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INFLUENCE OF TRANSPORT CURRENT ON THE MAGNETIZATION OF A HARD SUPERCONDUCTOR*

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The influence of transport current on the magnetization of cold-worked Nb-Zr wire in a transverse field has been studied at 4.2°K. The magnetic moment (diamagnetic or paramagnetic) is reduced by the transport current and tends to zero as the critical current is approached.[1] At any given field the curve of magnetic moment versus transport current is not single-valued, but is seen to depend on the sequence of application of the current and field and also on the history of the transport current at the final field. The results can be understood on the basis of the Bean model for the magnetization of a hard superconductor[2] when the field produced by the transport current is taken into consideration.

The sample consists of a noninductive, close-wound, single-layer coil, 3 cm in length, 1.4 cm in diameter, of severely cold-worked, Formvar insulated, 10-mil diameter Nb-Zr (25%) wire. The magnetization of the sample is determined by ballistically measuring the emf induced in a pick-up coil surrounding the sample when the latter is suddenly driven well above its transition temperature by a heat pulse.

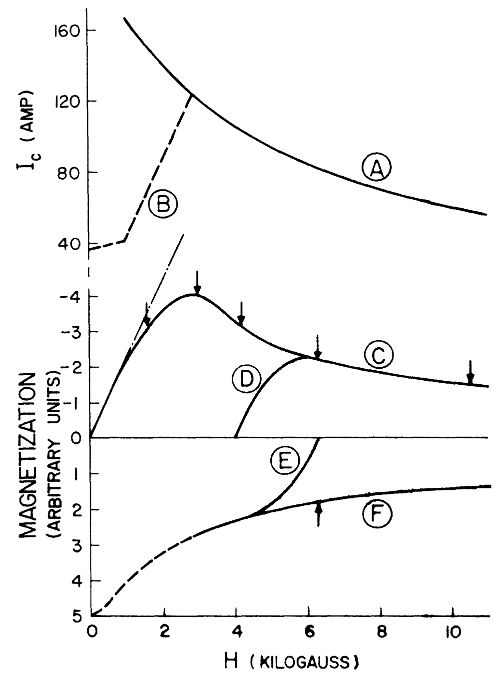

FIG. 1. Curve A–Critical current vs transverse external field. Curve B–Critical current for initial resistive transition vs external field for paramagnetic critical state. Curve C–Initial magnetization. Curves D and E–Approach to saturation magnetization after cooling in 4.0 and 6.3 kG, respectively. Curve F–Saturation paramagnetic moment vs external field after cooling in 12 kG.

Curve C of Fig. 1 shows the initial magnetization as the field is increased, and curve F gives the paramagnetic moment vs final field after cooling in a field of 12 kG. The maximum magnetization in a field H_a is independent of previous history provided the final change of the applied field which induces the magnetization is sufficient to achieve saturation of the flux screening or flux trapping currents at the final field. Curves D and E of Fig. 1 show the approach to saturation magnetization for different initial conditions, i.e., cooling in 4.0 and 6.3 kG, respectively. No evidence of a Meissner effect upon cooling in a field was observed at any field.

Curve A of Fig. 1 gives the critical current I_c vs H_a. This critical current is reproducible (no training occurs) and independent of the sequence of application of field and current and of the magnetization, provided the latter lies on curve C and the solid part of curve F or inside the region defined by these and the horizontal axis. Curve B gives the critical current for the initial resistive transitions (approximately independent of the sequence of application of current and lowering of the field) which occur when the sample has a magnetization represented by the dashed section of curve F. If Joule heating is minimized, the resistive transitions (curve B) do not quench but may influence the magnetization. In our measurements significant Joule heating occurs before the residual current is interrupted. Partly or wholly for this reason we observe that subsequent resistive transitions occur at progressively larger currents until curve A is reached and the magnetization reduces to zero.

The behavior of the magnetization of our specimen with and without transport current can be qualitatively understood in terms of the model of a hard superconductor proposed by Bean[2] and extended by Kim, Hempstead, and Strnad.[3] According to this model, the magnetization of a hard superconductor in fields greater than a "bulk" critical field H_{FP} at which penetration first occurs (approximately 0.8 kG for our sample) is due to currents induced in the specimen by changes in the external field. These currents are lossless up to a critical current density which is a function of the local magnetic field. When every region of the specimen carries the maximum supercurrent determined by the magnetic field at that region, a critical state is reached. For every applied field $H_a > H_{FP}$ there corresponds a diamagnetic and paramagnetic critical state of the specimen for a constant temperature and given orientation with respect to H_a. Since the average internal field $\bar{B}$ is $<H_a$ for the diamagnetic case and $>H_a$ for the paramagnetic case, and the critical current density generally decreases with increasing field, the critical magnetization $|M|$ should exhibit the property that $|M|$ diamagnetic $>$ $|M|$ paramagnetic. The magnetization data presented in Fig. 1 are consistent with the above discussion.

The influence of transport current on the magnetization was studied for the magnetic moments indicated in Fig. 1 by arrows. Figure 2(a) schematically describes various current-field sequences of operation which have been explored. For instance, in procedure IId the field is changed from zero to the final value H_a and maintained at this value while a current I is applied, then removed, and a measurement of the resulting magnetization is made. For the paramagnetic case the procedures depicted in Fig. 2(a) would show the field to change to H_a from a higher value [10 kG for Fig. 2(c)]. To insure nearly isothermal conditions, H and I were changed smoothly at approximately 80 G/sec and 2 A/sec, respectively.

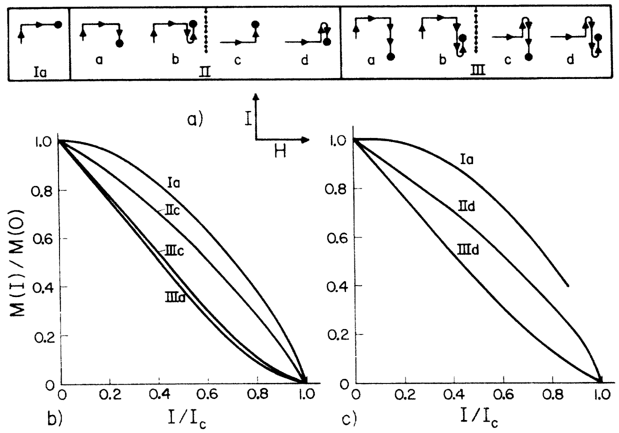

FIG. 2. (a) Various current-field operations grouped according to approximate equivalence of experimental data. (b) Diamagnetic moment at 6.3 kG after current-field operation indicated. Curves IIIa and IIIc show typical maximum deviation of data from same group of operation. (c) Paramagnetic moment at 6.3 kG after procedure shown.

Figures 2(b) and 2(c) give some of the results for the diamagnetic and paramagnetic cases, respectively, at $H_a = 6.3$ kG of $M(I)/M(0)$ vs I/I_c, where I is the maximum transport current flowing in the wire during the operation.

For each of the procedures of Fig. 2(a), the results can be given approximately by $M(I)/M(0) = 1 - (I/I_c)^n$. For a given operation for diamagnetic moments, n is a function of H_a and decreases with H_a increasing from 1.5 to 4.2 kG and remains nearly constant for H_a of 4.2, 6.3, and 10.5 kG. This behavior remains to be carefully studied for paramagnetic moments.

First we discuss magnetization of the specimen carrying a transport current I [procedure Ia of Fig. 2(a)]. Consider an infinite sheet of a Bean superconductor parallel to the y-z plane with thickness w extending from $x = 0$ to $x = w$ in an applied field H parallel to z (see Fig. 3). Suppose that a transport current of average density $\bar{j}_t = I/A$ is flowing parallel to the y axis where A is the cross-sectional area of the Nb-Zr wire. After a suitable change of H to a final value H_a, the sample is in a critical state with a local total current density $|\vec{j}_T| = |\vec{j}_i + \vec{j}_t|$, where $\vec{j}_i$ and $\vec{j}_t$ are the induced and transport current densities, respectively. Assume that $|\vec{j}_T|$ is independent of $B(x)$. Then $|\vec{j}_T| =$ constant which we take to be $|I_c|/A$. The internal magnetic field $B(x)$ can be

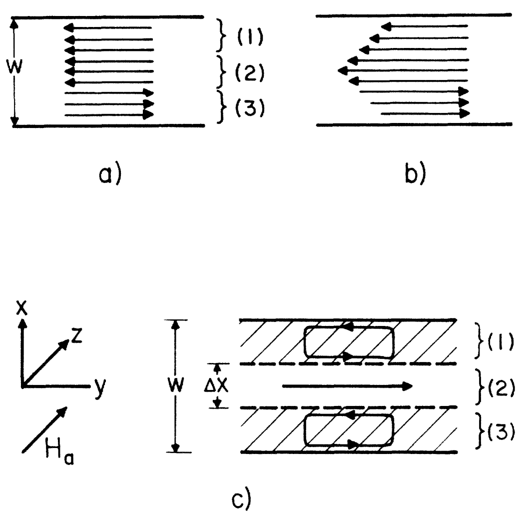

FIG. 3. (a) Assumed distribution of currents in critical state after magnetization with transport current present. Critical current density independent of local field. (b) Diamagnetic case. Trial distribution of currents with transport current present. Critical current density greater at lower fields. (c) Artificial model. Regions (1) and (3) saturated with critical circulating currents. Region (2) saturated with critical transport currents.

calculated from the relation

$$B(x) = H_a + \frac{4\pi}{10}\int_0^w j_T(x')\left\{\frac{x'-x}{|x'-x|}\right\}dx', \tag{1}$$

where currents flowing in the direction of $+x$ are taken to be $+$. By definition, the magnetization $M(I)$ as a function of the transport current I is given by

$$4\pi M(I) = \frac{1}{w}\int_0^w \{B(x) - H_a\}dx. \tag{2}$$

We would expect a distribution of currents as shown schematically in Fig. 3(a) and readily calculate from Eq. (2) for this distribution that

$$M(I)/M(0) = 1 - (I/I_c)^2. \tag{3}$$

With the assumed distribution, $M(I)$ does not depend on the presence of I in the sheet, and the role of I appears only in establishing the relative width of regions 1 and 2 of Fig. 3(a). Consequently, insofar as a close-wound single layer of cylindrical wires is equivalent to an infinite sheet, Eq. (3) is applicable to the data obtained by procedure Ia of Fig. 2(a), although in the noninductive winding I alternates direction through the layer. At 4.2, 6.3, and 10.5 kG, our results for $M(I)$ diamagnetic give $n = 2$ within experimental accuracy.

For $H_a < 4$ kG, I_c changes rapidly with field and the assumption of $|j_T| =$ constant in Eq. (1) is no longer valid and the current density would increase appreciably towards the center of the sheet for a diamagnetic moment. Applying Eq. (2) with various distributions of current such as shown in Fig. 3(b), we obtain $M(I)/M(0) \approx 1 - (I/I_c)^n$, where $n > 2$, in qualitative agreement with our data at 1.5 and 2.8 kG where $n \approx 3$ and 2.5, respectively.

The data (see Fig. 2 for illustration) indicate that some of the nine procedures explored leave the specimen in macroscopically equivalent magnetization states. Inspection of the results suggests a grouping of the procedures as shown in Fig. 2(a) yielding three main curves for the paramagnetic and diamagnetic case which occupy the relative positions shown in Fig. 2, where at any I/I_c the curves of group I and III are nearly symmetrically displaced from that of group II. The processes which we believe give rise to this equivalence, relative position, and symmetry can be easily described in terms of a simple though artifical picture incorporating the basic feature of the Bean model.

Consider a sheet [see Fig. 3(c)], arbitrarily divided into three layers, and assume that transport current can only flow in the middle layer of thickness Δx, where $\Delta x/w = I/I_c$. ($H_a \parallel z, I \parallel y$). The upper and lower layers are initially in a critical state with circulating currents of density I_d which we take to be diamagnetic to simplify discussion.

(A) A transport current I is initially present in the middle layer. (i) Remove I. This is equivalent to introducing a current $|I|$ of opposite direction. The flux associated with the latter induces currents opposing this flux change. In layer 1 the induced currents die out since they bring the total current density above the critical limit and $\bar{B}$ increases by $\Delta\bar{B}$. In layer 3 the induced currents successfully oppose the change, maintain $\bar{B}$ constant, and I_d is now subcritical having decreased by $\Delta\bar{I}_d$. The diamagnetic moment M of the sheet decreases by ΔM. (ii) Replace I. The diamagnetic moment remains $M - \Delta M$. In layer 1 the currents become subcritical, while in layer 3 they return to critical. (iii) Remove and reverse I. This is equivalent to introducing a current $|2I|$ in the final direction, hence, the changes of (i) are doubled.

(B) No transport current is present initially. Layers 1 and 3 fill and share the sheet equally. Introducing a transport current displaces circulating currents from the middle sheet and also disturbs the initial state in the remaining volume according to the processes discussed above in (i).

Applying this artificial model to the operations of Fig. 2(a) for the paramagnetic and diamagnetic cases leads to complete agreement with the empirical observations presented above. Pursuing this simple model leads to the expectation that after the quenching of the magnetization produced by one cycle of current, additional cycling (magnitude remaining constant) will not disturb the magnetization further, in agreement with our measurements within experimental accuracy.

Although we have assumed, for simplicity, that the transport and circulating currents occupy physically separate regions, we may expect that in a real superconductor, where both types of currents are superimposed and the situation is more complicated, the phenomena considered above still occur and account for our observations. As the transport current is changed, the total current distribution and the flux configuration in the specimen is modified in such a way that the local total current density tends to rise above critical in some elements of volume while it becomes subcritical in others of equivalent effective volume. Our discussion indicates that the field associated with the transport current as well as the transport current itself can influence the magnetization. Our results confirm and extend the Bean model of a hard superconductor and indicate that the critical magnetization curve (diamagnetic and paramagnetic) can be obtained from the I_c vs H curve and vice versa.

Below ≈3 kG, the behavior of the paramagnetic magnetization conforms to the above discussion until "anomalous" resistive transitions at critical currents I_c' (curve B of Fig. 1) perturb the measurements. This phenomenon is tentatively attributed to the sudden local onset of an intermediate state which disrupts the critical state, since over part of the cross section of the wire the local field becomes $H_a - 2I_c'/10r \approx H_{FP}$. At the same H_a and I_c' on the initial magnetization curve, the sample is not in a critical state and the appearance of an intermediate state is not "catastrophic."

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OSCILLATIONS IN GaAs SPONTANEOUS EMISSION IN FABRY-PEROT CAVITIES

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In injection lasers,[1-3] just below the threshold for single-mode operation, equally spaced lines in the spectrum have been observed. The lines are due to stimulated emission in low-loss modes of the Fabry-Perot cavity and they have been discussed by several workers.[4-6] In this Letter we report the observation of oscillations in the spectra of some GaAs injection lasers a factor of more than 40 at 2°K and 500 at 77°K below the threshold current for single-mode operation. As threshold is approached, these oscillations merge continuously with the equally spaced lines discussed above. However, they do not result from stimulated emission but arise from multiple reflections of the spontaneous emission between the ends of the Fabry-Perot cavity. This phenomenon has been theoretically discussed previously[7,8] but not observed. From the study of these oscillations as a function of current it is possible to measure, among other things, the internal loss of the laser and the variation of index of refraction in the region of the absorption edge.

The lasers studied were made by diffusing Zn into Te-doped GaAs and had cleaved ends and