A Direct Method for Viewing Ferromagnetic Phase Transition

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Every physics student learns about phase transition phenomena, but only a few examples are obvious in daily life. A good example that can be demonstrated is the transformation of ferromagnetic materials into paramagnetic at T_C. With simple circuits and a commercial inductance, the so-called Rowland ring as a specimen, we can observe the phase transition process directly on the oscilloscope and even extract the critical exponent of ferromagnetic transition.

Theory

Without any applied magnetic field, a ferromagnetic material with temperature below T_C, critical temperature or Curie temperature, can be regarded as an enormous number of little magnets located randomly in different domains. When an external magnetic field is applied, those little magnets are forced to align in order and a net magnetization, M, exists. The magnetization increases with increasing external field until saturation occurs, but does not return to zero if we remove this field. As a consequence, a hysteresis curve results. With rising temperature, the thermal energy will distort those ordered magnets, and magnetization, of course, decreases. When T_c is approached from below, M drops continuously to zero. The observed $M(T)$ just below T_c is well described by a power law $M \propto (T_c - T)^{\beta}$, where β, a critical exponent, is typically between 0.33 and 0.37.

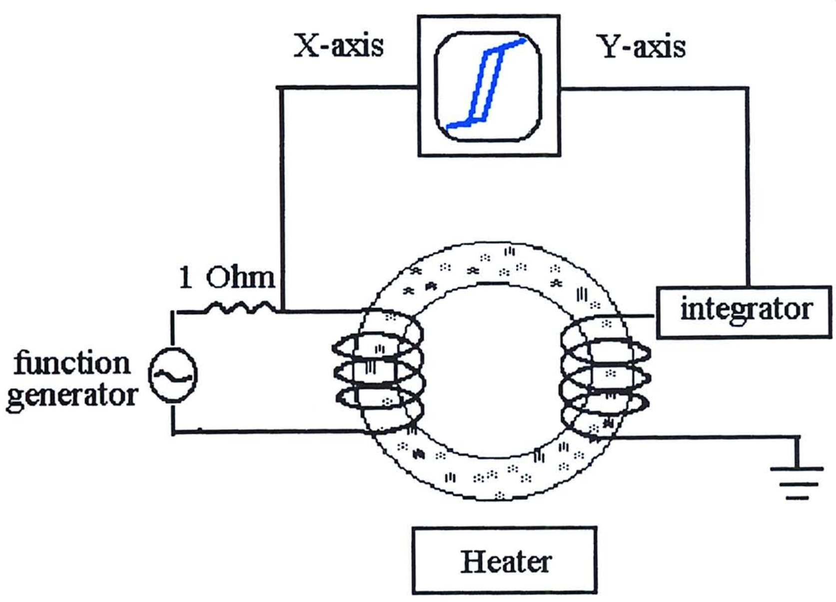

Fig. 1. Experimental setup for observing ferromagnetic phase transition.

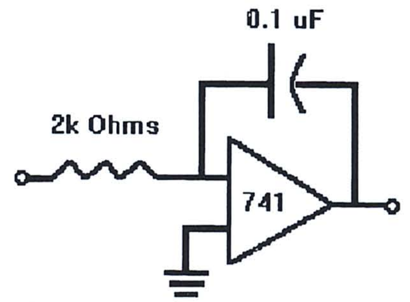

Fig. 2. Simple circuit for integrating induced emf.

Experimental Setup and Results

The setup diagram is shown in Fig. 1. Our specimen is a cheap commercial inductance made of ferromagnetic powder. A function generator produces an ac electric field to induce alternative magnetic flux, which generates induced emf in a secondary coil. It can be simply expressed by Faraday's law, $\varepsilon = -N_2 \frac{d\Phi_B}{dt}$, or after integration, $\int_0^T \varepsilon dt = -N_2 \oint d\Phi_B$, where N_2 is the number of turns of secondary coil, Φ_B is magnetic flux, and T is the time of a cycle. Thus, we need to integrate the emf to calculate the change in magnetic flux during a period. We can see the hysteresis on the oscilloscope in x-y mode. Figure 2 shows a simple home-made integrator with good frequency response between 10 Hz and 10 kHz.

The alternating frequency of about 500 Hz is applied to induce magnetic flux. The sample is heated in an electric oven and its temperature measured with a chemical thermometer. We can see the

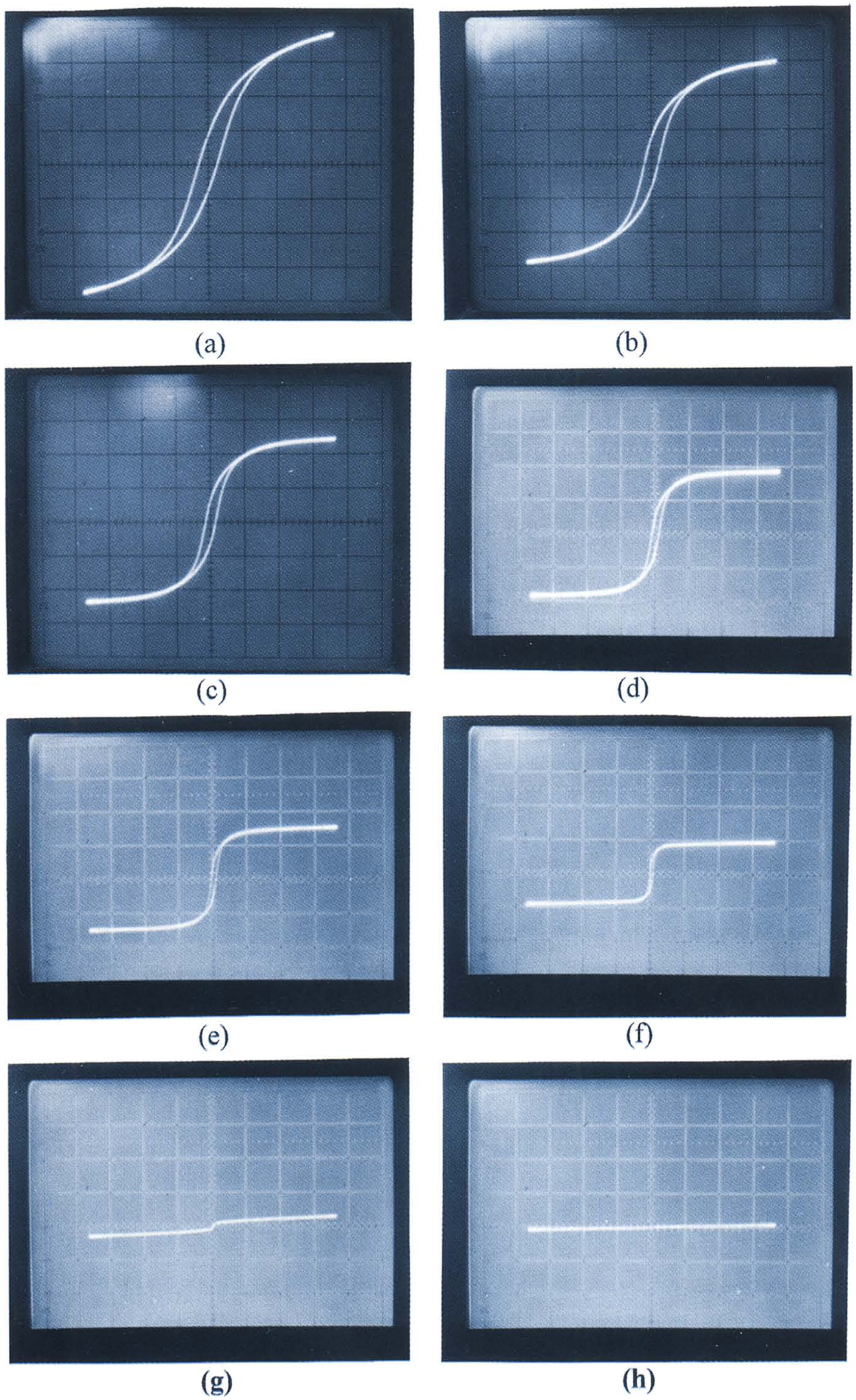

Fig. 3. Hysteresis curves for our sample with T_c = 135° C. From (a) to (h), T = 27°, 77°, 98°, 115°, 121°, 131°, 133°, and 135° C, respectively.

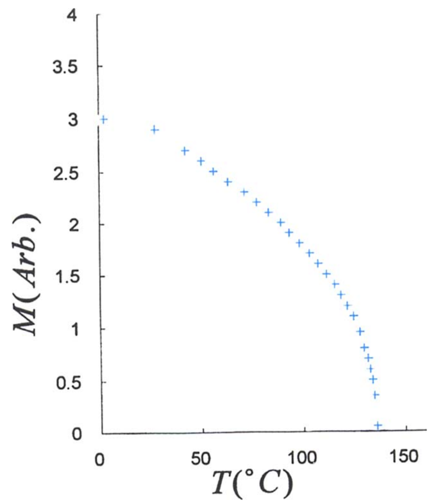

Fig. 4. Variation with temperature of magnetization of a Rowland ring.

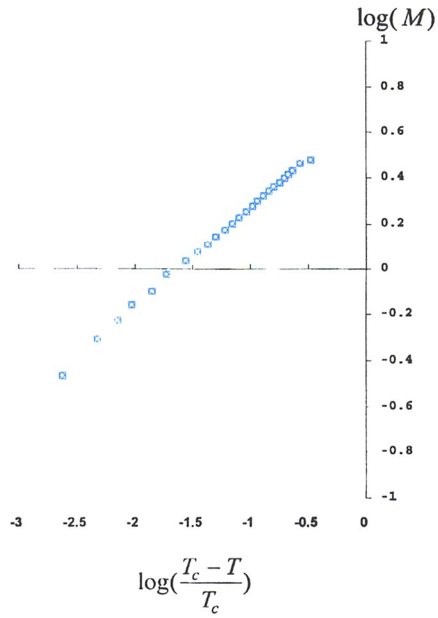

Fig. 5. Log-log plot of magnetization versus reduced temperature for a Rowland ring. The critical exponent is given by the slope of 0.4 ± 0.05.

hysteresis loop decreasing as temperature rises and vanish as it approaches $T_c \approx 135°C$ of our sample. Eight selected pictures with different temperatures exhibiting this transition process are shown in Fig. 3. This is a remarkably direct method for observing the ferromagnetic transition in the introductory physics laboratory. Moreover, we also obtain the *M-T* curve, and even the critical exponent of ferromagnetic transition. All that needs to be measured is the temperature and magnetization, which is proportional to the integrated emf.

Figures 4 and 5 show the *M-T* curve, and a log-log plot of magnetization versus reduced temperature, $\tau \equiv \frac{T_c - T}{T_c}$ for our specimen. The slope of about 0.4 ± 0.05 agrees well with typical values.

It should be pointed out that the hysteresis loop decreases dramatically as the temperature comes close to T_c; therefore, it is possible to warm up above T_c first of all, and then take measurements during the cooling-down period. For accuracy, it is also necessary to adjust the scale of the oscilloscope's *y*-axis.