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ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Anleitung Nr:

Superconductivity

Authors: Philip Maechler (2009) and M. Leopold (2011)
Translation: Paolo Molignini, Felix Winterer, Gumbsch Thomas,
Ye Tao (2012),
revision: Thomas Ihn (2015)

Contents

1 Introduction

This manual is intended to give a short introduction to superconductivity, to get you familiar with key components of the experimental setup, and to provide sufficient details to guide you through the experiment. Interested students should consult additional literature (in particular, we recommend: Ibach-Lüth, Festkörperphysik, Springer-Verlag) to gain a deeper understanding of this fascinating phenomenon.

1.1 The Phenomenon

In 1911, Heike Kamerlingh Onnes discovered that the electrical resistance of mercury suddenly vanishes below a temperature of 4.19 Kelvin. A new phenomenon that had not even been surmised, now called superconductivity, was thus discovered. Generally, superconductors are materials in which the electrical resistance drops to unmeasurably small values when they are cooled below a critical temperature, T_{c}, of a value characteristic to the particular material. Similarly, at a fixed temperature below the critical temperature T_{c}, superconducting materials cease to superconduct in the presence of an external magnetic field with strength greater than some critical value, H_{c}. The critical magnetic field at a given temperature T is approximately given by

$$H_{\mathrm{c}}(T) = H_{\mathrm{c}}(0)\left[1 - \left(\frac{T}{T_{\mathrm{c}}}\right)^2\right]. \tag{1}$$

Intuitively, this effect seems related to the destruction of superconductivity by circular currents, because an external magnetic field induces circular currents in a superconductor to create a magnetization opposing the external field.

Thermodynamically speaking, superconductivity can be regarded as a phase of matter with a continuous phase transition from the normal to the superconducting state. As a result, a state in the phase-diagram shown in Fig. 1 is independent of the path followed for reaching the state. Given that $\rho = 0$ (ρ denotes the electrical resistivity), one can use the relevant Maxwell equations to show that the magnetic field $\mathbf{B}$ must vanish inside a superconductor, i.e.

$$\mathbf{B} = 0. \tag{2}$$

This effect called the Meissner-Ochsenfeld effect can be used to explain the very famous experiment of a magnet levitating over a superconductor (or, equivalently, a superconductor levitating over a magnet) shown in Fig. 2.

Figure 3 highlights key differences between a superconductor and a perfect conductor (i.e. a material with $\rho = 0$).

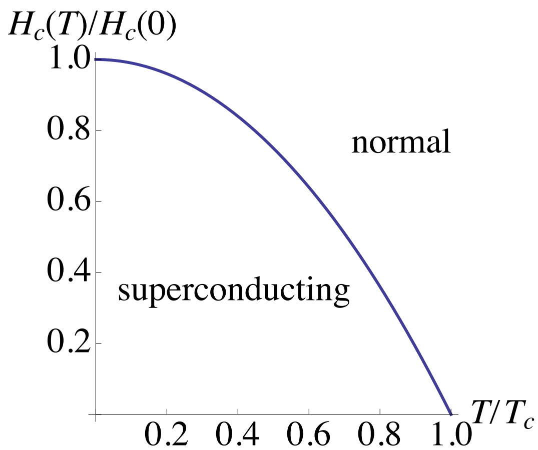

Figure 1: Phase diagram for critical magnetic field as a function of the temperature T.

Figure 2: A magnet levitates over a superconductor cooled by liquid nitrogen.

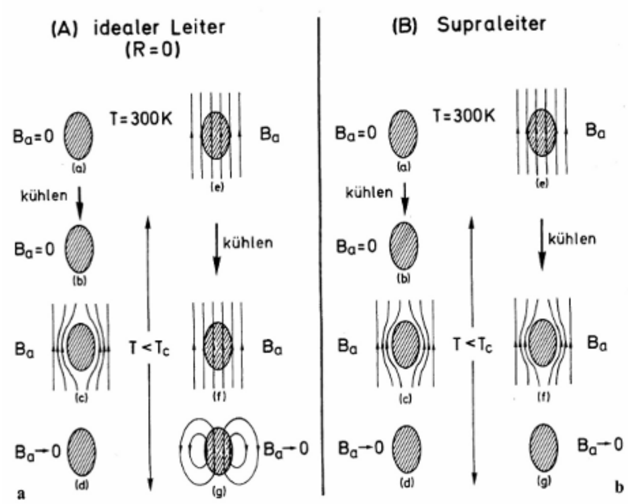

Abb. 10.4. Magnetisches Verhalten eines idealen Leiters (A) und eines Supraleiters (B). (**a**) Beim idealen Leiter hängt der Endzustand (*d*) oder (*g*) davon ab, ob die Probe zuerst unter T_c abgekühlt und dann das Magnetfeld $\boldsymbol{B}_a$ eingeschaltet wurde oder ob umgekehrt im $\boldsymbol{B}_a$-Feld abgekühlt wurde: $(a \to b)$-Probe verliert Widerstand durch Abkühlen bei abgeschaltetem Magnetfeld. (*c*) Anlegen des $\boldsymbol{B}_a$-Feldes an widerstandslose Probe. (*d*) $\boldsymbol{B}_a$-Feld abgeschaltet. $(e \to f)$-Probe verliert Widerstand im Magnetfeld. (*g*) Magnetfeld $\boldsymbol{B}_a$ abgeschaltet. (**b**) Beim Supraleiter ergeben sich gleiche Endzustände (*d*) und (*g*) unabhängig von der Reihenfolge zwischen Anlegen des Magnetfeldes $\boldsymbol{B}_a$ und Abkühlen der Probe: $(a \to b)$-Probe verliert Widerstand bei abgeschaltetem Magnetfeld. (*c*) Anlegen des $\boldsymbol{B}_a$-Feldes an supraleitende Probe. (*d*) $\boldsymbol{B}_a$-Feld abgeschaltet. $(e \to f)$-Probe wird supraleitend im angelegten Magnetfeld $\boldsymbol{B}_a$. (*g*) Magnetfeld $\boldsymbol{B}_a$ abgeschaltet

Figure 3: A superconductor and a perfect conductor in comparison [from Ibach and Lüth: "‘Solid state physics"’, Figure 10.4]

A superconductor shows perfect diamagnetic behavior, expressed as

$$\mathbf{M} = -\mathbf{H}_{\mathrm{a}}, \tag{3}$$

where $\mathbf{H}_{\mathrm{a}}$ denotes the applied external field and $\mathbf{M}$ the magnetization (in SI units). Therefore, the magnetization curve has the shape shown in Fig. 4.

1.2 Type-I and type-II superconductors

Pure samples of many materials show similar magnetization curves to the curve shown in Fig. 4. In contrast, almost every alloy or so-called high-temperature superconductor (i.e. a superconductor with $T_{\mathrm{c}} > 23$ K) has different-looking magnetization curves. They are called type-II superconductors.

In the absence of an applied external field, type-I and type-II superconductors have similar thermal properties and their electrical resistance vanishes at temperatures below T_{c}. If a strong magnetic field $\mathbf{H}_{\mathrm{a}}$ were applied, the two types differ in the transition between the normal and the superconducting states. An almost perfect type-I superconductor (little impurity or flaws and a homogenous magnetization) expels an applied magnetic field $\mathbf{H}_{\mathrm{a}}$ until superconductivity is destroyed abruptly above $|\mathbf{H}_{\mathrm{a}}| > H_{\mathrm{c}}$. A type-II superconductor expels an applied field completely until a first critical magnetic field, $H_{\mathrm{c}1}$. Above $H_{\mathrm{c}1}$, the external field is no longer completely expelled, while the

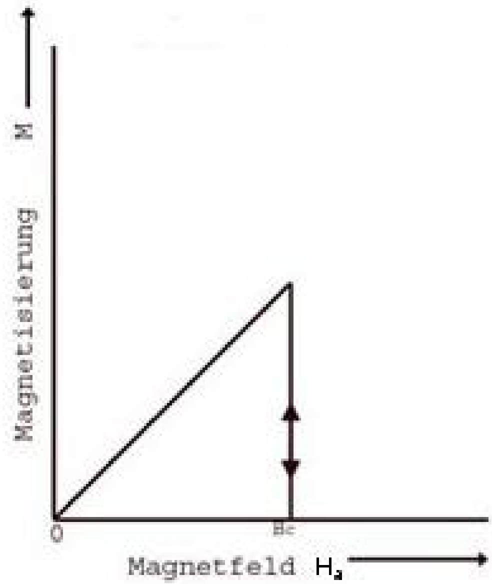

Figure 4: Idealized magnetization curve of a type-I superconductor.

sample nevertheless remains superconducting. Magnetic field lines enter the sample through small magnetic flux lines. The magnetic flux in these lines is an integer multiple of the magnetic flux quantum $\Phi_0 = h/(2e)$. It is worth noting that this experimentally-verified result can be regarded as evidence for superconducting charge carriers with twice the elementary electric charge (cf. Cooper pairs in section 2.3). Finally, it is only when the applied filed reaches a value of H_{c2} that flux permeates the material to completely eliminate superconductivity.

It turns out[1] that for decreasing thickness, the reaction or sensitivity of the superconductor to the external field decreases; the external field H_c needed to destroy superconductivity increases if the smallest dimension of the superconductor is of a thickness comparable to the London penetration depth.
Based on London theory (section 2.1), the superconductor can be divided into a normal and a superconductive phase, in which the former is located near the boundaries of the superconductor having a thickness comparable to the London penetration depth. The magnetization curves for superconductors of type-II have the shape shown on the right side of Fig. 5, the magnetization

[1]consult additional literature for more details

curve of a type-I superconductor is given on the left side.

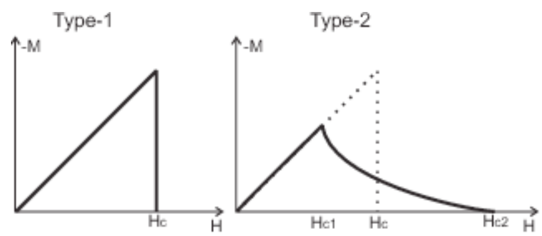

Figure 5: Magnetization curves of type-I and type-II superconductors in comparison.

From Ginzburg-Landau theory (section 2.2), it can be shown that the mean free path of the electrons in the normal conducting state plays a very important role in explaining these properties. Ginzburg and Landau used numerical integration to show that the transition between superconductors of type-I and II takes place at $\kappa = 1/\sqrt{2}$, where κ is the Ginzburg-Landau parameter as defined in section 2.2. It is possible to build superconductors of type-II by adding impurities to a superconductor of type-I thereby decreasing the mean free path (without actually changing the electrical properties). That is why type-II superconductors are often alloys or transition metals with higher electrical resistance in the normal state.

2 Theory

2.1 London Theory

The suppression of magnetic field inside a superconductor cannot extend to exactly at the interface between the superconductor and the outside, because otherwise an infinitely large current density at the surface would be required to produce the field discontinuity ($\mathbf{H}_{\mathrm{a}}$ to 0). The London Theory gives a phenomenological description through the London equations (n: charge carrier density; $\mathbf{j}$: current density).

The first London equation

$$\frac{\partial \mathbf{j}}{\partial t} = \left(\frac{nq^2}{m}\right) \mathbf{E} \tag{4}$$

describes ideal conduction (vanishing resistivity, but the presence of a kinetic inductance).

The second London equation

$$\nabla \times \mathbf{j} = -\left(\frac{nq^2}{m}\right) \cdot \mathbf{B} \tag{5}$$

describes the Meissner-Ochsenfeld effect.

Together with the first Maxwell equation

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} \tag{6}$$

one obtains $\nabla^2 \mathbf{B} = \nabla \times \mu_o \mathbf{j} = -\left(\frac{\mu_0 n e^2}{m}\right) \mathbf{B}$.
It follows that

$$\Delta \mathbf{B} = \frac{\mu_0 n q^2}{m} \mathbf{B}. \tag{7}$$

To deal with the surface layer, one considers a plane orthogonal to the x-direction and a magnetic field $\mathbf{B} = (0, 0, B_z)$. With Eq.(7) it follows that

$$\frac{\partial^2 B_z(x)}{\partial x^2} - \left(\frac{\mu_0 n e^2}{m}\right) B_z(x) = 0.$$

This equation is solved by

$$B_z(x) = B_z(0) e^{-\frac{x}{\lambda_L}}, \tag{8}$$

where

$$\lambda_{\mathrm{L}} = \left(\frac{m}{\mu_0 n q^2}\right)^{\frac{1}{2}} \tag{9}$$

is the London penetration depth. Since $n = n(T)$, one concludes $\lambda = \lambda(T)$. More specific information concerning this topic can be found in the next section.

2.2 Ginzburg-Landau Theory

The Ginzburg-Landau theory (named after Lew Dawidowitsch Landau and Witali Lasarewitsch Ginzburg), based on thermodynamic arguments , is another theory describing the macroscopic properties of superconductors. Ginzburg and Landau introduced a complex order parameter Ψ, which they normalized according to $|\Psi|^2 = n_{\mathrm{s}}$, where $n_{\mathrm{s}} = n_{\mathrm{s}}(T)$ is the density of superconducting charge carriers. The aim was then (the motivation for that step originates from Landau's theory of second-order phase transitions) to approximate the free energy F (an independent thermodynamic quantity) close to the phase transition using the parameter Ψ. This order parameter describes how far the system is in the superconducting state. In doing so $\Psi = 0$ corresponds to the normal state. $\Psi \neq 0$ is therefore possible only for temperatures below T_{c}.
An approximation of the free energy around the critical point T_{c} is

$$F_{\mathrm{s}} = F_{\mathrm{n}} + \alpha n_{\mathrm{s}} + \left(\frac{\beta}{2}\right) n_{\mathrm{s}}^2 + \frac{1}{2m}\left|\left(\frac{\hbar}{i}\nabla - 2e\mathbf{A}\right)\Psi\right|^2 + \frac{|\mathbf{B}|^2}{2\mu_0} \tag{10}$$

where F_{n} denotes the free energy in the normal state, α and β are phenomenological parameters, $\mathbf{A}$ is the vector potential through $\mathbf{B} = \nabla \times \mathbf{A}$. One can rewrite this equation via the Legendre-transform $G = F - \mathbf{B} \cdot \mathbf{H_a}$ and approximate the Gibbs-energy G (also called free enthalpy). The quantity $\mathbf{H_a}$ denotes the external magnetic field. The result is

$$G_{\mathrm{s}} = G_{\mathrm{n}} + \alpha n_{\mathrm{s}} + \left(\frac{\beta}{2}\right) n_{\mathrm{s}}^2 + \frac{1}{2m}\left|\left(\frac{\hbar}{i}\nabla - 2e\mathbf{A}\right)\Psi\right|^2 + \frac{|\mathbf{B}|^2}{2\mu_0} - \mathbf{B} \cdot \mathbf{H_a}. \tag{11}$$

In thermodynamic equilibrium $\partial G_{\mathrm{s}}(0)/\partial n_{\mathrm{s}} = 0$ must hold at the point of vanishing field. Hence,

$$n_{\mathrm{s}}(0) = -\frac{\alpha}{\beta} \quad \text{and} \quad G_{\mathrm{s}}(0) - G_{\mathrm{n}}(0) = -\frac{\alpha^2}{2\beta}. \tag{12}$$

Therefore, $\beta > 0$ must hold. Otherwise, Gibbs' energy would be inverted for arbitrary big values of n_s. With $\beta > 0$, $\alpha \leq 0$ follows directly. The temperature dependencies of α and β are within a first order approximation around T_c given by

$$\alpha = (T_\mathrm{c} - T)\left(\frac{\partial\alpha(T_\mathrm{c})}{\partial T}\right) \quad \text{and} \quad \beta = \text{const.} \equiv \beta_c. \tag{13}$$

Yet the difference of the Gibbs energy of the phases (normal and superconducting) is equal to the magnetic energy

$$-\frac{H_\mathrm{c}^2}{2\mu_0} = -\frac{\alpha^2}{2\beta}. \tag{14}$$

Thus it follows, that

$$H_\mathrm{c} = \alpha_0(T_\mathrm{c} - T), \tag{15}$$

where

$$\alpha_0 = \left(\frac{\mu_0}{\beta_c}\right)^{1/2}\left|\left(\frac{\partial\alpha(T_c)}{\partial T}\right)\right| > 0$$

is a constant.
The (first and second) Ginzburg-Landau equations

$$\alpha\Psi + \beta|\Psi|^2\Psi + \frac{1}{2m}\left(\frac{\hbar}{i}\nabla - 2e\mathbf{A}\right)^2\Psi = 0 \tag{16}$$

$$\frac{\nabla^2\mathbf{A}}{\mu_0} = \mathbf{j_s} = -\frac{i\hbar e}{2m}\left(\Psi^\star\nabla\Psi - \Psi\nabla\Psi^\star\right) - \frac{2e^2}{m}|\Psi|^2\mathbf{A} \tag{17}$$

follow from Eq. (10) and after minimizing for Ψ and $\mathbf{A}$.

Now, one can define the penetration depth as

$$\lambda_\mathrm{L} = \sqrt{\frac{m}{(2e^2)\mu_0\Psi_0^2}} = \sqrt{\frac{m\beta}{(2e^2)\mu_0|\alpha|}}, \tag{18}$$

where Ψ_0 denotes the order parameter in the equilibrium state and $2e$ is the charge of the Cooper pair (see BCS theory).
A further characteristic quantity of the superconductor is the coherence length ξ, which describes how fast the density of the superconducting charge carriers (hence, the Cooper pairs) decays. It is given by

$$\xi = \sqrt{\frac{\hbar^2}{2m|\alpha|}}. \tag{19}$$

The ratio of these quantities is known as the Ginzburg-Landau parameter

$$\kappa = \frac{\lambda_\mathrm{L}}{\xi}. \tag{20}$$

Upon suppression of the external field $\mathbf{H}_\mathrm{a}$, the energy of a superconductor is increased by $\mathbf{H}_\mathrm{a}^2/(2\mu_0^2)$ per volume unit. Therefore, it can be favorable for a superconductor to split into a very large number of normal and superconducting layers, in which the width of the superconducting layers needs to be less than λ_L and the normal layers should be even narrower. Since the normal layers, being very thin, contribute little to the total energy, the resulting flux of the external magnetic field through the superconducting layers would dramatically reduce the sample's magnetic energy penalty for being superconducting. However, such a configuration would be unfavorable if there were a surface energy at play.

When all superconducting layers are thinner than λ_L, a sample plate of thickness d must contain at least d/λ_L of such layers. This configuration would be prohibited by a surface energy α_ns, whose contribution from interface area exceeds the gain in bulk magnetic energy, meaning

$$\frac{2d}{\lambda_\mathrm{L}}\alpha_\mathrm{ns} > \frac{\mathbf{H}_\mathrm{c}^2}{2\mu_0^2}d \quad \Rightarrow \quad \alpha_\mathrm{ns} > \frac{\lambda_\mathrm{L}\mathbf{H}_\mathrm{c}^2}{4\mu_0^2} \quad \text{or} \quad \Delta > \frac{\lambda_\mathrm{L}}{2}, \quad \text{with } \Delta = \frac{2\mu_0}{\mathbf{H}_\mathrm{c}^2}\alpha_\mathrm{ns}.$$

The energies refer to the volume of a plate with unity surface area ($S = 1\ \mathrm{m}^2$). The parameter Δ was chosen to be in units of length. It turns out that the empirical values for Δ for a pure superconductor are an order of magnitude bigger than the London penetration depth λ_L.

The surface energy can be positive or negative. If it is always positive the material belongs to the type-I superconductors, because the field is then always pushed out of the bulk of the superconductor for temperatures below T_c, but this impenetrability abruptly drops upon reaching T_c. As mentioned before, Ginzburg and Landau found through numerical integration that the transition between the two types of superconductivity occurs at $\kappa = 1/\sqrt{2}$. If $\kappa < 1/\sqrt{2}$ the material is a type-I superconductor, otherwise it is a type-II superconductor. It is now also clear why a reduction of the mean free path of the free electrons can lead to a type-II superconductor: the mean free path is proportional to the coherence length ξ. Reducing the mean free path increases the Ginzburg-Landau-Parameter $\kappa = \lambda_\mathrm{L}/\xi$, progressively leading to a type-II superconducting behavior.

2.3 BCS theory

The BCS theory offers (at least for metals) a microscopic explanation of superconductivity. This theory was developed in 1957 by John Bardeen, Leon N. Cooper and John R. Schrieffer, for which they earned the Nobel prize in physics in 1972. Almost half a century had then elapsed between the first discovery of superconductivity and its theoretical explanation. It is therefore not surprising that we are still lacking a theory to explain the high-temperature superconductive ceramics discovered in 1986.

Let us return now to the BCS theory. Since this theory is both very comprehensive and not easy to understand, only fragments and the most important conclusions will be presented here. In 1956 Cooper discovered that the model for free electrons in the approximation $T = 0$ K, the so-called Fermi gas at $T = 0$ K where electrons are governed by Fermi-Dirac statistics (more details can be found in the literature of solid state physics), breaks down if even a very small interaction between pairs of electrons is allowed. One can think of this phenomenon in the following, simplified way:

Along its path through the solid body, the electron leaves behind a deformation trace of the ion cores due to its negative charge (in the quantum mechanical description this is called electron-phonon interaction, and phonons represent quantized lattice vibrations). This trace leads to a concentration of positive charge of the ion cores, which then acts attractively towards another electron. In this simplified model the lattice deformation leads therefore to an attractive electron-electron interaction. It is also important to note here that the deformation (corresponding to a polarization of the lattice structure) is delayed with respect to the electron (the electrons have a high speed, whereas the lattice follows more slowly). The two electrons being related by the lattice deformation have then a separation of around 1000 Å. Thus, the repulsive Coulomb potential between the electrons no longer plays a significant role.

These spatially correlated electrons are named Cooper pairs after their deviser. Cooper pairs represent so called *spin-singlets* having a total spin zero. They can therefore be considered as bosons and do not need to satisfy Pauli's exclusion principle. In particular, an unlimited number of Cooper pairs can occupy the ground state. The experimental foundation upon which this assumption was constructed was a dependence of the critical temperature T_c on the isotopic composition of the probed superconductive materials. The mass-dependent phonons (respectively their dispersion) offered then a plausible explanatory model for the observed phenomenon.

It can be shown within BCS theory that binding electrons in Cooper pairs

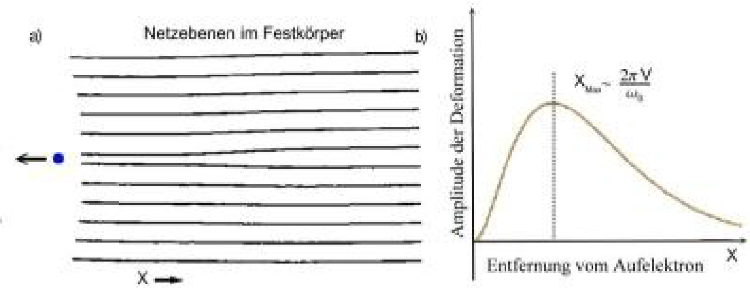

Figure 6: Illustration of the lattice distortion caused by a single electron (left), and of the delayed response of the lattice to the presence of the electron (right). Taken from Ibach-Lüth, Festkörperphysik, Fig. 10.7.

and condensing them into the ground state is energetically more favorable than keeping individual electrons. The superconducting state can now be described by a macroscopic wave function, the Bose-Einstein wave function. This macroscopic wave function can no longer be influenced by local obstacles (like atom cores and lattice impurities in general), which generally lead to electric resistance. Resistance-free electric transport, namely superconductivity, can thereby be achieved.

Another essential assertion of BCS theory is the existence of a temperature-dependent energy gap Δ (respectively 2Δ) in the excitation spectrum of a superconductor. Furthermore $\Delta(T_c) = 0$, since no energy gap should be found at the transition between normal and superconducting states. This energy gap is therefore of a different nature compared the gap in a semiconductor. Computing the difference in energy between the ground state and the first excited state of a Cooper pair, it can be found that the minimal energy required for an excitation is 2Δ. This is exactly the energy needed to split a Cooper pair into uncorrelated electrons. This value is related to the critical magnetic field and to the critical current density. The critical current density can be estimated to be

$$j_c \approx \frac{e n_s \Delta}{\hbar k_F}.$$

Here, n_s is the density of Cooper pairs (see also Ginzburg-Landau theory) and k_F is the Fermi wave vector, i.e., the k-value of an electron originating from splitting a Cooper pair corresponding to a Fermi energy $E_F = \hbar^2 k_F^2 / 2m$ (k_F is of the order of 10^8 cm^{-1}). The critical magnetic field is given by

$$H_c = \lambda_L j_c \approx \lambda_L \frac{e n_s \Delta}{\hbar k_F}.$$

Besides that, there is also a correlation of the energy gap with the condensation energy density. Superconductivity collapses if the external magnetic field exceeds the value H_c, which is equivalent to the statement that the energy density of the magnetic field $\mu_0 H_c^2/2$ exceeds the condensation energy density for Cooper pairs, because from this point on Cooper pairs start to split. The condensation energy density is given by

$$E_{\mathrm{Con}} = -\frac{1}{2} Z(E_{\mathrm{F}}) \Delta^2,$$

where $Z(E_{\mathrm{F}}) = D(E_{\mathrm{F}})/2$ is half of the density of states (DOS) at the Fermi energy for a free electron gas (the factor $1/2$ comes from the fact that only states of *pairs* are considered).

The BCS theory also provides an equation which (for a type-II superconductor) links the Ginzburg-Landau-parameter κ to the critical magnetic fields H_{c1} and H_{c2}, namely,

$$\frac{\xi}{\lambda_{\mathrm{L}}} = \kappa = \sqrt{\frac{H_{c2}}{2H_{c1}}}.$$

Here we end with our brief overview of BCS theory. For a better understanding a more thorough study of the suggested (or other) literature is necessary.

3 Experiment: description of the measurement setup

Before describing the assignments and the relevant measurements, the two main components of the measuring device will be presented.

3.1 The cryostat

The cryostat (see Fig. 7) is an apparatus in which samples can be cooled to very low temperatures and at the same time be subjected to an external magnetic field. Nowadays, such cryostats have become a standard piece of equipment in many laboratories and research facilities. Using so-called ^{3}He-^{4}He mixture cryostats, temperatures in the milli-Kelvin domain can be reached and magnetic fields up to 10–20 Tesla can be generated with superconducting magnets. The cryostat used in this experiment is composed of four cylindrical compartments having different functions. The outermost compartment serves as a vacuum insulation layer, insultating the inner chambers from ambient temperatures. Inside this layer is the compartment in which liquid nitrogen stabilizes the temperature to 77 K. Within this liquid nitrogen bath, another vacuum layer thermally insulates the innermost chamber, the liquid ^{4}He bath (4.2 K), from the nitrogen bath. Inside the liquid-He bath the superconucting coil generating the external magnetic field is situated. Refrigeration with liquid nitrogen is adequate for superconductivity only if the coil is made of a high-temperature superconductor, e.g. cuprates. These types of solenoids are, however, difficult and expensive to produce. For this reason most solenoids are made of an alloy such as niobium-titanium: its critical temperature is 9.2 K and it remains superconducting up to 15 Tesla). Since they normally have a low critical temperature, they must be cooled in the liquid helium bath. The sample is located in the central liquid ^{4}He chamber as well.

The first cooldown of the experiment with the cryostat **must be conducted under the assistant's supervision**. The following is a brief description of the cooling procedure. Note that the electrical circuits used in the measurement and in other preparations should be set up independent of the following steps:

1. At the beginning, the vacuum chamber separating the liquid nitrogen bath from the ^{4}He-bath must be evacuated with the pump to ensure optimum thermal isolation. Turn on the pump with all valves closed. Then open all the valves from the pump to the vacuum chamber, starting with the valve closest to the pump and ending with the valve closest to the cryostat. When you open new volumes to the pump that contain much

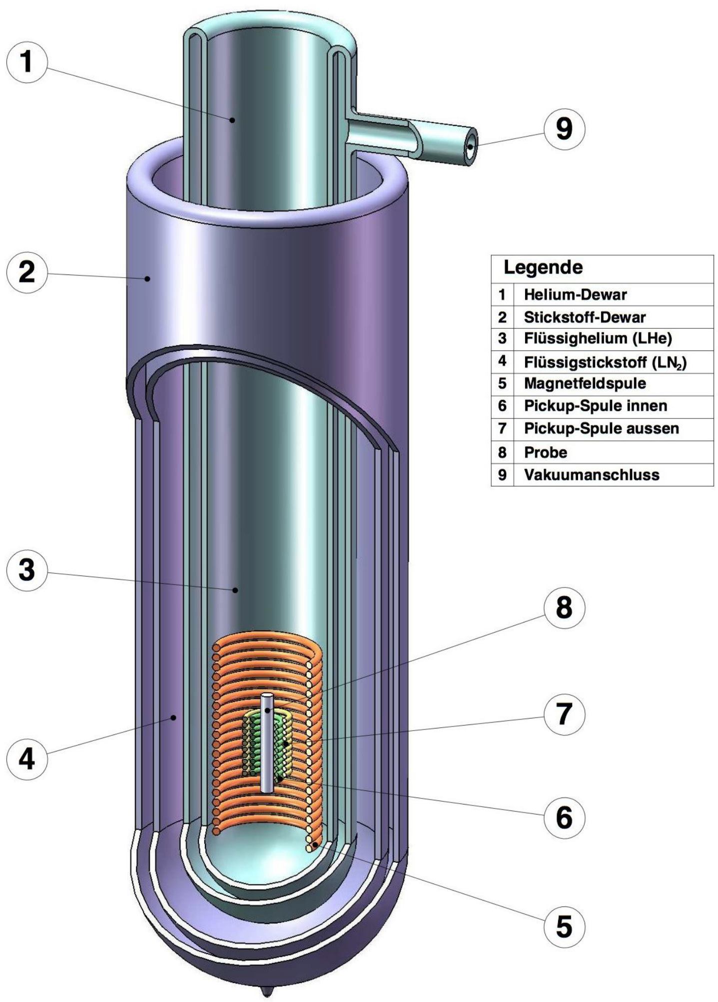

Figure 7: The cryostat used for the experiment.

higher pressures than the pumped volume, open the valve gradually and slowly. This will avoid damage to the pump.

2. In order to remove residual helium that could have diffused through the glass of the vacuum compartment, the latter is flushed with nitrogen gas. To this end, fill a rubber bladder with nitrogen gas, attach it to the pumping system and then release its content into the vacuum compartment. Make sure that you admit nitrogen into the vacuum system **only after** you have closed the valve to the pump! Otherwise the high pressure of nitrogen will damage the pump severely.

3. For completing the flushing cycle, the vacuum compartment has to be pumped for some time. Eventually, the pressure on the barometer indicator should reach approximately 0.03 mbar and stay stable. You need to repeat the flush and pump cycle (2 and 3) for at least 3 times to ensure successful cooling later on.

   In the meantime you can fill a sufficient quantity of liquid nitrogen needed for cooling (around 10 ℓ) from the nitrogen storage dewar into a smaller dewar and bring it to the experiment.

4. After repeated flushing and after the vacuum has reached the pressure of 0.03 mbar, close all the valves, beginning with the chamber valve, and turn off the pump (you may leave the pump running throughout the rest of the experiment if you suspect a leak in the vacuum chamber valves).

5. In the next step the cryostat is the pre-cooled with liquid nitrogen. For this purpose, pour liquid nitrogen from the small handy dewar into the liquid nitrogen chamber (second compartment) through a funnel at the top of the cryostat. Fill the liquid to the top of the chamber. Top-up liquid nitrogen until the nitrogen in the chamber only boils ("fizzles") slightly. This indicates that the cryostat is completely pre-cooled to 77 K.

   Safety instructions, please read carefully: A brief skin contact with liquid nitrogen is, in principle, not dangerous (as opposed to skin contact with liquid helium, which can easily cause blistering and burning!), because as soon as the liquid reaches the skin, a fine gaseous insulating layer is created between the warm skin and the cold nitrogen. Nevertheless, there is still a risk of burning and injury when you touch refrigerated material (e.g. connecting pipes) and if liquid nitrogen gets trapped under your clothes. For these reasons, wear insulating gloves and safety goggles **all the time**, and work very carefully, when you handle cryogenic liquids and gases!

6. Finally, the innermost chamber of the pre-cooled cryostat is filled with liquid helium. For safety reasons, please do this only under the assistant's supervision (first time), or in the presence of another person in the room (when you feel safe). It has to be noted that the compartment containing liquid nitrogen has to be constantly topped up during the experiment, because the liquid nitrogen constantly boils off.

3.2 The Pick-up Coil System

The pick-up coil system (see Fig. 7 and Fig. 8) measures the magnetization of the sample. It consists of two oppositely-wound coils housed inside a white plastic casing at the end of a long rod. The (warm) assembly is to be inserted **very slowly** into the liquid helium bath of the cryostat. If you insert it to fast, you boil off a lot of He and you risk to be burned by He. The insert is kept at liquid helium temperatures during the measurement.

The actual pick-up coil circuit is made of an inner coil that surrounds the sample and an outer coil that surrounds the inner coil. The two coils are concentric and wound in opposite directions. In data collection configuration, the two coils and an external potentiometer (a pair of variable resistors with a constant total resistance) will be connected all in series to form a single closed loop. The signal is measured as the voltage between points 1 and 2. Point 1 is between the two variable resistors of the potentiometer. Point 2 is between the two coils.

Before performing measurements on a real sample, you need to perform a background calibration in the absence of the sample. The goal of this calibration step is to make sure that the voltage drop between Point 1 and Point 2 remains approximately zero when you sweep the external magnetic field. This is achieved by adjusting the values of the two variable resistors of the external potentiometer. Once a good background has been achieved, save a background dataset for later use in the data analysis. It is a useful and not completely trivial exercise to show that the voltage drop between Point 1 and Point 2 will be proportional to sample magnetization, when the potentiometer is well-adjusted.

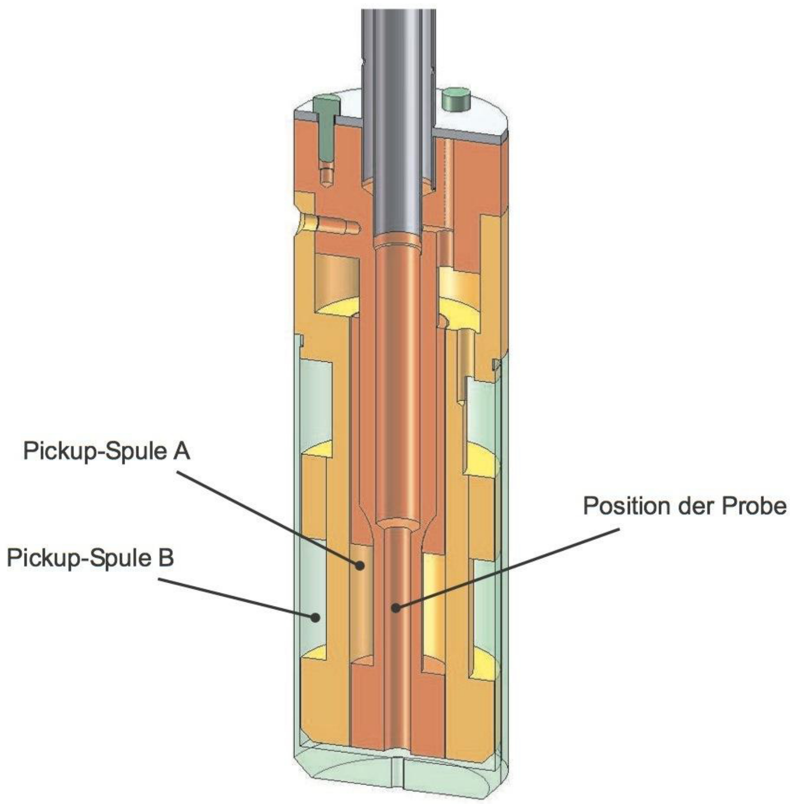

Figure 8: Detailed cross section of the sample stage.

4 Measurement and Tasks

4.1 Measurement

The final objective is to record the magnetization curve of three different superconductors, including, if possible, a type-I and two type-II superconductors. Usually you can carry out all measurements within one day, so that you need to cool down the cryostat only once. A second cooldown may be necessary, if you did not finish whithin the first cooldown, or if your measurements turn out to have flaws.

The measurement is carried out with a modern computer-controlled implementation of an X-Y recorder. The X-input (channel 1) is used to monitor the current flowing through the magnet, which can later be used to calculate the applied magnetic field. Connect a 0.05 Ω precision resistor in series with the magnet and the current source. Measure the voltage drop across this precision resistor via the input of channel 1 and record it using Labview. To wire up the Y-signal for monitoring the magnetization, you need to connect both coils and the potentiometer in series. Point 1 and Point 2 of the circuit described previously need to be fed to the integrator inputs. The output of the integrator goes is the Y-signal (channel 2).

When everything is wired and the assembly is at liquid He temperatures, balance the pick-up coil as described above to obtain approximately zero measured voltage during field sweeps (in the absence of a sample, of course).

When you start measuring real samples, make sure that they are screwed securely to the sample rod. Precool the attached sample with liquid nitrogen and insert the sample into the cryostat without causing bending and deformation. These samples are soft metals and should be handled with some care to avoid damaging and jamming the setup.

Finally, please make sure that you record all experimentally relevant details in your lab book to help you with trouble shooting and future report writing.

4.2 Tasks

1. Make sure to finish the measurement as described in section 4.1
2. A famous example of an experiment with superconductors is the levitating magnet experiment (see Fig. 2). Explain this experiment.
3. What is the difference between a sample of pure lead and a sample having mixed components (e.g. Pb and In)? How are they made?
4. Which microscopic interactions form the basis of superconductivity?

5. Estimate the condensation energy density from the measured $M(H)$ curves, and calculate the corresponding energy gap (BCS formula). For type-II superconductors, also determine $(\partial M/\partial H)/H_{\mathrm{c2}}$, H_{c1}, H_{c2}, H_c (an area comparison), and κ (Ginzburg-Landau parameter).

6. Discuss (possibly with the aid of literature) why

   the traces for type-I superconductors show 'softer' maxima and a less abrupt decrease of the magnetization above H_{c} than expected from theory. (hint: demagnetization)

   the magnetization curve during upward field sweep and downward field sweep show extensive hysteresis. (Keyword: pinned (frozen) vortex)

7. Where are the key applications using superconductors? Why are superconductors important for these applications? Which superconducting materials are best suited for these applications?

8. Side note: For those interested, there is a possibility, after consulting with the assistant and the course heads, for working on a hardware upgrade of the experimental system to enable measuring the temperature dependence of $M(H)$.