Project title: Topological Phases of ultracold atoms in 2d Optical Lattices: a Density Matrix Renormalization Group study
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Final Summary Report

Introduction

The field of topological phases – which appear in solids in the presence of a strong spin-orbit coupling – is quite recent and involves both fundamental open questions as well as potential applications, e.g. in quantum computing. Because they permit to go beyond certain limits of traditional condensed matter materials, ultracold atoms in optical lattices provide a great tool to explore this physics. In particular, due to precise experimental control, they permit unprecedented comparison with the theory. But they have specific features, such that along with experimental efforts, specific theoretical studies of those systems, are necessary. Therefore, in this project, we have implemented a Density Matrix Renormalization Group (DMRG) approach to study phases of ultracold atoms in quasi-two dimensional systems. Such direct numerical simulations permit to give an accurate quantitative description, which improves our theoretical understanding and will assist the analysis of experiments.

Density Matrix Renormalization Group [1,2] is a variational method that permits to compute the ground state, and first excited states, of a quantum system, along with the associated observables. This method is particularly interesting for strongly-correlated interacting systems. It is very powerful for unidimensional systems, because of the area law of entanglement entropy. And it can be extended to two-dimensional systems in cylindrical or stripe geometries, by mapping the short-range bidimensional Hamiltonian on a long-range unidimensional one [3] (see Fig. 1). Stripe geometries are particularly adapted when we want to observe the edge effects, as in our case.

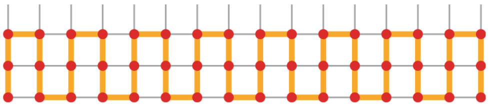

Figure 1: Mapping of a bidimensional hamiltonian on a unidimensional one (reproduced from [3]).

Results

Due to their experimental relevance [4], we have studied strongly-interacting bosonic ladders, subject to a uniform magnetic field. We have explored the phase diagram as a function of the different parameters, and identified phases with Meissner or vortex current patterns (see Fig. 2), with and without a charge gap in a hard-core model **[5]**. We have studied their properties in detail, thus preparing the ground for upcoming experiments. This study agrees with predictions obtained from bosonization in previous studies [6,7] as well as with the study carried out by Sebastian Greschner and Temo Vekua from the University of Hannover, with whom we have collaborated.

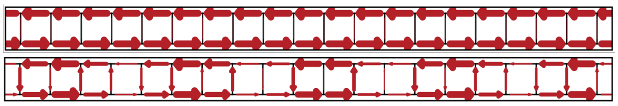

Figure 2: Examples of Meissner (top) and vortex (bottom) current patterns on a two-leg-ladder subject to a uniform synthetic magnetic flux [5].

In the case of intermediate interactions, we have found that vortex lattices (i.e. regular commensurate arrangements of vortices, see Fig. 3) can form when the vortex density becomes commensurate **[8]**. Those phases had been predicted in [6], but never observed before. Moreover, we have observed the reversal of the current circulation-direction in and near certain vortex lattices, which we have

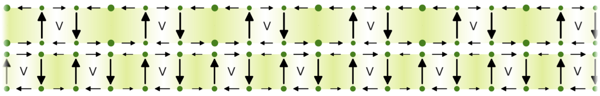

Figure 3: Vortex lattices with densities 1/3 (top) and 1/2 (bottom) [8].

explained as a consequence of the spontaneous symmetry breaking that occurs in these phases. Indeed, in the vortex lattice at vortex density 1/2, for instance, the unit-cell is spontaneously doubled; this leads to a doubling of the effective magnetic flux, which can be interpreted as a reversed magnetic field in some cases, consistently with the observation of the current reversal.

On the way to truly bidimensional systems, we have then studied the three-leg ladder subjected to a homogeneous magnetic field (which has also been realized experimentally in the weakly-interacting limit [9,10]). In this case, no analytical prediction was available, as the use of bosonization is more challenging. In the regime of a transverse hopping rate which is equal or greater than the longitudinal one, we have demonstrated the occurrence of a Meissner phase and different types of incommensurate vortex phases, as well as vortex lattices, one of them displaying a staggered current-pattern **[11]**. We have also carried out a careful study of the Mott-Insulator to superfluid transition that occurs at the filling of 1/3 bosons per site (i.e. one boson per rung) when the transverse hopping rate decreases.

Conclusion

The realization of this project has permitted to observe for the first time phases and effects in the strongly-interacting regime that had been previously predicted (such as the Meissner and vortex phases and the formation of vortex lattices). But we also demonstrated unforeseen effects, such as the current reversal on the two-leg ladder and all the phases on the three-leg ladder. This project therefore sets the stage for upcoming experiments with ultra-cold atoms in the strongly-interacting regime, as well as for the study of the three-leg ladder in the field-theoretical context. Furthermore, it paves the way towards establishing the in-depth link to the two-dimensional parent system (i.e. a quantum Hall setup), which will shed new light onto the strongly-correlated topological phases found there, whose understanding remains a challenge.

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