Versuch 41
Temperature measurement

Abbildung 1: *Setup of the experiment.*

I Measurement setup

- Pyrometer
- Pt100 thermometer (class B)
- Constant current source 1 mA
- Dewar flask
- Gas thermometer
- Temperature bath
- Thermocouple for high temperatures (PtRh, type B or type S) with calibration table
- Multimeter
- Butane gas bunsen burner
- Safety glasses and protective gloves

II Literature

- W. Walcher, *Praktikum der Physik*, B.G.Teubner Stuttgart,
- Standard works of physics: Gerthsen, Bergmann-Schäfer, Tipler.
- Homepage of the lab course:
  http://www.physi.uni-heidelberg.de/Einrichtungen/AP/

III Preparation

Prepare to answer questions on the following topics: Temperature, absolute zero, gas laws, changes of state of the ideal gas, real gases, van der Waals equation, thermocouple, Planck's radiation law.

Comprehension questions:

1. What kind of thermometers are available? What physical principles are they based on? What are the advantages or disadvantages of using them?
2. How does a gas thermometer work? Why is this thermometer suitable for absolute temperature measurement? Can any gas be used? Up to which temperatures do you think a gas thermometer is suitable - which gas would you use?

3. The temperature of the boiling water and the melting temperature of the ice (ice-water mixture) are taken as fixed temperature points, which can be realised relatively easily. On which external parameters do these fixed points depend?

4. What is the principle way to determine the temperature, independent of a working substance?

5. How does a thermocouple work?

6. How can the surface temperature of stars be determined? How do the spectra of Sirius (T≈10000 K) and the Sun (T ≈ 6500 K) differ?

IV Tasks

- Temperature measurement using a gas thermometer and a platinum resistance thermometer in the range between the boiling point of water and the boiling point of liquid nitrogen.

- Measurements with an infrared thermometer in the range from 0°C to 100°C.

- As a typical application of a thermocouple, the PtRh-element is used to measure the temperature distribution of a Bunsen burner flame.

V Basics

The thermal state of a material is characterised by the temperature. To measure this quantity, instruments (thermometers) are used which utilise the temperature dependence of various physical quantities. These include, for example, expansion thermometers (liquid thermometers, gas thermometers), whose principle is based on the temperature dependence of the volume of a substance. Another large class of thermometers are resistance thermometers such as platinum thermometers or semiconductor thermometers (NTC, PTC). With these the electrical resistance depends on the temperature. Thermocouples consist of two different metal wires that are in contact with each other. An electrical voltage is generated between the terminals, which depends on the temperature difference between the contact point and the terminal ends. In this experiment you will also carry out measurements with a pyrometer. Such a thermometer measures the „heat radiation“ emitted by a body, which ideally depends only on the temperature.
There are different temperature scales worldwide, such as Celsius or Fahrenheit, which are based on two different fixed points. On the Celsius scale these are the melting point and the boiling point of water. The lower fixed point of the Fahrenheit scale corresponds to the temperature of a special cold mixture, the upper fixed point to the „body temperature of a healthy person“. Such definitions are not very well reproducible. From a physical point of view, there is only one temperature scale, which can be derived from the first and second law of thermodynamics: The thermodynamic temperature scale or the Kelvin scale. The current international temperature scale was established in 1990 (ITS-90). It defines special temperature fixed points in the range from 0.65 K to 2200 K. Between these temperature values, interpolation is carried out using defined thermometers that have been calibrated at the fixed points. These include in particular the platinum resistance thermometers (measuring range approx. 10 K to approx. 1200 K), the He gas thermometer and the He vapour pressure thermometer for temperatures below 30 K, and in the high temperature range the radiation thermometers.

VI Gas thermometer

The operating principle of a gas thermometer can be described by means of the ideal gas equation:

$$pV = NkT, \tag{1}$$

where p is the pressure, V is the volume, T the absolute temperature, N is the number of particles and k represent the Boltzmann constant.
If a gas is in a closed container, the temperature of the gas can be determined by a pressure measurement while keeping the volume constant (law of Amontons):

$$T \propto p \quad \text{for} \quad V = \text{constant}. \tag{2}$$

The setup of the gas thermometer used in the practical course is shown in Figure 2. It consists of a glass balloon filled with air, which is connected to an electric manometer via a capillary.
The accuracy with which the temperature can be measured depends on the constancy of the volume and the gas used. Two systematic errors must be taken

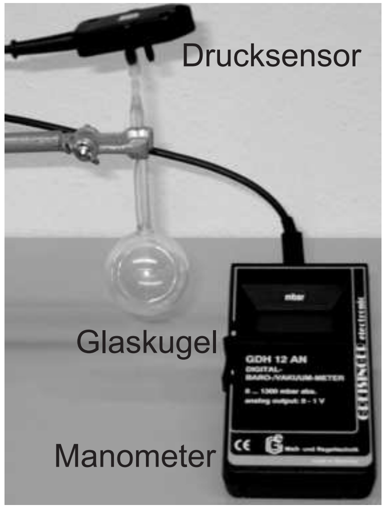

Abbildung 2: *Principle of a gas thermometer.*

into account. Firstly, the glass balloon expands when heated, which changes the volume of air. However, this error can be neglected due to the much larger expansion coefficient of air compared to that of glass. On the other hand, the air trapped in the capillary between the glass ball and the manometer remains approximately at room temperature. Temperature changes in the glass balloon therefore cause this „harmful volume" to be compressed or expanded, which also changes the volume of air. Furthermore, air can only be considered as an ideal gas to a limited extent. Far above the liquefaction point and at low pressure the conditions of an ideal gas are certainly well met. However, you will also perform measurements at temperatures of liquid nitrogen. As the pressure in the glass balloon at this temperature is significantly lower than atmospheric pressure, no liquefaction occurs and the air in the glass container can still be considered ideal.

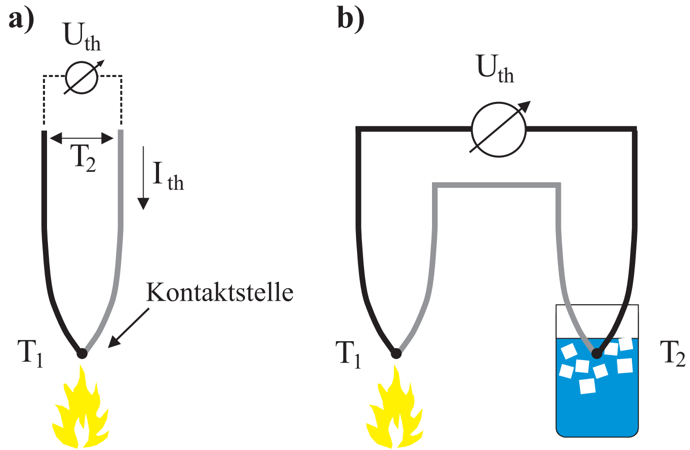

Abbildung 3: *Theory of operation of a thermocouple.*

VII The thermocouple

The mode of operation of a thermocouple is based on the Seebeck effect: If two different metals are brought into contact with each other, an electrical voltage builds up at the contact point, the amount of which depends on the type of metal and the temperature (Figure 3 left). Electrons flow from the metal with the lower work function into the metal with the higher work function. A thermoelectric voltage U_{th} is generated. When the circuit is closed a thermo current I_{th} flows; the energy" required for this „is taken from the heat source. If the temperature at the contact point is T_1 and at both ends of the metals T_2, the thermoelectric voltage is:

$$U_{th} = K(T_1 - T_2), \tag{3}$$

where K is a constant which depends on the type of both metals.
Thermocouples are very often used in industry and technology. The advantages of these sensors are small dimensions, good mechanical and chemical stability, applicability over a very wide temperature range and low manufacturing costs. However, thermocouples also have disadvantages. Only relative temperatures can be measured. If the temperature T_1 is to be determined absolutely, the reference temperature T_2 must be known. For simple measurements of low accuracy, the approximately constant room temperature T_2 is sufficient as the reference

temperature (this method is also very accurate for measurements of very high temperatures). For precise measurements of the absolute temperature, however, a constant reference temperature is required. For this purpose, a thermocouple with two contact points is used (Figure 3 right), whereby one contact is set to a defined reference temperature T_2.
The voltage applied to a thermocouple is very low. With the platinum-rhodium thermocouple used here the voltage at 50°C is 2 μV, at 1000°C 4.9 mV. A comparison list between temperature and thermoelectric voltage is available at the laboratory.

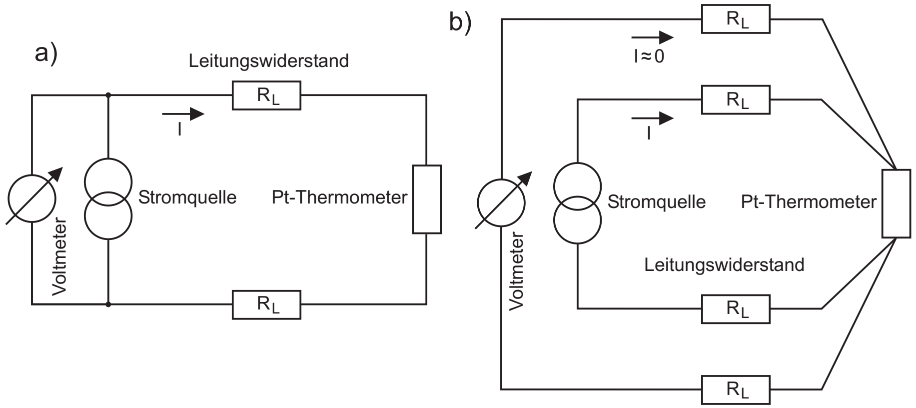

Abbildung 4: *a) Two-wire circuit and b) Four-wire circuit for measuring the resistance of a Pt thermometer.*

VIII The platinum resistance thermometer

The temperature dependence of a Pt resistor can be determined with good accuracy by a second degree polynomial[1]:

$$R(T) = R_0(1 + AT + BT^2), \tag{4}$$

with the coefficients

$$A = 3,9083 \times 10^{-3}[°\mathrm{C}^{-1}]$$
$$B = -\,5,775 \times 10^{-7}[°\mathrm{C}^{-2}].$$

R_0 is the nominal resistance at 0°C. A Pt100 thermometer has the property R_0 = 100 Ω. Thus the temperature can be calculated from the measured resistance R. From equation (4) results:

$$T(R) = \frac{-R_0A + \sqrt{R_0^2A^2 - 4R_0B(R_0 - R)}}{2R_0B}. \tag{5}$$

Platinum thermometers are available in four accuracy classes. The thermometers used in the experiment are in the accuracy class B. In this class the Temperature error is:

$$\Delta T = 0,30\,°\mathrm{C} + 0,005\,|T|. \tag{6}$$

[1]The DIN IEC 751 specifies for the platinum resistance actually two temperature ranges (-200°C to 0°C and 0°C to 850°C), which are defined by different polynomials. In this experiment however, it is sufficient to use the indicated square approximation.

The resistance of a Pt-thermometer can be measured in the simplest case according to Ohm's law by two different methods. Either a constant voltage is applied to the Pt resistor and the current is measured or a constant current is applied and the voltage drop across the Pt resistor is measured. With both measuring methods, self-heating always occurs of the Pt-thermometer, which falsified the actual temperature measurement. It is therefore useful to apply a constant current as small as possible to the resistance and measure the voltage drop across the Pt resistor with a voltmeter. In the experiment you will use a constant current source which supplies a current of 1 mA.

When measuring the voltage, it must be taken into account that the Pt resistor is connected to more or less long supply lines which have also an electrical resistance. With the two-wire circuit in figure 4 a) the total resistance includes the resistance of the measuring leads and the resistance of the Pt-thermometer. This measurement error can be avoided by a so-called four-wire circuit. The measuring current is fed in via two measuring leads and two others are used for measuring the voltage drop. Since the voltage measurement is carried out with a high-impedance voltmeters (internal resistance some MΩ), only a very small current flows through the lines and the voltage drop on the lines is negligible.

IX The pyrometer

Any body whose temperature is greater than 0 K transmits thermal radiation. The intensity depends only on the temperature. To quantify the radiated intensity, the model of a black body is used. This is an idealised body that completely absorbs all the incident electromagnetic radiation. According to Kirchhoff's radiation law, such a body also has a maximum emission capacity ϵ =1. The intensity distribution of the radiation emitted by a black radiator is described by Planck's radiation law:

$$M_\lambda(\lambda, T)\,\mathrm{d}A\,\mathrm{d}\lambda = \frac{2\pi hc^2}{\lambda^5}\frac{1}{e^{\left(\frac{hc}{\lambda kT}\right)}-1}\,\mathrm{d}A\,\mathrm{d}\lambda, \tag{7}$$

where M_λ describes the radiant power which is radiated into the half space by the area element dA in the wavelength range λ to $\lambda + d\lambda$. The intensity distribution is shown in figure 5 for different temperatures in the range from 300 K to 10000 K.

The total power radiated by a body is described by the Stefan-Boltzmann law. Integration of equation (7) over the whole radiating area A and over all wavelengths results

$$P = \epsilon(T)\sigma AT^4, \tag{8}$$

where σ describes the Stefan-Boltzmann constant and T the absolute temperature. The factor $\epsilon(T) \leq 1$ takes into account that real bodies have a smaller emissivity than the idealised black body. The radiated power of a body therefore only depends on the area and the temperature. Contactless pyrometers and thermal imaging cameras are based on this property.

At room temperature (≈300 K), the maximum radiation in the long-wave infrared range is at a wavelength of about 10 μm (figure 5). Commercial IR-pyrometers work in this range. The pyrometers used in the practical course integrate the radiation emitted by a body in the range from 8 μm to 14 μm.

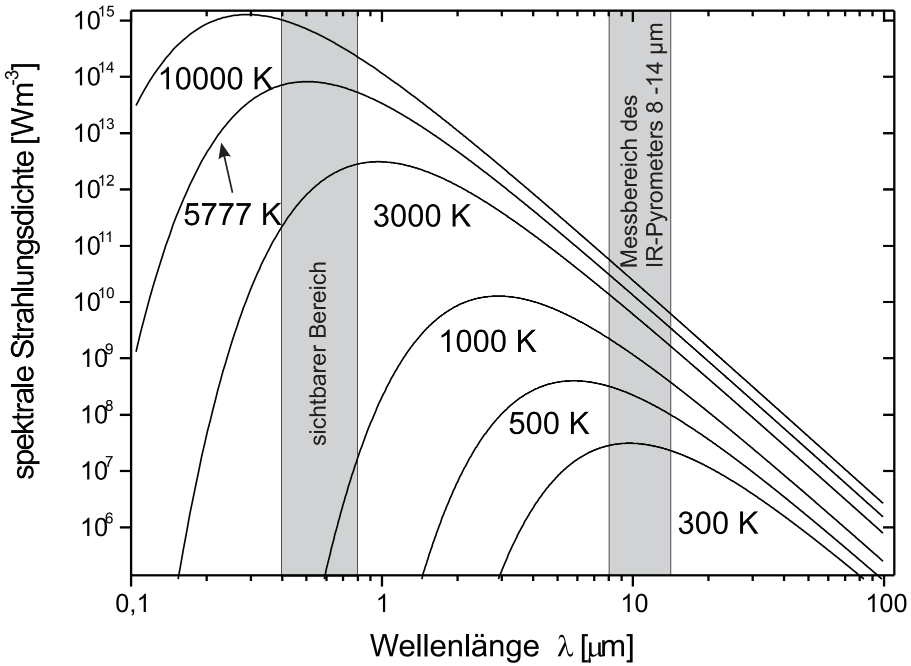

Abbildung 5: *Spectral intensity distribution of a black body at different temperatures. The temperature of 5777 K corresponds to the effective temperature of the solar surface.*

X Execution of the experiment

Attention:

contact with liquid nitrogen or dry ice causes severe frostbite and eye damage. When handling dry ice and liquid nitrogen, always put on gloves and protective goggles. As considerable amounts of nitrogen and carbon dioxide evaporate during the experiment, the room should be well ventilated.

1. Sketch the experimental setup

2.1 Calibration of thermometers at 0°C

Setting up the Pt100 thermometer:

Build a four-wire circuit. To do this, plug in the connector of the Pt100 thermometer into the adapter box. The four connecting leads can then be tapped at the 4 mm sockets. Next, connect one white and one red socket each to the corresponding sockets of the power source. If you connect the voltmeter to the two still free sockets of the power source (red socket to the connector `"Com"`of the voltmeter), you have a two-wire circuit (see figure 4) and you measure the voltage drop over the cables. To get a four-wire circuit, you have to connect the voltmeter directly to the adapter box. You should try out both circuits at least once in the following measurement. At 0°C the Pt100 resistance is 100 Ω. With a measuring current of 1 mA, you will get a voltage drop of 100 mV with the four-wire circuit. In the two-wire circuit, you will measure a higher value, as you also measure the supply line resistances. However, the cables are relatively short and the effect is therefore very small.

Use a water-ice mixture for the measurement at 0°C. Fill the pot half full with crushed ice and place the glass balloon in the middle of the pot. Pour in water and stir well with a glass rod. The glass ball must be completely covered with water! Observe the voltage at the Pt100 and the temperature displayed on the pyrometer at the same time. The temperature of the melting ice in water as the fixed point and zero point of the temperature scale must be reached as well as possible. For this purpose you have to wait for the minimum voltage value of the Pt100 thermometer. When the voltage has stabilised, record the voltage, the pressure of the gas volume and the pyrometer temperature. The pyrometer temperature is measured on the water surface. It will systematically differ from the „true“ temperature because the absorption capacity of water is not one.

2.2 Temperature measurement up to T= 100°C

Now turn on the hot plate and heat the water to about 10°C. Switch off the heating plate just before the desired temperature is reached and stir the water well to achieve an even temperature distribution. Record pressure, pyrometer reading and Pt100 voltage. Repeat these measurements in steps of about 10 degrees. Do not try to get exactly 10°C, 20°C, ...by repeatedly switching the heating plate on and off. Which value is finally set, whether 10°C or 11,5°C, is completely irrelevant. Wait about 2 minutes while stirring continuously and then read the voltage on the Pt100, the pressure and the pyrometer display for each step. Take the temperature of the boiling water as the last measuring point. Read the air pressure on the barometer in the corridor and note this value.

2.3 Temperature of dry ice and liquid nitrogen at boiling point

Let the glass balloon cool down for some time. Then fill the Dewar flask with dry ice and alcohol. The alcohol improves the heat contact with the glass balloon. To do this, use the ready-made dry ice and alcohol mixture in the two Dewar flasks on the washbasin. If necessary, add some more dry ice. Wait until the temperature has stabilised. Stir well! Once the measured values have stabilised, note the voltage and pressure. The pyrometer cannot be used at these low temperatures.

Pour the dry ice-alcohol mixture back into the Dewar flasks on the washbasin after the measurement.

Now fill the Dewar flask step by step with liquid nitrogen and push the glass ball **slowly** in until it is completely covered by the nitrogen. Wait until the strong evaporation has stopped and the temperature values stabilize. Record the PT100 voltage and pressure of the gas thermometer.

3. Measurement of very high temperatures with the PtRh thermocouple

Measure the temperature distribution in the flame with the PtRh-thermocouple with strong air supply and with weak Air supply. The PtRh thermocouple consists of two platinum wires, which are, however, alloyed with rhodium to different degrees. Attention: Different thermocouples (type S and type B) are present during the measurement. Make sure to use the correct calibration table. Draw the approximate shape of the flame and enter the thermoelectric voltage for different points (five measurements with strong and weak air supply). At the end of the measurement, turn off the gas and pour out the water and ice.

XI Evaluation

1. Enter the pressure values measured at the four fixed points against the temperature in a diagram. Select a temperature range from -280°C to 110°C on the x-axis. Calibrate the temperature scale by taking the temperature of the water-ice mixture as 0°C. Enter the measured pressure there. A second calibration point is obtained by converting the pressure p_{gem} measured at the temperature of the boiling water to the pressure p_{NB} under normal conditions:

$$p_{NB} = p_{gem} \frac{1013,25\,\mathrm{hPa}}{p_{LD}}, \tag{9}$$

where p_{LD} describes the air pressure. Assign the temperature 100°C to this pressure value and enter the value on the graph. Now you can use the calibration line of the gas thermometer through both measuring points. At what temperature does the pressure become zero? Now enter the measured pressure value at the temperature of the liquid nitrogen. Which temperature value do you read? Compare with the literature value T_{N2} = 77 K (-195.8°C). You can also use this literature value as an additional calibration point to better determine the absolute zero point. At which temperature do you now get the pressure p=0? Finally, enter the pressure that you recorded during the measurement with dry ice. What temperature do you get for this? Complete the diagram with a Kelvin scale.

2. Calibration of the Pt100 resistance thermometer. Using the previously prepared calibration curve, determine the temperature values of the gas thermometer in the range from 0°C to 100°C Enter the resistance of the Pt100 element to the temperature in another diagram. What correlation do you find? Create a straight line through the measured values in the range from 0°C to 100°C. Compare the slope with the linear term of the polynomial in equation (4).

3. Apply the temperature measurements with the pyrometer against the temperature of the gas thermometer. What do you observe? Explanation?

4. Sketch the shape of the flame and enter the temperatures for weak and strong air supply. The temperatures belonging to the thermoelectric voltages can be found in the calibration table.