A quantum materials simulator based on Coulomb-confined quantum dots

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One of the significant promises of quantum technology is the ability to simulate complex materials for applications such as novel electronics and improved electrodes for batteries. Analogue quantum simulators based on semiconductor quantum dots have already started to investigate these types of problems with the realisation of one-dimensional correlated phases [1-3], ferromagnetism [4], and resonating valence bond states [5]. However, all these quantum simulators have been well within the reach of classical simulation techniques due to the small number of sites and particles. Here, we show that atomically precise Coulomb-confined quantum dots allow for the controllable simulation of two-dimensional quantum materials. As illustrated in figure 1, we use the sub-nanometre precision of these quantum simulators to simulate a metal-to-insulator transition (MIT) of interacting electrons on a square extended Fermi-Hubbard lattice of 15,000 sites -- well beyond the limit of classical simulations. The collective behaviour of the lattice is measured using temperature dependent transport measurements where we see the opening of an energy gap driven by electron-electron interactions (a Mott insulator). These analogue devices provide a promising route for quantum simulation of interacting electrons on arbitrary two-dimensional lattices such as quantum spin liquids, topological quantum matter, and unconventional superconductivity.

References

[1] T. Hensgens, T. Fujita, L. Janssen, et al., Nature, 548 (2017)
[2] C. J. van Diepen, T.-K. Hsiao, U. Mukhopadhyay, et al., Phys. Rev. X, 4, 041025 (2021)
[3] M. Kiczynski, S. K. Gorman, H. Geng, et al., Nature, 606 (2022)
[4] J. P. Dehollain, U. Mukhopadhyzy, V. P. Michal, et al., Nature, 579 (2020)
[5] C.-A. Wang, C. Déprez, H. Tidjani, et al., npj Quantum Information, 9, 58 (2023)

Figures

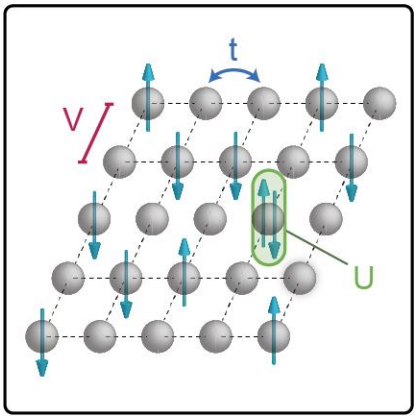

Figure 1: Schematic of the extended Fermi-Hubbard model on a 2D square lattice. The sites (grey) hold up to 2 electrons (blue arrows) with electron hopping terms t, and on-site (inter-site) electron-electron interaction U (V).