Ultrafast Rydberg experiments with ultracold atoms in optical tweezers

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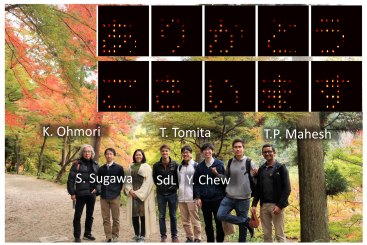

Recent works:

(This poster) Chew *et al.*, arXiv:2111.12314 (in press)

(See also) Bharti et al., arXiv:2201.09590

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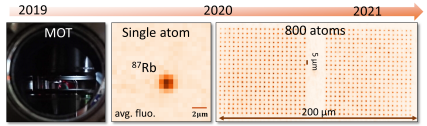
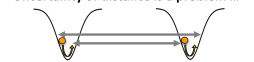
Ultracold atoms in arrays of optical tweezers

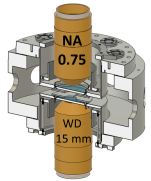


Uncertainty of distance is a problem ...



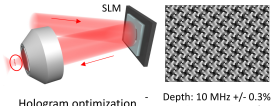
$J = \frac{C_3}{R^3}$ Interaction noise $\frac{\Delta J}{J} = 3\frac{\Delta R}{R}$ Position noise

High NA setup for holographic tweezers

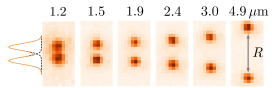


Diffraction limited
600 nm waist @ 810 nm

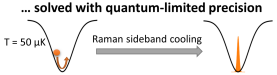
Tilt < 1 mrad
(0.05 deg)

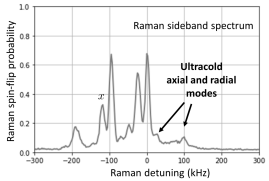


Controllable atom-atom separation down to 1.2 μm

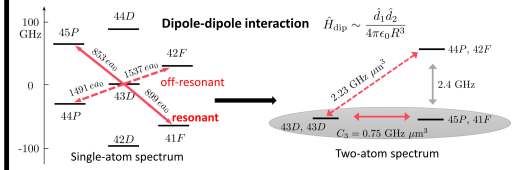


... solved with quantum-limited precision





Nanosecond Förster oscillation

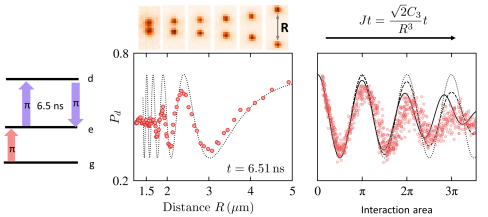


Förster resonance

$J = \sqrt{2}C_3/R^3$

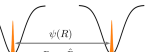
$\Psi(t) = \cos(Jt)\,|dd\rangle - i\sin(Jt)\,|\tilde{pf}\rangle$

Ultrafast, nanosecond-scale, Förster oscillation



Theory

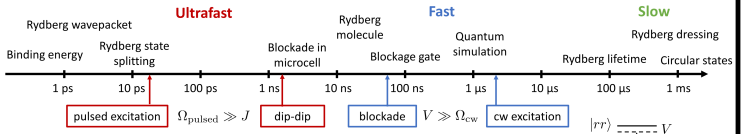
- Dashed: entanglement between internal and external d.o.f

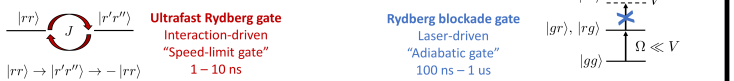


$\Psi(t) = \int dR\,\psi(R)\left[\cos\left(\frac{\sqrt{2}C_3}{R^3}t\right)|R;dd\rangle - i\sin\left(\frac{\sqrt{2}C_3}{R^3}t\right)|R;\tilde{pf}\rangle\right]$

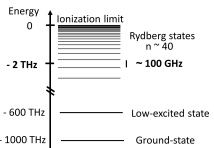
- Solid: perturbation ("leakage") from off-resonant channels

The Rydberg timescale





Rydberg formula $E_n = -\frac{13.6\,\mathrm{eV}}{n^2}$



Dipole-dipole coupling $\hat{H}_{\mathrm{dip}} \sim \frac{\hat{d}_1\hat{d}_2}{4\pi\epsilon_0 R^3}$

$J = \frac{C_3}{R^3} \gg V = \frac{C_6}{R^6}$

First-order (resonant dip-dip)

Second-order (van der Waals)

$C_3 \sim 1\,\mathrm{GHz}.\mu\mathrm{m}^3$

1 μm -> **nanosecond timescale !**

Ultrafast, speed-limit, CZ gate

Advantage: min. time in the dangerous Rydberg state |r>

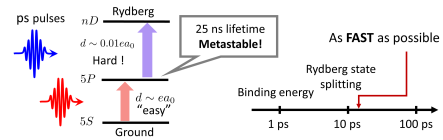
Challenge: coherent errors in |rr> from (coupling to R, many interaction channels) $\frac{\hat{d}_1\hat{d}_2}{4\pi\epsilon_0 R^3}$

Adiabatic, Rydberg blockage, CZ gate

Advantage: no dangerous interacting state |rr>

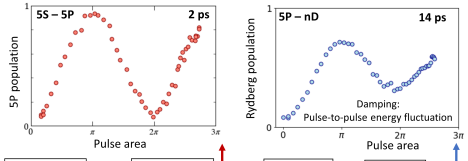
Challenge: Rydberg decoherence |r> (spont., BBR, E-field, not trapped, laser phase noise, Doppler, ...)

Picosecond Rydberg excitation



As **FAST** as possible !

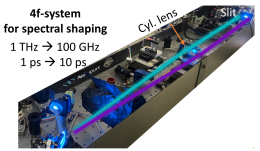
Ultrafast, picosecond, Rabi oscillation



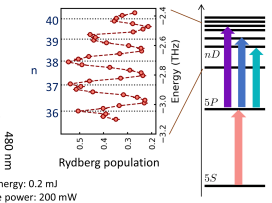
4f-system for spectral shaping

1 THz → 100 GHz

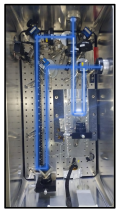
1 ps → 10 ps



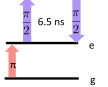
Rydberg spectroscopy



Measurement of conditional phase

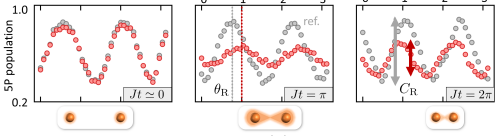


Phase-locked pair of ps pulses with delay-line interferometer

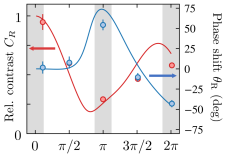


0 – 6.5 ns delay
3 as resolution

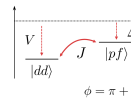
Ramsey interferometry on pair of atoms



Quantitative agreement with ab-initio calculations



- Energy defect of $\Delta E = 8$ MHz
- Other pair states $V = -21.7$ MHz



$\phi = \pi + \frac{\Delta E + V}{2}t = 1.17\pi$

Overshoot the ideal π-phase shift of CZ gate

Towards an ultrafast CZ gate

Technical

- 480nm pulses with better stability

Coherent control

- Ultrafast spin-dependent Rydberg excitation
- Tuning CZ phase with E-field
- Motional squeezed state / decoupling
- Leakage (fine-tuning off-resonant channels)