International Advance Journal of Engineering, Science and Management (IAJESM)
ISSN -2393-8048, July-December 2021, Submitted in October 2021, iajesm2014@gmail.com

Review on Role of Magnetism and Crystal Structure in Superconductivity

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ABSTRACT

Superconductivity, the phenomenon of zero electrical resistance, has attracted significant scientific interest since its discovery. In recent years, researchers have increasingly recognized the crucial role of magnetism and crystal structure in influencing the emergence and properties of superconductivity. This paper aims to provide a comprehensive review of the intricate interplay between magnetism, crystal structure, and superconductivity. We discuss the fundamental principles underlying superconductivity, explore the impact of magnetism on superconducting behavior, and elucidate the influence of crystal structure on the manifestation and enhancement of superconducting properties.

Keywords: superconductivity, magnetism, crystal structure, Meissner effect, BCS theory, magnetic impurities.

INTRODUCTION

1.1 Background and Significance

Superconductivity is a fascinating phenomenon in which certain materials can conduct electric current with zero resistance when cooled below a critical temperature. This discovery, made over a century ago, has revolutionized various fields, including electronics, energy transmission, and medical imaging. Understanding the underlying mechanisms of superconductivity is crucial for further advancements in these areas.

Magnetism and crystal structure have been found to play pivotal roles in influencing the emergence and properties of superconductivity. The interaction between magnetism and superconductivity has been of particular interest due to their intertwined nature. The presence of magnetic impurities or the effects of magnetic fields can significantly impact the behavior of superconducting materials. Additionally, the crystal structure of a material, including its lattice arrangement and atomic positioning, can have profound effects on the manifestation and enhancement of superconducting properties.

Objective of the Review:

The objective of this review is to provide a comprehensive understanding of the role of magnetism and crystal structure in superconductivity. By analyzing existing research, experimental findings, and theoretical models, we aim to unravel the intricate interplay between these factors and their influence on superconducting behavior. This review seeks to:

1. Examine the fundamental principles of superconductivity, including the Meissner effect, Cooper pairs, and different types of superconductors.
2. Investigate the impact of magnetism on superconductivity, exploring phenomena such as magnetic field penetration, magnetic impurities, and unconventional superconductors.

FUNDAMENTAL PRINCIPLES OF SUPERCONDUCTIVITY

2.1 Meissner Effect and Zero Electrical Resistance

The Meissner effect is a fundamental phenomenon in superconductivity where a superconductor expels virtually all magnetic fields from its interior when cooled below its critical temperature. This expulsion of magnetic fields results in the formation of perfect diamagnetism within the superconductor, leading to the levitation of magnets above the superconducting surface. The Meissner effect demonstrates the crucial role of magnetism in superconductivity, as the expulsion of magnetic fields indicates the formation of Cooper pairs and the onset of zero electrical resistance.

The absence of electrical resistance is one of the defining characteristics of superconductors. At temperatures below the critical temperature, superconducting electrons form pairs known as Cooper pairs. These pairs arise due to the interaction between electrons and lattice vibrations (phonons) in the material. Cooper pairs are held together by an attractive force mediated by the exchange of virtual phonons, leading to the formation of a macroscopic quantum state where all Cooper pairs share the same quantum wavefunction. As a result, these paired electrons can move through the lattice without scattering off impurities or lattice vibrations, giving rise to the phenomenon of zero electrical resistance.

2.2 Cooper Pairs and BCS Theory:

The concept of Cooper pairs and their formation is central to the understanding of superconductivity. The BCS (Bardeen-Cooper-Schrieffer) theory, proposed in 1957, provides a comprehensive explanation for the behavior of Cooper pairs and the emergence of superconductivity. According to the BCS theory, the lattice vibrations, or phonons, create an attractive interaction between electrons, resulting in the formation of Cooper pairs. This attractive interaction arises from the electron-phonon interaction, which effectively lowers the energy required for electron pairing. Cooper pairs are composed of two electrons with opposite spin and momentum, forming a bosonic entity. This bosonic nature allows Cooper pairs to condense into a single quantum state, exhibiting macroscopic quantum coherence. The BCS theory also explains the energy gap phenomenon in superconductors, where the energy required to break a Cooper pair and disrupt the superconducting state is significantly higher than the thermal energy at low temperatures.

2.3 Type I and Type II Superconductors:

Superconductors can be classified into two types based on their response to magnetic fields: Type I and Type II superconductors.

Type I superconductors exhibit a complete Meissner effect, meaning they expel all magnetic fields below their critical temperature. They have a single critical magnetic field (Hc) above which they undergo a sudden transition to a normal conducting state. Type I superconductors are characterized by a sharp superconducting-to-normal transition, and their critical magnetic field is typically low. They are often elemental superconductors, such as lead (Pb) and tin (Sn).

Type II superconductors, on the other hand, display a mixed state in the presence of magnetic fields. They can tolerate a certain amount of magnetic field penetration while still maintaining superconductivity. Type II superconductors have two critical magnetic fields: an upper critical field (Hc2) and a lower critical field (Hc1). Below Hc1, the superconductor behaves as a Type I superconductor with complete Meissner effect. However, above Hc1 and below Hc2, the magnetic field penetrates the superconductor in the form of quantized vortices, with superconductivity persisting in the regions between these vortices. Type II superconductors are commonly found in various compounds and materials, including high-temperature superconductors and certain metal alloys.

MAGNETISM AND SUPERCONDUCTIVITY

3.1 Magnetic Field Penetration and Flux Quantization

In Type II superconductors, magnetic fields can partially penetrate the material in the form of quantized magnetic flux lines or vortices. These vortices carry discrete units of magnetic flux and are surrounded by circulating supercurrents. The penetration of vortices is due to the energy minimization between the applied magnetic field and the supercurrents flowing around the vortices.

Flux quantization is another important phenomenon observed in superconductors. It states that the magnetic flux passing through a closed loop in a superconducting material is quantized, meaning it can only take discrete values. This quantization is a consequence of the macroscopic quantum coherence of Cooper pairs and their ability to carry an integer number of magnetic flux quanta, given by the flux quantum $\Phi 0 = h/2e$ (where h is Planck's constant and e is the elementary charge).

3.2 Influence of Magnetic Impurities on Superconductivity:

The presence of magnetic impurities in a superconducting material can significantly affect its superconducting properties. Magnetic impurities create local magnetic moments that can disrupt the formation and motion of Cooper pairs, leading to the suppression or destruction of superconductivity. These moments can act as scattering centers, causing electron scattering and impeding the coherence of Cooper pairs. As a result, the critical temperature and the magnitude of the superconducting energy gap can be reduced. The influence of magnetic impurities on superconductivity can be understood within the framework of the Abrikosov-

Gor'kov theory. This theory considers the scattering of Cooper pairs by magnetic impurities and provides insights into the behavior of the superconducting state in the presence of impurities.

3.3 Magnetic Frustration and Pairing Mechanisms:

In certain materials, magnetic frustration can play a role in the pairing mechanism for superconductivity. Magnetic frustration arises when competing magnetic interactions prevent the formation of a unique, low-energy ground state. This frustration can give rise to exotic magnetic states, such as spin liquids or spin glasses, which can be conducive to unconventional superconductivity. The interplay between magnetic frustration and superconductivity is a subject of active research. The frustration of magnetic interactions can induce unconventional pairing mechanisms, where the symmetry of the superconducting order parameter differs from conventional s-wave pairing. Examples include d-wave and p-wave pairings, which have unique symmetries in momentum space and can be realized in certain strongly correlated electron systems.

CRYSTAL STRUCTURE AND SUPERCONDUCTIVITY

4.1 Structural Phase Transitions and Superconducting Properties

The crystal structure of a material can undergo structural phase transitions, where there is a change in the arrangement of atoms or unit cells. These phase transitions can have a profound impact on the superconducting properties of the material. Changes in the crystal structure can modify the electronic band structure, alter the phonon spectrum, and affect the electron-phonon coupling, all of which can influence the superconducting behavior. Structural phase transitions can lead to changes in the symmetry of the crystal lattice, resulting in modifications to the pairing mechanism and the symmetry of the superconducting order parameter. Examples of structural phase transitions that have been found to impact superconductivity include pressure-induced transitions, charge-density wave transitions, and transitions driven by chemical substitutions.

Understanding the interplay between structural phase transitions and superconductivity is crucial for designing and optimizing superconducting materials with desired properties.

4.2 Lattice Mismatch and Strain Effects:

Lattice mismatch refers to the difference in lattice parameters between different materials or crystal structures. When a superconducting material is grown on a substrate with a different lattice constant, lattice mismatch can occur, leading to strain in the material. Lattice mismatch and strain can have a significant influence on the superconducting properties of the material. Strain affects the electronic structure, phonon properties, and lattice vibrations, thereby influencing the superconducting transition temperature (Tc) and other superconducting characteristics. In some cases, strain can enhance Tc by optimizing the electron-phonon coupling or modifying the density of states near the Fermi level. Conversely, strain can also suppress superconductivity by introducing defects, disrupting the crystal structure, or altering the electronic band structure. Understanding the effects of lattice mismatch and strain on superconductivity is essential for developing strategies to control and enhance superconducting properties in heterostructures and thin films.

4.3 Layered Structures and Interlayer Coupling:

Many superconducting materials exhibit layered crystal structures, where the material consists of stacked layers held together by weak interlayer interactions. In such materials, the interlayer coupling can play a crucial role in determining the superconducting properties.

Interlayer coupling influences the electronic band structure, the density of states, and the strength of the superconducting pairing interactions. It can lead to the emergence of two-dimensional superconductivity within the layers and affect the superconducting coherence length perpendicular to the layers. The interplay between interlayer coupling and the intralayer superconductivity can result in unique phenomena, such as anisotropic superconducting properties, layered vortex structures, and enhanced critical currents.

4.4 Interface Effects and Proximity-induced Superconductivity:

Interfaces between different materials or layers can give rise to novel superconducting phenomena through proximity-induced superconductivity. When a superconductor is in close contact with another material, the superconducting correlations can extend into the neighboring material, leading to the formation of superconducting states even in non-superconducting materials.

Interface effects can modify the electronic band structure, induce superconductivity in materials with a low carrier density, or generate unconventional pairing states. The proximity-induced superconductivity has been observed in various heterostructures, including superconductor/ferromagnet interfaces, superconductor/topological insulator interfaces, and superconductor/semiconductor interfaces. Understanding the interface effects and proximity-induced superconductivity is essential for developing hybrid systems with tailored functionalities and exploring new avenues for superconducting devices.

EXPERIMENTAL TECHNIQUES AND OBSERVATIONS

5.1 Neutron Scattering and X-ray Diffraction

Neutron scattering and X-ray diffraction are powerful experimental techniques used to investigate the structural and magnetic properties of materials, including superconductors.

Neutron scattering involves bombarding a material with a beam of neutrons and analyzing the scattered neutrons to obtain information about the arrangement of atoms and their magnetic interactions. Neutron scattering can provide insights into the crystal structure, magnetic ordering, and excitations in superconducting materials. By studying the scattering patterns, researchers can determine the positions of atoms, investigate the magnetic correlations and fluctuations, and understand the interplay between magnetism and superconductivity.

X-ray diffraction, on the other hand, utilizes X-rays to study the crystal structure of materials. When X-rays interact with the crystal lattice, they undergo constructive interference, resulting in a diffraction pattern that can be analyzed to determine the arrangement of atoms. X-ray diffraction is particularly useful for studying the long-range order and symmetry of superconducting materials. It can provide information about the crystal structure, lattice parameters, and phase transitions, shedding light on the structural factors that influence superconductivity.

5.2 Magnetometry and Magnetic Resonance Imaging:

Magnetometry techniques and magnetic resonance imaging (MRI) are essential tools for studying the magnetic properties and behavior of superconducting materials.

Magnetometry involves the measurement of magnetic fields and their effects on superconducting samples. One widely used technique is the Superconducting Quantum Interference Device (SQUID) magnetometry, which allows for highly sensitive measurements of magnetization, magnetic susceptibility, and critical magnetic fields. Magnetometry techniques provide valuable information about the response of superconductors to magnetic fields, critical temperatures, and critical currents. They can also be used to study the behavior of vortices in type II superconductors and investigate the effects of magnetic impurities on superconductivity.

MRI, a widely used technique in medical imaging, can also be adapted to study superconducting materials. MRI enables the spatially resolved mapping of magnetic field distributions, critical currents, and flux pinning in superconductors. This imaging capability is crucial for understanding the behavior of superconducting devices, optimizing their performance, and studying the dynamics of magnetic vortices.

5.3 Scanning Tunneling Microscopy

Scanning Tunneling Microscopy (STM) and Scanning Tunneling Spectroscopy (STS) are powerful techniques for investigating the local electronic properties and atomic-scale structures of superconducting materials.

STM allows for the imaging of material surfaces with atomic resolution by scanning a sharp tip over the sample surface. It can reveal the surface morphology, atomic structure, and defects in superconducting materials. STM can also be used to manipulate individual atoms or molecules on the surface, providing insights into the effects of local defects on superconductivity.

STS, on the other hand, measures the local density of states (LDOS) by monitoring the tunneling current between the STM tip and the sample. STS provides valuable information about the energy-momentum relationship of electrons in superconducting materials. It can reveal the presence of superconducting energy gaps, coherence peaks associated with Andreev reflection, and spatial variations in the LDOS. STS can also be used to investigate the effects of external parameters such as temperature and magnetic fields on the electronic structure.

THEORETICAL MODELS AND COMPUTATIONAL APPROACHES

6.1 Mean Field Theory and Ginzburg-Landau Theory:

Mean Field Theory (MFT) and Ginzburg-Landau Theory (GLT) are theoretical frameworks commonly used to describe the macroscopic behavior of superconducting systems.

MFT provides a simplified description of superconductivity by assuming that the interactions between electrons can be averaged out, and the behavior of the system can be described by a self-consistent mean field. Within MFT, the superconducting order parameter is treated as a classical field, and the thermodynamic properties of the system, such as the critical temperature and the free energy, can be obtained by minimizing the mean-field free energy functional.

GLT extends the concept of MFT by including fluctuations around the mean-field solution. It provides a phenomenological description of the superconducting transition near the critical temperature and incorporates the effects of external magnetic fields. The Ginzburg-Landau free energy functional includes terms that describe the condensation energy, the magnetic field energy, and the coupling between the superconducting order parameter and the external field.

6.2 Electronic Structure Calculations:

Electronic structure calculations, such as density functional theory (DFT) and more advanced methods, play a crucial role in understanding the electronic properties of superconducting materials.

DFT provides a powerful framework for calculating the electronic band structure, density of states, and other electronic properties of materials. It is based on solving the Schrödinger equation for the electron density using an effective potential derived from the electron-electron interaction. DFT calculations can provide insights into the Fermi surface topology, the nature of the electronic bands near the Fermi level, and the role of electron-phonon interactions in superconductivity. More advanced electronic structure methods, such as GW calculations or dynamical mean field theory (DMFT), can capture the electronic correlation effects that are crucial in strongly correlated superconductors. These methods take into account the electronic correlations beyond the mean-field level and provide a more accurate description of the electronic structure and the superconducting properties.

6.3 Strongly Correlated Systems and Quantum Spin Liquids:

Strongly correlated systems, where electron-electron interactions play a significant role, often exhibit unconventional superconductivity. Theoretical models and computational approaches are essential for understanding the complex physics of these systems. Quantum spin liquids are examples of strongly correlated systems that exhibit exotic magnetic and superconducting properties. They are characterized by the absence of magnetic long-range order, even at low temperatures, due to strong quantum fluctuations. Theoretical models, such as the Kitaev model and Heisenberg models on frustrated lattices, have been proposed to describe quantum spin liquids and their potential for hosting unconventional superconductivity. Computational techniques, such as exact diagonalization, density matrix renormalization group (DMRG), and quantum Monte Carlo methods, are used to study the properties of strongly correlated systems. These methods allow for the exploration of the phase diagrams, the calculation of correlation functions, and the investigation of the interplay between magnetism and superconductivity.

Theoretical models and computational approaches provide valuable insights into the microscopic mechanisms, the phase diagrams, and the emergent phenomena in strongly correlated superconducting systems, contributing to our understanding of unconventional superconductivity.

EMERGING MATERIALS AND FUTURE DIRECTIONS

7.1 High-Temperature Superconductors:

High-temperature superconductors (HTS) are a class of materials that exhibit superconductivity at relatively high temperatures, above the boiling point of liquid nitrogen (-196°C). These materials have the potential for practical applications due to the feasibility of cooling them with readily available and inexpensive cryogenic materials. Understanding the mechanisms behind the high-temperature superconductivity and further enhancing their critical temperatures are active areas of research. This field includes the exploration of different families of HTS materials, such as cuprates, iron-based superconductors, and other unconventional systems.

Topological superconductors are a fascinating class of materials that exhibit a combination of superconductivity and nontrivial topological properties. These materials can host Majorana fermions, which are quasiparticles that are their own antiparticles and have potential applications in quantum computing and topological quantum computation. Exploring the properties and behavior of topological superconductors, understanding their stability, and identifying new materials that exhibit these properties are ongoing research endeavors.

Magnetic skyrmions are topologically protected spin textures that can exist in certain magnetic materials. These structures have garnered significant interest due to their potential for storing and manipulating information in spintronic devices. Recent studies have shown intriguing connections between magnetic skyrmions and superconductivity. The interaction between skyrmions and superconductivity can lead to novel phenomena, such as the creation of topological superconducting states and the manipulation of skyrmions using superconducting currents. Investigating the interplay between magnetic skyrmions and superconductivity opens up new avenues for fundamental research and potential technological applications. Quantum criticality refers to the behavior of a material near its quantum phase transition, which occurs at absolute zero temperature. Quantum critical points can have a profound impact on superconductivity, leading to unconventional superconducting phases. Understanding the connection between quantum criticality and superconductivity is crucial for unraveling the underlying mechanisms of unconventional superconductivity. Researchers are actively exploring the role of quantum criticality in the emergence of novel superconducting states, such as quantum spin liquids, non-Fermi liquids, and strange metals. These studies provide insights into the interplay between magnetism, quantum fluctuations, and superconductivity, and offer opportunities for the discovery of new materials and phenomena.

The investigation of emerging materials and future directions in superconductivity is an active and rapidly evolving field. Researchers are pushing the boundaries of our understanding and exploring new frontiers in search of materials with higher critical temperatures, novel properties, and potential technological applications. The pursuit of these scientific and technological advancements holds great promise for the field of superconductivity.

CONCLUSION

8.1 Summary of Key Findings

In this review, we have examined the role of magnetism and crystal structure in superconductivity. The key findings can be summarized as follows:

The Meissner effect and zero electrical resistance are fundamental characteristics of superconductors. The Meissner effect refers to the expulsion of magnetic fields from the interior of a superconductor, leading to perfect diamagnetism. Zero electrical resistance allows for the efficient flow of electrical current without any energy loss.

Cooper pairs and the BCS theory provide a framework for understanding the microscopic mechanism of superconductivity. Cooper pairs, formed by the interaction of electrons with lattice vibrations (phonons), are responsible for the long-range coherence and zero electrical resistance in superconductors. The BCS theory describes the pairing mechanism and the formation of the superconducting energy gap.

Superconductors can be classified into Type I and Type II based on their response to magnetic fields. Type I superconductors expel all magnetic fields below a critical field, while Type II superconductors exhibit a mixed state with both superconducting and normal regions in the presence of magnetic fields. Type II superconductors can host magnetic vortices and exhibit complex magnetic behavior.

Magnetic field penetration and flux quantization are important phenomena in superconductivity. In Type II superconductors, magnetic fields can penetrate the material in the form of quantized magnetic vortices. The flux quantization condition ensures that the magnetic flux through a superconducting loop is quantized, leading to persistent currents and the Meissner effect.

The presence of magnetic impurities in superconductors can disrupt the formation of Cooper pairs and suppress superconductivity. Magnetic impurities introduce local magnetic moments that can scatter Cooper pairs and disrupt their coherence. The interplay between magnetism and superconductivity is an active area of research. Magnetic frustration and unconventional pairing mechanisms play a significant role in certain superconducting materials. In unconventional superconductors, the pairing of electrons occurs through mechanisms beyond the conventional BCS theory. Magnetic frustration, arising from competing magnetic interactions, can promote unconventional pairing states, such as spin triplet pairing, which may lead to novel superconducting properties.

8.2 Future Perspectives and Challenges

Future Perspectives:

Advancing High-Temperature Superconductivity: The quest for higher critical temperatures (Tc) in superconductors remains a significant goal. Continued research efforts aim to identify new materials or improve existing ones to achieve superconductivity at even higher temperatures, enabling practical applications at more accessible cooling conditions.

Harnessing Topological Superconductors: Topological superconductors hold great potential for quantum computing and topological quantum computation. Future research will focus on exploring and understanding the unique properties of topological superconductors, including the manipulation of Majorana fermions and the development of robust quantum information storage and processing technologies.

Expanding the Role of Magnetic Skyrmions: The interplay between magnetic skyrmions and superconductivity presents intriguing possibilities. Further investigations will explore the interaction mechanisms between these phenomena, with potential applications in novel spintronic devices and the development of new superconducting materials with enhanced functionalities.

Challenges:

Understanding Complex Materials: Superconductivity often emerges in complex materials with intricate crystal structures and strong electron-electron interactions. Unraveling the interplay between various factors, such as lattice structure, magnetic interactions, and electronic correlations, poses significant challenges in understanding the underlying mechanisms of superconductivity.

Controlling and Manipulating Superconducting Properties: Developing techniques to control and manipulate the properties of superconducting materials is essential for practical applications. Challenges include stabilizing high-temperature superconductivity, controlling the behavior of vortices, and tuning the critical parameters of superconductors to optimize their performance for specific applications.

Fabrication and Integration: The fabrication of high-quality superconducting materials and the integration of superconductors with other functional materials and devices remain technical challenges. Achieving reliable and reproducible synthesis methods, interface engineering, and device integration techniques are crucial for advancing the practical applications of superconductivity.

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