A fully optical attoclock to image tunnelling wavepackets

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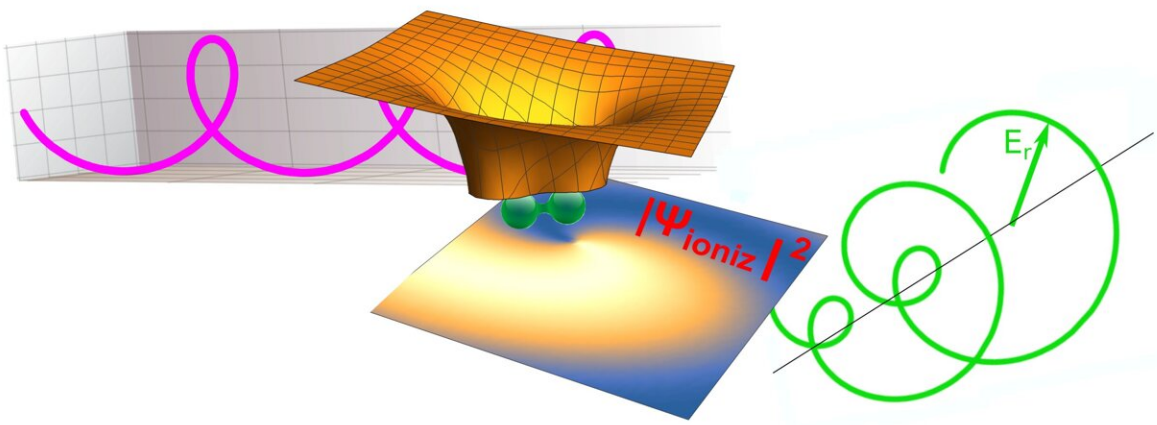

Image of a molecule (two connected green spheres) that is irradiated by strong field, loses its electron, and the electron, during of this process radiates light which we then detect and analyze. Credit: Babushkin et al.

Attoclocks, or attosecond clocks, are instruments that can measure time intervals on the attosecond scale by measuring the time it takes for electrons to tunnel out of atoms. The attosecond procedure was first introduced by a research team led by Ursula Keller in 2008.

Researchers at Leibniz University Hannover, Max Born Institute and

other institutes in Europe have recently developed a new, all-optical attoclock. This clock, introduced in a paper published in *Nature Physics*, could be used to collect time-resolved measurements in condensed-matter systems, which has never been achieved so far.

"Tunneling is an inherently quantum-mechanical process, and therefore beyond our 'classical imagination'," Ihar Babushkin, one of the researchers who carried out the study, told *Phys.org*. "Tunneling of electrons out of atoms happens when we put atoms in very strong electric field. The field can be made so strong, that it 'tears off' electrons from atoms, but the electrons must tunnel through a barrier before they leave atom."

Tunnelling, the process through which electrons leave atoms, happens very quickly. Some physicists have even suggested that during tunneling electrons travel faster than light and tried to test this hypothesis using existing attoclock measurement tools.

"The currently fastest time that can be measured is around one attosecond," Babushkin explained. "One attosecond is 10^{-18} seconds, that is related to one second approximately as one second to the age of universe, or even more."

In the past, most researchers studied tunnelling by trying to catch electrons after they leave atoms. While this method led to some interesting findings, it is often very complex and expensive to implement, while also not examining tunneling directly.

In their paper, Babushkin and his colleagues introduced an alternative method for studying tunnelling directly, which is also cheaper and more precise than previous techniques. This new method specifically looks at the radiation released by electrons during the tunnelling process and its subsequent dynamics.

"This is possible because whatever happens to an electron, it radiates some light," Babushkin said. "Our method is very unusual from the point of view of 'normal intuition'. Suppose you try to measure something very short, such as the flap of a butterfly's wings. To do this, you need a clock that works faster that the flap. What if you instead you try to use an ancient sun clock, which can measure hours, but not minutes and definitively not seconds? It might sound counterintuitive, yet the period of the light waves that we catch up to measure the attosecond time scales is one billion (10^9) times larger than attosecond. But, as we showed, this is indeed possible!"

Essentially, the attoclock developed by Babushkin and his colleagues catches the light radiating from electrons as they leave atoms and measures its polarization. For it to work as a 'clock', however, the strong electric field leaving the atom, also known as 'driving field' had to vary in time and be circularly polarized.

"If the light is circularly polarized, the electric field rotates with time as a hand of a clock," Babushkin said. "To make light radiating at the lowest possible frequency, we needed to take two frequency components in the driving field. With this, the response of the electron can be in terahertz range (one terahertz corresponds to 10^{12} Hertz, and one Hertz is the measure of frequency corresponding to one oscillation per second)."

In their experiments, the researchers found that by measuring the polarization of the terahertz radiation emitted by the electron they could access its dynamics at the attosecond scale. This was an unexpected result, as terahertz and attosecond time scales differ by nine orders of magnitude.

"Since measuring the light polarization is much more precise than measuring electrons, our optical attoclock can be much more precise

than the usual attoclock procedure," Babushkin said. "Although in the present article we made a proof-of-principle presentation of the attoclock which extracts mostly the same information as the traditional, in the future we can go even beyond one attosecond and measure times already in zeptosecond range, something that was so far non-existing in physics."

The researchers have already successfully used their attoclock prototype to measure something that had never been detected using the traditional attoclock, namely a slight asymmetry in the ionization process. In the future, they feel that it could also be used to collect time-resolved measurements in systems where electrons cannot be detected, such as solids.

Currently, due to their high fabrication costs, attoclocks can only be produced in relatively few laboratories worldwide. As the system created by Babushkin and his colleagues was build using far cheaper components than those underpinning other existing realizations of the attoclock, it could ultimately enable the collection of attoclock measurements in more institutes worldwide.

"Our attoclock could have many different applications," Babushkin added. "We are particularly interested in trying to apply it in solids. This is one of the directions where the traditional attoclock procedure do not work at all. Currently, the processes excited by strong optics fields in solids is on the edge of the attosecond science and we believe that our new tool will help to gather a lot of interesting information."

More information: All-optical attoclock for imaging tunnelling wavepackets. *Nature Physics*(2022). DOI: 10.1038/s41567-022-01505-2.

Attosecond ionization and tunnelling delay time measurements in

Helium. *Science*(2008). DOI: 10.1126/science.1163439.