Scientific report
Experiments with Mott insulators

Robert Saers

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The aim of this joint project between The Johannes Gutenberg Universität in Germany, and Umeå Universitet in Sweden was to efficiently transfer the knowledge of cold bosonic atoms in deep three-dimensional optical lattices. It was supposed to be a fruitful project for both teams, where the group in Germany would benefit from new scientific ideas and viewpoints, aswell as experienced extra personnel available in the laboratory. The Swedish group should benefit by an efficient learning period for a graduate student, with time raising the knowledge in the whole scientific group in Umeå. The results of the research should be published in international scientific journals.

The experimental work was performed on the same apparatus that first realized the superfluid to Mott insulator transition for ultra-cold bosonic atoms [1]. The original experiment consist of a sample of bosonic Rubidium, adiabatically loaded from a Bose-Einstein Condensate (BEC), into a three-dimensional optical lattice. The optical lattice consist of three retro-reflected, far detuned, laser beams. The beams have been aligned along the Cartesian axes, and to avoid interference effects in-between beam pairs, the light frequencies of the different beams differ by an amount larger than any frequency of the studied system.

When the optical lattice potential is raised, it will create a potential with simple cubic geometry. The potential barrier will suppress inter-well tunneling, and increase the repulsion between bosons trapped within one well. When the potential barrier height passes a critical value, the system will rearrange from the original superfluid and phase coherent sample, to a number squeezed state, where coherence between wells is lost. This state is referred to as the Mott insulator state [2].

For the experimental work undertaken during this project, the apparatus was modified. In one Cartesian axis, a super-lattice replaced the old potential. The super-lattice was created by overlapping two standing waves, implemented with two laser wavelength, differing by approximately a factor of two. The shapes of the potentials in the other two axes were kept as before, in a simple cubic configuration.

The properties of the super-lattice were controllable by modifying the phase and the irradiance of its two laser beams. Modifying these two parameters, the system could be tuned from a single-well superfluid, or Mott insulator, to an array of double-well potentials, with variable tunneling strength between the two wells of the double-well. A schematic view of the well shapes is shown in figure 1.

The experimental sequence consisted a preparation part, a tunneling part

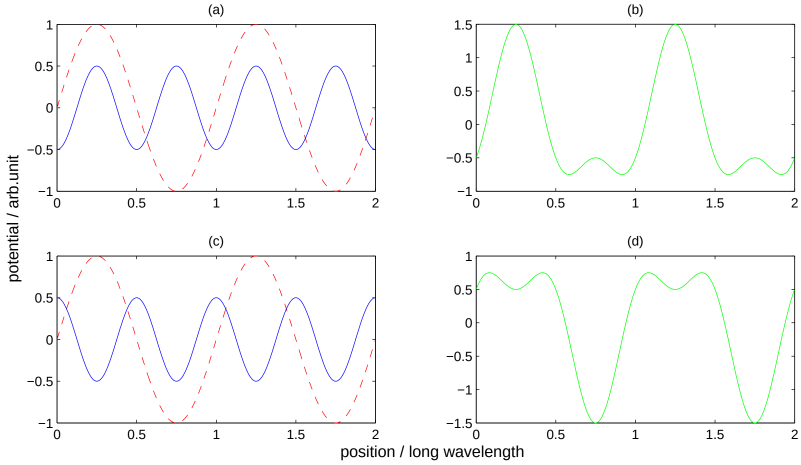

Figure 1: The figure show two different situations for the super-lattice. To the left (a and c) the two standing wave components for the super-lattice are shown for two different phase situations, using the same amplitude relations in both examples. To the right, the resulting lattice potential from (a) is shown in (b), and from (c) is shown in (d). In (b) the potential is an array of double-wells, with barrier heights set by the amplitudes of the two lattice components. In (d) the lattice have been tuned to a single-well.

and a detection part. In the preparation the double-well potentials were loaded with one or two atoms in one side in the double-well. To achieve such a configuration, a BEC was loaded into the super-lattice, with the amplitude and phase, such that a single-well configuration with high lattice barriers, and therefore a regular Mott insulator was produced. The phase and amplitude of the super-lattice could then be tuned, so that the single-well turned into a double-well. Changing the ramp slow enough so that the atoms follow their original well adiabatically ensured that all atoms were loaded on one of the sides in the double-well.

The actual experiment was performed in the double-well configuration, by lowering the potential barrier between the wells. By setting the height of the barrier, the tunneling rate was controllable. The tunneling rate of a single particle, and a particle pair differ in a system where repulsive atoms are used. For wells with two atoms, the energy of the system is higher when the two atoms occupy the same well, than when they are incommensurably spread. Since all atoms are loaded into one of the wells in the preparation sequence, tunneling of one atom in an atom pair will be suppressed by the atom-atom repulsion energy. For resonant tunneling, such a pair must tunnel, not atom by atom, but pair by pair.

The detection of the tunneling process was done by time of flight absorption imaging. The sample was released and let to expand according to the momentum distribution before release. Since all double-wells act as Mott insulating systems with respect to each other, the detected signal is the sum of all double-well experiments. Two slightly different detection schemes were used for the experiment. In one sequence, the sample was abruptly released by quickly turning of the magnetic trapping potential and the optical lattice. An interference pattern from a double slit could then be detected, where the phase and contrast of the fringes revealed the occupation probabilities of the one and two atom state in the double-well. In the other detection method, the atoms on one of the sites in the double-well were adiabatically lifted to a higher band of the neighboring well. By slowly ramping down the lattice potential, the band population was mapped into velocity space, revealing the population of the two wells in the double-well [3].

The tunneling of single atoms and atom pairs have been detected successfully, and the tunneling rates agree with theoretical models of resonant, and off-resonant tunneling. The tunneling amplitude and frequency have been measured for atom pairs, both in the case of a symmetric potential, and for a tilted potential, where one well in the double-well have a higher energy than the other.

The results obtained from this project is currently being organized for submission of an article.

References

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