Programmable quantum simulator with 2D ion crystals

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Trapped ions are a versatile platform for quantum simulations of spin models due to their good coherence properties, the possibility to induce variable range spin-spin interactions as well as the ease of site-resolved single-particle control and readout. Existing trapped-ion quantum simulators employ 1D chains of ions trapped in linear Paul traps, 2D crystals in Penning traps or purely digital simulators based on a reconfigurable arrangement of 2-ion crystals in a quantum-CCD architecture. In our experiment, we make use of the advantages of simulators based on linear Paul traps, namely the possibility to perform high-fidelity global rotations and entangling interactions as well as local rotations and two-qubit gates, which allows for a flexible analog-digital operating mode. However, by using a modified design of a linear Paul trap we go beyond 1D chains and trap 2D crystals with up to 100 Ca^+ ions while keeping the above mentioned global and local control capabilities.

To engineer spin-spin interactions, state-dependent forces are induced via a stimulated Raman transition of a long-lived ground-state qubit. These forces make out-of-plane modes of a 2D crystal act as an entanglement mediator. With this, we implemented Ising, transverse field Ising and XY spin-spin interaction models with variable interaction range. Using tightly focused laser pulses on the $40Ca^+$ quadrupole transition, we are able to control each particle state independently, and to create entanglement between arbitrary pairs of ions.

We show that it is possible to combine multiple single particle unitary rotations with a spin-spin interaction model of choice, and to perform two-qubit entangling gates between any pair of ions in a 2-dimensional crystal of ions, thus qualifying our platform as a programmable analog-digital quantum simulator. This paves the way to explore complex dynamics of entangled states in a lattice of spins.

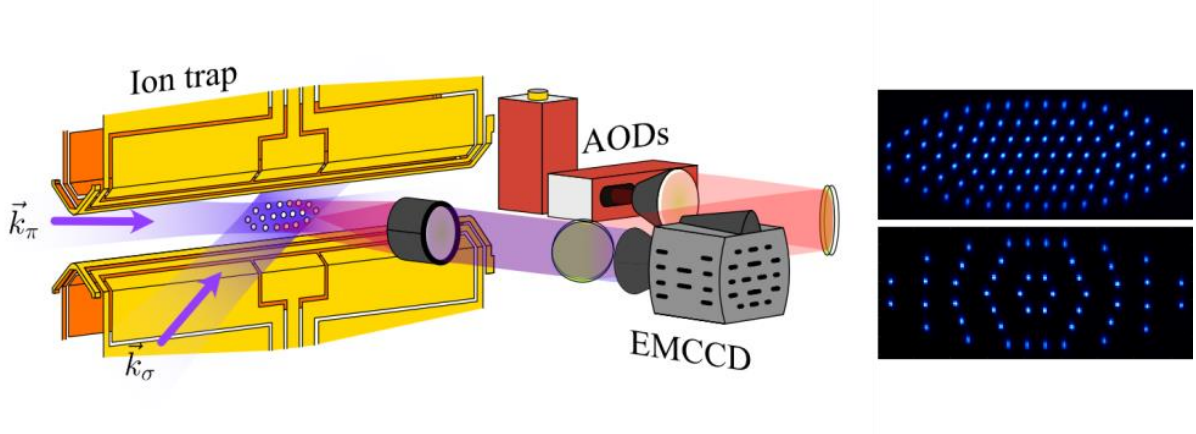

Figure 1: (Left) Experimental setup of the programmable quantum simulator. (Upper right) Camera image of a 91-ion crystal. (Lower right) Preparation of arbitrary product states in a 91-ion crystal. Bright ions are prepared in the spin-up state, dark ions in the spin-down state.