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This research project covers three topic areas:

1. Compressed Sensing,
2. Open quantum systems, and
3. Quantum thermodynamics.

In this description, we give a short introduction to each topic area, where we also emphasize the main reasons for dealing with the subjects. After the introductory parts, we briefly describe the research to be carried out.

Compressed sensing is a signal processing technique for acquiring and reconstructing a signal from as little data as possible. This idea might be best explained with audio signals. In order to reconstruct an audio signal from acoustic measurements, one can measure the air pressure over time, which describes the sound waves. From such a procedure one can obtain a full description of any audio signal. However, a large number of measurements is needed here, while often, audio signals are compressible: Most audio signals are made up from only a few frequencies. By only saving the amplitudes of those frequencies one obtains a much shorter description of the audio signal. By also only measuring the frequencies in a recording process, one can also sense the signal in a compressed way. In such a compressed sensing scheme, much fewer measurement values are needed compared to the scenario where the air pressure is recorded. This example demonstrates the basic idea behind compressed sensing: First, one identifies the right description of the signal in terms of frequencies and, secondly, one finds measurement procedures to directly measure those frequencies is the basic idea of compressed sensing. Typically, the reconstruction of the signal also relies on convex optimization methods, so that it can be done with standard mathematical computer software.
This compressed sensing approach has a much wider range of applications than it might first seem. It is crucial that some signals can be most naturally described and compressed as vectors (set of numbers specified by one index), others as matrices (two indices), or even as tensors (some fixed number of indices). While compressed sensing for vectors and matrices is a well-developed theory with numerous applications (e.g., image processing, network tomography, self-calibration of hardware, improvement of radars) it is still in the very early stages when it comes to tensors. Tensors seem to be rather new objects in the research field of compressed sensing but they are fundamental and well-studied mathematical objects in quantum many-body and quantum information theory. We aim to exploit this connection in order to develop compressed sensing methods for the study of quantum processes, i.e., to study how quantum systems (e.g. trapped ions in very small quantum computers) evolve in time. But also the other way around, we will use tensor methods from quantum physics to develop compressed sensing for certain types of tensors.

Open quantum systems are open in the sense that they are coupled to an environment. Strictly speaking, every quantum systems is –to some extent– open, otherwise we could not know anything about it. However, most quantum systems are studied as closed systems and interactions with the environment are neglected. For this simpler case, very powerful algorithms (DMRG) for the simulation of quantum systems are used. It is a challenging endeavour to extend these algorithms to open systems. The challenge is to use compressibility of certain tensors in a computation friendly way. By using compression ideas from compressed sensing, we aim to overcome this challenge and to practically simulate open quantum systems.

A research field where open quantum systems play an important role, is quantum thermodynamics. In this field, one aims at the extension of thermodynamics to the quantum world. Notably, thermodynamics provides the basis for the development of engines but has also many other fundamental and practical applications. Corner stones of the theory are the First and the Second Law. These laws essentially say that one cannot build perpetual motion machines, which are machines generating work without consuming certain resources. They can be derived from classical statistical mechanics, describing gases and materials composed of many classical particles.
As a classical theory, thermodynamics is applicable to macroscopic objects. However, with the miniaturization of technological devices, developing a thermodynamical theory for microscopic systems becomes a practically relevant task. But it is also important from a fundamental point of view: In modern physics, one is convinced that quantum mechanics is the fundamental theory giving rise to classical mechanics. Therefore, the justification of usual thermodynamics by classical statistical physics should be at least complemented by a justification relying on quantum physics.
The Second Law already has been extended to microscopic systems. But it is only given as a mathematical condition and it is unclear how it can actually be tested in concrete situations. With our research, we aim to develop practical algorithms to determine whether or not certain processes fulfil the microscopic Second Law. Importantly, standard thermodynamics is only applicable for systems that equilibrate to so-called thermal states. For interacting quantum systems it is unclear, however, under what conditions such equilibrium situations are reached. Here, we aim to discover mechanisms leading to such equilibrium situations. This will further justify the theory of quantum thermodynamics and tell us when it is applicable to concrete physical situations.

Summarizing, with this research we will exploit methods used in compressed sensing to develop new simulations of open quantum systems and to solve open problems in quantum thermodynamics. Conversely, we aim at the development of new compressed sensing methods by using tools from quantum many-body physics.