Exploring Quantum-Classical Boundary

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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 a bulk solid composed of many nuclei and electrons interacting with each other, and becomes localized in space. This change, referred to as "collapse" in quantum mechanics, is often accepted as a discontinuous event, but a basic question arises: When and how the delocalized wave function becomes localized? Our dream is uncovering this mystery by observing the spatiotemporal evolution of a wave function delocalized over many particles interacting with each other. Having this dream 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 such as an ensemble of ultracold Rydberg atoms and a bulk solid, envisaging the quantum-classical boundary connected smoothly.

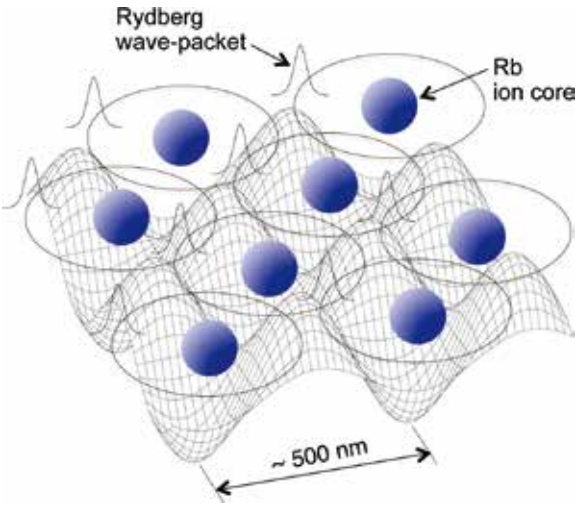

Figure 1. Schematic of the many-body system of ultracold Rydberg atoms.[2]

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," *Nat. Phys.* **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," *Nat. Commun.* **4**, 2801 (2013).
- H. Katsuki *et al.*, "Real-Time Observation of Phase-Controlled Molecular Wave-Packet Interference," *Phys. Rev. Lett.* **96**, 093002 (2006).

1. Manipulation and Visualization of Two-Dimensional Phase Distribution of Vibrational Wave Functions in Solid Parahydrogen Crystal[3)]

Solid parahydrogen, which is known to have an exceptionally long vibrational coherence lifetime as a molecular solid, offers an ideal testbed to perform coherent control experiments in the condensed phase. Here we demonstrate the spatial manipulation and visualization of the relative phase of vibrational wave functions in solid parahydrogen. Spatial distribution of vibrational excitation is generated by femtosecond impulsive Raman excitation. It is shown that the imprinted initial phase can be manipulated by wave-front modulation of the excitation laser pulses with a spatial light modulator. An interferometric measurement is used to convert the spatial phase distribution of the vibrational wave functions to the amplitude distribution. We have confirmed that the spatial profile of the scattered anti-Stokes pulse reveals the spatial phase distribution of the wave functions. The read-and-write scheme demonstrated in this experiment is applicable to a broad range of Raman memory systems accessible by Λ-type transitions.

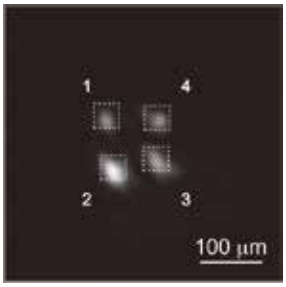

Figure 2. (a) O K-edge XAS of liquid water at different positions of liquid layerImage of the anti-Stokes pulse retrieved by irradiating a probe pulse into the *p*-H_2 crystal in which the 2×2 spatial distribution of the wave function is prepared by the impulsive Raman excitation (IRE).

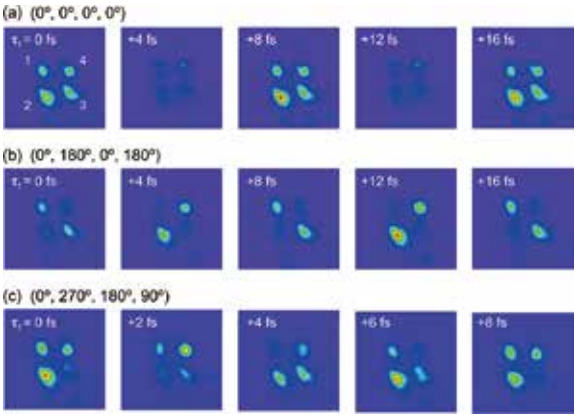

Figure 3. False color plots of the temporal evolution of the CCD images of the anti-Stokes pulse as the function of the delay τ_f between two IREs. The origin of τ_f ($\tau_f = 0$) is arbitrary and is set to 0 for the leftmost panel in each row (a), (b), or (c). The signal is retrieved by the irradiation of a probe pulse at its delay $\tau_{probe} \sim 250$ ps. The delay τ_f is scanned around 25 ps. The first IRE encodes different relative phases among regions 1–4 shown in Figure 2. Note that the time step for (c) is half of the other two cases.

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.*, *Phys. Rev. B* **92**, 094511 (2015).

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