optics & photonics
focus

Spying on Quantum Gases

A detective can only guess what mafia clans discuss inside their hideout. In a similar way, scientists usually only have indirect access to the behavior of trapped ultracold atomic gases. A novel microscopy technique now offers the possibility to directly observe what is happening inside the trap.

Suppose you are a police officer trying to spy on a mafia clan. They work out their criminal plans inside their hideout, but all you can observe is what they do once they leave. To some extent, scientists are facing a similar situation when experimentally studying ultracold atomic gases: quantum gases are manipulated inside a trap but their observation usually happens when they leave the trap and have expanded freely for some time. Now, researchers led by Herwig Ott at the Johannes Gutenberg University in Mainz (Germany) have demonstrated a technique that allows direct observation and manipulation of cold gases while they are still inside the trap.

The dream of every police officer it to have access to where the suspects gather to know what they are doing or even to interfere with their decisions. Indeed, even though images taken in the aftermath of a gathering do provide valuable information, a hidden camera would be a lot more useful. And being able to interfere with the discussion would be even better. However, installing cameras or even a mole inside an environment that is extremely susceptible and critical towards even the slightest outside influence is very challenging — and yet, that is what Ott and his team have achieved.

In order to appreciate the novelty of the new microscopy technique, it is important to understand how ultracold quantum gases, in particular trapped Bose-Einstein Condensates (BEC), are commonly studied and observed. The particles, for example Rubidium atoms, are trapped and cooled down to a fraction of a millionth of a degree Kelvin above absolute zero. For the actual experiment they are loaded inside a lattice structure created by standing laser waves. At a certain point, the trap is switched off, the atoms fall out of the trap and start to expand freely. Typically after a few milliseconds of this free expansion, a CCD camera takes a picture of the gas. The resulting shadow picture contains valuable information about the momentum distribution of the particles. These so-called Time-Of-Flight (TOF) pictures are of fundamental importance in almost all current studies involving BECs. However, when it comes to studying the actual lattice, or even manipulating the atoms while they are inside the trap, the TOF is of very limited use.

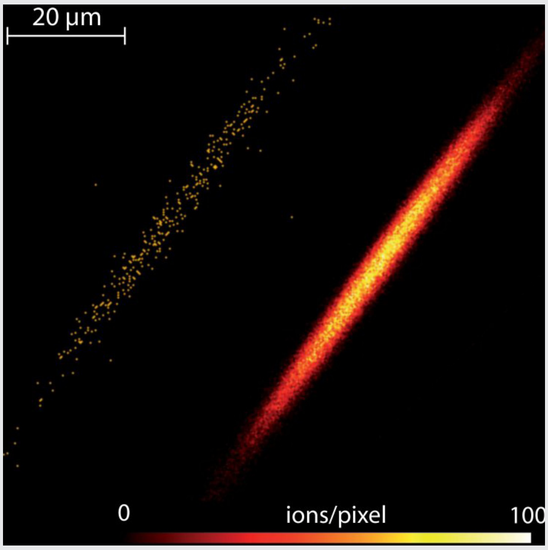

Figure 1: Looking inside the trap. The electron beam is scanned through the BEC very quickly. Since only few atoms are ionized during each run (left), this process is repeated 300 times to acquire an image of the spatial distribution of the atoms (right).

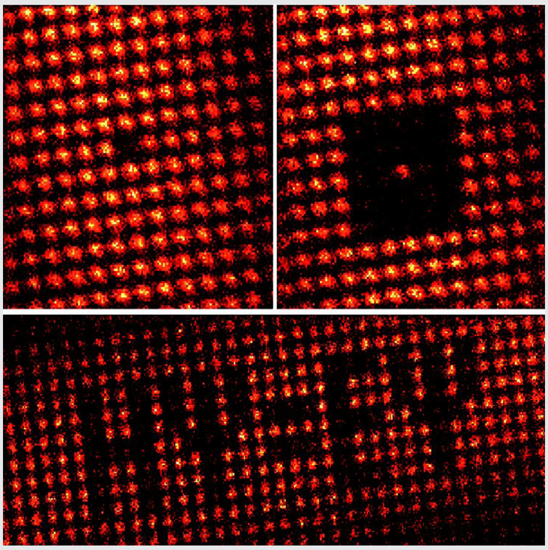

Figure 2: Playing with quantum pixels. Once the lattice structure is filled with the atoms, the electron beam can be used to deterministically empty certain lattice sites, which opens new possibilities for realizing experiments and pixel-like arrangements.

Ott's group has adapted the working principle of a scanning electron microscope (SEM) to detect and manipulate ultracold atoms directly inside the trap where the actual experiment is happening. "In our experiments," Ott explains, "an electron beam scans through the cloud of ultracold atoms, line by line. This electron beam ionizes some of the atoms and these ions can then be detected by an appropriate setup. Contrary to imaging techniques with cameras, we can hereby directly detect single atoms inside the trap with great accuracy." The speed of the electron beam has to be high enough to avoid temporal evolution of the system during imaging. Therefore, only very few atoms are ionized in a single scan through the BEC and many scans are needed to generate an image of the density distribution inside the trap.

The very idea of ionizing atoms in a BEC can be used in different ways in ultracold quantum gases: from imaging to imprinting density patterns inside an atomic gas. The key to these applications is the precision with which the electron beam is positioned and the fact that ionized atoms are detected as they leave the BEC. By keeping the beam at a certain position, the probability of ionizing atoms at this position increases with time and, before long, essentially all the atoms there have been ionized. "In this way," Ott points out, "we can deterministically kick out atoms from a specific lattice site, which gives us completely new possibilities in the way in which we fill such an optical lattice with atoms." In their follow-up experiments [1], for example, Ott's team is imprinting patterns onto the atomic distribution inside the optical lattice, just like pixels on a black/white screen. Hereby, experimentalists can directly access specific sites and decide where the atoms of their BEC should be located.

"This new idea and the versatility of this new technique are truly an outstanding development," Klaus Sengstock comments enthusiastically. Sengstock, Director of the Institute for Laser Physics at the University of Hannover (Germany) and active in several areas of ultracold gases [2], is convinced that this SEM-like technique will soon be used to study many open questions of ultracold gases. "Unfortunately," Sengstock says jokingly, "one can not yet buy Ott's apparatus and simply connect it the experiments, but for applications of optical lattices it is truly fantastic. Think of the overlap of condensed matter physics and quantum optics, where we are now one step closer to being able to use optical lattices for the study of open problems in magnetism and frustrated systems. Many challenging problems, especially in quantum information, require the possibility to address specific lattice sites and Ott's microscope now allows us to both image and manipulate optical lattices with extreme precision and accuracy."

"It all started with our fascination of the SEM and the question of whether we are able to use the underlying principles in our own field," Ott concludes. "Now, it seems that the simplicity and beauty of this technique finally makes its way to experimental usefulness." Both researchers point out how important it is to know not only the momentum distribution but also the spatial distribution of the atoms for experiments. "In many ways," Sengstock adds, "ultracold gases are a great tool to study complex many-body effects, but in situ manipulation of the gases inside the trap was very difficult. This microscope finally enables us to study and manipulate these systems in a very powerful new way and supports us in the challenge of doing great physics with tiny systems."

[1] P. Würtz *et al.*, *Experimental Demonstration of single-site addressability in a two-dimensional optical lattice*, arXiv:0903.3827.

[2] C. Ospelkaus *et al.*, *Ultracold heteronuclear molecules in a 3d optical lattice*, Phys. Rev. Lett. **97**, 120402 (2006).

Armand Niederberger

Tatjana Gericke, Peter Würtz, Daniel Reitz, Tim Langen, and Herwig Ott
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