Ultrafast Quantum Simulator using Ultracold Rydberg-excited Atomic Mott-insulator

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Abstract

The ensemble of Rydberg atoms is a unique platform for quantum simulation and quantum computation because of their special properties. In our research group, we are developing a novel approach for Rydberg-based quantum simulations and computations, where we use broadband pulsed lasers to excite ^{87}Rb atoms, in Bose-Einstein condensates (BEC), Mott-Insulator (MI) lattice and optical tweezers, to Rydberg states in a timescale of 10 to 100 picoseconds at the speed limit set by the Rydberg splitting.

In this poster, I will give the overview of our ultrafast quantum simulator in which we generate a strongly correlated ultracold Rydberg ensemble of ^{87}Rb atoms excited from an unity filling MI using broadband picosecond laser pulses. We observe and control its ultrafast many-body electron dynamics by performing the time-domain Ramsey interferometry with attosecond precision. I will also discuss the future prospects and outlook of our ultrafast quantum simulator.

Preprint: arXiv: 2201.09590 (2022), Related works: Nature Photon. 16, 724 (2022), Phys. Rev. Lett. 124, 253201 (2020), Nature Commun. 7, 13449 (2016), contact: vikas@ims.ac.jp

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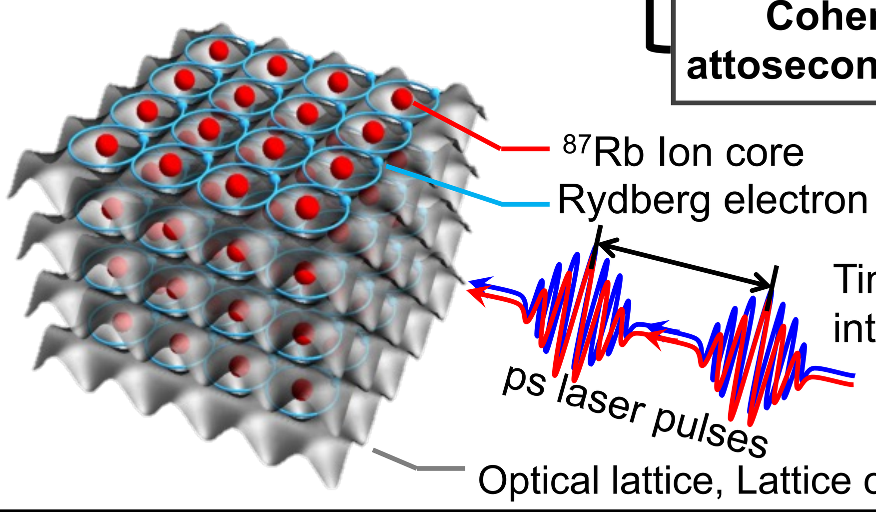
Introduction

Ultrafast quantum simulator

Quantum simulation of many-body electron dynamics within a nanosecond

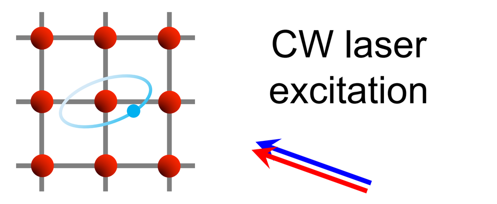
Ultracold Rydberg atoms in an optical lattice
+
Coherent control with attosecond (10^{-18} s) precision



Ultracold Rydberg atoms

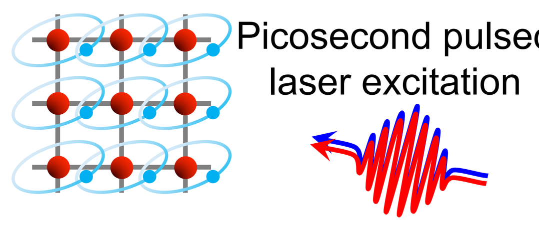
Advantages of Rydberg atoms
- Strong interactions due to large dipole moments.
- High controllability of the strength and nature of interactions.
- Interactions can be actively switched on and off.

Conventional approach



One Rydberg atom prevents the excitation of surrounding atoms (Rydberg blockade).

Our approach



Picosecond laser pulse (broadband) circumvents the Rydberg blockade.

Important works

Nature Photon. 16, 724 (2022): Ultrafast energy exchange between two Rydberg atoms in optical tweezers. This work executes an ultrafast two-qubit gate.

Phys. Rev. Lett. 124, 253201 (2020): Ultrafast creation of Rydberg electrons in atomic BEC and MI lattice. This work demonstrates the Metal-like quantum gas.

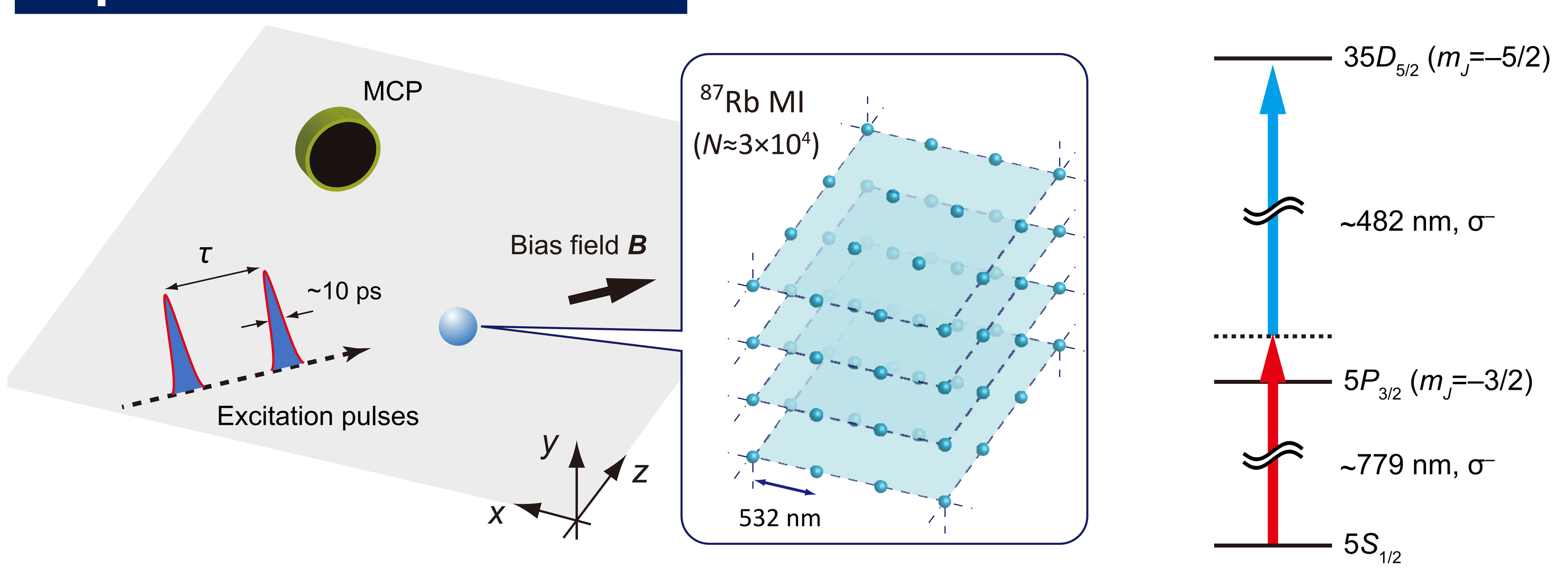
Nature Commun. 7, 13449 (2016): Ultrafast observation of beyond mean-field effect in disordered ensemble of Rydberg atoms in optical dipole trap.

See also:
- Phys. Rev. Lett. 121, 173201 (2018)
- Acc. Chem. Res. 51, 1174 (2018)
- Phys. Rev. A 94, 053607 (2016)

Single-atom decoherence is negligible in our ultrafast approach

Experiment

Experimental schematic

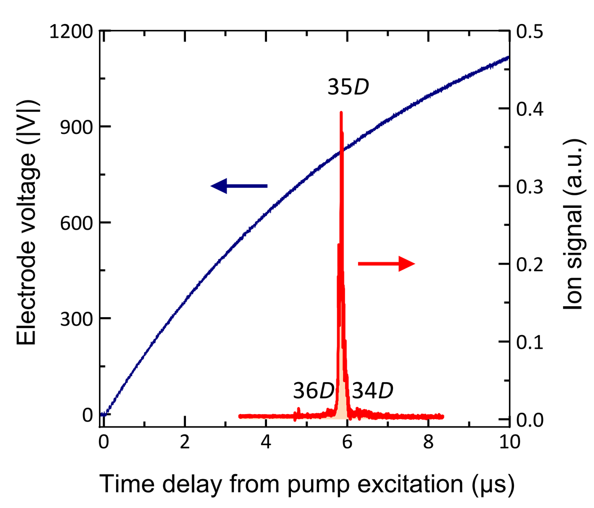


Atomic samples

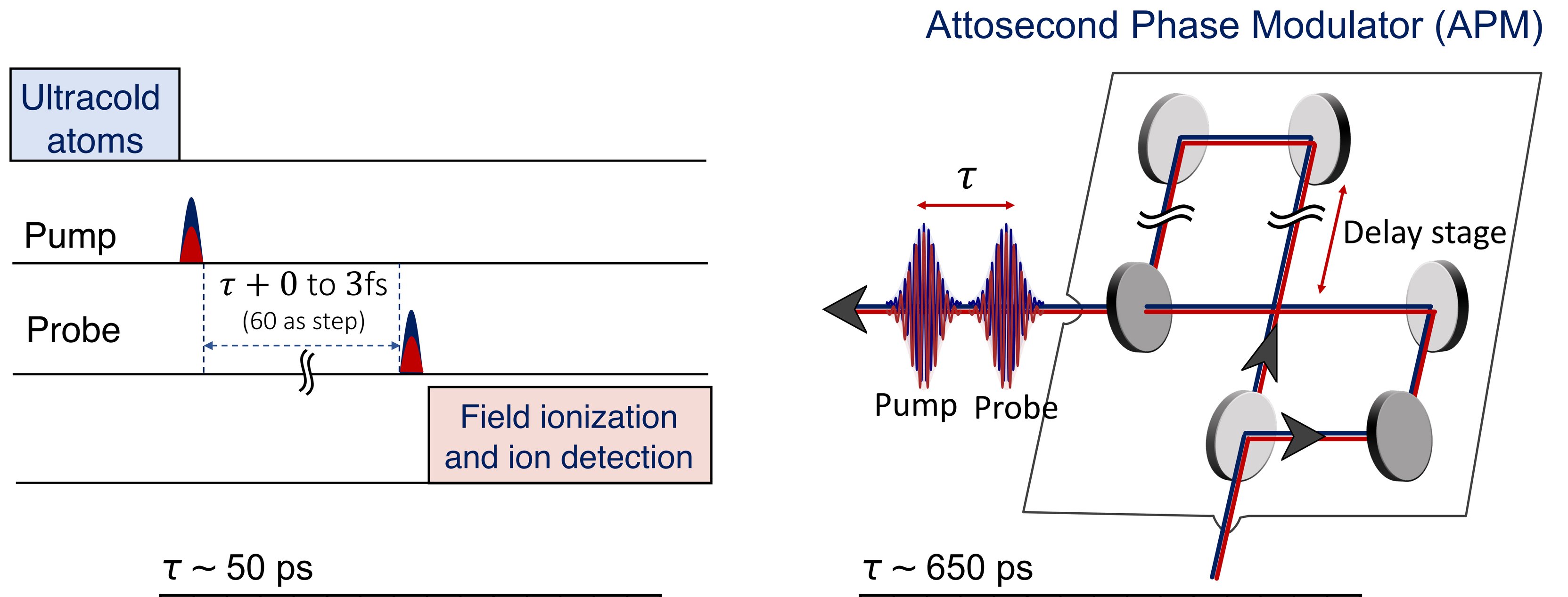
Ground state: $5S_{1/2}$ ($m_J = -1/2$)
High density Mott-insulator (ordered): Density: ~ 10^{12} atoms/cc
Low density reference sample: Density: ~ 10^{10} atoms/cc

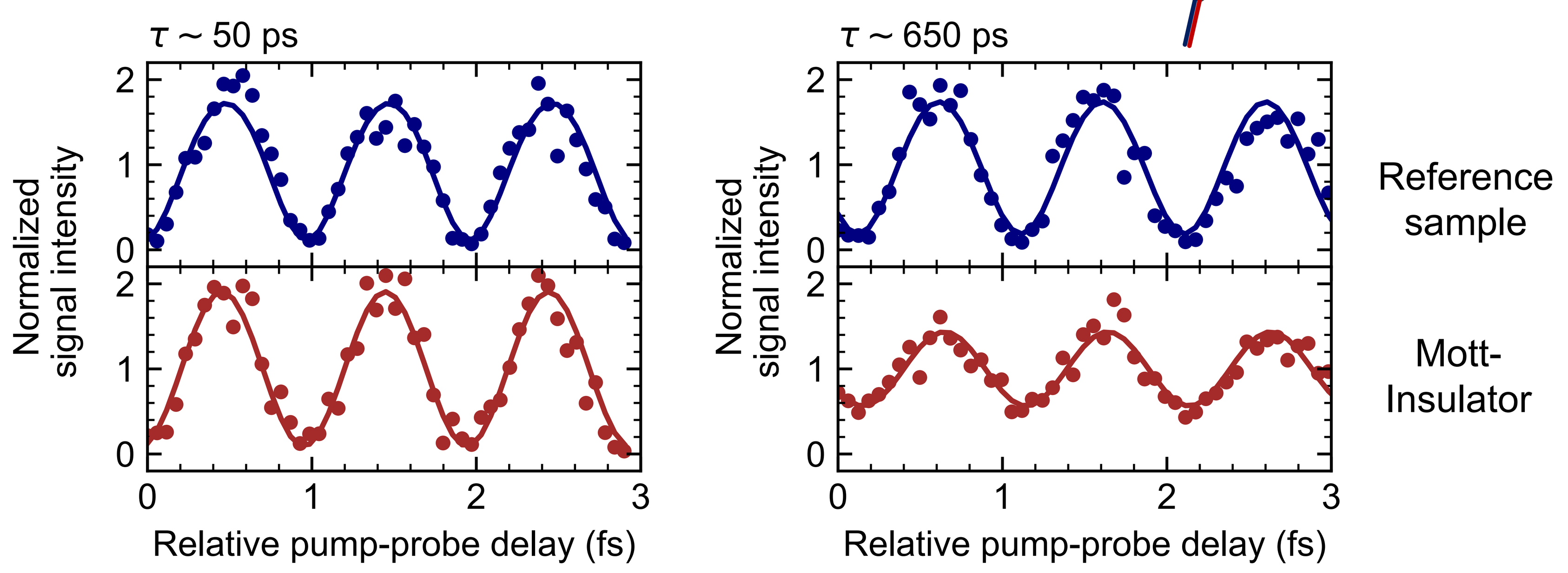
Rydberg excitation

Rydberg state: $35D_{5/2}$ ($m_J = -5/2$), Rydberg population: ~5.6 %
Excitation bandwidth ~ 170 GHz



Time domain Ramsey interferometry





Atomic coherence between ground and Rydberg sates

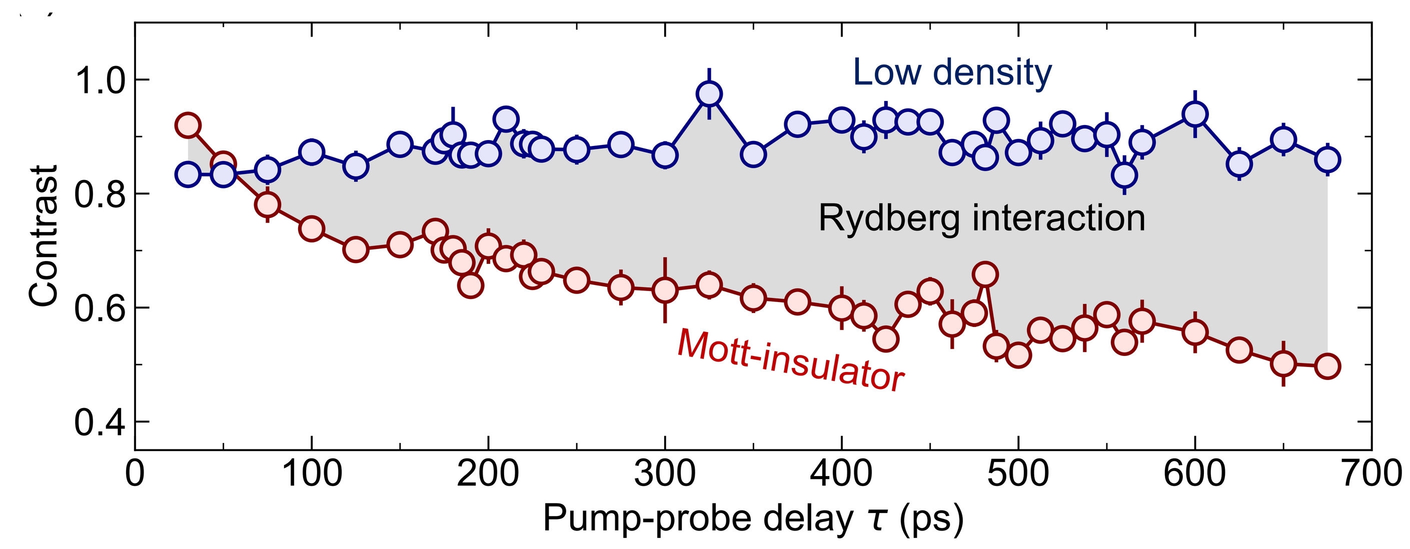
$P(\tau) \propto [1 + \cos(E_{rg}\tau/\hbar)]$
$E_{rg}/h = \sim 10^{15}$ Hz

Observables

Relative Ramsey Contrast: $C_R = C_H/C_L$
Phase shift: $\phi_H - \phi_L$

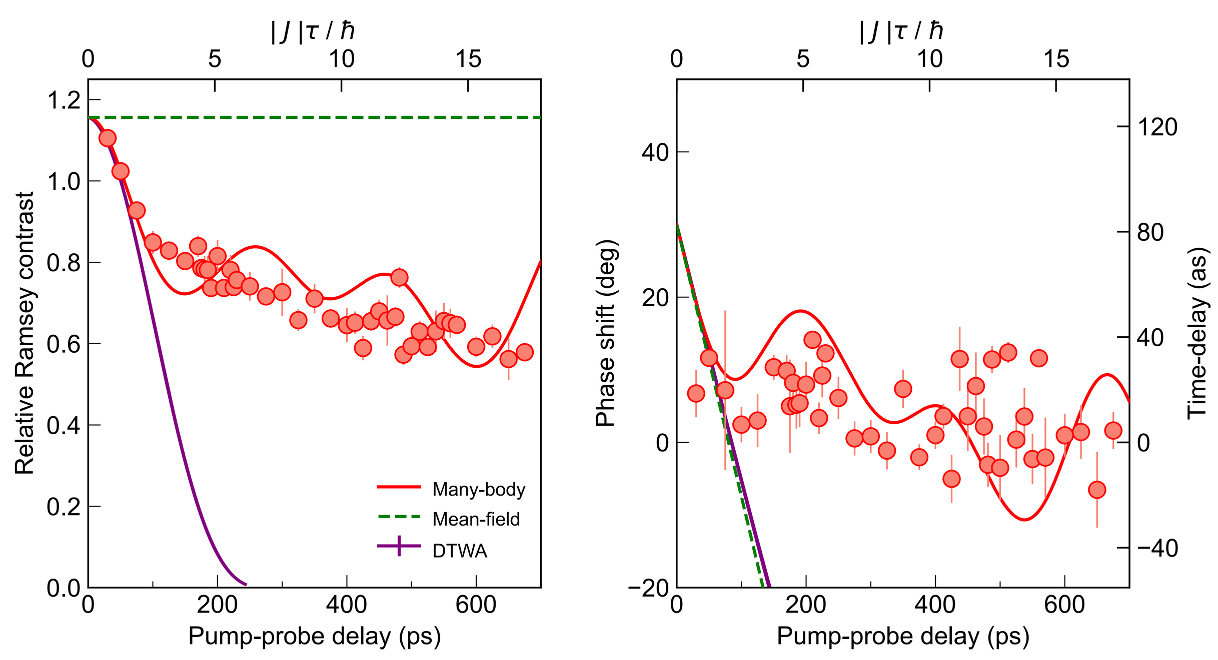
Analysis and discussion

Ramsey contrasts



Ultrafast many-body dynamics

Comparison with:
- Many-body correlation model.
- Mean-field theory.
- Discrete truncated Wigner approximation (DTWA).



Quantum Ising system

$$H = \sum_j \frac{1}{2} E_{eg} \hat{\sigma}_j^z + \sum_{j<k} U_{jk} \hat{n}_j \hat{n}_k$$

U_{jk} : long range anisotropic van der Waals interaction

Conclusions

✓ Ultrafast dynamics is governed by many-body correlations originated from long-range interactions among Rydberg atoms.
✓ Interaction energy: C_6/h: 0.372 GHz μm^6.
✓ DTWA fails at longer time delay.

Future prospects and outlook

- Our work can be extended to other interaction regimes (by tuning n or l).
- Recently, implemented with 29S state: *(manuscript under preparation)*
  - Single pair potential even at NN distance.
  - We investigate the repercussion of atomic motion on ultrafast many-body dynamics.
- Other quantum spin models, like Heisenberg and XY model, could be implemented.
- Our approach could uncover the many-body electron dynamics in a metal-like quantum gas regime. [Phys. Rev. Lett. 124, 253201 (2020)]
- Recently, ultrafast approach has been combined with optical tweezer array. [Nat. Photon. 16, 724 (2022)]

Acknowledgements

- The authors acknowledge Hisashi Chiba and Yasuaki Okano for their support.
- This work was supported by MEXT Quantum Leap Flagship Program (MEXT Q-LEAP) and JSPS Grant-in- Aid for Specially Promoted Research.