Final summary report

Stakes and challenges of the research topic

One of the major challenges one faces when exploring quantum physics is the engineering of genuine quantum systems, which do not exist as such in nature. Ultracold dilute gases have proven to be of very high potential in this field of research, as the unprecedented experimental control over all relevant parameters allows one to tailor these systems almost at will. This fascinating possibility has attracted a lot of attention from two distinct communities in physics during the past few years: quantum information and condensed matter. On the one hand, atomic systems are of interest for quantum information because the internal state of an atom can be used as a quantum bit (qubit), be easily manipulated and be read out for example by interaction with a resonant electromagnetic field. On the other hand, the use of dipolar potentials created by off-resonant laser light allows one to experimentally implement paradigmatic condensed matter Hamiltonians with ultracold gases. It is then possible to study some of their most important properties, which remain yet out of reach of experimental investigation in solid-state systems. As quantum information science and condensed matter physics meet in ultracold atoms experiments, the knowledge of the modern atomic physicist has to encompass important parts of both areas, and be truly interdisciplinary. He can then provide a very solid and mutually fruitful link between all of these areas.

State of the art and objective of the project

Optical lattices are one of the most important experimental tools that permit the convergence between quantum information science and condensed matter physics. They consist of a periodic potential obtained by interfering several counter-propagating laser beams. The potential wells can be tailored such that the cold atoms occupy only the lowest energy state, thus realising effective low-dimensional systems. One can also allow for tunnelling between the sites. In this case, optical lattices constitute an almost perfect implementation of the so-called Hubbard model, which describes among others the transition between strongly correlated insulating and conducting systems. By tuning the lattice parameters, it is possible for example to make these interactions of either ferromagnetic or antiferromagnetic type, which gives access to strongly correlated magnetic phases. These interactions are also believed to play an important role in the context of high-Tc superconductivity. Last but not least, the use of spin-dependent lattices offers an ideal mean to parallelise 2-qubits operations, an essential step towards complex quantum computing.

Experiments with optical lattices have so far suffered from an important drawback: because of the dense periodic structure, it has been impossible to probe or to manipulate the atoms at the level of a single lattice site. For quantum processing, this means that only simple algorithms have been implemented, in which the same operation was applied to all pairs of qubits. In condensed matter-like experiments, this lack of a local probe also constitutes a severe limitation. Dilute gases are intrinsically inhomogeneous, as they have to be trapped by an external potential; this means that any measurement performed on a macroscopic scale inevitably leads to a blurred, incomplete characterisation of the system.

The main objective of the project was to develop and demonstrate new experimental techniques that allow imaging and manipulating ultracold atoms in an optical lattice with single-atom and single-site resolution. This objective could be reached even beyond our most optimistic expectations and, with these novel techniques at hand, we were able to perform several spectacular experiments illustrating fundamental aspects of the behaviour of quantum many-body systems that could never be observed before.

Work carried out to achieve the project's objective

The principle of the imaging technique that we developed in the frame of the project works as follows: After the system has been prepared in the state that we want to observe, the atoms are pinned in place by an extremely deep three-dimensional optical lattice. We then illuminate the atoms with near resonant light such that the atoms continuously fluoresce. Using a particular configuration of laser beams to excite the fluorescence, we achieve a so-called optical molasses and make sure that the atoms remain pinned at their original position as they fluoresce. We then image the gas through a specially designed high-numerical aperture microscope objective to obtain a picture of the system with a diffraction-limited resolution of 700 nm. The possibility to let the atom fluoresce for a very long time and the use of a high detection efficiency CCD detector ultimately provide the sensitivity to detect every single atom present in the system.

One of the main challenges we faced when developing this technique was to combine the opposite requirements of an experimental setup capable of efficiently producing ultracold gases with those of a high-resolution optical imaging system. This was only possible with the design and construction of a new type of experimental setup, which Prof. Stefan Kuhr and his team started in 2008. As this project began, the last pieces of the apparatus, including the microscope objective, had to be put together. It took the first 8 months of the project to produce the first strongly correlated ultracold gases and to get the imaging system to work.

The second main objective of the project was to demonstrate the manipulation of the spin of individual atoms localized in an optical lattice. This required further developments of the experimental setup, which took us another 6 months. The achievement of this part of the projected marked the end of the “development phase” of the project. The following 10 months were devoted to the “exploitation phase”, during which we performed fundamental experiments on strongly correlated ultracold gases by taking full advantage of the new possibilities offered by our imaging and manipulation techniques.

Main results of the project

Several remarkable results were obtained during the project. The first one is the development of a new imaging system with single-atom sensitivity and sub-micrometre resolution. We could demonstrate the immense potential of this technique by recording in-situ images of a strongly correlated gas in the so-called Mott-insulating phase with unprecedented resolution, thereby revealing the density distribution atom by atom, lattice site by lattice site. The second main result of the project is the development of a technique to manipulate the spin of individual atoms in a dense ultracold gas. This we could demonstrate by imprinting arbitrary spin patterns in the Mott-insulating phase with high fidelity. This technique could be used in the near future as one of the basic tools in a quantum-computing device.

In the "exploitation phase", we performed several fundamental experiments yielding spectacular results. Among others, we could observe directly, in the Mott insulating phase, the quantum fluctuations that appear as entangled "particle-hole" pairs (see Figure 1). Such fluctuations have no equivalent in classical system and their existence is a striking demonstration of the validity of the concepts that underlie the quantum theory of many-body systems. In another experiment, we measured the propagation velocity of correlations in our system and could show that it is bounded by an effective "speed of light". Such an observation, which was made here for the first time, sheds new light on the locality structure of quantum mechanics and could well be a generic feature of many-body systems.

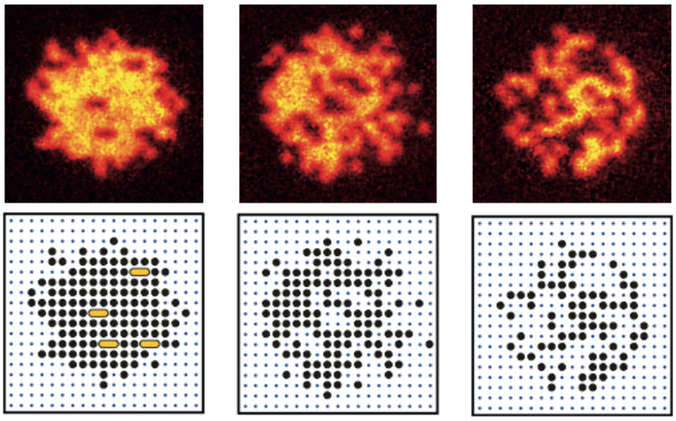

Figure 1 – Fluorescence images of an ultracold gas in the Mott insulating showing the quantum fluctuations. These fluctuations give appear as virtual particle-hole pairs, which appear as neighbouring holes on the uniformly filled background (left picture). As one approaches a quantum phase transition (here the Mott-insulator-to-superfluid transition), the quantum fluctuations become more pronounced (middle and right pictures) [Images from: Endres *et al.*, Science **334**, 200 (2011)].