Ultrafast Quantum Simulator and Computer

Department of Photo-Molecular Science
Division of Photo-Molecular Science II

OHMORI, Kenji
Professor
[ohmori@ims.ac.jp]

Education

1987	B. E. The University of Tokyo
1992	Ph.D. The University of Tokyo

Professional Employment

1992	Research Associate, Tohoku University
2001	Associate Professor, Tohoku University
2003	Professor, Institute for Molecular Science Professor, The Graduate University for Advanced Studies
2004	Visiting Professor, Tohoku University (–2005)
2007	Visiting Professor, Tokyo Institute of Technology (–2008)
2009	Visiting Professor, The University of Tokyo (–2011)
2012	Visiting Professor (Humboldt Awardee), University of Heidelberg
2014	Visiting Professor, University of Strasbourg (–2016)

Awards

1998	Award by Research Foundation for Opto-Science and Technology
2007	JSPS Prize
2007	Japan Academy Medal
2008	Norman Hascoe Distinguished Lecturer, University of Connecticut, USA
2009	Fellow of the American Physical Society
2012	Humboldt Research Award (Germany)
2017	Hiroshi Takuma Memorial Prize of Matsuo Foundation
2018	Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology of Japan
2021	National Medal with Purple Ribbon (by His Majesty the Emperor of Japan)

Member

Assistant Professor
- SUGAWA, Seiji[*]
- DE LÉSÉLEUC, Sylvain
- TOMITA, Takafumi

IMS Research Assistant Professor
- CHEW TORII, Yuki
- MATSUBARA, Takuya
- TAMURA, Hikaru

Post-Doctoral Fellow
- BHARTI, Vineet
- CHAUHAN, Vikas
- JAUNET-LAHARY, Titouan

Visiting Scientist
- DENECKER, Tom[†]
- TSUGAOKA, Masato[†]
- KITADE, Sota[†]
- POITRINAL, Martin[†]
- TETTEKPOE, Jean-Samuel[†]
- MARTIN, Romain[†]
- PRAVONGVIENGKHAM, Metkham[†]
- MAITY, Arnab[†]
- GANESAN, Karthikeyan[†]
- STEINER, Lea-Marina[‡]
- WEDOWSKI, Roxana[‡]
- MAURUCUO URBINA, Jorge Antonio[§]
- WATANABE, Genki[§]
- GUILLEMANT, Oscar[§]
- DUBON, Joaquin[§]

Graduate Student
- TIRUMALASETTY PANDURANGA, Mahesh
- VILLELA, Rene
- TANAKA, Aito

Technical Fellow
- SUZUI, Mitsukazu
- MATSUO, Yukiko
- NAKAI, Airi
- KATAOKA, Kensuke

Secretary
- FUJIKAWA, Taketoshi
- KAWAMOTO, Minako
- MAKINO, Akane
- INUKAI, Kazuhisa
- SAKAI, Shiho
- TANAKA, Ryo
- NISHIOKA, Wakako
- KOSHIDA, Yoko
- YAMAGISHI, Mei
- OKADA, Mitsuya

Keywords Quantum Simulation, Quantum Computing, Attosecond

It is observed in a double-slit experiment by Tonomura and coworkers that single electrons recorded as dots on a detector screen build up to show an interference pattern, which is delocalized over the screen.1) This observation indicates that a delocalized wave function of an isolated electron interacts with the screen, which is composed of many nuclei and electrons interacting with each other, and becomes localized in space. This change, referred to as "collapse" in quantum theory, is often accepted as a discontinuous change, but a basic question arises: When and how the delocalized wave function becomes localized? Our objective is uncovering this mystery by observing the spatiotemporal evolution of a wave function delocalized over many particles interacting with each other. Having this objective in mind, we have developed coherent control with precisions on the picometer spatial and attosecond temporal scales. Now we apply this ultrafast and ultrahigh-precision coherent control to delocalized wave functions of macroscopic many-particle systems of an array of ultracold rubidium (Rb) Rydberg atoms, as depicted schematically in Figure 1 and named "ultrafast quantum simulator," envisaging the quantum-classical boundary connected smoothly.

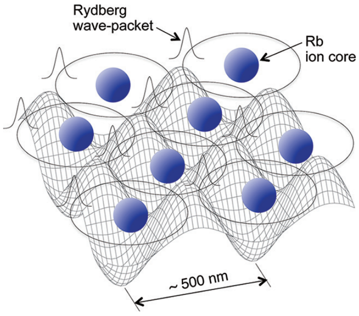

Figure 1. Metal-like quantum gas. A schematic of the many-body quantum simulator with ultracold Rydberg atoms, named "ultrafast quantum simulator," where electronic wave functions spatially overlap between neighboring atoms.2)

Selected Publications

- H. Katsuki *et al.*, "Visualizing Picometric Quantum Ripples of Ultrafast Wave-Packet Interference," *Science* **311**, 1589–1592 (2006).
- H. Katsuki *et al.*, "Actively Tailored Spatiotemporal Images of Quantum Interference on the Picometer and Femtosecond Scales," *Phys. Rev. Lett.* **102**, 103602 (2009).
- K. Hosaka *et al.*, "Ultrafast Fourier Transform with a Femtosecond-Laser-Driven Molecule," *Phys. Rev. Lett.* **104**, 180501 (2010).
- H. Goto *et al.*, "Strong-Laser-Induced Quantum Interference," *Nature Physics* **7**, 383–385 (2011).
- H. Katsuki *et al.*, "All-Optical Control and Visualization of Ultrafast Two-Dimensional Atomic Motions in a Single Crystal of Bismuth," *Nature Commun.* **4**, 2801 (2013).
- N. Takei *et al.*, "Direct Observation of Ultrafast Many-Body Electron Dynamics in an Ultracold Rydberg Gas," *Nature Commun.* **7**, 13449 (2016).
- C. Liu *et al.*, "Attosecond Control of Restoration of Electronic Structure Symmetry," *Phys. Rev. Lett.* **121**, 173201 (2018).
- M. Mizoguchi *et al.*, "Ultrafast Creation of Overlapping Rydberg Electrons in an Atomic BEC and Mott-Insulator Lattice," *Phys. Rev. Lett.* **124**, 253201 (2020).
- Y. Chew *et al.*, "Ultrafast Energy Exchange between Two Single Rydberg Atoms on a Nanosecond Timescale," *Nature Photonics* **16**, 724 (2022).
- V. Bharti, S. Sugawa *et al.*, "Picosecond-Scale Ultrafast Many-Body Dynamics in an Ultracold Rydberg-Excited Atomic Mott Insulator," *Phys. Rev. Lett.* **131**, 123201 (2023).

1. Development of an "Ultrafast Quantum Simulator" by Optical Control with Precisions on the Attosecond Temporal and Submicron Spatial Scales[6)]

We develop a novel quantum simulator that can simulate quantum many-body dynamics for more than 1000 particles within one nanosecond, combining our two unique experimental resources: "coherent control with attosecond precision"[3)] and "a strongly correlated ultracold Rydberg gas."[4–6)]

We have completed a standard hardware of this ultrafast quantum simulator composed of an array of ultracold Rb atoms trapped in an optical lattice and excited to Rydberg levels with a coherent picosecond (ps) laser pulse.[5,6)] The broad bandwidth of the ps laser pulse has allowed us to excite the atoms in the neighboring lattice sites to Rydberg levels simultaneously for the first time.

Very recently in 2023, quantum magnetism has successfully been simulated with this standard hardware assembled with ~30,000 Rb atoms.[6)] Our novel scheme above completes the simulation in just several hundreds of picoseconds, accelerating the simulation speed by three orders of magnitude compared to any other quantum simulators of magnetism so far. This innovative acceleration solves the issue with external noise on the timescale of ~1 microsecond or slower in general, which has been one of the biggest concerns for quantum simulation. Moreover, we have succeeded in simulating the formation dynamics of "quantum entanglement," which is difficult to measure in actual magnetic materials, on the fastest timescale of several hundred picoseconds, as schematically depicted in Figure 2.

We continue upgrading this ultrafast quantum simulators, generously supported by the Q-LEAP program of the MEXT of Japan.

2. Development of an Ultrafast Quantum Computer with Cold Atoms[7)]

We have developed arbitrary two dimensional optical trap arrays for cold atoms with optical tweezers, which are necessary for quantum computing.

We have succeeded in loading a single atom into each trap of those arbitrary arrays, and reassembling those atoms with a movable optical tweezers. Such an array of cold atoms has been manipulated with an ultrafast laser for the first time, leading to a completely new quantum computer we refer to as an "ultrafast quantum computer." With this ultrafast quantum computer, we have recently succeeded in executing a controlled Z gate,[7)] accelerating a two-qubit gate (a fundamental arithmetic element essential for quantum computing) of cold-atom quantum computers by two orders of magnitude. It is also two orders of magnitude faster than the noise from the external environment and operating lasers, whose timescale is in general 1 microsecond or slower, and thus can be safely isolated from the noise. Moreover, the speed of this two-qubit gate is faster than that of the fast two-qubit gate demonstrated recently by "Google AI Quantum" with superconducting qubits.[8)] We continue upgrading this ultrafast quantum computers, generously supported by the Moonshot program of the Cabinet Office of Japan.

References

1) K. Tonomura *et. al.*, *Am. J. Phys.* **57**, 117 (1989).
2) K. Ohmori, *Found. Phys.* **44**, 813–818 (2014).
3) H. Katsuki *et al.*, *Acc. Chem. Res.* **51**, 1174–1184 (2018).
4) N. Takei *et al.*, *Nat. Commun.* **7**, 13449 (2016).
5) M. Mizoguchi *et al.*, *Phys. Rev. Lett.* **124**, 253201 (2020).
6) V. Bharti, S. Sugawa *et al.*, *Phys. Rev. Lett.* **131**, 123201 (2023).
7) Y. Chew *et al.*, *Nat. Photonics* **16**, 724 (2022). (Cover-Page Highlight)
8) B. Foxen *et al.*, *Phys. Rev. Lett.* **125**, 120504 (2020).

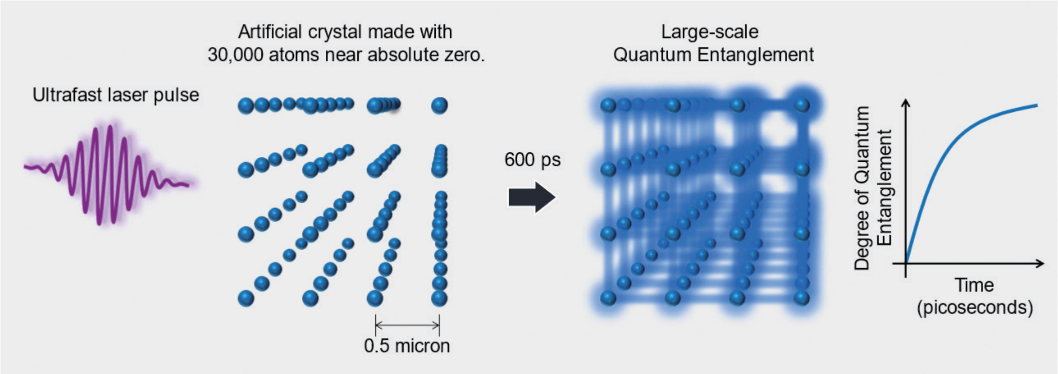

Figure 2. Conceptual diagram of ultrafast quantum simulation of magnetic material.[6)] A large-scale array of 30,000 atoms, with a spacing of 0.5 micron, is controlled with a ~10 picosecond ultrafast laser pulse. After irradiating an ultrafast laser pulse, large-scale "quantum entanglement" is formed in only ~600 picoseconds. Image source: Prof. Seiji Sugawa (U. Tokyo).

Award

DE LÉSÉLEUC, Sylvain; The 12th Young Scientist Award of National Institutes of Natural Sciences (2023).

---

* Present Address; The University of Tokyo
† Moonshot Program Visiting Scientist
‡ DAAD Program Visiting Scientist
§ IMS International Internship Program