A newly-developed “quantum microscope” uses photoionization and an electrostatic magnifying lens to directly observe the electron orbitals of an excited hydrogen atom.

Subject Areas: Atomic and Molecular Physics, Quantum Physics

The wave function plays a fundamental role in quantum theory, yet a direct observation of it remains elusive. Observable properties, such as the position of an atom or the momentum of an electron, arise from projecting the wave function onto an eigenstate. However, each projection only reveals a portion of the underlying wave function and often destroys uniquely quantum features, like superposition and entanglement. The full quantum state is only realized by statistically averaging over many measurements. A tool that directly magnifies the microscopic state of a quantum particle onto the laboratory scale could, potentially, render some quantum properties directly perceptible. More practically, such a quantum microscope could aid development of atomic and molecular-scale technologies.

Writing in Physical Review Letters, Aneta Stodolna, of the FOM Institute for Atomic and Molecular Physics (AMOLF) in the Netherlands, and her colleagues demonstrate how photoionization microscopy directly maps out the nodal structure of an electronic orbital of a hydrogen atom placed in a dc electric field [1]. This experiment—initially proposed more than 30 years ago—provides a unique look at one of the few atomic systems that has an analytical solution to the Schrödinger equation. To visualize the orbital structure directly, the researchers utilized an electrostatic lens that magnifies the outgoing electron wave without disrupting its quantum coherence. The authors show that the measured interference pattern matches the nodal features of the hydrogen wave function, which can be calculated analytically. The demonstration establishes the microscopy technique as a quantum probe and provides a benchmark for more complex systems.

Methods for imaging a wave function are often indirect. One such strategy involves making many so-called weak measurements of a quantum system, in order to tiptoe around wave function collapse [2]. Alternatively, a series of strong measurements on identically prepared systems can be used to reconstruct the quantum state. For example, researchers have mapped out the complete quantum state of photons and other fields by making a series of measurements in different bases and then inverting those results through a tomographic procedure [3]. Tomographic inversion, which, in general, involves generating an image from a set of projections, has proven useful in other experiments as well. For example, one group used high-harmonic XUV spectra to reconstruct the valence electron wave function in N₂ [4], while another group used angle-resolved photoelectron emission spectra to reconstruct the orbitals of molecules on a thin film [5]. All of these experiments combine a series of partial views of the quantum system to reconstruct the wave function.

More direct methods also exist, in which elements of the wave function appear in a single measurement. Scanning tunneling microscopy of molecules on a thin film, for example, has provided images of the nodal structure in molecular orbitals [6]. More recently, measurements of outgoing electrons from multiphoton ionization of molecules showed evidence of nodal planes in molecular orbitals [7]. In these photoionization studies, researchers can select and/or manipulate the molecules using static fields or laser techniques to control or induce a dipole. However, measuring the nodal structures of atomic orbitals is more challenging, since atoms don’t have a dipole or external degrees of freedom. Stodolna et al. overcome this by applying a dc electric field that defines a quantization axis in hydrogen and aligns the orbitals before measuring them. This allows direct observation of the transverse orbital state, which is the projection of the orbital onto the plane perpendicular to the electric field.

In their elegant experiment, Stodolna et al. observe
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ture of the quasibound Rydberg orbital. Under nonreso-
This avoids the complex reconstructions of indirect meth-
ods. The team starts with a beam of hydrogen atoms that
they expose to a transverse laser pulse, which moves the
population of atoms from the ground state to the 2s and
2p orbitals via two-photon excitation. A second tunable
pulse moves the electron into a highly excited Rydberg
state, in which the orbital is typically far from the central
core. By tuning the wavelength of the exciting pulse,
the authors control the exact quantum numbers of the
state they populate, thereby manipulating the number
of nodes in the wave function. The laser pulses are tuned
to excite those states with principal quantum number \( n \) equal to 30.

The presence of the dc field places the Rydberg electron above the classical ionization threshold but below the
field-free ionization energy. The electron cannot exit
tagainst the dc field, but it is a free particle in many
other directions. The outgoing electron wave accumu-
lates a different phase, depending on the direction of its
initial velocity. The portion of the electron wave ini-
tially directed toward the 2D detector (direct trajec-
tories) interferes with the portion initially directed away
from the detector (indirect trajectories). This produces
an interference pattern on the detector. Stodolna et al. show convincing evidence that the number of nodes in the
detected interference pattern exactly reproduces the
nodal structure of the orbital populated by their excitation
pulse. Thus the photoionization microscope provides the
ability to directly visualize quantum orbital features
using a macroscopic imaging device.

To confirm this interpretation, the authors de-tuned the
excitation laser pulse from the excited state. Under
these conditions, the excited electron is still a free particle,
but it does not acquire the characteristic nodal struc-
ture of the quasibound Rydberg orbital. Under nonreso-
nant conditions the interference pattern disappeared and
was replaced by an isotropic background contribution. The
appearance of nodal features only under resonant excitation solidifies the interpretation that the detected
interference pattern is generated by the quantum state
selectively populated.

The present work on the hydrogen atom clearly illus-
trates how the photoionization microscope images an
electron orbital. In contrast, the authors’ previous
work with photoionization microscopy found that or-
bital information can be obscured by multielectron ef-
fects [5]. Future research will try to understand how the
electron-electron interaction manifests in photoionization
microscopy. Further nuances could be investigated by
introducing a magnetic field to perturb the outgoing
electron wave function. On this front there are already pro-
posals for applying photoionization microscopy to inves-
tigate chaotic motion in quantum systems [9], and the
Aharonov-Bohm effect [8]. More generally, the develop-
ment of a quantum microscope that can image orbital
features could aid atomic and molecular scale technolo-
gies, for example, by visualizing the nature of the chem-
ical bond binding a molecular wire [10].

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