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A REVIEW OF THE MEISSNER EFFECT, CRITICAL MAGNETIC FIELDS, AND THEIR APPLICATIONS IN HIGH-TEMPERATURE SUPERCONDUCTORS

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Abstract
Superconductivity is a phenomenon in which a material exhibits zero electrical resistance and perfect diamagnetism through the Meissner effect when cooled below its critical temperature. In type-II superconductors, critical magnetic field parameters, including H_{c1}, H_{c2}, and H_{irr}, play essential roles in determining the stability of the superconducting phase under external magnetic fields. This review discusses the relationship among the Meissner effect, critical magnetic fields, magnetic vortices, flux pinning, synthesis methods, and the applications of high-temperature superconductors (HTSs), particularly YBCO and BSCCO. The reviewed studies indicate that microstructure, doping, and crystal quality strongly influence critical magnetic field performance and superconducting stability. However, previous studies have generally examined the Meissner effect and critical magnetic fields separately. Therefore, a more comprehensive review is needed to integrate recent developments in the theory, experimental investigation, and applications of modern superconductors.

1. Introduction

Superconductivity is a phenomenon in which the electrical resistance of a material decreases dramatically to an extremely low value, or even becomes virtually zero, when cooled below a specific critical temperature. A superconductor is a material that exhibits zero electrical resistance and perfect diamagnetism when subjected to sufficiently low temperatures (Knorr et al., 1992). This phenomenon was first discovered by the Dutch physicist Heike Kamerlingh Onnes in 1911 (Abbas et al., 2015).

Based on their critical temperatures, superconductors are generally classified into two categories: Low-Temperature Superconductors (LTS) and High-Temperature Superconductors (HTS). The field of superconductivity advanced significantly following the discovery of high-temperature superconductivity in 1986 by J. Georg Bednorz and K. Alex Müller (Vikhreva et al., 1998). One of the most extensively studied HTS materials is the Bi–Sr–Ca–Cu–O (BSCCO) system (bismuth strontium calcium copper oxide) (Mohammed et al., 2012). This material exhibits high structural and chemical stability and has long been utilized in magnetic resonance imaging (MRI) systems and particle accelerator magnets. However, the requirement for liquid helium cooling results in high operating costs. In contrast, high-temperature superconductors (HTSs) can operate at liquid nitrogen temperatures, making them more cost-effective and energy-efficient for large-scale applications. Furthermore, HTSs are capable of carrying higher electrical current densities under strong magnetic fields than low-temperature superconductors (LTSs) (Coombs et al., 2024).

In type-II superconductors, two important parameters are the lower critical magnetic field (H_{c1}) and the upper critical magnetic field (H_{c2}). When the applied magnetic field lies between these two critical values, the material enters the mixed state, which is characterized by the formation of magnetic flux vortices (Zhao et al., 2024). The relationship between the critical magnetic fields of a type-II superconductor can be expressed as follows:

$$H_{c1} < H < H_{c2}$$

The upper critical magnetic field is expressed as follows:

$$H_{c2} = \frac{\Phi_0}{2\pi\xi^2}$$

where $\Phi_0$is the magnetic flux quantum and $\xi$is the coherence length. The relatively short coherence length of high-temperature superconductors (HTSs) results in a very high upper critical magnetic field (H_{c2}), making these materials highly promising for applications involving extreme magnetic fields, such as fusion reactors, magnetic levitation (maglev) systems, advanced magnetic resonance imaging (MRI), superconducting power transmission cables, and superconducting magnetic energy storage (SMES) systems (Dong et al., 2024).

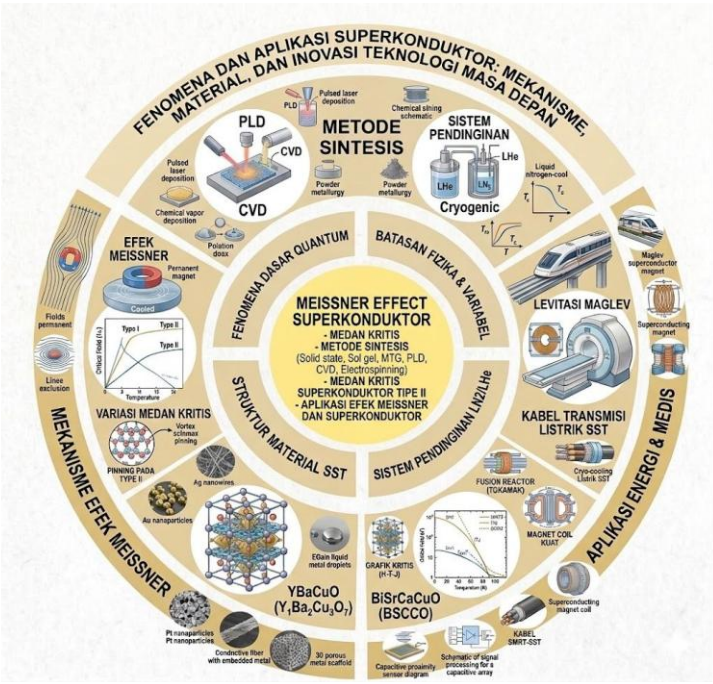

Figure 1. Circular Segmentation Plot of the Meissner Effect in Superconductors

Although numerous review studies on superconductivity have been published, most have focused separately on theoretical aspects, material characterization, or technological applications. Consequently, the fundamental relationship among the Meissner effect, critical magnetic fields, and the behavior of high-temperature superconductors (HTSs) has not yet been comprehensively addressed within a single integrated review. Previous reviews have generally emphasized the fundamental mechanisms of superconductivity, the development of HTS materials, or the performance of specific applications without systematically examining how critical magnetic field parameters influence the stability of the superconducting state, magnetic vortex dynamics, and the effectiveness of perfect diamagnetism under high magnetic fields.

Therefore, a comprehensive review that integrates recent theoretical and experimental findings is needed to provide a more systematic understanding of the mechanisms underlying the Meissner effect and critical magnetic fields in high-temperature superconductors. This review aims to examine recent advances in superconductivity, identify the various phenomena that influence superconducting properties, and analyze the factors governing material performance in high-magnetic-field applications. By providing this integrated perspective, the present review is expected to establish a more structured scientific foundation for understanding the relationship between the Meissner effect and critical magnetic fields, while also highlighting opportunities for future research in modern superconductivity.

2. Literature Review

2.1. Meissner Effect in Superconductors

The history of the Meissner effect can be traced back to the experiments conducted by Keesom and colleagues in 1932 (Keesom & van den Ende, 1932; Keesom & Kok, 1932a, 1932b), which revealed that the electronic heat capacity of tin and thallium exhibits a discontinuous jump near the critical transition temperature (T_c) between the normal (N) and superconducting (S) states. The critical temperature is an intrinsic property of each superconducting material. The Meissner effect demonstrates the fundamental interaction between electricity and magnetism, highlighting the unique electromagnetic behavior of superconductors. Unlike ordinary electrical conductors, superconductors expel magnetic flux from their interior when cooled below their critical temperature and subjected to magnetic fields, resulting in perfect diamagnetism. This phenomenon enables magnetic levitation (maglev), in which a magnet can stably levitate above a superconducting material due to magnetic flux exclusion (Keesom & van den Ende, 1932; Keesom & Kok, 1932a, 1932b).

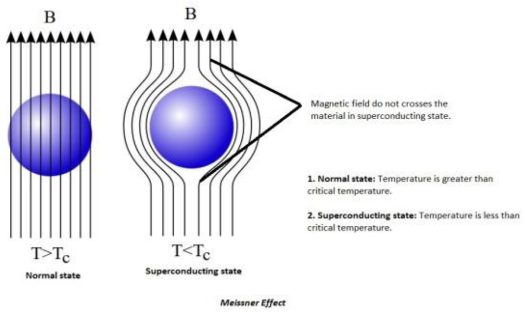

Figure 2. Meissner Effect

Recent advances in research on the Meissner effect have shown that this phenomenon is not always ideal, as described by classical superconductivity theory (Talantsev, 2019). Several studies have reported deviations from ideal behavior, including magnetic flux trapping and the emergence of a paramagnetic response under specific conditions, particularly in type-II superconductors (Keesom & van den Ende, 1932; Keesom & Kok, 1932a, 1932b). Investigations employing high-resolution magnetic field imaging techniques, such as nitrogen-vacancy (NV) center magnetometry, have further demonstrated that the magnetic field distribution around superconductors is highly complex and is influenced by the material's microstructure, external environmental conditions, and vortex dynamics within the superconducting system (Hirsch, 2024). These findings indicate that, in practice, the Meissner effect is a dynamic phenomenon whose behavior strongly depends on the intrinsic properties of the superconducting material and the experimental conditions under which it is observed (Asl & Sheykhi, 2020).

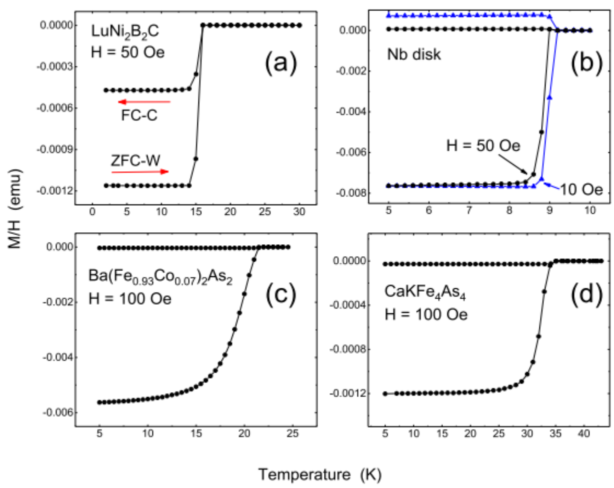

Figure 3. Temperature-dependent total magnetic moment measured using a Quantum Design MPMS. The zero-field-cooled warming (ZFC-W) and field-cooled cooling (FC-C, Meissner expulsion) curves measured in single crystals of (a) $LuNi_2B_2C$ borocarbide, (b) niobium, (c) $Ba(Fe_{0.93}Co_{0.07})_2As_2$, and (d) $CaKFe_4As_4$ under the magnetic fields applied in the experiments described below are presented.

Subsequent theoretical developments have shown that the understanding of the Meissner effect and critical magnetic fields continues to evolve (Schilling, 2026). Recent studies suggest that the magnetic response of superconductors is not always perfectly diamagnetic but can become paramagnetic depending on the system conditions (Shirai et al., 2016). Furthermore, thermodynamic aspects, such as energy conservation and reversibility during the superconducting phase transition, have become major focuses of contemporary research (Vikhreva et al., 1998). These findings indicate that superconductivity is not merely a long-established phenomenon but also involves complex quantum dynamics.

2.2. Critical Magnetic Field

The critical magnetic field, which defines the stability limit of the superconducting phase, demonstrates that superconductivity is associated not only with electrical properties but also with thermodynamic aspects and interactions with externally applied magnetic fields (Wen et al., 2025).

Furthermore, the concept of the critical magnetic field serves as an important parameter for determining the stability limit of the superconducting phase (Dailledouze et al., 2025). The critical magnetic field depends not only on temperature but is also influenced by the material's microstructure, spin–orbit interactions, system dimensionality, and external pressure (Fournais & Kachmar, 2011). Recent studies have shown that in modern materials, such as nickelate-based superconductors and multilayer systems, the critical magnetic field can exhibit significant variations due to quantum effects and complex material configurations (Chen et al., 2022). Moreover, in Type II superconductors, the presence of two critical magnetic field limits (Hc1 and Hc2) gives rise to a mixed state characterized by the partial penetration of magnetic flux in the form of vortices (Bernardo et al., 2015), thereby adding further complexity to the relationship between the Meissner effect and the critical magnetic field.

The critical magnetic field is one of the fundamental parameters in superconductivity, defining the stability limit of the superconducting phase under the influence of an external magnetic field. When a material is in the superconducting state, it exhibits both zero electrical resistance and perfect diamagnetism. However, these properties persist only until the applied magnetic field reaches a certain threshold, known as the critical magnetic field. Once the applied magnetic field exceeds this threshold, the superconducting state collapses, and the material returns to its normal state (Wen et al., 2025).

In general, the critical magnetic field does not depend on a single parameter but is governed by temperature, material structure, and microscopic interactions within the system. The relationship between the critical magnetic field and temperature indicates that the critical magnetic field decreases as the temperature increases and becomes zero at the critical temperature (Tc). This behavior demonstrates that the stability of the superconducting phase arises from the thermodynamic energy balance between the normal and superconducting states (Vikhreva et al., 1998; Wen et al., 2025).

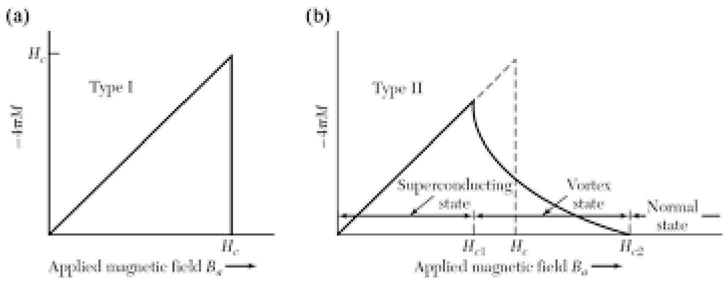

Figure 4. Critical Magnetic Field (Hc) Curves for Type I and Type II Superconductors

In Type I superconductors, there is only one critical magnetic field (Hc), which serves as the single boundary between the superconducting and normal phases. In contrast, Type II superconductors possess two critical magnetic fields, namely the lower critical field (Hc1) and the upper critical field (Hc2). Within the field range between Hc1 and Hc2, the material exists in the mixed state, where magnetic flux begins to penetrate the material in the form of quantized vortices. The presence of these vortices indicates that the Meissner effect is no longer perfect, allowing partial magnetic flux penetration without completely destroying the superconducting state (Talantsev, 2019; Bernardo et al., 2015).

Experimental studies have demonstrated that the characteristics of the critical magnetic field are strongly influenced by the material's microstructure, including crystal defects, grain boundaries, and flux pinning mechanisms. Flux pinning plays a crucial role in stabilizing vortices, thereby enhancing the material's ability to carry electrical current under high magnetic fields (Tamura et al., 2025). Furthermore, investigations of modern materials, such as nickelate-based superconductors and multilayer systems, have shown that the critical magnetic field is also affected by spin–orbit interactions, quantum effects, and the complex dimensionality of the system (Chen et al., 2022; Fournais & Kachmar, 2011).

Furthermore, the suppression of superconductivity by an applied magnetic field is not solely governed by orbital effects but can also be influenced by spin polarization, commonly referred to as the Pauli limiting effect. This observation indicates that the concept of the critical magnetic field involves multiple interacting physical mechanisms (Fournais & Kachmar, 2011). Moreover, in certain unconventional superconducting systems, the magnetic response may exhibit anomalous behavior, such as the emergence of a paramagnetic response that deviates from classical theoretical predictions (Shirai et al., 2016; Schilling, 2026).

Therefore, the critical magnetic field serves not only as an experimental boundary but also as a key parameter for understanding the fundamental nature of superconductivity and the interaction between magnetic fields and Cooper pairs. A comprehensive understanding of the critical magnetic field is essential for both the development of superconductivity theory and practical applications, including superconducting magnets and magnetic levitation technologies (Dias et al., 2016; Tamura et al., 2025).

Current research on superconductors extends beyond fundamental phenomena such as the Meissner effect to include the exploration of high-temperature superconductors and emerging material classes, such as nickelate superconductors and hydrogen-rich materials under high pressure. Recent studies have demonstrated that superconducting properties can be tailored through doping, two-dimensional (2D) structural engineering, and the application of external pressure, all of which significantly influence the critical magnetic fields and the stability of the superconducting phase. Nevertheless, despite the availability of numerous review articles, relatively few have comprehensively examined the relationship between these modern superconducting materials and the interplay between the Meissner effect and the critical field parameters (Hc1, Hc2, and Hirr), particularly in the context of practical applications. Therefore, a more integrated review is needed to bridge the phenomenological, materials science, and application-oriented aspects of modern superconductors.

2.3. Synthesis Methods for Type II Superconductors

2.3.1. Solid-State Reaction

The solid-state reaction method is one of the most widely used synthesis techniques for producing bulk superconducting materials, such as YBCO and BSCCO. This method involves mixing precursor powders according to the desired stoichiometric composition, followed by milling, calcination, pelletization, and high-temperature sintering. During the sintering process, atoms diffuse and react to form the desired superconducting phase. The main advantages of this method are its relatively simple processing procedure, low cost, and ability to produce materials in large quantities. However, it has several limitations, including relatively poor compositional homogeneity and large grain sizes.

2.3.2. Sol-Gel

The sol-gel method is a solution-based synthesis technique used to achieve a more homogeneous elemental distribution at the molecular level. In this method, metal precursors are dissolved in a specific solvent to form a sol, which subsequently undergoes a gelation process to form a gel. The gel is then dried and heated to produce the superconducting material. The sol-gel method offers several advantages, including better compositional control, smaller particle sizes, and lower synthesis temperatures compared with conventional methods. Therefore, this method is widely applied in the fabrication of superconducting nanoparticles and thin films.

2.3.3. Melt Textured Growth (MTG)

The Melt Textured Growth (MTG) method is used to improve crystal orientation and intergrain connectivity in Type II superconductors. In this method, the material is heated until a partial melting phase occurs and is subsequently cooled under controlled conditions to form a textured crystal structure. This technique can produce high critical current values because more uniform grain orientation reduces the barriers to Cooper pair transport. The MTG method is widely used in the synthesis of bulk YBCO for applications in magnetic levitation and superconducting permanent magnets.

2.3.4. Pulsed Laser Deposition (PLD)

Pulsed Laser Deposition (PLD**)** is a thin-film deposition method that utilizes high-energy laser pulses to ablate a superconducting target material. The ablated material is subsequently deposited onto a substrate, forming a thin film with a specific crystallographic orientation. The PLD method enables the fabrication of high-quality thin films with excellent thickness control. This technique is widely used in the fabrication of YBCO and REBCO thin films for applications in SQUID sensors, superconducting cables, and quantum electronic devices.

2.3.5. Chemical Vapor Deposition (CVD)

The Chemical Vapor Deposition (CVD) method involves introducing precursor gases into a high-temperature reaction chamber, where chemical reactions occur and form a superconducting layer on a substrate. This method is capable of producing thin films with high purity and well-developed crystalline structures. One advancement of this technique is Metal Organic Chemical Vapor Deposition (MOCVD), which is widely used in the industrial production of REBCO-based high-temperature superconducting (HTS) cables.

2.3.6. Spray Pyrolysis Method

The spray pyrolysis method involves spraying a precursor solution onto a heated substrate, resulting in thermal decomposition and the formation of a superconducting layer. This technique is relatively simple, inexpensive, and suitable for large-scale fabrication of thin films. However, the crystalline quality and layer homogeneity are generally lower compared with PLD and CVD methods.

2.3.7. Electrospinning Method

The electrospinning method is used to produce superconducting nanofibers with a high surface area. In this technique, a precursor solution is passed through a high-voltage electric field, producing fine fibers that are subsequently calcined to form superconducting materials. This method has recently been developed to enhance flux pinning mechanisms and improve critical field performance in modern HTS materials.

In general, each synthesis method possesses distinct characteristics, advantages, and limitations. Bulk synthesis methods, such as solid-state reaction and MTG, are more suitable for large-scale magnet applications and magnetic levitation, whereas thin-film deposition techniques, such as PLD and CVD, are primarily utilized in modern electronic devices, sensors, and superconducting cables. Therefore, the selection of an appropriate synthesis method plays a crucial role in determining crystal structure quality, flux pinning capability, and critical magnetic field performance in Type II superconductors.

2.4. Critical Magnetic Field in Type II Superconductors

Table 1.1. Comparison of the Characteristics of the Meissner Effect and Critical Magnetic Fields in Various Type II Superconductors

Paper Title	Material / Doping	Composition	Conditions	Hirr	Hc1	Hc2	Dimension
NV Magnetometry Meissner (2018)	Undoped	Nb, YBCO	T < Tc, low magnetic field	~0.1–0.5 T	~10–100 mT	~1–10 T	3D
Megabar Pressure SC (2019)	High pressure	LaH_{10}, H_3S	P > 100 GPa, low temperature	High	Low	>100 T	3D
PME YBCO (2016)	Oxygen doping	$YBa_2Cu_3O_7{-}\delta$	Magnetic field up to 14 T	~5–10 T	~50 mT	~100 T	3D
Holographic SC (2019)	Theoretical model	–	Simulation	–	–	–	–
Odd-Frequency SC (2016)	Undoped	s-wave SC	Quantum model	–	Small	High	3D
MgB_2 & BSCCO (2022)	Pb doping	MgB_2, BSCCO	External magnetic field	~2–5 T	~0.05 T	~20–50 T	3D

Paper Title	Material / Doping	Composition	Conditions	Hirr	Hc1	Hc2	Dimension
Dirac Materials (2019)	Undoped	Graphene-like materials	Thin-film configuration	Low	Very small	Moderate	2D
Maglev SC (2019)	Undoped	Bulk YBCO	External magnetic field	~1–3 T	~0.01–0.1 T	~100 T	3D
Hydrogen SC	High pressure	H_3S	Extreme pressure	High	Low	>100 T	3D
Flux Pinning HTS (2025)	Doping and defects	YBCO, BSCCO	High magnetic field	~5–10 T	~0.1 T	~100 T	3D
Nickelate SC	Doping	Nickelate	Pressure and doping	~1–5 T	~10 mT	~10–30 T	Quasi-2D
N-S-N Systems (2025)	Interface engineering	Metal–SC–metal	High magnetic field	–	–	~10–50 T	2D/3D

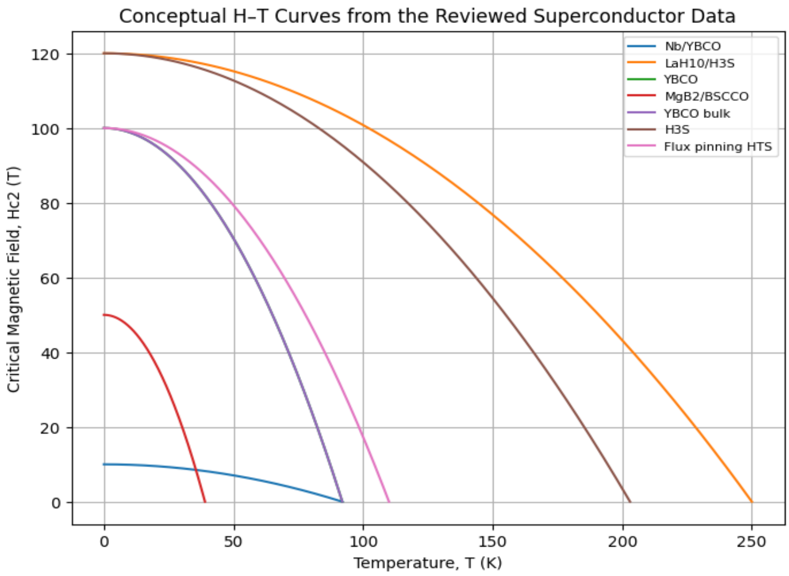

Figure 5. H–T Curve Based on the Data Presented in Table 1.1

The H–T curve illustrates the relationship between the upper critical magnetic field (Hc2) and temperature for various Type II superconducting materials. Based on the curve, it can be observed that the critical magnetic field decreases with increasing temperature and eventually reaches zero as the temperature approaches the critical temperature (Tc). High-temperature superconducting materials, such as YBCO, BSCCO, and H_3S, exhibit significantly higher Hc2 values compared with conventional superconductors, enabling them to maintain superconducting properties under extremely high external magnetic fields. The curve also demonstrates that improvements in material quality through doping, flux pinning, and crystal structure optimization can enhance vortex stability and expand the superconducting region in the H–T phase diagram, making these materials more promising for high-field applications such as MRI, maglev systems, and fusion reactors.

3. Discussion

Applications of the Meissner Effect

The Meissner effect has numerous important applications in modern technology. One of the most well-known applications is in magnetic levitation trains (maglev), where superconductors can levitate above magnetic tracks without direct contact, thereby significantly reducing friction. In addition, this effect is utilized in superconducting magnetic energy storage (SMES) systems, highly sensitive magnetic field sensors (SQUIDs), and medical technologies such as Magnetic Resonance Imaging (MRI).

In the industrial and defense sectors, this phenomenon also has potential applications in electromagnetic shielding systems and stealth technologies based on magnetic field manipulation. In the commercial sector, demonstrations of the Meissner effect are often used in technology showrooms to showcase magnetic levitation as an educational tool and a means of promoting superconducting innovations.

4. Conclusion

Based on the results of the literature review, it can be concluded that the Meissner effect and critical magnetic fields are two fundamental and interrelated aspects of superconductivity, particularly in Type II superconductors. The Meissner effect demonstrates the ability of a material to expel magnetic fields; however, in Type II superconductors, this phenomenon is not completely maintained due to the presence of a mixed state characterized by magnetic flux penetration in the form of vortices.

The critical magnetic field parameters, namely Hc1, Hc2, and Hirr, play an important role in determining the stability limits of the superconducting phase under the influence of external magnetic fields. These parameters are strongly influenced by factors such as temperature, material microstructure, doping, and system dimensionality (2D or 3D). High-temperature superconducting materials, such as YBCO and BSCCO, exhibit higher critical magnetic field values compared with conventional superconductors, making them more promising for applications under extreme conditions.

The development of new materials, such as nickelates and hydrogen-based superconductors under high pressure, demonstrates that superconducting properties can be engineered through modern approaches, thereby providing opportunities to enhance material performance. Furthermore, applications of the Meissner effect in technologies such as maglev systems, MRI, and magnetic sensors indicate that this phenomenon is not only theoretically significant but also possesses substantial practical value.

Therefore, a deeper understanding of the relationship between the Meissner effect and critical magnetic fields is essential to support the development of more efficient and applicable next-generation superconductors in the future.

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