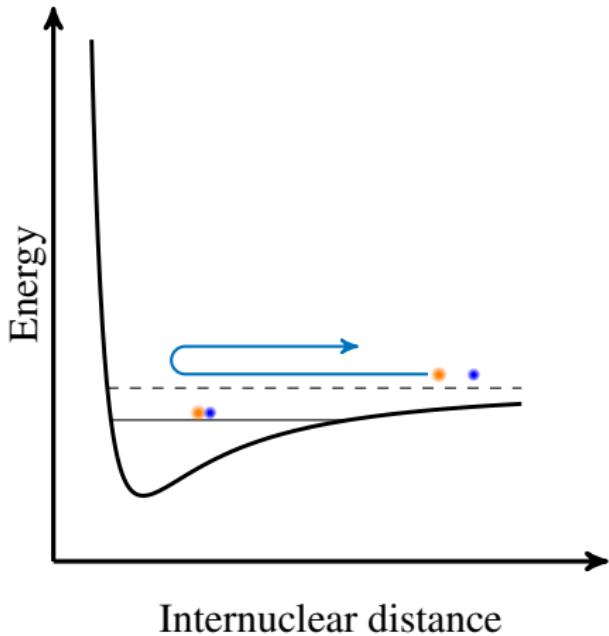
Scattering length a

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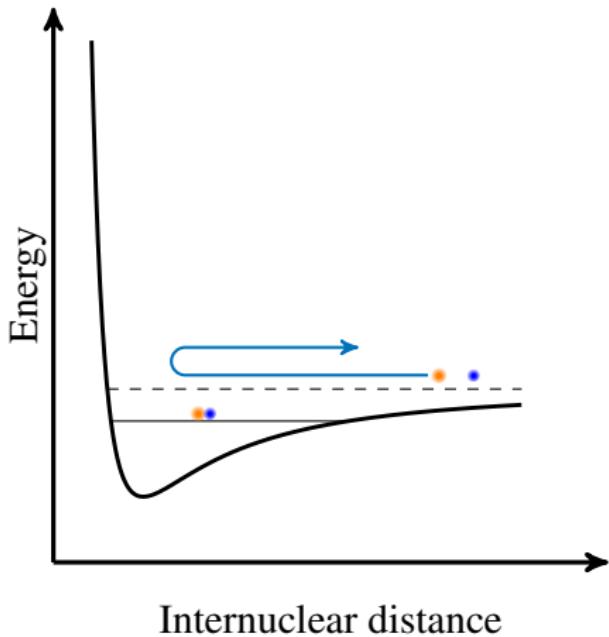
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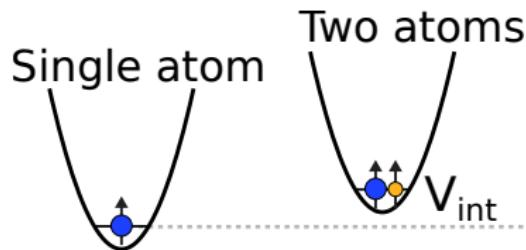


Scattering length a

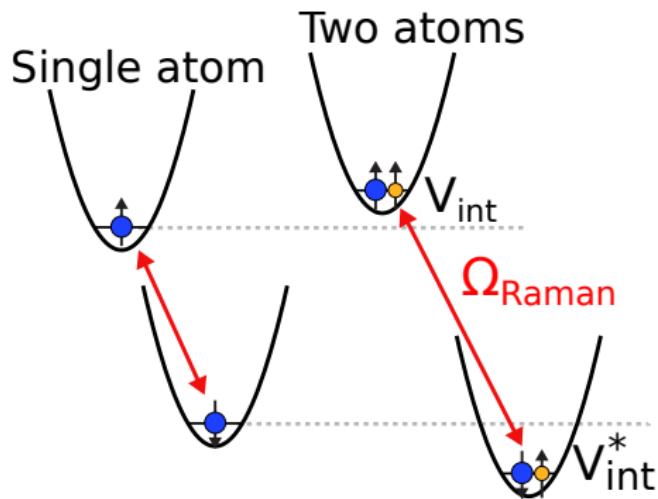
- Binding energy
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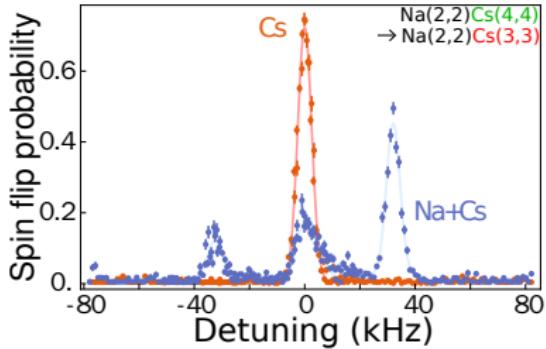
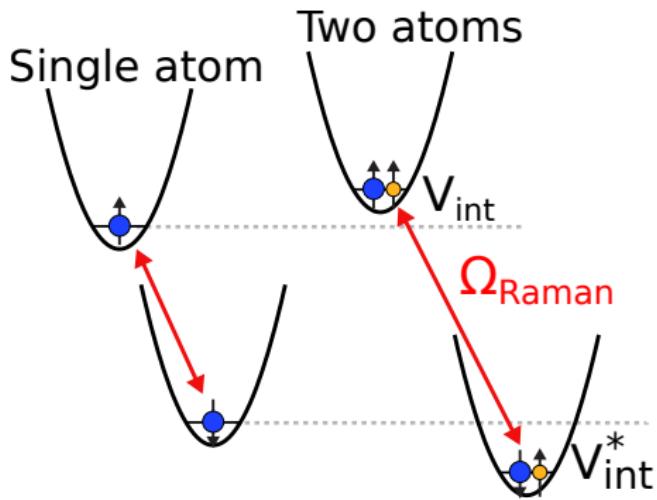
Interaction shift



Interaction shift



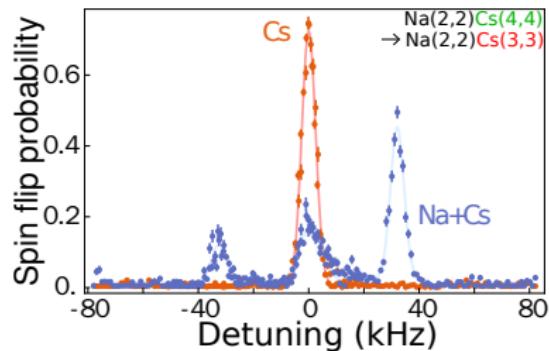
Interaction shift



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

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

To center of mass
and relative coordinates

$$M = m_1 + m_2$$

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

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

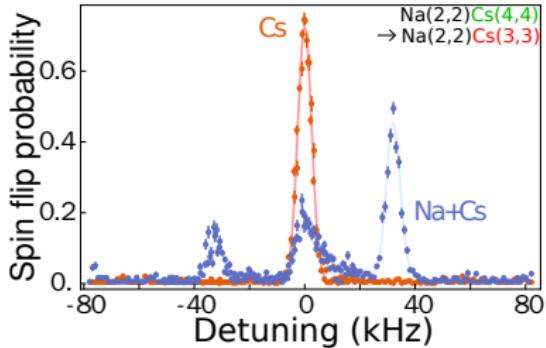
$$\omega_{R,i}^2 = \frac{m_2 \omega_{1,i}^2 + m_1 \omega_{2,i}^2}{m_1 + m_2}$$

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

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

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

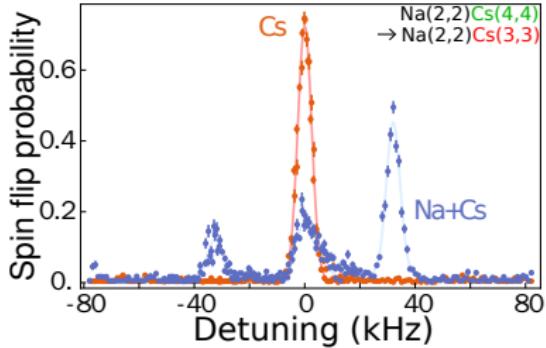
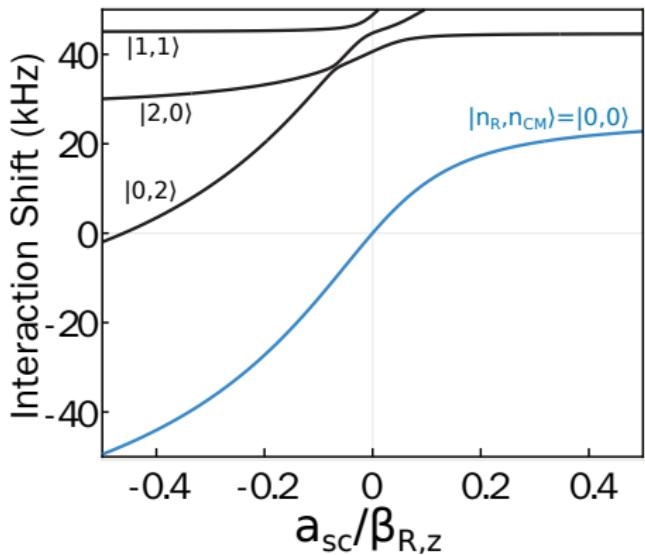
$$p_{R,i} = \frac{m_2 p_{1,i} - m_1 p_{2,i}}{m_1 + m_2}$$



Center of mass

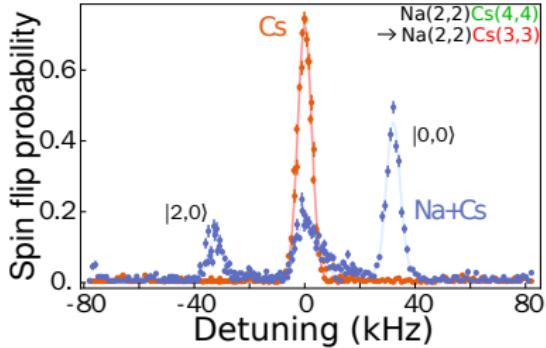
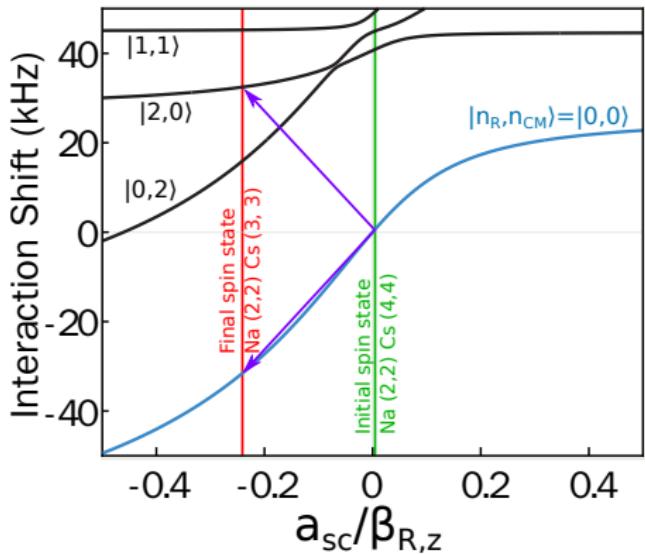
$$H = \underbrace{\sum_{i=x,y,z} \left(\frac{M \Omega_i^2 X_i^2}{2} + \frac{P_i^2}{2M} \right)}_{\text{Center of mass}} + \underbrace{\sum_{i=x,y,z} \left(\frac{\mu \omega_{R,i}^2 X_{R,i}^2}{2} + \frac{p_{R,i}^2}{2\mu} \right) + V_{int}(\vec{r}_R)}_{\text{Relative}} + \underbrace{\sum_{i=x,y,z} \mu (\omega_{1,i}^2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

Interaction shift



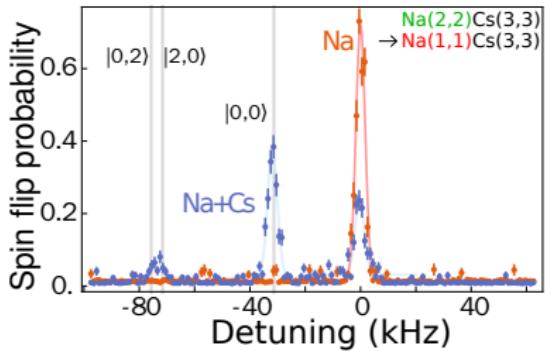
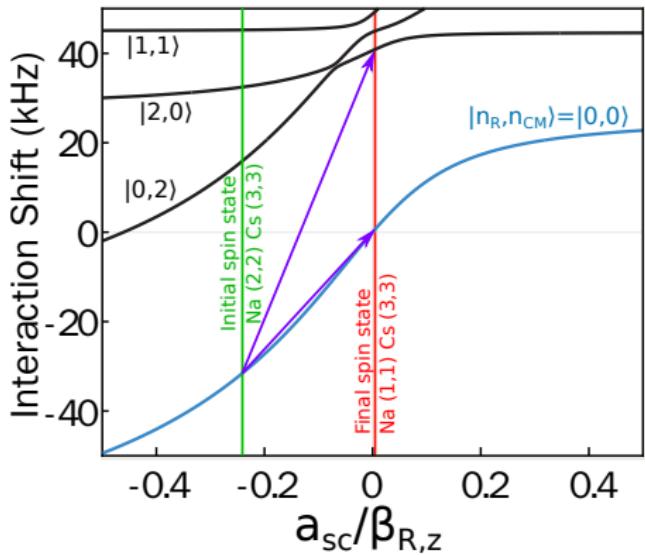
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Interaction shift



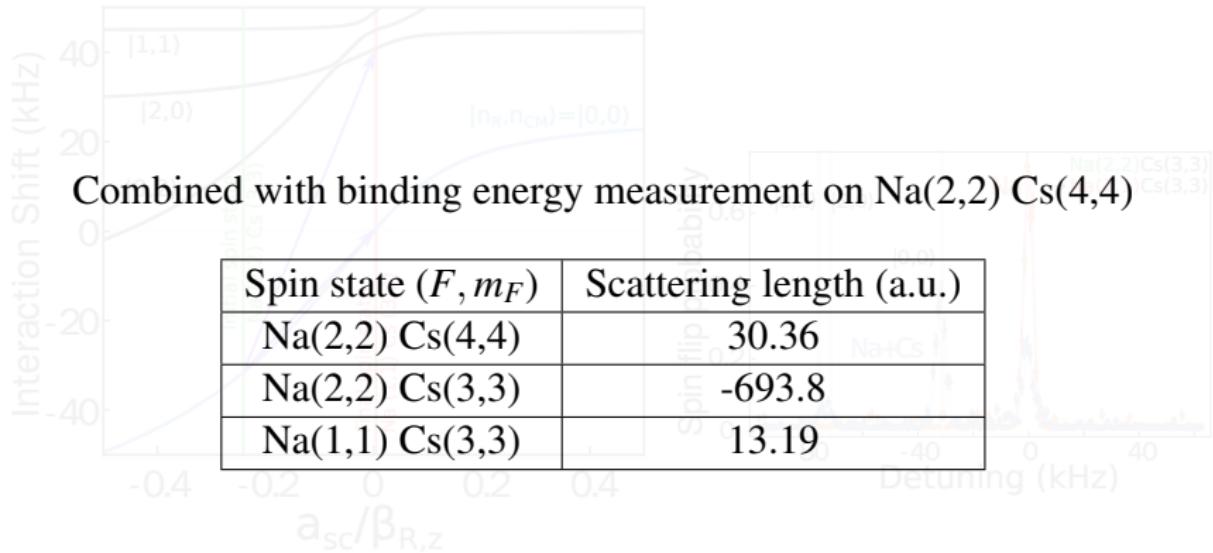
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Interaction shift



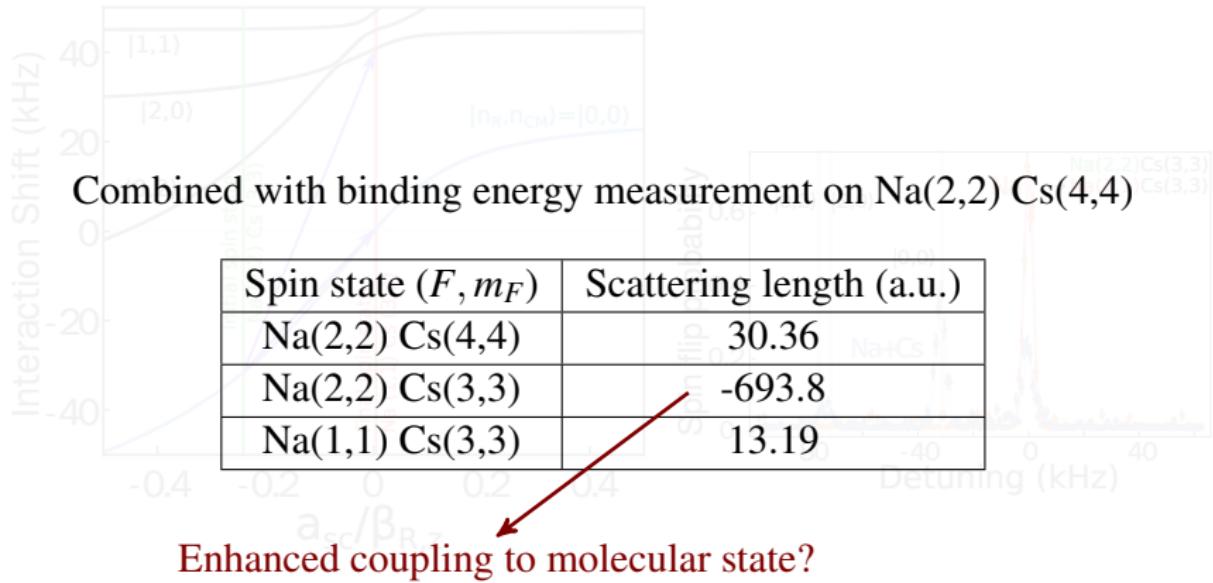
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Interaction shift

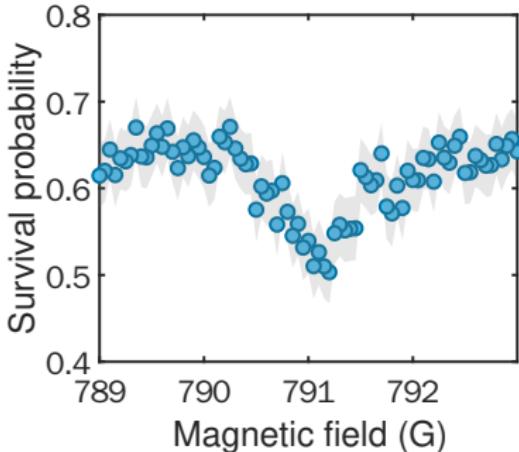
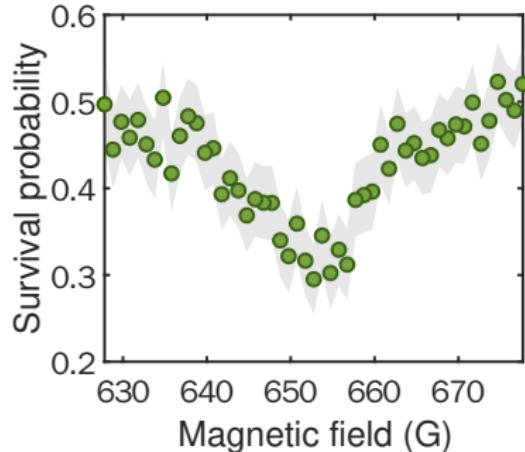


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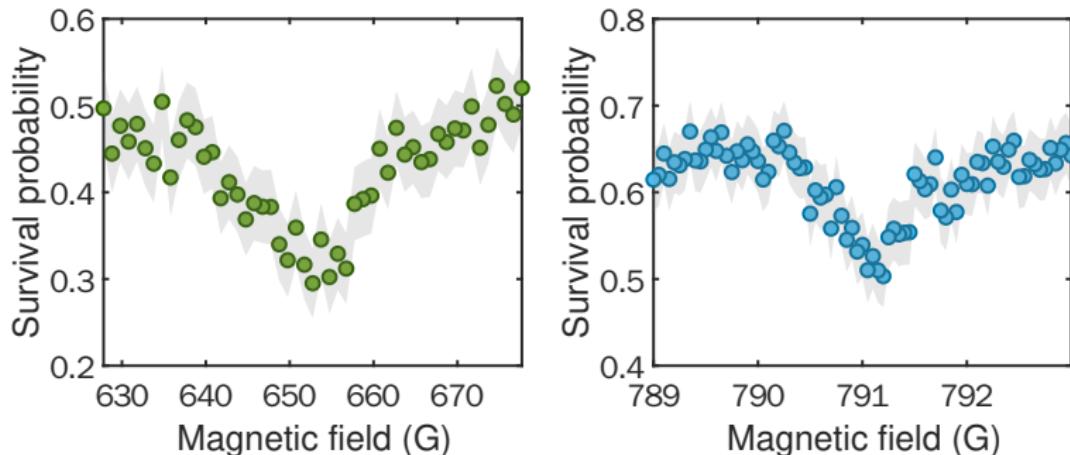
Na (1, -1) Cs (3, -3) Feshbach resonance



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

