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Equivalence of Hysteresis and Phase Equilibria: The Thermodynamic
Origin of Hysteresis in Superconductors*

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It is the purpose of this letter to describe thermodynamic properties of hysteresis loops and show that they are also general properties of equilibrium phase systems. In the examples given the major hysteresis loops of "irreversible" superconductors will be considered. It will be obvious, however, that many of the thermodynamic properties must hold also for the hysteresis loops of ferromagnets. We will show that the thermodynamic argument for the stability of trapped flux given in other work⁽¹⁾ also accounts for hysteresis.

Consider the magnetization curve of an ideal "reversible" superconductor (either Type I or Type II) as shown in Fig. 1a. The single line in the M-H plane denotes the locus of all accessible (stable) states available to the superconductor. Now consider the initial magnetization curve and the major hysteresis loop of an irreversible superconductor as shown in Fig. 1b. The area above curve A and below curve C denotes the inaccessible (unstable) states for superconductivity. The points enclosed between curve A and B and the ordinate are metastable and are accessible only once through a single path (corresponding to an initial minor hysteresis loop) when the system is kept isothermal. Every point in the area enclosed by the major hysteresis loop is a point accessible to the superconductor. By varying only the applied field, H, the superconducting system can be moved from any point to any other point (along forward and reverse curves and the diamagnetics connecting them). This procedure can be repeated indefinitely.

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Now consider the end points of the major hysteresis loop (shown as 1 and 2 in Fig. 1b). These points are states where each thermodynamic parameter is invariant and a unique value of free energy describes each point. Since two curves connect these points on the M-H plane, the most general treatment is to assume that two possible paths exist in either one or both of the F-M planes and F-H planes. We will show that all the points in the major hysteresis loop area lie on a single curve in the F-H plane. [The analysis is general for other hysteresis loops since it is independent of the relative values of the free energies at the two end points, ~~and does not require that the free energy at the high field (normal state) is lower than the free energy at zero field (superconducting state).~~]

Transfer the major hysteresis loop to the F-M plane in which two arbitrary free energy paths connect points (1) and (2) as shown in Fig. 2. Since every point enclosed in the loop corresponds to an experimentally obtainable state, it is immediately obvious that an infinite number of distinguishable (different values of H, M) states exist with the same free energy along the dashed line shown or any other horizontal line connecting the two curves. When only magnetic work is done (i.e., no appreciable pressure-volume changes) the free energy change along any path equivalent to a reversible path is given by

$$dF = -\int M dH - \int S dT$$

Since an isothermal path exists ($\int S dT = 0$) which has the property that no free energy change occurs between any two arbitrary points along the path, this path corresponds to one in which dH is zero. We therefore find that the major hysteresis loop in a superconductor has the general property that all states of the system between the forward and reverse curves at a given value of H have the same free energy independent of the value of M. The energy associated with $H\Delta M$ for two equal free energy states is equivalent to an isothermal (latent) heat term which is in

turn equivalent to a $T\Delta S$ term. The entropy change (ΔS) must now be considered to distinguish equal free energy states with different internal field distributions.

Changes in Internal Field Distribution When the Average Value of the Internal Field is Invariant

We will now use the results of an argument given in other work⁽²⁾ to show that the difference in superconducting states corresponding to the forward and reverse paths on the hysteresis loop for the same value of internal field result from changes in the uniformity of the internal field. The path between the forward and reverse curves of the major hysteresis ^{100%} for which the internal field is invariant is the diamagnetic. This is the actual experimental path traversed when the direction of field change is reversed. The concept of diamagnetism is equivalent to that of a surface shielding current whose magnitude is proportional to the difference between external and internal fields (the magnetic moment). Whenever such a field difference exists a surface current (Ampere current) will flow if the internal field is uniform. The current will flow through the region over which the field difference exists. Thus the surface shielding current is determined by two factors, the field difference and the degree of uniformity of the internal field. In general the diamagnetics connecting the hysteresis loop occur between points of different absolute moments (field differences). Nevertheless the shielding current is the same. Therefore the uniformity (entropy) must change so that it makes up for the difference in magnetic moment.

The Origin of Hysteresis

From the above discussion we find that entropy changes occur when either H or B is invariant. We therefore conclude that M can be functionally related to S . The argument previously given⁽¹⁾ that the superconductor with defects is in its lowest free energy state when it traps flux, then can predict the thermodynamic

$$\frac{\partial F}{\partial H} = \frac{\partial M}{\partial S} = \frac{\partial M}{\partial T}$$

properties of the hysteresis loop.

It was postulated⁽¹⁾ that the increase in free energy of the superconducting state due to defects can be reduced by a positive contribution in the HM or TS term in

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

However if M and S are functionally related there can exist a range of different values of M and S that correspond to the same free energy. This leads to a multiplicity of distinguishable states of equal free energy.

We now consider the problem of whether each of the states are unique or whether the system is made up of varying volumes of a limited number of unique states.

Consider the case of two solutions made of the same chemical components that differ only in the relative concentrations of the components. If they have the same free energy at the same temperature they cannot be in equilibrium unless they are immiscible i.e. they exist as separate phases. If they were miscible then all intermediate compositions would have the same free energy and the entropy of mixing would be equivalent to a reversible latent heat or pressure-volume term. Therefore it would be possible through a simple experimental operation to cause a reversible concentration separation. Such a situation is a contradiction of the concept of the chemical potential.

We must therefore consider the hysteresis loop to represent either a second order transition (i.e. order-disorder) or a first order phase transition. Since the free energies are equal along the constant H line, the HAM term is equivalent to a latent heat. Therefore the hysteresis loop represents superconducting phases (immiscible) that are in equilibrium. The relative volumes of each being determined by the value of H. The two end points are then equivalent to points

where the phases become miscible. The high field point corresponding to miscibility with the normal state and the zero field point corresponding to one in which only a single value of M and S is available to the system. We propose that the two phases are respectively one in which the internal field is completely uniform and the other in which it exists with its maximum gradient. The volume of uniform phase increases with increasing cold-working or defect concentration. In the limit of high defect concentration only this phase exists. Under this condition the area under the hysteresis loop approaches zero. This in fact is observed experimentally.⁽²⁾ The major hysteresis loop of cold worked samples in which the upper critical field is trapped is a single line corresponding to the diamagnetic.⁽²⁾ This observation confirms the postulate that only one phase exists. The diamagnetic, in addition, requires that the phase is one in which the internal field is completely uniform.⁽²⁾

In other work we will show that experiments on how the superconductor actually "traps" flux, support this argument and show that only the uniform field phase is stable in the absence of an external field. It is worth noting that the phenomena of "training," flux jumps, the absence of size effects in samples that show low field hysteresis, the changes in critical currents with field and cold working, and the absence of any evidence for pinning sites in thermal experiments in zero applied field⁽³⁾ are logical consequences of this explanation.

Figure Captions

Fig. 1a - Typical Magnetization Curve for a Reversible Superconductor

Fig. 1b - Initial Magnetization Curve and Major Hysteresis Loop for an Irreversible Superconductor

Fig. 2 - Arbitrary Free Energy Paths Corresponding to the Forward and Reverse Curves of the Major Hysteresis Loop

References

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- (2) D. G. Schweitzer and B. Bertman, "Evidence of the Instability of Flux Gradients in "Irreversible" Superconductors", submitted to Phys. Rev. Letters.
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$-4\pi M$
(H-B)

H →

$+4\pi M$
(B-H)

(Ia)

$-4\pi M$

0

(2)

$+4\pi M$

(1)

(Ib)

H →