PII: S0143-0807(97)85764-9

Measurement of Curie temperature for gadolinium: a laboratory experiment for students

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Received 8 July 1997

Abstract. A simple experiment to be performed by students of physics exemplifying Curie's law for the case of gadolinium is reported.

Résumé. Une expérience, destinée aux étudiants de physique, concernant une mesure de la temperature Curie de gadolinium est presentée.

1. Introduction

Above the characteristic temperature Θ, called the Curie temperature, ferromagnetic substances become paramagnetic. The magnetization vector $\boldsymbol{M}$ then changes with temperature according to the Curie law (Servay 1992):

$$\boldsymbol{M} = C\frac{\boldsymbol{B}}{T} \tag{1}$$

where C is Curie's constant, $\boldsymbol{B}$ is the magnetic field vector, also called the magnetic induction, and T is the absolute temperature. This law is valid when the magnetizing field is of relatively low intensity, far from the magnetic saturation of the substance. In the laboratory experiment, it is more convenient to make use of the Curie–Weiss law:

$$\chi = \mu - 1 = \frac{C'}{T - \Theta} \tag{2}$$

where χ and μ are, respectively, the magnetic susceptibility and magnetic permeability of the substance, C' is a constant characteristic for a given substance and Θ is the Curie temperature.

The simplest and most direct method of measuring the permeability μ of a substance is to prepare the sample in the shape of a torus and wind a toroidal coil around it. The self-inductance of such a coil is equal to $L = \mu L_0$, where L_0 is the self-inductance of a similar air–core toroid. Thus,

$$\mu = \frac{L}{L_0}. \tag{3}$$

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However, it is not easy to obtain the core of a toroidal shape, so other simpler shapes are often applied. For a core of cylindrical rod shape, inserted into a coil, equation (3) should be replaced by

$$\mu = \gamma\frac{L}{L_0} \tag{3a}$$

where γ is a geometrical factor, taking into account the fraction of magnetic lines which are closed in an investigated core.

Finally, we can write equation (2) in the form

$$y = \left(\frac{\gamma L}{L_0} - 1\right)^{-1} = \frac{T - \Theta}{C'}. \tag{2b}$$

It can be seen that y is a linear function of the temperature T, characterized by the slope $1/C'$ and the intercept $-\Theta/C'$. This function is equal to zero if $T = \Theta$. Thus, the intersection of the straight line with the horizontal (temperature) axis directly determines the value of the Curie temperature. The value of the constant γ does not influence the position of the point of intersection, and owing to this fact the Curie temperature could be measured for magnetic cores of other than toroidal shape, for example, for a small rod inserted into a cylindrical coil. Based on this fact we have assumed that $\gamma = 1$. However, this assumption is not valid when the permeability value μ is measured, it applies only for calculations of Θ.

2. Experimental

2.1. General considerations

The experimental verification of the Curie–Weiss law for typical, ferromagnetic substances such as Fe, Co

0143-0807/97/060453+03\$19.50

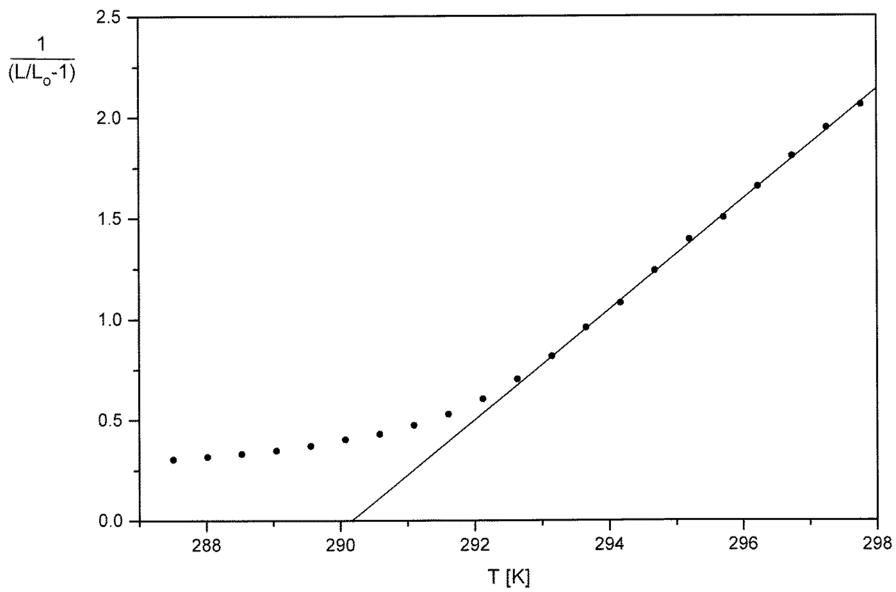

Figure 1. The dependence of $y = (L/L_0 - 1)^{-1}$ on temperature T for gadolinium.

and Ni is difficult in a student laboratory. The Curie temperature of those elements is high, and measurements thus need to be done in an anti-oxidizing atmosphere. This also limits the accuracy of the sample temperature measurement (which should be 0.5 °C or better). The measurement of the self-inductance L of the coil, as well as the sample temperature T, can be done with the required precision in the vicinity of room temperature. The use of special ferromagnetic alloys, with a value of Θ close to room temperature, can be more useful and interesting in teaching the metallurgy of alloys, than in a physics course. Among the elements, only gadolinium (Gd) has a value of Curie temperature which is very convenient for measurements. According to different authors this value varies from 317 K (Servay 1992) through 293 K (Ashcroft and Mermin 1976, Wilkes 1973) and 290 K (von Ardenne 1973), down to 289 K (Kittel 1956, Legwold *et al* 1953, Flippen 1963). The first value seems to be incorrect. The others are grouped within a range of 4 K (289 K to 293 K). Maybe it is related to the purity and degree of crystallization of particular samples. Although the cost of gadolinium is high, only a small sample, about 1 g, is sufficient to perform the laboratory experiment.

2.2. Experimental details

In our experiment, the gadolinium sample (of 99.9% purity) in the form of a rectangular rod of dimensions $2.5 \times 2.5 \times 20$ mm^3 was cut out of a polycrystalline block. Measurements of the photoelectric work function Φ of thin, ultra-high vacuum evaporated gadolinium films gave the value $\Phi = 3.1$ eV for our material, equal to that obtained by Eastman (1970) for high-purity films evaporated in a vacuum of 10^{-8} Pa.

The Gd rod was inserted inside a small coil from an electromagnetic relay (dry reed switch). Its inductance without the rod was 17.7 mH. With the gadolinium rod this value increased several times, depending on the temperature. The inductance of the coil was measured using a low-cost digital multimeter (Metex 6850D), with the RS output connected to a computer. The temperature of the gadolinium sample was measured using a platinum temperature sensor of the type Pt 100 (its resistance at 0 °C was exactly 100 Ω), adhering directly to the coil. This sensor was connected to the second digital electronic multimeter, working as a resistance meter. The Gd rod, coil and Pt 100 sensor were immersed in silicone oil in a small aluminium container. This container was mounted on the head of a heat pump that could be cooled or heated by two Peltier thermoelements. In our experiment, the temperature was changed from 287 K to 298 K (14 °C to 25 °C). To reduce the temperature difference between the rod and the Pt 100 sensor, the cycle of heating and cooling was performed slowly, with a duration of about 80 min.

The sample can, of course, be cooled and heated without a heat pump, using for example a mixture of water and ice for cooling and an electric heater.

3. Results

The changes of the function $y = (L/L_0 - 1)^{-1}$ with temperature are presented in figure 1. In the temperature range above the Curie point, the curve follows the linear expression of equation (2b) well, and a linear regression gives

$$y = 0.273T - 79.2. \tag{4}$$

The point of intersection indicates the value of 290.1 K (17.1 °C), which is equal to the Curie temperature Θ of gadolinium. For our sample, we have obtained $\Theta = 290.1 \pm 0.5$ K. The error is due to the limit of the accuracy of the resistance meter. The value of Θ is in good agreement with those reported by von Ardenne (1973), Kittel (1956), Legwold *et al* (1953) and Flippen (1963), and is reproducible at consecutive cycles of cooling and heating. At lower temperatures (in the ferromagnetic phase), the function $y = y(T)$ shows a different behaviour, in accordance with theoretical considerations.

4. Conclusions

We propose a simple experiment that might be introduced into a student laboratory. At our University it is intended for students in the second year at the Faculty of Physics and Astronomy. The low cost of the experimental set-up (about 250–300 US dollars) makes it accessible for most laboratories. The experiment itself would increase the students' knowledge of the magnetic properties of matter, which are very important, as the description of the Curie law is present in almost all textbooks of physics (e.g. Servay 1992) but it does not appear in most student laboratories. The experiment may also be realized in computer-assisted form, for students with a good background in this subject.

Acknowledgment

This work was supported by the University of Wrocław, via grant no 2016/W/IFD.

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