International Research Journal of Natural and Applied Sciences
ISSN: (2349-4077)
Impact Factor 7.032 Volume 12, Issue 04, April 2025
Website- www.aarf.asia, Email : editor@aarf.asia , editoraarf@gmail.com

A study on Electrodynamics of the Josephson Vortex Lattice with a Reference to High Temperature Superconductors

Dr Vikash Kumar

Department of physics,

MAGADH UNIVERSITY BODH-GAYA (Bihar)

Abstract

The discovery of high-temperature superconductors (HTS) in the late 20th century revolutionized the field of condensed matter physics. These materials exhibit superconductivity at significantly higher temperatures than conventional, low-temperature superconductors, opening up possibilities for various technological applications. However, their complex behavior, particularly in the presence of magnetic fields, continues to be a subject of intense research. Among the intriguing phenomena observed in HTS is the formation and dynamics of the Josephson vortex lattice, which plays a crucial role in their electrodynamic properties. Understanding this lattice and its interaction with the superconducting condensate is essential for unlocking the full potential of these remarkable materials. Conventional superconductivity is well-described by the Bardeen-Cooper-Schrieffer (BCS) theory, which posits the formation of Cooper pairs – bound states of electrons – mediated by lattice vibrations (phonons). These Cooper pairs condense into a macroscopic quantum state, leading to zero electrical resistance and perfect diamagnetism (Meissner effect). However, HTS, often complex copper oxides, exhibit superconductivity at temperatures far exceeding the limits predicted by conventional BCS theory with phonon-mediated pairing. The exact mechanism responsible for high-temperature superconductivity remains a topic of active investigation, with various theories involving electronic correlations, magnetic fluctuations, and other exotic pairing mechanisms.

Keywords:

Electrodynamics, Josephson, Vortex, Lattice, Temperature, Superconductors

Introduction

One of the key differences between conventional and high-temperature superconductors lies in their anisotropy and the presence of a layered structure. Many HTS materials consist of superconducting copper-oxide planes weakly coupled along the crystallographic c-axis. This layered structure leads to a highly anisotropic superconducting state, characterized by different superconducting properties parallel and perpendicular to the planes. When a magnetic field is applied to such a material, it can penetrate in the form of Abrikosov vortices – quantized flux lines carrying a quantum of magnetic flux. In a three-dimensional isotropic superconductor, these vortices form a regular Abrikosov vortex lattice. (Koshelev , 2021)

However, in the case of layered HTS, the weak coupling between the superconducting planes introduces a new type of vortex: the Josephson vortex. Imagine the superconducting planes as a stack of weakly coupled superconducting thin films separated by insulating or weakly conducting layers. When a magnetic field is applied parallel to these layers, it can penetrate into the interlayer regions, where the superconducting order parameter is suppressed. These interplanar magnetic flux lines are the Josephson vortices. They are characterized by their core residing in the insulating barrier and circulating Josephson currents flowing within the adjacent superconducting layers.

The interplay between Abrikosov vortices (intralayer vortices) and Josephson vortices (interlayer vortices) leads to the formation of a complex vortex lattice structure in HTS. The properties of this Josephson vortex lattice, including its geometry, stability, and dynamics, are significantly influenced by factors such as the applied magnetic field strength and orientation, temperature, and the degree of anisotropy of the superconducting material.

The electrodynamics of the Josephson vortex lattice are fundamentally different from that of the Abrikosov vortex lattice in conventional superconductors. Josephson vortices exhibit unique properties due to their origin in the Josephson effect, the tunneling of Cooper pairs between weakly coupled superconductors. These vortices can exhibit a different pinning behavior, dissipation mechanisms, and response to electromagnetic fields compared to Abrikosov vortices. For instance, Josephson vortices can be easily depinned and move along the interlayer regions, leading to significant energy dissipation and limiting the critical current density of the superconductor. (Morawitz, 2022)

Understanding the dynamics of the Josephson vortex lattice is crucial for optimizing the performance of HTS in various applications. The motion of these vortices under the influence of a Lorentz force (due to transport current) leads to energy dissipation and electrical resistance. Pinning centers, such as defects or impurities in the material, can trap these vortices and prevent their motion, thus enhancing the critical current density. Research efforts are focused on understanding the mechanisms of vortex pinning in HTS and developing strategies to introduce effective pinning centers.

Furthermore, the interaction between Abrikosov and Josephson vortices can lead to complex phase diagrams and novel phenomena. For example, depending on the field orientation and strength, the vortex lattice can undergo transitions between different configurations, such as a lattice of purely Abrikosov vortices, purely Josephson vortices, or a mixed state. The electromagnetic response of the superconductor is strongly influenced by these vortex lattice transitions.

The study of the electrodynamics of the Josephson vortex lattice in HTS relies on a variety of experimental techniques, including transport measurements, AC susceptibility, torque magnetometry, and various forms of microscopy such as scanning tunneling microscopy (STM) and Lorentz microscopy. These techniques provide insights into the vortex lattice structure, its dynamics, and its response to external stimuli. Theoretical models, based on extensions of the Ginzburg-Landau theory and Josephson junction arrays, are also crucial for interpreting experimental observations and predicting new phenomena. (Volkov, 2019)

Review of Literature

Steklov et al. (2020): Layered superconductors, with their unique anisotropic nature, host a fascinating interplay between two fundamental types of magnetic flux quanta: Abrikosov vortices (intralayer) and Josephson vortices (interlayer). These topological excitations, arising from the quantization of magnetic flux, exhibit distinct characteristics and behaviors, yet their coexistence and interaction give rise to a rich tapestry of electromagnetic phenomena and critical current properties. Understanding this delicate dance is crucial for unlocking the full potential of these materials in various technological applications.

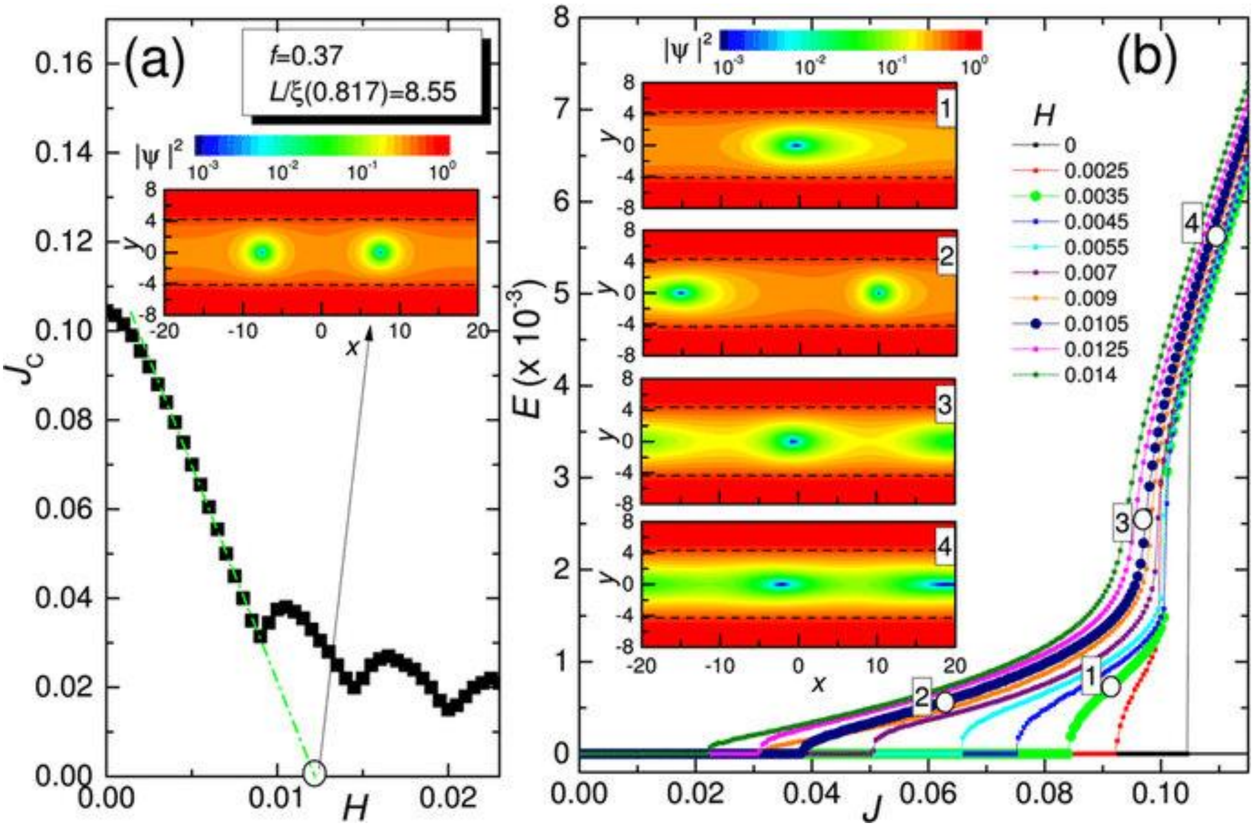
Anderson et al. (2019): Abrikosov vortices, also known as flux lines, are well-established in type-II superconductors subjected to a magnetic field. Within each superconducting layer, the magnetic field penetrates in the form of quantized flux tubes, each carrying a quantum of magnetic flux $\Phi 0=h/2e$.

Carlson et al. (2021): The superconducting order parameter is suppressed at the vortex core, creating a normal region surrounded by circulating supercurrents that screen the magnetic field. These vortices interact with each other via repulsive Lorentz forces and can be pinned by material inhomogeneities, leading to dissipationless current flow up to a critical current density.

Schmid et al. (2022): Josephson vortices, on the other hand, are unique to layered superconductors where superconducting layers are weakly coupled via thin insulating or normal metallic barriers.

Electrodynamics of the Josephson Vortex Lattice with a Reference to High Temperature Superconductors

When a magnetic field is applied parallel to the layers, or when a current flows perpendicular to the layers, magnetic flux can penetrate the Josephson junctions between the layers. These vortices reside primarily in the insulating or normal barrier, and their core represents a region where the phase difference across the junction changes by 2π. Unlike Abrikosov vortices, Josephson vortices carry magnetic flux along the layers and are associated with circulating currents within the superconducting layers adjacent to the junction.



The interplay between these two types of vortices arises from the inherent layered structure and the anisotropy it introduces. Several scenarios highlight their intricate relationship:

Firstly, perpendicular magnetic fields can induce both Abrikosov and Josephson vortices. While the primary response is the formation of Abrikosov vortices within each layer, the presence of Josephson junctions allows for a transverse modulation of the magnetic field and the superconducting order parameter across the layers. This modulation can be viewed as a stack of weakly coupled Abrikosov vortices, where the coupling strength is determined by the Josephson coupling energy. In this regime, the Josephson coupling can influence the Abrikosov vortex lattice structure, leading to phenomena like dimensional crossover and changes in the vortex dynamics.

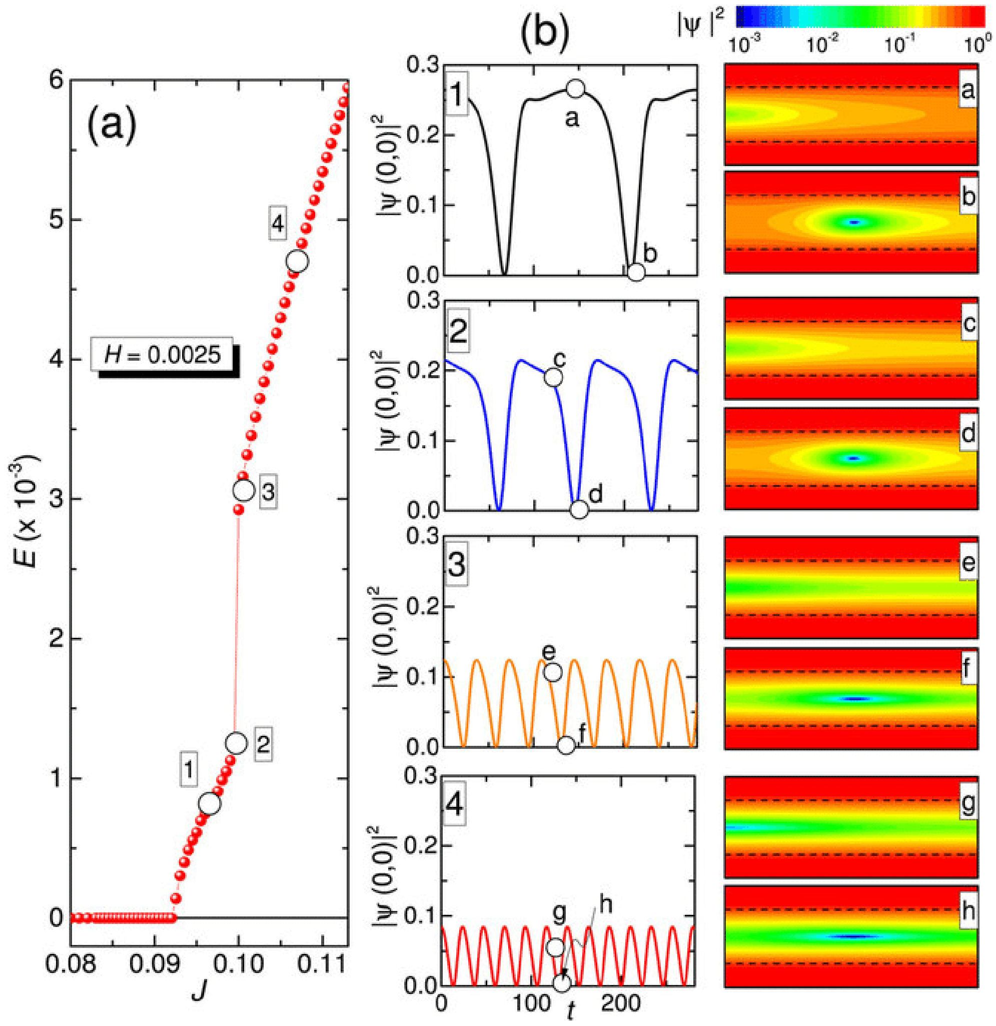
Secondly, parallel magnetic fields predominantly generate Josephson vortices residing in the interlayer regions. However, these Josephson vortices can influence the behavior of Abrikosov vortices that might be present due to a small perpendicular field component or thermal fluctuations. The circulating currents associated with Josephson vortices can exert Lorentz forces on Abrikosov vortices, affecting their motion and pinning characteristics.

Conversely, the presence of Abrikosov vortices can modify the effective Josephson coupling between layers, influencing the properties of Josephson vortices.

Thirdly, current flow can drive the motion of both types of vortices. A current flowing parallel to the layers primarily exerts a Lorentz force on Abrikosov vortices, leading to dissipation if they are not effectively pinned. However, this current can also induce a magnetic field that can generate or influence Josephson vortices. Similarly, a current flowing perpendicular to the layers directly drives the motion of Josephson vortices, and the resulting magnetic field can interact with any existing Abrikosov vortices within the layers.

The strength of the interplay between Abrikosov and Josephson vortices depends critically on the anisotropy of the layered superconductor, characterized by the ratio of the London penetration depth parallel and perpendicular to the layers ($\gamma=\lambda c/\lambda ab$). In highly anisotropic materials, the Josephson coupling is weak, and Josephson vortices are more easily formed and move relatively independently of Abrikosov vortices. Conversely, in less anisotropic materials with stronger interlayer coupling, the distinction between the two types of vortices becomes blurred, and they exhibit a more tightly coupled behavior.

The consequences of this interplay are significant for the critical current density of layered superconductors. The motion of both Abrikosov and Josephson vortices contributes to dissipation and limits the maximum current that can be carried without resistance. Understanding how these vortices interact with pinning centers and with each other is crucial for optimizing the superconducting properties. For instance, introducing artificial pinning centers can effectively trap both types of vortices, enhancing the critical current.



Furthermore, the interplay between Abrikosov and Josephson vortices gives rise to unique phenomena like the dimensional crossover in the vortex lattice structure as a function of temperature and magnetic field. At low temperatures or high fields, the Abrikosov vortices in different layers are strongly coupled, forming a three-dimensional lattice. As temperature increases or the field decreases, the interlayer coupling weakens, and the vortex system can decouple into a collection of two-dimensional Abrikosov vortices within each layer, with Josephson vortices mediating the weak interactions between them.

The interplay between Abrikosov (intralayer) and Josephson (interlayer) vortices is a fundamental aspect of the physics of layered superconductors. Their coexistence and interaction, influenced by the material's anisotropy and external conditions, dictate the electromagnetic response and critical current properties of these complex systems. Continued research into this delicate dance is essential for advancing our understanding of superconductivity and for harnessing the unique properties of layered superconductors in future technological applications, ranging from high-field magnets to novel electronic devices. The intricate choreography of these flux quanta continues to inspire and challenge physicists in their quest to unravel the mysteries of the superconducting state.

Conclusion

The Josephson vortex lattice is a fundamental aspect of the electromagnetic behavior of high-temperature superconductors, stemming from their layered structure and weak interlayer coupling. Understanding the formation, stability, and dynamics of this lattice is essential for comprehending the unique electrodynamic properties of HTS and for paving the way for their successful implementation in technological applications such as high-field magnets, energy transmission lines, and electronic devices. Continued research into the intricate interplay between Abrikosov and Josephson vortices and the development of strategies to control their behavior remain critical for unlocking the full potential of these fascinating materials. The quest to unravel the mysteries of high-temperature superconductivity and harness the power of the Josephson vortex lattice continues to drive exciting advancements in condensed matter physics and materials science.

References

1. N.N. Bogolyubov Steklov ' A New method in the theory of superconductivity' .SSSR, Moscow) Nov, 2020.

2. P. W. Anderson Random-Phase Approximation in the Theory of Superconductivity . Phys. Rev. 112, 2019.

3. R. V. Carlson and A. M. Goldman Phys. Rev. Lett. (PRL) 34, 11 (2021).

4. Albert Schmid and Gerd Schön Phys. Rev. Lett. 34, 941 – (2022)

5. S.N. Artemenko and A.F volkov, sov. Phys. JETP 42, 896 (2020)

6. S. N. Artemenko and A. F. Volkov, Sov.Phys USP 22,295(2019)

7. V. Kresin and H. Morawitz, Phys. Rev. B 37, 7854 (2021).

8. V. Kresin and H. Morawitz, Phys. C 153-155, 1327 (2022).

9. A. E. Koshelev Phys. Rev. B 76, 054525 – (2021)

10. Josephson vortex ... Matthew J. W. Dodgson arXiv:1304.6735 v1 [cond-mat.supr-con] 24 Apr 2021.