Single weakly-bound NaCs molecule in an optical tweezer

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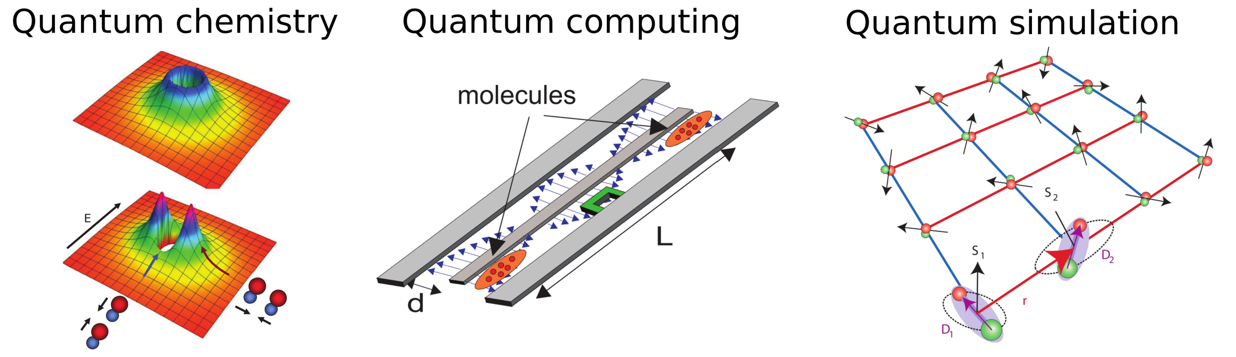
Background

Ultracold molecules

- Dipolar molecules can interact through dipole-dipole interactions that are long-range, anisotropic, and tunable.
- Molecules possess rich internal structures, including electronic, vibrational, rotational and hyperfine degrees of freedom.
- The ability to control the quantum states of molecules can lead to a wide variety of applications.

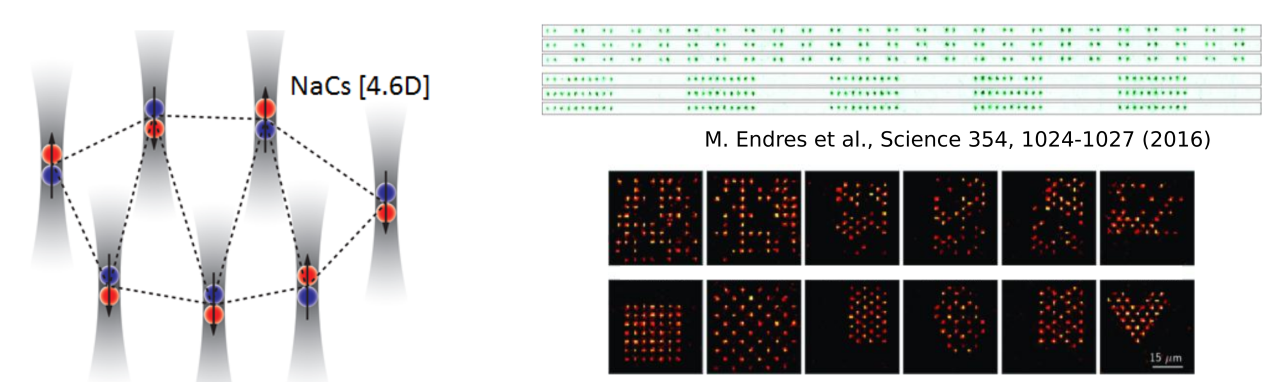
Quantum chemistry | Quantum computing | Quantum simulation



Nature 464, 1324 (2010) | Phys. Rev. Lett. 97, 33003 (2006) | Nat. Phys. 2, 341 (2006)

Our goal

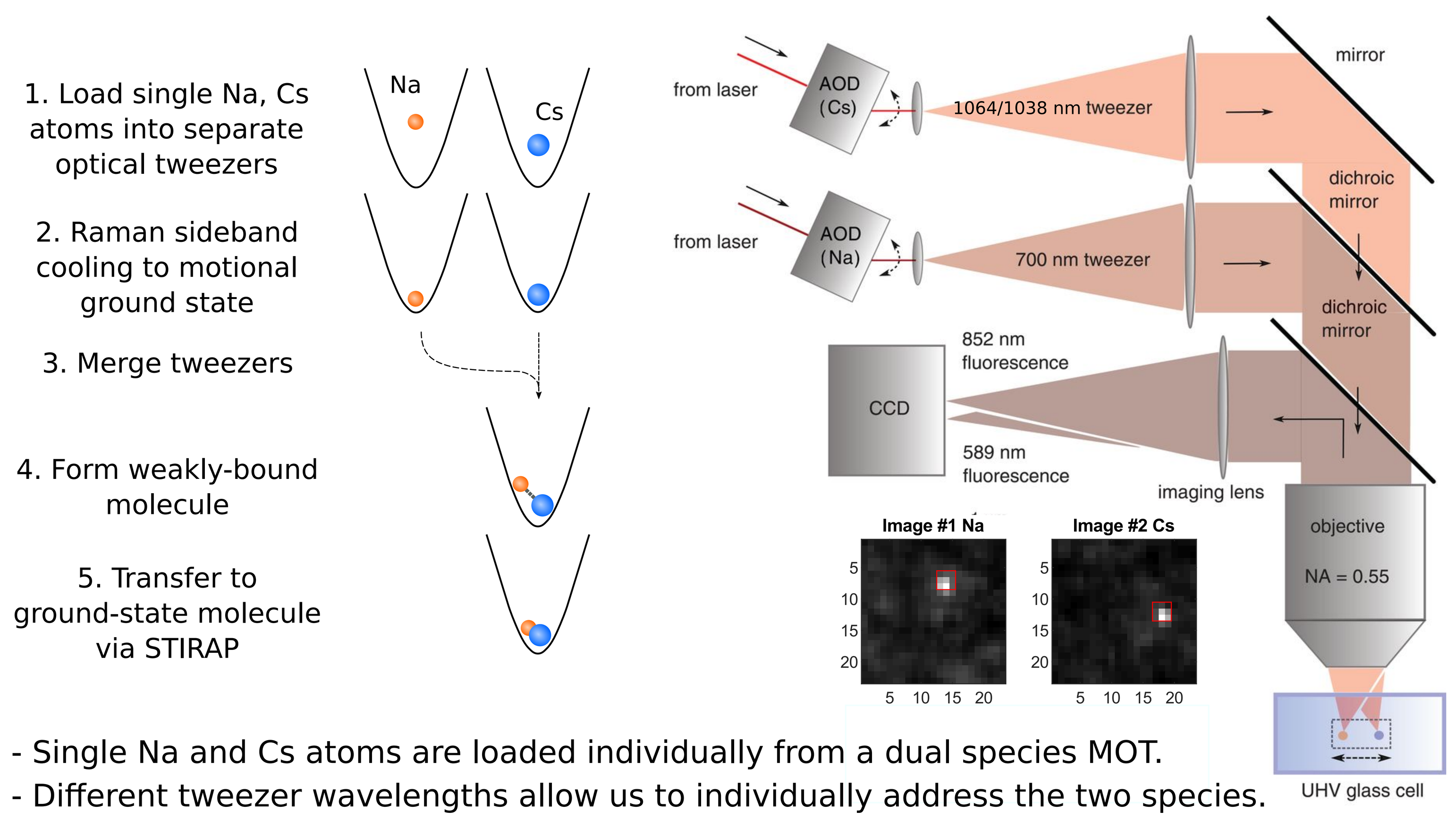
- We aim to achieve single particle quantum control of ultracold molecules by assembling individual NaCs molecules in an optical tweezer array from laser-cooled atoms.
- Tweezer array platforms have been demonstrated to be flexible and well-suited for single-site addressing.
- We choose to assemble from atoms due to the existing well-established laser-cooling techniques for atoms, which can in turn give us low entropy molecules.



M. Endres et al., Science 354, 1024-1027 (2016)

D. Barredo et al., Science 354, 1021-1023 (2016)

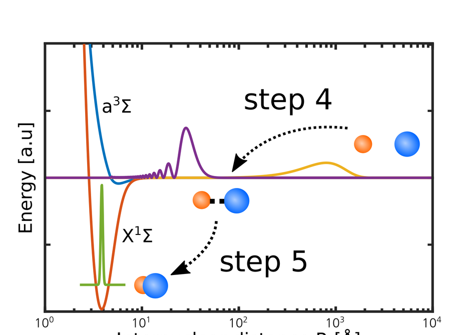
Experimental scheme and setup



- Single Na and Cs atoms are loaded individually from a dual species MOT.
- Different tweezer wavelengths allow us to individually address the two species.
- Acousto-optic beam deflectors are used for merging and trap array generation.
- Raman sideband cooling gives Na 94%, Cs 96% in ground state.
- Relative motional ground state population of atom pair after merging the traps is ~60%

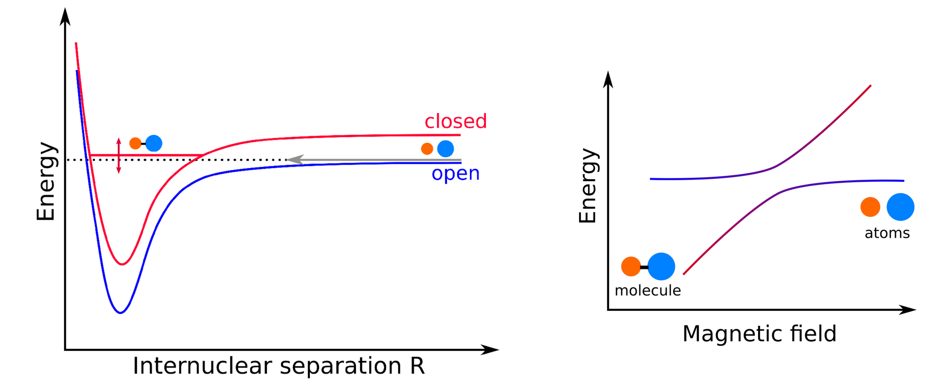
Forming a weakly-bound molecule

- This is a crucial step to bridge the disparity in wavefunction spread of free atoms and ro-vibrational ground-state molecules.
- We take two different approaches:
  (1) Magnetoassociation using a Feshbach resonance
  - Well-established method in bi-alkali bulk-gases, but never demonstrated in the high trapping intensity regime of optical tweezers.
  - Requires favorable Feshbach resonance for molecular transfer.
  (2) Two-photon Raman transition via an excited molecular state to coherently transfer to the v=-1 state of a3Σ
  - Method generally applicable to wide variety of species, including polyatomics



Magnetoassociate to Feshbach molecules

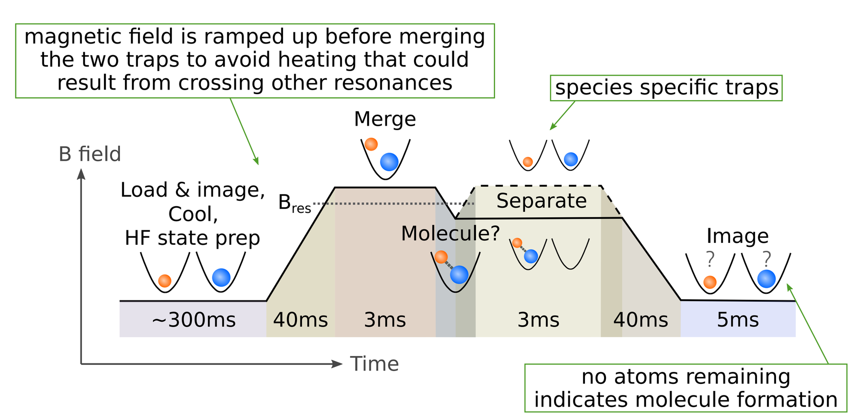
- Magnetic Feshbach resonances arise when the energy of a bound molecular state crosses that of the scattering atoms due to a difference in magnetic moments between the different channels.
- Adiabatically ramping the magnetic field across a resonance can magnetoassociate the atoms into a molecule.
- Feshbach resonances in Na|F=1,mF=1>+Cs|F=3,mF=3> channel have been predicted but never measured.

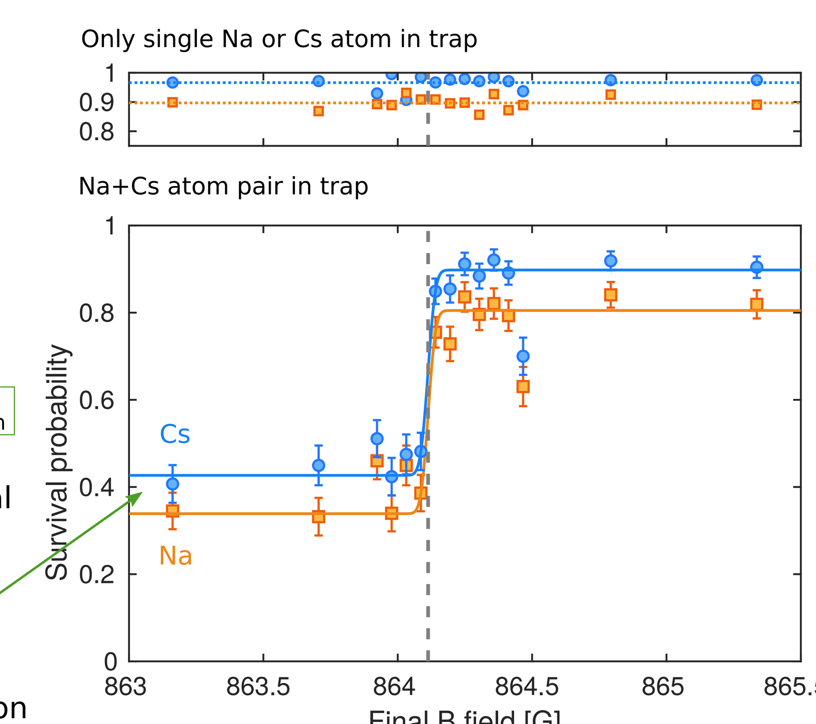


s-wave Feshbach resonance detection by magnetoassociation

- A single pair of atoms in lowest hyperfine state gives no inelastic collisions or 3-body collisions
- We directly use magnetoassociation to detect the feshbach resonances.

Experimental sequence





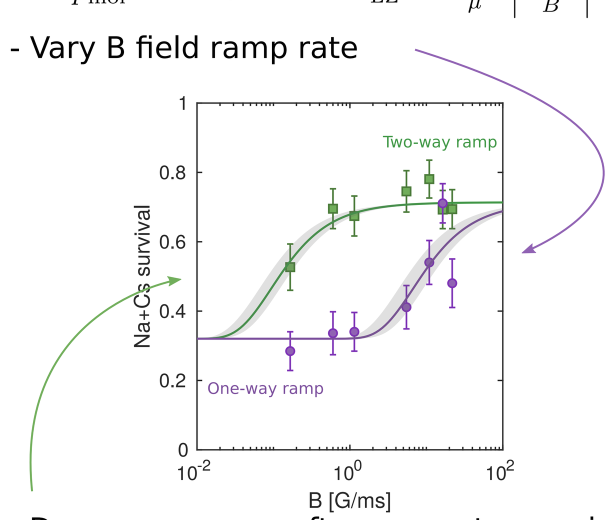
- B field is ramped from 865.5G down to various final values
- Observe simultaneous drop in survival of both Na and Cs atoms when both atoms are present in trap
- Molecule conversion efficiency of ~45-50%
  - Potential to scale up to record lattice filling fraction
  - Not fundamentally limited (no three-body collisions as in bulk gases)
  - Current technical limitations: relative motional ground state population

Adiabaticity

- Adiabaticity of magnetoassociation process follows Landau-Zener relation

$$p_{mol} = 1 - e^{-2\pi\delta_{LZ}} \qquad \delta_{LZ} = \frac{2\pi\hbar^2}{\mu}\left|\frac{a_{bg}\Delta}{\dot{B}}\right|$$

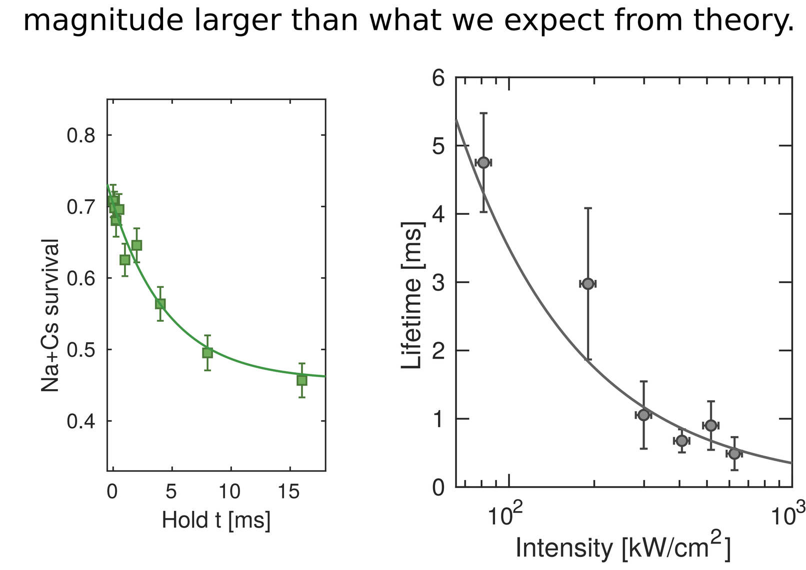
- Vary B field ramp rate



- Do reverse ramp after magnetoassociation
- Recovery of atoms indicates adiabatic association and dissociation
- Two-way ramp recovery probability limited by lifetime of Feshbach molecules in optical tweezer

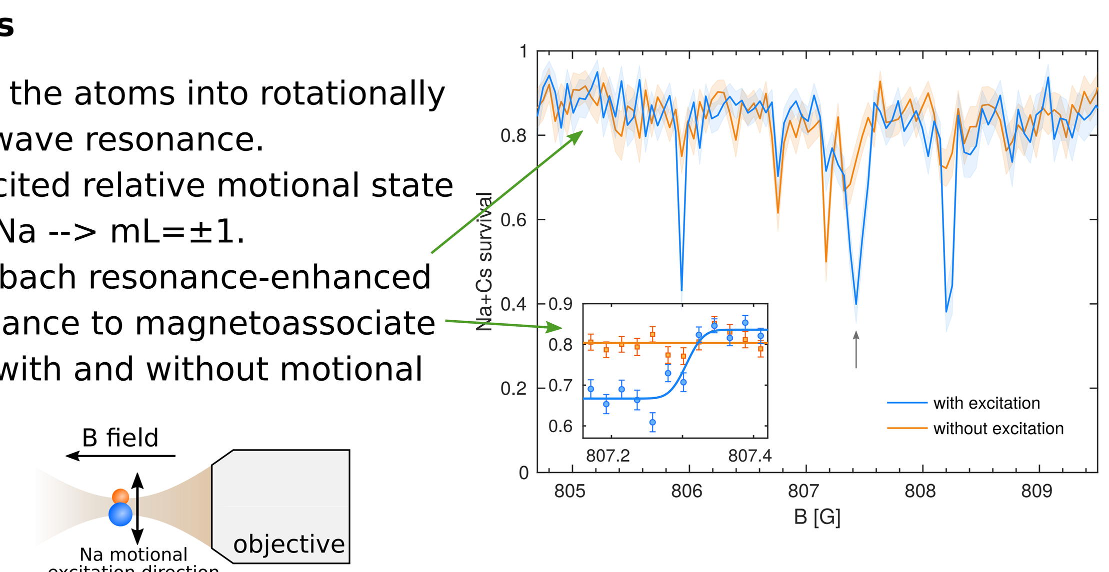
Lifetime

- Find a lifetime that is limited by the scattering of the tweezer light (1064nm).
- At low tweezer intensities, measure a lifetime of 4.7ms, which is sufficient for STIRAP transfer to rovibrational ground state.
- However, scattering rate we find is ~2 orders of magnitude larger than what we expect from theory.



p-wave Feshbach molecules

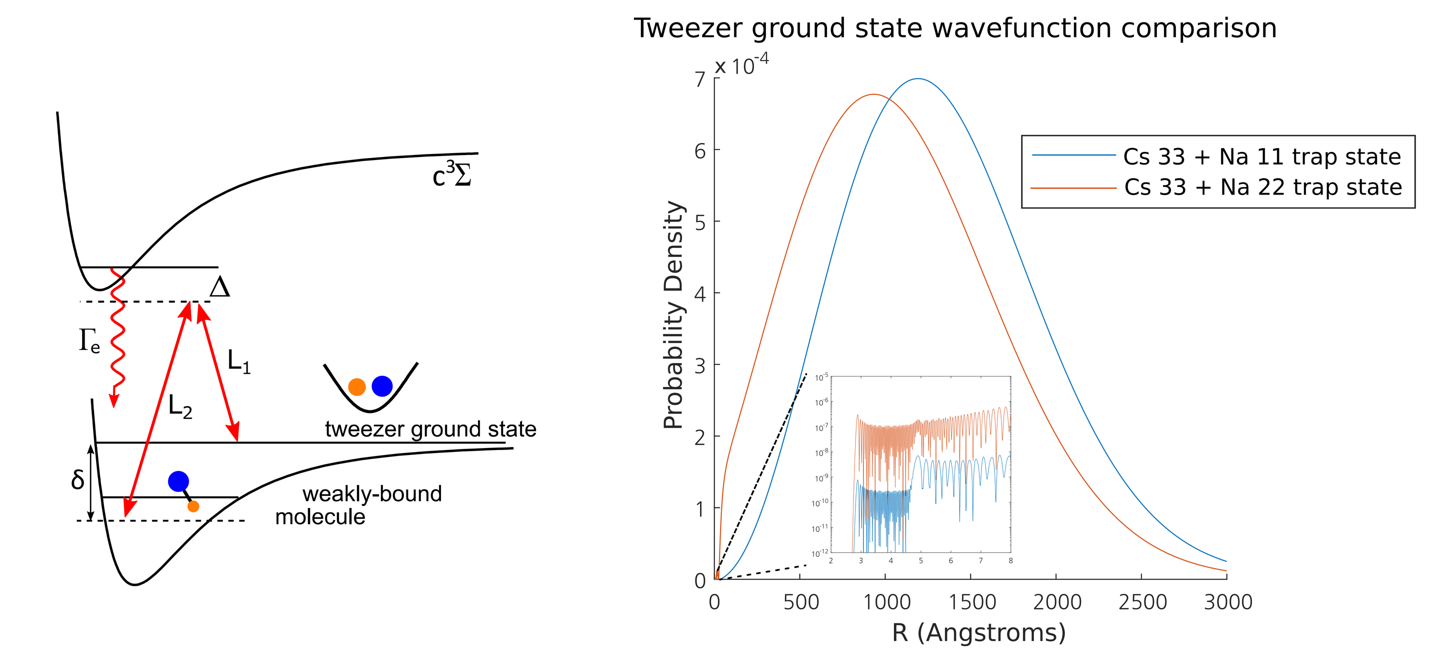
- We can also magnetoassociate the atoms into rotationally excited molecules by using a p-wave resonance.
- Prepare the atom pair in an excited relative motional state by exciting the radial motion of Na --> mL=±1.
- Detect the resonances by Feshbach resonance-enhanced photo-association and use resonance to magnetoassociate the atoms, comparing between with and without motional excitation.



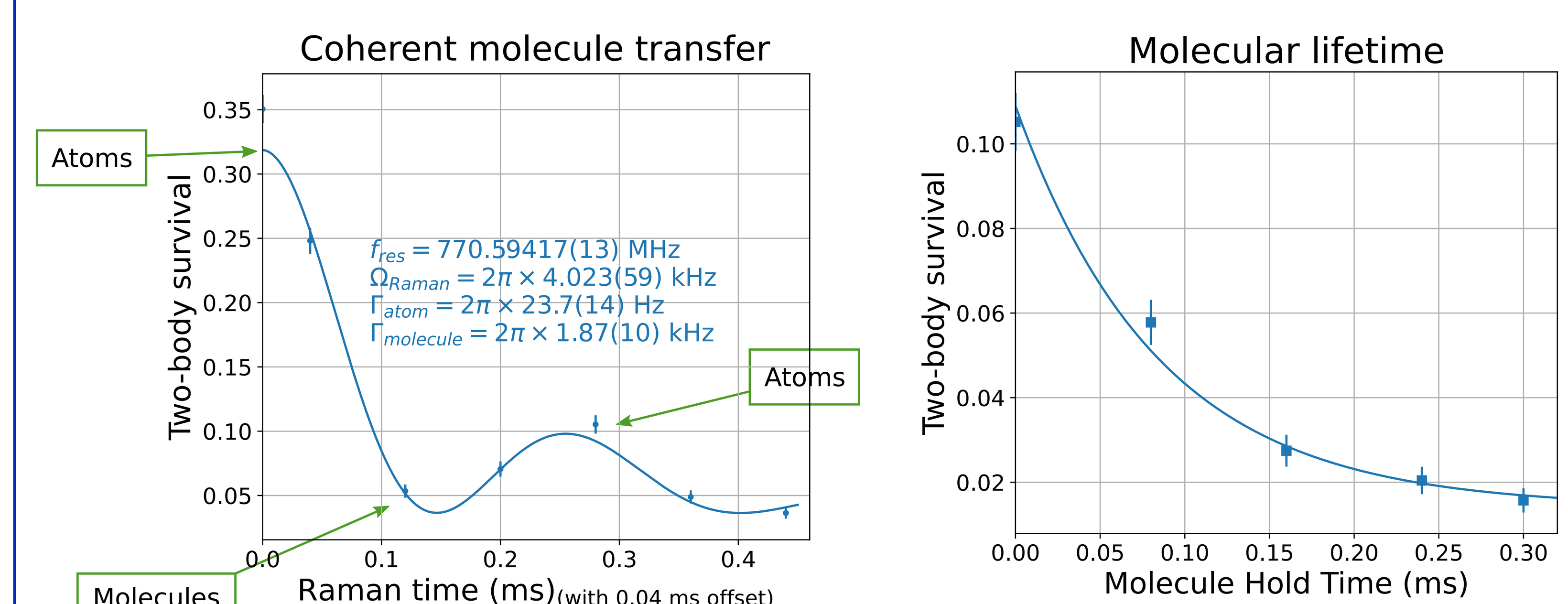
J. T. Zhang et al., arXiv:2003.07850 (*Phys. Rev. Lett.*, accepted)

Optical transfer to weakly-bound molecule

- Use a pair of Raman beams detuned from the c3Σ v = 0 state to drive a two photon optical Raman transition from the tweezer ground state to the weakly-bound molecule state a3Σ v=-1.
- Binding energies of typically 100s of MHz leads to significant cross coupling for our typical single photon detunings of 10s to 100s of GHz. Optimum is equal power in each beam.
- The small vibrational wavefunction overlap between the tweezer ground state and the excited bound state can be enhanced by choosing the Na|F=2,mF=2>+Cs|F=3,mF=3> hyperfine combination which has a large scattering length.



- Using this hyperfine combination, Rabi oscillations between the trap ground state and weakly bound molecule can be observed.
- Scattering is higher than expected, and we are working towards finding a better single photon detuning to get full contrast oscillations.

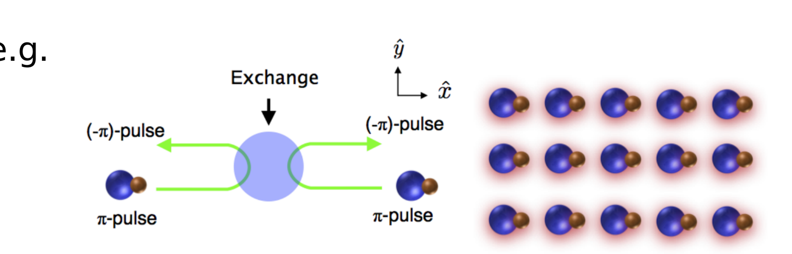


For more, see talk:
Session T06: Spectroscopy and Collisions of Ultracold Molecules
T06.00001 : Single weakly-bound NaCs molecule in optical tweezers
10:30 AM–10:42 AM, Friday, June 5, 2020

Outlook

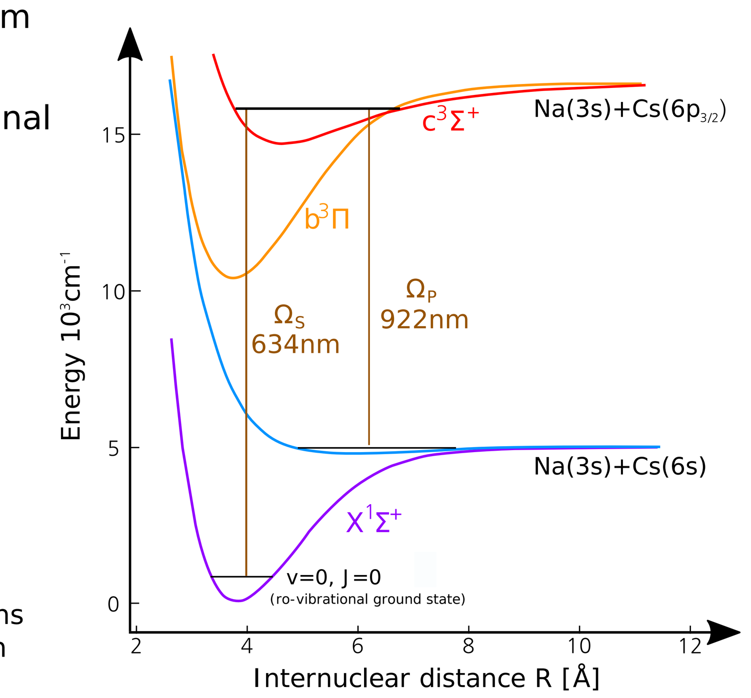
- Investigate higher than expected scattering rate from tweezer light of the weakly-bound molecules
- STIRAP from Feshbach molecular state to ro-vibrational ground state
- Scale up to tweezer array for quantum computation

e.g.



Ni et. al, Chemical Science 9, 6830 - 6838 (2018)

- dipolar exchange interaction used for entangling gate operations
- separate gate zone and storage zones to minimize perturbation on storage qubits



Acknowledgements

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