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Discrete-time Quantum Machines Using Neutral Atoms in Optical Lattices

Neutral atoms trapped in optical lattices have been instrumental in the past years to advance our understanding of quantum phases of matter, for the determination of fundamental constants, and for numerous applications in quantum technology, ranging from quantum sensors and time-keeping, up to quantum simulations of complex many-body systems. Neutral atoms in optical lattices also provide a promising platform to store and process quantum information, where large ensembles of identical atoms can be prepared and manipulated with control at the single-particle and single-site level [1].

In this colloquium, I will present experiments in which the optical lattice potentials are made to depend on the electron spin state of caesium atoms in order to realize discrete-time quantum machines [2]. In a discrete-time quantum machine, the time evolution—instead of being determined by a static Hamiltonian—is governed by a series of discrete operations, which are rapidly applied in sequence. Using the extra degree of freedom provided by the spin, we can transport atoms in space along different spin-dependent quantum paths with subnanometer precision. In this way, we can achieve fast delocalization of matter waves on a time scale of 10 µs, which is two orders of magnitudes faster than the tunnelling time in a shallow optical lattice. Very recently, using optimal quantum control theory, we could speed up the delocalization process up to so-called *quantum speed limit* of our optical lattice system.

An example of a discrete-time quantum machine at the single particle level is provided by quantum walks: Depending on its spin state, the atom is moved, at regular time steps, either one site to the left or to the right, delocalizing it over multiple quantum paths. By “reprogramming” the operations defining one step of the quantum walk, we have simulated charged particles in external electric [3] and magnetic fields [4], and studied novel topological phases of periodically driven band insulators [5]. On a more fundamental level, relying on ideal negative measurements, we have tested the “quantumness” of the walk, demonstrating a 6-σ violation of the Leggett-Garg inequality, which rules out any macro-realistic interpretation based on well-defined trajectories [6].

I will conclude with an outlook towards Hong-Ou-Mandel-like interference experiments, which enable the detection of quantum statistics using a pair of distant atoms [7]. Generalizations to a higher number of identical atoms hold the promise to construct an atom BosonSampling machine with a large number of indistinguishable particles, which can be scaled well above the 50-particle limit of classical simulations based on today’s supercomputers.

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