B3: Magnetization and susceptibility of a paramagnetic salt

1. Overview on the topic and summery of the objectives

Magnetism is one of the oldest known physical phenomena. Nevertheless, the description of real systems is usually very complicated and a field of current research, in which new concepts are applied (the renormalization group, K.G. Wilson, Nobel Prize 1982) [1.]. In the experiment a system should be studied that can be viewed as a prototype of a simple paramagnet. It is the salt $Gd_2(SO_4)_3 \times 8\ H_2O$ (Gadolinium sulfate).

2. Theoretical basis [2.] [3.]

If matter is exposed to a static magnetic field, it gets magnetized*. A magnetic moment* is formed, which size and direction can be manyfold and depend on the material properties. In this respect diamagnetism and paramagnetism which exhibit no and permanent magnetic moments, respectively, have to be distinguished. Ferromagnetism on the other hand is representative for systems that exhibit ordering phenomena.

Paramagnetism, which should be investigated here, is caused by permanent magnetic moments*, that originate from unpaired electrons.
In a simple model these moments can be considered as localized and noninteracting: This can be described in two steps:

A) Assuming the Russell-Saunders coupling* and with the help of Hunds rules* the total orbital angular momentum L and the total spin S as well as the resulting total angular momentum J can be determined. The angular momentum and the magnetic moment are connected via the Landé g-factor*. Thus, the size of the atomic moments can be calculated.

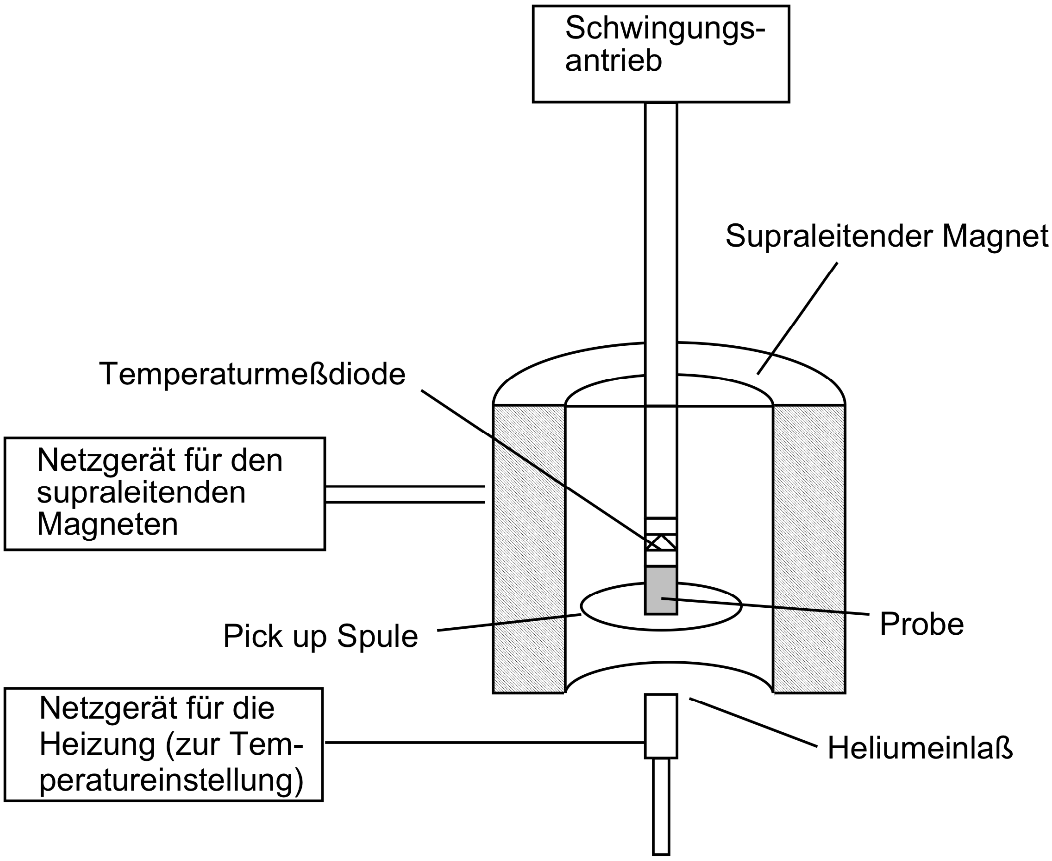
B) In an applied magnetic field, the state **$|J,J_z\rangle$** splits (Zeeman effect)*: "the moment aligns". The statistics provide the occupation numbers and thus the solution of the model the Brillouinfunction*, giving the value of the magnetization for all fields and temperatures. For small fields we get the definition of the susceptibility for which Curies law* is valid.

3. Working principle of the employed equipment

The main item for the measurement of the magnetic moment of the sample is a (Foner- or) vibrational magnetometer.
The sample is moved sinusoidally back and forth by a drive. Through the superconducting coil, the static magnetic moments μ are aligned in the sample. The moving magnetic moment of the sample induces a voltage in the 'pick up' coil. As the amplitude and the oscillation frequency is keept constant by the control electronics and fluctuations are compensated, the induced voltage, which is rectified phase sensitively, can be used as a measure of μ. With a known sample, the magnetometer can be calibrated in absolute units. The setup is located in a dewar and is operated at liquid He. For more details see [4].
The display of the magnetometer is in "emu" (electro-magnetic-units):

$$1 \text{ emu} = 1 \text{ erg/G} = 1 \text{ G cm}^3$$

4. Experimental setup



5. Notes on the experimental procedure

The different sample temperatures which are necessary to measure, can be adjusted by pumping the sample tube if they are below 4.2K. For higher temperatures, the He flowing from a vent can be tempered with a resistive heating. The temperature is displayed on a computer that reads the voltage of a diode and converts it by means of a calibration curve into K. The adjustments of the temperature are carried out by the assistant.
When measuring $\sigma(T)$ a current is put in the superconducting coil, which is then short cutted. In that way the magnetic field stays constant for very long times.
The mass of the sample is 199.95 mg. In a field of 1 kG the sample holder shows a diamagnetic moment of $-15 \cdot 10^{-5}$ emu.

6. Questions for the understanding of the experiment

Why Gadolinium sulfate is a very 'simple' system?

How do the classical and quantum mechanically derived magnetization curves (Brillouinfunktion and Langevinfunktion) differ?

Why it is useful to determine first the angular momentum and then the g-factor in the evaluation?

What is the electronic configuration of Gd^{3+} and the total spin?

7. Tasks

a) Measure σ(H), (σ = magnetic moment, H = magnetic field) from 0 to 70 kg at temperatures T = 1.5 K, 4.2 K, and 15 K. Record the data with the computer and parallel with the XY-recorder. Determine the saturation magnetization σ_S. Measure σ(H) for small field values from 0 to 1 kG in addition (only with the computer).

b) Measure σ(T) between T = 3 K and 150 K at H = 1 kG (only with the computer).

c) The three magnetization curves σ(H) for small fields shall be presented in one figure, likewise the three curves for large fields. These shall be conducted to a curve σ(H/T), as is often found in textbooks. Plot χ, $1/\chi$, and χT over T. What can you learn from the different kinds of plotting?
For all computer printouts, the scaling of y- and x-axis must be checked and if necessary converted in the correct units.
The entire data analysis and printing of the diagrams is done during the experiment. A separate data analysis with an external computer (e.g. at home) is not necessary / desired.

d) Determine the Curie constant C and σ_S (σ_S in multiples of μ_B).

e) Determine the angular momentum J of the Gd^{3+} ions from σ_S and C. This value can only be integer or half-integer!

f) With the correct value of J you can now determine g.

g) Check if σ(H,T=const.) is described by the corresponding Brillouinfunktion by drawing the magnetization with the help of the tabulated Brillouinfunktion together with the curves you recorded.

Notes for the evaluation:

The display of the magnetometer is in "emu" (electro-magnetic-units):

$$1emu = 1\frac{erg}{G} = 1G \cdot cm^3$$

For the check of the Brillouinfunktion $B_J(x)$ with $x = \mu H/kT$ some numerical values for J=7/2.

x	$B_J(x)$	x	$B_J(x)$
0.01	0.00428	1.5	0.54264
0.05	0.02142	1.75	0.60222
0.1	0.04282	2.0	0.65321
0.2	0.08541	2.6	0.74673
0.4	0.16905	3.5	0.83449
0.6	0.24931	5.0	0.90997
1.0	0.39484	7.5	0.96203
1.25	0.47365	10.0	0.98259

8. Literature

[1] K.G.Wilson, Spektrum der Wissenschaft 10(1979)

[2] C. Kittel, Introduction to Solid State Physics, chapter on para- and diamagnetism.

[3] N.W. Ashcroft, N.D. Mermin, Solid State Physics, Chapter 31,(32).

[4] Manual (in part) of the company PAR for the magnetometer model 150

Further Reading

• U. Köbler, " Vibrationsmagnetometer, Faradaywaage, SQUID und Messbeispiele" in the 24. IFF-Ferienkurs "Magnetismus von Festkörpern und Grenzflächen" (Forschungszentrum Jülich GmbH, 1993) chapter 3