

Magnetism and magnetic measurements

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Chapter 1

Introduction

1.1 Magnetism and magnetic ordering

1.1.1 Definitions and the origin of magnetism

Magnetic moment of an electron

Magnetism has its origin in the motion of charged particles, and the intrinsic magnetic moments (*spins*), of particles. The definition of the magnetic moment due to movement of charge is

$$\vec{\mu} = I\vec{S},$$

where \vec{S} is a vector area enclosed by the current loop. From this, an *angular orbital magnetic moment* of an electron on its orbit can be calculated

$$\vec{\mu}_l = I\vec{S} = \frac{-e\omega}{2\pi} \cdot \pi r^2 = \frac{-e}{2m_e c} \hbar \vec{l} = -\mu_B \vec{l},$$

where $\hbar \vec{l}$ is the orbital angular momentum ($l = 0, 1, 2, \dots$ is the quantum number describing the orbit, s, p, d, ... respectively), $\mu_B = e\hbar/2m_e c = 9.27400968(20) \cdot 10^{21} \text{ erg} \cdot \text{G}^{-1}$ is the Bohr magneton, and other symbols have their usual meaning. An electron has an intrinsic angular momentum, spin \vec{s} (derived from the Dirac equation):

$$\vec{\mu}_s = -g_s \frac{e}{2m_e c} \hbar \vec{s} \approx -2\mu_B \vec{s},$$

where $g_s = 2.002319 \approx 2$ is the electron g -factor [1] and \vec{s} is the spin. Thus, the total intrinsic magnetic moment of an electron is

$$\vec{\mu}_{int} = -\mu_B(\vec{l} + 2\vec{s}).$$

Spin-orbit coupling

An electron moving on the orbit sees the electric field of the nucleus partly as a magnetic field, which interacts with the spin of the electron. The energy shift calculated for this phenomenon is:

$$\Delta E = \frac{1}{2m_e^2 c^2} \frac{1}{r} \frac{\partial U}{\partial r} \vec{l} \cdot \vec{s},$$

where $U = V \cdot e$ is the potential energy of the electron in the central field.

When we take into account all the electrons in the shell

$$\vec{L} = \sum_i \vec{l}_i, \quad \vec{S} = \sum_i \vec{s}_i, \quad \vec{J} = \vec{S} + \vec{L}.$$

For a closed shell, owing to the Pauli exclusion principle, $\vec{L} = \vec{S} = 0$. For an underfilled shell

$$\Delta E = \xi \cdot \vec{L} \cdot \vec{S}.$$

The energy of the state depends on the value of the total angular momentum \vec{J} . The spin - orbit interaction is, therefore, responsible for splitting of energy levels in atomic spectra, but each of the energy levels is $(2J+1)$ times degenerate, as determined by the possible values of $m_J = -J, \dots, +J$.

The Zeeman effect

Now, we have to take into account the interaction of the magnetic moment with the external magnetic field $E = -\vec{\mu} \cdot \vec{H}$. The $(2J+1)$ degeneracy is removed by applying an external magnetic field, which leads to further splitting of electron energy levels into $(2J+1)$ states and is known as the Zeeman effect. The potential energy of the atom in an applied external magnetic field H is:

$$E = m_J g_L \mu_B H,$$

where g_L is the Landé factor:

$$g_L = \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)}.$$

1.1.2 Magnetic properties of non-interacting localized magnetic moments

Having learned the quantum origin of magnetism, we can now discuss the possible magnetic behaviour of the matter and how to recognize it. Before we start analyzing the magnetic behaviour of substances, however, we need one more definition - the magnetic susceptibility χ :

$$\chi = \frac{\langle \mu \rangle}{H},$$

where H is the external field applied to the sample and $\langle \mu \rangle$ is the average magnetic moment along the \vec{H} direction per unit volume. χ has no dimension. Often $\langle \mu \rangle$ is calculated not per unit volume, but per mole or per gram, the molar (or mass) susceptibility gaining a unit $\text{cm}^3\text{mol}^{-1}$ or cm^3g^{-1} , respectively.

Diamagnetism

Diamagnetism is an underlying property of matter. In a case when no magnetic interactions have to be taken into account, the total susceptibility of the sample is a sum of paramagnetic and diamagnetic susceptibilities [2]:

$$\chi = \chi_D + \chi_P.$$

The value of χ_D is negative, independent of the temperature and the strength of the applied field, and can be calculated from quantum mechanics (per one electron):

$$\chi_D = -\frac{e^2 \langle r^2 \rangle}{6m_e}.$$

where $\langle r^2 \rangle$ is the average squared radius of the orbit and the other symbols have their usual meaning. χ_D depends on the size of the atoms and is tabulated for different ions in so-called Pascal tables [3].

For bulk molecular samples, it can be roughly estimated:

$$\chi_D = \kappa M \cdot 10^{-6} \text{cm}^3 \text{mol}^{-1},$$

where M is the molecular weight of the compound and $\kappa = 0.4 \div 0.5$ [2].

When χ_D is dominant, the total susceptibility is also negative and the substance is considered diamagnetic. Fig. 1.1 shows the schematic behaviour of a diamagnetic substance.

The magnetic moments in a purely diamagnetic substance are induced by an external magnetic field and are directed opposite to the field. The magnetic moment of the system is then independent of the temperature and changes linearly with the magnetic field.

While performing magnetic measurements, diamagnetic contribution of the constituent atoms and of the sample holder must be taken into account.

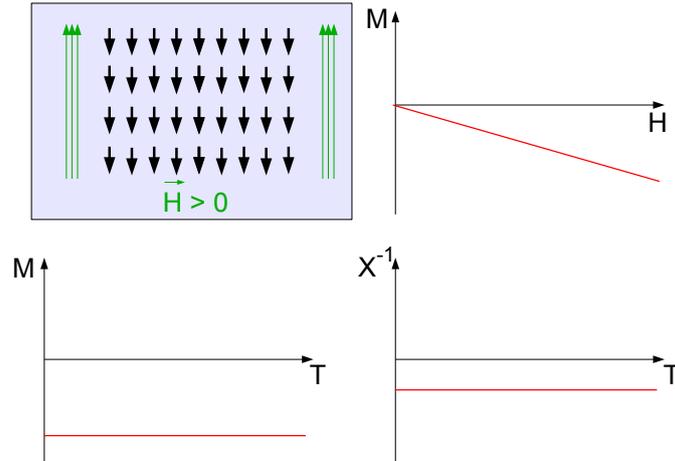


Figure 1.1: A schematic drawing of the field-induced magnetic moments in a purely diamagnetic substance, the macroscopic magnetization versus field, magnetization versus temperature and inverse magnetic susceptibility versus temperature.

Paramagnetism

The paramagnetic susceptibility χ originates from unequal thermal occupation of energy levels E_n in the applied magnetic field H . The microscopic magnetic moment of an energy level n is equal to

$$\mu_n = -\frac{\partial E_n}{\partial H}.$$

The macroscopic molar magnetization is then the sum of μ_n weighed by the Boltzmann distribution law:

$$M = \frac{N_A \sum_n (-\partial E_n / \partial H) \cdot \exp(-E_n / kT)}{\sum_n \exp(-E_n / kT)}, \quad (1.1)$$

where $k = 1.3806488(13) \cdot 10^{-16} \text{ erg} \cdot \text{K}^{-1}$ is the Boltzmann constant. This expression is the fundamental expression of molecular magnetism [2].

If we define a partition function

$$Z = \sum_n \exp(-E_n / kT),$$

then, after a few simple transformations, we obtain a formula for molar paramagnetic susceptibility

$$\chi = N_A k T \frac{\partial^2 \ln Z}{\partial H^2}.$$

This formula requires the knowledge of E_n as a function of the field H . A solution was proposed by Van Vleck in 1932. He expanded the energies E_n according to the increasing powers of H :

$$E_n = E_n^{(0)} + E_n^{(1)} \cdot H + E_n^{(2)} \cdot H^2 + \dots$$

then

$$\mu_n = -E_n^{(1)} - 2E_n^{(2)} \cdot H + \dots$$

Another assumption is that H/kT is small. The exponent in (1.1) becomes

$$\exp(-E_n/kT) = \exp(-E_n^{(0)}/kT)(1 - E_n^{(1)}H/kT).$$

Including these two approximations into equation (1.1) we obtain:

$$M = \frac{N_A \sum_n (-E_n^{(1)} - 2E_n^{(2)} \cdot H) \exp(-E_n^{(0)}/kT)(1 - E_n^{(1)}H/kT)}{\sum_n \exp(-E_n^{(0)}/kT)(1 - E_n^{(1)}H/kT)}. \quad (1.2)$$

We have to add another condition of magnetization vanishing in zero field:

$$\sum_n E_n^{(1)} \exp(-E_n^{(0)}/kT) = 0. \quad (1.3)$$

After incorporating (1.3) into (1.2), we obtain a formula for M , and therefore for the susceptibility as a function of temperature:

$$\chi = \frac{N_A \sum_n ((E_n^{(1)})^2/kT - 2E_n^{(2)}) \exp(-E_n^{(0)}/kT)}{\sum_n \exp(-E_n^{(0)}/kT)}, \quad (1.4)$$

which is the Van Vleck formula. Values of $E_n^{(0)}$ are the eigenvalues of the Hamiltonian in the zero field, while $E_n^{(1)}$ and $E_n^{(2)}$ can be calculated from the perturbation theory:

$$E_n^{(1)} = \langle n | H_Z | n \rangle$$

$$E_n^{(2)} = \sum_m \frac{\langle n | H_Z | m \rangle^2}{E_n^{(0)} - E_m^{(0)}} \quad E_m^{(0)} \neq E_n^{(0)}$$

where $H_Z = \mu_B \sum_i (\vec{l}_i + 2\vec{s}_i) \cdot \vec{H}$ is the Zeeman Hamiltonian and $|n\rangle$ are the eigenstates of the Hamiltonian in the zero field [2].

A paramagnetic substance is the simplest case of magnetic behaviour. If we assume a situation in which the ground state has no first-order angular momentum ($\vec{L} = 0$) and has a large separation energy from the first excited states [2] - there is no magnetic coupling between the spin carriers. When an external magnetic field is applied, the energies of $2S + 1$ Zeeman components are given by

$$E_n = m_S g_s \mu_B H, \quad m_S = -S, \dots, +S.$$

The energies E_n are linear in H , so the second order Zeeman coefficients vanish and the Van Vleck formula (1.4) simplifies to

$$\chi = \frac{N_A \sum_n (E_n^{(1)})^2 \exp(-E_n^{(0)}/kT)}{kT \sum_n \exp(-E_n^{(0)}/kT)}. \quad (1.5)$$

If the temperature is large and H/kT is small, then $E_n^{(0)} = 0$ and $E_n^{(1)} = m_S g \mu_B$, we obtain a formula

$$\chi = \frac{N_A g^2 \mu_B^2}{3kT} S(S+1) \equiv \frac{C}{T}, \quad (1.6)$$

which is known as the **Curie law** that describes the behaviour of a paramagnet in large temperatures.

In the case of large H/kT , the magnetization reaches a value called the saturation value $M_{\text{sat}} = N_A g \mu_B S$ when all the spins align parallel to the applied magnetic field. The magnetization versus field dependence of a paramagnet is well described, without regard to the magnitude of H/kT , by the Brillouin function, which is given below:

$$\frac{M}{M_{\text{sat}}} = B_S(y),$$

where $B_S(y)$ is the Brillouin function:

$$B_S(y) = \frac{2S+1}{2S} \coth\left(\frac{2S+1}{2S}y\right) - \frac{1}{2S} \coth\left(\frac{1}{2S}y\right),$$

and y is defined by:

$$y = \frac{g \mu_B S H}{kT}.$$

The macroscopic behaviour of a paramagnetic substance is illustrated in fig. 1.2.

1.1.3 Models of spontaneous long-range magnetic ordering

In this Section systems with an existing coupling mechanism between the metal centers and therefore with magnetic ordering below a critical temperature T_C will be described.

In general, the coupling between the spins is well described by the Heisenberg Hamiltonian:

$$H_H = - \sum_{i,j} J_{ij} \vec{s}_i \cdot \vec{s}_j,$$

where J_{ij} is the interaction parameter between two neighbouring spins on sites i and j . $J_{ij} > 0$ indicates ferromagnetic coupling, while $J_{ij} < 0$ – antiferromagnetic. If we consider the case of a single spin, with a field applied along the z direction, $J_{ij} = J$ for a pair of nearest neighbours, the total Hamiltonian can be written as:

$$H = g \mu_B S_z H - J z \langle S_z \rangle S_z,$$

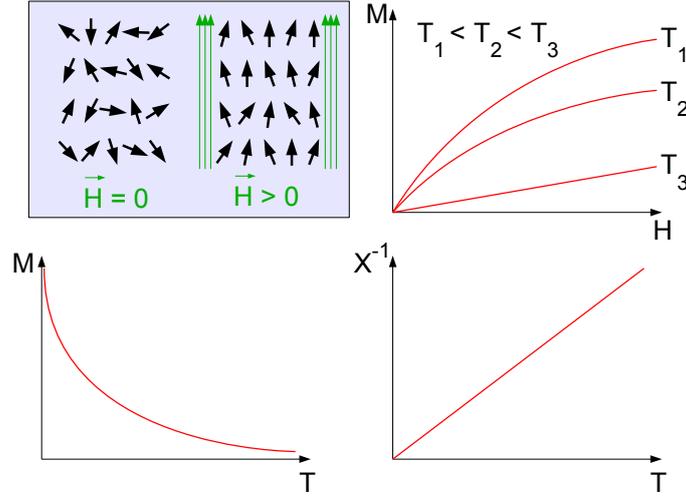


Figure 1.2: A schematic drawing of the spin alignment in a paramagnetic substance without (left) and with applied magnetic field (right), together with the macroscopic magnetization versus field, magnetization versus temperature and inverse magnetic susceptibility versus temperature which obeys the Curie law.

where z is the number of neighbours. The eigenvalues are thus

$$E(S, m_S) = m_S(g\mu_B H - Jz \langle S_z \rangle).$$

$\langle S_z \rangle$ can be calculated from the Boltzmann distribution

$$\langle S_z \rangle = \frac{\sum_{m_S=-S}^S m_S \exp(-E(S, m_S)/kT)}{\sum_{m_S=-S}^S \exp(-E(S, m_S)/kT)},$$

which can be simplified, after expanding the exponents up to the first order, into

$$\langle S_z \rangle = \frac{\sum_{m_S=-S}^S m_S [1 - m_S(g\mu_B H - Jz \langle S_z \rangle)/kT]}{\sum_{m_S=-S}^S [1 - m_S(g\mu_B H - Jz \langle S_z \rangle)/kT]}.$$

After the summation, an expression for $\langle S_z \rangle$ can be extracted:

$$\langle S_z \rangle = -\frac{S(S+1)g\mu_B H}{3kT - zJS(S+1)}.$$

For a polyatomic system in the molecular field approximation, the magnetization per one mole of substance is

$$M = N_A \cdot \langle m \rangle = -N_A g \mu_B \langle S_z \rangle,$$

from which a formula for susceptibility $\chi = \partial M / \partial H$ can be concluded:

$$\chi = \frac{N_A g^2 \mu_B^2 S(S+1)}{3kT - zJS(S+1)} \equiv \frac{C}{T - \theta},$$

which is known as the **Curie-Weiss law**. C is the previously defined Curie constant and θ is the Weiss temperature

$$\theta \equiv \frac{zJS(S+1)}{3k}.$$

It indicates the intermolecular interactions: positive value means ferromagnetic, negative - antiferromagnetic interactions [2].

The Weiss theory predicts $\theta = T_C$, but in fact it is only an upper limit for the critical temperature, which is often decreased by short range of the interactions and the quantum nature of the moments [4].

Ferromagnetism

In a ferromagnetic substance, the moments tend to align parallel to each other giving rise to a spontaneous magnetization below T_C even without applying the external magnetic field. The typical behaviour of a ferromagnetic sample is depicted in fig. 1.3.

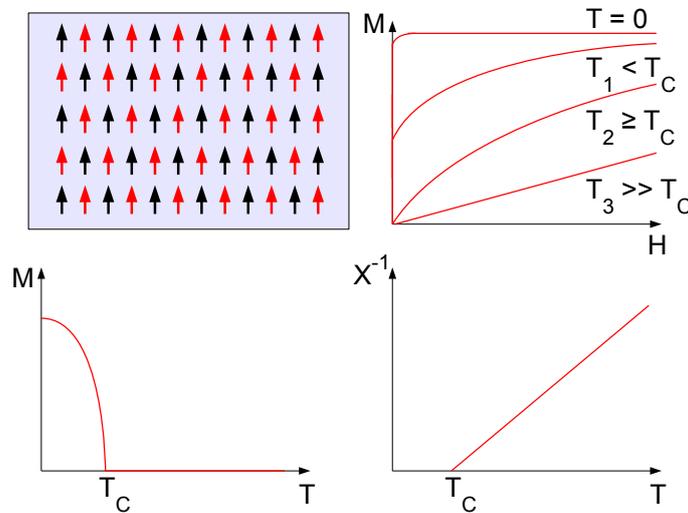


Figure 1.3: A schematic drawing of the spin alignment in a ferromagnetic substance, together with the macroscopic magnetization versus field in different temperatures, magnetization versus temperature and inverse magnetic susceptibility versus temperature which obeys the Curie-Weiss law above T_C .

The magnetization in zero temperature rises instantly to its saturation value (meaning all the moments aligned in the same direction). Closer to the T_C ,

spontaneous magnetization is still present, but the saturation value is reached only in higher fields (T_1 in fig. 1.3). Above the T_C , spontaneous magnetization vanishes and the sample becomes paramagnetic. Inverse susceptibility obeys the Curie-Weiss law above the T_C with a positive θ value.

Despite exhibiting spontaneous magnetization below T_C , a sample of a ferromagnet is not necessarily magnetised due to the existence of magnetic domains. Ferromagnetic materials may display a **hysteresis** below T_C (fig. 1.4).

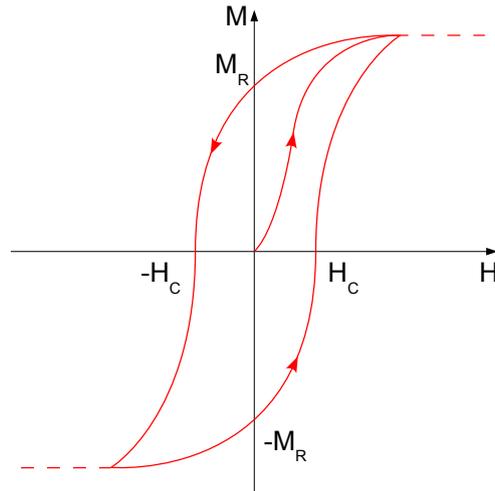


Figure 1.4: A schematic drawing of a typical ferromagnetic hysteresis loop close to $T = 0$ K. H_C - coercivity field, M_R - remnant magnetization.

Starting at the zero point ($M = 0, H = 0$), below T_C , a positive field is applied, giving rise to the *initial magnetization curve*. Then the field is lowered back to zero, however, a *remnant magnetization* M_R is displayed by the sample in $H = 0$. Further applying a field of negative direction lowers the magnetization to zero at $H = H_C$, which is called *the coercive field*. The process is symmetric and further changes of the field in positive and negative direction will cause the magnetization to follow the hysteretic loop. Increase in the temperature will cause the loop to shrink (lower value of H_C) and magnetization will not reach its saturation value as soon as in fig. 1.4. When the critical temperature is reached, the loop vanishes completely.

Most technological applications of hard magnetic materials and magnetic recording rely on the existence of the hysteresis [5].

Antiferromagnetism

In the case of an antiferromagnetic substance, the magnetic interactions tend to align the neighbouring moments antiparallel to each other and, as a result, there

is no spontaneous magnetization below the critical temperature, which in case of the antiferromagnet is called the Néel temperature T_N .

In the simplest case, an antiferromagnet can be imagined as two identical interpenetrating ferromagnetic sublattices, which respective magnetizations are of identical value but opposite directions. The behaviour of an antiferromagnet is shown in fig. 1.5.

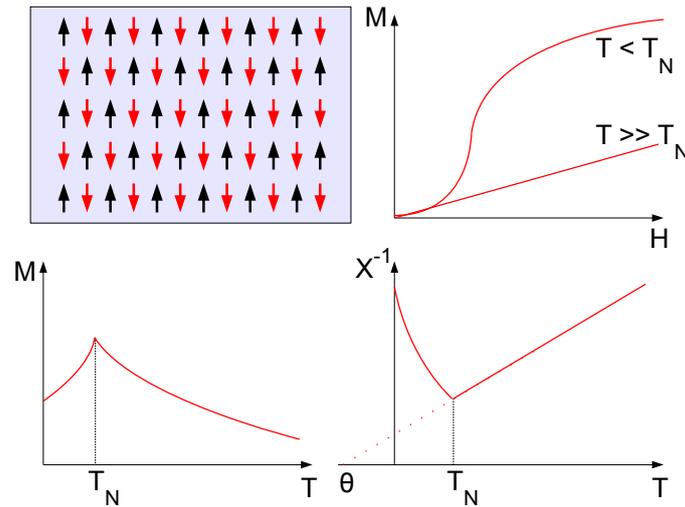


Figure 1.5: A schematic drawing of the spin alignment in an antiferromagnetic substance, together with the macroscopic magnetization versus field in different temperatures, magnetization versus temperature and inverse magnetic susceptibility versus temperature which obeys the Curie-Weiss law above T_N .

The magnetization behaviour in field is similar to the one of a paramagnet in high temperatures. In temperatures below T_N , a spin-flip transition may occur when the external field is strong enough to overcome the molecular field and align all the spins in the same direction. The difference between antiferromagnetism and other types of magnetic ordering is clearly visible in the inverse susceptibility as a function of temperature - it has a minimum at T_N and it obeys the Curie-Weiss law in higher temperatures with a negative value of θ .

Ferrimagnetism

A ferrimagnet is a substance much like the antiferromagnet, but in this case the sublattices do not exactly compensate each other and a spontaneous magnetization remains. That may happen due to the sublattices being composed of atoms of different spins and/or to unequal number of atoms in each sublattice. Ferrimagnetism was predicted by L. Néel before being confirmed by experiment [5].

In the molecular field model, two colinear sublattices are considered, with different magnetizations, M_A and M_B . Let $w_{AB} = w_{BA} = -w$ ($w > 0$), $w_{AA} = \alpha_A w$ and $w_{BB} = \alpha_B w$ (w_{AA} and $w_{BB} > 0$) be the various molecular field coefficients. The Curie constants of the sublattice i , $C_i = N_A g^2 S_i(S_i + 1) \mu_B^2 / 3k_B$ ($i = A, B$). In this model, the susceptibility is predicted to be:

$$\frac{1}{\chi} = \frac{T - \theta_P}{C} - \frac{\gamma}{T - \theta}, \quad (1.7)$$

where in general case:

$$C = C_A + C_B, \quad (1.8)$$

$$\theta = \frac{w(2 + \alpha_A + \alpha_B)C_A C_B}{C_A + C_B}, \quad (1.9)$$

$$\gamma = \frac{w^2 C_A C_B [C_A(1 + \alpha_A) - C_B(1 + \alpha_B)]^2}{(C_A + C_B)^3}, \quad (1.10)$$

$$\theta_P = w \frac{\alpha_A C_A^2 + \alpha_B C_B^2 - 2C_A C_B}{C_A + C_B}. \quad (1.11)$$

In a simple case of sublattices interacting only with each other and assuming that there are no interactions between atoms of the same sublattice, equation (1.7) becomes much easier for application. In such a case we assume $\alpha_A = 0 = \alpha_B$. Equations (1.9) and (1.11) can be now summarized in one:

$$\theta = \frac{2wC_A C_B}{C_A + C_B} = -\theta_P, \quad (1.12)$$

and the equation (1.10) becomes:

$$\gamma = w^2 \frac{C_A C_B (C_A - C_B)^2}{(C_A + C_B)^3}. \quad (1.13)$$

Having incorporated both equations (1.12) and (1.13) into eq. (1.7), we obtain a formula:

$$\frac{1}{\chi} = \frac{T^2 - w^2 C_A C_B}{T(C_A + C_B) - 2wC_A C_B} \quad (1.14)$$

This model describes the susceptibility well in high temperatures. The reciprocal susceptibility follows a hyperbolic law, with the following asymptotes: in high temperatures a Curie-Weiss line with $\theta_{CW} = \theta_P$ and near the critical temperature a vertical asymptote $T = \theta$ (see fig. 1.6).

The behaviour of a macroscopic ferrimagnetic sample is gathered in fig. 1.6. Below T_C , and in the absence of the external magnetic field, there are two typical cases of the behaviour of the magnetization (depicted in fig. 1.6 in red and green). The first case is similar to the ferromagnetic behaviour, while in the second the

spontaneous magnetization passes through zero at a *compensation temperature* $T_{comp} < T_C$. This case occurs when the thermal variation of the magnetization of the sublattice which dominates over that of the other at low temperatures is faster than the other [5]. Magnetization versus field resembles the one of a ferromagnet – with the spontaneous magnetic moment vanishing in T_C .

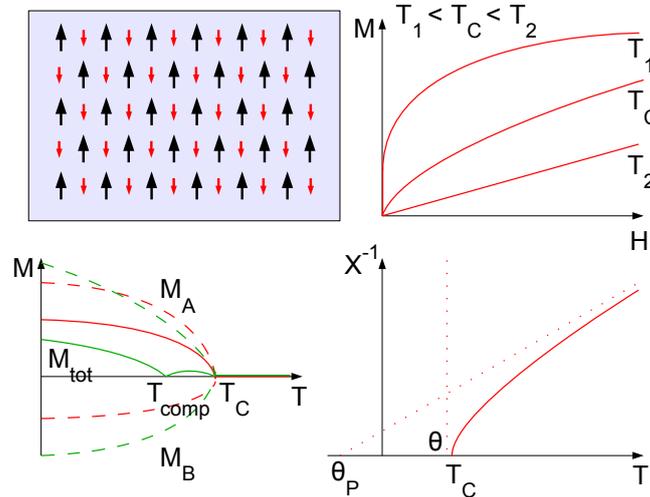


Figure 1.6: A schematic drawing of the spin alignment in a ferrimagnetic substance at $T = 0$, together with the macroscopic magnetization versus field in different temperatures, magnetization versus temperature (two typical cases in red and green) and inverse magnetic susceptibility.

Chapter 2

Magnetic measurements

2.1 SQUID magnetometry - the idea

2.1.1 The Josephson tunneling effect

The tunneling effect through an insulating barrier between superconductors was discovered by B. D. Josephson in 1962 [6], for which he was awarded a Nobel Prize in 1973 [7].

A Josephson junction (fig. 2.1) is a thin layer of an insulator between two superconductors. Cooper pairs in a superconductor can tunnel through an insu-

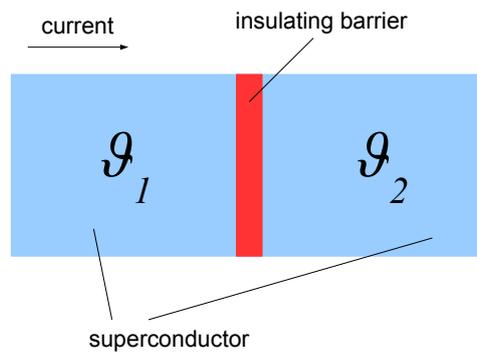


Figure 2.1: A scheme of a Josephson junction.

lating barrier. The total current through a Josephson junction depends largely on the phase difference between the superconductors on both sides [4]

$$\delta = \vartheta_1 - \vartheta_2.$$

The phases ϑ_1 and ϑ_2 are arbitrary but fixed, hence δ is also fixed. The Josephson current is then given by

$$J(\delta) = J_0 \sin(\delta).$$

If there is an electrical time-dependent potential across the Josephson junction, δ will also be time-dependent:

$$\delta(t) = \delta_0 + \frac{1}{\phi_0} \int_0^t V(t') dt',$$

where $\phi_0 = h/2e$ is the flux quantum and $V(t)$ is the difference of potentials on two sides of the junction. If $V(t) = 0$, a current $J(\delta_0)$ can pass the barrier without resistance (DC Josephson effect). If the current surpasses the critical current J_C , the junction will have a measurable resistance.

If $V(t) = V_0 = \text{const}$, the DC current will disappear. The voltage drop will generate an alternating supercurrent at a frequency $\omega = V_0/\phi_0$ (AC Josephson effect).

The Josephson effect was first observed by P. W. Anderson and J. M. Rowell in 1963 [8].

2.1.2 SQUID

The abbreviation SQUID stands for Superconducting QUantum Interference Device. A DC SQUID [4] is a superconducting ring with two Josephson junctions (fig. 2.2)

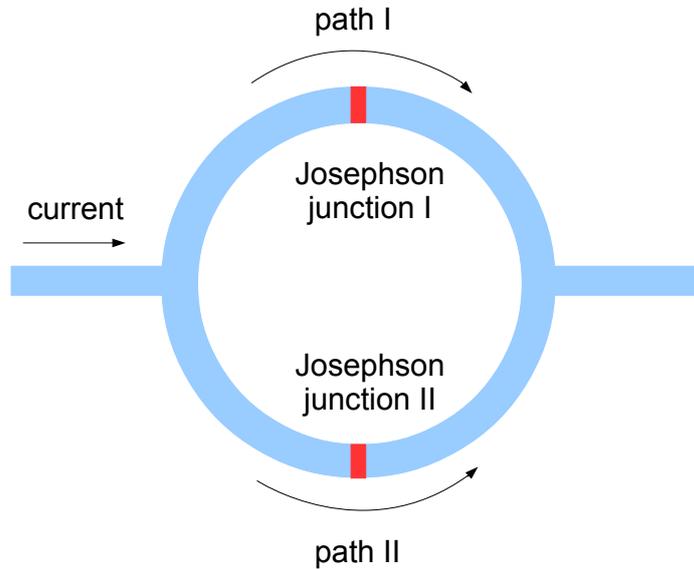


Figure 2.2: A scheme of a DC SQUID.

It uses quantum interference between the two paths that enclose an area with a magnetic flux within the ring. For the two paths through the device the phase difference is:

$$\Delta\vartheta = \delta_{I/II} + \frac{1}{\phi_0} \int_{I/II} \vec{A}(\vec{s}) d\vec{s},$$

where I/II indicates which Josephson junction the current is passing and $\vec{A}(\vec{s})$ is the vector potential along a path \vec{s} .

The gauge invariance demands that the total phase difference is zero or $n \cdot 2\pi$.

The induced flux in the ring by the external field is $\phi_{ext} = \oint \vec{A}(\vec{s}) d\vec{s}$. The critical current through the DC SQUID is then given by:

$$I_C = I_0 \left| \cos \frac{\pi \phi_{ext}}{\phi_0} \right|.$$

The critical current is modulated by the magnetic flux flowing through the ring. I_C is maximum when ϕ_{ext} satisfies the quantization condition (is an integer multiple of ϕ_0). This allows a measurement of magnetic flux with great precision.

The first SQUID was constructed by R. Jaklevic, J. Lambe, A. Silver and J. Mercerau in 1964 [9].

Modern SQUID magnetometers

A simple idea of the construction of a SQUID magnetometer [4] is presented in fig. 2.3.

The sample travels through the detection coil which is connected to the input coil. It communicates with the SQUID ring by means of mutual inductance. The output of the SQUID is proportional to the critical current in the SQUID which is a periodic function of the flux. There is a second feedback coil which also communicates with the SQUID by their mutual inductance. The feedback system allows calculating the flux that passed through the SQUID ring and thus measuring the sample magnetization.

Modern SQUID magnetometers are equipped with superconducting magnets and precise temperature control systems which allow measurements in a large range of fields and ultra-low temperatures.

2.2 Quantum Design MPMS XL system

The system used in our laboratory is a Quantum Design MPMS 5XL. In addition to the classic DC and AC measurements, a more sensitive Reciprocating Sample Option is installed, improving the sensitivity to 10^{-8} emu. The system is equipped with a superconducting magnet and a precise temperature control system, allowing measurements in the temperature range 1.8 - 300 K and in fields 0 - 50 kOe.

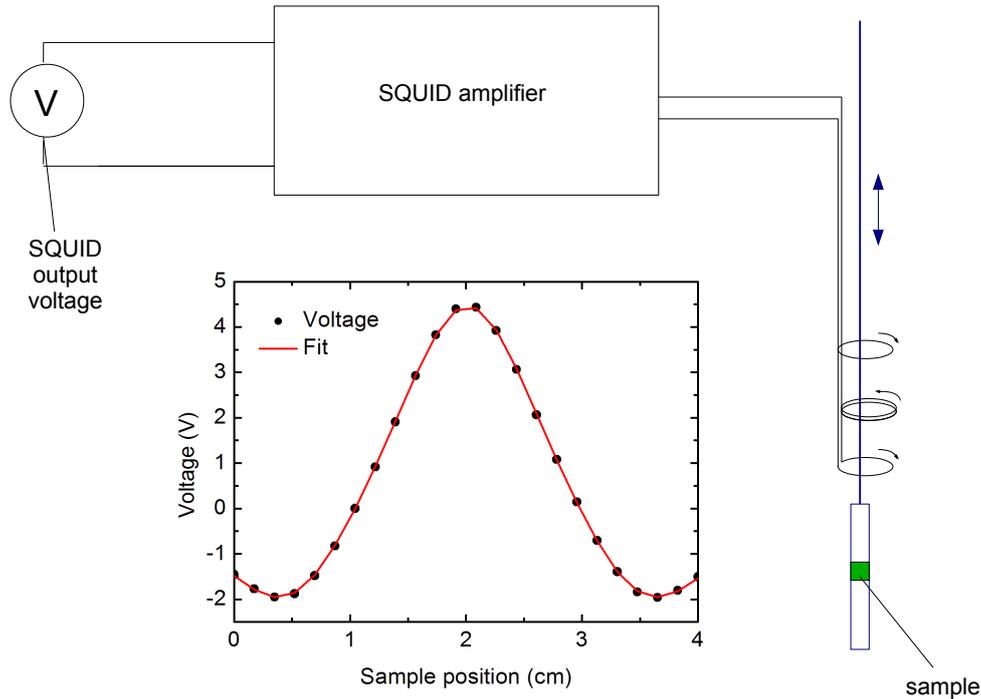


Figure 2.3: A scheme of a SQUID magnetometer

2.2.1 DC measurements

In a basic DC measurement, the magnetic moment of the sample is measured by reading the output of the SQUID detector while the sample moves upward, from the initial position, through the SQUID pickup coils. This upward movement completes one vertical scan. Voltage readings that are taken as a function of the sample's position in the coils comprise the raw measurement data. At each position in the coils, the software typically reads the SQUID output voltage several times, and multiple scans are averaged together to improve the resolution [10]. These measurements have the typical accuracy of 0.1%.

The Reciprocating Sample Option measures the magnetic moment of the sample in an alternative way. Instead of moving the sample steadily through the SQUID pickup coils, like in the case of the basic DC measurement, and stopping the motor for each data reading, it moves the sample rapidly and sinusoidally through the coils. Lock-in techniques that use digital signal processor reduce the contribution of low-frequency noise to the measurement. RSO measurements have a sensitivity of approximately $5 \cdot 10^{-9}$ emu [11].

Most of the measurements of static magnetic susceptibility for this Thesis were done using this option, except for the signals of range larger than 10^{-1} emu, in

case of which classic DC measurements were performed.

2.2.2 AC measurements

In AC magnetic measurements, a small AC drive magnetic field is applied to the sample, in addition to the DC field, causing a time-dependent moment in the sample. The field of the time-dependent moment induces a current in the pickup coils, allowing measurement without sample motion. The AC susceptibility (differential susceptibility) $\chi_{AC} = dM/dH$ obtained from these measurements has both real and imaginary components, χ' and χ'' :

$$\chi = \chi' + i\chi''.$$

Since the AC measurement is sensitive to the slope of $M(H)$ and not to the absolute value, small magnetic shifts can be detected even when the absolute moment is large.

In the limit of low frequency where AC measurement is most similar to a DC measurement, the real component χ' is just the slope of the $M(H)$ curve. The imaginary component, χ'' , indicates dissipative processes in the sample.

In conductive samples, the dissipation is due to eddy currents. Relaxation and irreversibility in spin-glasses give rise to a nonzero χ'' . In ferromagnets, a nonzero imaginary susceptibility can indicate irreversible domain wall movement. Also, both χ' and χ'' are very sensitive to thermodynamic phase changes, and are often used to measure transition temperatures [12], [13].

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