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REVERSIBLE MAGNETIZATION OF SURFACE SUPERCONDUCTIVITY*

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Direct measurements of the surface superconducting magnetization of the PbTl system shows that this state is a thermodynamic reversible one.

SINCE THE PREDICTION of surface superconductivity in type II materials many experiments have shown the existence of such a thermodynamic state [1]. Most of those results are obtained from the dynamic response of the superconducting state to the external perturbation (i.e. surface impedance, a.c. susceptibility, thermal conductivity, etc.). On the other hand very little experimental information is available to describe the equilibrium thermodynamic properties of the state. This is so because the small ratio of the superconducting volume to the total volume of the sample makes difficult the measurements of extensive thermodynamic properties.

Based on Ginzburg and Landau theory, Fink and Kessinger [2] made theoretical calculations of the spatial dependence of the order parameter near the surface and the contribution of the superconducting sheath to the total magnetization. They arrived to the conclusion that the state is a superconducting singly connected region of thickness of the order of the coherence length of the material. The associated susceptibility is always greater than $-1/4\pi$ due to the finite penetration of the field in the superconducting region. The thermodynamic transition should be reversible either as a function of magnetic field or temperature.

To our knowledge only one experiment [3] has been done to measure the magnetization of the surface superconducting state. In that experiment the magnetization was obtained from torque measurements above H_{c2}. According to these authors the experimental results showed that the transition to the superconducting state was not reversible, in contradiction with theory [2]. To explain their results they proposed for the surface state a multiply connected pinned structure. A second indication of such irreversible state is given by Gollub *et al.* [4] in their measurements to determine the contribution of thermodynamic fluctuations to the magnetization. In their experiment the magnetization was measured as a function of temperature at constant magnetic field. It was found that below the surface critical temperature the magnetization was never reversible if the surface superconductivity was not fully suppressed. No detailed investigation of the surface magnetization is reported by these authors.

Other aspect of interest in the superconducting surface state is the possibility of using it as a "surface thermometer" [5]. Since research on heat transfer in our laboratory is based in the use of this thermometer, we consider of importance to study the magnetization of the surface in order to establish under which conditions the surface transition is well described by theory [2] and, if not, to investigate which can be the influence of the results on the definition of the surface temperature.

By means of the SQUID [6] we made direct measurements of surface magnetization in the PbTl system. The samples were rectangular foils less than half a millimeter thick, 15 mm long and 3 mm wide. They were thermally anchored to a copper rod that was connected through a thermal resistance to a helium bath maintained at constant temperature. The temperature of the rod was changed by means of a heater and it was measured using a calibrated germanium thermometer. The sample was magnetically coupled to the SQUID by means of a superconducting transformer. All the samples were annealed four days at 320°C and for five minutes at 3°C below the melting temperature.

To avoid induced current around the foil, surface superconductivity was suppressed at the edges of the sample by chrome plating.

Fields up to 350 Oe were applied parallel to the long axis of the sample by a superconducting coil.

Two samples of $Pb_{95}Tl_5$ and $Pb_{99}Tl_1$ were measured. A typical experimental curve is shown in Fig. 1. Contrary to previous measurements [3, 4] our magnetization curves are reversible when measured between the surface critical temperature and the critical temperature of the bulk, for all the range of magnetic fields we measured (see insert Fig. 1). As was said before a multiply connected model for the surface sheath was

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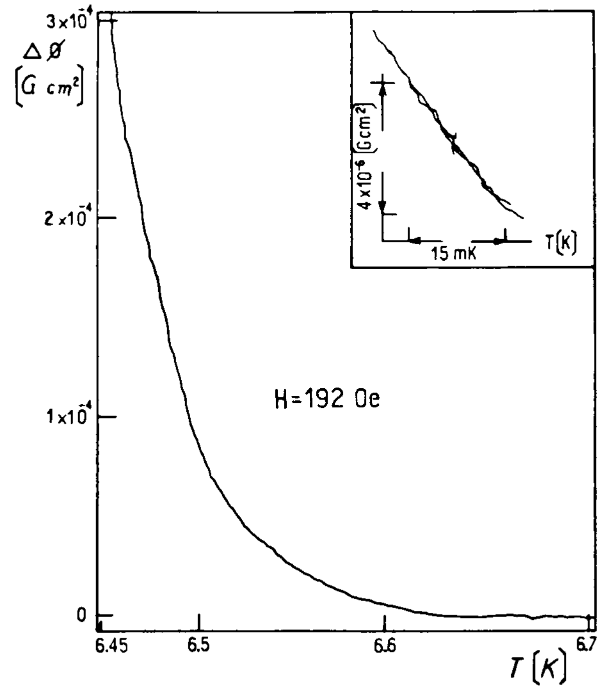

Fig. 1. Typical magnetometer signal. In the insert, an enlargement of the signal is shown. The double line corresponds to cooling and heating, and shows that hysteresis is less than experimental error.

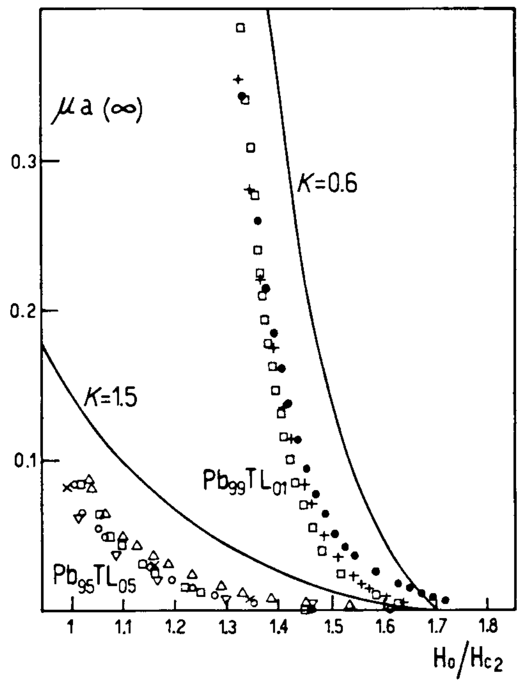

Fig. 2. Results for both alloys compared with Fink and Kessinger's calculations for $\mu a(\infty)$, as defined in [2]. Experimental points were taken at different magnetic fields x 48 Oe, ▽ 96 Oe, ○ 144 Oe, □ 192 Oe, △ 240 Oe, ● 288 Oe, + 336 Oe.

proposed [3] to explain the irreversible curves observed by other authors. Our results do not require such a model and are in agreement with the reversible nature of the transition as predicted by theory.

Since our experimental set up measures the total flux change in the sample it is necessary to substract the possible contribution of bulk thermal fluctuations. Due to the large surface to volume ratios of our samples and using the results of Gollub *et al.* [4] it is possible to show that the fluctuations contribution is, at most, 10% of the measured values. This contribution was not taken into account when comparing with theory.

To compare our results with theory [2] we need to characterize our samples by their Ginzburg–Landau parameter κ. For the 5% sample κ was determined by measuring H_{c2} and using the thermodynamic critical field of Pb [7]. For the 1% sample H_c is greater than H_{c2} and κ was obtained by measuring H_{c3} and H_c. The thermodynamic field agrees within experimental error with that reported in [7]. The values so obtained are $\kappa = 1.6$ for the 1% sample and $\kappa = 0.6$ for the other, in agreement with the values obtained by Bon Mardion *et al.* [8].

Figure 2 shows our experimental data for both samples at different magnetic fields and the corresponding theoretical curves of Fink and Kessinger [2]. The parameter $\mu a(\infty)$ is defined in [2] and is proportional to the magnetization per unit volume of a slab of thickness much larger than the thickness of the superconducting sheath. It can be seen that the agreement is only qualitative.

Our data show that the irreversible behaviour found by other authors [3, 4] should be related to induced currents around the sample and not to the nature of the surface state. In [4] it was found that when gold plating a strip on the sample the irreversibility was greatly reduced. Some preliminary results from experiments performed by us show that magnetization is indeed irreversible when the sample is not plated or when it is partially copper plated instead of chrome plated. The hysteresis observed by us differ in magnitude and shape from that reported in [4]. This could be explained if the irreversible behaviour depends on the shape and size of the cross section of the sample since our rectangular samples have an area about twenty times smaller than that of the cylinder used by Gollub *et al.* [4].

It is worthwhile to think how a temperature sweep can induce surface currents and contribute to a non reversible magnetization. It is evident that if the thickness of the surface sheath is temperature independent, a temperature sweep should not induce a net surface current and the magnetization should be a measurement of the increase of the order parameter as a function of temperature. But it is known [2] that the thickness of surface increases when the temperature is decreased. That will tend to reduce the normal cross section of the sample and if the superconducting region is multiply connected there will be induced currents in order to maintain the magnetic flux constant.

Sweeping the magnetic field will also induce currents in order to maintain a constant flux through the sample. This currents should be greater than those induced when sweeping temperature because the increase in thickness of the sheath is small compared to the total cross section.

There is no simple explanation however for the effect that the induced currents produce on the irreversibility observed in [4] and in our preliminary work. This makes difficult a comparison with the results of [3] since their measurements were done by sweeping field at constant temperature.

Research is now under way to understand the irreversible behaviour further.

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