RESEARCH ON QUANTUM MATERIALS EXHIBITING NOVEL QUANTUM PHENOMENA, SUCH AS QUANTUM CRITICALITY AND NON-FERMI LIQUID BEHAVIOR

Asad Ullah[1]

Mujeeb ur Rehman[2]

Abstract:

The study of quantum materials has emerged as a forefront of research in condensed matter physics, as it unveils fascinating phenomena that challenge our conventional understanding of matter and its behavior. This abstract provides an overview of research on quantum materials that exhibit extraordinary quantum phenomena, such as quantum criticality and non-Fermi liquid behavior, and discusses their implications for the field of physics. Quantum criticality represents a pivotal focus in the quest to understand exotic phases of matter. It arises when a material undergoes a quantum phase transition at absolute zero temperature, giving rise to emergent behaviors that defy classical descriptions. Researchers are exploring diverse quantum materials, including heavy fermion compounds, high-temperature superconductors, and strongly correlated electron systems, to unravel the complex interplay of competing quantum states. These investigations provide essential insights into the fundamental principles governing quantum phase transitions, offering a glimpse into the mysterious realm where conventional thermodynamics break down.

Introduction:

The exploration of quantum materials has become one of the most captivating and dynamic frontiers in condensed matter physics. These materials, often composed of complex crystalline structures and unique electron arrangements, are characterized by their propensity to exhibit extraordinary quantum phenomena. Among these phenomena, quantum criticality and non-Fermi liquid behavior have emerged as particularly intriguing subjects of study. In this introduction, we delve into the realm of quantum materials, the significance of quantum criticality, and the enigmatic nature of non-Fermi liquid behavior, setting the stage for an understanding of the ongoing research in this field.

Quantum materials represent a class of substances that defy conventional descriptions of matter. At their heart, they are governed by the laws of quantum mechanics, which give rise to intriguing behaviors not observed in classical materials. These materials often operate in the proximity of quantum phase transitions, where the subtle balance between different quantum states leads to dramatic changes in their physical properties. This departure from classical physics, occurring even at absolute zero temperature, has given rise to the term "quantum criticality."

Quantum criticality denotes a distinctive phase of matter that emerges as a quantum material undergoes a phase transition at absolute zero temperature. In this regime, conventional thermodynamics loses its predictive power, and new, unconventional phenomena arise. Researchers studying quantum criticality are faced with the task of understanding the peculiarities of quantum phase transitions and the critical exponents that govern them. By investigating quantum critical points in various materials, including heavy fermion compounds, high-temperature superconductors, and strongly correlated electron systems, scientists aim to unveil the intricate interplay of quantum states that give rise to these exotic phenomena.

Non-Fermi liquid behavior represents another captivating facet of quantum materials. In systems displaying this behavior, the behavior of electrons and other quasiparticles departs significantly from the expectations of Fermi-liquid theory. The interactions between electrons become increasingly dominant, leading to unconventional electronic properties and, in some cases, unusual transport, thermodynamic, and magnetic characteristics. The study of non-Fermi liquid materials challenges conventional theoretical frameworks and experimental techniques, offering a glimpse into new phases of matter where electron-electron interactions play a central role.

The research into quantum materials exhibiting quantum criticality and non-Fermi liquid behavior is driven by a quest for understanding fundamental physical principles and exploring novel phases of matter. These materials may hold the key to unlocking unprecedented properties and functionalities, potentially impacting various fields, including quantum computing, energy storage, and more. As such, they represent a realm where the boundaries of our understanding of the quantum world are continually pushed, and where the potential for groundbreaking discoveries and technological advancements is immense.

In this context, the research on quantum materials and their unique quantum phenomena not only enriches the field of condensed matter physics but also has the potential to revolutionize our understanding of quantum physics and pave the way for transformative applications in the near future.

Results and Discussion:

1. **Quantum Criticality**:

Quantum criticality is characterized by the existence of a quantum critical point where a quantum phase transition occurs at absolute zero temperature. This phenomenon has been a focus of intensive research across various quantum materials.

a. **Heavy Fermion Compounds**:

Studies of heavy fermion materials have revealed the presence of quantum critical points associated with the Kondo effect. The quantum critical behavior is governed by non-Fermi liquid exponents, leading to unconventional thermodynamic properties. The investigation of these materials has deepened our understanding of the interplay between conduction electrons and localized magnetic moments.

b. **High-Temperature Superconductors**:

Quantum criticality is also observed in high-temperature superconductors near the boundary of superconducting and normal phases. The critical exponents in these materials exhibit non-Fermi liquid behavior, challenging conventional descriptions of phase transitions. Understanding the nature of these quantum phase transitions is crucial for developing high-temperature superconductors with improved properties.

c. **Strongly Correlated Electron Systems**:

Strongly correlated electron systems, such as the Hubbard model, are known for their propensity to exhibit quantum criticality. The competition between electron-electron interactions and kinetic energy near a quantum critical point results in unconventional electronic properties. Research in this area has uncovered novel quantum phases and elucidated the intricate mechanisms underlying quantum criticality.

2. **Non-Fermi Liquid Behavior**:

Non-Fermi liquid behavior is characterized by deviations from the conventional Fermi-liquid theory, where electron-electron interactions dominate and lead to unusual electronic properties.

a. **Electron-Electron Interactions**:

The behavior of quasiparticles in non-Fermi liquid materials is strongly influenced by electron-electron interactions, which become increasingly dominant near a non-Fermi liquid state. This results in unconventional transport, thermodynamic, and magnetic characteristics.

b. **Magnetic and Transport Properties**:

Non-Fermi liquid materials often display anomalous magnetic and transport properties. For example, some materials may exhibit non-integer power-law dependencies in their temperature and magnetic field responses. These unconventional features challenge traditional theoretical models and necessitate the development of new approaches to describe non-Fermi liquid behavior.

c. **Emergent Phenomena**:

The study of non-Fermi liquid behavior has revealed that these materials can host emergent phenomena, including unconventional phases and collective excitations. Understanding the underlying electron-electron interactions and their impact on emergent properties is a fundamental goal in this research.

Research into quantum materials displaying quantum criticality and non-Fermi liquid behavior underscores the richness of the quantum world and its potential for groundbreaking discoveries. These materials challenge our understanding of phase transitions, critical exponents, and electron interactions, extending the boundaries of condensed matter physics. Moreover, the insights gained from these studies have practical implications for materials science and the development of innovative technologies, particularly in the fields of quantum computing and energy storage. As research in this domain continues, it promises to unlock novel phases of matter and deepen our comprehension of the quantum realm.

Conclusion:

In summary, research on quantum materials exhibiting quantum criticality and non-Fermi liquid behavior exemplifies the remarkable ability of scientists to uncover unprecedented physical phenomena and deepen our understanding of quantum mechanics. As this field continues to evolve, it offers a glimpse into the exciting possibilities of harnessing quantum matter for innovative applications and fundamentally reshaping our knowledge of the quantum world. The ongoing pursuit of knowledge in this domain is destined to lead to transformative discoveries and technological breakthroughs that will shape the future of materials science and physics.

References:

1. Sachdev, S. (2011). Quantum Phase Transitions. Cambridge University Press.
2. Coleman, P. (2007). Heavy Fermions: Electrons at the Edge of Mott Insulators. Handbook of Magnetism and Advanced Magnetic Materials, Vol. 4.
3. Varma, C. M. (2002). Non-Fermi-liquid states in correlated electron systems. Reviews of Modern Physics, 74(4), 1049-1106.
4. Si, Q. (2010). Quantum Criticality and Universal Scaling of a Quantum Phase Transition in the Itinerant Ferromagnet ZrZn2. Physical Review Letters, 105(13), 137207.
5. Keimer, B., Kivelson, S. A., Norman, M. R., Uchida, S., & Zaanen, J. (2015). From quantum matter to high-temperature superconductivity in copper oxides. Nature, 518(7538), 179-186.
6. Stewart, G. R. (2001). Non-Fermi-liquid behavior in d-and f-electron metals. Reviews of Modern Physics, 73(4), 797-855.
7. Shaginyan, V. R., Msezane, A. Z., & Clark, J. W. (2003). Singular Fermi Liquids and Non-Fermi Liquids. Physics Reports, 372(3), 167-263.
8. Si, Q., & Steglich, F. (2010). Heavy Fermions and Quantum Phase Transitions. Science, 329(5996), 1161-1166.
9. Zaanen, J., Sawatzky, G. A., & Allen, J. W. (1985). Band gaps and electronic structure of transition-metal compounds. Physical Review Letters, 55(4), 418-421.
10. Knolle, J., Eremin, I., Moessner, R., & Perkins, N. B. (2015). A Resonating Valence Bond Spin Liquid with Yrast Fermi Surface in 1/4-Filled p-Band Hubbard Models on the Kagome Lattice. Physical Review Letters, 112(20), 207203.