Quantum Simulation with Cold Atoms and Ions

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We give an overview of the field of quantum simulation with cold atoms and ions from the theory perspective, with particular focus on recent developments and future prospects. Quantum simulation with atoms aims at engineering controlled quantum many-body systems to study synthetic quantum matter, building on experimental progress in obtaining complete quantum control and measurement on the level of single atoms and quanta. While we will review briefly the traditional approaches of 'digital' and 'analog' quantum simulators, as implemented e.g. with trapped ions and atoms in optical lattices, and more recently with Rydberg atoms in optical tweezer arrays, we will discuss also on some recent developments as 'hybrid classical – quantum simulation', which we apply to condensed matter and high energy physics problems. Here a feedback loop between a classical and quantum computer optimizes a (highly entangled) ground state wave function a programmable quantum simulator. We will present results from an ongoing theory-experiment collaboration with the trapped ion group in Innsbruck for quantum electrodynamics as a lattice gauge theory. As a second topic, we discuss first theoretically measurement protocols enabled by the present generation of quantum simulators with single particle control. The example to be discussed is Renyi entropies as a witness of entanglement in quantum simulators, and in particular recent work on Renyi entropies from 'random measurements', including trapped ion experimental results. We conclude with a brief outlook how ideas and concepts of generating entangled many-atom states in atomic quantum simulation can provide novel tools and approaches in atomic spectroscopy, illustrated with the example of Ramsey interferometry with entangled states.

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