COMMENTS AND ADDENDA

The Comments and Addenda section is for short communications which are not of such urgency as to justify publication in Physical Review Letters and are not appropriate for regular Articles. It includes only the following types of communications: (1) comments on papers previously published in The Physical Review or Physical Review Letters; (2) addenda to papers previously published in The Physical Review or Physical Review Letters, in which the additional information can be presented without the need for writing a complete article. Manuscripts intended for this section may be accompanied by a brief abstract for information-retrieval purposes. Accepted manuscripts will follow the same publication schedule as articles in this journal, and galleys will be sent to authors.

Regular Flux Jumps in the Mixed State of Niobium†

M. Levy, R. Kagiwada,* F. Carsey, and I. Rudnick

Department of Physics, University of California, Los Angeles, California 90024

(Received 9 February 1970)

Unusually regular flux jumps are reported in the mixed state of niobium. The most prominent experimental effects produced by these flux jumps are thermal spikes. The effect of the flux jumps on the ultrasonic attenuation coefficient is also reported. The regularity of of the interval between the flux jumps is believed to be caused by a surface barrier. The thermal spikes are interpreted as being due to avalanching of the flux lines at the surface barrier.

We have observed some unusually regularly spaced thermal spikes, which are produced by flux jumps, in a cylindrical niobium sample of $\frac{1}{2}$ in. length and $\frac{1}{4}$ in. diam with an approximate resistivity ratio of 150 and a transition temperature $T_c = 9.21$ °K. Magnetization measurements have been performed on this sample which show steps in the magnetization coincident with the thermal spikes. Thermal spikes [1-9] and ultrasonic attenuation effects [3-6] caused by flux jumps have been previously reported in type-II superconductors, but the flux jumps did not have the present regularity. However, some of the reported [8,9] flux jumps showed other kinds of periodicity.

Reversible measurements using transverse ultrasonic waves on this sample have already been reported.[10] For the measurements reported here, the ends of the cylindrical niobium sample were polished in addition to being spark cut. Figure 1 shows ultrasonic attenuation data obtained with longitudinal waves at various temperatures on this niobium single crystal. Both the temperature of the sample and the ultrasonic attenuation coefficient are recorded as functions of magnetic field. The data taken at 1.65 °K prominently show the unusually spaced thermal spikes. It can also be seen in this figure that there are ultrasonic spikes

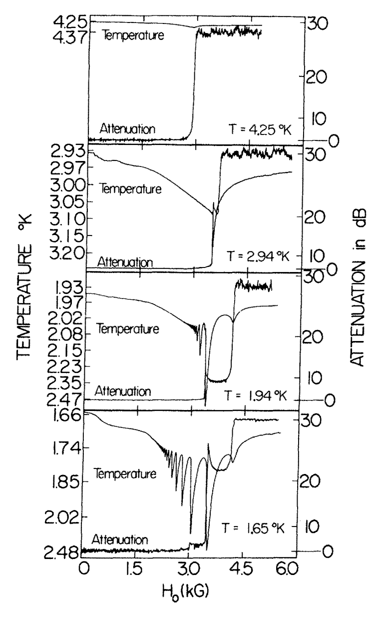

FIG. 1. Recordings of ultrasonic attenuation and temperature as a function of magnetic field for four temperatures: (a) $T = 4.25$ °K, (b) $T = 2.94$ °K, (c) $T = 1.95$ °K, and (d) $T = 1.65$ °K. The attenuation measurement is for the seventh echo of a longitudinal wave propagated in the [111] direction. $dH/dt = 25$ G/sec.

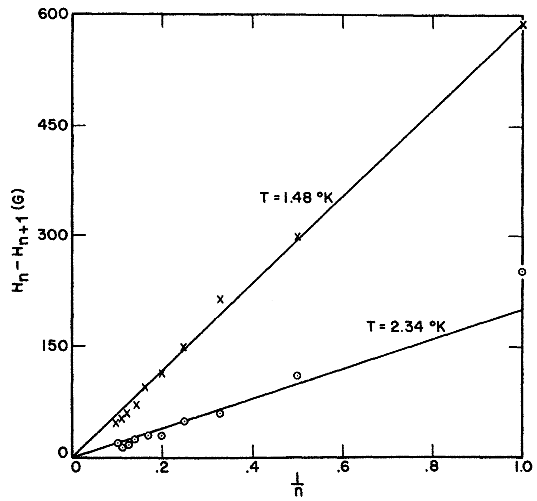

FIG. 2. Field interval between temperature spikes shown in Fig. 1 versus $(1/n)$. The largest spike has been designated $n=1$.

and steps coincident with the last few thermal spikes. All the data reported in Fig. 1 were taken with increasing magnetic field at a rate of $dH/dt = 25$ G/sec starting from a virgin sample. The thermal behavior is independent of the type of ultrasonic wave generated. In fact it is independent of the ultrasonics entirely. Figure 1(a) shows that there was only a slight heating as one went through H_{c2} at 4.25 °K. As the temperature was lowered, as shown in Figs. 1(b)–1(d) a step appeared in the attenuation. Preceding this step, however, were temperature spikes which increased in amplitude as the field was increased and vanished above H_{c2}. As one sees by referring to Fig. 1(d), these temperature spikes are most pronounced at the lower temperatures. The three largest temperature spikes have a one-to-one correspondence with the attenuation steps. For the smaller temperature spikes there appears to be no correspondence. This is due to the low sensitivity of the particular ultrasonic echo that was used. When a much later echo was used, a one-to-one correspondence was observed. Now, if one labels the last and largest spike as $n=1$, the next largest as $n=2$, and so forth, n increasing with decreasing field, and at the same time one measures the field interval between spikes, i.e., $\Delta H_n = H_n - H_{n+1}$, one obtains the relationship shown in Fig. 2. This is only a representation that we have chosen to fit the data, and we do not mean to imply that it is the only relationship which might fit them. If we measure the slope of these lines, $H_f = (H_n - H_{n+1})/(1/n) = n\,\Delta H_n$, namely, $\Delta H_n = H_f/n$, for the data as plotted in Fig. 2 and for other similar graphs, we obtain the points shown in Fig. 3. This is a plot of H_f versus the reduced temperature T/T_c. The rate of change of the magnetic field used in obtaining these data varied from about 9 to 70 G/sec. For these different rates, the field at which the temperature spikes occurred seemed to be independent of the rate. For all these experiments, the magnitude of the temperature spikes was a monotonically increasing function of the spacing between spikes. These data were obtained first in an ultrasonic investigation using previously described apparatus[11] and repeated in an ac-type magnetization probe[12] in which the sample was supported in a nylon cup and kept in good contact with a carbon thermometer.

It is evident in Fig. 1 that the temperature spikes are superimposed on a gradual increase in temperature. This gradual increase depends on the rate of change of the external magnetic field. As the rate is lowered, this temperature change is decreased. We believe that this background heating is probably due to eddy currents. There are obvious changes in the shape of the background heating in the mixed state and at H_{c2}. We construe this to be evidence for the fact that part of the background heating is connected with eddy currents in the mixed state of the niobium single crystal.

A record of both the temperature of the sample and the ultrasonic attenuation coefficient while the magnetic field is changed through a complete cycle

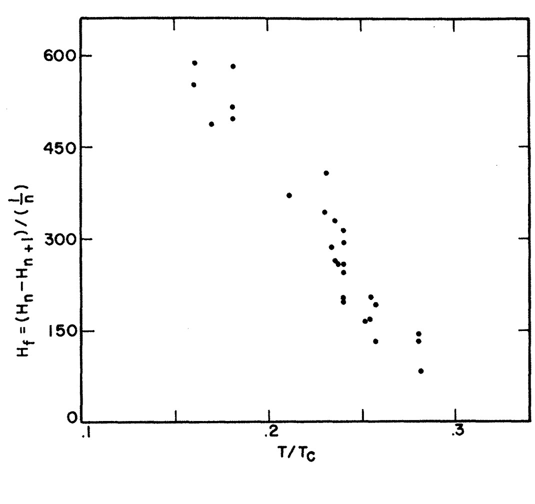

FIG. 3. Slopes $H_f = (H_n - H_{n+1})/(1/n)$ versus reduced temperature T/T_c with $T_c = 9.21$ °K. The He^4 gas pressure was approximately 10 μ.

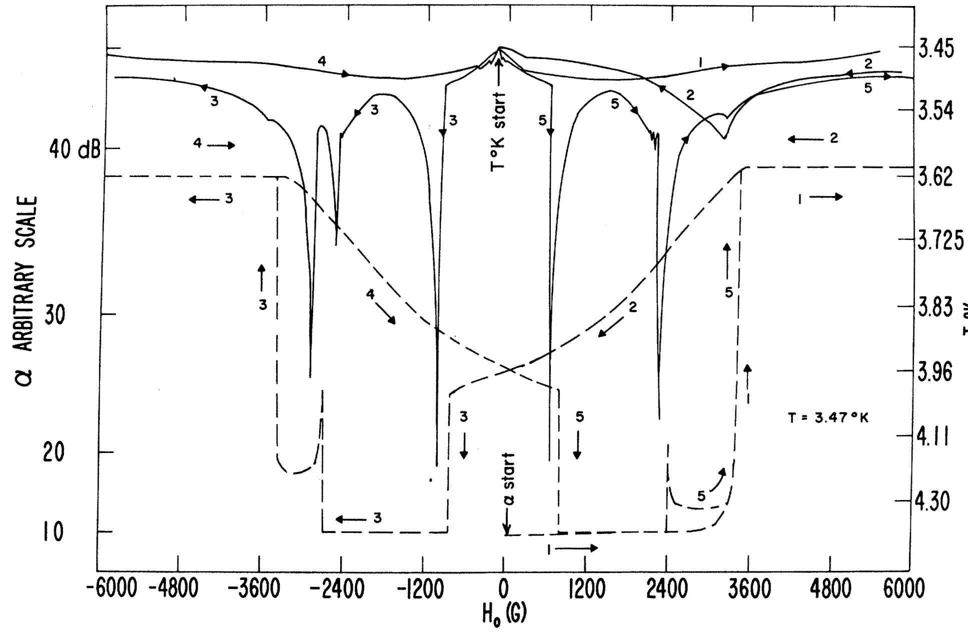

FIG. 4. Thermal (solid line) and acoustic (dashed line) hysteresis in the niobium sample No. 2 reported. The T°K curve has been shifted to the left 0.17 kG (as shown).

is shown in Fig. 4. The cycle starts from the virgin state up through $+H_{c2}$ (curve 1) and back down through zero (curve 2) to $-H_{c2}$ (curve 3), then up through zero (curve 4), and finally to $+H_{c2}$ (curve 5). At this temperature, no spikes occur on both the initial increase and decrease of the magnetic field. After the polarity of the field is reversed, the niobium is no longer in the virgin state and the spikes start to appear. (For clarity, the temperature curves have been shifted to the left by about 0.17 kG.) Curves 1, 2, and 4 show no thermal spikes. There are parts of these curves which show cooling indicative of the magneticaloric effect reported[13] on reversible niobium.

All these data (the points in Fig. 3) were obtained with about 10 μ He^4 transfer gas in the sample chamber.[11] When this pressure is increased, as is necessary to achieve the condition $T/T_c \leq 0.15$ the amplitude of the spike decreases and the otherwise observed regularity disappears. This is shown in Fig. 5. At all temperatures, the spike amplitude decreased with increased pressure, finally disappearing around 100 μ. In the other limit of Fig. 3, the range $T/T_c \simeq 0.3$, the degree of regularity could not be measured because the spike separation became comparable to the spike width. Thus, above $T/T_c = 0.3$ there were a few spikes present. Above $T/T_c = 0.425$ the spikes disappeared completely and the curves became smooth.

Although there seems to be no adequate theoretical explanation for these effects, a qualitative discussion of them will be presented next. As was mentioned earlier, there is considerable evidence that the thermal and ultrasonic spikes coincide with flux jumps. A possible explanation for these flux jumps is that there is a surface barrier to flux penetration. Thus the internal and external magnetic fields are not in equilibrium. When the difference between the two fields is sufficient to overcome the surface barrier, magnetic flux lines start to penetrate the sample irreversibly, producing heat which in turn lowers the barrier and one has an "avalanche" effect until equilibrium between the external and internal fields is attained. Once this occurs, there is no longer a mechanism for heating and the niobium crystal comes to thermal equilibrium with its surroundings. The thermal contact is weak when there is less than 10 μ of helium gas in the chamber and strong when the helium pressure in the chamber is greater than 30 μ.[14] As yet the field and temperature dependence of this barrier has not been theoretically predicted. When one starts with a virgin sample, the flux

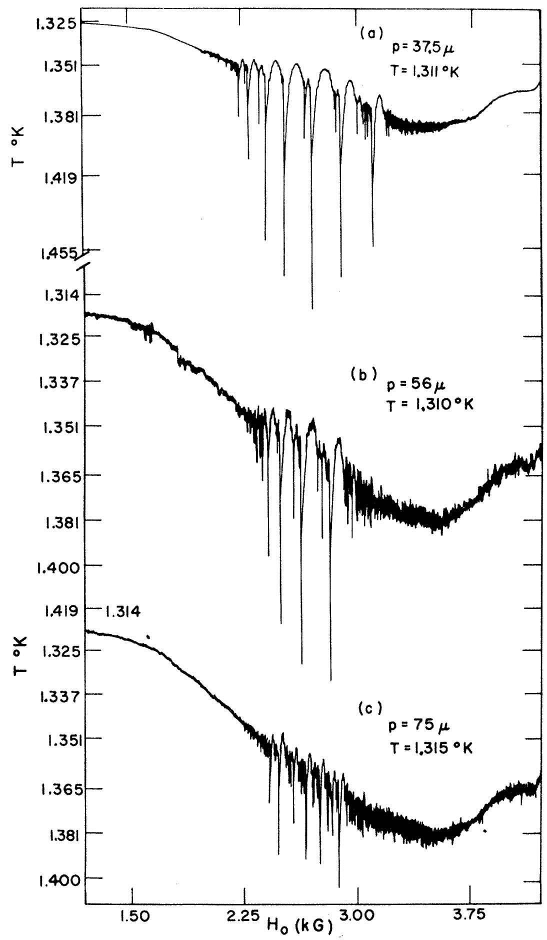

FIG. 5. Temperature spikes in niobium at different pressures, as shown. Data obtained at 10 μ are shown in Fig. 1.

jumps do not appear above $T/T_c \simeq 0.425$. If the barrier picture is reasonable, then it is possible that above this temperature, either energy or temperature fluctuations are sufficient to overcome the barrier. Following this type of reasoning then, strongly thermally coupling the niobium sample to its surroundings by increasing the helium gas pressure in the container should produce larger energy fluctuations, which in turn make flux penetration more erratic, and since now the thermal contact is stronger, thermal equilibrium is reached more rapidly and thus the magnitude of the thermal spikes is decreased. We have searched for this effect in four other niobium samples with smaller resistivity ratios and, although we did find flux jumps, they did not exhibit any regularity under any circumstances although the search involved the temperature region 1.3–4.2 °K and the pressure region from less than 10 to more than 100 μ. As with the regular flux jumps, the value of dH/dt had no effect. The rate was varied between the limits 12–50 G/sec in this part of the investigation.

The question should be asked: Is this a spurious effect? Insofar as this sample is concerned, it is not. The effect has been reproduced over a span of 2 years. Therefore, we present these results, because we believe that the regularity of these flux jumps should yield a theoretical clue about the details of the mechanism for irreversible flux penetration in type-II superconductors which exhibit a more complicated periodicity.

The authors would like to acknowledge stimulating discussions with Professor K. Maki, Professor P. Pincus, and Professor P. Wyder.

---

†Research supported by AFOSR Grant No. AF-AFOSR-70-1847 and by the Office of Naval Research, Contract No. N00014-69-A-0200-4014.

*Present address: Physics Department, University of Southern California, Los Angeles, Calif.

[1]P. W. Anderson and Y. B. Kim, Rev. Mod. Phys. 36, 39 (1964).

[2]N. H. Zebouni, A. Veukataran, G. N. Rao, C. G. Grenier, and J. M. Reynolds, Phys. Rev. Letters 13, 606 (1964).

[3]S. H. Goedmoed, C. Van Kolmeschate, J. W. Metselaar, and D. De Kerk, Physica 31, 573 (1965).

[4]L. J. Neuringer and Y. Shapira, Solid State Commun. 2, 349 (1964).

[5]L. T. Claiborne and N. G. Einspruch, J. Appl. Phys. 37, 925 (1966).

[6]R. S. Kagiwada, M. Levy, and I. Rudnick, Phys. Letters 22, 29 (1966).

[7]S. L. Wipf and M.S. Lubell, Phys. Letters 16, 103 (1965).

[8]G. del Castillo and L.O. Oswald, in Proceedings of the 1968 Summer Study on Superconducting Devices and Accelerators, Report No. BNL50155 (unpublished), pp. 601–611.

[9]A. D. McIntruff, in Ref. 8, pp. 612–618.

[10]R. Kagiwada, M. Levy, I. Rudnick, H. Kagiwada, and K. Maki, Phys. Rev. Letters 18, 74 (1967).

[11]J. L. Brewster, M. Levy, and I. Rudnick, Phys. Rev. 132, 1062 (1963).

[12]W. A. Fietz, Rev. Sci. Instr. 36, 1621 (1965).

[13]T. Ohtsuka, Phys. Letters 17, 194 (1965).

[14]There are three major means of heat transfer from the niobium sample through the copper holder to the wall of the evacuated sample chamber, which is immersed in liquid helium. These are radiation, heat conduction through solid material, and heat conduction through helium gas. Heat transferred by radiation or by conduction through the solid material is independent of helium gas pressure. The radiation process is several orders of magnitude smaller than heat conduction through the solid material. The heat transferred by conduction due to helium gas from the copper material is nearly independent of the pressures used in this experiment. These pressure changes will affect the heat transfer between the niobium sample and the copper material surrounding it, and will also change the heat capacity of the gas in the immediate vicinity of the sample, thus also making the gas an effective heat reservoir.