Progress in the investigation of ultrafast electron dynamics using short light pulses

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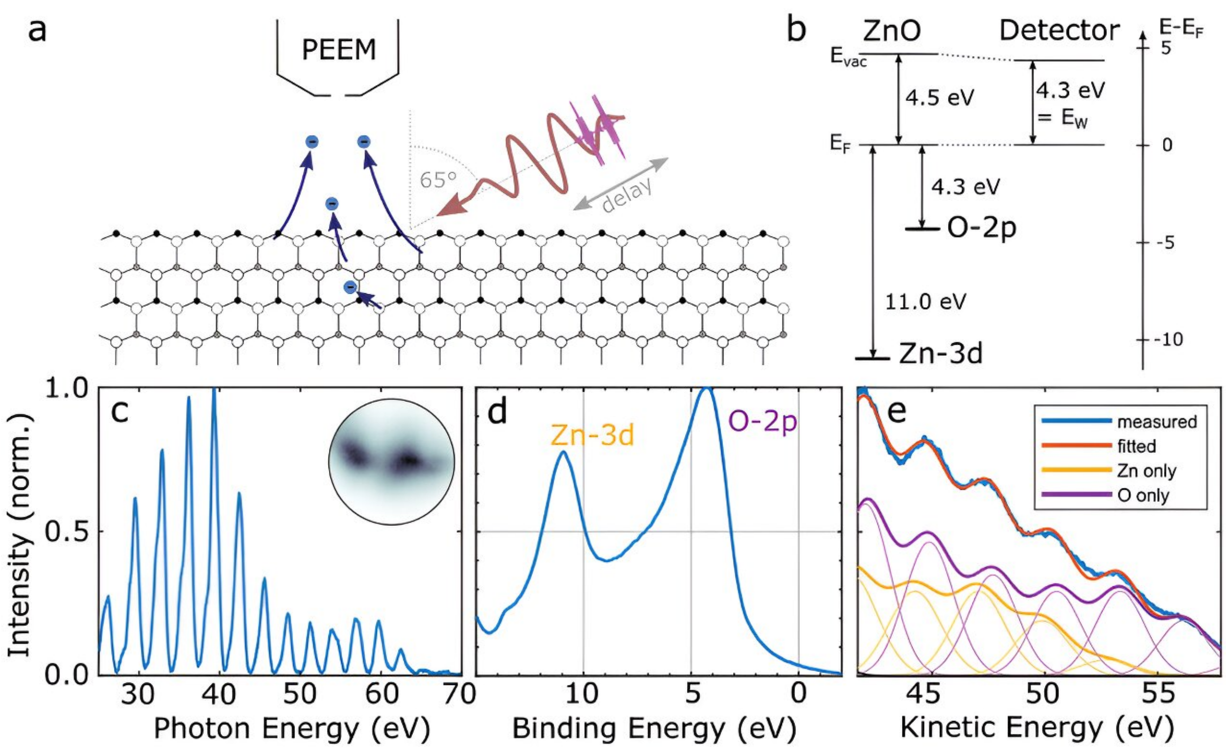

Characterization of the experimental setup. a) Schematic of the steps involved in the experiment. A pair of XUV pulses (drawn in violet) photoemits electrons from a ZnO crystal. The electrons experience the dynamic field of an NIR laser pulse (drawn in red) close to the surface at a variable waiting time. The emission site of the electrons, as well as their kinetic energy after interaction with the NIR field are recorded using a photoemission electron microscope (PEEM). b) Energy diagram of the ZnO surface and the electron detector, which are electrically contacted and thus have their Fermi levels aligned. c) Optical spectrum of the XUV pulses used for photoemitting electrons from the surface. The inset shows the linear photoemission pattern generated by the XUV pulses from a ZnO surface. The field of view (FOV) of the inset is 180 µm. d) Measurement of the electronic states close to the Fermi level of the ZnO surface. It was performed using a helium gas discharge lamp emitting a photon energy of 21.2 eV and a hemispherical analyzer for electron detection after photoemission. e) Kinetic energy spectrum of photoelectrons emitted from a ZnO surface using the spectrum shown in (c). The energy-dependent emission cross-section of the Zn-3d and O-2p states indicated in (d) was used as a fitting parameter in combination with the optical spectrum shown in (c) to replicate the modulated spectrum shown in blue. The contribution to the emission from Zn-3d and O-2p by the individual harmonics is shown in lighter colors, respectively. Credit: *Advanced Physics Research* (2023). DOI: 10.1002/apxr.202300122

When electrons move within a molecule or semiconductor, this occurs on unimaginably short time scales. A Swedish-German team, including Dr. Jan Vogelsang from the University of Oldenburg, has now made significant progress towards a better understanding of these ultrafast processes: The researchers were able to track the dynamics of electrons released from the surface of zinc oxide crystals using laser pulses with spatial resolution in the nanometer range and at previously unattained temporal resolution.

With these experiments, the team demonstrated the applicability of a method that could be used to understand better the behavior of electrons in nanomaterials and new types of solar cells, among other applications. Researchers from Lund University, including Professor Dr. Anne L'Huillier, one of last year's three Nobel laureates in physics, were involved in the study published in the journal *Advanced Physics Research*.

In their experiments, the research team combined a special type of electron microscopy known as photoemission electron microscopy (PEEM) with attosecond physics technology. The scientists use extremely short-duration light pulses to excite electrons and record their subsequent behavior. "The process is much like a flash capturing a fast movement in photography," Vogelsang explained. An attosecond is incredibly short—just a billionth of a billionth of a second.

As the team reports, similar experiments had so far failed to attain the temporal accuracy required to track the electrons' motion. The tiny elementary particles whizz around much faster than the larger and heavier atomic nuclei. In the present study, however, the scientists combined the two technologically demanding techniques, photoemission electron microscopy, and attosecond microscopy, without compromising either the spatial or temporal resolution.

"We have now finally reached the point where we can use attosecond pulses to investigate in detail the interaction of light and matter at the atomic level and in nanostructures," said Vogelsang.

One factor that made this progress possible was using a light source that generates a particularly high quantity of attosecond flashes per second—in this case, 200,000 light pulses per second. Each flash released, on average, one electron from the surface of the crystal, allowing the researchers to study their behavior without them influencing each other. "The more pulses per second you generate, the easier it is to extract a small measurement signal from a dataset," explained the physicist.

Anne L'Huillier's laboratory at Lund University (Sweden), where the experiments for the present study were carried out, is one of the few research laboratories worldwide with the technological equipment required for such experiments.

Vogelsang, a postdoctoral researcher at Lund University from 2017 to 2020, is currently setting up a similar experimental laboratory at the

University of Oldenburg. In the future, the two teams plan to continue their investigations and explore the behavior of electrons in various materials and nanostructures.

More information: Jan Vogelsang et al, Time-Resolved Photoemission Electron Microscopy on a ZnO Surface Using an Extreme Ultraviolet Attosecond Pulse Pair, *Advanced Physics Research* (2023). DOI: 10.1002/apxr.202300122

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