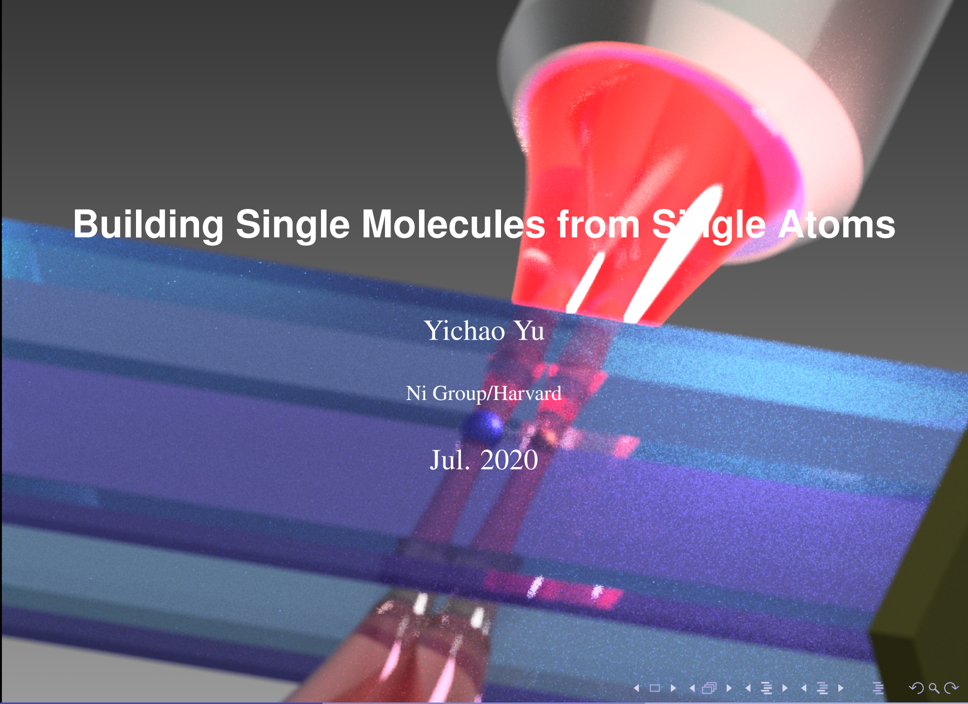


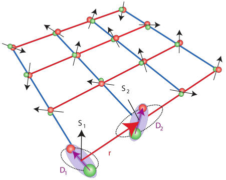
Building Single Molecules from Single Atoms

Yichao Yu

Ni Group/Harvard

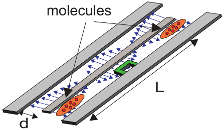
Jul. 2020

Quantum Simulation



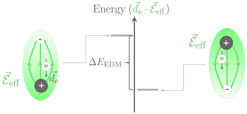
Nat. Phys. 2, 341 (2006)

Quantum Computing



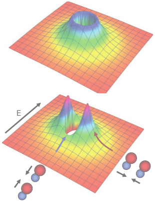
PRL. 97, 33003 (2006)

Precision Measurement



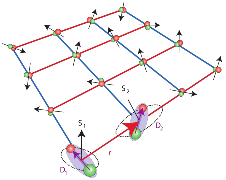
Science 343, p. 269-272 (2014)

Quantum Chemistry



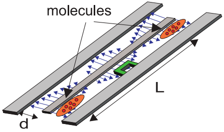
Nature 464, 1324 (2010)

Quantum Simulation



Nat. Phys. 2, 341 (2006)

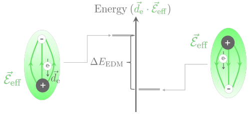
Quantum Computing



PRL. 97, 33003 (2006)

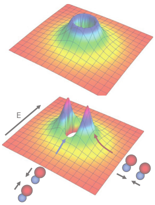
- Full quantum control
- Entanglement
- . . .

Precision Measurement



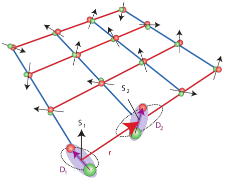
Science 343, p. 269-272 (2014)

Quantum Chemistry



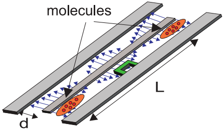
Nature 464, 1324 (2010)

Quantum Simulation



Nat. Phys. 2, 341 (2006)

Quantum Computing



PRL. 97, 33003 (2006)

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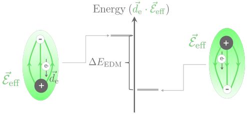
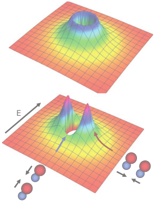
Precision Measurement



Science 343, p. 269-272 (2014)

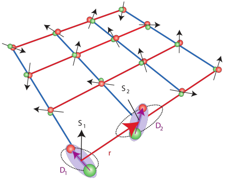
Quantum Chemistry



Nature 464, 1324 (2010)

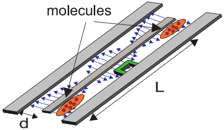
New Approach?

Quantum Simulation



Nat. Phys. 2, 341 (2006)

Quantum Computing



PRL. 97, 33003 (2006)

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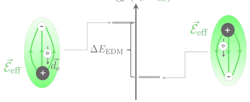
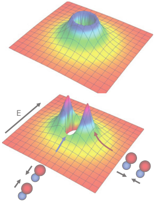
Precision Measurement



Science 343, p. 269-272 (2014)

Quantum Chemistry



Nature 464, 1324 (2010)

New Approach!

Entanglement

Single particle control

Entanglement

i.e. interaction

Single particle control

Entanglement

i.e. interaction

Dipolar molecules

Single particle control

Entanglement

i.e. interaction

Single particle control

Dipolar molecules

- Strong and tunable interaction ($\approx kHz$ at $\approx \mu m$ distance)
  - Fast gate operations
  - Long coherence time
- Rich internal structure (Electronic, vibrational, rotational, hyperfine, etc.)

Entanglement

i.e. interaction

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Single particle control

Optical tweezers

Entanglement

i.e. interaction

Dipolar molecules

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  - Fast gate operations
  - Long coherence time
- Rich internal structure (Electronic, vibrational, rotational, hyperfine, etc.)

Single particle control

Optical tweezers

- Single site resolution
- $\cdots$

Entanglement

i.e. interaction

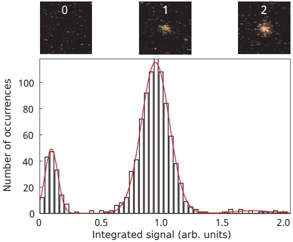
Dipolar molecules

Single particle control

Optical tweezers

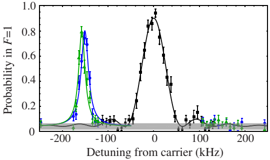
- Single site resolution
- . . .

Loading



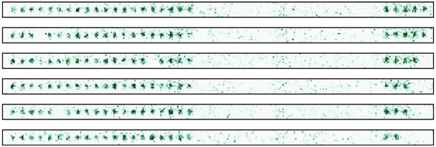
Nat. Phys. 6, 951 (2010)

Cooling



PRX. 2, 041014 (2012)

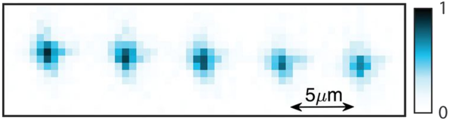
Rearranging



Science 354, 1024 (2016)

Ultracold molecule in tweezers

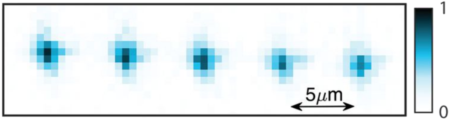
Direct cooling



Science 365, 1156 (2019)

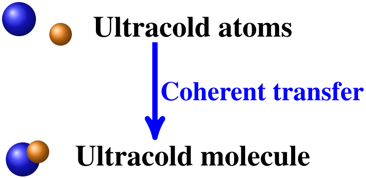
Ultracold molecule in tweezers

Direct cooling



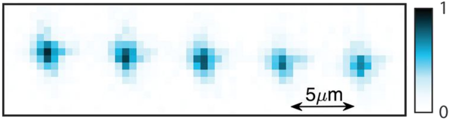
Science 365, 1156 (2019)

Assembly



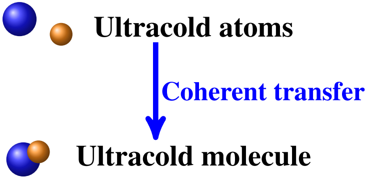
Ultracold molecule in tweezers

Direct cooling



Science 365, 1156 (2019)

Assembly

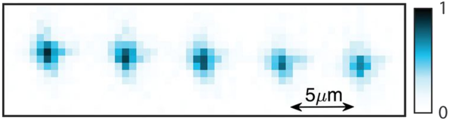


Challenges

- Temperature in tweezer
- Quantum control

Ultracold molecule in tweezers

Direct cooling



Science 365, 1156 (2019)

Assembly

Ultracold atoms

Coherent transfer

Ultracold molecule

Challenges

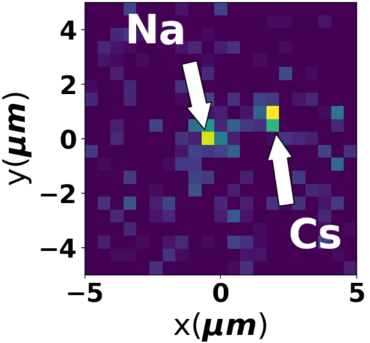
- Temperature in tweezer
- Quantum control

- Creating molecules
- Maintain coherence

Outline

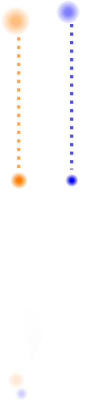
Experiment overview

Loading

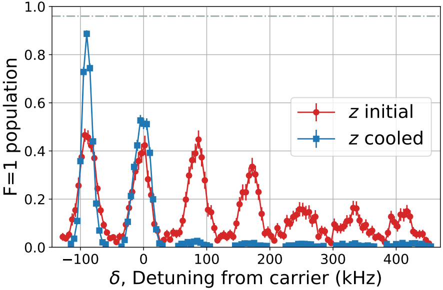


Loading probability per site: 60%
Post select on initial and final state.

Experiment overview



Cooling



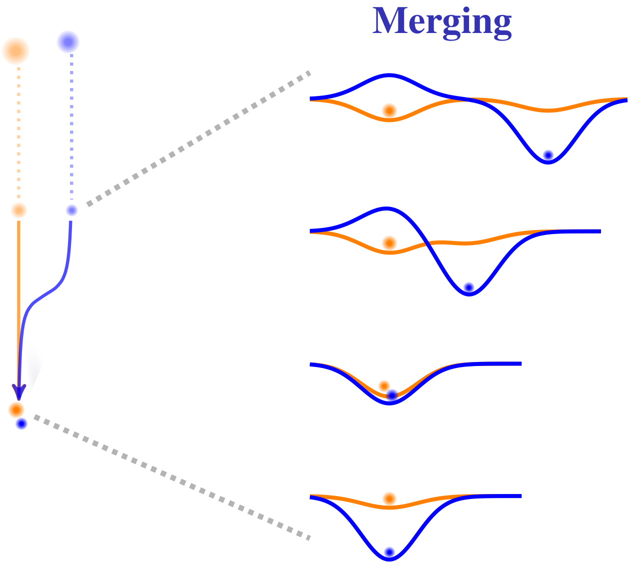
Cs: 96% ground state[1]

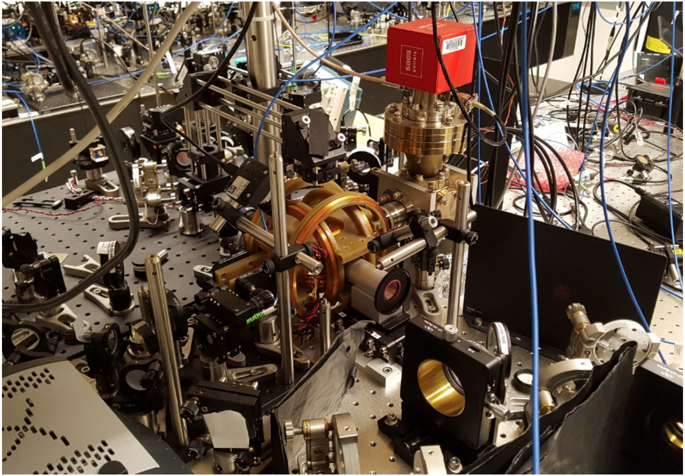
Na: 94% ground state[2]

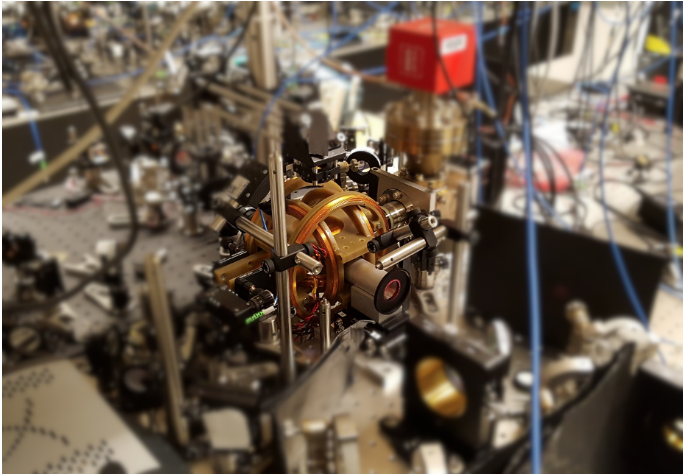
[1] Phys. Rev. X 9, 021039

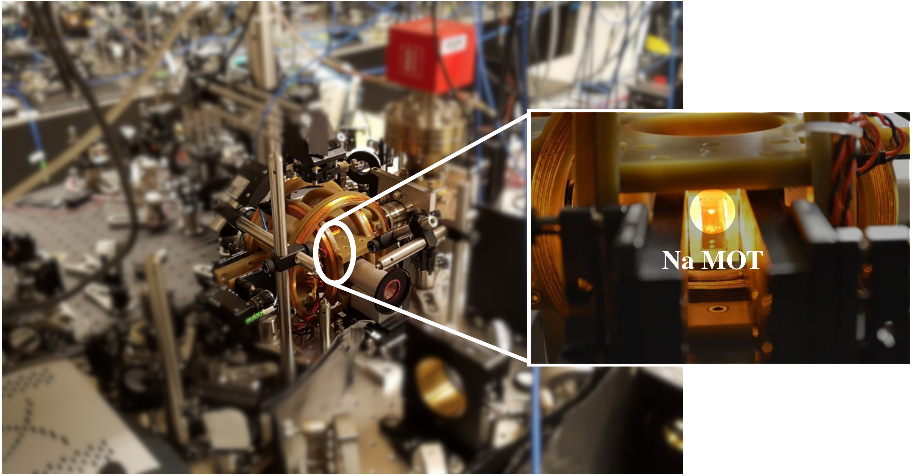
[2] Phys. Rev. A 97, 063423

Experiment overview

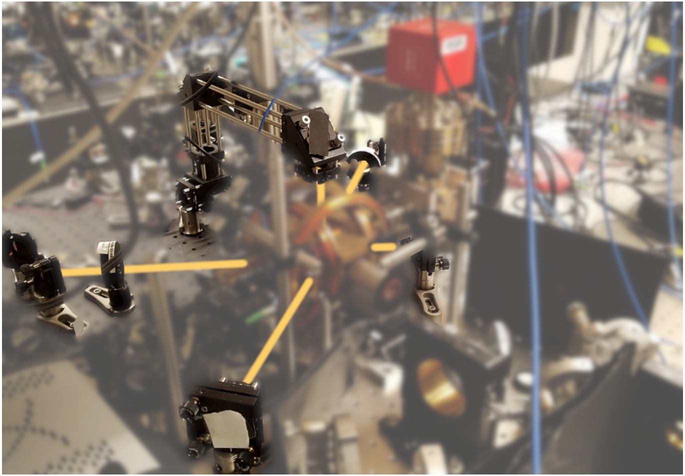



saes
getters

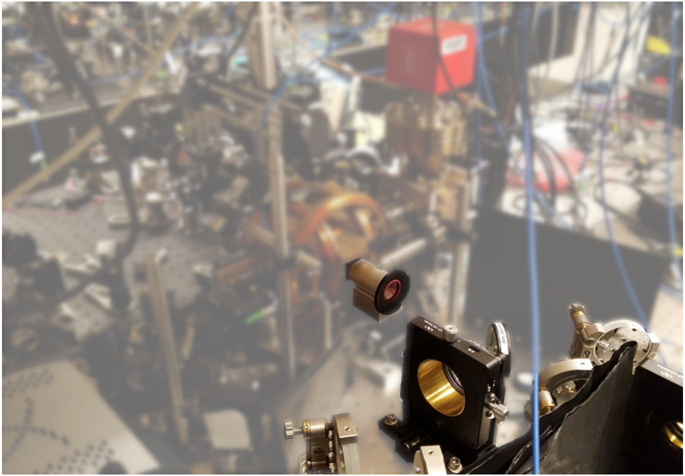



Na MOT

MOT beam path



Tweezer beam path

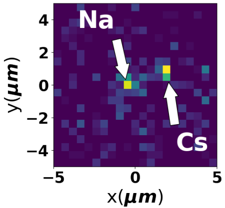


Outline

Raman sideband cooling

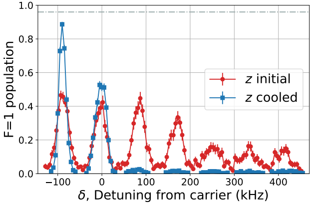
Outline

Loading



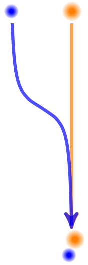
NJP. 19, 023007 (2017)

Cooling



PRA. 97, 063423 (2018)

Merging



PRX. 9, 021039 (2019)

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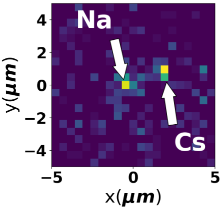
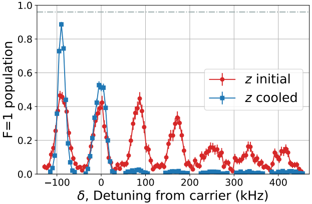


NJP. 19, 023007 (2017)

Cooling



PRA. 97, 063423 (2018)

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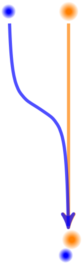
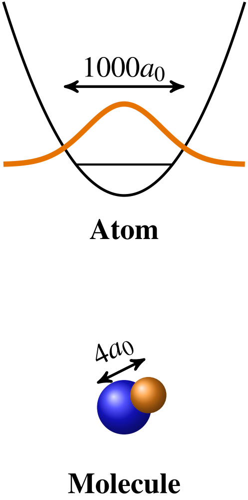
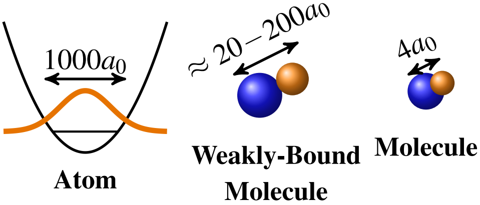
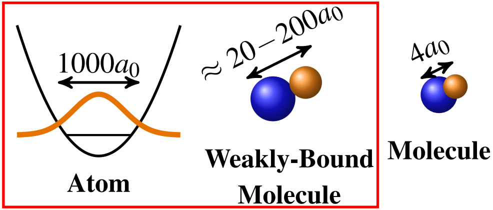


PRX. 9, 021039 (2019)




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



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Atom
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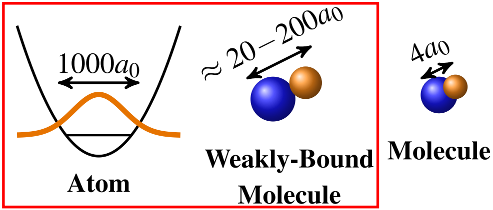
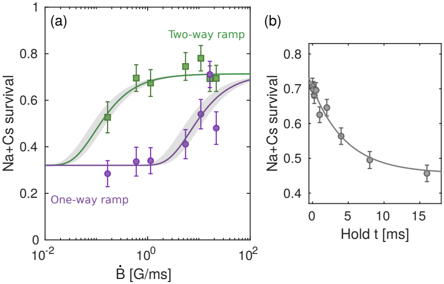
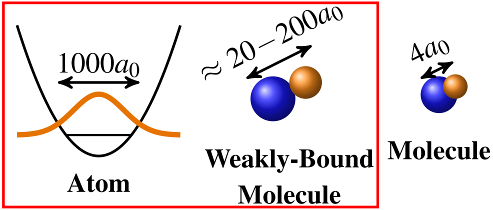


Feshbach molecule



PRL. 124, 253401 (2020)



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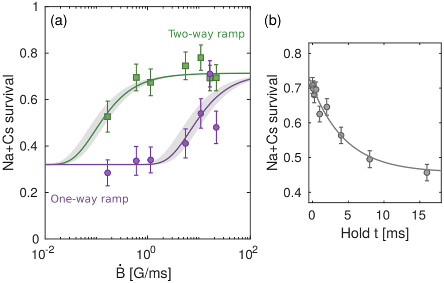
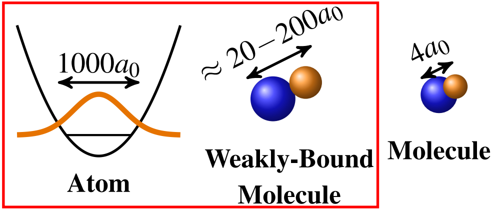


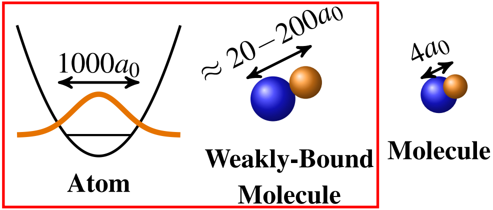
PRL. 124, 253401 (2020)

- Requires Feshbach resonance
- Usually large magnetic field



Optical transfer

- More general
- Faster



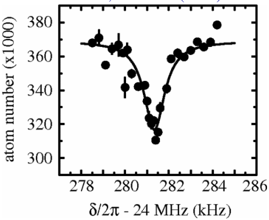
Optical transfer

- More general
- Faster

Previous results

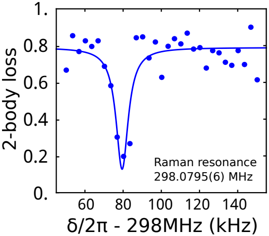
Rb_2 Science 287, p. 1016-1019 (2000)

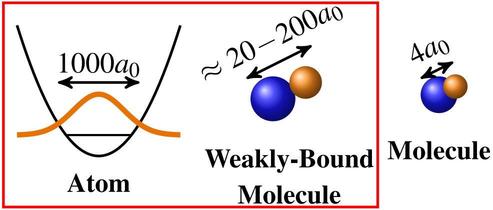
PRL. 93, 073002 (2004)



Sr_2 PRL. 109, 115302 (2012)

NaCs PRX. 9, 021039 (2019)





Optical transfer

- More general
- Faster

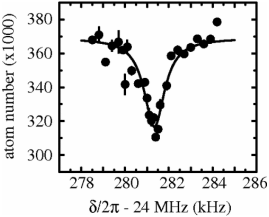
Limitations so far

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

Previous results

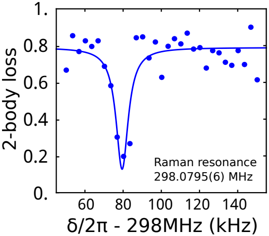
Rb_2 Science 287, p. 1016-1019 (2000)

PRL. 93, 073002 (2004)

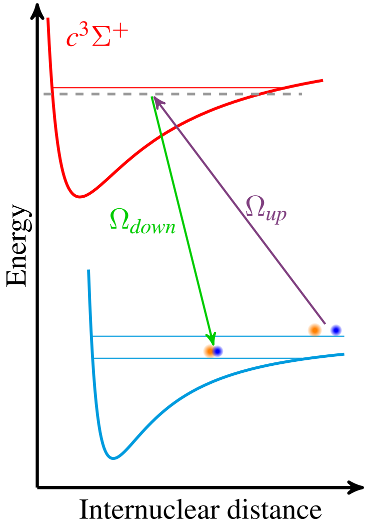


Sr_2 PRL. 109, 115302 (2012)

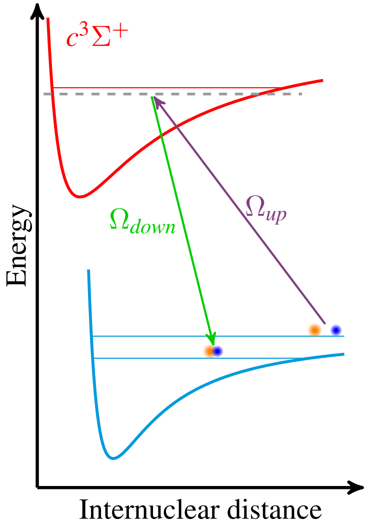
NaCs PRX. 9, 021039 (2019)



Raman transfer



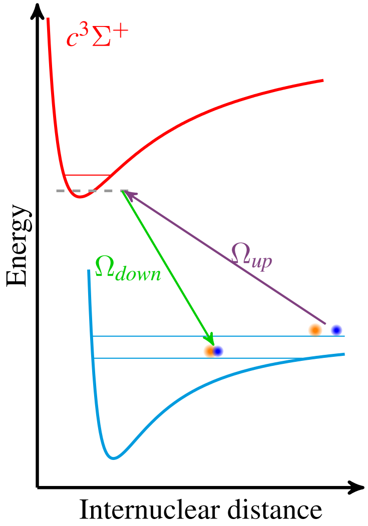
Raman transfer



Near threshold states

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

Raman transfer



Near threshold states

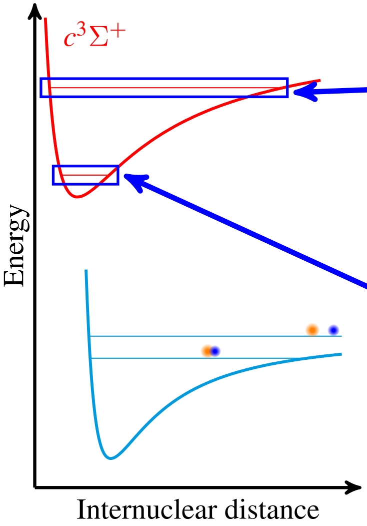
- Stronger coupling (Ω_{up} and Ω_{down})
- Closely spaced
- Fast scattering

Deeply bound states

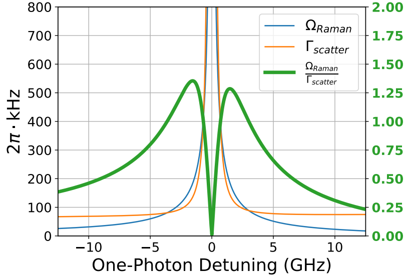
- Weaker coupling
- Sparsely spaced
- Allow larger detuning
- Slower scattering

arXiv:1701.03121(2017)

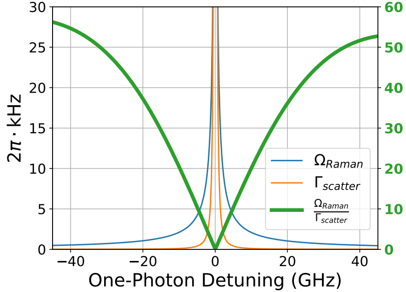
Raman transfer



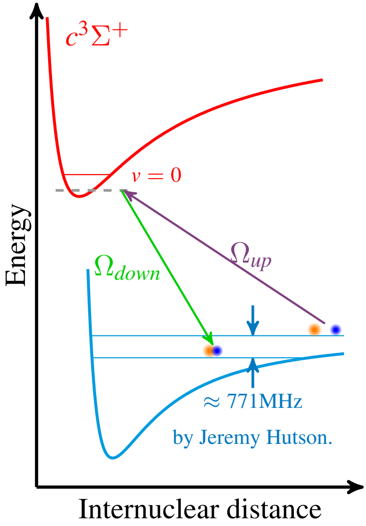
Near threshold states



Deeply bound states

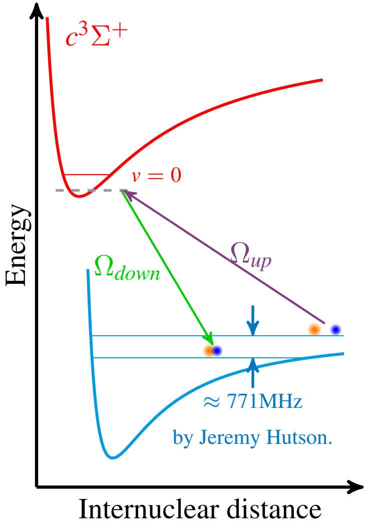


Experiment



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

Experiment



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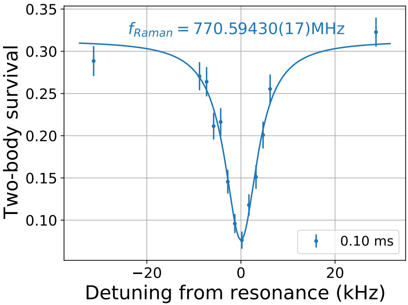
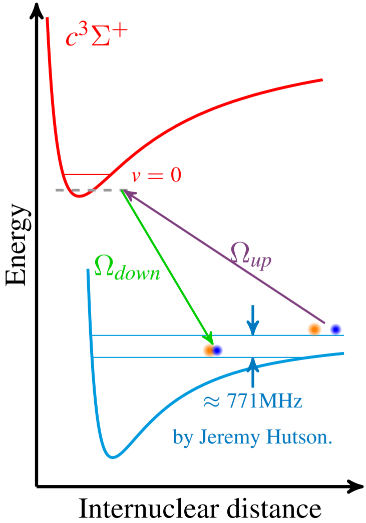


$f_{Raman} = 770.59430(17)$MHz
0.10 ms
Two-body survival
Detuning from resonance (kHz)
0.35
0.30
0.25
0.20
0.15
0.10
−20
0
20

Experiment



$c^3\Sigma^+$
$v = 0$
Energy
Ω_{down}
Ω_{up}
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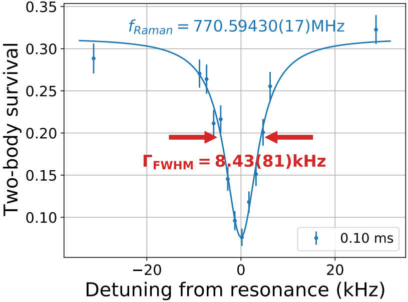
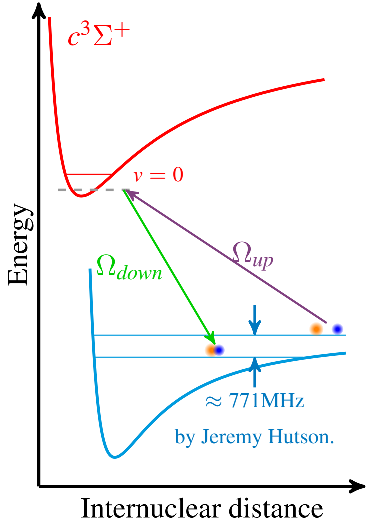
by Jeremy Hutson.
Internuclear distance



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

Experiment



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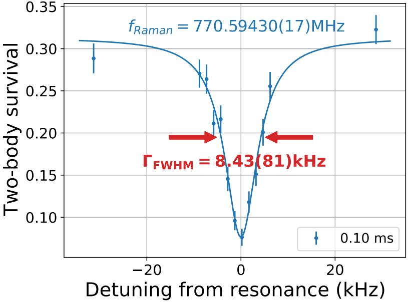

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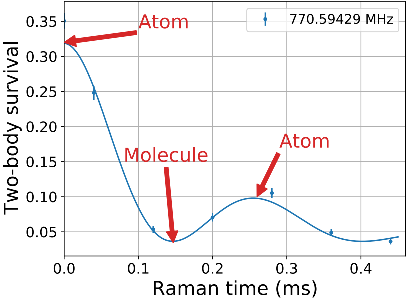
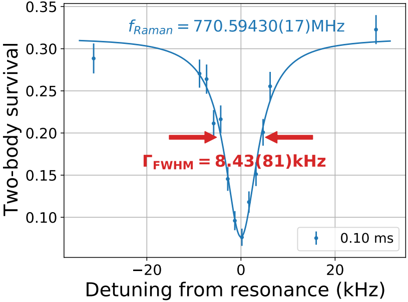
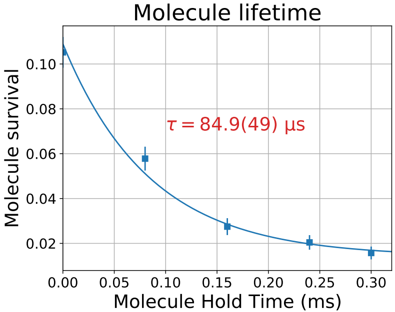


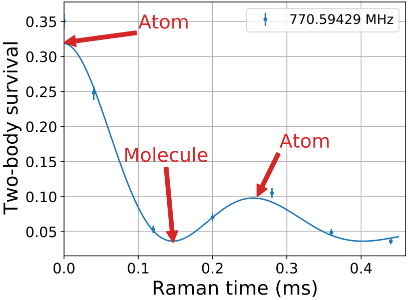
Atom
770.59429 MHz
Molecule
Atom
Two-body survival
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.0
0.1
0.2
0.3
0.4
Raman time (ms)

Experiment

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







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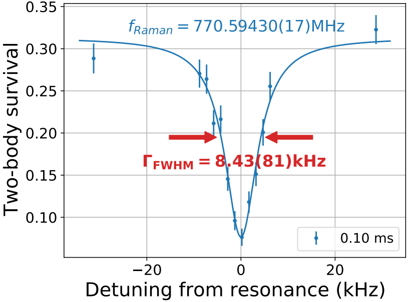
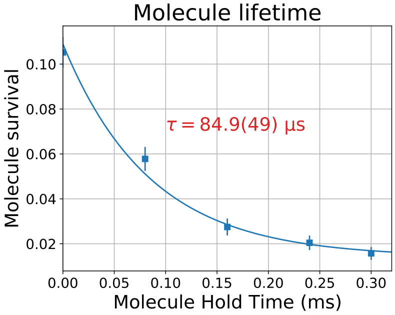
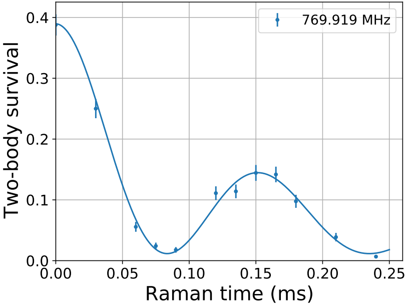
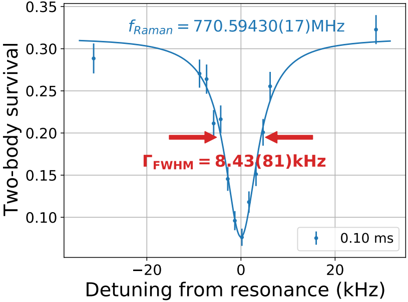


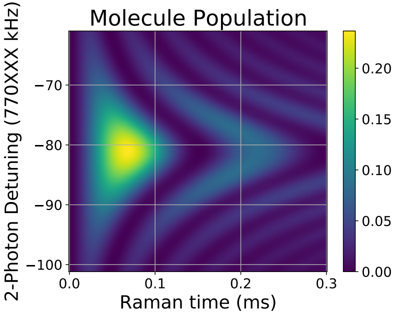


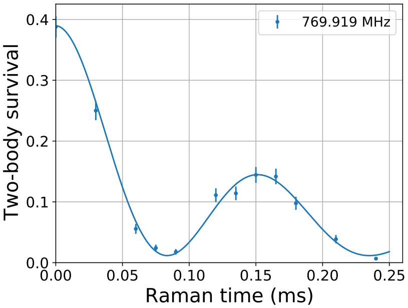


Experiment

- Transferred 65% of ground state atom to molecule.
- Improving signal
- Single molecule spin state
- $> 50\%$ of molecule in motional ground state.







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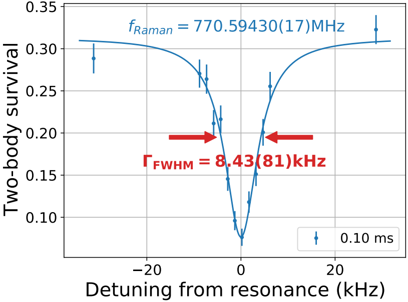

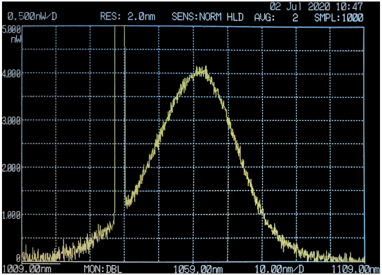

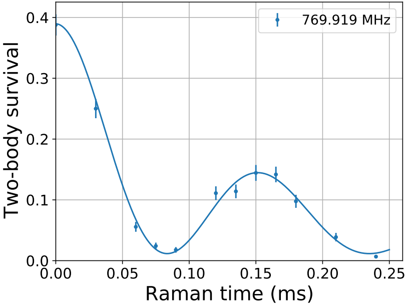

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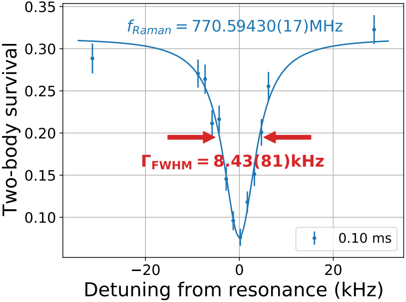

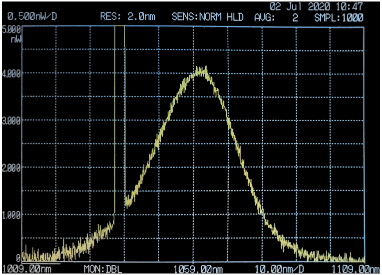

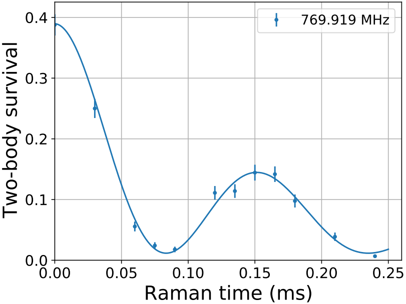

Conclusion and outlook

- Full quantum control of atoms in optical tweezers
- Coherent all-optical creation of single molecucle
- Improve molecule lifetime and signal contrast
- Feshbach molecule ($\tau = 4.7(7)$ ms)

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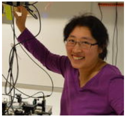
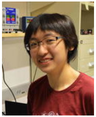
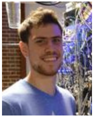


Kang-Kuen Ni

Kenneth Wang



Jessie Zhang



Lewis Picard

William Cairncross

Lee Liu
Postdoc @JILA

Jonathan Hood
Assnt Prof @Purdue

Nick Hutzler
Assnt Prof @Caltech

Theory

Jeremy Hutson

Single Atom in Tweezer

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

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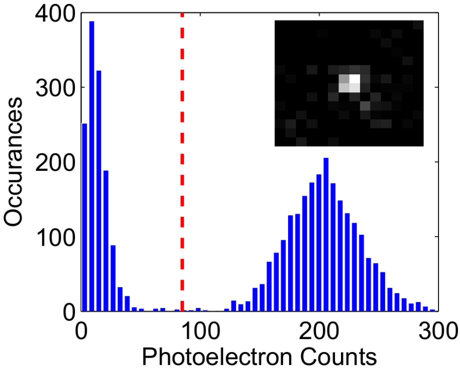

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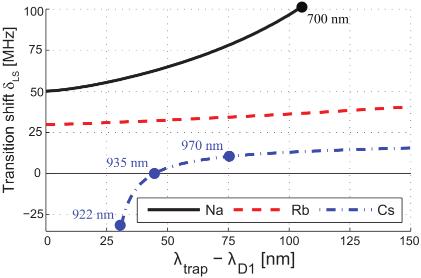
Issues with Na

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

Real Issue with Na: Light Shift



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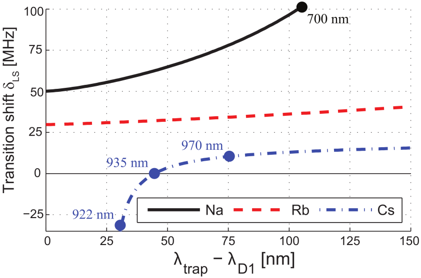
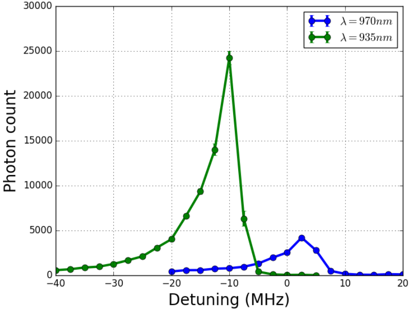


Cs single atom imaging



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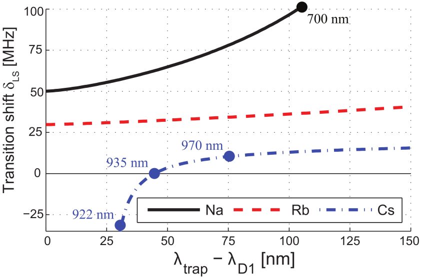

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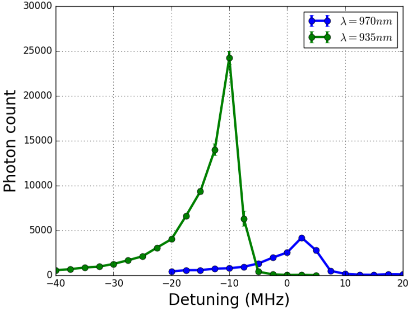

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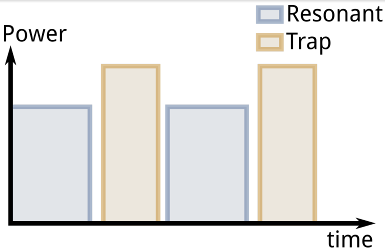
Trap modulation

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

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

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



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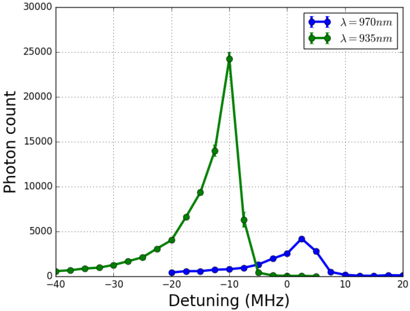

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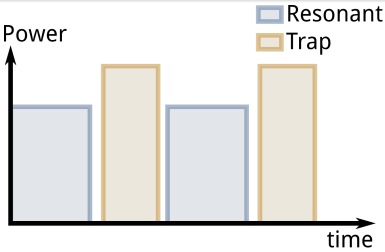

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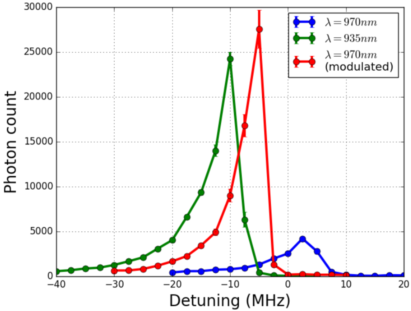

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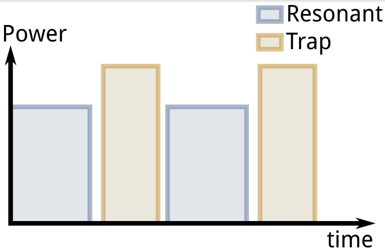

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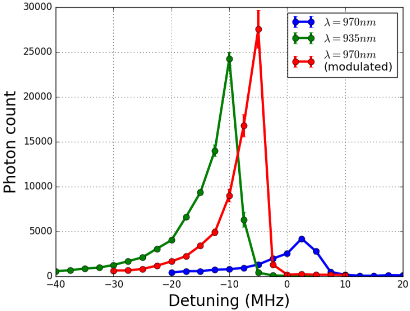
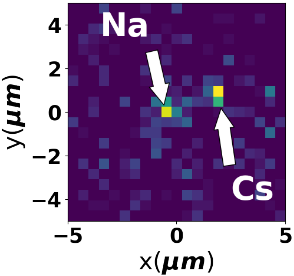
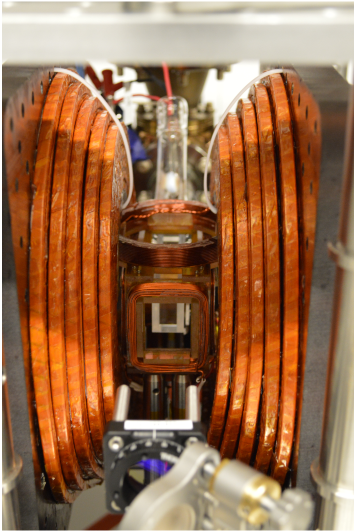




Na (1, -1) Cs (3, -3) Feshbach resonance



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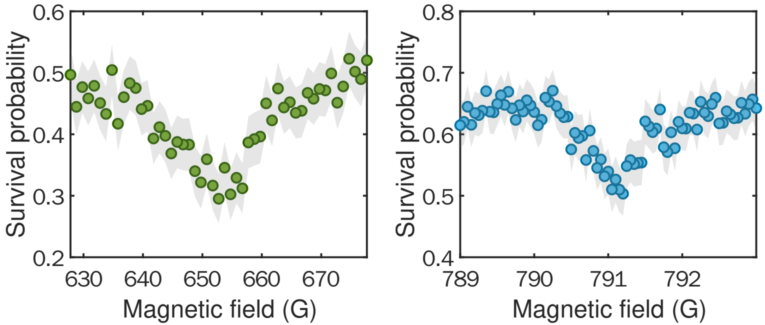

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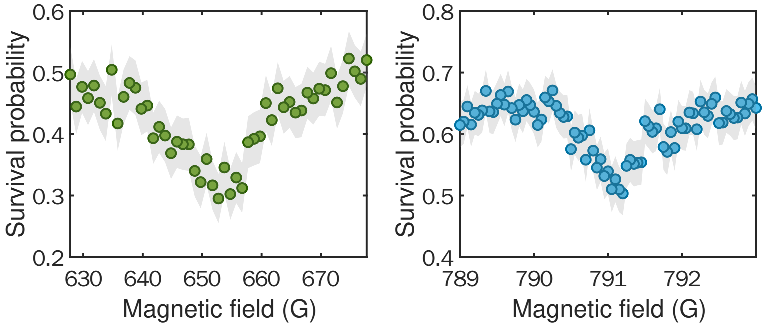
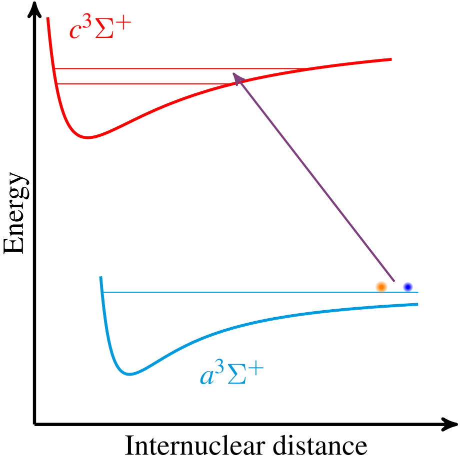


	s-wave	*p*-wave
Predicted (based on interaction shift)[1]	663 G	799 G
Measured	652(3) G	791.2(2) G

[1] In collaboration with Bo Gao

Photoassociation (PA) Spectroscopy



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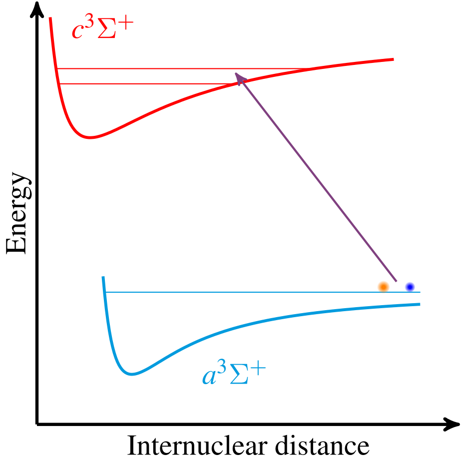

Single Atom PA

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

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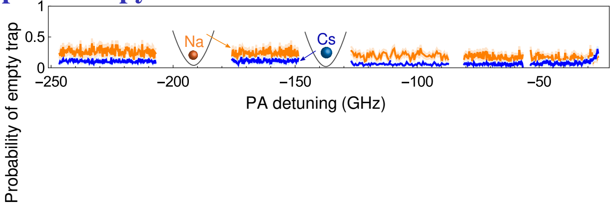

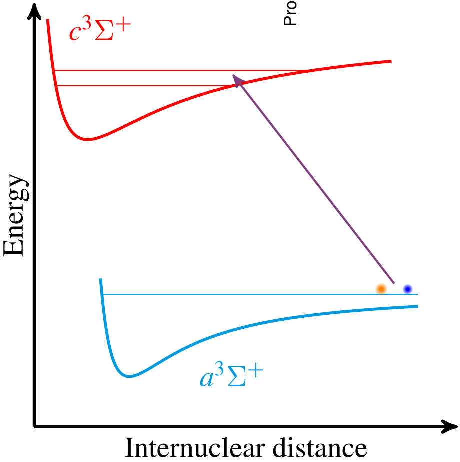

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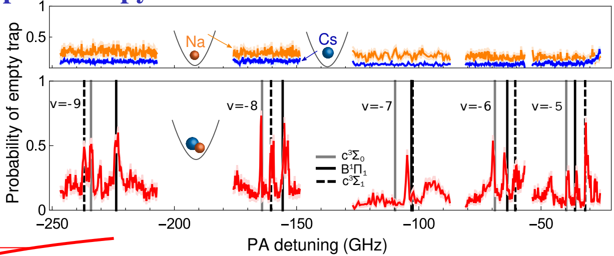

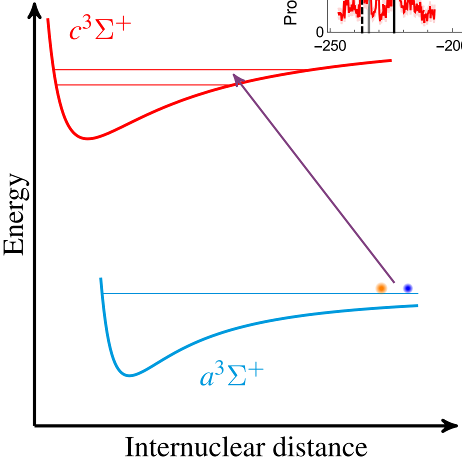

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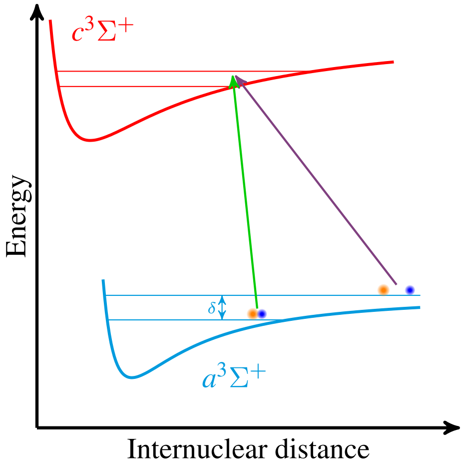
Electromagnetically Induced Transparency (EIT) Spectroscopy



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