Practical course M

Experiment M2.3
Transport properties of copper

Room 126

Universität zu Köln
II. Physikalisches Institut

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1 Preparation

In this experiment you measure the electrical resistivity, the thermal conductivity, and the Hall effect of copper as a function of temperature and magnetic field. You should familiarize yourself with the following topics:

- Measurement methods
  - Electrical resistivity (4-wire resistance measurement)
  - Thermal conductivity (Steady-state method)
- Distinction between metals, semiconductors, and insulators
- Drude model of the electrical conductivity
- Electron dynamics of the free electron model:
  - Electrical conductivity,
  - Thermal conductivity,
  - Wiedemann-Franz law,
  - Hall effect.

You should answer the following questions:

- Under which conditions does the Wiedemann-Franz law hold?
- What is Fermi energy? What is Debye temperature?
- Which scattering mechanisms affect the thermal/electrical conductivity?
- What is residual resistivity ratio? ?
- What is the thermal conductivity of copper, stainless steel, diamond and glas at room temperature? What makes the differences?
- The same for the resistivity.
- What is the origin of the field dependence of electrical/thermal resistivity? (↪ Appendix) What is Kohler's rule?
- Which measuring conditions must be considered for the electrical/thermal conductivity?
- What systematical errors can be made here?
- What must be kept in mind while measuring the Hall effect?

- Calculate the current which is necessary to create a magnetic field of one Tesla in a copper coil. Use the following data of the coil: Wire: 1 mm diameter copper, 10 layers winding (i. e. 10 windings per mm coil length), inner diameter 4 cm, outer diameter 6 cm, length 10 cm. Consider a long coil and use the room temperature resistance of copper. What is the used electrical power? Is the operation of a coil under these conditions possible? (Use appropriate approximations.)
- How can one create big static magnetic fields ($H \gtrsim 1$ T)? Why is this relatively complex?

2 Experimental procedure

The measurements at low temperature and in a magnetic field are made with a prepared dipstick, and are controlled by a computer. These measurements run overnight. The data can be obtained from your tutor on the next day or sent via e-mail. First, the theoretical concepts are discussed. After that measurements at a model are made. It is recommended to bring a pocket calculator with you to check the measured values. In order to do this, the room temperature values of the thermal conductivity and the resistivity of copper should be known.

The electrical resistivity and the thermal conductivity are measured at ambient pressure and in vacuum, respectively. The electrical resistivity is measured with 5 different current values up to 100 mA and the thermal conductivity is measured with 5 different sample-heater current values up to 5 mA (Please note that the heater will be damaged by a larger current!).

3 Analysis

The following analysis should be done:

(1) Analyse the manually measured room temperature data of the model:
   - Determine the resistivity as a function of current. Are the values for the current reasonable?
   - Do the same for the thermal conductivity.
   - Determine the temperature gradient as a function of current and plot it. What dependency is expected? What kind of plot is reasonable?
   - Determine the room temperature value of κ and ρ from the data.

(2) Resistivity:
   - Plot $\rho(T)$ for all applied magnetic fields (0 T, ± 2 T, ± 4 T, ± 6 T).
   - Discuss the deviations between the curves for same absolute values but different signs of the magnetic field, e.g. 2 T and -2 T.
   - How can $\rho(T)$ at zero-field be described for higher temperatures? (Fit)
   - Determine the residual resistivity ratio (RRR). What can you infer about the sample quality?

- Subtract the residual resistivity and make a linear fit to the double-log data. Which power law is expected for $\rho(T)$ at zero-field and for low temperatures? Is it fulfilled?
- Plot and discuss $\rho(B)$ for 10 K, 20 K, 30 K, and 40 K.
- Draw the Kohler plot for the resistivity and discuss the result.

(3) Hall effect:

- Plot $U_H(B)$ for 10 K, 20 K, 30 K, and 40 K.
- Determine the Hall coefficient R_H for each of these temperatures. (Linear fit)

(4) Thermal conductivity:

- Plot $\kappa(T)$ for all applied magnetic fields (0 T,±2 T,±4 T,±6 T).
- Discuss the deviations between the curves for same absolute values but different signs of the magnetic field, e.g. 2 T and −2 T.
- Plot and discuss $\kappa(B)$ for 10 K, 20 K, 30 K, and 40 K.
- Draw the Kohler plot for the thermal conductivity and discuss the result.

(5) Wiedemann-Franz law:

- Determine and plot the Lorenz number $L(T)$ for all applied magnetic fields (0 T, ±2 T, ±4 T, ±6 T).
- Discuss possible deviations from the Sommerfeld value of L.

(6) Further analysis:

- Determine the charge-carrier density n, the Fermi velocity v_F and the Fermi energy E_F.
- Calculate and plot the temperature-dependent average scattering time $\tau(T)$.
- Calculate and plot the temperature-dependent mean free path $l(T)$ of the electrons.

4 Files

The file `appendix.pdf` belongs to this instruction.

5 Geometry data and thermoelectric power

The values for thickness d, width b, distance between the contacts of the thermocouple l_{TC} and the heater resistance R_{PH} are:

	d/mm	b/mm	l_{TC}/mm	l_R/mm	R_{PH}/kΩ
Cryo	0.1111 ± 0.0015	2.16 ± 0.05	16.2 ± 0.5	12.2 ± 0.5	1
Model	0.1111 ± 0.0015	15.28 ± 0.09	49.8 ± 0.5	48.8 ± 2.0	10

The thermoelectric power is $S = 5.9 \times 10^{-5}$ V/K at room temperature.

6 Result files

For the analysis you will get (one or two days later) two files, `M2.3-date.RHO.mtw` for the resistivity and the Hall effect, and `M2.3-date.WLF.mtw` for the thermal conductivity, where `date` is the date of the experiment. The data in these files are already averaged over 150 points. The files are plain text and can be opened with a standard text editor.

6.1 Resistivity and Hall effect (`RHO.mtw`-File)

The meaning of each column can be taken from the header of the `RHO.mtw`-File. The abbreviations mean (with dimensions):

(1) Temperature in K

(2) Magnetic field in T,

(3) R-current (-): Negative current (resistivity) in A,

(4) R-current (+): Positive current (resistivity) in A,

(5) R-voltage (-): voltage for negative current (resistivity) in V,

(6) R-voltage (+): voltage for positive current (resistivity) in V,

(7) Hall-voltage (-): Hall-voltage for negative current in V,

(8) Hall-voltage (+): Hall-voltage for positive current in V.

6.2 Thermal conductivity (`WLF.mtw`-File)

The meaning of each column can be taken from the header of the `WLF.mtw`-File. The abbreviations mean (with dimensions):

(1) Temperature in K,

(2) Magnetic field in T,

(3) SH-current (0): Zero sample-heater current in A,

(4) SH-current (+): Positive sample-heater current in A,

(5) SH-voltage (0): Sample-heater voltage for zero current in V,

(6) SH-voltage (+): Sample-heater voltage for positive current in V,

(7) TC-voltage (0): Thermocouple voltage for zero current in V,

(8) TC-voltage (+): Thermocouple voltage for positive current in V,

(9) S_TC: Thermopower of the thermocouple in V/K.

7 Literature

[1] Neil W. Ashcroft, David N. Mermin, Solid State Physics, Cengage Learning Emea (1976)

[2] John M. Ziman, Prinzipien der Festkörpertheorie, Harri Deutsch Verlag (1998)

[3] John M. Ziman, Electrons And Phonons: The Theory of Transport Phenomena in Solids, Oxford University Press (2001)

[4] Max Kohler, Zur magnetischen Widerstandsänderung reiner Metalle, *Annalen der Physik* **424**, 211-218 (1938)

[5] Max Kohler, Wärmeleitung der Metalle im starken Magnetfeld, *Annalen der Physik* **440**, 181-189 (1949)

[6] Appendix: `appendix.pdf`

Workplace:

Operating instruction according § 20 GEFSTOFFV

As at 5/2011

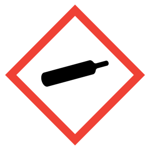
Date: 31.05.2011

Helium, *liquid, cryogenic*

Kp.: -269°C Fp.: -272°C Solubility (H_2O/20°C): 0.86 ml/100 ml rel. Vapour density$_{(Air)}$ = 1 : 0.14

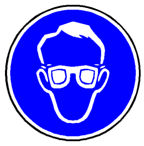
Physical danger:
Cracks/scratches in the Dewar vessel may lead to spontaneous implosion!
If the lid of a Helium tank remains open, air will sublimate into the tank and the overpressure relief valve. Block of pressure release due to this, can cause a life-threatening pressure increase within the tank.

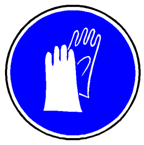
Dangers to health:
In high concentration, Helium leads to suffocation without warning!
H 281 Contains cryogenic gas; may cause cryogenic burns or injury.
Depending on the duration of the contact, deep tissue destruction, frostbite, and severe eye damage may occur.



Attention

Safety instructions Prevention:
P282 wear protective gloves / face protection shield / eye protection with cold insulation.





Technical measures:
P403 Store the Helium tank in a well-ventilated place.

- Conect the Helium tank to the recovery.

Filling of Helium only by instructed persons in a well-ventilated place.

- Liquid Helium should only be filled in dry and well-isolated Dewar vessel.
- Dewar vessel and recovery lines must be labeled unambiguously.
- Shut-off valves should not be apruptly opened or closed.
- Removal of ice on valves and vessels by use of warm air only.
- If a dangerously high pressure builds due to heat, suitable safety devices must be installed. In case of icing, ensure that the overpressure is released.

Organizational measures:
Transport only specially suited Helium tanks or Cryogenic containers in elevators ***without accompanying persons***.

Behaviour in case of danger: In case of massive gas release leave the room. Alert other people. Ventilate the room. Rescue injured persons in compliance with self-security.

First Aid

Skin or eye contact:
P 315 Seek immediate medical advice/attention.
P 336 Warm frozen parts with lukewarm water. Do not rub the concerned area. Cover and keep the burned area sterile. Consult a physician.
Inhalation: High concentration may cause suffocation. Symptoms are loss of mobility and consciousness. Expose the victim to fresh air in compliance with self-security. Keep warm and calm. Consult a physician. If breathing stopped, begin artificial respiration.

Emergency number:

Emergency medical services: 01-112

Nearest hospital: **01-4792213** Evangelisches Krankenhaus, Weyertal 76, 50931 Köln

Maintainance main building: 2200

*If necessary: * Specify location*

(Signiture)

Workplace:	**Operating instruction according § 20 GEFSTOFFV**	As at 5/2011 *Date:* 31.05.2011

Superconducting magnetic cryostat

Physical Danger:

Any freely movable objects could be pulled into the magnetic field and may reach high velocities by this.

The superconductivity in the coils of the superconducting magnet may break down abruptly. Thus the energy stored in the magnetic field is then released as heat to the Helium bath whereby large volume of Helium evaporates.

High magnetic fields may damage magnetic data storage media like hard disks or credit cards and may lead to loss of information.

Danger to health:

High magnetic fields can impair the proper function of cardiac pacemaker and other electronic implants.

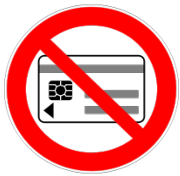
Safety instructions:

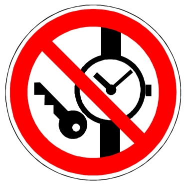
Keep precision mechanical devices like watches and magnetic data storage media like computer hard disks, cards with magnetic stripe or floppy disks in sufficient safe distance from the magnet.

Technical measures: -

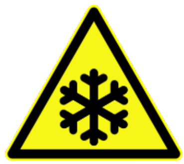
Organizational measures:

Before runnning the magnet remove all parts that might be attracted by the magnetic field from its surrounding.





Behaviour in case of danger: In case of massive gas release leave the room. Alert other people. Ventilate the room. Rescue injured persons in compliance with self-security. In case of injuries caused by parts attracted by the magnet provide first aid.



First Aid

Skin or eye contact with cold Helium gas:
P 315 Seek immediate medical advice/attention.
P 336 Warm frozen parts with lukewarm water. Do not rub the concerned area. Cover and keep the burned area sterile. Consult a physician.
Inhalation: High concentration may cause suffocation. Symptoms are loss of mobility and consciousness. Expose the victim to fresh air in compliance with self-security. Keep warm and calm. Consult a physician. If breathing stopped, begin artificial respiration.

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Questionnaire for the M-practical course

Transport properties of Copper

Please fill in the form after you finished the experiment and discuss the criticism with your tutor wherever applicable.

The valuation is based on the german school mark system (1:best – 6:worst)

Semester: Winter 20___/___ Summer 20___

		1	2	3	4	5	6	Abstention
Query 1: How much did you learn from the experiment in terms of concepts in physics as well as technical skills?	in physics	◻	◻	◻	◻	◻	◻	◻
	tech. skill	◻	◻	◻	◻	◻	◻	◻
Query 2: How do you rate the quality of the experimental equipment?		◻	◻	◻	◻	◻	◻	◻
Query 3: Is the experiment up-to-date with recent topics in physics?		◻	◻	◻	◻	◻	◻	◻
Query 4: What is the advance in your experimental skills?		◻	◻	◻	◻	◻	◻	◻
Query 5: Did you have fun carrying out the experiment?		◻	◻	◻	◻	◻	◻	◻
Query 6: Is the tutorial of the experiment explicit?		◻	◻	◻	◻	◻	◻	◻

Query 7:
How much time did you invest in the preparation? ______ h

	1	2	3	4	5	6	
Query 8: How do you assess the experiment in total?	◻	◻	◻	◻	◻	◻	◻

study course: **Master** ◻ **Teacher** ◻

Comments and suggestions

	1	2	3	4	5	6	
Overall mark for your tutor	◻	◻	◻	◻	◻	◻	◻

Name of your tutor: ____________________________________