Classical and quantum simulations with ultracold 4-component fermionic mixtures in optical lattices Popular project abstract (SONATINA 1) – Dr. Agnieszka Cichy

Ultracold quantum gases provide a unique opportunity for *quantum simulations* of interacting many-body systems. Tremendous progress in experimental techniques in the last years has allowed to control all the important aspects of such simulations and thus, has offered insight into physical mechanisms that eluded understanding in conventional condensed matter setups. The full understanding of experiments is not possible without reliable theoretical description. Obviously, quantum simulations are not possible with analog computers, even with the most powerful supercomputers. Numerical methods aimed at description of the relevant physics are hence often called *classical simulations*.

This project is motivated by another recent development in ultracold gases experiments, which have used alkaline-earth-like (AEL) atoms, which offer many advantages over the more traditionally used alkali-metal atoms. The latter allowed to investigate many interesting systems, but the relative simplicity of their internal structure introduced many limitations. On the other hand, AEL atoms set truly new perspectives for investigation of new states of matter. This allowed experimental realization of the two-band Hubbard model. It is important to emphasize that ultracold gases experiments changed the status of this model – the physics of such systems is no longer *modelled* with Hubbard-type models, but it is *described* by it. This has become possible, since ultracold atoms provide an experimental situation in which only the desired mechanisms are turned on. This has opened new avenues for research, in which theoretical description can be *directly* compared to experiment.

The main aim of the project is to provide theoretical description for novel ultracold atomic gases experiments, in close coordination with them, by application of various advanced numerical methods such as the dynamical mean field theory, hybrid Monte Carlo and tensor networks. In other words, we will perform classical simulations of phenomena occurring in quantum simulators, to achieve full understanding of a broad class of interacting many-body systems. The main research hypothesis is that the investigated class of phenomena is crucial from the point of view of generic mechanisms of unconventional, including high-temperature, superconductivity and superfluidity as well as quantum magnetism. By isolating the relevant mechanisms in a fully controlled way, this will shed new light on the most important problems of condensed matter physics.

The research work in the project will be divided into 2 sub-projects, concerning different kinds of physical phenomena in ultracold gases in the lattice: orbital magnetism (in particular parameter regimes most favourable for observing magnetically ordered phases) and superfluidity (in particular the BCS-BEC crossover and the stability of exotic phases).

It is important to emphasize the key innovative features of the proposed project: coordination with forefront ultracold atomic gases experiments; investigation of novel physical mechanisms whose experimental realization has become possible only recently or is expected to be possible soon; usage of advanced numerical methods, including the relatively little explored matrix product states (MPS) solvers for dynamical mean field theory (DMFT) and methods orginating from lattice gauge theory (hybrid Monte Carlo (HMC)); usage of more standard methods, MPS and DMFT, which are, however, still not so widely used in the Polish condensed matter community; usage of graphical cards (GPUs) for computations, which can allow efficient tackling of some time-intensive computations.

The successful realization of the project will lead to a better understanding of quantum magnetism, the BCS-BEC crossover and unconventional superfluidity in systems of direct experimental interest – it will provide description of recent experiments and will motivate further experiments. As such, it will lead to important and innovative insights about the generic mechanisms of quantum magnetism, superconductivity and superfluidity. The scientific problems solved in this project will have a strong impact in the field of theoretical and experimental condensed matter physics. Their impact on experiments with ultracold atomic gases may lead to technological progress (e.g. may help in the construction of quantum computers, as well as various devices based on the phenomenon of superconductivity) and thus also to general development of civilization and society.