

Magnetic Susceptibility Under Phase Transitions

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Goals of the Experiment

In this experiment, a simple and inexpensive technique is used to measure the change of magnetic susceptibility of a nickel slug as it undergoes a phase transition from being ferromagnetic to only being paramagnetic. The temperature of this transition is also measured.

Introduction

The sample is placed in a coil, which is part of an LC oscillator. The effect of the sample is to change the inductance of the coil. The change in inductance produces a corresponding change in frequency of the LC oscillator, which is measured by a computer.

When the sample is placed in the coil the inductance becomes

$$L = L_0(1 + \alpha\chi), \quad (1)$$

where χ is the magnetic susceptibility [1] of the sample and α is a constant that depends on geometrical factors, such as the fraction of the coil that is occupied by the sample (filling factor) and the samples demagnetization coefficient ([1]).

The oscillating frequency of the circuit is

$$f = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{CL_0(1 + \alpha\chi)}}. \quad (2)$$

If χ is small compared to unity, the operating frequency can be expanded as

$$f \approx f_0(1 - \alpha\chi/2), \quad (3)$$

where $f_0 = 1/(2\pi\sqrt{L_0C})$ is the frequency of the circuit with the coil empty.

When the magnetic sample undergoes its phase transition at temperature T_C the change in frequency is related to the change in magnetic susceptibility by

$$\frac{(\Delta f)_T}{f_0} = -\frac{1}{2}(\alpha\Delta\chi)_T. \quad (4)$$

By measuring the frequency change with and without the sample in the coil, one can determine the magnetic susceptibility of the material from Eq. (3). From Eq. (4) one obtains the change of susceptibility when the sample undergoes its transition.

Advance Preparation

1. Find the definitions of H , B , M , and χ (Most advanced undergraduate text books will address these ideas). Find the boundary conditions satisfied by B and H .
2. Define a) paramagnetism, b) diamagnetism, and c) ferromagnetism.
3. What is the “demagnetization factor”. Find the demagnetization factors for a) a long thin rod with magnetization along the axis of the rod, b) a sphere, and c) a thin wide disk with magnetization normal to the plane of the disk.
4. What is the meaning of the “skin depth” δ (you can look this up in most condensed matter textbooks, e.g. Ref [1])? Find an expression (e.g. from Ref [1]) for the skin depth for frequency ω and electrical conductivity σ .

Apparatus

Overview

In this experiment, the sample is either a nickel cylinder $1" \times 1/4"$ (99.998% pure) or a bundle of nickel wires, each with diameter 0.125 mm (99.98% pure). It is placed in a closely fitted Pyrex tube around which 15 turns of wire is wrapped (the inductance of the coil is about $1\mu\text{H}$). The tube and lead wires are mounted on standoffs to an aluminum plate, which is centered in an oven.

The type K (alumel/chromel) thermocouple is placed in the oven, near the sample. The signal from the thermocouple is fed into a National Instruments SCB-68 circuit board, which is left open for observation, and if desired or necessary- changing the input channels. This can be done by unscrewing the Flathead screw of the channel, removing or inserting the wire, and tightening the screw.

The LC oscillator operates around 1 MHz, and (aside from the inductor) is encased in a "black box" on top of the oven. The schematic can be seen in Figure 1. Its output is sent to the SCB-68 board, and can be monitored on the oscilloscope. With the toggle switch in the "Int." position, the oscillator uses an internal inductor to create an output signal. In the "Ext." position, the inductance of whatever is connected to the BNC input will operate the oscillator; in this case, it is the coil inside the oven. The red LED indicates that the oscillator is working properly, regardless of the position of the toggle switch. If the LED is off, the board is either not powered, or the "Ext." coil is not connected properly. When the LED is on, the oscilloscope should show a 5 volt square wave with a frequency close to 1 MHz (if nothing is connected to the Ext. input, the oscilloscope will show a 5 volt DC signal).

The input data from the SCB-68 board is sent to a data acquisition card (can be seen through the window of the computer), also made by National Instruments. You will be using a development environment called LabVIEW for data collection and analysis. You are not expected to be familiar with LabVIEW, and a brief introduction to its "language" is provided in the next section.

LabVIEW

Short for "Laboratory Virtual Instrument Engineering Workbench", LabVIEW is an IDE for a visual, or graphical, programming language from National Instruments (sometimes called "G"). Instead of typing code with a keyboard, the programmer uses the mouse to drag and drop "virtual instruments" (VIs) onto a blank page. LabVIEW has many VIs, all with different functions, and can easily perform logic and use loops like programming languages with which you may already be

familiar. These VIs have specific input and output terminals to connect them (via virtual "wires") to other VIs, inputs, outputs, or other elements that perform logic, math, wave analysis, etc.

You will use a homemade LabVIEW program to run the experiment. The files you will need are in a folder on the Desktop called "MagSuscept2020", and it contains the main program and empty folders to which the program will write its output files. The program is relatively simple- it reads in the digital and analog inputs from the oscillator and thermocouple, respectively, displays the data as icons, graphs and numerical indicators, and selectively outputs the data (namely the frequency vs temperature plot) to a file (or files) that can later be analyzed via Python or Excel. The program has three panels for saving data- one section for saving only the temperature data, one for frequency data, and one for both. Click on the "save?" button for each section you would like to save, before running the program. By default, the data will be saved to the previously mentioned Desktop folder, in the appropriately labeled sub-folder. This can be changed by writing a different path in the corresponding section.

Feel free to edit the program in any way. When your experiment is over, the program will be deleted and the original program will be copied to its place, ready for the next group of students.

Principles of the Oscillator Circuit

The oscillator circuit (shown in Fig. 1) is based on the "Colpitts" oscillator configuration [2]. The Colpitts oscillator consists of an amplifier (the two transistors in the circuit of Fig. 1) with a feedback circuit made up of two series capacitors in parallel with an inductor. At the resonant frequency of the feedback circuit [$\omega_0 = \sqrt{C_1 C_2 / ((C_1 + C_2)L)}$] the phase of the feedback becomes positive causing the circuit to oscillate at this frequency. The amplifier consists of an FET in a "common source" configuration (see Ref. [2]) followed by a npn transistor in an emitter follower configuration. The emitter follower serves the purpose of lowering the output impedance of the amplifier. The gain of the amplifier is controlled by setting the bias voltage of the FET drain through R_4 , and has been adjusted to maximize the amplitude of the oscillations.

The output of the oscillator is fed to a comparator (configured with a small amount of positive feedback to prevent oscillations at the switching point), whose output switches between 0 and 5 volts depending on whether the input is positive or negative. The comparator effectively acts as a 1-bit digital-to-analog converter (DAC). The comparator output is fed to the SCB-68 board.

Experimental Procedures

Setting Up

On the Desktop, start LabVIEW by clicking "National Instruments LabVIEW 2011 (32-bit)". The folder next to it contains the main program, and empty folders for saving your data.

A window should open, with sections on the left side reading "New" and "Open". Under "Open", look for and click on "magSuscept2020.vi"

The main user panel will appear, showing a large graph, a thermometer readout, and a few other indicators. At the top left, go to Window >Open Block Diagram to see the LabVIEW workbench. On the main user panel, the three sections for saving data have a path written that must be changed in order for the program to run. In each section, delete the current pathname, and write "C:\Users\Student\Desktop\MagSuscept2020\", followed by the name of each section- "Temperature\", "Frequency\", or "Freq-T\". This will allow LabVIEW to save your data to a file in this folder. The name of the file is fixed and numbered, but you can add a prefix to the name by typing it after the last "backslash".

Run the program by clicking the "Run" button (black arrow) in the top left corner. If it immediately generates an error message, it probably has to do with the file pathnames- so double check those. Also, data will not save unless you click on the "save?" buttons.

The inductance of the oscillator depends on the entire length of wire parallel from one capacitor to the other, which means that the wires running from the back of the oven and into the oscillator matter in terms of their position to each other. For the most accurate data, make sure the wires are completely still before running the program and for the duration of data collection (don't bump into the table, or stomp your feet too hard). You can view on the oscilloscope how much the frequency changes by just displacing the wires a small amount.

Measurement of the Susceptibility of the Nickel Slug

First measure the frequency difference between the empty coil and the coil with the sample by running the program while the instructor adds and removes the sample from the coil.

Have the instructor place the nickel slug into the coil. Make sure to click on the "save" buttons for the kind of data you want to save. Begin recording data by starting the program. Turn on the oven. Continue recording until the oven reaches a temperature of about 450°C. Stop the program, turn off the oven, and start the program again, such that the cooling run is saved to a separate file. Start the program again as the oven cools.

Finally, make a run with the empty coil over the same temperature range as the run with the sample.

Measurement of the Susceptibility of the Nickel Wires

Repeat the measurements made in the last section with the nickel wires instead of the slug (it is not necessary to do the run with the empty coil again). Before or after making the run, determine the mass of the Nickel sample.

Questions

The answers to these questions should be integrated into your lab report.

1. For each of the samples, plot the $f(T)/f_0(T)$ vs. T for both increasing temperature and decreasing temperature. Give a qualitative description of the data, including any differences between the samples, and between the data for increasing temperature and decreasing temperature. Attempt to explain your observations. For example, explain why the frequency *increases* when the nickel slug is placed in the coil.
2. Determine the temperature of the phase transition, including the corresponding uncertainty of your measurement.
3. For the sample of Nickel wire, determine the **absolute** susceptibility of Nickel. To do this, you will need to estimate the filling factor of the sample. The filling factor can be estimated if you know the mass of the sample, the volume of the coil, and the fraction of the inductance attributable to the coil. The volume of the coil is about . . . , and the inductance of the coil is about $1\mu\text{H}$, whereas the total inductance of the circuit is about $1.6\mu\text{H}$. You also need to consider the role of the demagnetization factor. Don't forget to estimate the uncertainty of your result.
4. Suggest possible ways that the experiment could be improved.

References

- [1] Ashcroft and Mermin, *Solid State Physics*, Saunders College, 1976
- [2] Horowitz and Hill, *The art of Electronics*, Cambridge University Press

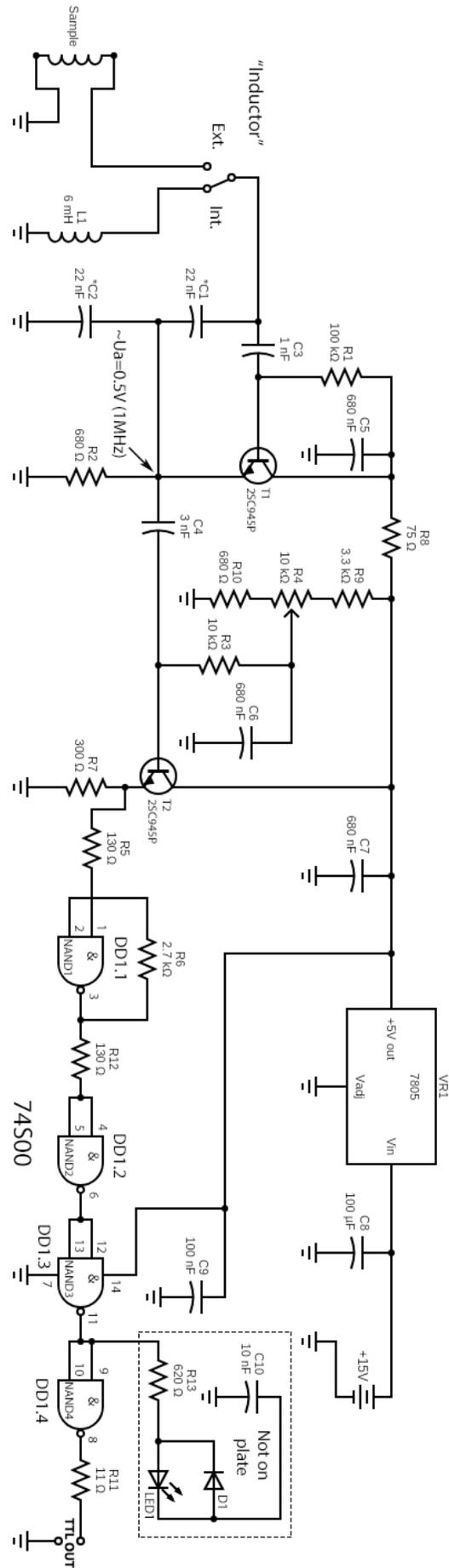


Figure 1: Oscillator Circuit