Superconductivity: The Meissner Effect

Physics 1D - Las Positas College | Shahaf Dan

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Summary

This paper is written for an Introduction to Quantum Mechanics Course at Las Posiats[1] College. The paper will explore, discuss, evaluate, and introduces the concepts of superconductivity, the Meissner Effect, Quantum Locking, and Magnetic Levitation, as well as their history and modern uses and applications.

Superconductivity was discovered a little over a century ago, and has revolutionized the scientific world, as it had allowed the development of many new inventions and discoveries in the engineering world. Superconductivity opened many doors in the world of modern physics and was quickly followed by the experimental discovery of the the Meissner Effect: the internal expulsion of magnetic fields within a superconductor. The Meissner effect served as an introduction to magnetic levitation[2], quantum locking, and more. This paper will explore the history of these discoveries, determine their significance and importance in modern physics and engineering, explore their conceptual physics as well as discuss modern applications and potential future technological uses.

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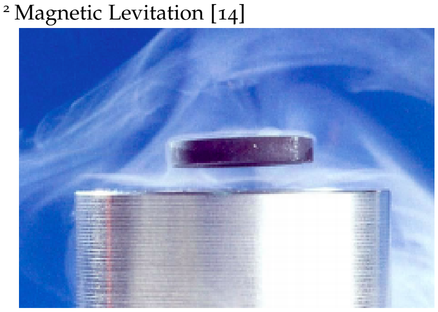
2 Magnetic Levitation [14]

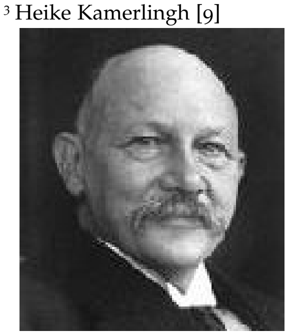


I. | Introduction

Quantum Mechanics, is the branch of physics that deals with the mathematical description of the motion and interaction of subatomic particles. As quantum mechanics exponentially expanded in its ideas and studies in the 1900's, new ideas that led into our modern applications of physics, and a whole new world for physicists to explore, was developed and born.

The study of quantum mechanics led to major discoveries in electricity and magnetism; one of the most known to scientists discovery, is the observation of the phenomenon known as superconductivity. It was first observed in mercury, cooled to an extremely low temperature of liquid Helium (4K, -269°C), which caused its resistance to the flow of electric current to suddenly disappear completely [6]. It was first observed by the Dutch physicist Heike Kamerlingh [3]

3 Heike Kamerlingh [9]



Onnes of Leiden University in 1911, who won a Noble prize in 1913 for his work, investigation, and discoveries on the properties of materials at low temperatures [9]. As those discoveries were significant to the physics world, many physicists began to explore the area of superconductivity, which led to the observation of the Meissner Effect. The paper discusses, explores and introduces the ideas and concepts of superconductivity, the Meissner effect, its history and its applications in the modern era.

II. | Understand Superconductivity

To understand superconductivity, it is best to understand first electric conductivity, and how magnetic fields are produced from it. Some materials have the ability to conduct electricity better than others, and that is due to their atomic structures and charge. The charge in those objects creates an electric field around them, as well as a potential difference. An external electric field in an object creates a current of mobile electrons and negatively charged ions in that field. This current flows differently in each material, due to a phenomenon known to electricians as Resistance. Resistance is the tendency of a material to "fight" the electric current in it, and is due to a materials resistivity. Resistivity is the measure of resisting power of a material to the flow of an electric current. Each material has a different resistivity measure at a set temperature, and as will be explored later in this research paper, an increase in the materials temperature increases a material's resistivity. The resistance of a material obeys to the following formulas: [4]

[4] E = Electric Field's Magnitude
$\varrho = Resistivity(in\Omega \cdot meter)$
$J = CurrentDensity(inA/m^2)$
$I = ElectricCurrent(inAmperes[A])$
$d = SeparationDistance$
$A = CrossSectionalArea$

$$\varrho = \frac{E}{J} \qquad J = \frac{I}{A} \qquad E = \frac{V}{d}$$

Algebraically it is concluded that:

$$\varrho = \frac{V \cdot A}{I \cdot d}$$

We then define the formula for resistance:

$$R = \frac{\varrho \cdot d}{A} = \frac{V}{I}$$

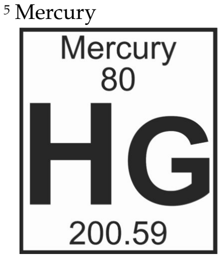
We learn that the resistance of a material is the quotient of the uniform voltage resulting from the electric field and the constant current flowing through it.

Furthermore, it should be mentioned that Electric and Magnetic fields are not only related, rather are tied into one another. Magnetic fields are simply what electric fields become when an electrically charged object starts moving [7] since any electric charge (within an electric field) responds to a time varying magnetic flux. In fact, it is concluded that any particle with an electric charge is also a tiny magnet [7]. It should be mentioned that a magnetic field will always be perpendicular to an electric field.

III. | History of Superconductivity

In 1911, the Dutch Scientist Heike Kamerlingh Onnes of Leiden University first observed superconductivity, as he cooled down Mercury [5], a conductor material, to a very cool temperature of -269°C (4

[5] Mercury



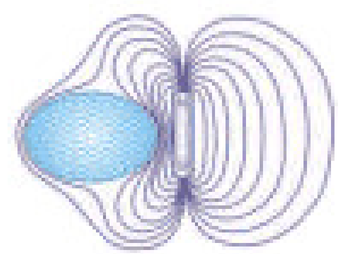
Kelvin degrees above the absolute zero temperature). As a result, the resistance of the mercury disappeared, and charge could flow within that mercury without any setback. After publishing his research in 1911 and winning a Nobel Prize in 1913, many other physicists found the superconductivity temperature for other materials such as lead (-266°C), Niobium (-263°C), and more. The observational phenomenon that at some very low temperature, specific for each material due to its atomic structure, was astonishing at that time. It was later understood that the sudden disappearance of resistance of a superconductor due to the decrease in temperature to its critical temperature, is simply a mere illusion, as it was the object's resistivity that became negligible, or completely disappeared.

In 1933, another milestone was accomplished as German researchers Walther Meissner and Robert Oschenfeld[6] discovered experimentally that a superconducting material will repel internally a magnetic field [7]. Meissner and Oschenfeld found out that due to the material's lack of resistance to electric current (hence called a 'superconductor'), "the induced currents exactly mirror the field that would have otherwise penetrated the superconducting material - causing the magnet to be repulsed" [9]. This strong demagnetization observation was then given the name the Meissner effect, and is in fact so strong, that magnets can levitate above superconducting materials due to their magnetic fields [1].

[6] Walther Meissner [9]

Robert Oschenfeld [9]

[7] Object Internally Repelling a Magnetic Field [9]



IV. | Types of Superconductors

In the following decades, throughout the second world war the superconductivity of many new materials were found, which allowed the development of new inventions and applications of superconductivity and magnetic levitation. In 1957, the first widely accepted theoretical understanding of the superconductivity (BCS theory) phenomenon was established by three physicists: John Bardeen, Leon Cooper, and John Schrieffer (BCS for their initials) [12]. The BCS theory explained superconductivity for materials with a required temperature of near absolute zero, and divided those materials into Type I and Type II [8](also named low and high temperatures, respectively) [4]. According to the BCS theory, Type I superconductors include metals and met-alloys.

These materials show some conductivity in room temperature. Those materials require extreme low temperatures to provide super conductivity, which according to the BCS theory results from "slow[ing] down molecular vibrations sufficiently to facilitate unimpeded electron flow" [11]. Type I[9] superconductors are known for their advantages of being malleable and ductile, easy to deal with,

[8] Note: Met-alloys (or Matelloids) are "chemical element which have the properties just like the mixture properties of metal and non metal. Or Which contain those properties in between the non metal and metal."[3] whereas metal-alloys are "mixture of metals.Some times mixture of metal may contain another element .They are recognized by their metallic bonding characteristics " [3]

[9] Table I: Examples of Type I Superconducting Elements. The critical temperature varies between elements, yet shows a consistency in being incredibly close to the absolute zero temperature for all Type I superconductors [11]

Material	Critical T
Lead [Pb]	7.196K
Mercury [Hg]	4.15K
Lithium [Li]	0.0004K

and available and easily made. These advantages of Type I superconductors, allow easy access to superconductors which can last for a long time in "tough" environmental factors. [10]. However, Type I superconductors have very low critical temperatures, which makes it difficult and expensive to turn them into superconductors [11].

Due to the it can be extremely difficult and challenging to cool down superconductor materials to their critical temperatures, research was done to find materials that did not require such low temperature, and type II superconductors were discovered. “Type 2 category of superconductors is composed of metallic compounds and alloys” [12]. [10] [11] and met-alloys.

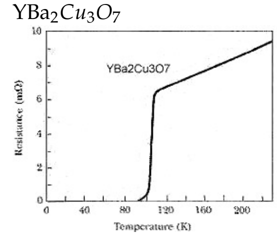
Material	Critical Temperature
YBa_2O_x	83K
$Tl_5Ba_4Ca_2Cu_{10}O_y$	242K
Cu_3MgO_4	147K
$YBa_2Cu_3O_7$	92K

They are usually “oxides and ceramics” [10]. The first type II alloy was made in 1930, prior to the discovery of the Meissner effect, but was only found to be a superconductor in the 1950’s [12]. The superconductors in this category, also known as ‘hard’ superconductors, require a higher, less cold, temperature, in order to become superconductors and diamagnetic. Hard superconductors differ from type I materials “in that their transition from a normal to a superconducting state is gradual across a region of "mixed state" behavior.” [12]. Unfortunately, although the Type II superconductors do not require a very low critical temperature, they are considered brittle, and not compatible for use.

Additionally, it should be mentioned that besides the two categories of superconductors, it has been found that some elements

[10] Table II: Examples of Type II Superconducting Elements. The critical temperature varies between elements, as none of them is critically close to the absolute zero temperature [12]

[11] Temperature vs. Resistance Graph for $YBa_2Cu_3O_7$

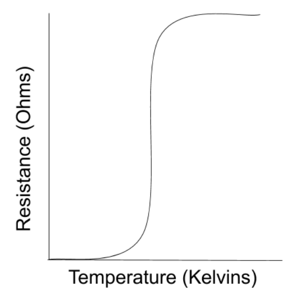


such as Zinc and Silver, are naturally diamagnetic, hence they repel magnetic fields, as do superconductors.

V. | Superconductivity and The Meissner Effect

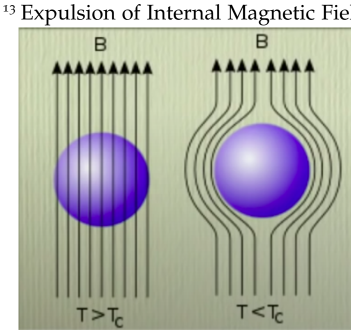
Superconductors, regardless of the category to which they belong, all obey the Meissner effect. The superconductivity concept complies with the discovery that as opposed to semi-conductors for which as temperature drop, their resistance decrease but never reaches zero in resistance [10], superconductors materials, which have been cooled down to a low (often extreme) temperatures, experience no resistance at all. In other words, once a superconductor material has been cooled down to (or below) its critical temperature Tc [12](varies for different materials and elements), it no longer experiences any resistance to electric flow and exhibits superconductivity. [13]. To understand this phenomenon, it first needs to be established that electric current is the flow of electrons inside a conductor body. When the resistance to electric current is zero, electrons can flow without any energy dissipation, which happens when the body's temperature is lowered to its Tc. Due to the low temperature, the atoms in the body stop vibrating (relatively to one another), which allows them to move flawlessly within the body, with no interactions with other particles. This results in no energy conversion to heat, and zero internal energy dissipation and no internal friction [13]. Therefore, since resistivity is negligible (or completely zero), the flowing current will be maximized, as well as the resulting electric field's magnitude.

[12] R vs. T (Superconductors)



As discussed in section III, in 1933, Meissner and his partner "showed by experiment that the magnetic field inside a superconductor is always zero" [4] due to the superconductivity properties of zero internal friction. The circulating friction-less current inside the superconductor, brings the system to an expulsion of any internal magnetic field. [13]

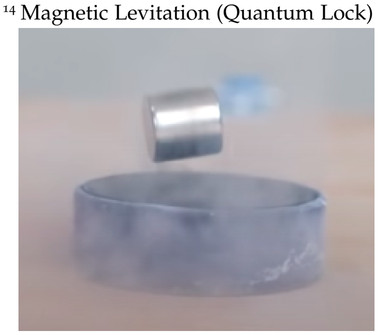
[13] Expulsion of Internal Magnetic Field



[1]

As determined, due to the maximal current density, a perpendicular external repelling magnetic force becomes extremely strong, and "in doing so, causing any magnet sitting on top to levitate" [10]. This phenomenon is known as magnetic levitation[14].

[14] Magnetic Levitation (Quantum Lock)

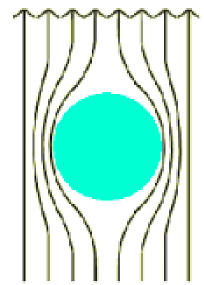


[13]

VI. | Quantum Locking and Magnetic Levitation

As explained, in the superconductivity quantum state, the electrical current flowing through the conductor experiences no resistance, and hence is maximized. By considering the electric field as a field of potential energy impacting other charged objects, we can consider that due to the lack of resistance, there is no energy loss, since the electric field is uniform across all the surface area of the conductor [1]. The perfect conservation of energy due to the no loss of energy [internally], creates a state where there is no change in the motion (parallel to the field) of the magnet, since it will 'break the balance' of conserved energy. Although the magnet could still move perpendicularly to the magnetic field (parallel to the electric field), it will not be able to move parallel to it. "The movement dissipates [potential] energy, [creates heat (or motion)], and thus breaks the quantum state of superconductivity" [1]. This forbidden motion of the superconductor "locks the magnetic flux lines inside" [1], which locks itself (the superconductor diamagnet) in place. This results in the magnetic levitation and suspension, also known as quantum locking [15]. Therefore, "the magnetic field inside a superconductor is always zero" [4].

[15] Quantum Locking inside a magnetic field[14]



The fluxons (quantum of electromagnetic flux) of the magnetic field can be rearranged, hence any perpendicular displacement will be impacted, allowing the locked magnet to become stabilized and quantum-ally locked in different angles and positions [10]. The displacement of the diamagnet which results in parallel quantum locking regardless of the angle, can also result in friction-less motion perpendicular to the magnetic flux. In other words, in circular magnets with uniform magnetic fields, the superconductor can move horizontally (perpendicular to the magnetic field) endlessly (considering no external friction) due to the absolute lack of internal friction and zero internal loss energy [13].

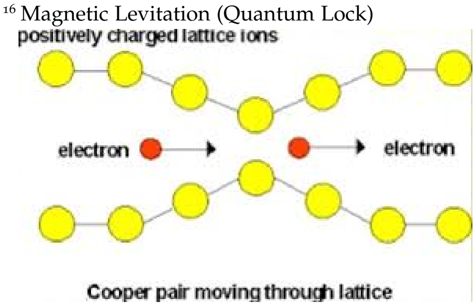
To emphasize the strength of the Meissner effect and magnetic levitation, a 3 inch in diameter, 2 millimeter thick superconductor disk (with a strong enough current) could carry 1000 kilogram, which is equivalent to a small car [1].

VII. | Sub-atomically: The Meissner Effect

On the subatomic level, the Meissner effect is explained through the movement and motion of electrons. In a regular conductor, the electrons moving in the electric current hit atoms and particles, and bounce off, which generates and transforms into heat energy (scattering), and results in significant energy dissipation [13]. In other words, in a regular conductor, if the current stops, electrons are not pushed anymore, and the scattering of them turns into heat energy. Interestingly, in superconductors, when cooled to the critical temperature, the electrons stop behaving as individual particles, and behave as one unified object (made of electrons), and the particles in the cooled body no longer vibrate relatively to one another, rather as one unified object. The electrons pair up with one another in cooper pairs [13], where they don't even have to be close to each other. The cooper pairing is a 'selection process' between the electrons based on their spin (+/- 1/2), which aligns opposite-spin (in a specific three dimensional direction) electrons; this creates a strong connection between the electrons [2]. Cooper pairing happens due to the positive ions surrounding the electrons, which due to the attraction between the positive charge of the ions and the negative charge of the electrons, attracts other nearby and close electrons to the ions surrounding the electron. That attraction is stronger than the repelling force of the two electrons, causing them to seems as if they were to attract each other. The particles in the cooled object have a coherent, shared, vibrational mode, allowing the cooper paired electrons to move flawlessly within it, without colliding into one another. Superconductivity, as a matter of fact, was developed and based on the principle of cooper pairs, according to which, "the interaction between electrons and photons generate an effective electron–electron interaction limited to a shell in momentum space around the Fermi surface. When this mutually attractive interaction overcomes the Coulomb repulsion, bound pairs may form" [2]

The cooper pair object [16] (the electrons as one item), is at its lowest energy level, and needs to be excited, so it can scatter. In order to excite the cooper pair, a specific and discrete amount of energy has to be transferred to it. In order for it [a cooper pair] to bump into anything, energy from the bumped object must be transferred to the cooper pair in a discrete amount X. The necessary amount of energy, E had to be bigger than X, E>X [13]. Experimentally, the Meissner effect had revealed that as we cool down an object below its critical temperature Tc, X(of each individual particle) will decrease significantly enough of its less than the minimum energy needed to scatter the Cooper pair [2]. In other words, anything that would bump into the cooper pair, won't have enough energy to do anything to it, and hence won't be able to move it. It results in the Cooper pair being quantumly locked, which seems to the human eye (in large groups of electrons [cooper pairs]) as magnetic levitation [10]. In order to override it, a large amount of energy would have to be used to excite the Cooper pair to the next level. This can be done with an object moving fast enough and bumping into the Cooper pair, or a current flowing through the Cooper pair with great enough voltage.

[16] Magnetic Levitation (Quantum Lock)



[13]

VIII. | Applications and Uses in the Modern Era

Quantum locking became an astonishing phenomena less than 100 years ago. As we are yet to completely understand it and as technology continually and exponentially advances, humanity and society have found numerous applications to the Meissner effect. An example of the modern use society had found to the scientific phenomenon of magnetic levitation, is with police work and illegal drugs and substances identification. A device, developed as part of a criminology research at Harvard University, suggests that illegal drugs which "are often a mixture of substances", can be identified using magnetic liquids. A device prototype that was developed "separates components of the sample by their respective densities" [8]. The device is made of the drug sample mixed with a magnetic liquid in a container, and two magnets from both sides of that container. "The magnetic liquid attempts to push particles of drugs away from the magnets in order to minimise the energy of the system, while gravity and buoyancy also act on them [which results in the] overall effect is that drugs with the same density as the liquid will stay in the middle of the container, while those of higher density will sink and those of lower density will rise" [8]. By comparing the results to a previously made index of illegal drugs reference, police officers will be able to quickly detect the type of illegal drugs used using mobile devices instead of laboratory checks.

An additional example of a modern use of the Messier effect, is in the transportation industry. Magnetic based transportation are not common due to their high expense , but are great for large distributional area. An example is the train system in Japan [17] "which functions based on the interaction of the magnetic fields of the vehicle and the support, through electro-dynamic repulsion" [5], and the magnetic levitation of the public vehicle is done by magnetic repulsion. Most transportation system are currently experimental and scientists and engineers attempt to personalize and individualize the magnetic levitation vehicle, so it will be available for individual transportation to the public. Such transportation is known for its many advantages: faster acceleration, better at climbing slops, more silent, energy consumption is much smaller, there is little to non gas pollution (negligible amounts), and overall better performance [5]. However, due to technological limitations we as a society face today, the mass production of such systems is extremely expensive and difficult and therefore is only done on a large-scale public projects over large distributional areas.

[17] Magnetically Levitated Train, Japan [5]

Furthermore, we see the use of magnetic levitation (the Meissner Effect) in the aviation industry as well. Although not fully super ted yet, and is considered completely experimental by the National Aeronautics and Space Administration (NASA), magnetic levitation, on the same concepts as the Japanese trains, is used for quicker and faster acceleration of airplanes. [18]. As a matter of fact, according to the Hamid Yaghoubi, the Director of Iran MagLev Technology, an magnetically levitated aircraft could accelerate "up to 600 mph (965

[18] Experimental MagLev Aircraft [14]

kph) without using any on-board fuel" [14]. Considering an aircraft will require much less fuel to accelerate and move, it's weight at liftoff could decrease with up to 20%, which will help to the quicker acceleration of the body. [14]. This technology, as it is currently considered experimental by most research institutions, could lead to technological innovations in the aviation[19]

, transportation, and even space industries, thanks to its features of minimal internal friction and energy dissipation that allow quicker acceleration and lower body-mass to accelerate.

[19] Experimental MagLev Aircraft [14]

According to Yaghoubi [14], in the near decades, we will start to see more uses of magnetic levitation in more places, used for more purposes. Examples include art galleries [20] , where magnetic levitation (the Meissner Effect) is already considered to be used to display items; as well as in the energy industry to produce 'green' energy, where wind turbines [21] will magnetically levitate around their base, and rotate [internally] without friction around their base, increasing the energy production. Engineers estimate that one MagLev (magnetically levitated) wind turbine, could supply enough energy to 750,000 houses and will require less than 100 acres of land [14]

[20] MagLev in Art Galleries [14]

[21] MagLev Wind Turbine [14]

All is all, there is no doubt that in the future, and possibly in the near few decades, we will begin to see many more application of the Meissner Effect in the news, and very possibly in our daily lives as well.

IX. | Conclusion and Summary

We have seen therefore and thereafter, the significance the Meissner effect, superconductivity, and the phenomenon of magnetic levitation will have in future technological inventions. We have explored the history of the discoveries, and have discussed the science behind these phenomena both on the subatomic, and physical level.

We have explored the conceptual physics behind superconductivity and the Meissner Effect. and seen that once a potentially superconducting material reaches its critical temperature, its atoms stop vibrating, and align in cooper pairs, which expels internal magnetic fields, locks the magnetic flux, and allows quantum locking with other body-magnets, and their magnetic levitation. Furthermore, we have explored the two types of superconductors, and have determined the advantages and disadvantages of each.

Our society is rapidly and exponentially developing technological inventions to better our future, as we have seen that magnetic levitation and quantum locking can be used to improve efficiency and effectiveness in criminology, the transpiration industry, and more.

As our modern society had already begun putting quantum locking and magnetic levitation up to good use, it is without a doubt that the discoveries and scientific observations discussed throughout this paper have been of a significance in the past, and will play a major role and our technological development in the near, and far, future.

X. | Bibliography

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