Laboratory #51: Magnetic Susceptibility Under Phase Transitions

Goal: Measure the change of magnetic susceptibility of nickel and ferrite samples as they undergo a phase transition between ferromagnetic and paramagnetic states. Determine the corresponding phase transition temperatures.

Equipment: Oven; “Colpitts” oscillator circuit outfitted with sample coil and thermocouple within the oven; logger pro computer interface; cylindrical nickel and ferrite slugs; nickel wire bundle encased in Pyrex tube.

(A) Physics:

The physics underlying the magnetic properties of materials is a rich subject with abundant practical application. Most materials display either weak paramagnetic or diamagnetic behavior, in which they develop a small magnetization density $\mathbf{M}$ reflecting partial alignment of atomic dipole moments in response to an externally generated magnetic field (that here dominates the auxiliary field $\mathbf{H}$), and oriented respectively along or opposite to it. The total magnetic field within the material is $\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$, in SI units (actually, this expression defines $\mathbf{H}$). This behavior is linear; that is, $\mathbf{M} = \chi \mathbf{H}$, where the magnetic susceptibility $\chi$ is a small ($\ll 1$) dimensionless number specific to a given material, positive for paramagnetic materials and negative for diamagnetic ones.

For certain materials, a purely quantum mechanical effect known as the exchange interaction leads to spontaneous long-range alignment of atomic magnetic dipole moments within microscopic domains. Application of an externally generated field leads to alignment (along its orientation) of the magnetizations of these domains, resulting in very large macroscopic magnetization of the material. This behavior is known as ferromagnetism. Only a few elements are ferromagnetic at room temperature, including Nickel, Iron, Cobalt, and Gadolinium, although many ferromagnetic alloys and compounds are known. Ferromagnetic materials are not linear, which is easily understood in that the magnetization cannot be increased beyond complete alignment of atomic dipoles. But, one can still define susceptibility (now a number often much greater than 1) over a limited range before the onset of this saturation. The ferromagnetic behavior of a material is present only below its Curie Temperature; at higher temperatures thermal fluctuations destroy the long-

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1 The experimental implementation, along with significant portions of this write-up, has been adapted from the corresponding description for a lab on this topic developed for the New York University Physics Dept. by Prof. T. Sleator. See Ref [1].
range order. Note also that ferromagnetic materials show hysteresis, in which the state of a material at any given time depends not just on the conditions (temperature and field strength $H$) at that time, but also on its previous state.

When a material is inserted into the bore of a coil with a given self-inductance $L_0$, the magnetic flux associated with a given current flowing through the coil is altered in a way that depends on the susceptibility. Thus the self-inductance becomes:

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

where $\alpha$ is a constant that depends on geometrical factors, such as the fraction of the coil bore volume occupied by the sample (filling factor) and the demagnetization factor (see Ref. [2]) of the sample.

In this experiment we place various samples within a coil that is part of an LC oscillator circuit. The frequency of oscillation of the circuit is:

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

If $\chi$ is small compared to unity, the frequency can be expanded as

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

where $f_0 = 1/(2\pi\sqrt{L_0C})$ is the frequency of the circuit with the coil empty. Thus $\chi$ can be determined by measuring the change in frequency when the sample is inserted. When a magnetic sample undergoes a phase transition at the Curie Temperature $T_c$, the observed change in frequency is thus related to the change in magnetic susceptibility by

$$\frac{(\Delta f)_\tau}{f_0} = -\frac{1}{2} (\alpha \Delta \chi)_\tau.$$

Since the oscillator involves a time-varying current through the inductor coil, and hence a time-varying magnetic flux, there is an additional contribution to the inductance due to eddy currents induced in electrically conductive samples. In this case, it is important to note that the effect will depend on the geometry of the sample, as well as on the skin depth (which itself is a function of frequency) characteristic of the current density distribution within the conducting material.
(B) Experiment

Familiarize yourself with the definitions of the terms used in the above discussion. Any advanced undergraduate textbook on electromagnetism (such as Griffiths’ Introduction to Electrodynamics) will do for the basic concepts behind magnetic properties of materials, eddy currents and the like. For further discussion, including deeper discussions of magnetic susceptibility, demagnetization factors, phase transitions, and skin depth, other sources such as those in Ref. [2] will be helpful.

The apparatus is very similar to that presented in Ref [1], although the data acquisition is much simpler thanks to the LabPro/LoggerPro computer interface and control/display software. Carry out the measurement steps as described in the Experimental Procedures section of Ref [1]:

(1) Calibrate the thermocouple readout. Measure \( f_0(T) \), the oscillator frequency as a function of temperature for the case of an empty coil.

(2) Measure the temperature dependence of the oscillator frequency through and on both sides of the phase transition, for each of the three samples provided:
   a. the nickel slug (1" x ¼”)
   b. the pyrex-encased sample of nickel wire segments (0.125 mm diam.)
   c. a ferrite sample of similar (but not identical) dimensions to the nickel slug. (Ferrites are non-conducting magnetic materials commonly used for electromagnetic interference rejection in electronic circuits.)

(3) Note that measurements should be taken twice for each sample – once as the oven is heated up, and once as it cools again past the phase transition.

For the analysis of the data you have collected, try to address the questions posed on page 4 of Ref [1]. In summary form these are:

   (1) Explain the trends in each of the plots of \( f(T)/f_0(T) \) versus temperature; why does the frequency increase when the nickel slug is inserted, in contrast with the behavior of the other samples?
   (2) Determine the phase transition temperature for each of the samples.
   (3) Determine the absolute susceptibility of nickel using the data from the wire-segment sample. Do this also for the ferrite sample.
   (4) Suggest possible ways of improving the experiment.

(C) References
