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FLUCTUATION INDUCED DIAMAGNETISM IN ALUMINUM*

H.L. Kaufman and Francisco de la Cruz

Department of Physics, Brown University, Providence, Rhode Island 02912

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The magnetic field and temperature dependence of the magnetization of bulk aluminum near the normal-superconductor transition has been measured. Due to the large amount of supercooling in one of the samples it was possible to extend the measurements well below the critical temperature. A comparison of the experimental results with theory is presented.

RECENT theoretical and experimental studies[1–7] have shown that the magnetization of a superconductor increases monotonically as its temperature is decreased towards the second order transition temperature, $T_{c2}(H)$. This enhanced diamagnetism, M', is attributed to thermodynamic fluctuations of the order parameter. Experimentally, the second order transition at T_{c2} can be achieved in type II superconductors. In type I materials, T_{c2} is below the critical temperature, T_c, and usually the transition to the superconducting state takes place at a temperature very close to T_c. Under 'ideal' conditions, however, a sample can remain in a metastable normal state below T_c.

There are several advantages in studying the contribution of thermodynamic fluctuations to the magnetization when the sample remains in a metastable state: (1) If the sample is in a metastable normal state (supercooling) all contributions to the temperature dependent magnetization should be due to thermodynamic fluctuations alone. That is, contributions from finite transition widths due to impurities, strains, demagnetization factors, etc., can be ruled out. (2) The very recent theory of Lee and Payne[7] to explain experimental results[6] in In and Pb is valid in the pure limit approximation ($l \gg \xi_0$). Very few pure type II superconductors are available to check the validity of the theory. The use of type I materials with transitions near T_c has the disadvantage that the range of temperatures over which the magnetization is large cannot be reached and a precise determination of M' near T_c is difficult. Supercooled samples however obviate these problems. (3) It would allow study of the induced diamagnetism in type I superconductors in the region $[H-H_{c2}(t)] \ll H_{c2}(t)$.

In order to observe the magnetization of macroscopic samples in metastable states it is convenient to choose materials with large coherence lengths (low κ). Due to the associated large positive surface energy, it is relatively easy to prepare such samples which will supercool.

The theory of the Lee and Payne has no free free parameters. The only material dependent quantities are the critical temperature, which scales the magnetization and the coherence length, which scales temperature and field. This theory has shown satsifactory agreement with the result of Gollub, Beasley, and Tinkham (GBT)[6] for In and Pb. As a further test of the theory it is again convenient to choose materials with large coherence length, such as Al, Zn or Cd.

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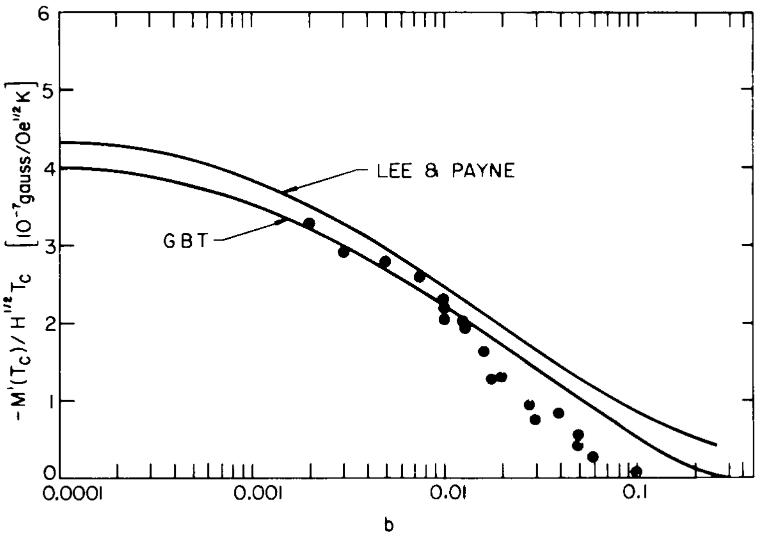

FIG. 1. Comparison of the experimental data for $M'(T_c)/H^{1/2}\,T_c$ with the theoretical values predicted by Lee and Payne and the results for pure In and Pb obtained by Gollub *et al.* The points shown correspond to the results of both samples.

The results reported here were obtained from two aluminum single crystals. The measurements were accomplished by the use of a quantum interferometer[8] (SQUID) connected to the sample by a superconducting flux transformer. The sensitivity was such that changes in sample magnetization of 6×10^{-9}G were detectable. The sample was placed in a vacuum jacket in good thermal contact with a liquid He^3 bath. The bath temperature was regulated by controlling the pumping speed of the He^3 system.

The dewar system was surrounded by room temperature magnetic shielding and the sample and detector regions by superconducting shields as well. This technique reduced the vertical component of the earth's magnetic field at the sample below 5×10^{-3}oe and the horizontal component to less than 10^{-3} oe. Furthermore, in order to discount the effect of the vertical asymmetry of the field, we performed the measurements with the applied field parallel to the vertical direction and measured the variation of the magnetization for opposing directions of the applied field. Other details of the experimental technique will be published elsewhere.

Our samples were cylinders $\sim$3.5 mm by $\sim$8.5 mm cut from a bulk single crystal using a spark erosion technique. One of the samples exhibited a large amount of supercooling whereas the other had the normal-superconducting transition at a temperature very close to $T_c(H)$. The variation in behavior between the samples was probably due to the different surface treatment given them. The one which supercooled was etched until a layer of about 0.1 mm was removed from the surface and then chemically polished. The other was polished without removing the layer damaged by the cutting process.

In order to compare our results with other experiments[6] and theory[7] it is convenient to scale the magnetization $(M'/H^{1/2}T)$, the temperature $(|dH_{c2}/dT|(T - T_c)H^{-1})$, and the magnetic field $(b = ehv_F^2 H/(4\pi)^2 k_B^2 T_c^2)$.

Figure 1 shows the variation of magnetization as a function of magnetic field at $T = T_c$. In order to make our data coincide with the values[6] for Pb and In when the ordinate is half Prange's value,[3] a value of 1.80×10^{-4}cm for the coherence length of Al must be chosen. There is no experimental support for this value of ξ_0, since supercooling data[9] from small Al spheres indicate a value of 1.25×10^{-4} cm. This latter value is in fair agreement with theoretical calculations incorporating anistropy effects present in real superconductors.[10]

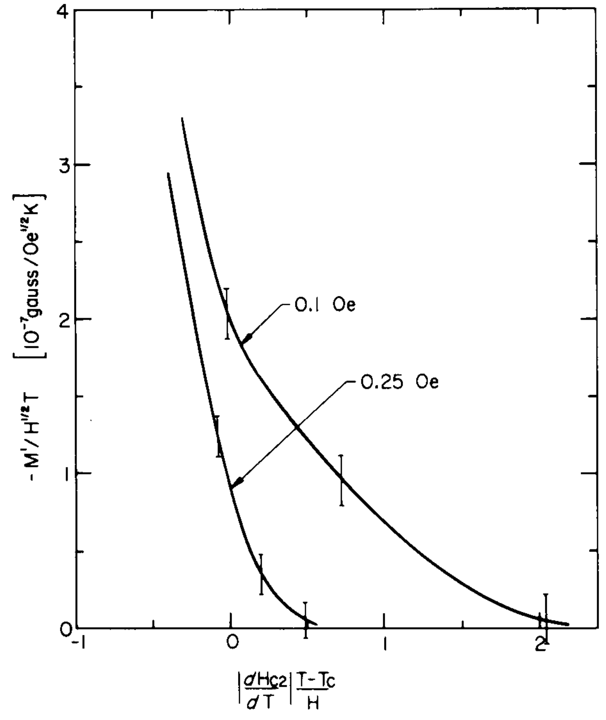

FIG. 2. Temperature dependence of $M'/H^{1/2}T$ for Al. The bars indicate estimated experimental error.

Furthermore, it is noteworthy that the coherence length used by GBT to scale the results for In was obtained from supercooling data, whereas the value used by Pb, $\xi_0 = 0.085 \times 10^{-4}$cm (corresponding to $H_s \approx 36$oe in reference 6), was obtained from surface impedance measurements[11] at low temperatures. The value for Pb obtained from supercooling,[12] $\xi_0 = 0.102 \times 10^{-4}$cm (which would correspond to $H_s \approx 26$oe in reference 6), agrees with theoretical calculations incorporating both anistropy and strong coupling corrections.[10] Therefore, no universal behavior can be obtained if the values for the coherence length from supercooling are used consistently for all materials. What is more, in the case of aluminum, even with $\xi_0 = 1.8 \times 10^{-4}$cm, it can be seen that at high fields there is a deviation from the 'universal' behavior.

Figure 2 shows the temperature dependence of the magnetization for two different fields. The scaling factor was obtained from supercooling data,[9] $|dH_{c2}/dT| \approx 3.7$oeK^{-1}. It is shown here how the supercooling is useful for a more precise determination of $M'(T_c)$. At present we do not have any explanation for the disagreement between theory and the results for Al. To determine whether these results are characteristic of superconductors with large coherence lengths experiments in other pure materials (Cd, Zn) and Al alloys are in progress.

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Nous avons mesuré la dépendance en champ magnétique et en température de la magnétisation d'un échantillon massif d'aluminium au voisinage de la transition état normal-état supraconducteur. Grâce au 'supercooling' important d'un des échantillon, nous avons pu étendre nos mesures bien au dessous de la température critique. Nous comparons les résultats expérimentaux à la théorie.