PHYSICS

Tracking the dynamics of electron expulsion

Electron holography is used to map out the wave function of a photo-emitted electron

By **Caterina Vozzi**

Since the birth of quantum mechanics, scientists have been dreaming of imaging, and possibly controlling, the motion of electrons in atoms and molecules. These electrons are described in the quantum theory by wave functions. However, the wave function is an elusive quantity: It is a complex function with an amplitude and phase, but its square modulus is usually the only quantity directly measurable in experiments. In addition, visualizing the electron dynamics requires extremely high temporal resolution, on the order of attoseconds (1 as = 10^{-18} s). On page 1150 of this issue, Villeneuve *et al.* (*1*) report on an elegant experiment that demonstrates the possibility of fully reconstructing the electron wave function in the photoionization of neon and thus paving the way for coherent control of the process.

The description of the interaction between light and atoms at the atomic scale, which is the quintessence of quantum mechanics, has received a strong push in recent years due to the development of attosecond technology. The main goal of attosecond science is the realization of time-resolved experiments for imaging and possibly controlling the electron dynamics in atoms and molecules. These experiments have allowed the visualization of extremely fast dynamics (*2*–*4*). In this framework, photoionization is the simplest experiment that grants access to information about the wave function of an electron escaping from an atom. Despite the extensive effort dedicated to the study of photoionization, questions still need to be fully addressed, such as what is the influence of electron correlation in the photoionization dynamics (*5*).

The wave function of a particular electronic state can be written as the sum of angular momentum components. One of the key aspects in photoionization experiments is the full reconstruction of this decomposition for the freed electron in amplitude and phase. Villeneuve *et al.* implemented a holographic approach for the full reconstruction of the electron wave function. In optical holography, information about the phase, which corresponds to the three-dimensionality of the object, is recorded in a two-dimensional (2D) image as an intensity modulation. This modulation is due to the interference between the light coming from the object and a reference beam. In the same way, the reconstruction of the electron angular momentum components can be inferred from the interference between different ionization pathways leading to the same final electron energy. The different XUV colors (photon energies) in a train of attosecond pulses can be used for exciting neon atoms and for triggering the photoionization process, as it was already done in helium atoms in (*6*) (see the figure).

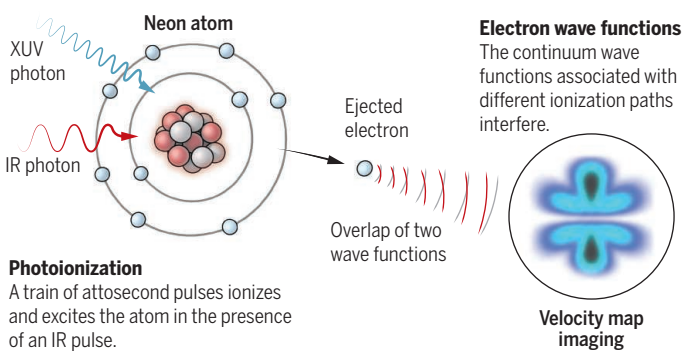
In Villeneuve *et al.*'s experiment, one XUV color promotes an electron to a resonant bound excited state of neon. Another laser pulse in the infrared (IR) Stark shifts this excited electron. As the reference, an isotropic electron wave function generated by direct ionization of neon atom by another XUV component does the trick. The 2D projection of the electron angular momentum can be recorded by a velocity map imaging spectrometer as a function of the delay between the XUV pulse train and the IR pulse. Each 2D electron momentum spectrum is an image of the electron wave function. The idea is simple and smart: The phase of the two interfering wave functions can be controlled with attosecond precision by changing the delay between the XUV and the IR pulse, and the angular momentum components of the electron wave function can be fully reconstructed in amplitude and phase, exploiting a simple fit with spherical harmonic functions.

The manipulation of the electric field at petahertz frequency allows the steering of the electron in a specific electronic state and the possibility to use interferometric techniques for visualizing this state. The strengths of this approach are the relative ease of the experiment and the need of a relatively simple theoretical model for the interpretation of the results. Its flexibility relies on the possibility of tuning the XUV photon energy in the attosecond pulse train for resonantly matching transition energies in different kind of atoms and molecules.

Over the past 15 years, several experimental approaches have been developed in strong-field physics and attosecond science for the visualization of atomic and molecular wave functions and their dynamics with impressive results (*7*, *8*). This further piece of the puzzle represents indeed a very exciting finding for fundamental research in atomic physics. However, we can also foresee more visionary applications of the proposed method. These results may lead, for example, to the realization of full coherent control of photoionization, not only in atoms, but also in molecular systems, with the possibility to exploit attosecond pulse trains to steer the outcome of a chemical reaction or to select a particular dissociation path after the photoionization of molecular samples. How far will it be possible to extend this picture, and how complex can the reconstructed quantum wave functions be? The answers constitute the boundaries of attosecond science that need to be investigated in the future. ■

Wave function holography

With an interferometric approach, it is possible to reconstruct the full electron wave function in amplitude and phase.



Photoionization
A train of attosecond pulses ionizes and excites the atom in the presence of an IR pulse.

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