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Ultrafast terahertz microscopy: from near fields to single atoms

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A new experimental frontier has recently emerged with the potential to significantly impact physics, chemistry, and materials science: the regime of ultrafast time resolution and ultrasmall spatial resolution. This is the domain in which single atoms, molecules, and electronic orbitals move. It also corresponds, on larger length scales, to the territory of low-energy elementary excitations such as plasmons, phonons, and interlevel transitions in excitons. These processes are of particular importance for nanomaterial functionality and typically survive for only femtoseconds to picoseconds after photoexcitation.

In this talk, I will show how these diverse dynamics can be studied with new techniques that combine terahertz technology with scanning probe microscopy. First, I will describe how ultrafast near-field microscopy has been employed to perform sub-cycle spectroscopy of single nanoparticles [1], reveal hidden structure in correlated electron systems [2], resolve transient interface polaritons in van der Waals heterostructures [3], and characterize the electronic properties of topological insulator surfaces [4]. Then I will discuss the development of a new technique: lightwave-driven terahertz scanning tunneling microscopy [5-7]. In this novel approach, the oscillating electric field of a phase-stable, few-cycle light pulse at an atomically sharp tip can be used to remove a single electron from a single molecular orbital within a time window faster than an oscillation cycle of the terahertz wave. I will show how this technique has been used to take ultrafast snapshot images of the electron density in single molecular orbitals and watch the motion of a single molecule for the first time [6].

[1] M. Eisele et al., Nature Photon. 8. 841 (2014).
[2] M. A. Huber et al., Nano Lett. 16, 1421 (2016).
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[4] F. Mooshammer et al., Nano Lett. 18, 7515 (2018).
[5] T. L. Cocker et al., Nature Photon. 7, 620 (2013).
[6] T. L. Cocker et al., Nature 539, 263 (2016).
[7] V. Jelic et al. Nature Phys. 13, 591 (2017).

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