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Thermodynamics of "Irreversible" Superconductors: Trapped Flux as the Lowest Free Energy State*

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In this and subsequent work it will be shown that a vast quantity of experimental data on what are commonly called irreversible superconductors can be analysed to show that superconductors containing defects are in their lowest free energy state when they retain flux in the absence of an external magnetic field.

The formation of defects in a crystalline material, (say by cold working or irradiation), requires a positive amount of work and will increase the free energy of the crystal through the internal energy term in

$$dF = dE - d(TS). \quad (1)$$

However, the configurational entropy associated with the defects lowers dF through a positive contribution to dS . Thus, the lowest free energy for a crystalline material at any given temperature can occur for a nonzero concentration of defects, and in fact does so.⁽¹⁾ In addition to this means of lowering the

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free energy, (which may be available to both the normal and superconducting states) the free energy of the superconducting state given by

$$dF = dE - d(TS) - d(HM) \quad (2)$$

can also be lowered by a term containing a positive M . Therefore the increase in free energy in the superconducting state arising from the increase in the internal energy due to defects, can be reduced when the superconductor containing defects "traps" flux. It has already been shown⁽²⁾ that the thermal properties of remnant flux in various superconducting systems cannot be explained by assuming the existence thermally activated pinning sites. The temperature dependence of the trapped flux was found to vary with thermodynamic properties of the materials.

In this work we will show that the "trapped" field lowers the free energy of the superconducting state by the same amount that the transport current raises it. Consequently the actual governing relationship between "trapped" flux (B_r) and critical current (I_c) is given by

$$(B_r)^2 \propto \Delta F \propto I_c^2 \quad (3)$$

(where ΔF is the existing difference in free energy between the normal and superconducting states in the presence of B_r and I_c)

$$\text{and not } I_c \propto B_r \quad (4)$$

$$\text{or } I_c \propto 1/B_r \quad (5)$$

which is common to models assuming the existence of Lorentz forces⁽³⁾ and internal field gradients. (In other work we will present experiments demonstrating that these gradients are metastable.)

If one considers the two relations

$$I_c = K_1 B_r \quad (6)$$

and

$$(I_c)^2 = K_2 (B_r)^2 \quad (7)$$

where the proportionality constants K_1 and K_2 can have the same temperature dependence, it is obvious that these relations cannot be distinguished if I_c and B_r are considered only at a single equivalent point at each temperature.

If we postulate that the maximum value of the "trapped" flux that occurs in zero field (B_m) (i.e. that value obtained when the sample is first driven normal with applied field before the field is removed) is determined by ΔF_0 (the difference in free energy between the normal and superconducting states in zero field) then

$$(B_m)^2 = \alpha_1 \Delta F_0 \quad (8)$$

Similarly if we consider that a transport current I raises the free energy of the superconducting state so that the conventional critical current at which resistivity first occurs (I_m) is the value at which the superconducting free energy reaches the normal value, then

$$(I_m)^2 = \alpha_2 \Delta F_0 \quad (9)$$

Now consider the case in which a superconductor containing "trapped" flux at a given temperature has some arbitrary transport current $I_c < I_m$ applied in zero external field. The increase in free energy due to the current must be compensated by expulsion of some of the "trapped" flux which reduced the free energy. Expressed in terms of reduced coordinates, the relation obtained from (8) and (9) that must hold at all temperatures is

$$\left(\frac{B_r}{B_m}\right)^2 + \left(\frac{I_c}{I_m}\right)^2 = 1 \quad (10)$$

It is worth noting that in this analysis the steady nonresistive current in zero external field associated with any value of B_r is a critical current since any increase will cause B_r to decrease. In the experiments carried out (in this case 5% Sb in Sn in the form of a cylinder with about 50 mil diameter and 1/2" long) the field was "trapped" in the direction of the long axis. A transport current was passed through the long axis (so that no Lorentz force is exerted on the internal field) and the magnetic moment corresponding to each value of the current was measured by integrating electronically the emf induced in a pickup coil when the sample was moved through the coil.

It is found that the fraction of the maximum flux expelled at all temperatures is the same continuous function of reduced current (I_c/I_m) and fits the quadrant of the circle described by equation (10) as shown in Fig. 1.

Just as in analagous thermal experiments⁽²⁾ it is found that flux in zero applied field is expelled only during the first time the current is increased. When the current is removed the value of the moment in zero field does not change. If the current is reapplied, no change in moment occurs until the current exceeds the previous value. Only when I_c reaches I_m is any resistivity detected.

The above behavior along with the observation that a single curve of the reduced functions is obtained at all temperatures (where I_m varied from ~4 amps to 60 amps) indicates that spurious effects such as heating or flux jumps are not affecting these results.

We therefore conclude that the results support the postulate that the maximum "trapped" flux lowers the free energy of the superconducting state by the same amount that the critical current I_m raises it. Thus the zero field state with remnant flux corresponds to a thermodynamically lower free energy state than the cold worked superconductor without flux.

Figure Caption

Fig. 1 - The isothermal functional dependence between critical current and remnant flux (in reduced coordinates) for different temperatures. The continuous line is the calculated dependence obtained by assuming the remnant flux is determined by the free energy of the superconducting state. The experimental points are obtained from a series of isothermal experiments in 5% Sb in Sn over a range of temperatures.

References

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