Quantum simulation of a Fermi–Hubbard model using a semiconductor quantum dot array

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Introduction

• Fermi-Hubbard model is a key concept in condensed matter physics and provides crucial insights into electronic and magnetic properties of materials.

• Quantum Simulations:
  • Potential to realize novel electronic and magnetic properties of low-dimensional condensed matter
  • Digital Simulations:
    • Require a large numbers of highly controlled quantum bits
    • Additional error-correction overhead
  • Analog Simulations:
    • Limited by the residual entropy of the initialized system

• Quantum Dots:
  • An array can be naturally described by a Fermi–Hubbard model in the low temperature, strong-interaction regime
  • Pure state initialization of highly entangled states is possible without the use of adiabatic initialization
Fermi-Hubbard model

- two species of fermionic particles (spin up, spin down)
  - confined in a lattice
  - move by hopping to neighbours
- extended model, which includes inter-site interaction

\[
H = - \sum_i \epsilon_i n_i - \sum_{\langle i,j \rangle, \sigma} t_{ij} (c_{i\sigma}^+ c_{j\sigma} + \text{h.c.}) + \sum_i \frac{U_i}{2} n_i (n_i - 1) + \sum_{i,j} V_{ij} n_i n_j
\]

- chemical potential
- tunneling
- on-site interactions
- inter-site interactions
Semiconductor QD-array

- Coupled semiconducting QD’s act according to the Fermi-Hubbard model naturally at low temperatures
- highly entangled states without adiabatic initialization
- coherent evolution of excitations spans many sites
Semiconductor QD-array: sample

- GaAs/AlGaAs heterostructure
  - creates 2-DEG
  - triple quantum dot device (dashed circles)
  - dashed circle (arrow): sensing channel, real-time charge sensing using radio-frequency reflectance
  - reservoirs (crossed square)
Semiconductor QD-array: sample

- electrostatically defined using voltages applied to gates
  - selectively depletes regions from the 2-DEG
  - 7 gates (barrier and plunger gates)
  - gates control set up Fermi-Hubbard model, using a toolbox, independent calibration of \{\mu', \delta\epsilon_i, t_{ij}\} and measurement of \{V_{ij}, U_i\}
Semiconductor QD-array: sample

- measurable observables, sample @ 45 mK
  - local charge occupation
  - global charge transport
  - degrees of freedom of the spin
  - nearest-neighbour singlet-triplet spin correlations
Sensing

• Using a SQD instead of QPC
• can also be operated as QPC
• usually operated at rf and not dc
• compare reflected amplitude with transmitted/sent amplitude
• advantages over QPCs
  • 30 times more sensitive
  • 3 times signal-to-noise ratio
Toolbox

Goals:

• Independent control of the Fermi–Hubbard parameters $\{\mu', \delta\varepsilon_i, t_{ij}\}$ to within several $k_B T$ and over a wide range of fillings and tunnel couplings.
  
=>Need according gate voltages $P_i, B_{ij}$

• Measurements

Nonidealities:

• Cross Talk

• Finite size of the array and inhomogeneity in interaction terms:

$$U_i + \sum_{i \neq j} V_{ij}$$

=>non-homogeneous filling

• When multiple electrons in array:
  
  • Higher wavefunction overlap of higher electron fillings have an effect on the tunnel couplings
Toolbox: Methods

• Linear combinations of gate voltages:

\[
\delta \begin{pmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \end{pmatrix} = \begin{pmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} \\ \alpha_{21} & \alpha_{22} & \alpha_{23} \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} \begin{pmatrix} P_1 \\ P_2 \\ B_{1L} \\ B_{12} \\ B_{23} \end{pmatrix}^T.
\]

• \( \alpha_{ii} \): Coupling of \( P_i \) to the energy offset \( \epsilon_i \)
• \( \alpha_{ij} \): Cross Terms
• All elements known \( \rightarrow \) Can deterministically control the on-site energies \( \epsilon_i \)

• Matrix has been measured multiple times for different fillings and tunnel couplings
• In between these points: Linear interpolation

• Simplify the tuning process: Virtual Gates
  • Virtual barrier gates: Change specific tunnel couplings without changing the energy offsets \( \epsilon_i \) of any of the dots
  • Virtual \( \delta \epsilon_i \) gate: Changing \( \delta \epsilon_i \) without changing the tunnel couplings

\[ \delta B_{12} \rightarrow \delta B'_{12} = \delta(P_1, P_2, P_3, B_{12}) \]
Toolbox: Verification
Toolbox: Measurements
Measurements

• use toolbox to emulate Fermi-Hubbard physics
• realization of coulomb blockade physics (Mott insulator)
• only tunneling, degeneration lifts \( \rightarrow \) minibands
Results

Minibands widen at expense of collective gap.

Agreement between measurements and numerical calculation
Conclusion

• accurate calibration and characterization of QD parameters
• large energy scales compared to temperature
  • strong quantum correlations
• larger QD-arrays require automation of used methods
• realize many-body physics
• possible extension to multiple dimensions