Eddy Currents and Supercurrents in Rotating Metal Spheres at Liquid Helium Temperatures*

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(Received June 4, 1951)

These experiments show that large eddy currents are set up in a tin sphere rotating at 4.6 or more revolutions per second in the earth's magnetic field and at 3.8°K. Within experimental determination, the eddy currents have the same magnitude and distribution on the sphere as the supercurrents which cause the Meissner effect at 3.7°K. These results are in accord with classical electromagnetic theory for a normal conductor and with the London theory for a superconductor. The Meissner effect has been produced in bulk tantalum metal by rotating the specimen while cooling through the superconducting transition temperature.

I. INTRODUCTION

FOR some time we have known[1] that a solid sphere of superconducting metal would show a perfect Meissner effect if the following experimental steps were taken: (a) rotate rapidly in the normal conducting state; (b) cool the sphere slowly through the superconducting transition temperature while still rotating; (c) stop the rotation and experimental investigation shows that the sphere has undergone a perfect Meissner effect. The present investigation has put some quantitative understanding behind the effects both from the experimental and theoretical side.

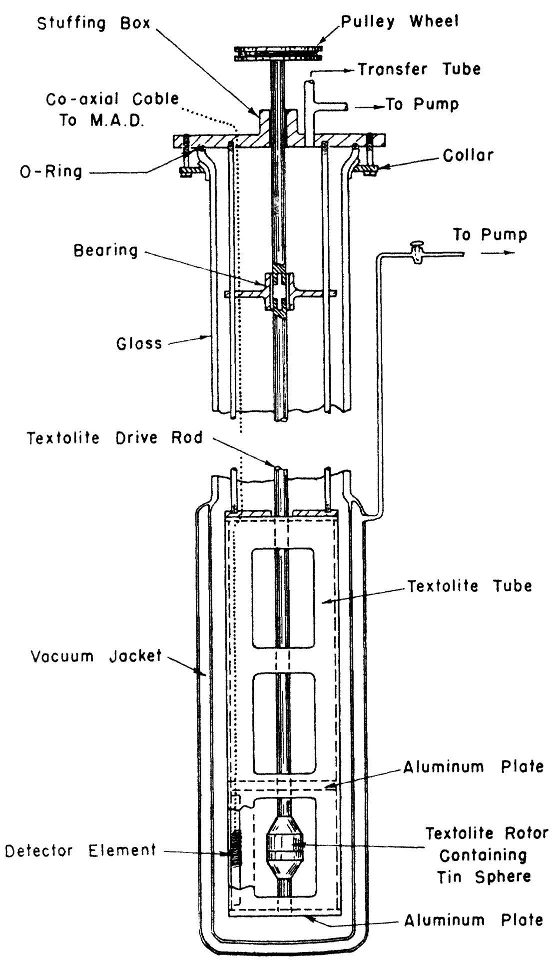

FIG. 1. Cryostat.

II. APPARATUS

Figure 1 shows the cryostat schematically. The sphere of tin housed in Textolite may be rotated at speeds, ω, through a driving torque on the shaft extending upward and out of the liquid helium bath. A magnetic detector (saturable core reactor) is shown in Fig. 1, and this is located close to the rotor in such a way that any changes in the vertical magnetic field component results in a steady signal on a meter. Most of the vertical field component of the earth was removed by use of compensating Helmholtz coils placed external to the Dewar flasks. Figure 2 shows the rotor and the detector element with the horizontal flux distorted by the eddy currents induced because of the rotation of the sphere.

The changes in the magnetic field were measured by a device known as the magnetic airborne detector (AN ASQ-3), which was provided by the Office of Naval Research. Although certain alterations have been made on the magnetic airborne detector, the operation of the detector is approximately the same as the original design. Figure 3 is a block diagram of the detector. The output of a 1000-cycle oscillator is carefully filtered so that there does not exist any other frequency components, especially the 2000-cycle component. After passing through the filter, the 1000-cycle output then is sent through a resonent series circuit consisting of a capacitor and the detector element. This resonant series circuit is shunted by a 200-ohm resistor. The detector element is the only part of the above circuit that is cooled to 4.2°K.

If the detector element is in a small magnetic field, a 2000-cycle component is generated. The output goes through a band-pass filter which transmits only the 2000-cycle component. The 2000-cycle component is

* This work was supported by the ONR.
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[1] Love, Blunt, and Alers, Phys. Rev. 76, 305 (1949).

then fed into a resistance-coupled amplifier with four stages. At the third stage, two leads are taken off and the signal presented on the oscilloscope. The output current from the fourth stage passes through a 5000-ohm resistor to an Ayrton shunt and galvanometer. In parallel with the fourth stages is a 1.5-volt dry cell battery and a resistance box. The dry cell battery is used to buck out the small detector current that exists as background signal. The magnetic field from the Helmholtz coils was set so as to produce a minimum deflection on the oscilloscope. A change in the magnetic field appears on the galvanometer as an unbalance. Field changes of 10^{-4} gauss gave deflection of three centimeters on the galvanometer scale with Ayrton shunt on one-tenth sensitivity. The sensitivity reported[2] for the equipment is better than ten microvolts per ten microgauss at the output of the 2000-cycle filter.

This experiment can be divided into two parts. The first part of the experiment consisted of finding the dependency of eddy currents induced on the tin sphere with respect to the rotational speed of the rotor. Above the transition temperature the sphere was rotated at varying speeds, and the deflections on the galvanometer and the speeds of rotation were recorded. After each determination of speed *versus* amplitude, the rotor was then stopped, and a check was made of the zero position of the galvanometer. At slow speeds the rotational speed was determined by the use of a stop watch. At faster rotational speeds where the revolutions could not be counted accurately, a stroboscope was used to measure the speed of rotation. The rotational speed was varied between 0.3 and 5.0 revolutions per second.

During the second part of the experiment, the specimen was rotated at a certain speed and cooled through the transition temperature. The deflection on the galvanometer was observed during the transition. If on passing through the transition temperature, a magnetic flux was frozen in, the deflection on the galvanometer would oscillate about a steady deflection with a frequency determined by the rotational speed of the rotor. But, on the other hand, if no flux were frozen in, the galvanometer would retain a steady deflection even if the rotation of the rotor was stopped. This would indicate a perfect Meissner effect.

These experiments were performed with a tin sphere one and one-half inches in diameter, and with a tantalum cylinder one inch in diameter and one and one-half inches long. The transition temperature for tin is 3.69°K, so in order to cool through the transition temperature of tin, it was necessary to pump on the liquid helium until the absolute pressure of the helium vapor was 441 mm of mercury. Since the transition temperature of tantalum is 4.38°K, tantalum when immersed in liquid helium at a pressure of 760 mm of mercury is in the superconducting state. With an overpressure on the helium greater than 980 mm of mercury, the tantalum was rotated as a normal conductor; and by reducing the pressure to the atmospheric pressure, the tantalum passed through its transition temperature while rotating.

[2] Trans. Am. Inst. Elec. Engrs. **66**, 641 (1947).

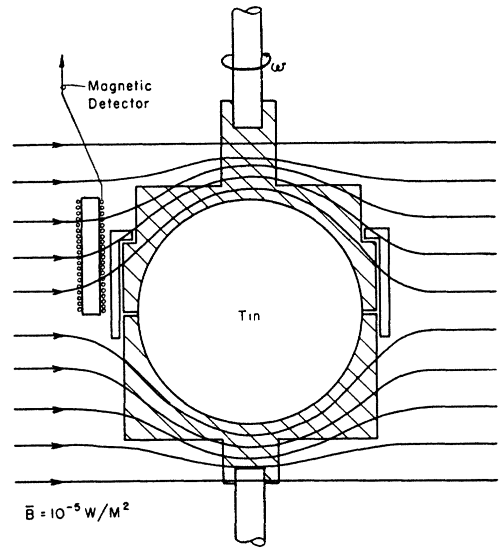

FIG. 2. Rotor and lines of $\bar{B}$ about a rotating sphere.

III. EXPERIMENTAL RESULTS

Tantalum on going superconducting has the property of freezing in most of the magnetic flux that exists in the material. In other words, it shows no Meissner effect. Figure 4 illustrates the large frozen-in moment produced in tantalum when allowed to go superconducting while at rest. Figure 4 shows the detector signal as a function of the angle of the rotor with respect to the position of the detector element. Such a large frozen-in moment existed that the less sensitive oscilloscope was used to give an indication of the magnitude of this frozen-in moment. The magnetic moment locked into the superconductor is independent of the angular orientation of the rotor. The direction of the magnetic moment is determined only by the direction of the magnetic field existing when the transition temperature was passed. The zero position of the rotor was therefore

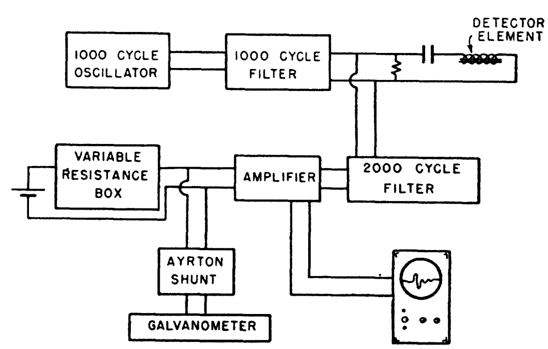

FIG. 3. Block diagram of magnetic detection equipment.

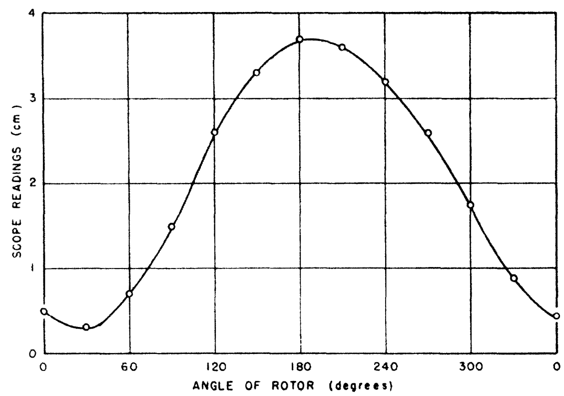

FIG. 4. Frozen-in moment of tantalum.

arbitrarily chosen. A rotation of the tantalum then gave a new position of the axis of the frozen-in moment with respect to the detector element.

The next part of the study on tantalum consisted of rotating the tantalum while cooling through the transition temperature. The speed of rotation was 0.35 revolution per second during the transition. The plot of the detector signal as a function of the angle of the rotor is shown in Fig. 5. There was a steady deflection with a small variation superimposed. This means a large Meissner effect had occurred.

Tin is a better behaved superconductor than tantalum in that tin freezes in a smaller amount of flux. Figure 6 is a typical plot of the galvanometer reading *versus* the rotational speed of the normal conducting tin rotor. Before going into the discussion of this graph, it would be best to explain further what the magnetic detector element measures. The detector element will measure only a vertical component of the magnetic induction, $\bar{B}$. By looking at Fig. 2 the lines of $\bar{B}$ are seen to be bent around the rotating specimen. If only a small amount of eddy currents is induced on the surface of the sphere, most of the lines of $\bar{B}$ continue straight on through the detector element and pass through the sphere. As the eddy currents increase, the lines of $\bar{B}$ are forced over the sphere. This gives a vertical component of $\bar{B}$ in the detector element which appears as an unbalance on the galvanometer scale. The graph, Fig. 6, shows an exponential rise at first with a gradual leveling off. However, the curve is still slightly rising with increases of the rotational speed. Table I gives the galvanometer deflection at various rotational speeds at a constant temperature of 4.2°K. At a higher temperature, say 20°K, the electrical conductivity is smaller, so that at the same rotational speeds one obtains a smaller galvanometer deflection.

With the sphere rotating at 4.6 revolutions per second, it was observed that the amplitude of the flux being kicked out by the eddy currents increased by 10 percent as the sphere was cooled from 4.2°K to the transition temperature. The deflection on the galvanometer remained at this maximum value while passing through the transition temperature. Further, the deflection on the galvanometer remained at this maximum value when the superconducting rotor was brought to rest.

IV. DISCUSSION

It is well known that for tantalum the Meissner effect is practically nonexistent because the metal freezes in all of the existing flux when it goes superconducting. Pure tantalum in bulk quantity is made by sintering together the small flakes or grains. Sound pulses were found to scatter very badly on passing through tantalum metal.[3] Thus from a physical point of view the metal is not homogeneous and one can understand that the Meissner effect might not be realized by a metal of this physical make-up. We have found that our specimen of pure tantalum was of this sort but that we could force it to have a complete Meissner effect through the technique of rotating in the normal state and cooling while rotating into the superconducting state. The cooling must be done very slowly and adequate rotational speeds must be used, else some frozen-in flux will result.

The results on tin show that the magnitude of the eddy currents produced are dependent on the speed of rotation and on the temperature. The dependence on temperature is connected with the electrical conductivity. These effects may be understood from the following classical electromagnetic theory:[4] A simple change of coordinate system will allow the sphere of metal to stay fixed and the magnetic field to rotate around. The equation to be satisfied is then (mks units):

$$\nabla^2\bar{B}-j\omega\mu\sigma\bar{B}=0,$$

where ω equals angular velocity, μ magnetic permeability, j equals $(-1)^{\frac{1}{2}}$, and σ is the electrical conductivity. The eddy currents induced by the rotating magnetic field produce a magnetic field which outside the sphere is equivalent to a magnetic dipole of strength $(4\pi/\mu)(BD/2)$ at the center of the sphere, where B is the magnetic field in which the sphere is rotated, and D

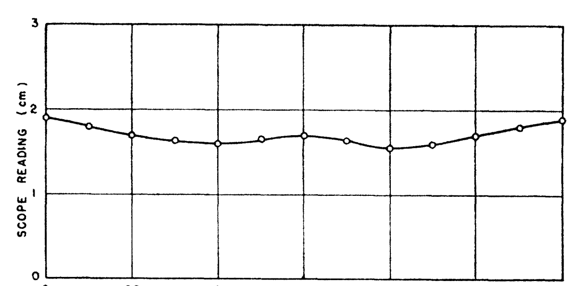

FIG. 5. Meissner effect of tantalum.

[3] W. C. Overton, Jr., Ph.D. thesis, Rice Institute, Houston, Texas (1950), unpublished.

[4] W. R. Smythe, *Static and Dynamic Electricity* (McGraw-Hill Book Company, Inc., New York, 1950), p. 395.

is given by

$$D=-a^3\left\{1-\frac{3}{(2\rho)^{\frac{1}{2}}a}\frac{\sinh(2\rho)^{\frac{1}{2}}a-\sin(2\rho)^{\frac{1}{2}}a}{\cosh(2\rho)^{\frac{1}{2}}a-\cos(2\rho)^{\frac{1}{2}}a}\right\}$$
$$-ja^3\left\{-\frac{3}{\rho a^2}+\frac{3}{(2\rho)^{\frac{1}{2}}a}\frac{\sinh(2\rho)^{\frac{1}{2}}a+\sin(2\rho)^{\frac{1}{2}}a}{\cosh(2\rho)^{\frac{1}{2}}a-\cos(2\rho)^{\frac{1}{2}}a}\right\},$$

with $\rho=\omega\mu\sigma$, and a is the radius of the sphere. When the conductivity, σ, and the angular velocity, ω, are low, the imaginary component is the predominant term. The axis of the dipole will then be nearly perpendicular to the applied magnetic field. If either the conductivity or angular velocity become very large, the imaginary component approaches zero, and the dipole axis then coincides with the direction of the magnetic field. At 4.2°K, for five revolutions per second and $\sigma=4\times10^{10}$ mhos/meter, the imaginary component is one one-tenth of the real component. The magnetic dipole axis is then almost parallel with the applied field.

In his recent book, Fritz London[5] has shown that the

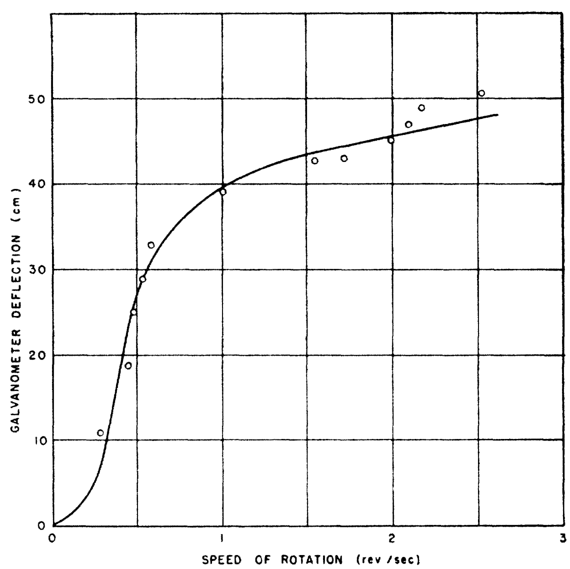

FIG. 6. Eddy currents in tin at 4.2°K.

[5] F. London, *Superfluids* (John Wiley and Sons, Inc., New York, 1950), Vol. I, pp. 34–35.

TABLE I. Galvanometer deflection at various rotational speeds, at 4.2°K.

Galvanometer deflection (cm)	Rotational speed (rev/sec)
11	0.30
19	0.40
25	0.45
29	0.55
33	0.70
39	1.0
43	1.6
43.5	1.7
45	2.0
47	2.2
49.5	2.35
50.5	2.55

magnetic field of a superconducting sphere at a large distance is equivalent to a magnetic dipole of strength, M, at the center of the sphere where M is given by

$$M=-(4\pi/\mu)(a^3B/2)$$
$$\times\{1-[3/(\mu/\lambda)^{\frac{1}{2}}a]\coth(\mu/\lambda)^{\frac{1}{2}}a+3/(\mu/\lambda)a^2\}.$$

Comparing this with the dipole set up by the eddy currents, one sees that they are equal in the limit of very fast speeds of rotation with high conductivity. At about 3.8°K with the sphere rotating at 4.6 revolutions per second, the detector element could not observe any change in the magnetic field when the sphere became superconducting. That is, the field change at the detector element was less than 10^{-4} gauss. The skin depth, $1/\sqrt{\rho}$, for the eddy currents was 0.6 mm at 4.6 revolutions per second, while the skin depth $(\mu/\lambda)^{-\frac{1}{2}}$ of supercurrents was 1.6×10^{-5} mm.

We may conclude that:

(1) The eddy currents in the tin sphere have the same space distribution as the superconducting Meissner currents, within the sensitivity of the magnetic detection equipment.

(2) The tantalum metal which has been sintered together to make the bulk specimen will perform like a normal superconductor if the magnetic field within the interior of the metal is largely removed by the rotation of the specimen while cooling through the transition temperature.