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PERSPECTIVE

Tracking ultracold many-body systems in real time

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Abstract

The variety of available probing techniques have established ultracold atoms as popular systems to study quantum many body physics. However, conventional approaches are usually destructive to the full ensemble, such that real time observation is challenging. In a recent publication, Manthey *et al* (2015 *New J. Phys.* **17** 103024) present a novel method to overcome this challenge via weak measurements based on laser excitation to Rydberg states. Their technique is even sensitive to the local density by selecting long-range Rydberg molecules as the final state. This achievement provides a new tool to characterize ultracold atom many-body systems, which might be especially valuable to study time correlations in out-of-equilibrium situations.

Ultracold atoms have been established as a powerful new system to study many-body physics with unprecedented control and detection possibilities [1]. One prominent and often studied example is degenerate bosonic atoms in optical lattice potentials, that can be driven from superfluid to the Mott insulating states and back [2]. Recent progress in detecting these systems led, for example, to the development of so called quantum gas microscopes [3, 4], which enable the observation of single atoms on single sites. These impressive detection methods are, however, always destructive to the whole ensemble and, up to today, are even limited to the measurement of the local parity of the site occupation number. As a result, these techniques cannot be used to probe the same atomic ensemble multiple times, preventing the measurement of correlations between different times in the dynamics.

An alternative method to weakly probe lattice gases using local ionization by electron bombardment [5] was pioneered by the group around H Ott in Kaiserslautern. This technique is non-destructive on the global scale and offers very good spatial resolution at lower detection efficiency when compared to optical fluorescence methods. The same group now developed a novel weakly disturbing detection method with very special characteristics [6]. By using occupation number dependent laser coupling to long-range Rydberg molecules they realized a system, that, in its current implementation, selectively probes doubly occupied lattice sites. They demonstrate how this method can be used to monitor the onsite occupation statistics in real time by observing the reduction of doubly occupied sites during the superfluid to Mott insulator transition (see figure 1).

The key ingredient of the novel technique is the selective coupling to long-range Rydberg molecules. These peculiar molecules consist of one (or more) ground state atom(s) and one Rydberg atom bound at very large internuclear distances [7, 8]. For the used Rydberg states ($n = 30$) the dimer binding energy exceeds 10 MHz, such that a single molecular association line is easily resolved by laser coupling. Obviously, molecules can only be excited if at least two atoms are in close vicinity, which corresponds to distances of approximately 100 nm for the chosen states. This distance is set by the extension of the electronic Rydberg wave function, that is, the size of the Rydberg atom. Importantly, this size is even widely tunable by the choice of the targeted Rydberg level, such that the atomic distance at which excitation preferably happens can be varied. In the current implementation the Rydberg state is chosen such, that its size roughly matches the extension of the onsite wavefunction in the optical lattice. Therefore, the excitation is mostly sensitive to pairs of atoms on the same site.

Ion counting is used for the final detection of the excited molecules, which are easily ionized, either by external fields or due to their intrinsic decay. This provides a very sensitive detection method that works down to

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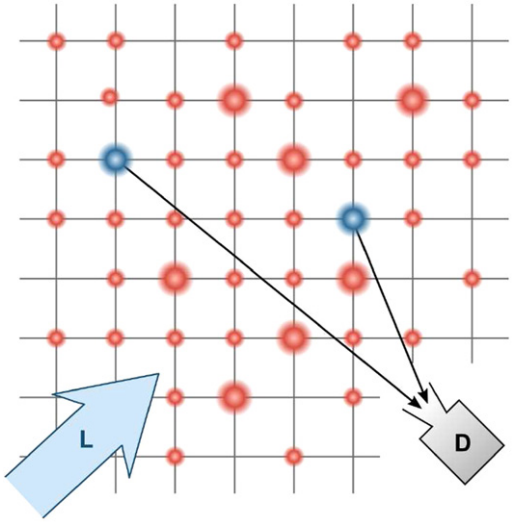

Figure 1. Illustration of the detection scheme. Ultracold atoms (small and large red balls) trapped in an optical lattice are laser excited to long-range Rydberg molecules. This process requires two atoms to populate a single lattice site (large balls). The laser (blue arrow, L) is weak, such that only a small fraction of the doubly occupied sites is actually converted to long-range Rydberg molecules (large blue balls), which are subsequently ionized and guided to a detector (D). This technique only weakly disturbs the system allowing for the real time observation of the dynamics.

a few tens of molecules. Ultimately, it is this sensitivity combined with the tunable and possibly weak optical excitation that enables the weak, occupation selective probing of the quantum gas.

In their recent work Manthey *et al* [8] demonstrate various aspects of their new detection technique. They use it to observe the emergence of the doubly filled Mott shell when varying the chemical potential. Furthermore, they show how local probing of double occupations can be realized when the Rydberg molecule excitation is combined with conventional in-situ imaging. Finally, they demonstrate that the quantum gas can be monitored in real time with minimal heating when it is adiabatically driven across the superfluid to Mott insulator transition.

The use of Rydberg excitation as a diagnosis tool for ultracold many-body systems is an example of the fruitful interplay of Rydberg physics and ultracold gases, a relatively new and rapidly growing field of research. The developed technique offers a powerful way to probe the real time dynamics of ultracold many-body systems. Especially, it might offer new insights into out-of-equilibrium systems and it might be transferred to fermionic lattice systems, for which the doublon fraction has already been used as a valuable observable [9]. Furthermore, the method might be extended to higher filling factors per lattice site or even to probe nearest neighbor correlations when selecting higher and thus larger Rydberg states.

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