number of current experiments.[2-6]

A comprehensive analysis of the work described here is in the process of preparation for publication.[11]

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MAGNETOTHERMAL EFFECTS IN TYPE II SUPERCONDUCTORS*

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The fundamental characteristic of type II superconductors is the existence of a magnetic mixed state[1] which occurs between a lower magnetic field H_{c1} and an upper field H_{c2}. Abrikosov's model,[1] comprised of a lattice of quantized, flux-enclosing supercurrent vortices, has recently received direct experimental confirmation.[2] New magnetothermal effects,[3] observed in massive rods of pure niobium (mono- and polycrystalline) and of niobium-31 % zirconium with magnetic field directions both parallel and perpendicular to the axis of the rods, are described here. These effects are related to the detailed structure of the flux penetration mechanism and possibly to the existence of collective modes of vibration of the Abrikosov vortices.

Temperature measurements were taken at different points of the samples with carbon-resistance thermometers. The samples were placed in a vacuum calorimeter, with one extremity of the sample in limited thermal contact with the helium bath. A heater was attached to the other extremity, and pick-up coils wound around the samples allowed ballistic measurements of the variations of magnetic flux. The temperature was recorded while the magnetic field strength was increased or decreased linearly in time. The sweep rates ranged from 0.8 to 13.5 Oe/sec. There were no heat or electric currents applied externally during the measurements. After each sweep of the field, the heater was used to drive the sample normal in zero field, thus excluding trapped flux.

Three distinct temperature phenomena were observed in the mixed state for both increasing and decreasing fields and over the whole range of sweep rates mentioned above: (1) A continuous heating rate $\dot{q}$, proportional to the absolute value of the time derivative of the applied field $|\dot{H}|$ and resulting in a temperature rise ΔT, started at the values of the field $H_1{}^*$ close to H_{c1}, passed through a maximum and decreased back to zero as H attained the value H_{c2}. The temperature rise ΔT was observed to disappear upon interruption of the sweep in a time less than one second. This over-all behavior of the temperature is shown in Fig. 1(a)

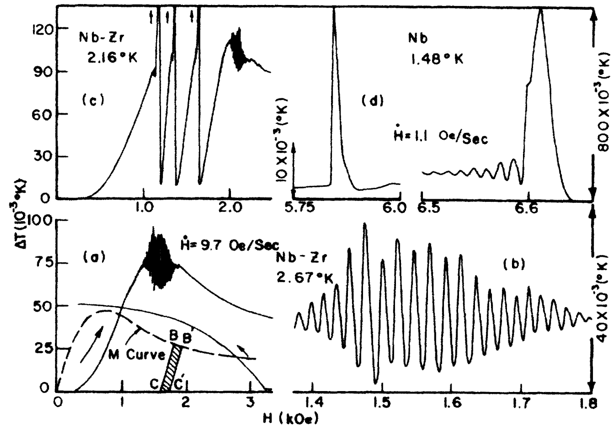

FIG. 1. Temperature change vs applied field ($H \perp$ rod). (a) The overall heating and the fluctuations in Nb-Zr, with the fluctuations separately displayed in (b). The heating pulses are shown in (c) for Nb-Zr and in (d) for polycrystalline Nb. Also shown in (a) is the irreversible magnetization cycle used to derive Eq. (1).

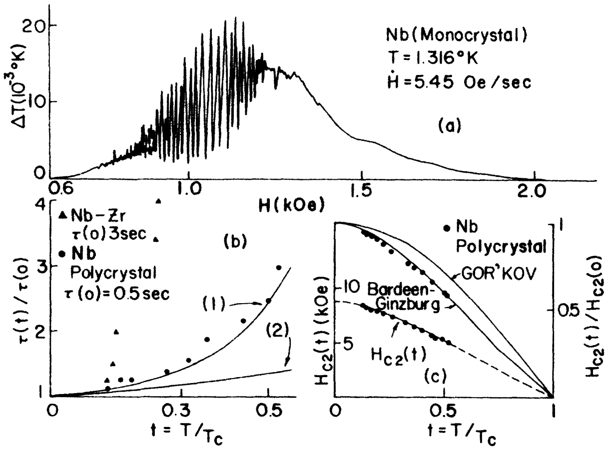

FIG. 2. (a) Typical temperature fluctuation appearing in the overall heating for Nb monocrystal. (b) Normalized period $\tau(t)/\tau(0)$ of fluctuations vs t. $\tau(0)$ is found by extrapolation of $\tau(t)$ vs t. The solid curves are alternative temperature dependences derived from Eq. (2). (c) H_{c2} vs $t=T/T_c$ for Nb polycrystal. The extrapolated value $H_{c2}(0)$ is used to plot $H_{c2}(t)/H_{c2}(0)$ vs t; the solid curves represent theoretical expressions.

for Nb-Zr and in Fig. 2(a) for Nb monocrystal. The range of available magnetic field strengths did not reach H_{c2} in the case of Nb-Zr. It did for Nb, allowing a precise measurement of H_{c2}. (2) Oscillatory fluctuations of the temperature were observed with periods $\tau \sim 1$-10 seconds. Such a fluctuation, shown in Fig. 1(a) for Nb-Zr, occurred at the maximum of the heating curve. Figure 1(b) reproduces this fluctuation at the actual scale of the recording. Figures 1(d) and 2(a) show this phenomenon in Nb polycrystal and Nb monocrystal, respectively. As the temperature was lowered, the number of such fluctuations increased in the case of the unannealed polycrystalline Nb and Nb-Zr samples, each set of fluctuations culminating into a giant heat pulse. In the case of the monocrystalline Nb sample, only one long set of fluctuations occurred at all the temperatures investigated (4.2°K to 1.3°K) [see Fig. 2(a)]. The period of the fluctuations increased strongly with increased temperature, as shown in Fig. 2(b) for both Nb and Nb-Zr. It was observed that the fluctuations stopped immediately if the sweep was stopped. The absence of any decay of the fluctuations on stopping the sweep was probably due to the simultaneous and sharp drop of the sample temperature to the bath temperature. (3) In the case of the polycrystalline samples, a series of heating pulses of very large amplitude (~1°K) appeared at discrete, reproducible values of H, as shown in Figs. 1(c) and 1(d). The pulses were also observed in decreasing field, but at respectively lower values of H. They were often, but not always, preceded by fluctuations [see Fig. 1(d) where both instances are shown]. They were always followed by a relaxation of the sample temperature to the bath temperature. Simultaneously with each of these heat pulses, sudden penetration (for $\dot{H} > 0$) or exclusion (for $\dot{H} < 0$) of magnetic flux was observed ballistically. These heat pulses were therefore related to discontinuous steps in the magnetic field penetration (flux jumps). The temperature behavior indicated that at the end of each step, a regenerated state of thermodynamic equilibrium was achieved. This phenomenon seems correlated to recent observations by LeBlanc[4] in magnetization measurements on Nb-Zr. In this context, the behavior of the monocrystal of Nb is marked by the absence of such heating spikes, as shown in Fig. 2(a).

Interpretation. – (1) In the case of samples having irreversible magnetization behavior, energy considerations were applied to the two irreversible magnetization cycles $OBCO$ and $OB'C'O$ shown in Fig. 1(a). These cycles can be experimentally approximated if one assumes the sample to be heated to $T > T_c$ at the points C and C' and cooled to $T < T_c$ at the point O. The paths BC and $B'C'$ of slope $\frac{1}{4}\pi$ are idealized approximations of the actual behavior of the magnetization M upon reversal of the field sweep. This approximation is supported by the experimental data of Kim et al.[5] Along these paths absence of heat production was assumed. This assumption is supported by the experimental observation, in all samples, that upon reversal of sweep, there exists a range of about 300 Oe during which no heating occurs. Taking the difference between the two cycles and assuming the equality of specific heats at points C and C', the calculation gave, for the rate of heat production $\dot{q}$ along the path BB',

$$\dot{q} \leq -M(1 + 4\pi dM/dH)\dot{H} = -M\dot{B}, \tag{1}$$

where the inequality sign occurs if one takes into account the possible existence of heat production along the actual paths approximated here by BC and $B'C'$. The temperature rise ΔT would be, under the present experimental conditions, proportional to $\dot{q}$, the constant of proportionality being determined by the thermal resistivity of the system. Equation (1) shows that $\dot{q}$ and ΔT vanish for $M = -H/4\pi$ or 0 and for $\dot{H} = 0$. This predicts correctly the appearance of heating at H_{c1}, its disappearance at H_{c2}, as well as its abrupt disappearance when the sweep is stopped. The phenomenon allows, therefore, a simple and accurate determination of H_{c2} for any massive, magnetically irreversible, superconductor of type II. Figure 2(c) shows the temperature dependence of $H_{c2}(t)$ for polycrystalline Nb. $H_{c2}(0)$ determined by extrapolation was found to be 8700 Oe. The same figure shows the plot of $H_{c2}(t)/H_{c2}(0)$ versus $t = T/T_c$. Excellent agreement was found with the Bardeen-Ginzburg[6,7] curve $H_{c2}(t)/H_{c2}(0) = (1-t^2)/(1+t^2)$, while the Gor'kov[8] curve $H_{c2}(t)/H_{c2}(0) = (1-0.24t^2+0.04t^4)(1-t^2)$ was clearly inapplicable. This result confirms those of Jones et al.[9] for Nb. The temperature dependence of $H_1{}^*$ is still under investigation.

(2) The cause and nature of the fluctuations is not clear. Their existence in all the three samples investigated, the reproducibility, and the large values of the period are noteworthy. A tentative identification of these fluctuations with one of the collective modes of vibration of the Abrikosov vortex lines predicted by deGennes and Matricon,[10]

$$\omega \simeq \frac{eBk^2\lambda d}{m^*c} \quad (\vec{k} \perp \vec{H}), \tag{2}$$

was attempted. Here, e, B, and c have their usual meaning, m^* is an effective mass of the supercurrent electrons, k is the wave number, λ is the penetration depth, and d is the interline distance. If $k = \pi/L$, where L is some unknown characteristic distance of the oscillating system, then, taking for the polycrystalline Nb $m^* = 50$ electronic masses, $B_{t=0} \simeq H_{c2}(0) = 8700$ Oe, $\lambda(0) \simeq 10^{-5}$ cm, and $\omega(t=0) \simeq 2.1$ sec^{-1}, one finds $L \simeq 0.25$ cm. This is of the same order as the radius of the Nb rod. This indicates that if the array of vortex lines were vibrating like a two-dimensional lattice, then the characteristic dimension of the lattice is of the order of the radius of the sample. The temperature dependence expected from Eq. (2) for the period is $\tau(t)/\tau(0) = [(1-t^4)/(1-t)]^{1/2}$ assuming L to be independent of temperature. This is shown by curve (2) in Fig. 2(b). If one assumes L to be of the nature of Bean's[11] penetration depth, with a temperature dependence $L \sim (1-t^2)^{-1}$, one gets $\tau(t)/\tau(0) = [(1-t^4)/(1-t) \times (1-t^2)^4]^{1/2}$ shown by curve (1) in Fig. 2(b). There is a fair agreement of the date for polycrystalline Nb with curve (1). The data for Nb-Zr do not agree with either curve. Pinning of the flux lines by bulk defects leads to the expectation that collective modes of vibration are high-frequency ones[12]; however, low frequencies would be favored if pinning by surface defects were the preponderant factor. The identification of the fluctuations with collective modes suffers from the basic contradiction between strong bulk pinning implied by the irreversible magnetic behavior and the negligible bulk pinning required for the existence of long-period modes. Another alternative is to consider the fluctuations as produced by a succession of small flux avalanches, but the regularity of their behavior seems to suggest some unknown coupling mechanism. Further investigation is underway on the effects of size, shape, and progressive annealing.

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LENGTH CHANGE OF ELECTRON-IRRADIATED GERMANIUM*

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The purpose of this Letter is to report length contractions in n-type germanium due to electron bombardment at liquid-helium temperature and to propose the interpretation that these length contractions are produced by an electronic effect which dominates over the expansions caused by the atomic effect. In contrast to n type, the length changes of a p-type sample irradiated under the same conditions are smaller by more than an order of magnitude.

Simultaneous length and conductivity changes have been observed in degenerate n-type germanium single crystals during bombardment by 4.5-MeV electrons at liquid-helium temperature and during subsequent isochronal annealing. The irradiated portion of the sample measured 5 mm long, 4 mm wide, and 0.7 mm thick. The linear-accelerator electron beam passed through the sample in the [001] direction, and the length changes were measured in the perpendicular [110] direction. Changes in length of the sample produced changes in the spacing of a system of parallel plate capacitors, and these capacitors were compared with a standard capacitor by means of an ac ratio bridge. All capacitors were of the three-terminal type and the method of measurement was similar in principle to that used by White.[1] The sample and supporting framework for the capacitors was shaped from one large single crystal of germanium to minimize extraneous effects. The sensitivity and long-term stability of the system were such that changes in length on the order of 0.3 angstrom were detectable. Annealing was of the isochronal type and was accomplished by means of a heater and double exchange gas-vacuum system. The sample was held at each annealing temperature for 10 minutes before recooling to liquid-helium temperature. All measurements were made at liquid-helium temperature.

Degenerate n-type material was chosen for our initial experiments, rather than intrinsic material as used by other investigators, since the electrical measurements by Klontz and MacKay[2] and the stored-energy measurements by Singh and MacKay[3] have shown that irradiation effects in n-type material are more than 100 times greater than in p-type material.

Figure 1 shows the length change in a degenerate n-type sample as a function of the irradiation flux. From this plot $\Delta L/L = -6.2\times10^{-24}$ per incident electron/cm^2. Figure 2 shows the results for the same sample during a later run consisting of a relatively light bombardment followed by an isochronal anneal with points taken every 5 degrees. The general characteristics of the length and conductivity curves are quite similar. An annealing peak between 35 and 40°K is evident in both curves. A second sample of degenerate n-type material showed similar behavior.

Irradiation of a degenerate p-type sample at liquid-helium temperature resulted in a barely detectable contraction. The length-change effect is at least an order of magnitude smaller in p type than in n type. The fact that length