Quantum simulation and many-body physics with hundreds of trapped ions

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Abstract: By employing forces that depend on the internal electronic state (or spin) of an atomic ion, the Coulomb potential energy of a trapped ion crystal can be modified in a spin-dependent way to mimic effective quantum spin Hamiltonians. We use simple models to explain how effective Ising interactions are engineered with trapped-ion crystals. We discuss the range of interactions that can be readily generated and an experimental implementation using single-plane ion crystals in a Penning trap.

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1. **Introduction**

Many problems in physics are poorly understood because the underlying quantum mechanics is too complex for meaningful modeling. Examples include correlated magnetic systems, such as spin liquids [1], and high-temperature (high-T_c) superconductivity, where the phase diagram of the Fermi-Hubbard model, a leading candidate for explaining high-T_c superconductivity, cannot be readily calculated. The source of this problem is the exponential increase in the difficulty of quantum many-body calculations as the number of bodies increases. For a system of interacting two-level quantum systems or spins, the complexity doubles with each additional spin, making a direct calculation of a general system of more than ~30 spins intractable on current computers [2].

In an attempt to tackle this difficulty, a number of groups are following a suggestion put forth by Feynman [3] that it might be possible to engineer interactions between well controlled quantum components in order to mimic a quantum many-body system that is not understood. Through measurement of the well-controlled quantum components, it may be possible to acquire some information about the behavior of the currently intractable quantum many-body system. Current platforms (i.e., well-controlled quantum systems) being used to simulate or emulate quantum many-body systems include neutral atoms in optical lattices [4], superconducting circuits [5], and trapped ions [6-11]. Each platform has particular strengths for emulating different types of quantum many-body systems. We will discuss crystalline arrays of trapped ions, which provide a promising platform for emulating quantum magnetic systems [9].

2. Quantum simulation with single plane arrays of trapped ions

Trapped ions, when cooled to sufficiently low temperatures, form crystalline arrays [12, 13]. Of particular note are the small linear arrays of ions generated by laser cooling in linear rf traps that have been used to demonstrate many different quantum information milestones [14]. We will describe our efforts to extend the techniques developed with small linear chains of ions to larger two-dimensional crystals of hundreds of ions formed in a Penning trap [15].

Penning traps use a uniform, static magnetic field B_o and static electric fields to provide confinement of charged particles. Axial trapping (along the z-axis or symmetry axis) is due to the electric field. Radial trapping is due to the Lorentz force generated by rotation through the magnetic field. In our work with $^9\mathrm{Be}^+$ ions, the axial confinement is characterized by a center-of-mass (COM) oscillation frequency of ~1 MHz, and the trap magnetic field $B_o = 4.465$ T produces a COM cyclotron frequency of 7.608 MHz. The radial confinement is determined by precisely controlling the array rotation with a rotating electric field (the so-called "rotating wall") [16]. Tuning the ratio of the axial to radial confinement allows controlled formation of a planar geometry and, after Doppler laser cooling, the formation of a 2D Coulomb crystal on a triangular lattice. We routinely generate single-plane crystals with ion numbers ranging between 100 and 400.

A two-level system (or effective spin) is isolated and controlled in each atomic ion (see Fig. 1). Our qubit or spin is the 124 GHz electron spin-flip transition in the ground state of $^9\mathrm{Be}^+$. We control the spins with an effective transverse magnetic field generated with 124 GHz microwaves [17]. The duration of a π-pulse is ~50 μs; the qubit T2 coherence is $\gtrsim$50 ms. By employing spin-dependent optical dipole forces from off-resonant laser beams, we engineer long-range Ising interactions between the ion qubits of the form $H_I = \frac{1}{N}\sum_{i<j} J_{i,j}\hat{\sigma}_i^z\,\hat{\sigma}_j^z$, where $\hat{\sigma}_i^z$ is the z-component of the Pauli spin matrix for ion i. The pairwise interaction strength $J_{i,j}$ depends on the distance $d_{i,j}$ between ions i and j approximately as a power law $J_{i,j} \sim J/d_{i,j}^{\alpha}$, where α can be tuned between $0 < \alpha < 3$ [11]. Both ferromagnetic ($J_{i,j} < 0$) and anti-ferromagnetic ($J_{i,j} > 0$) interactions can be implemented. We have benchmarked the engineered Ising interactions by comparing measurements of interaction-induced spin-precession with the predictions of mean-field theory [11]. We will discuss the prospects for simulating the transverse Ising model with hundreds of qubits.

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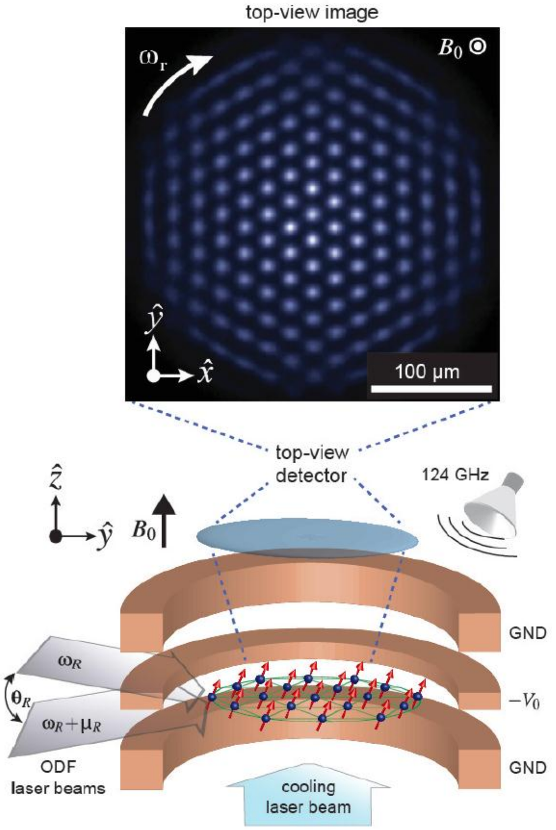

Fig. 1. Bottom: Simple sketch of the NIST Penning trap. Be$^+$ ions form a single plane triangular array. An effective spin is isolated in each ion and controlled with 124 GHz microwaves. Off-resonant laser beams generate a spin-dependent optical dipole force. The ions are detected by the cooling-laser-induced resonance fluorescence. Top: A resonance fluorescence image showing the center region of an ion crystal captured in the ions' rest frame; in the laboratory frame, the ions rotate at $\omega_r = 2\pi \times 43.8$ kHz. The spacing between ions is ~20 μm.

5. References

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