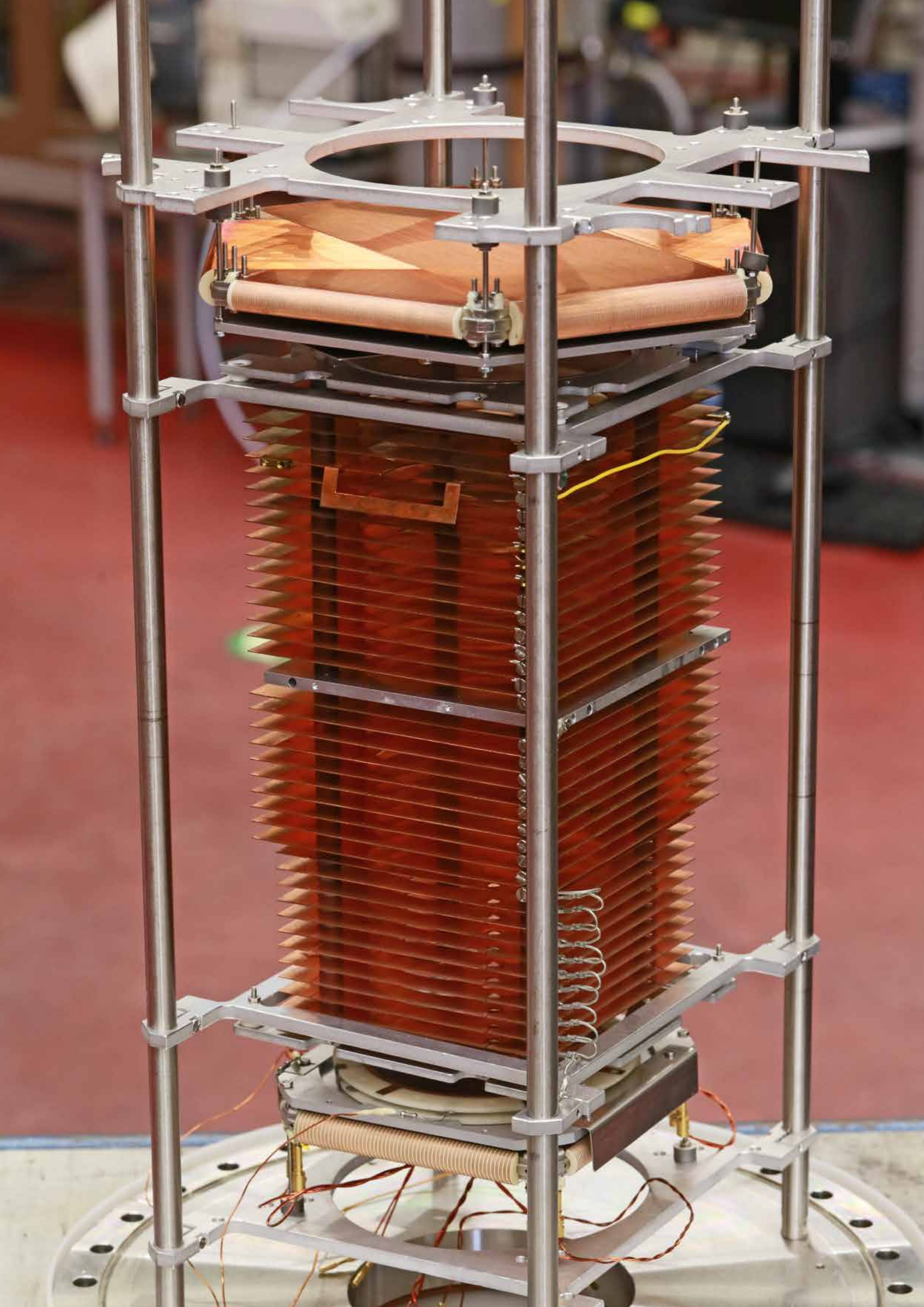


Tickling Schrödinger's cat

When a molecule flies apart and stays bound at the same time

By Dirk Eidemüller

In Erwin Schrödinger's thought experiment, a cat in a box is both dead and alive at the same time. What cannot exist in our world is by all means possible in the microcosm of quantum physics: things that are in fact mutually exclusive occur simultaneously. A reaction microscope such as COLTRIMS – a Frankfurt development – presents the enigma of quantum dynamics on a silver platter.

No other scientific theory is as triumphant in its predictions, yet at the same time as controversial in its interpretation, as quantum physics. Since its origins around 100 years ago following works by Niels Bohr, Werner Heisenberg, Erwin Schrödinger and a few other colleagues, the strange implications of quantum theory have confused generations of physicists and philosophers.

Can nature really be as bizarre as quantum physics claims? Are particles at the same time waves? Do things happen by sheer chance, without causal root? Can it be that particles far apart from each other nevertheless form a closely connected system, even if they are not connected by physical forces?

According to the current state of science, all these counterintuitive claims must be answered with a resounding 'Yes'! Yet even to Albert Einstein, who himself laid important foundations for later quantum theory through his work, they seemed so absurd that he opposed them throughout his entire life. Indeed, he even argued against them and for many years searched in vain for an alternative theory. Today, we know that Einstein was barking up the wrong tree. Quantum physics – strange as it might be – works, even if it severely overtaxes our everyday understanding of reality. However, impressive new instruments are meanwhile available that allow us to observe the mysterious happenings in the microcosm on a magnified scale. One such device is COLTRIMS (Cold Target Recoil Ion Momentum Spectroscopy).

"We also call this apparatus a 'reaction microscope' because it allows us to observe ultrafast chemical reactions and investigate the changes in atoms and molecules at the fundamental level of quantum physics in the process," explains Reinhard Dörner, head of an atomic physics research group at Goethe University.

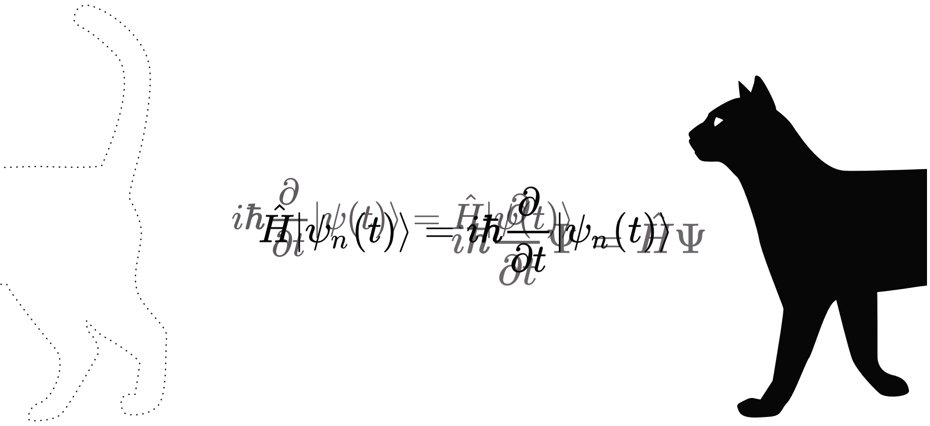
Microscope for atomic dynamics

Generally speaking, the operating principle of a reaction microscope is not that complicated: in a vacuum chamber, a very powerful laser beam or x-ray is fired at the molecule under study, which then bursts apart. As the fragments fly apart, they are guided by electromagnetic fields to sensitive detectors where they are registered. "In a nutshell, we shatter atoms and molecules to find out more about their structure," says Dörner. Since all parameters are known, conclusions can be drawn from the image on the detector about the original molecule, that is, the position of the individual atoms in the molecule and the orientation of the molecule in space.

In this way, it is possible to determine not only the general structure of molecules but also

The heart of the COLTRIMS reaction microscope: the many copper plates cut out in a circle at the centre produce electric fields. When a laser beam shatters a gas molecule in the centre of the device, these fields direct the electrons upwards and the positively charged ions downwards.

Photo: Uwe Dettmar



In our world, a cat cannot be dead and alive at the same time. However, Erwin Schrödinger calculated that in the quantum world this would be possible. Quantum particles can adopt multiple eigenstates at the same time.

their handedness, that is, whether the molecule is a levorotatory or dextrorotatory variant. This is important above all for drugs because biomolecules with the wrong chirality can be highly toxic in extreme cases. This analysis already works for simple molecules with up to 20 atoms.

Yet the technology is still relatively young and has only been established for about 20 years. “COLTRIMS was developed in Frankfurt, and the driving force behind it was Professor Horst Schmidt-Böcking,” says Dörner. “Ten years ago, there were still only about two dozen of these reaction microscopes worldwide. Today, there are already well over 100, and the number continues to rise.” What makes these devices attractive is their ability to visualise quantum processes on tiny spatial and temporal scales.

Because quantum particles behave not only like waves. They can also – when not under observation – exist in peculiar superposition states in which they adopt two or more eigenstates at the same time. Erwin Schrödinger found this consequence of his own theory so incongruous that he later turned his back on quantum theory and devoted himself to entirely new activities. He illustrated these superposition states with his famous paradox of “Schrödinger’s Cat”. In this thought experiment, a cat is confined in a box with a mechanism based on quantum physics that kills it with 50 percent probability. According to Schrödinger, the poor cat is in a half-dead and half-alive state as long as the box remains closed. The state of the dead-and-alive cat is “smeared” across the box, as it were.

Cat-like helium molecule

“However, what’s impossible with cats and other large objects can by all means be achieved with molecules,” explains Dörner. The working group in Frankfurt has devised a sophisticated experiment that visualises precisely this effect. To do this, the researchers cooled helium atoms down to an extremely low temperature. This noble gas does not, in fact, form any bonds. Nevertheless, at very low temperatures, two helium atoms can join together to form a very loosely bound molecule.

“We then fire two laser pulses one after the other at this helium molecule, one weak and one strong,” says Dörner. The first pulse transposes the molecule into one of the peculiar superposition eigenstates typical in quantum physics. Just as Schrödinger’s cat is both dead and alive, the helium molecule is now half-intact and half-broken. However, this superposition, which cannot occur in the macroscopic world and therefore contradicts how we see things, has very real effects when magnified with the help of the reaction microscope.

This is achieved with the second laser pulse, the strong one. It knocks the electrons out of the system, so that the “naked”, positively charged helium ions now repel each other. Due to the previously induced superposition eigenstate, this leads to interesting interference effects that can be measured at the detector.

ABOUT REINHARD DÖRNER

Reinhard Dörner, born in 1961, studied physics and philosophy in Frankfurt and Aachen and earned his doctoral degree in physics at Goethe University. A stay at Lawrence Berkeley National Laboratory in the USA followed, after which he returned to Frankfurt. He was appointed as professor at the university’s Institute of Nuclear Physics in 2002 and since then has also been dean of studies for physics several times. From 2010 to 2017, he was managing director of the Institute of Nuclear Physics. In 2016, he won the Helmholtz Prize, the highest award for metrology in Germany, which is conferred for special achievements in the development of precision measurements. Since 2016, he has also been a member of the editorial board of Physics Review Letters, the most important physics journal.

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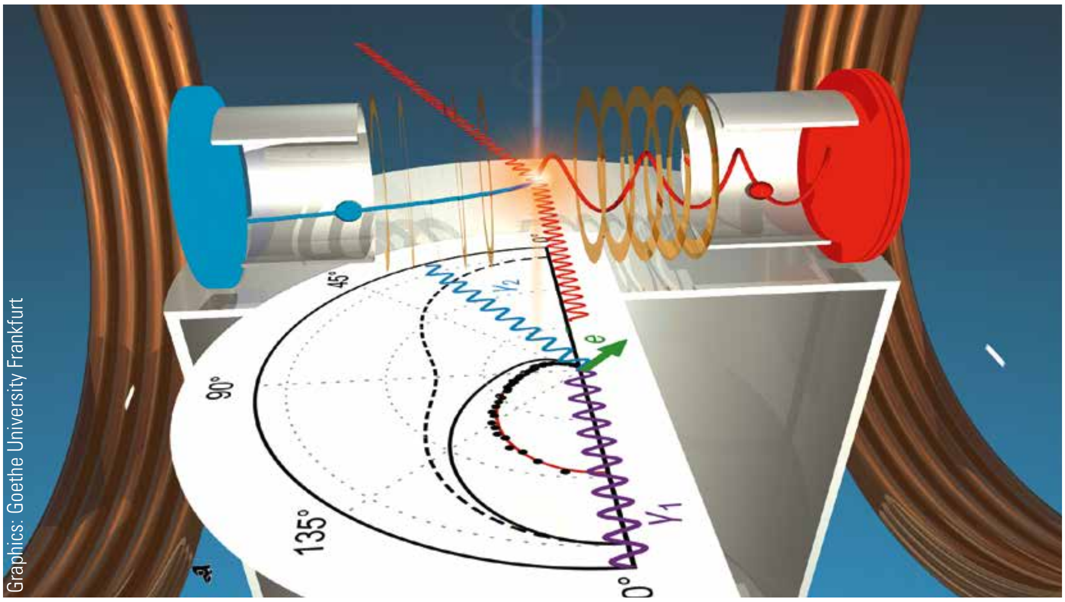
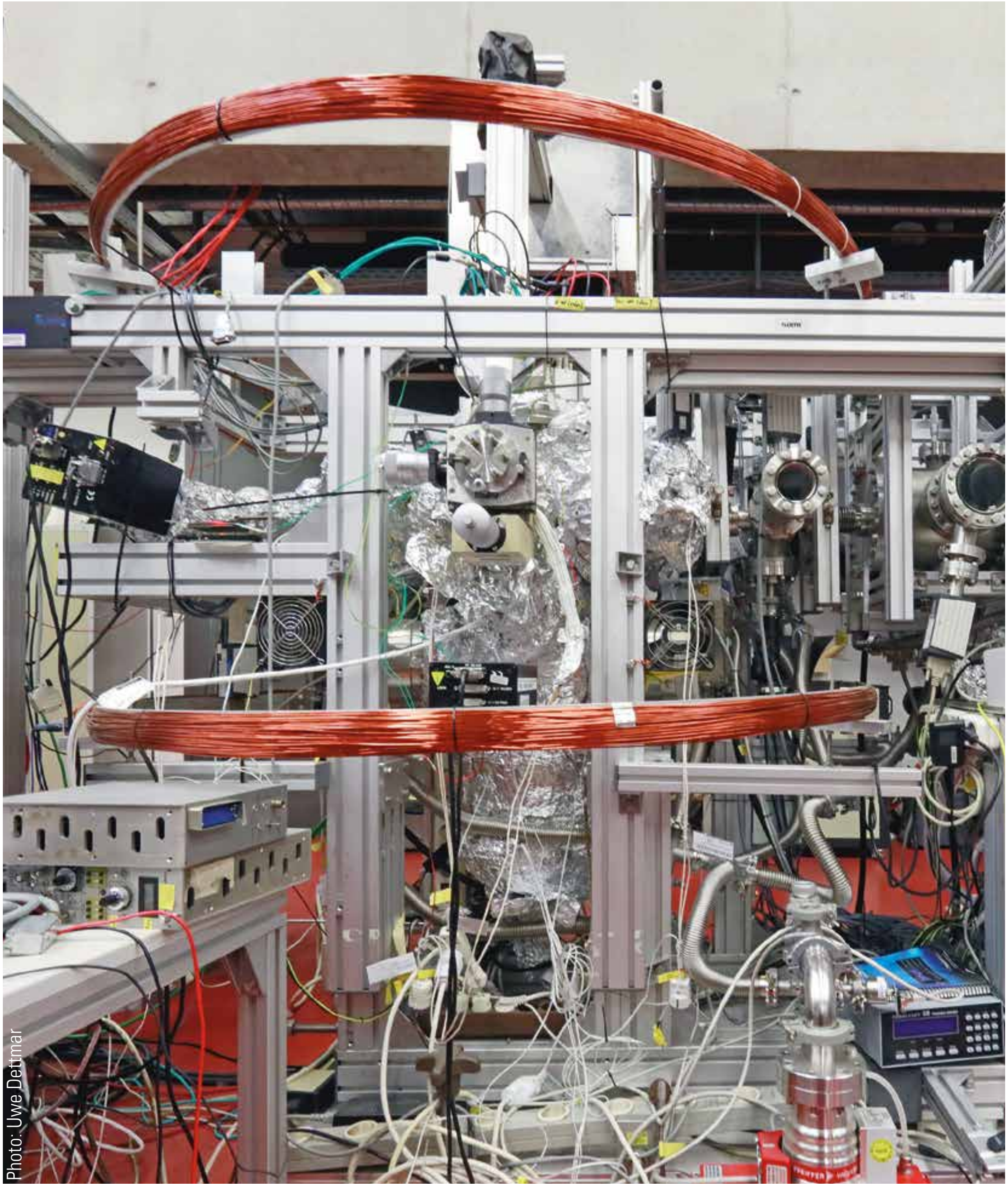


This is how the COLTRIMS reaction microscope works: if a laser beam or an x-ray (photon, wavy red line) knocks an electron out of a molecule, the electron is deflected to the right along a helical path by electric fields. The positively charged ion, on the other hand, is directed in a straight line to the left. Detectors on both sides measure how long the particles need until impact once the molecule has been shattered.



High-tech: the COLTRIMS reaction microscope in Frankfurt.

IN A NUTSHELL

- With the COLTRIMS reaction microscope, it is possible to observe extremely fast chemical reactions. For example, the current world record in short-time measurement (247 zeptoseconds) was established with such a reaction microscope.
- The instrument can, for example, visualise the superposition of two electron waves, each of which only occurs with a certain probability – an effect from the quantum world.

Photo: Uwe Dettmar

Photo: DESY, Reimo Schaaf

The PETRA III x-ray radiation source at the DESY accelerator centre in Hamburg produces high-energy x-rays. A COLTRIMS reaction microscope, nowadays one of many such instruments around the world, is mounted at beam pipe P04 in the "Max von Laue" experimental hall (long, curved building on the aerial photograph). Physicists from Frankfurt are also conducting experiments in Hamburg.

"We tickle Schrödinger's cat, as it were, and make it move," explains Dörner. "What we can then observe at the detector is how both the motionless, dead cat and the live, goaded cat influence the measurement result." Being able to visualise such phenomena, which drove eminent authorities such as Einstein and Schrödinger to despair, is, however, only one of the fascinating possibilities that reaction microscope open up.

Fastest time measurement

Because they magnify things on tiny scales, they have recently even enabled the fastest time measurement of a natural process. "We were able to determine how long a light pulse needs to fly through a hydrogen molecule," says Dörner. It takes 247 zeptoseconds – orders of magnitude shorter than light needs for a single oscillation. A zeptosecond is a trillionth of a billionth of a second. But no measuring device exists that could measure such an incredibly short interval directly. Instead, the scientists used the high-energy x-rays at the DESY accelerator centre in Hamburg, which they directed at hydrogen molecules in a reaction microscope housed there. The x-ray beam ejected an electron out of the molecule (consisting of two protons and two electrons) at one end or the other, something that only occurs with small probability.

Since quantum particles are at the same time waves, this reaction produced two superimposed electron waves (like in the case of Schrödinger's cat), but these were slightly staggered – like the ripples of water produced when you skim a flat pebble across a pond. In contrast to a direct time measurement, however, it is easy to determine the interference between these waves in the reaction microscope – and from this it is possible to calculate the length of time needed by the x-ray pulse to reach the electron on the one side or the other.

This record-breaking measurement demonstrates very impressively how reaction microscopes can be used to make extremely short time scales accessible. "Conversely, we also want to investigate with larger molecules how the dissemination of information decelerates when a large number of electrons are involved," says Dörner. What Einstein and Schrödinger would have said about these quantum tricks with time measurements based on particle waves and semi-stationary, semi-expanding cat molecules is, however, written in the stars. ●

Close-up of the main component of the COLTRIMS microscope: the electron detector consists of fine copper threads. When an electron hits these threads, a signal is triggered.

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(see page 24)