Ultrafast Quantum Simulator and Computer

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](image)

**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.²⁷

**Keywords** Quantum Simulation, Quantum Computing, Attosecond

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

**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
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2004 Visiting Professor, Tohoku University (~2005)
2007 Visiting Professor, Tokyo Institute of Technology (~2008)
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2012 Visiting Professor (Humboldt Award), 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
2017 Hiroshi Takuma Memorial Prize of Matsufo Foundation
2018 Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology of Japan
2021 Medal with Purple Ribbon (by His Majesty the Emperor of Japan)

**Selected Publications**

Quantum many-body problems are at the heart of a variety of physical functionalities including superconductivity and magnetism in solid materials. It is extremely hard, however, to solve such quantum many-body problems. In solving the Hubbard model with 1000 particles, for example, the diagonalization would take 10 to the power of 573 years even with the world’s fastest supercomputers. In this project, 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” and “a strongly-correlated ultracold Rydberg gas.”

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, as schematically illustrated in Figure 2. 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. With this standard hardware, we have succeeded in creating an exotic electronic state with spatially overlapping wave-functions as shown schematically in Figures 1 and 2. The degree of spatial overlap is actively tuned with ~50 nanometer precision. This exotic metal-like quantum gas under exquisite control opens up a completely new regime of many-body physics for simulating ultrafast many-body electron dynamics dominated by Coulomb interactions.

We have also completed a readout interface of our ultrafast quantum simulator, which is the time domain Ramsey interferometer of ultracold Rydberg atoms with attosecond precision, whose contrast is almost 100%. The phase and visibility of this Ramsey interferogram are highly sensitive to the nature and strength of many-body interactions among the Rydberg atoms.

2. Development of an Ultrafast Quantum Computer

So far we have developed arbitrary two dimensional optical trap arrays for cold atoms, which are necessary for quantum computing, in tight collaborations with Hamamatsu Photonics K.K. Their examples are shown in Figure 3, the world’s smallest arbitrary arrays of optical traps. (a) Square lattice; (b) Kagome Lattice; (c) Hexagonal (Honeycomb) lattice.

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 in just 6.5 ns, as depicted schematically in Figure 4. This is the world’s fastest controlled gate, which is the most important two-qubit gate (a fundamental arithmetic element essential for quantum computing). This high-impact result was highlighted on the front cover of the Oct 2022 Issue of Nature Photonics, and by more than 200 news articles worldwide, such as in Japan, US, Europe, China, etc.

References
12. Y. Chew et al., Nat. Photonics 16, 724 (2022). (Cover-PAGE Highlight)

* IMS International Internship Program

Figure 3. Examples of the world’s smallest arbitrary arrays of optical traps. (a) Square lattice; (b) Kagome Lattice; (c) Hexagonal (Honeycomb) lattice.

Figure 4. Conceptual diagram of the world’s fastest controlled gate for ultrafast quantum computing. Two single atoms captured in optical tweezers (red light) with a separation of a micrometer are entangled by an ultrafast laser pulse (blue light) shone for only 10 picoseconds.

Image source: Dr. Takafumi Tomita (IMS)

Award
OHMORI, Kenji; National Medal with Purple Ribbon by His Majesty the Emperor of Japan (2021).

Figure 2. Schematic of the standard hardware of the ultrafast quantum simulator.