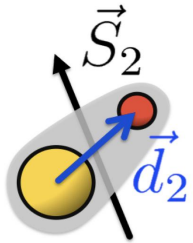
Ultracold Molecules 在 钠锂

Hongyin Liu

Triplet NaLi



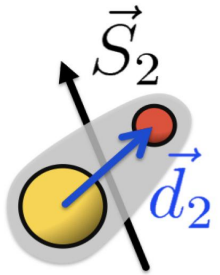
Ultracold Molecules with Electric and Magnetic Dipole Moments

A new ..

Platform for quantum simulation

System to study fundamental chemistry

Tool for quantum computation



Large molecules: precision measurements

Outline

Formation of ultracold molecules

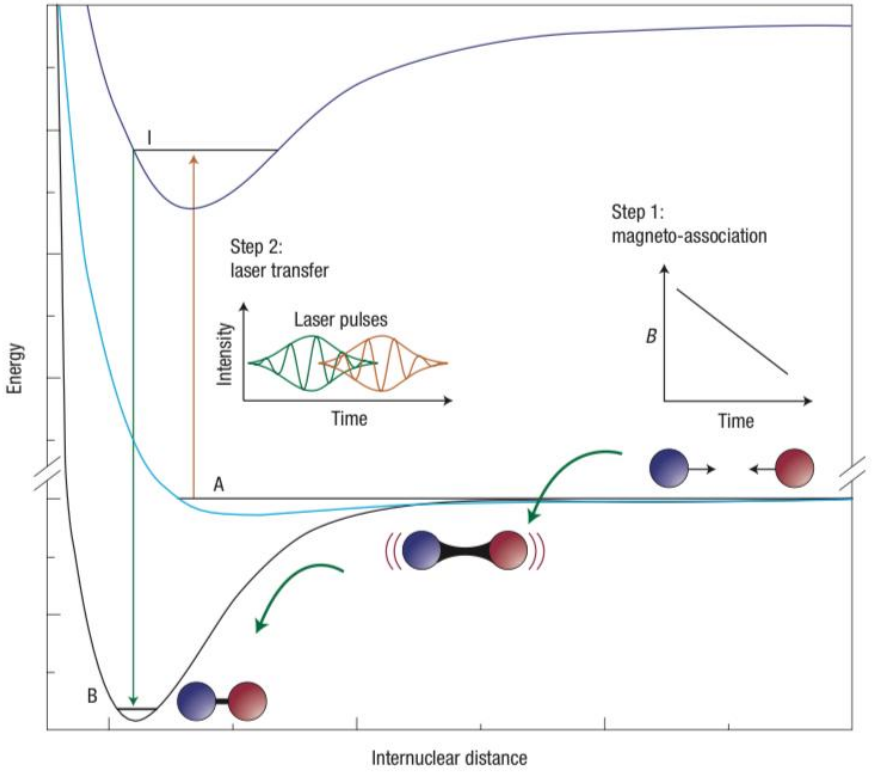
A brief Feshbach + STIRAP theory

Experiments of NaLi

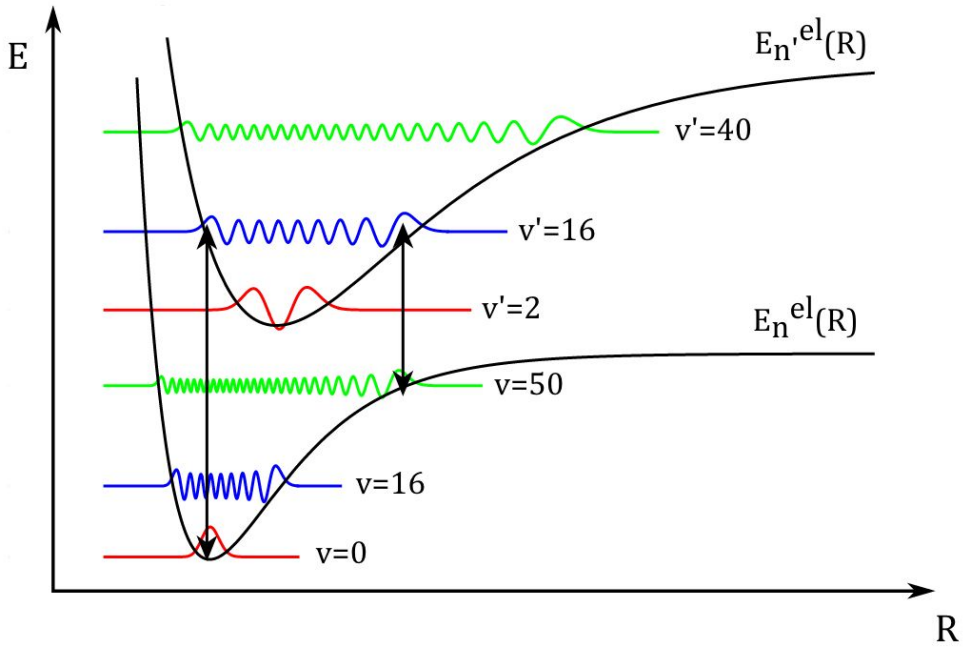
Outlook

How do we make ultracold molecules?

- Direct Cooling (will not talk about today)
- Magneto-association (Feshbach) or Photoassociation + Stimulated Raman Adiabatic Passage (STIRAP)

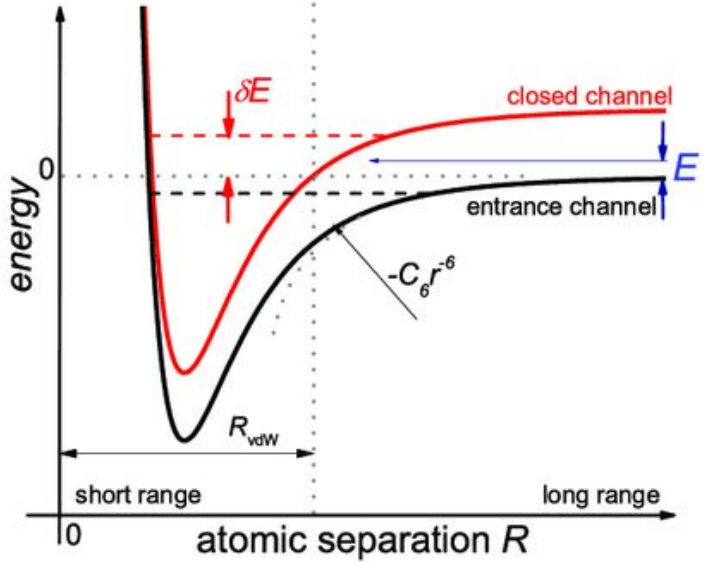


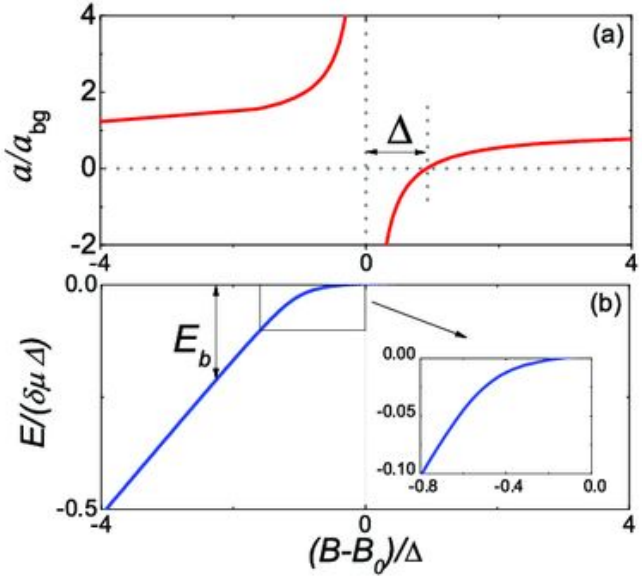
Photoassociation



$$A + B + \hbar\omega \rightarrow (AB)^*$$

Magneto-Association (Feshbach)

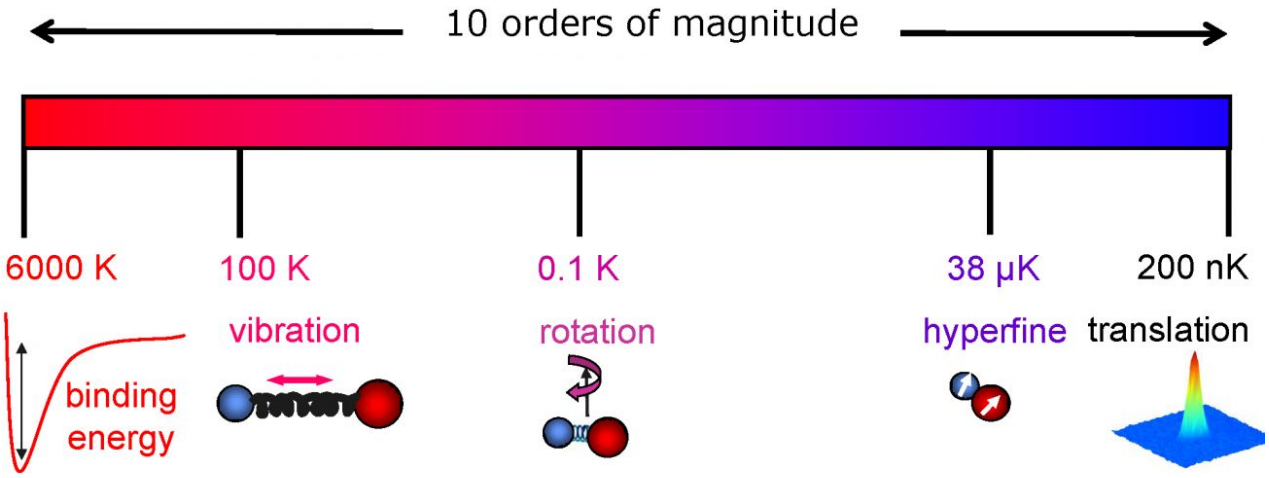




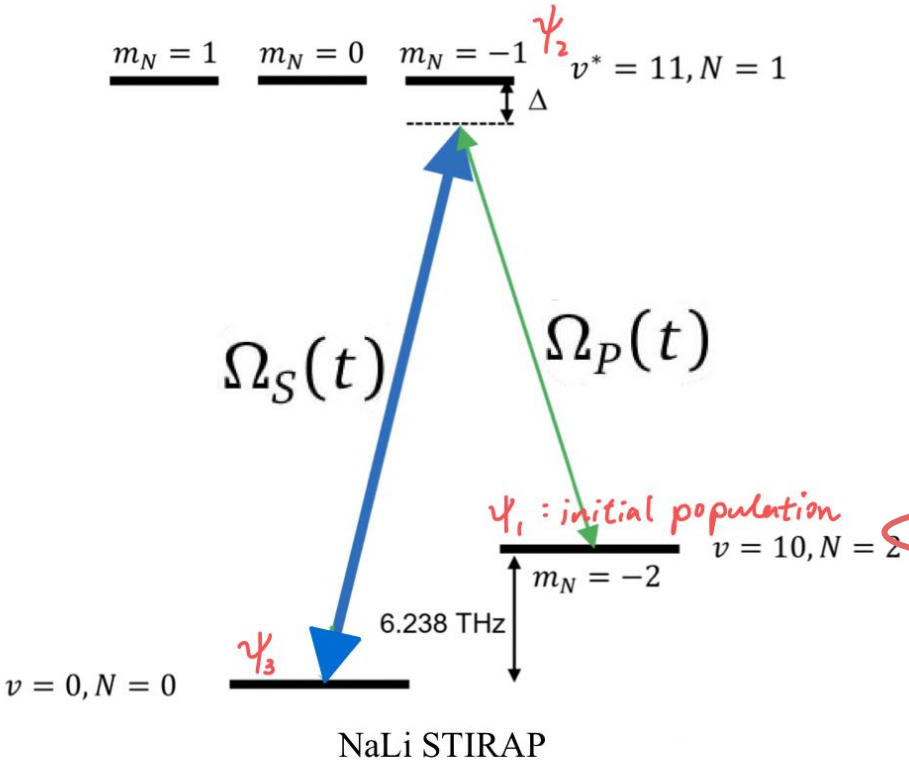
$$a_s = a_{bg}\left(1 - \frac{\Delta}{B - B_{res}}\right)$$

Molecular Structure for Diatomic Molecule

1. Hyperfine: $F = |\vec{F}| = |\vec{S} + \vec{I}_{\mathrm{Na}} + \vec{I}_{\mathrm{Li}}|$
2. N, Rotational degree of freedom (rigid rotor): $E_N = BN(N+1) - D[N(N+1)]^2$
3. v, Vibrational degree of freedom: stretching, contracting, bending, etc.



Stimulated Raman Adiabatic Passage (STIRAP)



NaLi STIRAP

$$H(t) = \hbar \begin{pmatrix} 0 & \frac{1}{2}\Omega_P(t) & 0 \\ \frac{1}{2}\Omega_P(t) & \Delta & \frac{1}{2}\Omega_S(t) \\ 0 & \frac{1}{2}\Omega_S(t) & 0 \end{pmatrix}$$

Eigenstates

$$\begin{aligned} \Phi_a &= \psi_1 \sin\vartheta(t)\sin\varphi(t) + \psi_2 \cos\varphi(t) + \psi_3 \cos\vartheta(t)\sin\varphi(t) \\ \Phi_b &= \psi_1 \sin\vartheta(t)\cos\varphi(t) - \psi_2 \sin\varphi(t) + \psi_3 \cos\vartheta(t)\cos\varphi(t) \\ \Phi_c &= \psi_1 \cos\vartheta(t) - \psi_3 \sin\vartheta(t) \end{aligned}$$

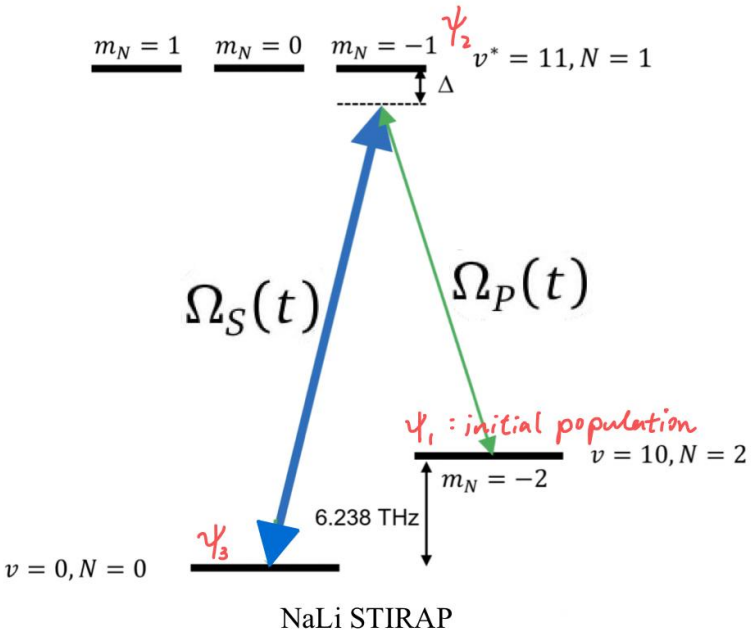
with

$$\vartheta(t) = \arctan\frac{\Omega_P(t)}{\Omega_S(t)},$$

$$\varphi(t) = \frac{1}{2}\arctan\frac{\sqrt{\Omega_P^2(t) + \Omega_S^2(t)}}{\Delta}$$

Note: in general, $\Delta_p \neq \Delta_s$, but STIRAP needs $\Delta_p \sim \Delta_s \sim \Delta$ to have the states we want

STIRAP continued…

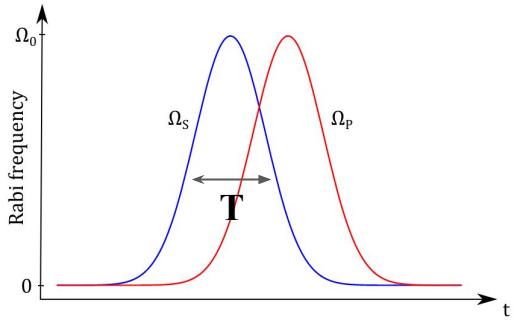


NaLi STIRAP

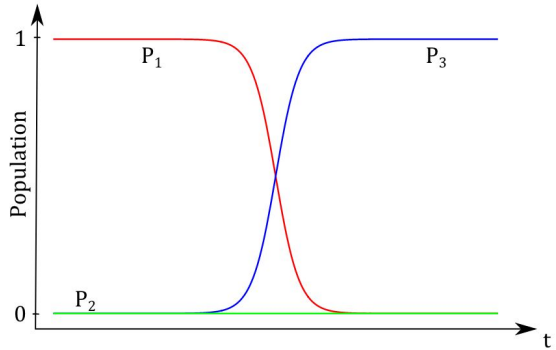
$$\Phi_c = \frac{\Omega_s}{\Omega}\psi_1 - \frac{\Omega_p}{\Omega}\psi_3$$

$$\Omega = \sqrt{\Omega_s^2 + \Omega_p^2}$$

Adiabatic Condition: $\Omega_0 T \gg 1$

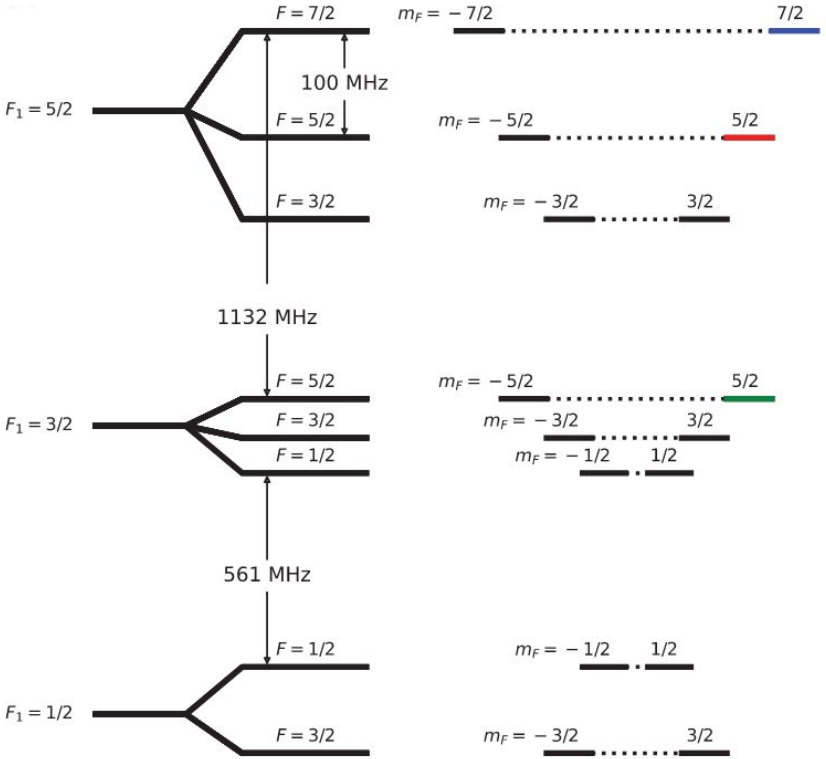


(a) Pulse sequence of Stokes (blue) and pump (red) pulses

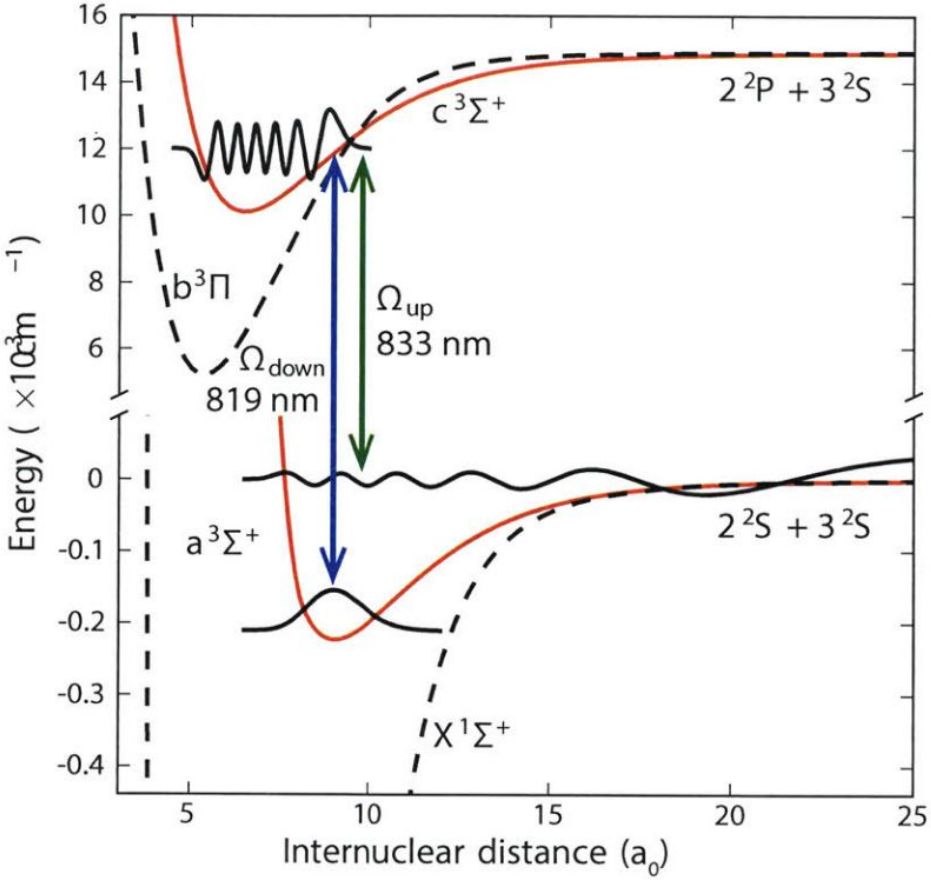


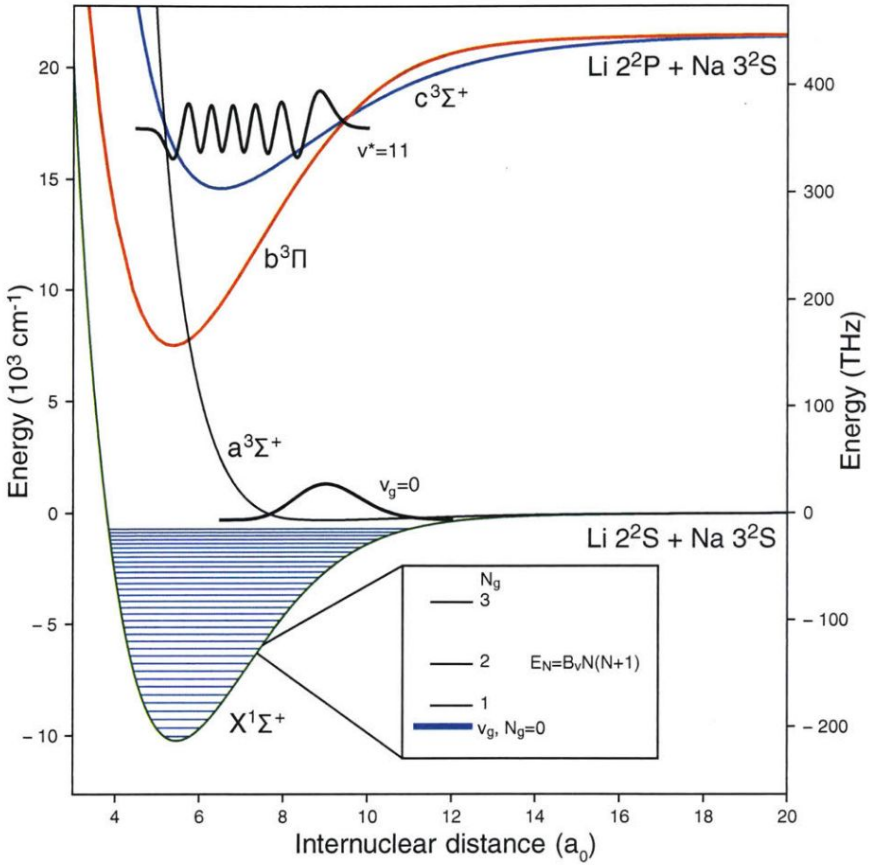
(b) Evolution of the populations of states ψ_1, ψ_2, ψ_3

The specifics of NaLi



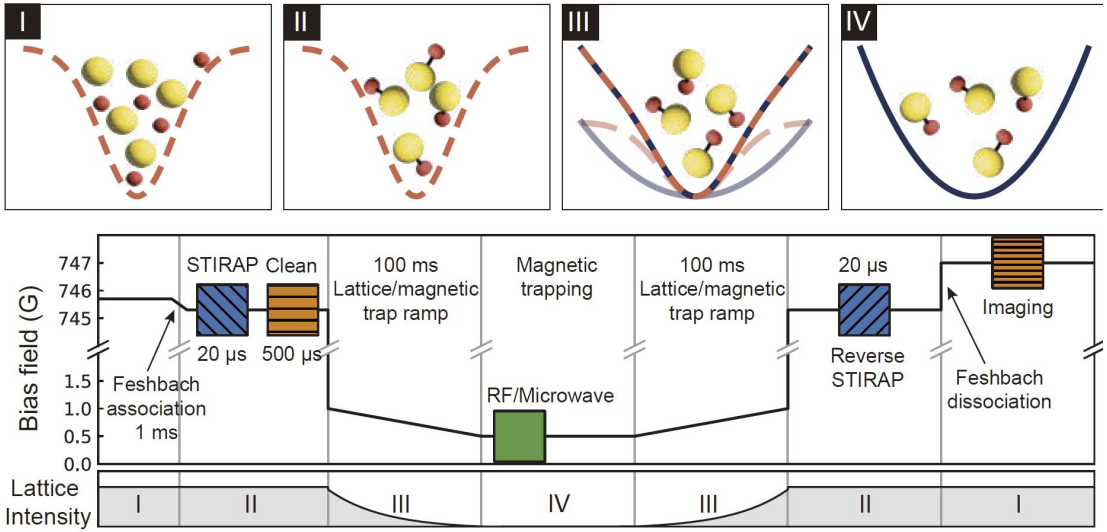
The specifics of NaLi





Experiments

Magnetic Trapping of ultracold molecules at high density



J.J. Park, Y.-K. Lu, A.O. Jamison, and W. Ketterle, Magnetic trapping of ultracold molecules at high density, Preprint, arXiv:2211.11120

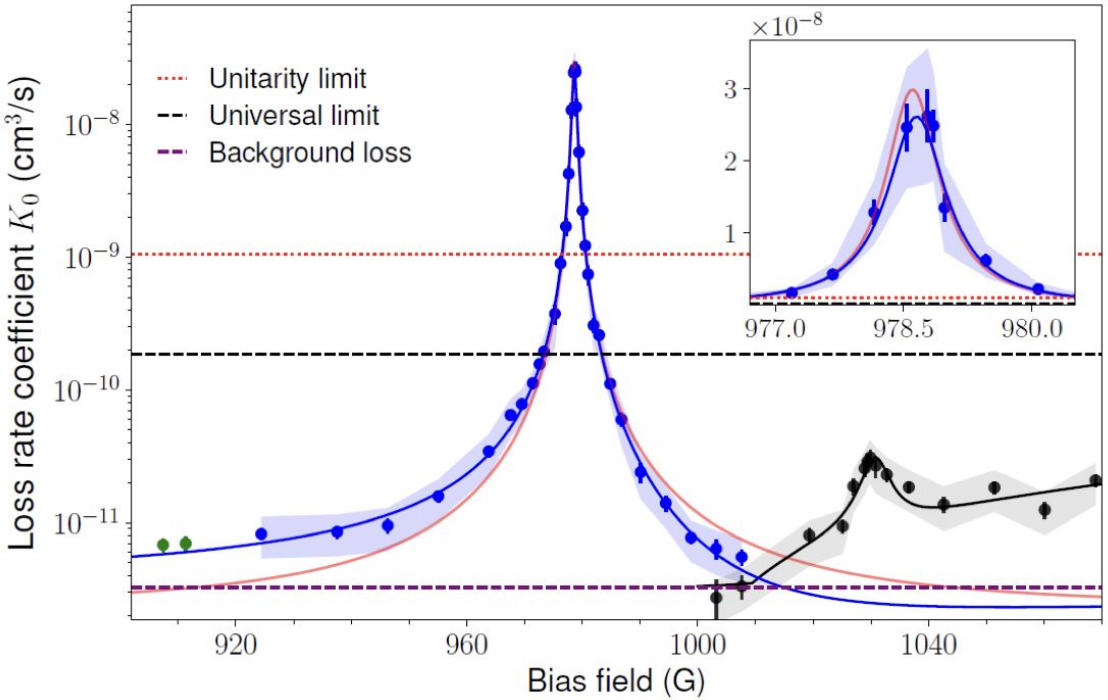
- High density of NaLi (10^{11} cm^{-3}) – 10^5 times higher
- Light free environment
- Sympathetic cooling of NaLi by Na to a temperature ~

$$0.8(1)\ \mu\mathrm{K}$$

compared to

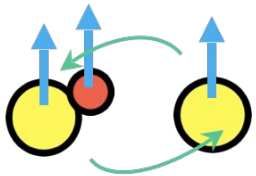
$$2.3(3)\ \mu\mathrm{K}$$

Atom-molecule Feshbach resonance



H. Son, J.J. Park, Y.-K. Lu, A.O. Jamison, T. Karman, and W. Ketterle, Control of reactive collisions by quantum interference, Science 375, 1006–1010 (2022).

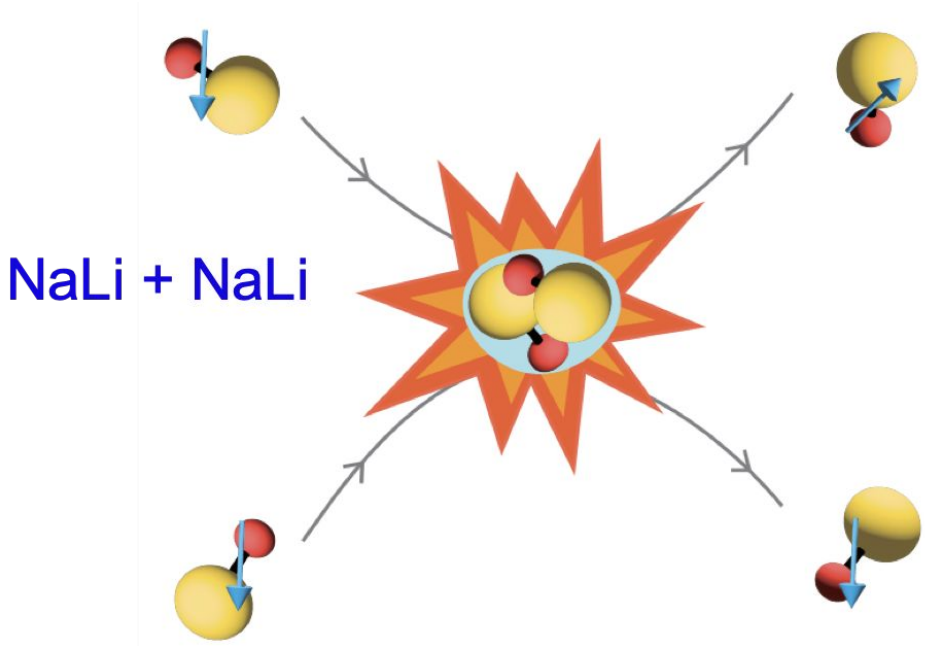
NaLi + Na

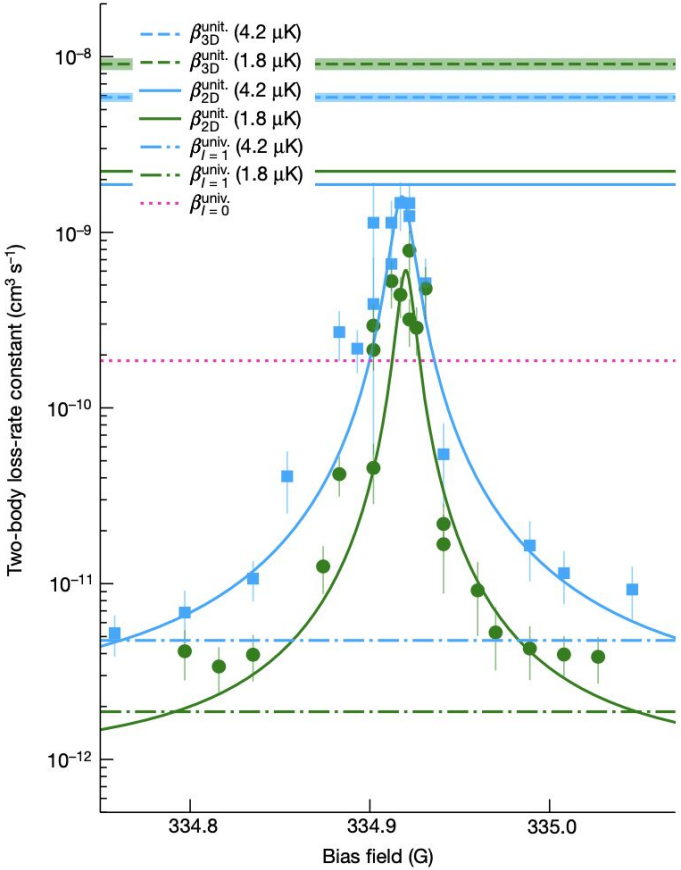


Magnetic control of pathway for collisions

- Tool to tune chemical reaction rates

Molecule- Molecule Feshbach Resonance





J.J. Park, Y.-K. Lu, A.O. Jamison, T. Tscherbul, and W. Ketterle, A Feshbach resonance in collisions between triplet ground state molecules, Nature 614, 54–58 (2023).

Collisional Complex

Long lifetimes (NaLi, RbK, NaK)

Sensitive to light (photo chemistry): NaK, RbK, RbCs

Now well understood in quartet potential of NaLi + Na

Previous work (NaK + K, Feshbach molecules) was long range, vdW potential

(Hefei/Shanghai, Innsbruck)

Exists also in reactive systems (NaLi+NaLi) – not understood

Outlook

- More studies on the Feshbach resonance in molecule-molecule collisions
- Rotational Coherence time of NaLi in magnetic trap, estimated 200ms (previously T2 limited by AC stark shifts in optical traps)
- Light assisted collisions in NaLi + NaLi collisions, and NaLi+Na collisions

Credit and Thanks to …