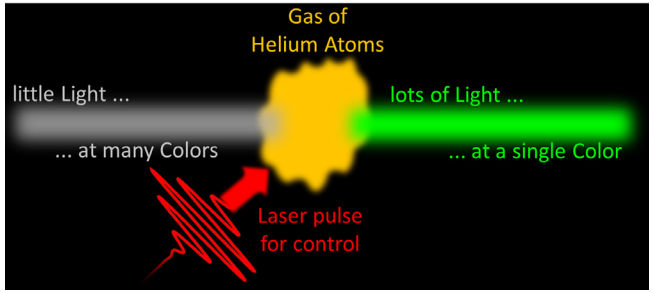
can be done for instance by increasing the intensity of the interacting laser light (i.e. its "brightness"), to large values. By focusing laser light with lenses or concave mirrors one can easily achieve intensities surpassing the sun's intensity on earth by many quadrillions (10^{15}). When these enormous intensities and correspondingly strong electromagnetic field strengths impinge on a molecule at exactly the right time, the binding electrons feel large accelerating forces and start rearranging. In fact, this principle can be used to steer electrons from one atom to the other. This unlocks a completely new route to chemistry: Not only by mixing of reactants and temperature increase, but by direct interference into the microscopic electronic processes, we can steer chemical reaction dynamics. In the future, this could lead to the production of completely new substances with a variety of applications in science and society.

Laser control of the quantum-mechanical motion of electrons on tiny length scales also opens up new perspectives for fundamental research in physics: In strong laser fields, atoms and molecules develop completely new properties. In our own research work at MPIK we could recently show that atoms that normally absorb light of a specific frequency lose this property in strong and short pulsed laser fields. Better even: The laser pulse could be used to "switch" – within just few femtoseconds – into a state in which the atoms emit laser-like light (see the figure below). This principle may in the future be used for ultra-fast optical switches at work in next-generation information processing or computers, possibly based on single molecules. In addition, the control of light on such short time scales enables new light sources in a large region of the electromagnetic spectrum from the long-wavelength infrared to short-wavelength x-rays. This again opens new paths and horizons both for fundamental science as well as technological applications.



Contact:

Dr. Robert Moshammer
Phone: +49 6221 516461
E-mail: robert.moshammer@mpi-hd.mpg.de

Dr. Christian Ott
Phone: +49 6221 516332
E-mail: christian.ott@mpi-hd.mpg.de

Prof. Dr. Thomas Pfeifer
Phone: +49 6221 516380
E-mail: thomas.pfeifer@mpi-hd.mpg.de

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK
HEIDELBERG

Saupfercheckweg 1
69117 Heidelberg

www.mpi-hd.mpg.de

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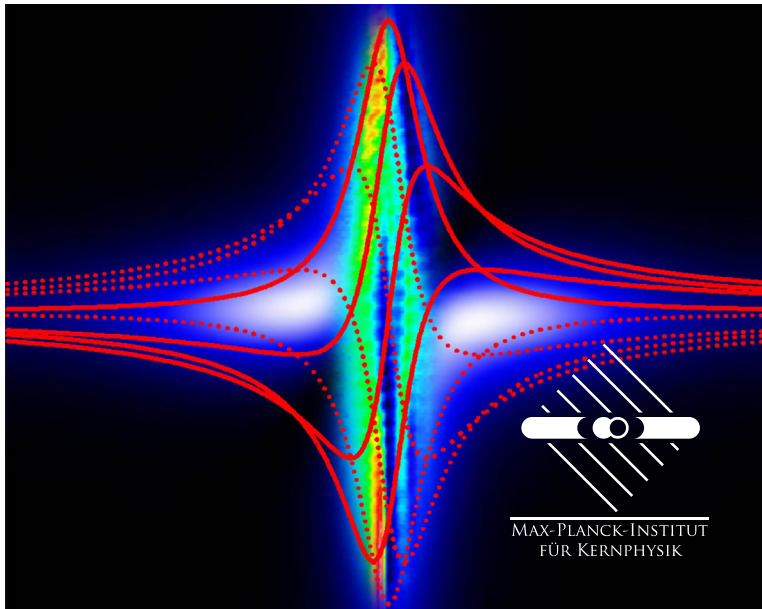
Motion Pictures and Sounds of Atoms and Molecules



Motion Pictures and Sounds of Atoms and Molecules

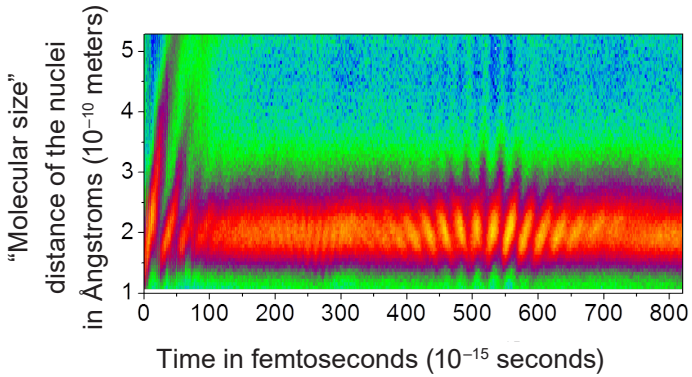
The air we breathe this very moment, the sunlight we see, the paper we feel in our hands, the chemical reactions that route stimuli and signals within our body – all these things and processes are based on the natural interplay of atoms and their electrons. Electrons move within and between the atoms, interacting with light that impinges on them or that they irradiate by their motion.
Can we understand how these elementary, microscopic processes proceed in nature? Is it possible to directly observe them, or at least: to make them measureable?

Recording a "Movie" of the Microcosm

To "see" the unimaginably small atomic particles, scientists rely on special imaging methods. Traditional light microscopes are not up to the challenge: the smallest length scales to be observed are about as large as the wavelength of visible light, i. e. a bit less than 1 micrometer (10^{-6} m, a thousandth of a millimeter). Atoms and molecules are another ten-thousand times smaller, the typical length scale is the Ångstrom (10^{-10} m, a ten-thousandth of a micrometer or a tenth of a nanometer).

What makes this observation more difficult is the unimaginably fast motion of these particles. For example, the two atoms in a nitrogen molecule – the main constituent of air – oscillate 80 trillion times (80×10^{12}) per second, one oscillation thus lasts only 12 femtoseconds (1 femtosecond is 10^{-15} s). The human eye cannot follow such a fast motion in time, even if it could see the atomic particles by sufficient spatial magnification.

What is required is thus not only an extremely highly resolving microscope (so-called Reaction Microscopes), but also an extreme slow-motion function. The latter is achieved by using very, very short flashes of light, with a duration shorter than the oscillation period mentioned above. With such pulses it is possible to scan and probe the fast molecular motion, e. g. immediately after "kicking" (or exciting) the molecule.



Observation of a vibrating hydrogen molecule using a Reaction Microscope and laser pulses of femtosecond duration, conducted at MPIK. One observes initial oscillations near time 0 after the initial "kick", the quantum-mechanical blurring (washed-out region between 150 and 350 femtoseconds) and the "revival" of the motion around 500 femtoseconds.

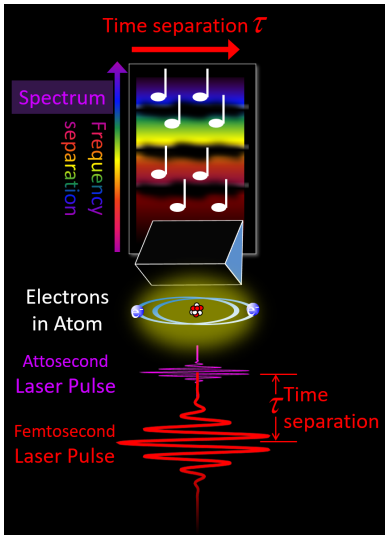
Listening Inside Atoms and Molecules: Spectroscopy

Atoms and molecules consist of their positively charged nuclei and negatively charged electrons, attracting and neutralizing each other. Moving between the atoms in a molecule, attracting them, these electrons form the "atomic glue" at the heart of a chemical bond. To understand chemistry and chemical reactions from the bottom up, it is thus important to study the electronic motion which leads to the making and breaking of molecular bonds.

The light electrons move even faster than the atomic nuclei, which are several thousand times more heavy. Electrons count their time to the beat of attoseconds, a thousandth of a femtosecond or 10^{-18} s. An attosecond compares to a second as a second compares to the age of the universe. In other words: Transferring our human perception of time to an electron's perspective, each second an entire universe evolves on a microscopic scale.

What can we do to unlock these microscopic realms of time and space, to explore the inner life of atoms and molecules? Direct observation becomes harder and harder at these scales, forcing us to rely on a methodology which can be compared to the human sense of hearing: time-resolved optical spectroscopy.

Just like listening to music, where we hear sequences of notes and tones of different frequency and acoustic color, in spectroscopy we analyze the color of light, its frequency spectrum to be more precise. By using either a prism or optical grating, one separates the light emitted by atoms or molecules into its differently colored frequency constituents. Initially this spectrum consists only of the analog of several notes with characteristic clangs (cf. overtones of instruments) played at the same time. In order to hear and record the microscopic "musical piece" played by the ensemble of moving electrons, the temporal order of notes has to be measured. This is also accomplished with short and strong laser pulses. By controlling the time delay with which they impinge on the electrons, they essentially provide the beat in the optical spectrum. The notes are now played sequentially and the "microscopic melody" comes to life in the spectrometer.



Listening to these fast natural tunes allows important insights into the energy and binding strength of the electrons. In combination with existing knowledge and theoretical modeling, it is even possible to reconstruct the entangled motion of electrons in atoms and molecules.

Steering Fastest Processes

Short laser flashes not only allow one to take snapshots of such ultrafast processes, but also to actively interfere with their evolution and, as a consequence, to steer them. This