Project A9:

Ultracold Bose gases with variable interactions

Project 1: Temporal pair correlations in many-body quantum systems with variable interaction

The pair correlation function $g^{(2)}(t)$ contains important information on the static and dynamic properties of a many-body quantum system. Depending on the specific system and the quantum statistics, the pair correlation function can show bunching as well as antibunching phenomena. The latter is a powerful indicator for the presence of strong correlations.

We have studied the temporal pair correlation function in a thermal cloud of atoms, a Bose-Einstein condensate and strongly interacting one-dimensional (1D) Bose gases (Fig 1). While the Bose-Einstein condensate shows no appreciable bunching or antibunching signal, we find pronounced bunching signals in thermal clouds [1] and antibunching behavior in strongly correlated 1D Bose gases [2]. The antibunching is induced by the transverse confinement of the 1D gases and is a tunable parameter. For sufficiently strong confinement, the repulsive interaction between the atoms translates into an antibunching of the atoms along one tube. This work is done in collaboration between with project A5, which provides the theoretical modeling of the 1D gases. We study several important aspects of the antibunching phenomena: (i) the temporal pair correlation function $g^{(2)}(t)$ is different for bosonic and fermionic atoms. This constitutes a breakdown of the Fermi-Bose mapping in 1D. (ii) The temporal pair correlation function gives access to the dynamical response of the system to an external perturbation. It therefore contains information on the dynamics of a strongly correlated many-body system.

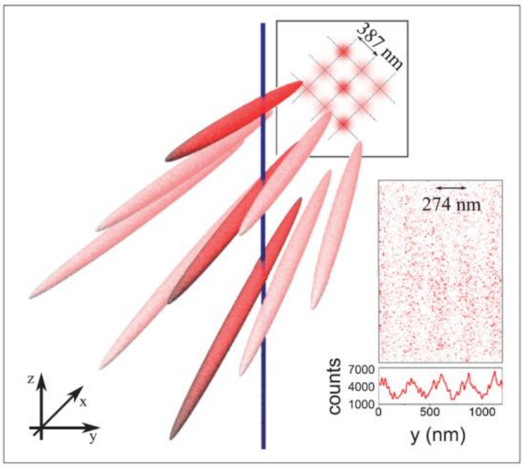

Fig 1: Strongly correlated 1D Bose gases in a two-dimensional optical lattice. The system is probed with a focused electron beam (blue). The time-resolved signal of the produced ions is used to extract the temporal pair correlation function.

[1] V. Guarrera, P. Würtz, A. Ewerbeck, A. Vogler, G. Barontini, and H. Ott, „Observation of local temporal correlations in trapped quantum gases“, Phys. Rev. Lett. 107, 160403 (2011).

[2] V. Guarrera, D. Muth, R. Labouvie, A. Vogler, G. Barontini, M. Fleischhauer, and H. Ott, “Spatiotemporal fermionization of strongly interacting one-dimensional bosons”, Phys. Rev. A 86, 021601(R) (2012).

Project 2: Thermodynamics of strongly correlated one-dimensional Bose gases

We are studying the equilibrium properties of a strongly interacting one-dimensional Bose gases. To this purpose, we load an ultracold cloud of atoms in a two-dimensional optical lattice, thus producing a two-dimensional array of 1D Bose gases (Fig. 1). For sufficiently strong transverse confinement, the system consists of independent tubes, each representing an individual 1D Bose gas. The thermodynamic properties of a 1D Bose gas are described by the so-called Yang-Yang theory [3], which describes the system for all interactions strengths and temperatures. Performing high precision density measurements allows us to experimentally study these quantities (Fig. 2).

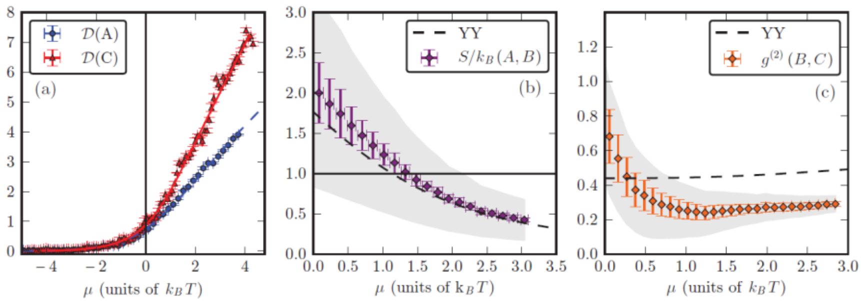

Fig 2: Phase-space density, entropy per particle and local pair correlation function of a strongly interacting 1D Bose gas.

We measure the phase space density, the entropy per particle as well as the temporal pair correlation function and find excellent agreement between experiment and theory [4]. On the basis of these findings we are exploring the deconfinement transition from weakly coupled Luttinger liquids to a 3D superfluid [5]. Decreasing the confinement of the optical lattice, the individual 1D gases are coupled to each other via tunneling processes. We find a two-step transition: at a critical coupling strength, the atoms start to tunnel and partially delocalized in the transverse direction. This results in a higher density than expected from the pure 1D theory. At the same time, the time of flight imaging reveals a small coherent fraction in the transverse direction. At a second, higher coupling strength, the system exhibits a true thermodynamic phase transition, indicating in a sharp increase of the density around the critical chemical potential μ_c=0.

[3] C. N. Yang and C. P. Yang, J. Math. Phys. 10, 1115 (1969).

[4] A. Vogler, R. Labouvie, F. Stubenrauch, G. Barontini, V. Guarrera, and H. Ott, “Thermodynamics of strongly correlated one-dimensional Bose gases”, Phys. Rev. A 88, 031603 (2013).

[5] A. Vogler, R. Labouvie, G. Barontini, V. Guarrera, and H. Ott, “Deconfinement transition from a Tomonaga Luttinger liquid to a 3D superfluid”, in preparation.

Project 3: Strongly interacting Rydberg atoms

Highly excited Rydberg atoms have a huge dipole moment with leads to a long-range interaction between the atoms. Rydberg atoms are therefore a promising candidate to study correlated many-body quantum systems. In our project we use resonant and off-resonant excitation of Rydberg atoms to induce correlations and anticorrelations between the atoms. Ultimately, we are interested to see effects of Rydberg-dressing – an excitation scheme were the interaction between excited Rydberg atoms is mapped to ground state atoms, thus inducing long-range interactions.

In first characterizing experiments, we have measured the lifetime of ultracold atomic clouds upon strong continuous driving [7]. In order to further characterize the blockade physics and the behavior of Rydberg atoms under off-resonant driving, we have recently demonstrated the concept of a so-called superatom, where a small atomic sample is confined to a region of space which is smaller than the blockade radius. The sample therefore acts as an effective two-level system which features antibunching phenomena (Fig. 3) and the collective enhancement of the coherent driving. Driving the superatom off-resonantly has allowed us to measure strong bunching signals and cascaded excitations [8].

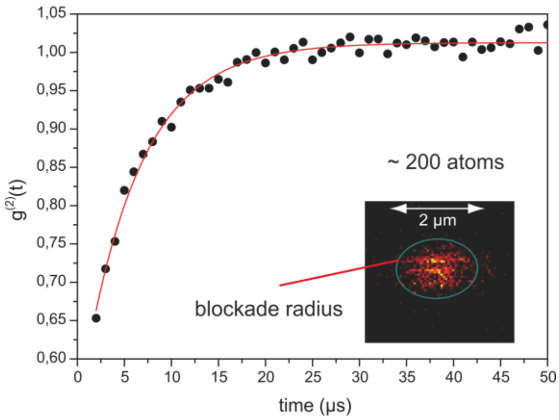

Fig 3: Antibunching signal from a superatom.

[7] T. M. Weber, T. Niederprüm, T. Manthey, P. Langer, V. Guarrera, G. Barontini, and H. Ott, „Continuous coupling of ultracold atoms to an ionic plasma via Rydberg excitation“, Phys. Rev. A 86, 020702(R) (2012).

[8] T. M. Weber, T. Niederprüm, T. Manthey, O. Thomas, V. Guarrera, G. Barontini, and H. Ott, “Creation, excitation and ionization of a superatom”, in preparation.