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.

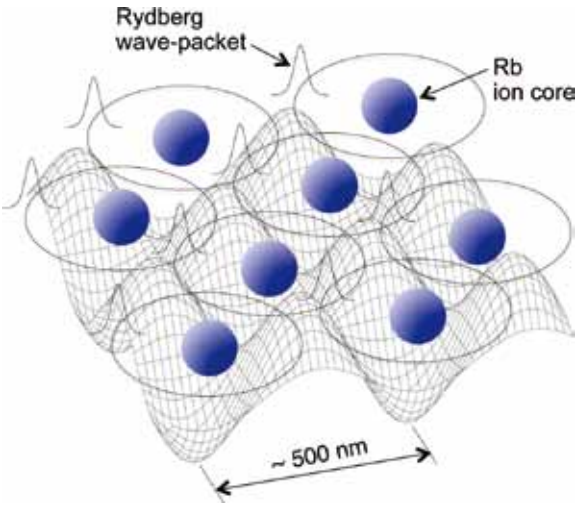

Figure 1. Schematic of the many-body system of ultracold Rydberg atoms.[2]

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. Hosak *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).

1. All-Optical Control and Visualization of Ultrafast Two-Dimensional Atomic Motions in a Single Crystal of Bismuth[3)]

In a bulk solid, optical control of atomic motion provides a better understanding of its physical properties and functionalities. Such studies would benefit from active control and visualization of atomic motions in arbitrary directions, yet, so far, mostly only one-dimensional control has been shown. Here we demonstrate a novel method to optically control and visualize two-dimensional atomic motions in a bulk solid. We use a femtosecond laser pulse to coherently superpose two orthogonal atomic motions in crystalline bismuth. The relative amplitudes of those two motions are manipulated by modulating the intensity profile of the laser pulse, and these controlled motions are quantitatively visualized by density functional theory calculations. Our control-visualization scheme is based on the simple, robust and universal concept that in any physical system, two-dimensional particle motion is decomposed into two orthogonal one-dimensional motions, and thus it is applicable to a variety of condensed matter systems.

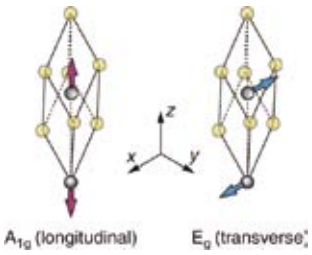

Figure 2. Crystal unit cell structure of Bi and the orientation of the A_{1g} (longitudinal) and E_g (transverse) phonon motions.

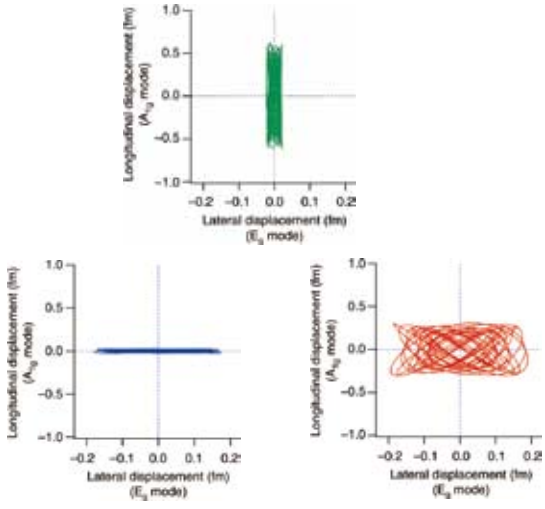

Figure 3. Traces of the atomic motions within a unit cell of Bi. Each trace represents the trajectory within the time window from 0.82 to 10.48 ps.

2. Ultrafast Coherent Control of an Ultracold Rydberg Gas[2)]

We employ an ensemble of ultracold Rb atoms as a model system to mimic a bulk solid. The model system offers longer coherence lifetime and more tunable parameters such as interatomic distance and interactions than a bulk solid. Since the interatomic distance is not shorter than submicrometers in this model system, longer than that of a bulk solid by more than three orders of magnitude, we generate Rydberg electronic wave-packets in those Rb atoms to induce interatomic interactions. Moreover these interactions can be actively tuned by changing the principal quantum numbers of Rydberg levels to be excited; the higher quantum numbers give larger diameters of Rydberg orbitals and hence stronger interactions. Briefly, a picosecond laser pulse produces Rydberg electronic wave-packets in laser-cooled Rb atoms. We measure the temporal evolution of those Rydberg wave-packets. We also measure the interferogram of two Rydberg wave-packets generated in each atom with a phased pair of picosecond laser pulses, whose delay is scanned in steps of attoseconds. Those temporal evolutions and interferograms of Rydberg wave-packets are measured as a function of the atom density, which can be converted to an atom–atom distance. We have observed that the interferogram is phase-shifted when we change the atom density. This observation suggests that the interatomic interactions have been induced by Rydberg wave-packets in Rb atoms. We plan to load these ultracold Rydberg atoms into an optical lattice to have better-defined interatomic configurations, as shown in Figure 1. Our ultrafast coherent control of an ultracold Rydberg gas could lead to the development of a novel simulator of quantum many-body dynamics.

3. Theoretical/Numerical Study on Strong-Laser-Induced Interference in the B State of I_2[4)]

In the B state of I_2, strong-laser-induced interference (SLI) was recently observed in the population of each vibrational eigenstate within a wave packet, which was initially prepared by a pump pulse and then strongly modulated by an intense femtosecond near-infrared (NIR) laser pulse. It was suggested that the interference as a function of the time delay occurs between the eigenstate reached by Rayleigh scattering and that by Raman scattering. To verify this mechanism and further discuss its characteristics, we theoretically/numerically study the SLI by adopting a two-electronic-state model of I_2. Numerical simulation reasonably reproduces the experimental signals and confirms the theoretical consequences, which include the π-phase shifts between Stokes and anti-Stokes transitions and (practically) no contribution from the energy shifts induced by the NIR pulse.

References

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2) K. Ohmori, *Found. Phys.* **44**, 813–818 (2014).
3) H. Katsuki *et al.*, *Nat. Commun.* **4**, 2801 (2013).
4) Y. Ohtsuki *et al.*, *Phys. Chem. Chem. Phys.* **16**, 5689 (2014).