Experiment Ma8: Superconductivity

1 Overview

Superconductivity is a phenomenon occurring at low temperatures.

H.K. Onnes achieved helium liquefaction in the year 1908 and observed in the year 1911 that the electrical resistivity of some metals sank abruptly below a certain temperature (called transition temperature T_c). Also the specific heat, the heat conduction and the magnetic properties of superconductors differ themselves from the ones of normal conductors. The transition from the normal conducting state to the superconducting state is reversible and for **type 1** (typically pure metals) superconductors occurs typically below 10 K. Superconductors of **type 2** (typically alloys, $T_c < 25$ K, or ceramics $T_c > 25$ K) are mostly exploited for technical applications, for example for constructing magnets for high magnetic fields. The transition temperature is characteristic for each material and it is related to the Debye temperature. Not all the metals become superconductors (for example ferromagnetism excludes superconductivity).

Purpose of this experiment is the measure of the transition temperature of two metals (Tin and Indium) and to investigate magnetic fields effects. Moreover some confidence with a low temperature setup should be gained.

2 Theory basics

In order to understand superconductivity it is important to keep in mind the theory of the **free electron gas** [1]. The **electron density of states** in a normal conductor and the **Fermi function** define the behavior at the Fermi surface. At the superconducting transition the behavior of the electrons changes in the proximity of the Fermi surface; an energy gap is formed around the Fermi-Energy.

This phenomenon is explained through a model, the BCS theory [4], that has been developed half a century after the discovery of superconductivity. This theory explains how two electrons can lower their energy forming a **Cooper pair** with the properties of a boson**.** Differently from normal electrons, which have factionary spin and are thus fermions, bosons have integer spin and do not underlie the Pauli exclusion principle. Further, the BCS model explains the **isotopic effect** (influence of the isotopic composition on superconductivity), the occurrence of an **energy gap** and other superconductors' properties [1],[2],[3],[4]. A pictorial way of describing how a metal can undergo the transition to the superconducting state and transport without any resistance can be found in Ref. [1].

The **Meißner-Ochsenfeld effect**¸ i.e. the expulsion of an external magnetic field in superconductors, will be exploited in order to proof the transition from the normal to the superconducting state [2]. There is a **critical magnetic field** B_c at which the superconducting phase is destroyed. This field depends upon temperature [1]. For $B < B_c$ the susceptibility of the superconducting phase of Type 1 superconductors is $\chi = -1$. Notice that the Meißner-Ochsenfeld effect is an additional property of the superconductor and not a consequence of zero resistivity, i.e. a superconductor is not only an ideal conductor.

The entropy of the superconductive phase is lower than the normal phase, implying that the electrons in the superconductive phase possess a higher degree of order than in the normal one. A discussion of this thermodynamic property of superconductors can be found in [1] as well as the microscopic explanation in [4].

3 Experimental details

3.1 Low temperature setup

The cryogenic system consists of two cryostats: one for the liquid nitrogen and, within this one, a second one for liquid helium (Fig. 1). Between the two cryostats there is an additional vacuum chamber for ensuring better isolation of the He-cryostat. The nitrogen cryostat is at atmospheric pressure while the pressure of the He cryostat can be lowered by means of a vacuum pump. Since the boiling point of fluids depends on pressure, you can lower the temperature of the liquid helium below 4.2 K by lowering the pressure. Both cryostats are made of glass and silver coated; a transparent window in the coating ensures optical access to the chamber. In this way it is possible to see the liquid nitrogen in the outer dewar and the liquid helium in the inner dewar. At 2.17 K the liquid He undergoes the superfluid transition (zero entropy, zero viscosity, ballistic thermal conductivity, Bose-Einstein condensation) and you can observe the different behavior. Since helium is rare, the evaporating gas is collected by backflows lines and recycled.

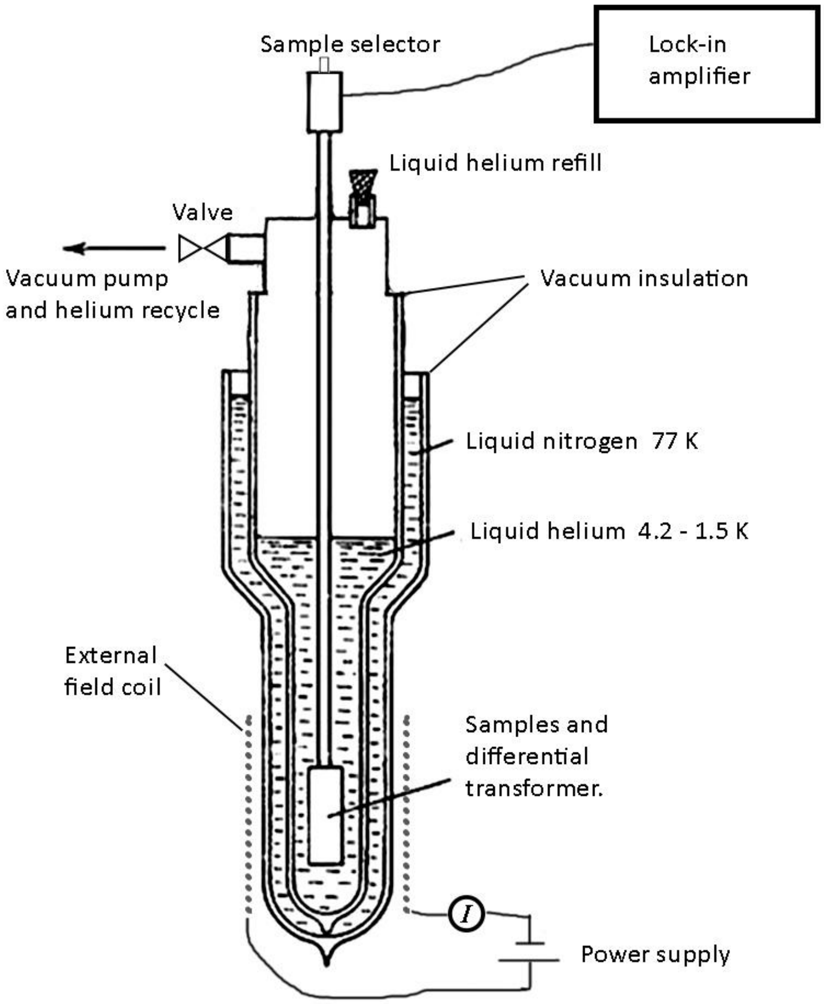

Figure 1: Low temperature setup

ATTENTION – PRECAUTIONS YOU NEED TO TAKE

A. All mechanical connections with the glass parts have to be applied carefully. **Risk of breaking!**
B. Liquid nitrogen and liquid helium must be filled in the cryostats just under the control of the supervisor.
C. Before filling the liquid nitrogen please be sure that there is no water left within the cryostat. **Risk of breaking!**
D. Before filling the liquid helium, please be sure the He cryostat and the connectors to the pump are sealed. Take care to avoid overpressure in the liquid helium dewar.
E. Avoid operating the outer field coil for long time at high current. Risk of overheating.

3.2 Measurement

The change of susceptibility, measured through an induction system, is used to proof the change from normal to superconducting state. The sample, placed within measuring coils, is located in the He bath-cryostat (Fig. 1). Through reduction of the pressure of the He chamber, the temperature can be reduced from 4.2 K to 1.5 K. The whole cryostat inserted in an outer coil, which is used to produce an additional magnetic field. The relation between current and magnetic field is given by the calibration relation:

$$B = (5.3 \pm 0.2)\ \mathrm{mT/A} \cdot I$$

The principle of measurement is based on the transformer (see Fig. 2). The induced secondary voltage depends upon the coupling of the inductances. A change of the susceptibility of the sample produces a change in the induced secondary voltage.

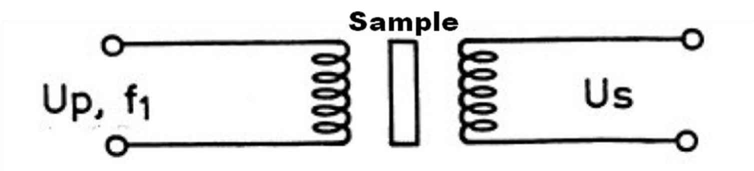

Figure 2: Transformer circuit for the determination of changes of the susceptibility of a sample; U_p is the primary voltage at frequency f_1 while U_s is the secondary voltage.

The secondary voltage will be registered as a function of the temperature or as a function of the external magnetic field. To increase the sensitivity of your measurement you will use two similar coupled inductances connected to each other (differential transformer). One of the two transformers will have an empty sample compartment. The change of the secondary voltage will be analyzed by the lock-in amplifier in a frequency- and phase-sensitive way (see Fig. 3).

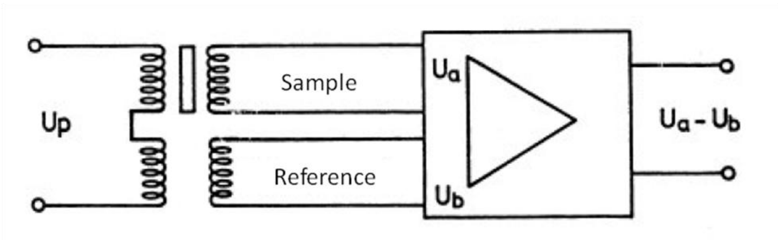

Figure 3: Sketch of the setup for the determination of changes in the sample voltage through the lock-in technique. For $T > T_c$ set U_a-$U_b = 0$, for $T < T_c$ you will measure $|U_a| < |U_b|$.

For an accurate determination of the T_c and the B_c at different temperatures, the transition from normal to superconductor will be measured pointwise. It is thus possible to obtain T_c and B_c from the behavior of the U_a - U_b as shown from the scheme in Fig. 4. The range $2\delta T_C$ characterizes the range on which transition between the two phases takes place. You can fit the data with a sigmoid function (e.g. error function).

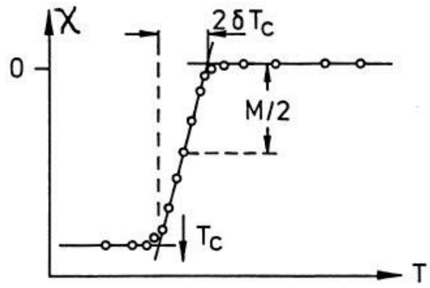

Figure 4: Behavior of χ during the transition from normal conducting state to superconducting state.

3.3 Instrument list

Cryostats, two stages vacuum pump, valves, gas flow meter, absolute pressure meter, Lock-in amplifier, oscilloscope, coil with power supply, multimeters.

4 Assignments

Experimental tasks. For task *a* and *b* you will reduce the temperature from 4.2 K to 1.5 K by lowering the pressure above the surface of the liquid helium. Beware for a given pressure the boiling point is given, i.e. the maximum temperature of the liquid (water at atmospheric pressure can have any temperature up to 100°C, but not above!). Since you can measure only pressure and *not* temperature, you should only reduce the pressure and the temperature once during the experiment.

a) Determine the transition temperature $T_c(B = 0)$ for two metals, Tin (Sn) and Indium (In). Please, choose your sampling frequency in a proper way in order to be able to follow the transition. (Tip: work with slowly falling pressure. Do not try to stop for the measuring points or go back to higher temperatures.)

Here are some suggested values for a proper sampling of the two samples:

Sn in the range	**(650,570)** mbar	-	sampling: **4** mbar
In in the range	**(440,420)** mbar	-	sampling: **4** mbar
	(420,416) mbar	-	sampling: **2** mbar
	(416,400) mbar	-	sampling: **1** mbar
	(400,390) mbar	-	sampling: **2** mbar

b) Determine for both samples the $B_c(T)$ value at four different temperatures (suggested values: 3 K, 2.7 K, 2.4 K, 2.1 K). Please check that the critical magnetic field depends quadratically upon T. Determine, by a linear regression of $B_c(T)$ versus $1 - (T/T_c)^2$, the value of $B_{c0} = B_c(T = 0\text{ K})$. Use the values at zero field too (Task a).

Practical implementation: for every temperature the following steps shall be performed:

1. Switch to the In-sample, set maximal current (no superconductivity), set U_a - $U_b = 0$ with the amplifier
2. Measure the $B_c(T)$ of In
3. Switch to the Sn-Sample with maximal current flowing (no superconductivity), rotate the sample selector until U_a - $U_b = 0$
4. Measure the $B_c(T)$ of Sn

Caution: the coil will overheat if operated long time at maximal current (several minutes, maximal temperature 100...120°C).

Theoretical tasks. You can do these tasks as preparation to the experiment or in the protocol.

c) Please give an estimation of the values of the **binding energy** and the relative distance between two electrons forming a Cooper pair; how many other Cooper pairs can be approximately found between the two electrons forming a Cooper pair?

Tip: You can guess the binding energy from the transition temperature and the distance from the speed of the electrons and the oscillation frequency of the atomic nuclei. For the determination of the Cooper pair density, you may use the electron density of states and think about which of these electrons transform into Cooper pairs.

d) Please calculate the theoretical values of thermodynamic critical fields B_{c0} for tin and indium and compare them with the experimental ones [1] (Chapter 4.6.2. Beware there is a mistake in the equation 4.59). In order to perform such calculations you will need the data:

Tin:	**Molecular Weight**=118.7 g/mol;	ρ=7.3 g/cm^3;	γ=1.78*10^{-3} J/mol K^2;
Indium:	**Molecular Weight**=114.8 g/mol;	ρ=7.3 g/cm^3;	γ=1.69*10^{-3} J/mol K^2;

5 References and literature

[1] Buckel, *Superconductivity*, VCH Verlag. - http://onlinelibrary.wiley.com/book/10.1002/9783527618507 (accessible in the Eduroam network or via VPN to the FU Berlin)
[2] M. Tinkham, *Introduction to superconductivity*, MacGraw-Hill
[3] N.W. Ashcroft, N.D: Mermin, *Festkörperphysik*, Oldenbourg Verlag.
[4] J. Bardeen, L.N. Cooper, I.R. Schrieffer, *Microscopic Theory of Superconductivity*, Physical Review Letters **108**, 1175 (1957).
[5] A.A. Abrikosov, *Fundamentals Of The Theory Of Metals* (in particular for Type 1 and 2 superconductors).

The values of the He vapor pressure can be converted into the temperature ones through the following table:

T, K	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10
.50	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.60	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.70	.00	.00	.00	.01	.01	.01	.01	.01	.01	.01	.02
.80	.02	.02	.02	.02	.03	.03	.03	.04	.04	.05	.06
.90	.06	.06	.07	.08	.09	.10	.11	.12	.13	.15	.16
1.00	.16	.18	.19	.21	.23	.25	.28	.30	.33	.36	.39
1.10	.39	.42	.46	.50	.54	.58	.62	.67	.72	.78	.83
1.20	.83	.89	.96	1.03	1.10	1.17	1.25	1.33	1.42	1.51	1.61
1.30	1.61	1.71	1.82	1.93	2.05	2.17	2.30	2.43	2.57	2.72	2.87
1.40	2.87	3.03	3.20	3.37	3.55	3.74	3.94	4.14	4.35	4.57	4.80
1.50	4.80	5.03	5.28	5.53	5.80	6.07	6.35	6.65	6.95	7.26	7.59
1.60	7.59	7.92	8.27	8.62	8.99	9.37	9.76	10.17	10.58	11.01	11.45
1.70	11.45	11.91	12.38	12.86	13.35	13.85	14.38	14.92	15.47	16.04	16.62
1.80	16.62	17.22	17.83	18.46	19.10	19.76	20.43	21.13	21.84	22.56	23.30
1.90	23.30	24.06	24.84	25.63	26.44	27.27	28.12	28.98	29.87	30.77	31.69
2.00	31.69	32.63	33.58	34.56	35.55	36.56	37.59	38.64	39.71	40.80	41.90
2.10	41.90	43.02	44.17	45.33	46.51	47.70	48.92	50.15	51.40	52.66	53.95
2.20	53.95	55.26	56.59	57.94	59.31	60.70	62.12	63.56	65.02	66.50	68.01
2.30	68.01	69.54	71.10	72.67	74.27	75.90	77.55	79.23	80.93	82.65	84.40
2.40	84.40	86.17	87.97	89.80	91.65	93.53	95.43	97.36	99.32	101.30	103.32
2.50	103.32	105.35	107.42	109.51	111.64	113.79	115.97	118.17	120.41	122.67	124.97
2.60	124.97	127.29	129.64	132.03	134.44	136.88	139.36	141.86	144.39	146.96	149.55
2.70	149.55	152.18	154.84	157.53	160.25	163.00	165.79	168.61	171.46	174.34	177.25
2.80	177.25	180.20	183.19	186.20	189.25	192.33	195.45	198.60	201.78	205.00	208.25
2.90	208.25	211.54	214.87	218.23	221.62	225.05	228.52	232.02	235.56	239.13	242.74
3.00	242.74	246.39	250.08	253.80	257.56	261.36	265.20	269.07	272.98	276.94	280.92
3.10	280.92	284.95	289.02	293.13	297.28	301.46	305.69	309.95	314.26	318.61	322.99
3.20	322.99	327.42	331.89	336.40	340.95	345.55	350.18	354.86	359.58	364.34	369.14
3.30	369.14	373.99	378.88	383.81	388.79	393.81	398.87	403.98	409.13	414.32	419.56
3.40	419.56	424.84	430.17	435.54	440.96	446.42	451.93	457.48	463.08	468.73	474.42
3.50	474.42	480.16	485.94	491.77	497.65	503.58	509.55	515.57	521.64	527.76	533.92
3.60	533.92	540.13	546.39	552.70	559.05	565.46	571.91	578.41	584.97	591.57	598.22
3.70	598.22	604.82	611.65	618.48	625.33	632.24	639.19	646.20	653.26	660.37	667.53
3.80	667.53	674.74	682.01	689.32	696.69	704.12	711.59	719.12	726.71	734.35	742.04
3.90	742.04	749.78	757.58	765.44	773.35	781.31	789.34	797.41	805.55	813.74	821.98
4.00	821.98	830.28	838.64	847.06	855.53	864.06	872.65	881.30	890.00	898.76	907.58
4.10	907.58	916.46	925.39	934.39	943.45	952.56	961.73	970.97	980.26	989.61	999.02
4.20	999.02	1008.49	1018.02	1027.61	1037.26	1046.97	1056.74	1066.58	1076.47	1086.43	1096.46
4.30	1096.46	1106.55	1116.70	1126.91	1137.19	1147.54	1157.95	1168.42	1178.96	1189.57	1200.25
4.40	1200.25	1210.99	1221.79	1232.66	1243.60	1254.61	1265.68	1276.82	1288.03	1299.30	1310.65
4.50	1310.65	1322.06	1333.54	1345.10	1356.72	1368.41	1380.17	1392.00	1403.90	1415.88	1427.92
4.60	1427.92	1440.03	1452.22	1464.48	1476.81	1489.21	1501.69	1514.24	1526.86	1539.55	1552.32
4.70	1552.32	1565.17	1578.09	1591.08	1604.15	1617.29	1630.51	1643.80	1657.17	1670.62	1684.14
4.80	1684.14	1697.75	1711.42	1725.18	1739.01	1752.93	1766.92	1780.99	1795.14	1809.37	1823.68
4.90	1823.68	1838.06	1852.54	1867.09	1881.72	1896.43	1911.22	1926.09	1941.06	1956.09	1971.22
5.00	1971.22	1986.42	2001.71	2017.09	2032.55	2048.09	2063.71	2079.43	2095.22	2111.10	2127.07
5.10	2127.07	2143.13	2159.27	2175.50	2191.82	2208.23	2224.71	2241.29	2257.96	2274.72	2291.57
5.20	2291.57	2308.50	2325.53								

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