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Article Review: Anomalous Meissner Effect in Multiband Superconductors

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Abstract:

As a material transitions below its critical temperature, a defining characteristic of superconductivity is the Meissner effect, which is the removal of magnetic fields from the material. Within the Ginzburg-Landau and BCS models, this effect is thoroughly comprehended in traditional (single-band) superconductors. . In multiband superconductors like MgB_2 and iron-based superconductors, exceptions to this usual pattern of action have been found. Clustering of anomalous vortices, mixed-phase vortex states, paramagnetic. Meissner responses are all examples of such phenomena. Type-1.5 superconductivity, giant paramagnetic Meissner responses, and implications for advanced superconducting applications are the main topics of this paper's review of recent experimental and theoretical results on the anomalous Meissner effect in multiband superconductors.

Keywords*:* Meissner effect, superconductors, Multiband Superconductivity.

مقالة علمية: تأثير مايسنر الشاذ في الموصلات الفائقة متعددة النطاقات

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الخلاصة:

عندما تنخفض درجة حرارة المادة عن درجة حرارتها الحرجة تتحول الى مادة موصلة فائقة ، تُعدّ ظاهرة مايسنر، التي تتمثل في إزالة المجالات المغناطيسية من المادة، سمةً مميزةً للموصلية الفائقة. ضمن نموذجي جينزبورغ-لانداو وBCS، تُفهم هذه الظاهرة فهمًا دقيقًا في الموصلات الفائقة التقليدية (أحادية النطاق). وقد رُصدت اضطرابات في هذا النمط السلوكي القياسي في الموصلات الفائقة متعددة النطاقات مثل MgB_2 والموصلات الفائقة القائمة على الحديد. وتُعدّ تجمعات الدوامات الشاذة، وحالات الدوامات ذات الطور المختلط، واستجابات مايسنر البارا مغناطيسية أمثلةً على هذه الظواهر. وتُشكّل الموصلية الفائقة من النوع ١,٥، واستجابات مايسنر البارا مغناطيسية العملاقة، وتداعياتها على تطبيقات الموصلات الفائقة المتقدمة، المواضيع الرئيسية التي تتناولها هذه الورقة البحثية في استعراضها للنتائج التجريبية والنظرية الحديثة حول ظاهرة مايسنر الشاذة في الموصلات الفائقة متعددة النطاقات.

الكلمات المفتاحية: تأثير مايسنر، الموصلات الفائقة، الموصلية الفائقة متعددة النطاقات.

1. Introduction:

The discovery of a material with zero electrical resistance was made possible by Heike Kamerlingh Onnes's groundbreaking 1911 explanation of superconductivity. The finding of superconductivity was an unforeseen byproduct of the experiment's primary objective, which was to liquefy helium—the final noble gas. Investigations exploring the relationship between temperature and resistivity [1]. At that time, various assumptions and speculations concerning metals' behavior at cold temperatures, ranging from constant declines to anomalous increases, that necessitate testing. At temperatures lower than 4.2 K, or -268°C, liquid mercury showed almost no resistance. The 1913 Nobel Prize in Physics went to Kamerlingh Onnes for his studies of materials at cryogenic temperatures rather than his work on superconductivity. A significant challenge in the generation, transmission, and distribution of energy is material resistance. Energy loss can be mitigated by employing appropriate conductors. The current target is to develop superconductors to facilitate the generation of alternative energy sources. Researchers are contemplating various strategies to enhance the synthesis of superconductors, which currently exist solely under low-temperature conditions [2]. The principal obstacle to widespread adoption of superconductors now lies in the fabrication of a superconductive material with the necessary properties for use in electrical and electronic applications [3].

2. Material and methods:

2.1 Conventional Meissner Effect

Superconducting materials have the Meissner Effect as one of their basic properties. Superconductivity, defined as the absence of internal magnetic fields and zero electrical resistance, occurs when a material's temperature drops below its critical temperature T_c Superconductivity is proven to be a separate thermodynamic state by this behavior, which distinguishes superconductors from regular conductors. Under the standard Meissner state, when the temperature drops below T_c, the magnetic field is ejected from the superconductor's interior [4]. Therefore, there is practically no magnetic flux density within the material's bulk:

$$B = 0$$

Inducing electric currents close to the superconductor's surface is what causes the magnetic field to be expelled. By creating their own magnetic field, these surface currents block the external magnetic field from permeating the material. The London Equations give a theoretical account of this occurrence. An electric field's effect on a superconductor's current density, J_s, is described by the first London equation. E:

$$\frac{dJ_s}{dt} = \frac{n_s e^2}{m} E$$

In this context, n_s stands for the density of superconducting charge carriers, e for the electron charge, and mmm for the electron mass. For superconducting currents, the relationship to magnetic fields is defined by the second London equation:

$$\nabla \times J_s = -\frac{n_s e^2}{m} B$$

The relationship between these relations and Maxwell's equations demonstrates that, as one moves away from the surface of a superconductor, the internal magnetic field weakens rapidly, as follows:

$$B(x) = B_0 e^{-x/\lambda_L}$$

in where B_0 stands for the surface magnetic field and λ_L is the so-called London penetration depth. Here we see the range of values for the parameter that describes the depth to which a magnetic field can marginally permeate a superconductor before quickly fading away.

The BCS Theory, which explains how electrons create bound states called Cooper pairs, provides the microscopic explanation of superconductivity. Together, these pairs diffuselessly traverse the crystal lattice, resulting in the Meissner effect's magnetic field exclusion and zero electrical resistance. [5,6]

2.2 Multiband Superconductivity

A phenomenon known as multiband superconductivity occurs when multiple electronic bands, each with its own superconducting gap, surpass the Fermi level. The critical temperature is frequently increased above forecasts made using single bands when these gaps interact and produce a cooperative effect. One example of this occurrence is the presence of two separate band gaps in magnesium diboride (MgB_2), while superconductors based on iron display a more unusual pairing, known as s± pairing, in which the gap switches sign between the electron and hole pockets [7,8]. Unusual physical phenomena, such as non-standard heat capacity and superfluid density as well as complex vortex patterns, emerge as a result of this multiband nature, unveiling a more varied and tuneable domain for superconducting physics. Seven and eight. Figure 1 shows the transport of several bands and superconductors [9].

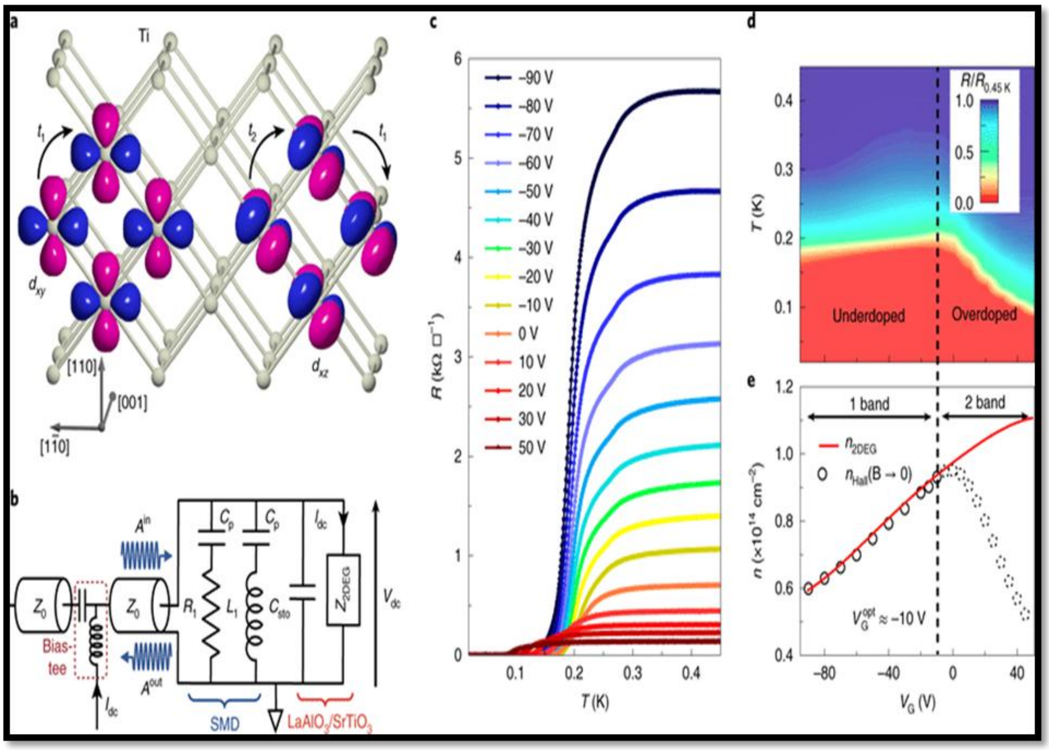

Figure 1: Superconductivity and multiband transport

3. The Paramagnetic Meissner Effect

3.1 Basic Mechanism

When field-cooling techniques are used to chill a superconductor, the paramagnetic Meissner effect occurs. Instead of releasing magnetic flux as expected, the material traps and compresses it in specific arrangements, leading to field amplification inside the sample. This appears to run counter to the basic principles of superconductivity since it causes a paramagnetic reaction.

3.2 Flux Compression and Trapping

An explanation that could be considered is that the magnetic flux is compressed and trapped during cooling. This trapped flux can take the shape of large vortices when the superconducting order parameter initially nucleates at the sample surface, and as the temperature decreases, its volume decreases, leading to regions where the magnetic field is amplified rather than emitted.

3.3 Giant Paramagnetic Meissner Effect

In 2015 it was shown that multiband superconductors can have a large paramagnetic response which is much larger than previous theoretical predictions. This important phenomenon occurs in the large crossover region between Type-I and Type-II superconductors, where Abrikosov vortices interact non-monotonically and multibody effects become significant. At this transition stage, different flux configurations can be blocked by surfaces. The resultant paramagnetic moment may be much larger than the diamagnetic Meissner response in the same applied field—approximately 30 times larger than previous theoretical predictions [10,11]. The effect changes with the applied magnetic field because of flux quantization and is superseded.

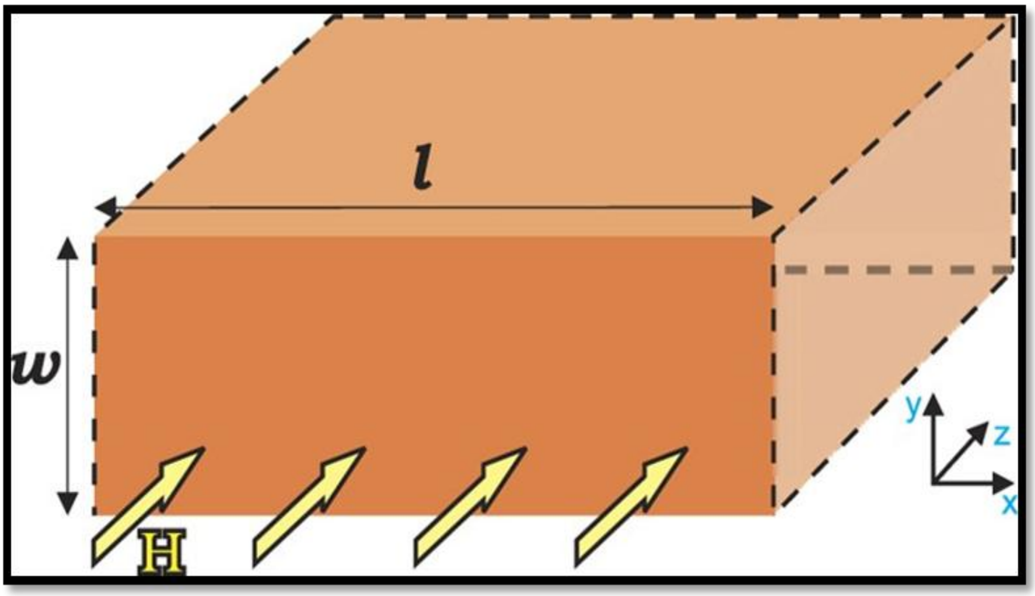

Figure 2 : Giant Paramagnetic Meissner Effect

4. Experimental Evidence

Various experimental methodologies can identify odd-frequency pairing and anomalous magnetic responses in multiband systems [12,13,14]:

1- Hybridization gaps in the electrical density of states indicate distinct signs of odd-frequency pairing [15].

2- Paramagnetic Meissner measurements directly assess the magnetic response.

3- Kerr effect assessments in materials exhibiting time-reversal symmetry violation

4-Angle-resolved photoemission spectroscopy (ARPES) can delineate superconducting gaps and ascertain nodal configurations [16,17].

5- Scanning tunneling microscopy elucidates regional discrepancies in gap magnitude [18]

5. Applications and Implication

5.1 Super current Diode Effects

In 2025, recently conducted studies on Josephson interferometers using multiband superconductors proved that magnetic fields can control the size and direction of supercurrent rectification independently. Important for cryogenic applications and superconducting quantum circuits, the nonreciprocal transport phenomena rely on the unusual magnetic response of multiband materials. electronics [19].

5.2 Disorder Robustness

Multiband superconductivity with flat bands has extraordinary disorder robustness, according to recent theoretical studies [20]. Even while the superconducting state could be disturbed by more typical sources, it does not. The stability of the Meissner effect in real materials and its practical uses are profoundly affected by this.

5.3 Quantum Computation

A significant step forward in topological quantum processing has been achieved with the discovery of materials like $PtBi_2$ that intrinsically support Majorana-bound states [21]. Particles known as Majorana fermions can be both their own antiparticles and fault-tolerant quantum bits. New possibilities for quantum information processing arise from the ability to generate and manipulate these states in intrinsic topological superconductors.

6. Conclusion

The intricate interplay between different superconducting gaps, interband coupling, and vortex dynamics is illustrated by the anomalous Meissner effect in multiband superconductors. The finding of Type-1.5 behavior and large paramagnetic reactions provides deep physics with important practical consequences while also challenging long-held assumptions. To make full use of these phenomena in next-generation superconducting systems, further theoretical and practical study is essential.

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