Thermogyromagnetic effect

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A new thermogyromagnetic effect has been detected and studied experimentally with the help of a sensitive SQUID magnetometer. The effect can be summarized by saying that a metal cylinder, in which a radial temperature gradient ∇T has been set up, becomes magnetized when it is rotated at a frequency Ω. The magnetic flux associated with the cylinder is $\mathbf{\Phi} = A\nabla T\mathbf{\Omega}$, where $A \sim 2\times 10^{-1}\ \Phi_0\cdot \mathrm{s}\cdot \mathrm{cm/deg}$. In a sense, this effect can be thought of as an analog of the Nernst–Ettinghausen effect. The latter effect is the onset of an electric current in a metal object in which gradients of the temperature and the magnetic field are set up in perpendicular directions.

In the Nernst–Ettinghausen thermomagnetic effect,[1] an emf arises in a conducting rod to which a temperature gradient ∇T and a magnetic field B are applied in perpendicular directions. The electric field which arises along the rod as a result of this effect is

$$\mathbf{E}=N[\mathbf{B}\cdot\nabla T], \tag{1}$$

where N is the Nernst constant. If the rod is bent into a closed ring, the Nernst–Ettinghausen effect gives rise to a current in the ring:

$$\mathbf{j}=-\sigma N[\mathbf{B}\cdot\nabla T], \tag{2}$$

where σ is the electrical conductivity. It is easy to see that a current as described by (2) also arises in a cylindrical sample with a radical temperature gradient in an axial magnetic field. The current lines in this case are concentric circles perpendicular to the axis of the cylinder. As a result, an additional magnetic field arises parallel to the axis of the cylinder.

In this letter we wish to describe an analogous effect, which we call a "thermogyromagnetic effect." This effect can be summarized by saying that an electric current is induced by rotation in a cylindrical sample with a radial temperature gradient:

$$\mathbf{j}=a[\mathbf{\Omega}\cdot\nabla T] \tag{3}$$

(Ω is the rotation frequency). The magnetic flux created by this current is thus

$$\mathbf{\Phi}=A\nabla T\mathbf{\Omega}, \tag{4}$$

where A is a constant.

As a test sample for observing this effect we used a titanium cylinder $\sim$30 mm in diameter and 120 mm long. A hole $\sim$10 mm was drilled in the cylinder along its axis. Before the measurements of the thermogyromagnetic effect, a radial temperature gradient was set up in the cylinder. For this purpose, a heater was inserted in the hole in the cylinder. It heated the cylinder to about 120 °C. The exterior of the cylinder was cooled by air at room temperature. Accordingly, a temperature difference $\Delta T \simeq 30$ °C was set up between the inner and outer surfaces of the cylinder. The heater was then removed from the sample, and the sample was connected to a small air turbine, which rotated the sample around its axis. This rotation was carried out inside a magnetic shield which made it possible to produce a magnetic vacuum $\sim 10^{-5}$ Oe at the sample. This measure was necessary because a metal object rotating in a magnetic field acquires, by means of Foucault currents, a magnetic field proportional to its conductivity.[2] As a result, the rotating conductor may induce a self-field comparable in magnitude to the external field. To avoid this magnetization of the cylinder by the geomagnetic field, we were obliged to construct a special magnetic shield and to carry out the measurements in magnetic vacuum.

The magnetic flux which arose from the rotation of the sample was measured with a SQUID magnetometer. For this purpose, a liquid-helium cryostat was placed inside a ferromagnetic shield. The cryostat cooled the SQUID. In addition, a second superconducting magnetic shield was placed inside the ferromagnetic shelf to stabilize the small remanent magnetic field and to protect the shielded SQUID and the test sample from stray pickup. An "anticryostat," by which we mean a vessel filled with a warm fluid, was placed in a helium bath inside this superconducting shield. The small air turbine with the cylindrical test sample was placed in this warm volume. The output signal from the magnetometer was calibrated in units of the magnetic flux quantum, $\Phi_0 = 2 \times 10^{-7}$ $G \cdot cm^2$. This calibration was carried out by putting a current-carrying coil in place of the sample. In the course of an experiment, the sample was removed from the warm vessel as quickly as possible and transferred to the measurement apparatus after the heater was turned off. The sample was then rotated at a rate of about 150 revolutions per second. The compressor feeding the compressed air to the small turbine was then disconnected, and the sample continued to rotate by inertia for another minute or so, at a gradually decreasing velocity. At this time, we measured the magnetic field induced by the sample as a function of the rotation velocity. To measure this velocity, we used an optical system with a chopped light beam, designed to avoid inducing any parasitic magnetic fields at the test sample.

About a minute after the first cycle of measurements, a second cycle was carried out (and so forth).

Figure 1 shows the results of measurements of the magnetic flux associated with the test sample as a function of the sample rotation velocity at various temperature gradients. On the basis of these results it can be concluded that the sample induces a magnetic flux proportional to its own rotation velocity, Ω. The time evolution of the temperature gradient between the inner and outer surfaces of the cylinder—this time evolution was used to calibrate the results—was measured independently (without a rotation). This behavior is shown by the solid curve in Fig. 2. The various points here show the time-dependent values of the slope of the thermogyromagnetic effect (in arbitrary units) found in the various series of experiments. On the basis of these results we can assume that the magnitude of the thermogyromagnetic effect is proportional to the temperature gradient. The slight discrepancy can apparently be explained by arguing that the flowing air used to rotate the turbine affects the cooling of the sample.

It has thus been established experimentally that a rotation induces a magnetic flux in

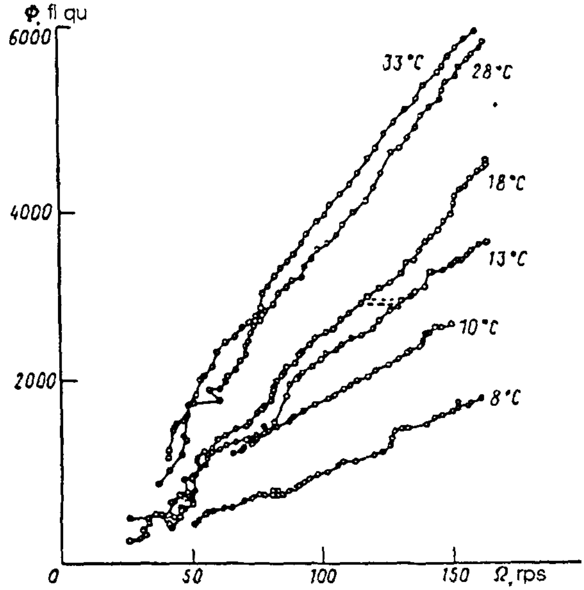

FIG. 1. The magnetic flux associated with the sample as a function of the sample rotation velocity for various temperature gradients. The units along the ordinate and the abscissa are flux quanta and revolutions per second, respectively.

a conducting cylinder when a temperature gradient has been set up in the cylinder, in complete accordance with Eqs. (3) and (4). The experiments yield the following value for the constant A:

$$A(4.77 \pm 1.84) \times 10^{-8}\ \text{cm}^{5/2} \cdot \text{g}^{1/2} \cdot\ \text{s}^{1/2}/\text{deg}. \qquad (5)$$

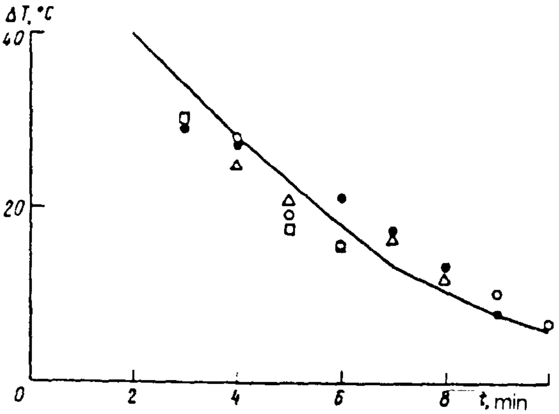

FIG. 2. Solid curve—Time evolution of the temperature difference between the inner and outer walls of the cylinder after the heater is turned off; points—values of the slope of the thermogyromagnetic effect (in arbitrary units) found at the corresponding times. The points of different shapes correspond to different series of experiments.

The sign of the effect corresponds to a revolution of ions. The generation of a magnetic field can be explained by means of the following mechanism. After a steady-state temperature is set up in a metal sample, there is no resultant electron current. The reason is that the current of "hot" electrons, which are transferring heat from the hot part of the sample to the cold part, is cancelled by a current of "cold" electrons caused by the thermal emf. However, since the conductivity of a metal can be assumed to be a linear function of the temperature, the mean free times τ for these electrons are different. This difference between the mean free times of the cold and hot electrons can be written

$$\Delta\tau=\frac{d\tau}{dT}\frac{dT}{dr}\Delta r=\tau\frac{\nabla T}{T}\lambda, \tag{6}$$

where T and ∇T are the temperature and its gradient, $\lambda=\tau V_F$ is the mean free path of an electron in the metal, and V_F is the Fermi velocity. As a result, the velocities acquired by the hot and cold electrons as the result of the Coriolis force in the rotating coordinate system will differ by an amount

$$\Delta V=\frac{\lambda^2}{T}[\mathbf{\Omega}\times\nabla T]. \tag{7}$$

In a metal sample in which there is a radial temperature gradient, rotation thus induces a circular current with a density

$$\mathbf{j}=en_0\frac{\lambda^2}{T}[\mathbf{\Omega}\times\nabla T]. \tag{8}$$

Here e is the charge of an electron, and n_0 is the number density of electrons in the metal. If the sample is a cylinder of radius R, this current creates a magnetic field

$$H(r)=\frac{4\pi}{c}\int_r^R j\,dr=\frac{4\pi}{c}en_0\frac{\nabla T}{T}\lambda^2\Omega(R-r), \tag{9}$$

so the resultant magnetic flux through the cylinder is

$$\Phi=2\pi\int_0^R H(r)r\,dr=\frac{4\pi^2}{3c}en_0\frac{\nabla T}{T}\lambda^2\Omega R^3. \tag{10}$$

In other words, the constant in Eq. (3) is

$$A=\frac{4\pi^2}{3c}\frac{en_0}{T}\lambda^2R^3. \tag{11}$$

For titanium we would have $n\simeq10^{23}$ cm^{-3}. Assuming $T=300$ K and a mean free path $\lambda\simeq3\times10^{-6}$ cm at $R\simeq3$ cm, we find

$$A\simeq2\times10^{-8}\ \mathrm{cm}^{5/2}\times\mathrm{g}^{1/2}\times\mathrm{s}^{1/2}/\mathrm{deg}. \tag{12}$$

Since we have used a simplified model and approximate values for the parameters, especially for the electron mean free path in titanium, we can assume that this value is consistent with the experimental result.

We repeated these experiments with cylinders of niobium and aluminum. Since the electrical conductivities of these metals (particularly aluminum) are higher than that of titanium, one might expect that the fields which they would induce by means of the thermogyromagnetic effect would also be higher. Indeed, the measurements provided qualitative support for that expectation. However, since these metals have proportionately higher thermal conductivities, they cooled off to a greater extent over the time between the removal of the heater and the beginning of the measurements. (This time, required to install the sample at the turbine, was 2 or 3 min.) Accordingly, it was more difficult to carry out experiments with these other metals. At a qualitative level, the experiments show that the thermogyromagnetic effect in niobium and aluminum is more pronounced than that in titanium and has the same sign.

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[1] L. D. Landau and E. M. Lifshitz, *Electrodynamics of Continuous Media* (Pergamon, Oxford, 1984), §27.
[2] L. D. Landau and E. M. Lifshitz, *Electrodynamics of Continuous Media* (Pergamon, Oxford, 1984), §63.

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