Journal of Engineering for
THERMAL ENERGY
AND POWER

ISSN: 1001-2060
Vol. 27 No. 2, 2024

# STRONGLY CORRELATED ELECTRON SYSTEMS: MOTT INSULATORS AND EMERGENT QUANTUM PHASES

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## Abstract

**Received**: 26/07/2024

**Revised:** 19/08/2024

**Accepted**: 26/09/2024

**DOI:** 10.12060/jet-ep-v27.i2-2

**Funding:**
This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Strongly correlated electron systems represent a central challenge in condensed matter physics, where electron–electron interactions dominate over kinetic energy and give rise to unconventional electronic, magnetic, and superconducting states. Unlike conventional metals and band insulators, these systems cannot be described adequately by single-particle theories. This paper reviews the fundamental concepts of strong electronic correlations, focusing on Mott insulators, Hubbard-type models, emergent quantum phases, and experimental realizations. The implications of correlated systems for modern materials engineering and future technologies are also discussed.

**Keywords:** Strongly Correlated Electrons, Mott Insulators, Hubbard Model, Quantum Phases, Condensed Matter Physics.

## 1. INTRODUCTION

In conventional solids, electrons can often be treated as weakly interacting quasiparticles described by band theory. However, in many materials—such as transition metal oxides, heavy fermion compounds, and high-temperature superconductors—electron–electron interactions play a dominant role. These systems are collectively referred to as strongly correlated electron systems (Imada et al., 1998).

Strong correlations lead to a wide range of exotic phenomena, including Mott insulating behavior, unconventional superconductivity, colossal magnetoresistance, and quantum spin liquids. Understanding these effects remains one of the most active areas of condensed matter research.

## 2. MOTT INSULATORS: BEYOND BAND THEORY

### 2.1. Failure of Conventional Band Theory

According to band theory, materials with partially filled bands should be metallic. However, Mott insulators defy this prediction and remain insulating due to strong Coulomb repulsion between electrons. This repulsion localizes electrons and prevents charge transport, even when band theory predicts metallicity.

### 2.2. Mott Transition

The Mott metal–insulator transition occurs when the ratio of on-site Coulomb interaction (U) to electronic bandwidth (W) exceeds a critical value. This transition can be driven by changes in pressure, chemical doping, or temperature.

## 3. THEORETICAL MODELS FOR STRONG CORRELATIONS

### 3.1. Hubbard Model

The Hubbard model is the simplest theoretical framework capturing the competition between kinetic energy and electron–electron interactions:

H=−t∑⟨i,j⟩,σ(ciσ†cjσ)+U∑ini↑ni↓H = -t \sum_{\langle i,j \rangle, \sigma} (c^\dagger_{i\sigma} c_{j\sigma}) + U \sum_i n_{i\uparrow} n_{i\downarrow}H=−t⟨i,j⟩,σ∑(ciσ†cjσ)+Ui∑ni↑ni↓

Here, *t* represents electron hopping, while *U* denotes on-site Coulomb repulsion.

### 3.2. t–J and Anderson Models

Extensions of the Hubbard model, such as the t–J model and Anderson lattice model, are used to study doped Mott insulators and heavy fermion behavior.

## 4. EMERGENT QUANTUM PHASES

### 4.1. Antiferromagnetism and Spin Liquids

At half-filling, Mott insulators often exhibit antiferromagnetic order. In geometrically frustrated lattices, long-range order may be suppressed, giving rise to quantum spin liquid states characterized by long-range entanglement.

### 4.2. Unconventional Superconductivity

Doping Mott insulators can lead to unconventional superconductivity, as observed in cuprate and iron-based superconductors. Pairing mechanisms in these materials differ fundamentally from conventional BCS theory.

## 5. EXPERIMENTAL REALIZATIONS

### 5.1. Transition Metal Oxides

Materials such as $V_2O_3$, NiO, and cuprates exhibit classic Mott insulating behavior. Experimental techniques like angle-resolved photoemission spectroscopy (ARPES) reveal correlation-induced band renormalization.

### 5.2. Ultracold Atoms in Optical Lattices

Ultracold atoms trapped in optical lattices provide highly controllable platforms for simulating Hubbard-type models, enabling direct observation of Mott transitions and correlated phases.

## 6. TRANSPORT AND SPECTROSCOPIC PROPERTIES

Strong correlations lead to anomalous transport behavior, including non-Fermi liquid resistivity and spectral weight transfer. Optical conductivity and neutron scattering experiments provide insights into correlation-driven dynamics.

## 7. ENGINEERING AND TECHNOLOGICAL IMPLICATIONS

### 7.1. Correlated Oxide Electronics

Strongly correlated oxides offer tunable electronic phases, enabling applications such as Mott transistors and neuromorphic computing devices.

### 7.2. Quantum Materials Design

Understanding strong correlations aids the rational design of quantum materials with tailored electronic and magnetic properties.

## 8. CHALLENGES AND OPEN QUESTIONS

Despite decades of research, many open questions remain, including the microscopic mechanism of high-temperature superconductivity and the nature of quantum spin liquids. Advanced computational techniques and machine learning are increasingly used to tackle these problems.

## 9. FUTURE DIRECTIONS

Future research aims to explore nonequilibrium correlated systems, topological correlated phases, and artificial heterostructures where correlation effects can be engineered.

## 10. CONCLUSION

Strongly correlated electron systems reveal the limitations of conventional band theory and showcase the richness of collective quantum behavior. Continued exploration of Mott insulators and emergent phases promises breakthroughs in both fundamental physics and next-generation electronic technologies.

## REFERENCES

1. Anderson, P. W. (1987). The resonating valence bond state in $La_2CuO_4$ and superconductivity. Science, 235(4793), 1196–1198.
2. Dagotto, E. (1994). Correlated electrons in high-temperature superconductors. Reviews of Modern Physics, 66(3), 763–840.
3. Georges, A., Kotliar, G., Krauth, W., & Rozenberg, M. J. (1996). Dynamical mean-field

theory of strongly correlated fermion systems. Reviews of Modern Physics, 68(1), 13–125.

4. Imada, M., Fujimori, A., & Tokura, Y. (1998). Metal-insulator transitions. Reviews of Modern Physics, 70(4), 1039–1263.
5. Lee, P. A., Nagaosa, N., & Wen, X.-G. (2006). Doping a Mott insulator: Physics of high-temperature superconductivity. Reviews of Modern Physics, 78(1), 17–85.
6. Mott, N. F. (1949). The basis of the electron theory of metals, with special reference to the transition metals. Proceedings of the Physical Society, 62(7), 416–422.
7. Sachdev, S. (2008). Quantum magnetism and criticality. Nature Physics, 4(3), 173–185.
8. Tokura, Y., Kawasaki, M., & Nagaosa, N. (2017). Emergent functions of quantum materials. Nature Physics, 13(11), 1056–1068.