[CONTRIBUTION FROM THE CHEMICAL LABORATORY OF THE UNIVERSITY OF CALIFORNIA]

A Static Low Temperature Method for Determining Small Residual Fields Accurately in Magnetic Experiments

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The technique of adiabatic demagnetization experimentation in this Laboratory has been developed around the iron-free solenoid type of magnet. In this way the complications due to considerable residual fields and hysteresis which interfere with precise measurements, when iron yoke magnets are used, have been largely avoided. However even the earth's field is large enough to interfere with some measurements and the iron in a typical reinforced concrete building will increase the field which remains when the current through a solenoid is reduced to zero.

For example, when a substance has been demagnetized adiabatically to a low temperature, it is desirable to apply some test to determine if any net directed magnetic moment remains. A very simple method of measuring any residual magnetic moment was used by Giauque and MacDougall.[1] They measured the e. m. f. induced in a coil surrounding the sample, while the substance was slowly warmed to temperatures above 1°K., in which region the magnetic properties were comparatively ideal. In such an experiment, the considerable change of magnetic susceptibility with temperature, will, in the presence of a residual field, produce an e. m. f. due to the changing magnetic moment induced by the residual field. The above authors found such an effect with gadolinium phosphomolybdate tridecahydrate and were able to explain it quantitatively by means of residual field measurements made with a flip-coil at a later date. Residual field measurements should be available at the same time as any other measurements which have a field dependence at small fields. It is undesirable to complicate an already complicated measuring system by operating a flip-coil or other rotating device in the proximity of the sample, and we prefer not to use methods which are based on the properties of ferromagnetic materials of high and variable permeability since the presence of such material should be avoided if possible. We have used a simple static method which avoids the above effects.

A convenient and well known method of measuring magnetic field strength at ordinary temperatures is based on the change of electrical resistance of bismuth with field. The ordinary instruments based on this effect are nowhere near sensitive enough for our present purpose. However, measurements of Beckman[2] have shown that the increase of resistance of bismuth with field is greatly enhanced at low temperatures. The bismuth coils used at ordinary temperatures are calibrated and are expected to retain their calibration for considerable periods. It is very improbable that such a coil would retain a low temperature calibration with sufficient accuracy after warming to ordinary temperatures, followed by recooling to the temperature of liquid helium. The following methods avoid the necessity of precalibration.

Some bismuth wire was made by heating the metal and extruding it through a die with a diameter of 0.024 in., under a pressure of 7000 atmospheres. A coil of twelve turns, with a diameter of 2 in. and a length of 1.5 in., was wound non-inductively. It was mounted in a dewar vessel near the center of, and co-axial with, a vertical solenoid magnet.[3] We have supported such coils in grooves cut in micarta, or etched in Pyrex tubing and both leave something to be desired in preventing breakage of the brittle bismuth wire. Potential and current leads were attached to each end of the wire. All measurements were made with the coil immersed in liquid helium at its boiling point 4.22°K.

A steady current of about 2.58×10^{-4} ampere was passed through the coil and the resistance was found to be 21.8645 ohms A small current was then passed through the solenoid magnet and the change in resistance was observed. The current through the magnet was then reversed and the quite different change in resistance of the bismuth was recorded. The procedure was repeated with several other small values of solenoid current. The relationship between field and the current through the solenoid is easily computed from its dimensions.

Since the change of resistance of the bismuth should depend on the magnitude and not the sign of the net magnetic field, a plot of ΔR against applied field should be symmetrical about a line parallel to the ΔR axis, and displaced from it by the amount of the component of the residual field along the axis of the solenoid. Such a plot is shown in Fig. 1. The method is independent of the character of the dependence of ΔR on the applied field.

It is, however, a matter of some interest to inquire concerning the relationship between the change in resistance and the absolute value of the vertical component of the magnetic field. The data are given in Table I. Values of the quantities A and B in Fig. 1 were selected to give a smooth function of $(R_{H} - R_{H=0})/H^2$ against H.

It is evident that ΔR is proportional to H^2 at fields of the order of 0–20 oersteds and that the rate of change then decreases rapidly and appears to approach a condition in which it depends very little on the applied field.

(1) Giauque and MacDougall, THIS JOURNAL, **60**, 376 (1938).

(2) Beckman, Comm. Phys. Lab. Leiden, No. 130a (1912).

(3) Giauque and MacDougall, THIS JOURNAL, **57**, 1175 (1935).

TABLE I

CHANGE OF RESISTANCE OF BISMUTH WITH MAGNETIC FIELD AT 4.22°K.

$H = H$(applied) $+ A$ oersteds; $A = 2.03$; $R_{H=0} = R(H$ applied $= 0) - B$ ohms; $B = 2.40 \times 10^{-3}$; $\Delta R = R_H - R_{H=0}$

H	$\Delta R \times 10^3$	$\Delta R \times 10^3/H^2$
+ (2.03)	(2.40)	0.582
− 2.87	4.76	.578
+ 6.93	27.53	.573
+11.83	79.74	.570
− 7.77	35.32	.585
−14.30	118.12	.578
+18.36	191.94	.569
	ΔR ohms	
+50.7	1.204	0.468
−46.5	1.022	.473
+50.8	1.181	.458
+93	1.630	.188
203	5.356	.130
391	12.72	.0832
671	25.45	.0565
1210	47.76	.0326
1618	61.33	.0234
3218	90.57	.0088
6206	112.1	.0029
8409[a]	120.5	.0017

[a] Reading at limit of ammeter and thus probably a little low.

The principal source of error in the data in Table I is due to the fact that the applied field was determined by reading an ammeter. ΔR was determined by means of an accurate potentiometer. More accurate results could have been obtained had the magnet current also been determined by a potentiometric method. However the results are such that a residual field of 2.03 oersteds gives considerably better internal consistency of all the data than 2.05 oersteds. Thus we conclude that the vertical component of the residual field was 2.03 ± 0.02 oersteds. This may be compared with the result of Giauque and MacDougall,[1] 2.0 ± 0.1 oersteds, determined with a flip-coil under approximately the same conditions.

During the period of the above experiments all large currents through the magnet produced a field which was in the same direction as the vertical component of the earth's field. In order to find out if the residual field was somewhat greater immediately after the full field of about 8000 oersteds was turned off, an experiment was tried to test this point. It was found that there was no observable change in the resistance of the bismuth coil after a field of about 8400 oersteds had been applied for three-fourths of a minute. In order to improve the sensitivity of the above test an applied field of 16.28 oersteds was used in the direction of the residual field both immediately before and after the large field was applied. This measurement showed that any change in the residual field was less than 0.01 oersted. The magnet was not used for an hour prior to this test.

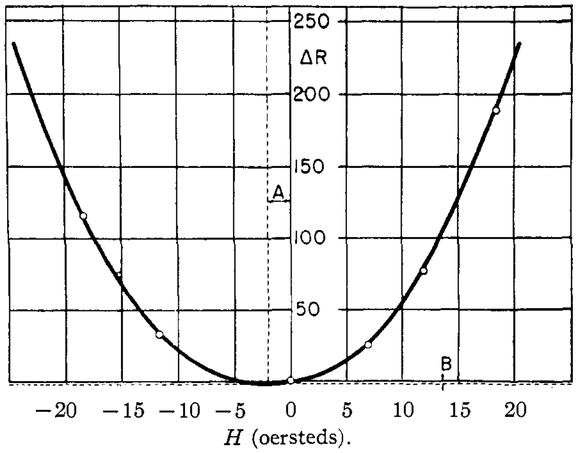

Fig. 1.—Measurement of a small residual magnetic field with a bismuth coil: ΔR = ohms $\times 10^{-3}$; A, residual field along solenoid axis; B, resistance due to the residual field.

Although the above accuracy was sufficient for the investigation of which it was a part, the sensitivity and simplicity of the method could be greatly increased and the result made available in a very short time by the following procedure: Send an accurately measured current through the solenoid and read the potential drop due to the current used in the bismuth coil. Reverse the solenoid current and adjust its value until the potential drop across the bismuth coil returns to the original value, thus restoring its resistance to the initial value. The component of the residual field will be equal to the field produced in the solenoid by one-half the difference in the direct and reverse solenoid currents. We have estimated that with an applied solenoid field of about 20 oersteds, and a current of some 5×10^{-3} ampere through the bismuth coil mentioned above, a potentiometer scale reading of about 1 cm. would be equivalent to 0.001 oersted in the residual field.

For some purposes it will be desirable to know the other components of the residual field. These could be determined with the assistance of auxiliary coils, which, while of necessity must be located at some distance in adiabatic demagnetization experiments, could produce a calculated field, in the desired direction at the location of the bismuth coil.

Summary

A method utilizing the electrical resistance of a bismuth coil at liquid helium temperature to measure accurately a small residual magnetic field has been described.

This static method has been devised to avoid the use of ferromagnetic materials, flip-coils and other rotating or oscillating devices, which are considered to provide undesirable complications during adiabatic demagnetization experiments at temperatures below 1°K.

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