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Review of the PhD thesis of Mr Jan Major

The manuscript of the PhD Thesis of Mr Jan Major – under the supervision of Prof. Jakub Zakrzewski – is entitled **Anderson localization in low-dimensional optical lattices**.

In the last ten years, the importance of (ultra-)cold atomic gases as prototypical systems for studying various fundamental processes in quantum physics has steadily grown. Because all basic ingredients (atoms, electromagnetic fields...) are well understood and can be tuned and controlled in the experiments, it has been possible to study experimentally some quantum phenomena in great detail. Beyond the most spectacular manifestations like Bose-Einstein condensation (already more than 20 years old), it has been possible to build systems described by relatively simple models, which nevertheless cannot be completely solved, and where experiments can bring solutions to open problems. A simple example is the Hubbard model, widely studied theoretically, which can be studied using ultra-cold atoms in optical lattices. In the last few years, this area has significantly developed in several directions. Firstly, using convenient geometries for several phase coherent laser beams made it possible to create optical lattices, that is spatially periodic effective potentials for the motion of cold atoms, thus creating the equivalent of usual crystals in solid state physics, but with several advantages: tunability of the periodic potential, direct experimental access to the wavefunction of the system thanks to the large lattice constant (fraction of a micrometer), absence or good control of the atom-atom interaction (in contrast with electrons experiencing Coulomb interaction). Secondly, it is possible, using combinations of electromagnetic fields, to add to the system a well controlled "disorder", some kind of random potential with known correlation functions. This has led to a revival of studies on disordered systems, emphasizing phenomena like Anderson localization (for non-interacting particles) or the recent explosive growth of papers on "many-body localization".

This manuscript contains several contributions in this field, at the intersection of quantum physics, atomic physics, solid state physics and statistical physics. The guideline is to consider experimentally realizable systems and to study how some microscopic fundamental quantum process manifests itself in measurable quantities. While it is fashionable to propose to simulate any

model with ultra-cold atoms, most studies in this area do not pay much attention to the feasibility of the experiment and whether unambiguous experimental signatures can be observed. In contrast, Mr Major starts from a plausible experimental setup, derives a model which describes a possible experiment, and studies e.g the transport and localization properties of this model. The price to pay is that the model is slightly more complex than the theorist's dream. But this is the only way to LEARN something new! Following this guideline, Mr Major has devised and studied several models for one and two-dimensional optical lattices, searching for signatures of fundamental quantum processes.

Several techniques – discussed in some detail in the manuscript – exist to adjust the properties of optical lattices. One can for example temporally modulate the depth of the trapping optical potential (by modulating the laser intensities), add a static or time-dependent magnetic field, or shake the lattice. These techniques make it possible to control the on-site energies in the lattice and/or the tunneling amplitudes between neighboring sites. In order to add some disorder to the system, Mr Major proposes to use two different sets of atoms (either different species of different sublevels); with a proper adjustment of the optical lattice, one set can be deeply trapped creating a frozen random effective potential for the other (mobile) atomic set. Although most of these techniques have previously been put forward in the literature, Mr Major ensures that the orders of magnitude are realistic.

In chapter 2, Mr Major studies localization properties in one-dimensional systems. While it is well known that Anderson localization is the generic scenario when the disorder is diagonal, i.e. on the on-site energies, the situation is much more rich if the inter-site hoppings are also random and if correlation between diagonal and non-diagonal disorders exist, which is likely to happen in optical lattice experiments. He especially concentrates on the random dimer model (and its generalization, the N-mer model), a situation where there may exist specific energies where no localization takes place; as correctly emphasized in the manuscript, this could be used as a simple filter to prepare mono-kinetic beams of cold atoms. A thorough analytic study of the problem makes it possible to understand the numerical details. In this chapter (and the accompanying appendix B), Mr Major shows that he masters both the theoretical and the numerical methods. He produces several interesting, original and significant results, which have been published in several papers. It should be emphasized that the generalized N-mer model is fully the development of his ideas, as testified by the fact that he is the only author of the corresponding Phys. Rev. A paper. Publishing a paper alone is not common for PhD students; it assesses that Mr Major has a high degree of scientific autonomy.

Chapter 3 deals with Anderson localization in a two-dimensional lattice, in the presence of an artificial random gauge field. The latter is created by techniques similar to the ones used in 1d (proper modulations of the lasers). It allows to create the equivalent of a random magnetic field if the product of the 4 tunneling amplitudes along the 4 sides of a square plaquette is a complex number with non-zero argument. This breaks the time-reversal invariance and consequently partially inhibits the interference between time-reversed paths. It is thus expected to reduce localization effects. In agreement with this picture, Mr Major observes numerically a rapid growth of the localization length when the random gauge field amplitude increases. As predicted by the scaling theory of localization, the dynamics remains localized. There also specificities of the model when the gauge field amplitude becomes large, and a plausible interpretation is given in the manuscript. Once more, the parameters used in this chapter are chosen to be reachable in an experiment. At the end of the chapter, there is a first quantitative analysis of the results, aiming at a future complete theoretical prediction of the localization length from microscopic parameters.

It should also be mentioned that Mr Major produced some other results, that he decided not to include in the thesis. A common approximation for cold atoms in optical lattices is to take into

account only the lowest band, neglecting all processes (real or virtual) where one atom jumps to excited bands. This is convenient because one ends with a Bose-Hubbard model, but the validity of the approximation in a real experiment is questionable. In a paper not included in the PhD manuscript, Mr Major reexamines this approximation and shows that it may be an oversimplification.

Altogether, the manuscript is well written, with general introductions so that the non-specialist can read it with great profit. It is also rather compact, concentrating on the most significant results. Nevertheless, I have some criticisms. The most important one is probably that the results obtained are not fully put into perspective, and especially compared with contributions by other groups in the same area. For example, 1d Anderson localization in correlated diagonal and non-diagonal disorders has been thoroughly studied by e.g. L. Tessieri and F. Izrailev. While some work of the latter is quoted (ref. [50]), the former is ignored. My feeling is that confrontation with his results could have enriched the manuscript.

To summarize, this manuscript contains original, significant and timely contributions to the transport and localization properties of ultra-cold atoms in optical lattices.

I strongly recommend the defense of this thesis.

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