Motional ground state preparation for Rubidium Neutral-Atom Quantum Computer

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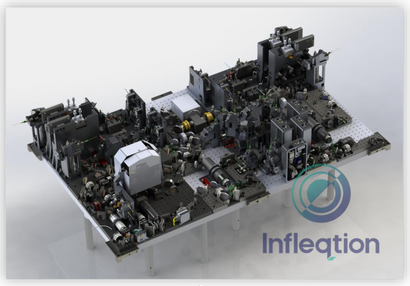
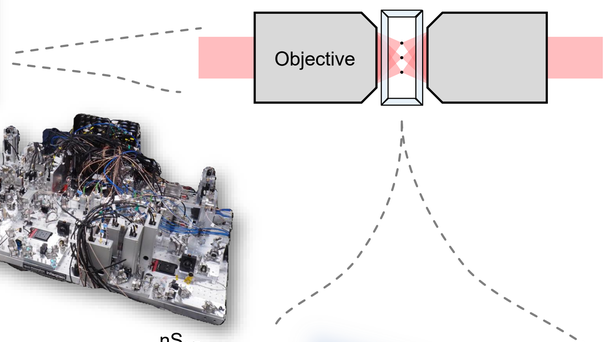
moonshot Goal 6 Cold-atom QC

National Institutes of Natural Sciences Institute for Molecular Science

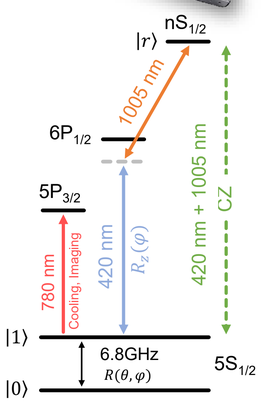
Neutral Atom QC

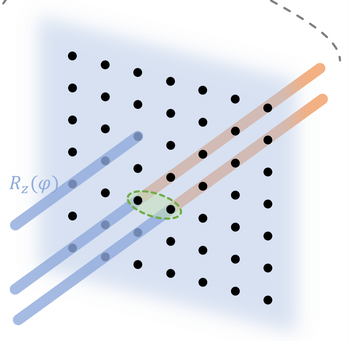


- Full-stack quantum computer
- First neutral-atom quantum computer in Japan
- High-resolution objective (1000 traps)
- 500 qubits, Fidelity >99%, Stable operation



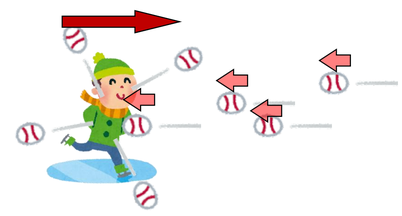
- Global qubits control via microwave $R(\theta, \varphi)$
- Cooling/imaging with 780 nm D2 line
- Ground state Raman sideband cooling with 795 nm D1 line
- CZ gate with two-photon (420+1005 nm) excitation to a Rydberg state
- Parallel local addressing of $R_z(\varphi)$, CZ gate





A. G. Radnaev *et al.*, arXiv:2408.08288 (2025)

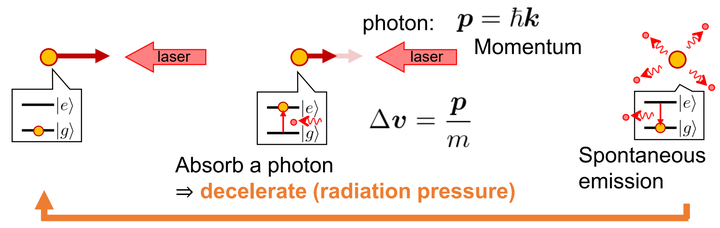
Cold atoms in tweezers



Laser cooling & Tweezer trap

- **Laser Cooling**

Cooling down (= **decelerate**) atomic motion using lasers



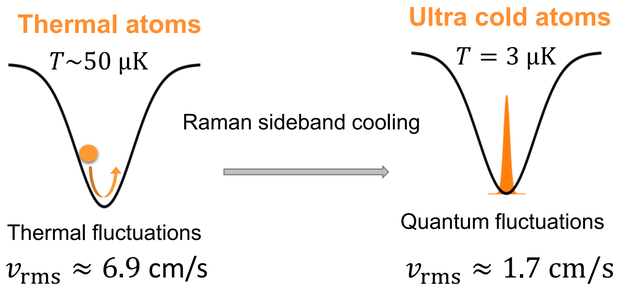
Temperature : 300 K → ~50 μK !!

- **Optical tweezer**

Beam size ~ 1 μm

Please check the poster from Jorge!!

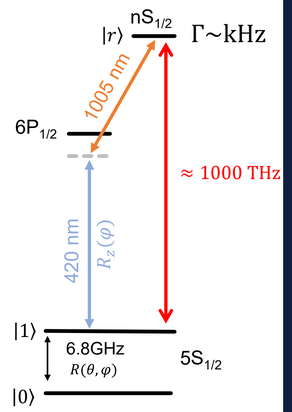
Temperature of atoms



- **Doppler effect**

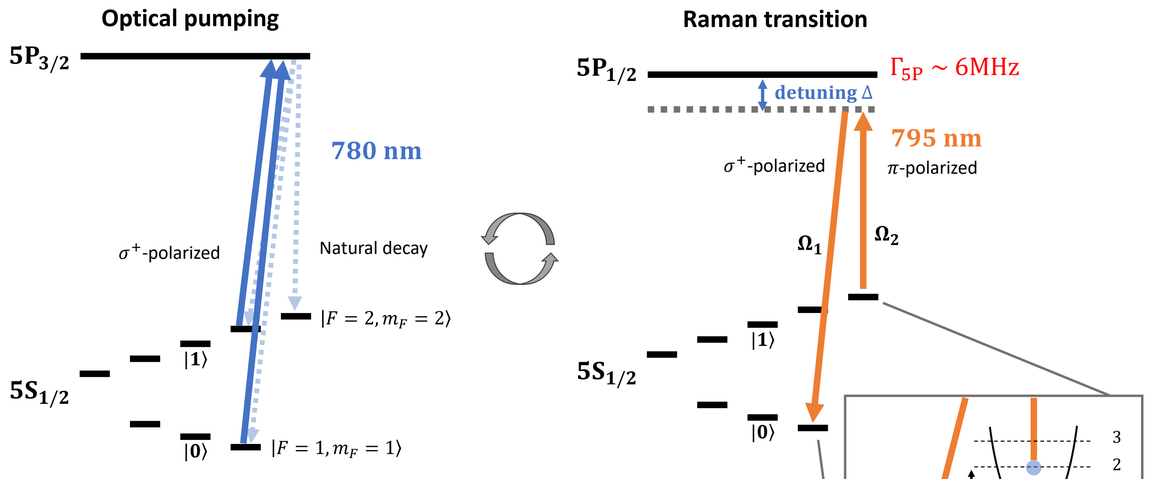
Thermal atoms : $\Delta f \sim 230$ kHz

Ultra cold atoms : $\Delta f \sim 58 kHz$



Raman sideband cooling

GOAL : Cool the atom by using **Raman transition** and **Optical pumping.**



- If $\Delta \gg \Omega_1, \Omega_2$, it behaves like effective two-level system.
- **Effective linewidth** Γ_{eff} controllable via laser intensity and detuning.
  → Allows resolution of motional sidebands.

$$\Omega_{\mathrm{eff}} = \frac{\Omega_1 \Omega_2}{2\,\Delta} \qquad \Gamma_{\mathrm{eff}} \approx \Gamma_{5P} \frac{\Omega_{\mathrm{eff}}}{\Delta} \ (\text{assuming } \Omega_1 = \Omega_2)$$

- 2-beam combination enables tuning to n → n-1 gaps.
  → Enables selective motional state control.
- In the **Lamb-Dicke regime**, motional heating is suppressed.

Lamb-dicke regime

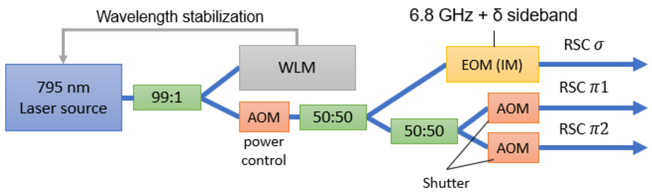
$$\eta = \frac{2\pi}{\lambda} \sqrt{\frac{\hbar}{2m\omega}} \ll 1$$

- When $\Delta = 10$ GHz, $\omega = 130$ kHz,

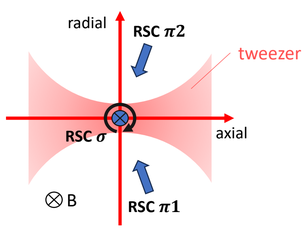
$\omega = 100$ kHz > $\Omega_{\mathrm{eff}} = 20$ kHz ≫ $\Gamma_{\mathrm{eff}} = 11.5$ Hz

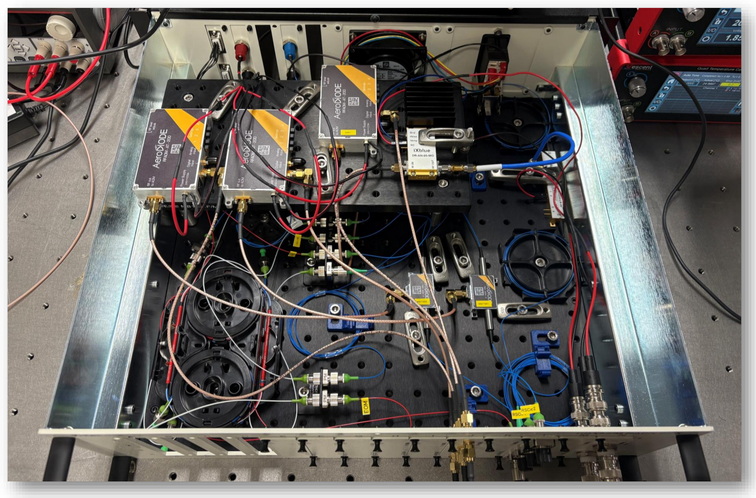
RSC setup

- All fiber setup
- 3 output from 1 laser source
- RSC σ is orthogonal to the tweezer.
- RSC π1,2 is 70° relative to the tweezer.



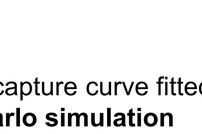
TO QPU…



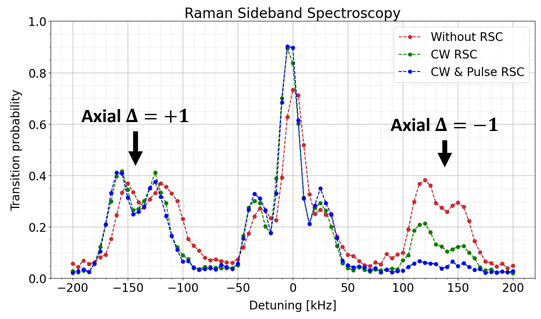


Experimental result

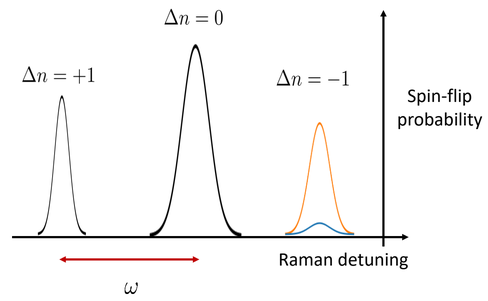
- These are the measurements I took using another setup in our group.



Raman side-band spectroscopy



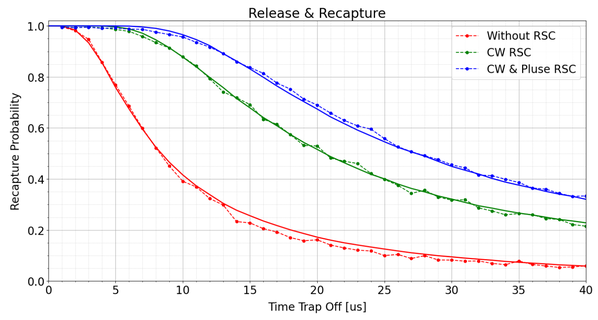
Measure $\bar{n}$ by the sideband asymmetry



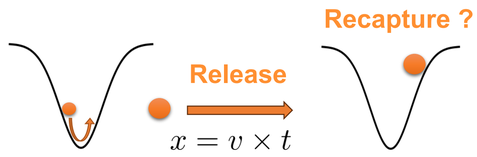
Without RSC	CW RSC	CW & Pulse RSC
$\bar{n}_{rad} = 3.87$	$\bar{n}_{rad} = 0.435$	$\bar{n}_{rad} = 0.193$

Around 84% of the atoms occupy the radial motional ground state!!

Release & Recapture



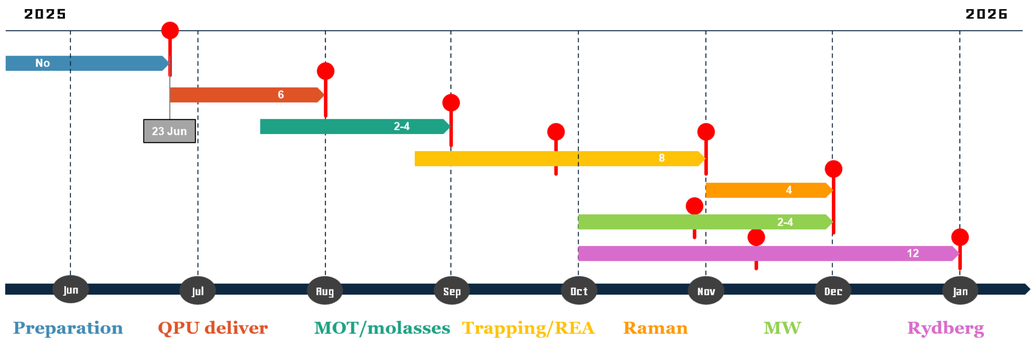
Without RSC	CW RSC	CW & Pulse RSC
$T = 73$ μK	$T = 20$ μK	$T = 13$ μK



- Release-and-recapture curve fitted with a **Monte Carlo simulation** to extract the atomic temperature.

Future Plans

Team Timeline



Before Tweezer Array is Ready…

- Optimize beam intensity and detuning
- Simulate expected cooling efficiency
- Build stable RSC setup

After Tweezer Array is Ready…

- Start experiments with atoms!!